Some topics in analysis related to topological groups and Lie algebras

Stephen Semmes
Rice University

Preface

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Part I

Basic notions and objects

Chapter 1

Absolute values and norms

1.1 Metrics and ultrametrics

Let X be a set. A nonnegative real-valued function $d(x, y)$ defined for $x, y \in X$ is said to be a *semimetric* on X if it satisfies the following three conditions. First,

$$d(x, x) = 0 \tag{1.1.1}$$

for every $x \in X$. Second,

$$d(x, y) = d(y, x) \tag{1.1.2}$$

for every $x, y \in X$. Third,

$$d(x, z) \le d(x, y) + d(y, z) \tag{1.1.3}$$

for every $x, y, z \in X$. If we also have that

$$d(x, y) > 0 \tag{1.1.4}$$

for every $x, y \in X$ with $x \ne y$, then $d(\cdot, \cdot)$ is said to be a *metric* on X. The *discrete metric* is defined on X by putting $d(x, y)$ equal to 0 when $x = y$, and equal to 1 when $x \ne y$.

Similarly, a nonnegative real-valued function $d(x, y)$ defined for $x, y \in X$ is said to be a *semi-ultrametric* on X if if it satisfies (1.1.1), (1.1.2), and

$$d(x, z) \le \max(d(x, y), d(y, z)) \tag{1.1.5}$$

for every $x, y, z \in X$. Note that (1.1.5) implies (1.1.3), so that a semi-ultrametric on X is a semimetric on X in particular. If a semi-ultrametric $d(x, y)$ on X satisfies (1.1.4), then $d(x, y)$ is said to be an *ultrametric* on X. It is easy to see that the discrete metric on X is an ultrametric.

Let $d(x, y)$ be a semimetric on X. The *open ball* in X centered at $x \in X$ with radius $r > 0$ with respect to $d(\cdot, \cdot)$ is defined as usual by

$$B(x, r) = B_d(x, r) = \{y \in X : d(x, y) < r\}. \tag{1.1.6}$$

Similarly, the *closed ball* in X centered at $x \in X$ with radius $r \geq 0$ is defined by

$$\overline{B}(x,r) = \overline{B}_d(x,r) = \{y \in X : d(x,y) \leq r\}. \tag{1.1.7}$$

A subset U of X is said to be an *open set* with respect to $d(\cdot,\cdot)$ if for every $x \in U$ there is an $r > 0$ such that

$$B(x,r) \subseteq U. \tag{1.1.8}$$

This defines a topology on X, by standard arguments. One can check that open balls in X are open sets, and that closed balls are closed sets. If $d(\cdot,\cdot)$ is a metric on X, then X is Hausdorff with respect to the topology determined by $d(\cdot,\cdot)$.

Suppose that $d(\cdot,\cdot)$ is a semi-ultrametric on X. If $x, y \in X$ satisfy $d(x,y) < r$ for some $r > 0$, then it is easy to see that

$$B(x,r) \subseteq B(y,r). \tag{1.1.9}$$

More precisely,

$$B(x,r) = B(y,r), \tag{1.1.10}$$

because we can interchange the roles of x and y in (1.1.9). Similarly, if $x, y \in X$ satisfy $d(x,y) \leq r$ for some $r \geq 0$, then

$$\overline{B}(x,r) \subseteq \overline{B}(y,r), \tag{1.1.11}$$

and hence

$$\overline{B}(x,r) = \overline{B}(y,r). \tag{1.1.12}$$

This implies that closed balls in X with positive radius are open sets, and one can check that open balls in X are closed sets in this situation.

1.2 Absolute value functions

Let k be a field. A nonnegative real-valued function $|\cdot|$ on k is said to be an *absolute value function* on k if it satisfies the following conditions. First, $|x| = 0$ if and only if $x = 0$. Second,

$$|x\,y| = |x|\,|y| \tag{1.2.1}$$

for every $x, y \in k$. Third,

$$|x + y| \leq |x| + |y| \tag{1.2.2}$$

for every $x, y \in k$. The standard absolute value functions on the fields $\mathbf{R}$ of real numbers and $\mathbf{C}$ of complex numbers are absolute value functions in this sense. The *trivial absolute value function* on any field k is defined by putting $|x|$ equal to 0 when $x = 0$, and equal to 1 when $x \neq 0$.

If $|\cdot|$ is any absolute value function on a field k, then $|1| = 1$, where the first 1 is the multiplicative identity element in k, and the second 1 is the multiplicative identity element in $\mathbf{R}$. This uses the fact that $1^2 = 1$ in k, so that $|1| = |1|^2$ by

(1.2.1). If $x \in k$ satisfies $x^n = 1$ for some positive integer n, then $|x|^n = |1| = 1$, and hence $|x| = 1$. In particular, $|-1| = 1$, because $(-1)^2 = 1$. It follows that

$$d(x, y) = |x - y| \tag{1.2.3}$$

defines a metric on k, using $|-1| = 1$ to get that (1.2.3) is symmetric in x and y.

A nonnegative real-valued function $|\cdot|$ on a field k is said to be an *ultrametric absolute value function* on k if it satisfies the first two conditions in the definition of an absolute value function, and

$$|x + y| \le \max(|x|, |y|) \tag{1.2.4}$$

for every $x, y \in k$. It is easy to see that (1.2.4) implies (1.2.2), so that an ultrametric absolute value function on k is an absolute value function on k. If $|\cdot|$ is an ultrametric absolute value function on k, then (1.2.3) is an ultrametric on k. The trivial absolute value function on any field k is an ultrametric absolute value function. The ultrametric associated to the trivial absolute value function as in (1.2.3) is the discrete metric.

Let p be a prime number. The *p-adic absolute value* $|x|_p$ of a rational number x is defined as follows. If $x = 0$, then we put $|x|_p = 0$. Otherwise, if $x \ne 0$, then x can be expressed as $p^j\,(a/b)$ for some integers a, b, and j, where $a, b \ne 0$, and neither a nor b is an integer multiple of p. In this case, we put

$$|x|_p = p^{-j}. \tag{1.2.5}$$

One can check that this defines an ultrametric absolute value function on the field $\mathbf{Q}$ of rational numbers. The corresponding ultrametric

$$d_p(x, y) = |x - y|_p \tag{1.2.6}$$

is known as the *p-adic metric* on $\mathbf{Q}$.

Let k be any field again, and let $\mathbf{Z}_+$ be the set of positive integers, as usual. If $x \in k$ and $n \in \mathbf{Z}_+$, then let $n \cdot x$ be the sum of n x's in k. An absolute value function $|\cdot|$ on k is said to be *archimedean* on k if there are $n \in \mathbf{Z}_+$ such that $|n \cdot 1|$ is arbitrarily large. Otherwise, $|\cdot|$ is said to be *non-archimedean* on k. If $|\cdot|$ is an ultrametric absolute value function on k, then it is easy to see that

$$|n \cdot 1| \le 1 \tag{1.2.7}$$

for every $n \in \mathbf{Z}_+$, so that $|\cdot|$ is non-archimedean on k. Conversely, it is well known that a non-archimedean absolute value function on k is necessarily an ultrametric absolute value function on k. In particular, (1.2.7) holds for every $n \in \mathbf{Z}_+$ in this case, which can be verified more directly. More precisely, if $|\cdot|$ is any absolute value function on k, then one can check that

$$|n^j \cdot 1| = |(n \cdot 1)^j| = |n \cdot 1|^j \tag{1.2.8}$$

for all positive integers j, n. If $|n \cdot 1| > 1$ for some $n \in \mathbf{Z}_+$, then (1.2.8) tends to $+\infty$ as $j \to \infty$, so that $|\cdot|$ is archimedean on k.

1.3 Equivalent absolute value functions

If a is a positive real number with $a \le 1$, then it is well known that

$$(r+t)^a \le r^a + t^a \tag{1.3.1}$$

for all nonnegative real numbers a, b. To see this, observe first that

$$\max(r,t) \le (r^a + t^a)^{1/a} \tag{1.3.2}$$

for every $a > 0$. We also have that

$$r + t = r^{1-a}\, r^a + t^{1-a}\, t^a \le \max(r^{1-a}, t^{1-a})\, (r^a + t^a). \tag{1.3.3}$$

If $a \le 1$, then it follows that

$$r + t \le \max(r,t)^{1-a}\, (r^a + t^a) \le (r^a + t^a)^{(1-a)/a+1} = (r^a + t^a)^{1/a}, \tag{1.3.4}$$

using (1.3.2) in the second step. This implies (1.3.1), as desired.

Let $d(x,y)$ be a semimetric on a set X. If $0 < a \le 1$, then one can check that

$$d(x,y)^a \tag{1.3.5}$$

also defines a semimetric on X. More precisely, one can verify that (1.3.5) satisfies the triangle inequality using (1.3.1) and the triangle inequality for $d(x,y)$. If $d(x,y)$ is a semi-ultrametric on X, then (1.3.5) is a semi-ultrametric on X for every $a > 0$.

Suppose that $d(x,y)$ is a semimetric on X again, and that (1.3.5) is a semimetric on X too for some $a > 0$. Observe that

$$B_{d^a}(x, r^a) = B_d(x,r) \tag{1.3.6}$$

for every $x \in X$ and $r > 0$, and that

$$\overline{B}_{d^a}(x, r^a) = \overline{B}_d(x,r) \tag{1.3.7}$$

for every $x \in X$ and $r \ge 0$. In particular, (1.3.6) implies that $d(x,y)$ and (1.3.5) determine the same topology on X.

Let k be a field, and let $|\cdot|$ be an absolute value function on k. If $0 < a \le 1$, then $|x|^a$ also defines an absolute value function on k. As before, this uses (1.3.1) to get the triangle inequality for $|x|^a$ from the triangle inequality for $|\cdot|$. If $|\cdot|$ is an ultrametric absolute value function on k, then $|x|^a$ is an ultrametric absolute value function on k for every $a > 0$.

Suppose that $|\cdot|$ is an absolute value function on k again, and that $|\cdot|^a$ is an absolute value function on k as well for some $a > 0$. Thus the metric associated to $|\cdot|^a$ on k is the same as the ath power of the metric associated to $|\cdot|$ on k. Hence these two metrics determine the same topoplogy on k, as in the preceding paragraph.

Let $|\cdot|_1$ and $|\cdot|_2$ be absolute value functions on k. If there is a positive real number a such that

$$|x|_2 = |x|_1^a \tag{1.3.8}$$

for every $x \in k$, then $|\cdot|_1$ and $|\cdot|_2$ are said to be *equivalent* on k. In this case, the metrics associated to $|\cdot|_1$ and $|\cdot|_2$ determine the same topology on k, as in the previous paragraph. Conversely, if the metrics associated to $|\cdot|_1$ and $|\cdot|_2$ determine the same topology on k, then it is well known that $|\cdot|_1$ and $|\cdot|_2$ are equivalent on k, in the sense of (1.3.8).

Let $|\cdot|$ be an absolute value function on $\mathbf{Q}$. A famous theorem of Ostrowski implies that $|\cdot|$ is either equivalent to the standard absolute value function on $\mathbf{Q}$, or $|\cdot|$ is the trivial absolute value function on $\mathbf{Q}$, or $|\cdot|$ is equivalent to the p-adic absolute value function on $\mathbf{Q}$ for some prime number p.

1.4 Completions

Let (X, d_X) and (Y, d_Y) be metric spaces, and let E be a dense subset of X. Suppose that f is a uniformly continuous mapping from E into Y, with respect to the restriction of d_X to E. If Y is complete with respect to d_Y, then it is well known that there is a unique extension of f to a uniformly continuous mapping from X into Y. More precisely, uniqueness only uses continuity of the extension.

If X is not complete, then it is well known that one can pass to a completion, which is given by an isometric mapping from X onto a dense subset of a complete metric space. The completion is unique up to isometric equivalence, because of the extension theorem mentioned in the preceding paragraph.

Let X be a set with a semimetric $d(x, y)$, and let E be a dense subset of X. If the restriction of $d(x, y)$ to $x, y \in E$ defines a semi-ultrametric on E, then one can check that $d(x, y)$ is a semi-ultrametric on X. In particular, the completion of an ultrametric space is an ultrametric space too.

Let k be a field, and let $|\cdot|$ be an absolute value function on k. If k is not complete with respect to the metric associated to $|\cdot|$, then one can pass to a completion. It is well known that the field operations on k can be extended to the completion, in such a way that the completion is also a field. The absolute value function on k can be extended to an absolute value function on the completion, which corresponds to the distance to 0 in the completion. The completion of k is unique, up to isometric isomorphic equivalence.

If $|\cdot|$ is an ultrametric absolute value function on k, then the extension of $|\cdot|$ to the completion of k is an ultrametric absolute value function as well. This is analogous to the earlier statement for ultrametric spaces, and can be obtained from that statement. Alternatively, let k_1 be any field with an absolute value function $|\cdot|$, and let k_0 be a subfield of k_1. It is easy to see that $|\cdot|$ is archimedean on k_1 if and only if the restriction of $|\cdot|$ to k_0 is archimedean on k_0.

Let p be a prime number. The field $\mathbf{Q}_p$ of *p-adic numbers* is obtained by completing $\mathbf{Q}$ with respect to the p-adic absolute value function $|\cdot|_p$. The corresponding extension of $|\cdot|_p$ to $\mathbf{Q}_p$ is also denoted $|\cdot|_p$, and defines an ultrametric absolute value function on $\mathbf{Q}_p$. If $x \in \mathbf{Q}_p$ and $x \neq 0$, then one can check that $|x|_p$ is an integer power of p.

Let k be a field with an absolute value function $|\cdot|$ again. If k has positive characteristic, then it is easy to see that $|\cdot|$ is non-archimedean on k. Suppose that $|\cdot|$ is archimedean on k, which implies that k has characteristic 0. If k is complete with respect to the metric associated to $|\cdot|$, then another famous theorem of Ostrowski implies that k is isomorphic to $\mathbf{R}$ or $\mathbf{C}$, in such a way that $|\cdot|$ corresponds to an absolute value function on $\mathbf{R}$ or $\mathbf{C}$ that is equivalent to the standard absolute value function.

1.5 Discreteness

Let k be a field, and let $|\cdot|$ be an absolute value function on k. Observe that

$$\{|x| : x \in k,\ x \neq 0\} \tag{1.5.1}$$

is a subgroup of the group $\mathbf{R}_+$ of positive real numbers with respect to multiplication. Of course, (1.5.1) is the trivial subgroup $\{1\}$ of $\mathbf{R}_+$ exactly when $|\cdot|$ is the trivial absolute value function on k. If 1 is not a limit point of (1.5.1) with respect to the standard topology on $\mathbf{R}$, then $|\cdot|$ is said to be *discrete* on k.

Put

$$\rho_1 = \sup\{|x| : x \in k,\ |x| < 1\}, \tag{1.5.2}$$

so that $0 \leq \rho_1 \leq 1$. If $|\cdot|$ is the trivial absolute value function on k, then $\rho_1 = 0$. Conversely, if $|\cdot|$ is not the trivial absolute value function on k, then there is a $y \in k$ such that $y \neq 0$ and $|y| \neq 1$. This implies that there is an $x \in k$ such that $x \neq 0$ and $|x| < 1$, by taking $x = y$ when $|y| < 1$ and $x = 1/y$ when $|y| > 1$. Thus $\rho_1 > 0$ when $|\cdot|$ is nontrivial on k.

If $|\cdot|$ is a discrete absolute value function on k, then $\rho_1 < 1$. Conversely, if $\rho_1 < 1$, then $|\cdot|$ is discrete on k. More precisely, the definition of ρ_1 implies that there is no $x \in k$ such that $\rho_1 < |x| < 1$. If $y \in k$ and $|y| > 1$, then we can apply the previous statement to $x = 1/y$, to get that $1/|y| \leq \rho_1$. It follows that 1 is not a limit point of (1.5.1) in $\mathbf{R}$ when $\rho_1 < 1$, as desired.

Suppose that $|\cdot|$ is an archimedean absolute value function on k. This implies that k has characteristic 0, as in the previous section. Hence there is a natural embedding of $\mathbf{Q}$ into k. This leads to an absolute value function on $\mathbf{Q}$, using $|\cdot|$ on k. It is easy to see that $\mathbf{Q}$ is archimedean with respect to this absolute value function, because k is archimedean with respect to $|\cdot|$. Using this and Ostrowski's classification of absolute value functions on $\mathbf{Q}$ mentioned in Section 1.3, we get that this absolute value function on $\mathbf{Q}$ is equivalent to the standard absolute value function. In particular, it follows that this absolute value function on $\mathbf{Q}$ is not discrete. This means that $|\cdot|$ is not discrete on k. If $|\cdot|$ is a discrete absolute value function on k, then $|\cdot|$ is non-archimedean on k, and hence $|\cdot|$ is an ultrametric absolute value function on k.

Suppose that $|\cdot|$ is a nontrivial discrete absolute value function on k, so that $0 < \rho_1 < 1$. If $y, z \in k$ and $|y| < |z|$, then

$$|y| \le \rho_1 \, |z|, \tag{1.5.3}$$

because $|y/z| = |y|/|z| < 1$, and hence $|y/z| \le \rho_1$, by the definition (1.5.2) of ρ_1. One can check that the supremum is attained in (1.5.2), since otherwise there would be distinct elements of (1.5.1) close to ρ_1, whose quotient would be close to 1 but not equal to 1. Thus ρ_1 is an element of (1.5.1), which implies that (1.5.1) contains all integer powers of ρ_1. In fact, one can verify that every element of (1.5.1) is an integer power of ρ_1 in this case.

Suppose that $|\cdot|$ is an ultrametric absolute value function on k. If $x, y \in k$ satisfy

$$|x - y| < |y|, \tag{1.5.4}$$

then

$$|x| = |y|. \tag{1.5.5}$$

More precisely,

$$|x| \le \max(|x - y|, |y|) = |y|, \tag{1.5.6}$$

by the ultrametric version of the triangle inequality. Similarly,

$$|y| \le \max(|x - y|, |x|), \tag{1.5.7}$$

which implies that $|y| \le |x|$ in this situation.

Let k_0 be a subfield of k that is dense with respect to the ultrametric associated to $|\cdot|$. The remarks in the preceding paragraph imply that

$$\{|x| : x \in k_0,\ x \ne 0\} \tag{1.5.8}$$

is the same as (1.5.1). In particular, if k is not already complete with respect to the ultrametric associated to $|\cdot|$, then the nonzero values of the extension of $|\cdot|$ to the completion of k is the same as (1.5.1).

1.6 p-Adic integers

Let k be a field, let x be an element of k, and let n be a nonnegative integer. Observe that

$$(1 - x) \sum_{j=0}^{n} x^j = \sum_{j=0}^{n} x^j - \sum_{j=0}^{n} x^{j+1} = \sum_{j=0}^{n} x^j - \sum_{j=1}^{n+1} x^j = 1 - x^{n+1}, \tag{1.6.1}$$

where x^j is interpreted as being the multiplicative identity element 1 in k when $j = 0$. If $x \ne 1$, then it follows that

$$\sum_{j=0}^{n} x^j = (1 - x^{n+1})\,(1 - x)^{-1}. \tag{1.6.2}$$

Let $|\cdot|$ be an absolute value function on k, so that

$$\left|\sum_{j=0}^{n} x^j - (1-x)^{-1}\right| = |x^{n+1}\,(1-x)^{-1}| = |x|^{n+1}\,|1-x|^{-1}. \tag{1.6.3}$$

If $|x| < 1$, then we get that

$$\lim_{n\to\infty}\left|\sum_{j=0}^{n} x^j - (1-x)^{-1}\right| = 0. \tag{1.6.4}$$

Let p be a prime number, and let y be an integer. Thus $x = p\,y$ satisfies

$$|x|_p = p^{-1}\,|y|_p \le p^{-1} < 1, \tag{1.6.5}$$

where $|\cdot|_p$ is the p-adic absolute value, as before. It follows that

$$\lim_{n\to\infty}\left|\sum_{j=0}^{n} p^j\,y^j - (1-p\,y)^{-1}\right|_p = 0, \tag{1.6.6}$$

as in (1.6.4). Note that $\sum_{j=0}^{n} p^j\,y^j$ is an integer for each nonnegative integer n.

Suppose that $z \in \mathbf{Q}$ satisfies $|z|_p \le 1$. This means that z can be expressed as a/b, where a and b are integers, $b \ne 0$, and b is not a multiple of p. Hence there is an integer c such that $b\,c \equiv 1$ modulo p, because the integers modulo p form a field. Thus z can be expressed as

$$z = (a\,c)/(b\,c) = a\,c\,(1-p\,y)^{-1}, \tag{1.6.7}$$

where y is an integer. This implies that z can be approximated by integers with respect to the p-adic metric, because of the analogous statement for $(1-p\,y)^{-1}$, as in the preceding paragraph.

Put

$$\mathbf{Z}_p = \{x \in \mathbf{Q}_p : |x|_p \le 1\}, \tag{1.6.8}$$

which is the set of *p-adic integers*. Of course, the set $\mathbf{Z}$ of integers is contained in $\mathbf{Z}_p$, by the definition of the p-adic absolute value. This implies that the closure of $\mathbf{Z}$ in $\mathbf{Q}_p$ with respect to the p-adic metric is contained in $\mathbf{Z}_p$, because $\mathbf{Z}_p$ is a closed set in $\mathbf{Q}_p$. Conversely, let $x \in \mathbf{Z}_p$ be given, and let us check that x is in the closure of $\mathbf{Z}$ in $\mathbf{Q}_p$. Of course, $\mathbf{Q}$ is dense in $\mathbf{Q}_p$, by construction. Thus x can be approximated by $z \in \mathbf{Q}$ with respect to the p-adic metric. In particular, if $|x-z|_p \le 1$, then $|z|_p \le 1$, by the ultrametric version of the triangle inequality. This means that x can be approximated by $z \in \mathbf{Q}$ with $|z|_p \le 1$ with respect to the p-adic metric. If $z \in \mathbf{Q}$ and $|z|_p \le 1$, then z can be approximated by integers with respect to the p-adic metric, as in the previous paragraph. This implies that x can be approximated by integers with respect to the p-adic metric, as desired.

1.7 Residue fields

Let k be a field, and suppose that $|\cdot|$ is an ultrametric absolute value function on k. It is easy to see that the open ball $B(0,r)$ in k centered at 0 with radius $r > 0$ with respect to the ultrametric associated to $|\cdot|$ is a subgroup of k as a commutative group with respect to addition. Similarly, the closed ball $\overline{B}(0,r)$ in k centered at 0 with radius $r \geq 0$ is a subgroup of k with respect to addition. The closed unit ball $\overline{B}(0,1)$ is a subring of k, which contains the multiplicative identity element 1 in k in particular. Note that $B(0,r)$ is an ideal in $\overline{B}(0,1)$ when $0 < r \leq 1$, and that $\overline{B}(0,r)$ is an ideal in $\overline{B}(0,1)$ when $0 \leq r \leq 1$.

Thus the quotient

$$\overline{B}(0,1)/B(0,r) \tag{1.7.1}$$

can be defined as a commutative ring when $0 < r \leq 1$, and

$$\overline{B}(0,1)/\overline{B}(0,r) \tag{1.7.2}$$

can be defined as a commutative ring when $0 \leq r \leq 1$. One can check that

$$\overline{B}(0,1)/B(0,1) \tag{1.7.3}$$

is a field, which is the *residue field* associated to $|\cdot|$ on k. More precisely, a nonzero element of (1.7.3) comes from an element x of $\overline{B}(0,1)$ that is not in $B(0,1)$. This means that $|x| = 1$, so that $1/x$ is an element of $\overline{B}(0,1)$ too. The element of (1.7.3) corresponding to $1/x$ is the inverse of the given element of (1.7.3), as desired.

If $|\cdot|$ is the trivial absolute value function on k, then $\overline{B}(0,1) = k$, $B(0,1) = \{0\}$, and the residue field (1.7.3) reduces to k itself. If k has characteristic $p > 0$, and $|\cdot|$ is any ultrametric absolute value function on k, then it is easy to see that the reside field (1.7.3) has characteristic p as well.

Let k be any field with an ultrametric absolute value function $|\cdot|$ again, and let k_0 be a subfield of k. The restriction of $|\cdot|$ to k_0 defines an ultrametric absolute value function on k_0, and there is a natural embedding of the residue field associated to k_0 into the residue field associated to k. If k_0 is dense in k with respect to the ultrametric associated to $|\cdot|$, then one can check that the embedding of the residue field associated to k_0 into the residue field associated to k is surjective, so that the residue fields are isomorphic. In particular, if k is not complete with respect to the ultrametric associated to $|\cdot|$, then the residue field associated to the completion of k is isomorphic to the residue field associated to k.

Let p be a prime number, and consider $k = \mathbf{Q}_p$ with the p-adic absolute value. In this case,

$$\overline{B}(0,p^{-j}) = p^j\,\mathbf{Z}_p \tag{1.7.4}$$

for every $j \in \mathbf{Z}$, where $p^j\,\mathbf{Z}_p$ is the set of $p^j\,x$, $x \in \mathbf{Z}_p$. As before, $\mathbf{Z}_p$ is a subring of $\mathbf{Q}_p$, $p^j\,\mathbf{Z}_p$ is an ideal in $\mathbf{Z}_p$ for each nonnegative integer j, and hence the quotient

$$\overline{B}(0,1)/\overline{B}(0,p^{-j}) = \mathbf{Z}_p/(p^j\,\mathbf{Z}_p) \tag{1.7.5}$$

is defined as a commutative ring when $j \geq 0$. There is a natural ring homomorphism from $\mathbf{Z}$ into (1.7.5), which is the composiiton of the inclusion of $\mathbf{Z}$ in $\mathbf{Z}_p$ with the quotient mapping from $\mathbf{Z}_p$ onto (1.7.5). Observe that

$$\mathbf{Z} \cap (p^j \, \mathbf{Z}_p) = p^j \, \mathbf{Z} \tag{1.7.6}$$

for every nonnegative integer j, which is the kernel of the homomorphism from $\mathbf{Z}$ into (1.7.5) just mentioned. Thus we get an injective ring homomorphism from

$$\mathbf{Z}/(p^j \, \mathbf{Z}) \tag{1.7.7}$$

into (1.7.6) for each nonnegative integer j. One can check that this homomorphism is surjective, because $\mathbf{Z}$ is dense in $\mathbf{Z}_p$, as in the previous section. This shows that (1.7.5) is isomorphic to (1.7.7) as a ring for every nonnegative integer j.

1.8 Norms and ultranorms

Let k be a field with an absolute value function $|\cdot|$, and let V be a vector space over k. A nonnegative real-valued function N on V is said to be a *seminorm* on V with respect to $|\cdot|$ if it satisfies the following two conditions. First,

$$N(t\, v) = |t| \, N(v) \tag{1.8.1}$$

for every $t \in k$ and $v \in V$. Second,

$$N(v + w) \leq N(v) + N(w) \tag{1.8.2}$$

for every $v, w \in V$. Note that (1.8.1) implies that $N(0) = 0$, by taking $t = 0$. If we also have that

$$N(v) > 0 \tag{1.8.3}$$

for every $v \in V$ with $v \neq 0$, then N is said to be a *norm* on V with respect to $|\cdot|$. In particular, k may be considered as a one-dimensional vector space over itself, and $|\cdot|$ may be considered as a norm on k with respect to itself.

A nonnegative real-valued function N on V is said to be a *semi-ultranorm* on V with respect to $|\cdot|$ on k if it satisfies (1.8.1) and

$$N(v + w) \leq \max(N(v), N(w)) \tag{1.8.4}$$

for every $v, w \in V$. If N also satisfies (1.8.3), then N is said to be an *ultranorm* on V with respect to $|\cdot|$. Of course, (1.8.4) implies (1.8.2), so that semi-ultranorms and ultranorms are seminorms and ultranorms, respectively. If N is a semi-ultranorm on V with respect to $|\cdot|$ on k, and if $N(v) > 0$ for some $v \in V$, then one can check that $|\cdot|$ is an ultrametric absolute value function on k. If $|\cdot|$ is an ultrametric absolute value function on k, then $|\cdot|$ may be considered as an ultranorm on k as a one-dimensional vector space over itself.

Let $|\cdot|$ be any absolute value function on k again. If N is a seminorm on V with respect to $|\cdot|$, then

$$d(v,w) = d_N(v,w) = N(v-w) \tag{1.8.5}$$

defines a semimetric on V. If N is a norm on V, then (1.8.5) is a metric on V. If N is a semi-ultranorm on V, then (1.8.5) is a semi-ultrametric on V. Thus (1.8.5) is an ultrametric on V when N is an ultranorm on V.

Suppose for the moment that $|\cdot|$ is the trivial absolute value function on k. The *trivial ultranorm* is defined on V by putting $N(v)$ equal to 1 when $v \neq 0$, and equal to 0 when $v = 0$. It is easy to see that this defines an ultranorm on V, for which the corresponding ultrametric is the discrete metric.

Let $|\cdot|$ be any absolute value function on k, and let a be a positive real number with $a \leq 1$. Remember that $|\cdot|^a$ defines an absolute value function on k too, as in Section 1.3. If N is a seminorm on V with respect to $|\cdot|$ on k, then $N(v)^a$ is a seminorm on V with respect to $|\cdot|^a$ on k. This uses (1.3.1) to get the triangle inequality for $N(v)^a$ from the one for N. If N is a norm on V with respect to $|\cdot|$ on k, then $N(v)^a$ is a norm on V with respect to $|\cdot|^a$ on k.

If $|\cdot|$ is an ultrametric absolute value function on k, then $|\cdot|^a$ is an ultrametric absolute value function on k for every $a > 0$, as in Section 1.3. In this case, if N is a semi-ultranorm on V with respect to $|\cdot|$ on k, then $N(v)^a$ is a semi-ultranorm on V with respect to $|\cdot|^a$ for every $a > 0$. If N is an ultranorm on V with respect to $|\cdot|$ on k, then $N(v)^a$ is an ultranorm on V with respect to $|\cdot|^a$ on k for every $a > 0$.

Let N be a semi-ultranorm on V with respect to $|\cdot|$ on k. If $v, w \in V$ satisfy

$$N(v-w) < N(w), \tag{1.8.6}$$

then

$$N(v) = N(w). \tag{1.8.7}$$

This is analogous to the corresponding statement for ultrametric absolute value functions mentioned in Section 1.5. If $N(v-w) \leq N(w)$, then

$$N(v) \leq \max(N(v-w), N(w)) = N(w), \tag{1.8.8}$$

by the semi-ultranorm version of the triangle inequality. We also have that

$$N(w) \leq \max(N(v-w), N(v)), \tag{1.8.9}$$

which implies that $N(w) \leq N(v)$ when (1.8.6) holds.

Suppose that N is a norm on V with respect to an absolute value function $|\cdot|$ on k. If V is complete with respect to the metric associated to N, then V is said to be a *Banach space* with respect to N. Otherwise, one can pass to a completion of V. The vector space operations on V can be extended to the completion, so that the completion becomes a vector space over k. The extension of N to the completion corresponds to the distance to 0 on the completion, and defines a norm on the completion. If N is an ultranorm on V, then the extension of N

to the completion of V is an ultranorm as well. The completion of V is unique, up to isometric isomorphic equivalence.

If N is a seminorm on V with respect to $|\cdot|$ on k, and if V_0 is a linear subspace of V, then the restriction of N to V_0 is a seminorm on V with respect to $|\cdot|$ on k. If V_0 is dense in V with respect to the semimetric associated to N, and if the restriction of N to V_0 is a semi-ultranorm on V_0, then it is easy to see that N is a semi-ultranorm on V. In particular, if N is an ultranorm on V, and if V is not already complete with respect to the ultrametric associated to N, then the extension of N to the completion of V is an ultranorm.

1.9 Bounded linear mappings

Let k be a field with an absolute value function $|\cdot|$, and let V, W be vector spaces over k. Also let N_V, N_W be seminorms on V, W, respectively, with respect to $|\cdot|$ on k. A linear mapping T from V into W is said to be *bounded* with respect to N_V and N_W if there is a nonnegative real number C such that

$$N_W(T(v)) \le C\, N_V(v) \tag{1.9.1}$$

for every $v \in V$. This implies that

$$N_W(T(v) - T(v')) = N_W(T(v - v')) \le C\, N_V(v - v') \tag{1.9.2}$$

for every $v, v' \in V$, and in particular that T is continuous with respect to the semimetrics associated to N_V and N_W on V and W, respectively. Conversely, if a linear mapping T from V into W is continuous at 0 with respect to these semimetrics, and if $|\cdot|$ is not the trivial absolute value function on k, then one can check that T is bounded with respect to N_V and N_W.

Let $\mathcal{BL}(V, W)$ be the space of bounded linear mappings from V into W, with respect to N_V and N_W. If $T \in \mathcal{BL}(V, W)$, then put

$$\|T\|_{op} = \|T\|_{op,VW} = \inf\{C \ge 0 : (1.9.1) \text{ holds}\}, \tag{1.9.3}$$

where more precisely the infimum is taken over all nonnegative real numbers C such that (1.9.1) holds for every $v \in V$. Note that the infimum is automatically attained in this situation, which is to say that (1.9.1) holds with $C = \|T\|_{op}$. One can verify that $\mathcal{BL}(V, W)$ is a vector space over k with respect to pointwise addition and scalar multiplication of mappings from V into W, and that (1.9.3) defines a seminorm on $\mathcal{B}(V, W)$ with respect to $|\cdot|$ on k. If N_W is a norm on W, then (1.9.3) is a norm on $\mathcal{BL}(V, W)$. If N_W is a semi-ultranorm on W, then (1.9.3) is a semi-ultranorm on $\mathcal{BL}(V, W)$. In particular, if N_W is an ultranorm on W, then (1.9.3) is an ultranorm on $\mathcal{BL}(V, W)$.

Let Z be another vector space over k, and let N_Z be a seminorm on Z with respect to $|\cdot|$ on k. Suppose that T_1 is a bounded linear mapping from V into W with respect to N_V and N_W, and that T_2 is a bounded linear mapping from W into Z with respect to N_W and N_Z. If $v \in V$, then

$$\begin{aligned} N_Z(T_2(T_1(v))) &\le \|T_2\|_{op,WZ}\, N_W(T_1(v)) \\ &\le \|T_1\|_{op,VW}\, \|T_2\|_{op,WZ}\, N_V(v), \end{aligned} \tag{1.9.4}$$

where the subscripts indicate the spaces involved in the corresponding operator seminorm. This implies that the composition $T_2 \circ T_1$ is bounded as a linear mapping from V into Z, with

$$\|T_2 \circ T_1\|_{op,VZ} \le \|T_1\|_{op,VW} \, \|T_2\|_{op,WZ}. \tag{1.9.5}$$

Let us suppose from now on in this section that N_W is a norm on W, and that W is complete with respect to the metric associated associated to N_W. Under these conditions, one can check that $\mathcal{BL}(V,W)$ is complete with respect to the operator norm (1.9.3), using standard arguments. More precisely, if $\{T_j\}_{j=1}^\infty$ is a Cauchy sequence in $\mathcal{BL}(V,W)$ with respect to the metric associated to the operator norm, then $\{T_j(v)\}_{j=1}^\infty$ is a Cauchy sequence in W with respect to the metric associated to N_W for every $v \in V$. This implies that $\{T_j(v)\}_{j=1}^\infty$ converges to a unique element $T(v)$ of W with respect to the metric associated to N_W, because W is supposed to be complete with respect to this metric. It is easy to see that T defines a linear mapping from V into W, because T_j is linear for each j. The Cauchy condition for $\{T_j\}_{j=1}^\infty$ with respect to the metric associated to the operator norm implies that the operator norms of the T_j's are bounded, which can be used to get that T is a bounded linear mapping. One can use the Cauchy condition for $\{T_j\}_{j=1}^\infty$ again to obtain that this sequence converges to T with respect to the metric associated to the operator norm, as desired.

Suppose for convenience that N_V is a norm on V, although this is not really needed. Let V_0 be a linear subspace of V that is dense in V with respect to the metric associated to N_V, and let T_0 be a bounded linear mapping from V_0 into W, with respect to the restriction of N_V to V_0. Note that T_0 is uniformly continuous with respect to the metric on V_0 associated to the restriction of N_V to V_0, and the metric on W associated to N_W, as in (1.9.2). It follows that there is a unique extension of T_0 to a uniformly continuous mapping from V into W, with respect to the metrics associated to N_V and N_W, respectively, as mentioned at the beginning of Section 1.4. One can check that this extension is a bounded linear mapping from V into W with respect to N_V and N_W, with the same operator norm as T_0 has on V_0.

1.10 Some norms on k^n

Let k be a field, and let n be a positive integer. The space k^n of n-tuples $v = (v_1, \ldots, v_n)$ of elements of k is a vector space over k with respect to coordinatewise addition and scalar multiplication. Let $|\cdot|$ be an absolute value function on k. It is easy to see that

$$\|v\|_1 = \sum_{j=1}^n |v_j| \tag{1.10.1}$$

and

$$\|v\|_\infty = \max_{1 \le j \le n} |v_j| \tag{1.10.2}$$

are norms on k^n with respect to $|\cdot|$ on k. If $|\cdot|$ is an ultrametric absolute value function on k, then (1.10.2) is an ultranorm on k^n.

Observe that

$$\|v\|_\infty \le \|v\|_1 \le n\,\|v\|_\infty \tag{1.10.3}$$

for every $v \in k^n$. Let

$$d_1(v,w) = \|v-w\|_1 \tag{1.10.4}$$

and

$$d_\infty(v,w) = \|v-w\|_\infty \tag{1.10.5}$$

be the metrics on k^n associated to (1.10.1) and (1.10.2), respectively. Thus

$$d_\infty(v,w) \le d_1(v,w) \le n\,d_\infty(v,w) \tag{1.10.6}$$

for every $v, w \in k^n$, by (1.10.3). In particular, this implies that (1.10.4) and (1.10.5) determine the same topology on k^n. This is the same as the product topology on k^n, corresponding to the topology determined on k by the metric associated to $|\cdot|$.

The standard basis vectors $e_1, \ldots, e_n$ in k^n are defined as usual by taking the jth coordinate of e_l to be equal to 1 when $j = l$ and to 0 when $j \ne l$, where $1 \le j, l \le n$. Thus

$$v = \sum_{l=1}^n v_l\,e_l \tag{1.10.7}$$

for every $v \in k^n$. Let W be a vector space over k, and let N_W be a seminorm on W with respect to $|\cdot|$ on k. If T is a linear mapping from k^n into W, then

$$T(v) = T\Big(\sum_{l=1}^n v_l\,e_l\Big) = \sum_{l=1}^n v_l\,T(e_l) \tag{1.10.8}$$

for every $v \in k^n$, and hence

$$N_W(T(v)) \le \sum_{l=1}^n |v_l|\,N_W(T(e_l)). \tag{1.10.9}$$

In particular,

$$N_W(T(v)) \le \Big(\max_{1\le l\le n} N_W(T(e_l))\Big)\,\|v\|_1 \tag{1.10.10}$$

for every $v \in k^n$. This means that T is bounded as a linear mapping from k^n equipped with $\|v\|_1$ into W, with operator seminorm less than or equal to

$$\max_{1\le l\le n} N_W(T(e_l)). \tag{1.10.11}$$

In fact, the operator seminorm of T is equal to (1.10.11) in this situation, because the operator seminorm of T is automatically greater than or equal to $N_W(T(e_l))$ for each $l = 1, \ldots, n$, since $\|e_l\|_1 = 1$. Similarly,

$$N_W(T(v)) \le \Big(\sum_{l=1}^n N_W(T(e_l))\Big)\,\|v\|_\infty \tag{1.10.12}$$

for every $v \in k^n$, by (1.10.9). This implies that T is bounded as a linear mapping from k^n equipped with $\|v\|_\infty$ into W, with operator seminorm less than or equal to

$$\sum_{l=1}^{n} N_W(T(e_l)). \tag{1.10.13}$$

Note that the operator seminorm of T is greater than or equal to (1.10.11), because $\|e_l\|_\infty = 1$ for each $l = 1, \ldots, n$.

Suppose now that $|\cdot|$ is an ultrametric absolute value function on k, and that N_W is a semi-ultranorm on W with respect to $|\cdot|$ on k. Using (1.10.8), we get that

$$N_W(T(v)) \le \max_{1 \le l \le n} (|v_l| \, N_W(T(e_l))) \le \Big(\max_{1 \le l \le n} N_W(T(e_l)) \Big) \|v\|_\infty \tag{1.10.14}$$

for every $v \in k^n$. This implies that T is bounded as a linear mapping from k^n equipped with $\|v\|_\infty$ into W, with operator seminorm less than or equal to (1.10.11). The operator seminorm of T is also greater than or equal to (1.10.11), as in the preceding paragraph. Hence the operator seminorm of T with respect to $\|v\|_\infty$ on k^n is equal to (1.10.11) in this case.

1.11 Inner products

Suppose for the moment that V and W are vector spaces over the field $\mathbf{C}$ of complex numbers, so that V and W may be considered as vector spaces over $\mathbf{R}$ as well. Let us say that a mapping T from V into W is *real-linear* if T is linear as a mapping from V into W as vector spaces over $\mathbf{R}$, and that T is *complex-linear* if T is linear as a mapping from V into W as vector spaces over $\mathbf{C}$. Thus a complex-linear mapping T from V into W is the same as a real-linear mapping that also satisfies

$$T(i\,v) = i\,T(v) \tag{1.11.1}$$

for every $v \in V$. A real-linear mapping T from V into W is said to be *conjugate-linear* if

$$T(i\,v) = -i\,T(v) \tag{1.11.2}$$

for every $v \in V$. This implies that

$$T(a\,v) = \overline{a}\,T(v) \tag{1.11.3}$$

for every $a \in \mathbf{C}$ and $v \in V$, where $\overline{a}$ is the usual complex-conjugate of a.

Suppose from now on in this section that $k = \mathbf{R}$ or $\mathbf{C}$, with the standard absolute value function. Let V be a vector space over k, and let $\langle v, w \rangle$ be a k-valued function defined for $v, w \in V$. If the following three conditions are satisfied, then $\langle v, w \rangle$ is said to be an *inner product* on V. The first condition is that $\langle v, w \rangle$ be linear in v for each $w \in V$. The second condition is that

$$\langle w, v \rangle = \langle v, w \rangle \tag{1.11.4}$$

for every $v, w \in V$ in the real case, and that

$$\langle w, v \rangle = \overline{\langle v, w \rangle} \tag{1.11.5}$$

for every $v, w \in V$ in the complex case. Note that $\langle v, w \rangle$ is linear in w for each $v \in V$ in the real case, and conjugate-linear in w for each $v \in V$ in the complex case. In the complex case, we also get that $\langle v, v \rangle$ is a real number for every $v \in V$, by (1.11.5). The third condition is that

$$\langle v, v \rangle > 0 \tag{1.11.6}$$

for every $v \in V$ with $v \neq 0$. Of course, $\langle v, w \rangle = 0$ when either $v = 0$ or $w = 0$, by the first two conditions. If$\langle v, w \rangle$ is an inner product on V, then we put

$$\|v\| = \langle v, v \rangle^{1/2} \tag{1.11.7}$$

for every $v \in V$, using the nonnegative square root on the right side. It is well known that

$$|\langle v, w \rangle| \le \|v\| \, \|w\| \tag{1.11.8}$$

for every $v, w \in V$, which is the *Cauchy–Schwarz inequality.* Using this, one can show that $\| \cdot \|$ defines a norm on V. If V is complete with respect to the metric associated to $\| \cdot \|$, then V is said to be a *Hilbert space* with respect to $\langle v, w \rangle$. Otherwise, one can pass to a completion, as usual.

Let n be a positive integer. The standard inner product on $\mathbf{R}^n$ is given by

$$\langle v, w \rangle = \langle v, w \rangle_{\mathbf{R}^n} = \sum_{j=1}^{n} v_j \, w_j. \tag{1.11.9}$$

Similarly, the standard inner product on $\mathbf{C}^n$ is given by

$$\langle v, w \rangle = \langle v, w \rangle_{\mathbf{C}^n} = \sum_{j=1}^{n} v_j \, \overline{w_j}. \tag{1.11.10}$$

In both cases, the corresponding norm is given by

$$\|v\| = \|v\|_2 = \Big(\sum_{j=1}^{n} |v_j|^2 \Big)^{1/2}. \tag{1.11.11}$$

It is easy to see that

$$\|v\|_\infty \le \|v\|_2 \le n^{1/2} \, \|v\|_\infty \tag{1.11.12}$$

for every $v \in \mathbf{R}^n$ or $\mathbf{C}^n$, where $\|v\|_\infty$ is as in (1.10.2). One can also check that

$$\|v\|_2 \le \|v\|_1 \le n^{1/2} \, \|v\|_2 \tag{1.11.13}$$

for every $v \in \mathbf{R}^n$ or $\mathbf{C}^n$, where $\|v\|_1$ is as in (1.10.1). More precisely, the first inequality in (1.11.13) can be verified using the first inequality in (1.10.3), and the second inequality in (1.11.13) can be obtained from the Cauchy–Schwarz inequality.

Let $(V, \langle \cdot, \cdot \rangle_V)$ and $(W, \langle \cdot, \cdot \rangle_W)$ be Hilbert spaces, both real or both complex, and let $\| \cdot \|_V$ and $\| \cdot \|_W$ be the corresponding norms on V and W, respectively. Also let T be a bounded linear mapping from V into W, with respect to $\| \cdot \|_V$ and $\| \cdot \|_W$. It is well known that there is a unique bounded linear mapping T^* from W into V such that

$$\langle T(v), w \rangle_W = \langle v, T^*(w) \rangle_V \tag{1.11.14}$$

for every $v \in V$ and $w \in W$. This mapping T^* is called the *adjoint* of T. The adjoint $(T^*)^*$ of T^* can be defined as a bounded linear mapping from V into W in the same way, and is equal to T. It is not difficult to show that

$$\|T^*\|_{op,WV} = \|T\|_{op,VW}. \tag{1.11.15}$$

Note that $T \mapsto T^*$ is a linear mapping from $\mathcal{BL}(V, W)$ into $\mathcal{BL}(W, V)$ in the real case, and that this mapping is conjugate-linear in the complex case.

Let $(Z, \langle \cdot, \cdot \rangle_Z)$ be another Hilbert space, which is real when V and W are real, and complex when V and W are complex, and let $\| \cdot \|_Z$ be the corresponding norm on Z. If T_1 is a bounded linear mapping from V into W, and T_2 is a bounded linear mapping from W into Z, then their composition $T_2 \circ T_1$ is a bounded linear mapping from V into Z, as before. It is easy to see that

$$(T_2 \circ T_1)^* = T_1^* \circ T_2^* \tag{1.11.16}$$

as bounded linear mappings from Z into V.

1.12 Infinite series

Let k be a field with an absolute value function $|\cdot|$, and let V be a vector space over k with a norm N with respect to $|\cdot|$ on k. An infinite series $\sum_{j=1}^\infty v_j$ with terms in V is said to *converge* in V if the corresponding sequence of partial sums $\sum_{j=1}^n v_j$ converges to an element of V with respect to the metric associated to N. In this case, the value of the sum $\sum_{j=1}^\infty v_j$ is defined to be the limit of the sequence of partial sums. If $\sum_{j=1}^\infty v_j$ converges in V and $t \in k$, then it is easy to see that $\sum_{j=1}^\infty t\, v_j$ converges in V too, with

$$\sum_{j=1}^\infty t\, v_j = t \sum_{j=1}^\infty v_j. \tag{1.12.1}$$

Similarly, if $\sum_{j=1}^\infty w_j$ is another convergent series in V, then $\sum_{j=1}^\infty (v_j + w_j)$ converges in V as well, with

$$\sum_{j=1}^\infty (v_j + w_j) = \sum_{j=1}^\infty v_j + \sum_{j=1}^\infty w_j. \tag{1.12.2}$$

A necessary condition for the convergence of an infinite series $\sum_{j=1}^{\infty} v_j$ with terms in V is that the corresponding sequence of partial sums be a Cauchy sequence with respect to the metric associated to N. This happens if and only if for every $\epsilon > 0$ there is a positive integer L such that

$$N\Big(\sum_{j=l}^{n} v_j\Big) < \epsilon \tag{1.12.3}$$

for all $l, n \in \mathbf{Z}_+$ with $n \geq l \geq L$. In particular, this implies that

$$\lim_{j \to \infty} N(v_j) = 0, \tag{1.12.4}$$

by taking $l = n$ in (1.12.3). Of course, if V is complete with respect to the metric associated to N, then the Cauchy condition (1.12.3) implies that $\sum_{j=1}^{\infty} v_j$ converges in V.

If $\sum_{j=1}^{\infty} N(v_j)$ converges as an infinite series of nonnegative real numbers, then $\sum_{j=1}^{\infty} v_j$ is said to converge *absolutely* with respect to N. Observe that

$$N\Big(\sum_{j=l}^{n} v_j\Big) \leq \sum_{j=l}^{n} N(v_j) \tag{1.12.5}$$

for every $l, n \in \mathbf{Z}_+$ with $n \geq l$, by the triangle inequality for N. If $\sum_{j=1}^{\infty} v_j$ converges absolutely with respect to N, then it is easy to see that the Cauchy condition (1.12.3) holds, using (1.12.5). If V is complete with respect to the metric associated to N, then it follows that $\sum_{j=1}^{\infty} v_j$ converges in V. In this case, we also have that

$$N\Big(\sum_{j=1}^{\infty} v_j\Big) \leq \sum_{j=1}^{\infty} N(v_j). \tag{1.12.6}$$

Suppose for the moment that N is an ultranorm on V with respect to $|\cdot|$ on k, so that

$$N\Big(\sum_{j=l}^{n} v_j\Big) \leq \max_{l \leq j \leq n} N(v_j) \tag{1.12.7}$$

for every $n \geq l \geq 1$. If (1.12.4) holds, then it follows that the Cauchy condition (1.12.3) holds too. If V is complete with respect to the ultrametric associated to N, then we get that $\sum_{j=1}^{\infty} v_j$ converges in V. Note that

$$N\Big(\sum_{j=1}^{\infty} v_j\Big) \leq \max_{j \geq 1} N(v_j) \tag{1.12.8}$$

in this situation. More precisely, the maximum on the right side of (1.12.8) is attained, because of (1.12.4).

Let us now take $k = \mathbf{R}$ or $\mathbf{C}$, with the standard absolute value function. Let $(V, \langle \cdot, \cdot \rangle)$ be a real or complex inner product space, and let $\| \cdot \|$ be the corresponding norm on V, as in the previous section. Suppose that $\sum_{j=1}^{\infty} v_j$ is an infinite series of pairwise-orthogonal vectors in V, so that

$$\langle v_j, v_l \rangle = 0 \tag{1.12.9}$$

when $j \neq l$. This implies that

$$\Big\| \sum_{j=l}^{n} v_j \Big\|^2 = \sum_{j=l}^{n} \|v_j\|^2 \tag{1.12.10}$$

for every $n \geq l \geq 1$. If $\sum_{j=1}^{\infty} \|v_j\|^2$ converges as an infinite series of nonnegative real numbers, then the Cauchy condition (1.12.3) holds, with $N = \| \cdot \|$. Hence $\sum_{j=1}^{\infty} v_j$ converges in V when V is a Hilbert space, in which case we have that

$$\Big\| \sum_{j=1}^{\infty} v_j \Big\|^2 = \sum_{j=1}^{\infty} \|v_j\|^2. \tag{1.12.11}$$

Conversely, if the Cauchy condition (1.12.3) holds, then $\sum_{j=1}^{\infty} \|v_j\|^2$ converges, because the partial sums are bounded.

1.13 Bounded bilinear mappings

Let k be a field, and let V, W, and Z be vector spaces over k. A mapping b from $V \times W$ into Z is said to be *bilinear* if $b(v, w)$ is linear in v for each $w \in W$, and linear in w for each $v \in V$. Let $| \cdot |$ be an absolute value function on k, and let N_V, N_W, and N_Z be seminorms on V, W, and Z, respectively, with respect to $| \cdot |$ on k. If there is a nonnegative real number C such that

$$N_Z(b(v, w)) \leq C\, N_V(v)\, N_W(w) \tag{1.13.1}$$

for every $v \in V$ and $w \in W$, then b is said to be *bounded* as a bilinear mapping from $V \times W$ into Z.

Let b be a bilinear mapping from $V \times W$ into Z that satisfies (1.13.1), and let $v, v' \in V$ and $w, w' \in W$ be given. Observe that

$$b(v, w) - b(v', w') = b(v - v', w) + b(v', w - w'), \tag{1.13.2}$$

so that

$$\begin{aligned} N_Z(b(v, w) - b(v', w')) &\leq N_Z(b(v - v', w)) + N_Z(b(v', w - w')) \\ &\leq C\, \|v - v'\|_V\, \|w\| + C\, \|v'\|_V\, \|w - w'\|_W. \end{aligned} \tag{1.13.3}$$

One can use this to check that b is continuous with respect to the semimetrics associated to N_V, N_W, N_Z and the corresponding product topology on $V \times W$.

Conversely, if a bilinear mapping b from $V \times W$ into Z is continuous at $(0,0)$ in $V \times W$ with respect to these semimetrics and the corresponding product topology on $V \times W$, and if $|\cdot|$ is not the trivial absolute value function on k, then one can verify that b is bounded as a bilinear mapping.

Suppose for the moment that N_V, N_W, and N_Z are norms on V, W, and Z, respectively, and let V_0, W_0 be dense linear subspaces of V and W with respect to the metrics associated to N_V and N_W. Let b_0 be a bounded bilinear mapping from $V_0 \times W_0$ into Z, using the restrictions of N_V and N_W to V_0 and W_0, respectively. If Z is complete with respect to the metric associated to N_Z, then there is a unique extension of b_0 to a bounded bilinear mapping from $V \times W$ into Z. More precisely, for each $w \in W_0$, one can first extend $b_0(v, w)$ to a bounded linear mapping from V into Z, as a function of v. This defines a bounded bilinear mapping from $V \times W_0$ into Z, which can be extended to a bounded bilinear mapping from $V \times W$ into Z in the same way.

Suppose now that $V = k^{n_V}$ and $W = k^{n_W}$ for some positive integers n_V and n_W, and let N_Z be any seminorm on Z again. Also let $e_1^V, \ldots, e_{n_V}^V$ and $e_1^W, \ldots, e_{n_W}^W$ be the standard basis vectors in k^{n_V} and k^{n_W}, respectively, and let b be a bilinear mapping from $k^{n_V} \times k^{n_W}$ into Z. Observe that

$$b(v, w) = \sum_{j=1}^{n_V} \sum_{l=1}^{n_W} v_j\, w_l\, b(e_j^{n_V}, e_l^{n_W}) \tag{1.13.4}$$

for every $v \in V$ and $w \in W$, so that

$$N_Z(b(v, w)) \le \sum_{j=1}^{n_V} \sum_{l=1}^{n_W} |v_j|\, |w_l|\, N_Z(b(e_j^{n_V}, e_l^{n_W})). \tag{1.13.5}$$

If we take $N_V(v)$ to be

$$\|v\|_{1,n_V} = \sum_{j=1}^{n_V} |v_j|, \tag{1.13.6}$$

and $N_W(w)$ to be

$$\|w\|_{1,n_W} = \sum_{l=1}^{n_W} |w_l|, \tag{1.13.7}$$

as in (1.10.1), then (1.13.5) implies that (1.13.1) holds with C equal to

$$\max\{N_Z(b(e_j^{n_V}, e_l^{n_w})) : 1 \le j \le n_V,\, 1 \le l \le n_W\}. \tag{1.13.8}$$

Similarly, if we take $N_V(v)$ to be

$$\|v\|_{\infty,n_V} = \max_{1 \le j \le n_V} |v_j|, \tag{1.13.9}$$

and $N_W(w)$ to be

$$\|w\|_{\infty,n_W} = \max_{1 \le l \le n_W} |w_l|, \tag{1.13.10}$$

as in (1.10.2), then (1.13.5) implies that (1.13.1) holds, with C equal to

$$\sum_{j=1}^{n_V} \sum_{l=1}^{n_W} N_Z(b(e_j^{n_V}, e_l^{n_W})). \tag{1.13.11}$$

If N_Z is a semi-ultranorm on Z, then we get that

$$\begin{aligned} &N_Z(b(v,w)) \\ &\le \max\{|v_j|\,|w_l|\,N(b(e_j^{n_V}, e_l^{n_W})) : 1 \le j \le n_V,\ 1 \le l \le n_W\} \end{aligned} \tag{1.13.12}$$

for every $v \in k^{n_V}$ and k^{n_W}. In this case, if we take $N_V(v)$ and $N_W(w)$ to be as in (1.13.9) and (1.13.10), respectively, then (1.13.1) holds with C equal to (1.13.8).

1.14 Minkowski functionals

Let k be a field with an absolute value function $|\cdot|$, and let V be a vector space over k. If $t \in k$ and $E \subseteq V$, then we put

$$t\,E = \{t\,v : v \in E\}. \tag{1.14.1}$$

Let us say that E is *balanced* in V if

$$t\,E \subseteq E \tag{1.14.2}$$

for every $t \in k$ with $|t| \le 1$. If $|t| = 1$, then it follows that

$$t\,E = E, \tag{1.14.3}$$

by applying (1.14.2) to both t and $1/t$. Note that a nonempty balanced subset of V contains 0.

Let us say that a balanced set $A \subseteq V$ is *absorbing* if for every $v \in V$ there is a $t_1 \in k$ such that $t_1 \neq 0$ and

$$v \in t_1\,A. \tag{1.14.4}$$

This implies that

$$v \in t\,A \tag{1.14.5}$$

for every $t \in k$ such that $|t| \ge |t_1|$, because A is balanced. Equivalently, this means that

$$t^{-1}\,v \in A \tag{1.14.6}$$

when $|t| \ge |t_1|$. Of course, if (1.14.4) holds with $t_1 = 0$, then $v = 0$. We also have that $0 \in A$, because A is balanced and nonempty, so that (1.14.5) holds for every $t \in k$. Clearly V is automatically balanced and absorbing as a subset of itself. If $|\cdot|$ is the trivial absolute value function on k, then V is the only balanced absorbing subset of itself.

Let N be a nonnegative real-valued function on V such that

$$N(t\,v) = |t|\,N(v) \tag{1.14.7}$$

for every $t \in k$ and $v \in V$. Put

$$B_N(0,r) = \{v \in V : N(v) < r\} \tag{1.14.8}$$

for every positive real number r, and

$$\overline{B}(0,r) = \{v \in V : N(v) \le r\} \tag{1.14.9}$$

for every nonnegative real number r. If $t \in k$ and $t \ne 0$, then

$$t\,B_N(0,r) = B_N(0,|t|\,r) \tag{1.14.10}$$

for every $r > 0$, and

$$t\,\overline{B}_N(0,r) = \overline{B}_N(0,|t|\,r) \tag{1.14.11}$$

for every $r \ge 0$. In particular, $B_N(0,r)$ is balanced in V for every $r > 0$, and $\overline{B}_N(0,r)$ is balanced in V for every $r \ge 0$. If $|\cdot|$ is not the trivial absolute value function on k, then $B_N(0,r)$ and $\overline{B}_N(0,r)$ are absorbing in V for every $r > 0$.

Let us suppose from now on in this section that $|\cdot|$ is not the trivial absolute value function on k. Let A be a balanced absorbing subset of V, and put

$$\begin{aligned} N_A(v) &= \inf\{|t| : t \in k,\ t \ne 0,\ v \in t\,A\} \\ &= \inf\{|t| : t \in k,\ t \ne 0,\ t^{-1}\,v \in A\} \end{aligned} \tag{1.14.12}$$

for each $v \in V$. Note that $N_A(0) = 0$, so that we could have included the possibility of $t = 0$ in the first formulation of $N_A(v)$. Of course, N_A is a nonnegative real-valued function on V, and one can check that

$$N_A(t'\,v) = |t'|\,N_A(v) \tag{1.14.13}$$

for every $t' \in k$ and $v \in V$. If $v \in A$, then $N_A(v) \le 1$, so that

$$A \subseteq \overline{B}_{N_A}(0,1). \tag{1.14.14}$$

If $v \in V$ satisfies $N_A(v) < 1$, then there is a $t \in k$ such that $|t| < 1$ and $v \in t\,A$. This implies that $v \in A$, because A is balanced in V, so that

$$B_{N_A}(0,1) \subseteq A. \tag{1.14.15}$$

Suppose for the moment that $|\cdot|$ is discrete on k, as in Section 1.5. If $v \in V$ and $N_A(v) > 0$, then it follows that the infimum in (1.14.12) is attained. If $v \in V$ and $N_A(v) \le 1$, then there is a $t \in k$ such that $|t| \le 1$ and $v \in t\,A$, because the infimum is attained when $N_A(v) = 1$. As before, this implies that $v \in A$, because A is balanced in V. Hence

$$A = \overline{B}_{N_A}(0,1) \tag{1.14.16}$$

in this situation.

1.15 Balanced subgroups

Let k be a field with an absolute value function $|\cdot|$ again, and let V be a vector space over k. Let us say that $E \subseteq V$ is a *balanced subgroup* of V if E is balanced as a subset of V, as in the previous section, and E is a subgroup of V as a commutative group with respect to addition. If $E \subseteq V$ is a nonempty balanced subset of V, then $0 \in E$ and $-E = E$. If we also have that

$$v + w \in E \tag{1.15.1}$$

for every $v, w \in E$, then it follows that E is a balanced subgroup of V.

Let N be a semi-ultranorm on V with respect to $|\cdot|$ on k. Note that $B_N(0, r)$ in (1.14.8) is the same as the open ball in V centered at 0 with radius $r > 0$ with respect to the semi-ultrametric associated to N, and that (1.14.9) is the same as the closed ball in V centered at 0 with radius $r \geq 0$ with respect to the semi-ultrametric associated to N. It is easy to see that $B_N(0, r)$ is a balanced subgroup in V for every $r > 0$, and that $\overline{B}_N(0, r)$ is a balanced subgroup for every $r \geq 0$. More precisely, (1.15.1) holds in both cases, by the semi-ultranorm version of the triangle inequality.

Of course, linear subspaces of V are balanced subgroups of V. If $|\cdot|$ is archimedean on k, then one can check that any balanced subgroup E of V is linear subspace of V. This uses the fact that for each $v \in E$ and positive integer n, the sum of n v's in V is an element of E. If $|\cdot|$ is the trivial absolute value function on k, then balanced subgroups of V are linear subspaces again.

If E is a balanced subgroup in V, and if the linear span of E in V is equal to V, then E is absorbing in V. More precisely, if $|\cdot|$ is the trivial absolute value function on E, then E is a linear subspace of V, and hence $E = V$. Otherwise, suppose that $|\cdot|$ is not the trivial absolute value function on k, and let $v \in V$ be given. Thus v can be expressed as a linear combination of elements of E, by hypothesis. This implies that $t\,v \in E$ when $t \in k$ and $|t|$ is sufficiently small, because E is a balanced subgroup of V.

Let us continue to suppose that $|\cdot|$ is not the trivial absolute value function on k. Let A is a balanced subgroup of V that is also absorbing in V, and let N_A be as in (1.14.12). We would like to check that N_A is a semi-ultranorm on V with respect to $|\cdot|$ on k. We have already seen that N_A satisfies the homogeneity condition (1.14.13), and so it is enough to show that N_A satisfies the semi-ultranorm version of the triangle inequality. Let $v, w \in V$ be given, and let r be a positive real number such that

$$N_A(v),\ N_A(w) < r. \tag{1.15.2}$$

This implies that there are nonzero elements $t_1(v)$, $t_1(w)$ of k such that

$$|t_1(v)|,\ |t_1(w)| < r \tag{1.15.3}$$

and

$$v \in t_1(v)\,A,\ \ w \in t_1(w)\,A, \tag{1.15.4}$$

by the definition (1.14.12) of N_A. Let us take t_1 to be equal to $t_1(v)$ or $t_1(w)$, in such a way that

$$|t_1| = \max(|t_1(v)|, |t_1(w)|). \tag{1.15.5}$$

Thus $t_1(v)\,A, t_1(w)\,A \subseteq t_1\,A$, because A is balanced. This implies that v and w are both elements of $t_1\,A$, by (1.15.4). It follows that

$$v + w \in t_1\,A, \tag{1.15.6}$$

because A is a subgroup of V with respect to addition. This means that

$$N_A(v + w) \le |t_1|, \tag{1.15.7}$$

by the definition (1.14.12) of N_A. Hence $N_A(v+w) < r$, by (1.15.3) and (1.15.5). This shows that

$$N_A(v + w) \le \max(N_A(v), N_A(w)), \tag{1.15.8}$$

since r is any positive real number that satisfies (1.15.2).

Chapter 2

Some basic notions related to Lie algebras

2.1 Modules and homomorphisms

Let k be a commutative ring with a multiplicative identity element $1 = 1_k$, and let A be a commutative group, for which the group operations are expressed additively. Suppose that scalar multiplication on A by elements of k is defined, so that $t\,a$ is defined as an element of A for every $t \in k$ and $a \in A$. If scalar multiplication satisfies the usual compatibility conditions with the group operations on A and the ring operations on k, then A is said to be a *module* over k. If k is a field, then a module over k is the same as a vector space over k. Any abelian group may be considered as a module over $\mathbf{Z}$, where $n\,a$ is the sum of n a's in A for each $a \in A$ and $n \in \mathbf{Z}_+$.

Let k be a commutative ring with a multiplicative identity element again, and let A be a module over k. A *submodule* of A is a subgroup A_0 of A with respect to addition that is invariant under scalar multiplication by k. If k is a field, then this is the same as a linear subspace.

Let k be a field with an ultrametric absolute value function $|\cdot|$, and let k_1 be the closed unit ball in k with respect to $|\cdot|$. Thus k_1 is a subring of k that contains the multiplicative identity element in particular, as in Section 1.7. Let V be a vector space over k, which may be considered as a module over k_1 as well. In this situation, a submodule of V as a module over k_1 is the same as a balanced subgroup of V, as in Section 1.15.

Let k be a commutative ring with a multiplicative identity element, and let B be a module over k. If X is a nonempty set, then the space of all functions on X with values in B is a module over k, with respect to pointwise addition and scalar multiplication of the functions on X.

Let A be another module over k. A mapping ϕ from A into B is said to be a *module homomorphism* if ϕ is a group homomorphism with respect to addition that is also compatible with scalar multiplication by elements of k. One may say that ϕ is *linear over* k or k*-linear* in this case as well. If k is a field, then this is the same as a linear mapping between vector spaces.

The collection of all module homomorphisms from A into B may be denoted $\mathrm{Hom}(A, B)$, or $\mathrm{Hom}_k(A, B)$, to indicate the role of k. This is a module over k too, with respect to pointwise addition and scalar multiplication of mappings from A into B. More precisely, $\mathrm{Hom}(A, B)$ may be considered as a submodule of the module of all B-valued functions on A.

Let C be another module over k. If ϕ is a module homomorphism from A into B, and ψ is a module homomorphism from B into C, then their composition $\psi \circ \phi$ defines a module homomorphism from A into C.

If ϕ is a one-to-one module homomorphism from A onto B, then the inverse mapping ϕ^{-1} is a module homomorphism from B onto A. In this case, ϕ is said to be a *module isomorphism* from A onto B. If ϕ is a module isomorphism from A onto B, and ψ is a module isomorphism from B onto C, then $\psi \circ \phi$ is a module isomorphism from A onto C.

A mapping β from $A \times B$ into C is said to be *bilinear over* k if $\beta(a, b)$ is linear over k in a as a mapping from A into C for every $b \in B$, and $\beta(a, b)$ is linear over k in b as a mapping from B into C for every $a \in A$. If k is a field, then this is the same as the usual notion of bilinearity for a mapping from a product of vector spaces over k into another vector space over k.

In particular, we can take $A = B$, so that β is a bilinear mapping from $A \times A$ into C. If

$$\beta(b, a) = \beta(a, b) \tag{2.1.1}$$

for every $a, b \in A$, then β is said to be *symmetric* on $A \times A$. Similarly, if

$$\beta(b, a) = -\beta(a, b) \tag{2.1.2}$$

for every $a, b \in A$, then β is said to be *antisymmetric* on $A \times A$. However, it is sometimes better to ask that

$$\beta(a, a) = 0 \tag{2.1.3}$$

for every $a \in A$. Of course,

$$\beta(a + b, a + b) = \beta(a, a) + \beta(a, b) + \beta(b, a) + \beta(b, b) \tag{2.1.4}$$

for every $a, b \in A$, because of bilinearity. It is easy to see that (2.1.3) implies (2.1.2), using (2.1.4). If $1 + 1$ has a multiplicative inverse in k, then (2.1.2) implies (2.1.3). If $1 + 1 = 0$ in k, then (2.1.1) and (2.1.2) are the same.

2.2 Algebras

Let k be a commutative ring with a multiplicative identity element, and let A be a module over k. If A is equipped with a mapping from $A \times A$ into A that is bilinear over k, then A is said to be an *algebra* over k. In this case, we may also say that A is an algebra over k in the strict sense. The bilinear mapping may be expressed as

$$(a, b) \mapsto a\,b, \tag{2.2.1}$$

and we may refer to $a\,b$ as the product of $a, b \in A$. If this bilinear mapping is symmetric, so that

$$a\,b = b\,a \tag{2.2.2}$$

for every $a, b \in A$, then we may say that A is *commutative*.

Let A be an algebra over k. If the associative law

$$(a\,b)\,c = a\,(b\,c) \tag{2.2.3}$$

holds for every $a, b, c \in A$, then A is said to be an *associative algebra* over k. This is sometimes included in the definition of an algebra, and we do consider associativity to be part of the definition of a ring here.

Let A be an algebra over k in the strict sense. An element e of A is said to be the *multiplicative identity element* in A if

$$e\,a = a\,e = a \tag{2.2.4}$$

for every $a \in A$. It is easy to see that this is unique when it exists.

Let A be any module over k, so that the space $\mathrm{Hom}_k(A, A)$ of module homomorphisms from A into itself is a module over k too. One can check that $\mathrm{Hom}_k(A, A)$ is an associative algebra over k, with composition of mappings as multiplication. The identity mapping on A is the multiplicative identity element in $\mathrm{Hom}_k(A, A)$.

Let A be an algebra over k in the strict sense, and let A_0 be a submodule of A, as a module over k. If, for every $a, b \in A_0$, we have that $a\,b \in A_0$, then A_0 is said to be a *subalgebra* of A. In this case, A_0 is also an algebra over k in the strict sense, with respect to the restriction of multiplication on A to A_0. If A is an associative algebra, then A_0 is associative as well.

Let A and B be algebras over k in the strict sense, so that A and B are modules over k in particular. Also let ϕ be a module homomorphism from A into B. If

$$\phi(a_1\,a_2) = \phi(a_1)\,\phi(a_2) \tag{2.2.5}$$

for every $a_1, a_2 \in A$, then one may say that ϕ is an *algebra homomorphism* from A into B. If A and B have multiplicative identity elements e_A and e_B, respectively, then one may require that

$$\phi(e_A) = e_B \tag{2.2.6}$$

too. If ϕ is a one-to-one algebra homomorphism from A onto B, then the inverse mapping ϕ^{-1} is an algebra homomorphism from B onto A, and ϕ is said to be an *algebra isomorphism* from A onto B. In this case, if A has a multiplicative identity element e_A, then $\phi(e_A)$ is the multiplicative identity element in B. An algebra isomorphism from A onto itself is called an *algebra automorphism* of A.

Let A be an algebra over k in the strict sense again. If $a \in A$, then put

$$M_a(x) = a\,x \tag{2.2.7}$$

for every $x \in A$. Note that M_a defines a module homomorphism from A into itself for every $a \in A$, because of bilinearity of multiplication on A. Thus

$$a \mapsto M_a \tag{2.2.8}$$

may be considered as a mapping from A into the space $\mathrm{Hom}_k(A, A)$ of module homomorphisms from A into itself. More precisely, (2.2.8) is a module homomorphism from A into $\mathrm{Hom}_k(A, A)$ as modules over k, because multiplication on A is bilinear.

Suppose for the moment that A has a multiplicative identity element e. In this case, M_e is the identity mapping on A. We also get that

$$M_a(e) = a\,e = a \tag{2.2.9}$$

for every $a \in A$, which implies that (2.2.8) is injective.

If $a, b, x \in A$, then

$$M_a(M_b(x)) = M_a(b\,x) = a\,(b\,x) \tag{2.2.10}$$

and

$$M_{a\,b}(x) = (a\,b)\,x. \tag{2.2.11}$$

If A is an associative algebra, then it follows that

$$M_a \circ M_b = M_{a\,b}, \tag{2.2.12}$$

as mappings from A into itself. This means that (2.2.8) is an algebra homomorphism from A into $\mathrm{Hom}_k(A, A)$, using composition as multiplication on the space $\mathrm{Hom}_k(A, A)$ of module homomorphisms from A into itself, as before.

2.3 Lie algebras

Let k be a commutative ring with a multiplicative identity element again, and let A be a module over k. Also let $[x, y]$ be a mapping from $A \times A$ into A that is bilinear over k. Suppose that

$$[x, x] = 0 \tag{2.3.1}$$

for every $x \in A$. This implies that

$$[y, x] = -[x, y] \tag{2.3.2}$$

for every $x, y \in A$, as in Section 2.1. If $1 + 1$ has a multiplicative inverse in k, then (2.3.2) implies (2.3.1), as before.

The *Jacobi identity* may be formulated as saying that

$$[[x, y], z] + [[y, z], x] + [[z, x], y] = 0 \tag{2.3.3}$$

for every $x, y, z \in A$. Alternatively, the Jacobi identity may be expressed as saying that

$$[x, [y, z]] + [y, [z, x]] + [z, [x, y]] = 0 \tag{2.3.4}$$

for every $x, y, z \in A$. It is easy to see that (2.3.3) is equivalent to (2.3.4), if we have (2.3.2). If $[x, y]$ is a bilinear mapping from $A \times A$ into A that satisfies (2.3.1) and either (2.3.3) or (2.3.4), then A is said to be a *Lie algebra* over k with respect to the Lie bracket $[x, y]$. In particular, A may be considered as an algebra over k in the strict sense, using $[x, y]$ as multiplication on A.

If

$$[x, y] = 0 \tag{2.3.5}$$

for every $x, y \in A$, then A is said to be *commutative as a Lie algebra.* Commutativity of A as an algebra over k in the strict sense with respect to $[x, y]$ means that $[x, y]$ is symmetric in x and y, as in the previous section. If $1 + 1$ is invertible in k, then commutativity of A as an algebra in the strict sense implies that A is commutative as a Lie algebra, because of (2.3.2). However, if $1+1 = 0$ in k, then any Lie algebra over k is commutative as an algebra over k in the strict sense.

Let A be any algebra over k in the strict sense, where multiplication on A is expressed as in (2.2.1). Put

$$[x, y] = x\,y - y\,x \tag{2.3.6}$$

for every $x, y \in A$, which defines a mapping from $A \times A$ into A. This mapping is bilinear over k, because multiplication on A is bilinear, by hypothesis. Of course, (2.3.6) satisfies (2.3.1) automatically. If A is associative with respect to the given operation of multiplication, then one can verify that (2.3.6) satisfies either of the Jacobi identities (2.3.3) or (2.3.4), so that A is a Lie algebra with respect to (2.3.6).

Let $(A, [x, y])$ be a Lie algebra over k, and let A_0 be a submodule of A, as a module over k. As in the previous section, A_0 is said to be a *subalgebra* of A if $[x, y] \in A_0$ for every $x, y \in A_0$. In this situation, A_0 is a Lie algebra over k with respect to the restriction of $[x, y]$ to $x, y \in A_0$. One may also refer to A_0 as a *Lie subalgebra* of A. If A is an associative algebra over k, and A_0 is a subalgebra of A, then A_0 is also a Lie subalgebra of A as a Lie algebra with respect to (2.3.6).

Let $(A, [\cdot, \cdot]_A)$ and $(B, [\cdot, \cdot]_B)$ be Lie algebras over k. Thus A and B are modules over k in particular, and we let ϕ be a module homomorphism from A into B. If

$$\phi([x, y]_A) = [\phi(x), \phi(y)]_B \tag{2.3.7}$$

for every $x, y \in A$, then ϕ is said to be a *Lie algebra homomorphism* from A into B. Remember that A and B may be considered as algebras over k in the strict sense, using $[\cdot, \cdot]_A$ and $[\cdot, \cdot]_B$ as multiplication on A and B, respectively. A Lie algebra homomorphism from A into B is the same as an algebra homomorphism from A into B, as algebras over k in the strict sense, as in the previous section.

Let A and B be algebras over k in the strict sense, with multiplication expressed as in (2.2.1), and let ϕ be an algebra homomorphism from A into B. Also let $[\cdot,\cdot]_A$ and $[\cdot,\cdot]_B$ be the corresponding commutators on A and B, as in (2.3.6). If $x, y \in A$, then

$$\phi([x,y]_A) = \phi(x\,y - y\,x) = \phi(x)\,\phi(y) - \phi(y)\,\phi(x) = [\phi(x), \phi(y)]_B. \tag{2.3.8}$$

This means that ϕ may be considered as an algebra homomorphism from A into B, using $[\cdot,\cdot]_A$ and $[\cdot,\cdot]_B$ as the algebra operations on A and B, respectively. If A and B are associative algebras with respect to their given operations of multiplication, then A and B are Lie algebras with respect to $[\cdot,\cdot]_A$ and $[\cdot,\cdot]_B$, respectively, as before, and ϕ may be considered as a Lie algebra homomorphism from A into B with respect to these Lie brackets.

2.4 The adjoint representation

Let k be a commutative ring with a multiplicative identity element, and let $(A, [x,y]_A)$ be a Lie algebra over k. If $x \in A$, then let $\operatorname{ad} x$ be the mapping from A into itself defined by

$$(\operatorname{ad} x)(y) = [x,y]_A \tag{2.4.1}$$

for every $y \in A$. This is the same as the multiplication operator on A corresponding to x, as in Section 2.2, using the Lie bracket on A as multiplication. In particular, $\operatorname{ad} x$ is a module homomorphism from A into itself, as a module over k, because $[x,y]_A$ is linear over k in y. Thus

$$x \mapsto \operatorname{ad} x \tag{2.4.2}$$

defines a mapping from A into the space $\operatorname{Hom}_k(A,A)$ of module homomorphisms from A into itself. Remember that $\operatorname{Hom}_k(A,A)$ is a module over k with respect to pointwise addition and scalar multiplication of mappings from A into itself. As before, (2.4.2) is a module homomorphism from A into $\operatorname{Hom}_k(A,A)$ as modules over k, because $[x,y]_A$ is linear in x over k.

If $\phi, \psi \in \operatorname{Hom}_k(A,A)$, then put

$$[\phi,\psi] = [\phi,\psi]_{\operatorname{Hom}_k(A,A)} = \phi \circ \psi - \psi \circ \phi, \tag{2.4.3}$$

which is an element of $\operatorname{Hom}_k(A,A)$ too. Of course, $\operatorname{Hom}_k(A,A)$ is a Lie algebra over k with respect to (2.4.3), because $\operatorname{Hom}_k(A,A)$ is an associative algebra over k with respect to composition of mappings. It is well known that (2.4.2) is a Lie algebra homomorphism from A into $\operatorname{Hom}_k(A,A)$, with respect to (2.4.3) on $\operatorname{Hom}_k(A,A)$. To see this, let $x, y, z \in A$ be given, and observe that

$$\begin{aligned} ([\operatorname{ad} x, \operatorname{ad} y])(z) &= (\operatorname{ad} x)((\operatorname{ad} y)(z)) - (\operatorname{ad} y)((\operatorname{ad} x)(z)) \\ &= (\operatorname{ad} x)([y,z]_A) - (\operatorname{ad} y)([x,z]_A) \\ &= [x,[y,z]_A]_A - [y,[x,z]_A]_A \\ &= [x,[y,z]_A]_A + [y,[z,x]_A]_A. \end{aligned} \tag{2.4.4}$$

This uses the fact that $[x,z]_A = -[z,x]_A$, as in (2.3.2), in the last step. We also have that

$$(\mathrm{ad}[x,y]_A)(z) = [[x,y]_A, z]_A = -[z,[x,y]_A]_A, \tag{2.4.5}$$

using (2.3.2) in the second step. The Jacobi identity (2.3.4) says exactly that the right sides of (2.4.4) and (2.4.5) are equal to each other. Thus

$$(\mathrm{ad}[x,y]_A)(z) = ([\mathrm{ad}\, x, \mathrm{ad}\, y])(z) \tag{2.4.6}$$

for every $z \in A$, so that

$$\mathrm{ad}[x,y]_A = [\mathrm{ad}\, x, \mathrm{ad}\, y] \tag{2.4.7}$$

as mappings from A into itself.

2.5 Derivations

Let k be a commutative ring with a multiplicative identity element, and let A be an algebra over k in the strict sense, where multiplication of $a, b \in A$ is expressed as $a\, b$. Also let δ be a module homomorphism from A into itself, as a module over k. If δ satisfies the product rule

$$\delta(a\, b) = \delta(a)\, b + a\, \delta(b) \tag{2.5.1}$$

for every $a, b \in A$, then δ is said to be a *derivation* on A. Let $\mathrm{Der}(A)$ be the collection of derivations on A. Remember that the space $\mathrm{Hom}_k(A,A)$ of all module homomorphisms from A into itself is a module over k with respect to pointwise addition and scalar multiplication of mappings on A. It is easy to see that $\mathrm{Der}(A)$ is a submodule of $\mathrm{Hom}_k(A,A)$, as a module over k. We also have that $\mathrm{Hom}_k(A,A)$ is an associative algebra over k, with respect to composition of mappings. This implies that $\mathrm{Hom}_k(A,A)$ is a Lie algebra over k with respect to the corresponding commutator bracket. It is well known that $\mathrm{Der}(A)$ is a Lie subalgebra of $\mathrm{Hom}_k(A,A)$ with respect to the commutator bracket.

More precisely, let $\delta, \delta' \in \mathrm{Der}(A)$ and $a, b \in A$ be given. Thus the commutator

$$[\delta, \delta'] = \delta \circ \delta' - \delta' \circ \delta \tag{2.5.2}$$

of δ and δ' is defined as a module homomorphism from A into itself. Observe that

$$\begin{aligned} ([\delta,\delta'])(a\, b) &= \delta(\delta'(a\, b)) - \delta'(\delta(a\, b)) \\ &= \delta(\delta'(a)\, b + a\, \delta'(b)) - \delta'(\delta(a)\, b + a\, \delta(b)) \\ &= \delta(\delta'(a))\, b + \delta'(a)\, \delta(b) + \delta(a)\, \delta'(b) + a\, \delta(\delta'(b)) \\ &\quad -\delta'(\delta(a))\, b - \delta(a)\, \delta'(b) - \delta'(a)\, \delta(b) - a\, \delta'(\delta(b)). \end{aligned} \tag{2.5.3}$$

The middle pair of terms in the last two lines cancel each other, so that

$$\begin{aligned} ([\delta,\delta'])(a\, b) &= \delta(\delta'(a))\, b + a\, \delta(\delta'(b)) - \delta'(\delta(a))\, b - a\, \delta'(\delta(b)) \\ &= ([\delta,\delta'])(a)\, b + a\, ([\delta,\delta'])(b), \end{aligned} \tag{2.5.4}$$

as desired.

Let $a \in A$ be given, and put

$$\delta_a(x) = a\,x - x\,a \tag{2.5.5}$$

for every $x \in A$. Of course, the right side of (2.5.5) is the same as the commutator bracket corresponding to multiplication on A. Note that δ_a is a module homomorphism from A into itself, because of bilinearity over k of multiplication on A. Similarly,

$$a \mapsto \delta_a \tag{2.5.6}$$

is a module homomorphism from A into $\mathrm{Hom}_k(A, A)$, as modules over k. If A is an associative algebra over k and $x, y \in A$, then

$$\begin{aligned} \delta_a(x\,y) &= a\,(x\,y) - (x\,y)\,a \\ &= (a\,x)\,y - x\,(y\,a) \\ &= (a\,x)\,y - (x\,a)\,y + x\,(a\,y) - x\,(y\,a) \\ &= \delta_a(x)\,y + x\,\delta_a(y), \end{aligned} \tag{2.5.7}$$

so that $\delta_a \in \mathrm{Der}(A)$.

Suppose now that $(A, [\cdot,\cdot]_A)$ is a Lie algebra over k. Let δ be a module homomorphism from A into itself, as a module over k. In this situation, the product rule says that

$$\delta([a, b]_A) = [\delta(a), b]_A + [a, \delta(b)]_A \tag{2.5.8}$$

for every $a, b \in A$. Thus $\delta \in \mathrm{Der}(A)$ when this holds. Let $x \in A$ be given, and let us verify that $\mathrm{ad}\,x = [x, \cdot]_A \in \mathrm{Der}(A)$. If $y, z \in A$, then

$$(\mathrm{ad}\,x)([y, z]_A) = [x, [y, z]_A]_A = -[y, [z, x]_A]_A - [z, [x, y]_A]_A, \tag{2.5.9}$$

using the Jacobi identity in the second step. It follows that

$$\begin{aligned} (\mathrm{ad}\,x)([y, z]_A) &= [[x, y]_A, z]_A + [y, [x, z]_A]_A \\ &= [(\mathrm{ad}\,x)(y), z]_A + [y, (\mathrm{ad}\,x)(z)]_A, \end{aligned} \tag{2.5.10}$$

as desired.

Let A be an algebra over k in the strict sense again, where the product of $a, b \in A$ is denoted $a\,b$. If $x, y \in A$, then let $[x, y] = x\,y - y\,x$ be the usual commutator bracket corresponding to multiplication in A. Let $\delta \in \mathrm{Der}(A)$ be given, and observe that

$$\begin{aligned} \delta([x, y]) = \delta(x\,y - y\,x) &= \delta(x)\,y + x\,\delta(y) - \delta(y)\,x - y\,\delta(x) \\ &= [\delta(x), y] + [x, \delta(y)] \end{aligned} \tag{2.5.11}$$

for every $x, y \in A$. Of course, we can also consider A as an algebra over k in the strict sense with respect to $[x, y]$. It follows from (2.5.11) that δ is a derivation on A with respect to $[x, y]$ as well.

2.6 Involutions

Let k be a commutative ring with a multiplicative identity element, and let A, B be algebras over k in the strict sense, where multiplication of x, y is expressed as $x\,y$. In particular, A and B are modules over k, and we let ϕ be a module homomorphism from A into B. If

$$\phi(a_1\,a_2) = \phi(a_2)\,\phi(a_1) \tag{2.6.1}$$

for every $a_1, a_2 \in A$, then one may say that ϕ is an *opposite algebra homomorphism* from A into B. Of course, this is the same as an ordinary algebra homomorphism when A or B is commutative. If A and B have multiplicative identity elements e_A and e_B, respectively, then one may also ask that

$$\phi(e_A) = e_B. \tag{2.6.2}$$

If ϕ is a one-to-one opposite algebra homomorphism from A onto B, then ϕ^{-1} is an opposite algebra homomorphism from B onto A, and ϕ is said to be an *opposite algebra isomorphism* from A onto B. In this case, if A has a multiplicative identity element e_A, then it is easy to see that $\phi(e_A)$ is the multiplicative identity element in B. An *opposite algebra automorphism* on A is an oppposite algebra isomorphism from A onto itself.

Let $[a_1, a_2]_A = a_1\,a_2 - a_2\,a_1$ and $[b_1, b_2]_B = b_1\,b_2 - b_2\,b_1$ be the corresponding commutator brackets on A and B. If ϕ is an opposite algebra homomorphism from A into B and $a_1, a_2 \in A$, then

$$\begin{aligned} \phi([a_1, a_2]_A) = \phi(a_1\,a_2 - a_2\,a_1) &= \phi(a_2)\,\phi(a_1) - \phi(a_1)\,\phi(a_2) \\ &= -[\phi(a_1), \phi(a_2)]_B. \end{aligned} \tag{2.6.3}$$

An opposite algebra homomorphism $x \mapsto x^*$ from A into itself is said to be an (algebra) *involution* on A if

$$(x^*)^* = x \tag{2.6.4}$$

for every $x \in A$. This implies that $x \mapsto x^*$ is a one-to-one mapping from A onto itself, which is its own inverse mapping.

Let $x \mapsto x^*$ be an opposite algebra automorphism on A. An element a of A is said to be *self-adjoint* with respect to $x \mapsto x^*$ if

$$a^* = a, \tag{2.6.5}$$

and a is said to be *anti-self-adjoint* with respect to $x \mapsto x^*$ if

$$a^* = -a. \tag{2.6.6}$$

The collections of self-adjoint and anti-self-ajoint elements of A are submodules of A, as a module over k. If $1 + 1 = 0$ in k, then self-adjointness and anti-self-adjointness are the same. If $1+1$ is invertible in k and $a \in A$ is both self-adjoint and anti-self-adjoint, then $a = 0$.

Suppose that $x \mapsto x^*$ is an algebra involution on A. If a is any element of A, then

$$a + a^* \tag{2.6.7}$$

is self-adjoint with respect to $x \mapsto x^*$, and

$$a - a^* \tag{2.6.8}$$

is anti-self-adjoint with respect to $x \mapsto x^*$. If $1 + 1 = 0$ in k, then (2.6.7) and (2.6.8) are the same. If $1 + 1$ is invertible in k, then every element of A can be expressed as the sum of self-adjoint and anti-self-adjoint elements of A, using (2.6.7) and (2.6.8). This expression is unique in this case, because 0 is the only element of A that is both self-adjoint and anti-self-adjoint.

Let $a, b \in A$ be given, and let $[a, b] = a\,b - b\,a$ be their usual commutator in A. If $x \mapsto x^*$ is an opposite algebra automorphism on A, and a, b are anti-self-adjoint with respect to $x \mapsto x^*$, then

$$([a, b])^* = -[a^*, b^*] = -[-a, -b] = -[a, b], \tag{2.6.9}$$

using (2.6.3) in the first step. Thus $[a, b]$ is anti-self-adjoint as well.

Suppose now that k is the field $\mathbf{C}$ of complex numbers, and that A and B are algebras in the strict sense over $\mathbf{C}$. A conjugate-linear mapping ϕ from A into B is said to be a *conjugate-linear algebra homomorphism* if it preserves products as in (2.2.5), and ϕ is said to be a *conjugate-linear opposite algebra homomorphism* if it satisfies (2.6.1). If A and B are considered as algebras over the real numbers, then ϕ may be considered as a real-linear algebra homomorphism or opposite algebra homomorphism from A into B, as appropriate. If ϕ is a one-to-one conjugate-linear algebra homomorphism or opposite algebra homomorphism from A onto B, then ϕ^{-1} is a conjugate-linear algebra homomorphism or opposite algebra homomorphism from B onto A, as appropriate, and ϕ is said to be a *conjugate-linear algebra isomorphism* or *opposite algebra isomorphism* from A onto B, as appropriate. In particular, if $A = B$, then ϕ is said to be a *conjugate-linear algebra automorphism* or *opposite algebra automorphism* on A, as appropriate.

A conjugate-linear algebra homomorphism $x \mapsto x^*$ from A into itself is said to be a *conjugate-linear (algebra) involution* on A if it satisfies (2.6.4) for every $x \in A$. In this case, $x \mapsto x^*$ is a conjugate-linear opposite algebra automorphism on A, as before. Suppose that $x \mapsto x^*$ is a conjugate-linear opposite algebra automorphism on A, which may be considered as a real-linear opposite algebra automorphism of A as an algebra over $\mathbf{R}$. In particular, A may be considered as a vector space over $\mathbf{R}$, and the collections of self-adjoint and anti-self-adjoint elements of A are real-linear subspaces of A, which is to say that they are linear subspaces of A as a vector space over $\mathbf{R}$. In this situation, the anti-self-adjoint elements of A are exactly those that can be expressed as i times a self-adjoint element of A.

2.7 More on multiplication operators

Let k be a commutative ring with a multiplicative identity element, and let A be an algebra over k in the strict sense again, where multiplication of $a, b \in A$ is expressed as $a\,b$. If $a \in A$, then

$$M_a(x) = a\,x \tag{2.7.1}$$

defines a module homomorphism from A into itself, as in Section 2.2. This is the operator of left multiplication by a on A. Similarly,

$$\widetilde{M}_a(x) = x\,a \tag{2.7.2}$$

defines a module homomorphism from A into itself, which is the operator of right multiplication by a on A. Of course, if A is commutative, then (2.7.1) and (2.7.2) are the same.

As before,

$$a \mapsto \widetilde{M}_a \tag{2.7.3}$$

defines a mapping from A into the space $\mathrm{Hom}_k(A, A)$ of all homomorphisms from A into itself, as a module over k. Bilinearity of multiplication on A implies that (2.7.3) is a module homomorphism from A into $\mathrm{Hom}_k(A, A)$, as modules over k. If A has a multiplicative identity element e, then $\widetilde{M}_e$ is the identity mapping on A. We also have that

$$\widetilde{M}_a(e) = e\,a = a \tag{2.7.4}$$

for every $a \in A$ in this case, so that (2.7.3) is injective.

Observe that

$$\widetilde{M}_a(\widetilde{M}_b(x)) = \widetilde{M}_a(x\,b) = (x\,b)\,a \tag{2.7.5}$$

and

$$\widetilde{M}_{b\,a}(x) = x\,(b\,a) \tag{2.7.6}$$

for every $a, b, x \in A$. If A is an associative algebra, then we get that

$$\widetilde{M}_a \circ \widetilde{M}_b = \widetilde{M}_{b\,a} \tag{2.7.7}$$

for every $a, b \in A$, as mappings from A into itself. This implies that (2.7.3) is an opposite algebra homomorphism from A into $\mathrm{Hom}_k(A, A)$, using composition of mappings as multiplication on $\mathrm{Hom}_k(A, A)$, as usual.

Let $[x, y] = x\,y - y\,x$ be the usual commutator of $x, y \in A$. If A is an associative algebra, then it follows that

$$\widetilde{M}_{[a,b]} = \widetilde{M}_{a\,b-b\,a} = \widetilde{M}_{a\,b} - \widetilde{M}_{b\,a} = \widetilde{M}_b \circ \widetilde{M}_a - \widetilde{M}_a \circ \widetilde{M}_b \tag{2.7.8}$$

for every $a, b \in A$. Similarly,

$$M_{[a,b]} = M_{a\,b-b\,a} = M_{a\,b} - M_{b\,a} = M_a \circ M_b - M_b \circ M_a \tag{2.7.9}$$

for every $a, b \in A$ in this situation, using (2.2.12) in the third step. If $a, b, x \in A$, then

$$M_a(\widetilde{M}_b(x)) = M_a(x\,b) = a\,(x\,b) \tag{2.7.10}$$

and

$$\widetilde{M}_b(M_a(x)) = \widetilde{M}_b(a\,x) = (a\,x)\,b. \tag{2.7.11}$$

These are the same when A is an associative algebra, in which case

$$M_a \circ \widetilde{M}_b = \widetilde{M}_b \circ M_a \tag{2.7.12}$$

for every $a, b \in A$.

If $a \in A$, then let $\mathrm{ad}\, a$ be the mapping from A into itself defined by

$$(\mathrm{ad}\, a)(x) = [a, x] = a\,x - x\,a = M_a(x) - \widetilde{M}_a(x) \tag{2.7.13}$$

for every $x \in A$. Equivalently,

$$\mathrm{ad}\, a = M_a - \widetilde{M}_a, \tag{2.7.14}$$

which is a module homomorphism from A into itself, as a module over k. We also have that

$$a \mapsto \mathrm{ad}\, a \tag{2.7.15}$$

is a module homomorphism from A into $\mathrm{Hom}_k(A, A)$, as modules over k. If A is an associative algebra, then

$$\mathrm{ad}[a, b] = [\mathrm{ad}\, a, \mathrm{ad}\, b] = (\mathrm{ad}\, a) \circ (\mathrm{ad}\, b) - (\mathrm{ad}\, b) \circ (\mathrm{ad}\, a) \tag{2.7.16}$$

for every $a, b \in A$, as mappings from A into itself. More precisely, if A is an associative algebra over k, then A is also a Lie algebra over k with respect to the commutator bracket $[x, y]$. Thus (2.7.16) follows from the analogous statement for Lie algebras. Alternatively, one can use (2.7.14) to reduce to the properties (2.7.8), (2.7.9), and (2.7.12) of the multiplication operators M_a and $\widetilde{M}_a$.

2.8 Matrices

Let k be a commutative ring with a multiplicative identity element, and let A be a module over k. If $n \in \mathbf{Z}_+$, then we let $M_n(A)$ be the space of $n \times n$ matrices with entries in A. An element of $M_n(A)$ may be given as $a = (a_{j,l})$, where $a_{j,l} \in A$ for every $j, l = 1, \ldots, n$. It is easy to see that $M_n(A)$ is also a module over k, with respect to entrywise addition and scalar multiplication.

Suppose that A is an algebra over k in the strict sense, where multiplication of $x, y \in A$ is expressed as $x\,y$. If $a, b \in M_n(A)$, then their product $c = a\,b$ is defined as usual by

$$c_{j,r} = \sum_{l=1}^{n} a_{j,l}\, b_{l,r} \tag{2.8.1}$$

for every $j, r = 1, \ldots, n$. It is easy to see that this is bilinear in a and b over k, so that $M_n(A)$ is an algebra in the strict sense over k with respect to matrix multiplication. If A is an associative algebra over k, then $M_n(A)$ is associative with respect to matrix multiplication.

Suppose for the moment that A has a multiplicative identity element e. The *identity matrix* $I = I_n$ in $M_n(A)$ is the $n \times n$ matrix whose diagonal entries are equal to e, and whose other entries are equal to 0. This is the multiplicative identity element in $M_n(A)$.

If $a = (a_{j,l}) \in M_n(A)$, then the *transpose* $a^t = (a^t_{j,l}) \in M_n(A)$ is defined as usual by

$$a^t_{j,l} = a_{l,j} \tag{2.8.2}$$

for every $j, l = 1, \ldots, n$. Note that the mapping $a \mapsto a^t$ from a matrix to its transpose defines a module homomorphism from $M_n(A)$ into itself, which is to say that it is linear over k. Let $x \mapsto x^*$ be an opposite algebra automorphism on A, as in Section 2.6. If $a = (a_{j,l}) \in M_n(A)$, then let $a^* = ((a^*)_{j,l}) \in M_n(A)$ be defined by

$$(a^*)_{j,l} = (a_{l,j})^* \tag{2.8.3}$$

for every $j, l = 1, \ldots, n$, which is to say that we apply $x \mapsto x^*$ to the entries of the transpose a^t of a. One can check that this defines an opposite algebra automorphism on $M_n(A)$, and an involution on $M_n(A)$ when $x \mapsto x^*$ is an involution on A.

If A is a commutative algebra, then the identity mapping on A defines an algebra involution on A. In this case, a^* reduces to the transpose a^t of A.

Suppose now that k is the field $\mathbf{C}$ of complex numbers. Let $x \mapsto x^*$ be a conjugate-linear opposite algebra automorphism on A, as in Section 2.6. In this situation, $a \mapsto a^*$ is a conjugate-linear opposite algebra automorphism on $M_n(A)$, and a conjugate-linear involution on $M_n(A)$ when $x \mapsto x^*$ is a conjugate-linear involution on A.

In particular, we can take $A = \mathbf{C}$, as a commutative algebra over itself. Of course, complex-conjugation may be considered as a conjugate-linear involution on $\mathbf{C}$. If $a = (a_{j,l}) \in M_n(\mathbf{C})$, then let $a^* = ((a^*)_{j,l}) \in M_n(\mathbf{C})$ be defined by

$$(a^*)_{j,l} = \overline{a_{l,j}} \tag{2.8.4}$$

for every $j, l = 1, \ldots, n$, which is the same as the complex-conjugate of the entries of the transpose a^t of a. This defines a conjugate-linear involution on $M_n(\mathbf{C})$, as before.

2.9 Traces of matrices

Let k be a commutative ring with a multiplicative identity element, and let n be a positive integer. If A is a module over k, then $M_n(A)$ is a module over k as well, with respect to entrywise addition and scalar multiplication, as in the previous section. If $a = (a_{j,l}) \in M_n(A)$, then the *trace* of a is defined as an element of A as usual by

$$\operatorname{tr} a = \sum_{j=1}^{n} a_{j,j}. \tag{2.9.1}$$

It is easy to see that this defines a homomorphism from $M_n(A)$ into A, as modules over k. We also have that

$$\operatorname{tr} a^t = \operatorname{tr} a \tag{2.9.2}$$

for every $a \in M_n(A)$, where the transpose a^t of a is defined as in the previous section.

Suppose that A is an algebra over k in the strict sense, where multiplication of $x, y \in A$ is expressed as $x\,y$. If $a, b \in M_n(A)$, then the products $a\,b$ and $b\,a$ are defined as elements of $M_n(A)$ as in the previous section. Observe that

$$\operatorname{tr}(a\,b) = \sum_{j=1}^{n} a_{j,l}\, b_{l,j} \tag{2.9.3}$$

and

$$\operatorname{tr}(b\,a) = \sum_{j=1}^{n} b_{l,j}\, a_{j,l}. \tag{2.9.4}$$

If A is a commutative algebra over k, then we get that

$$\operatorname{tr}(a\,b) = \operatorname{tr}(b\,a) \tag{2.9.5}$$

for every $a, b \in M_n(A)$. Equivalently, this means that

$$\operatorname{tr}(a\,b - b\,a) = 0 \tag{2.9.6}$$

for every $a, b \in M_n(A)$.

The *nth general linear algebra* $gl_n(A)$ with entries in A is defined as an algebra over k in the following way. As a module over k, $gl_n(A)$ is the same as $M_n(A)$. We use the commutator $[a, b] = a\,b - b\,a$ as the bilinear operation on $gl_n(A)$, where the products $a\,b$ and $b\,a$ are as defined in the previous section. This makes $gl_n(A)$ into an algebra over k in the strict sense. If A is an associative algebra over k, then $M_n(A)$ is an associative algebra over k too, so that $gl_n(A)$ is a Lie algebra over k.

Put

$$sl_n(A) = \{a \in gl_n(A) : \operatorname{tr} a = 0\}, \tag{2.9.7}$$

which defines a submodule of $gl_n(A)$ as a module over k, or equivalently a submodule of $M_n(A)$. If A is a commutative algebra over k, then

$$[a, b] \in sl_n(A) \tag{2.9.8}$$

for every $a, b \in gl_n(A)$, as in (2.9.6). In particular, this means that $sl_n(A)$ is a subalgebra of $gl_n(A)$ with respect to the commutator $[a, b]$ when A is commutative. In this case, $sl_n(A)$ is called the *nth special linear algebra* with entries in A. If A is a commutative associative algebra over k, then $sl_n(A)$ is a Lie algebra over k with respect to $[a, b]$.

2.10 Vector spaces and linear mappings

Let k be a field. If V and W are vector spaces over k, then the space $\mathcal{L}(V, W)$ of linear mappings from V into W is a vector space over k with respect to pointwise addition and scalar multiplication. This is the same as the space $\mathrm{Hom}_k(V, W)$ of module homomorphisms from V into W, where V and W are considered as modules over k. Similarly, if V is a vector space over k, then the space $\mathcal{L}(V) = \mathcal{L}(V, V)$ of linear mappings from V into itself is an associative algebra over k with respect composition of mappings.

The *general linear algebra* $gl(V)$ associated to a vector space V over k is defined as a Lie algebra over k in the following way. As a vector space over k, $gl(V)$ is the same as $\mathcal{L}(V)$. If T_1 and T_2 are linear mappings from V into itself, then their commutator

$$[T_1, T_2] = T_1 \circ T_2 - T_2 \circ T_1 \tag{2.10.1}$$

defines a linear mapping from V into itself as well. This defines a bilinear operation on $gl(V)$, which we use to define the Lie bracket on $gl(V)$. This satisfies the requirements of a Lie algebra, because $\mathcal{L}(V)$ is an associative algebra over k with respect to composition of linear mappings.

Suppose that V is a finite-dimensional vector space over k, with dimension $n \geq 1$. Let $v_1, \ldots, v_n$ be a basis for V, as a vector space over k. Thus every $v \in V$ can be expressed in a unique way as

$$v = \sum_{l=1}^{n} t_l\, v_l, \tag{2.10.2}$$

where $t_1, \ldots, t_n \in k$. Let $a = (a_{j,l})$ be an $n \times n$ matrix with entries in k. If $v \in V$ is as in (2.10.2), then put

$$T_a(v) = \sum_{j=1}^{n} \Big(\sum_{l=1}^{n} a_{j,l}\, t_l \Big)\, v_j, \tag{2.10.3}$$

which defines an element of V. Of course, T_a is a linear mapping from V into itself, and

$$a \mapsto T_a \tag{2.10.4}$$

is a linear mapping from $M_n(k)$ into $\mathcal{L}(V)$. More precisely, (2.10.4) is a one-to-one mapping from $M_n(k)$ onto $\mathcal{L}(V)$, and

$$T_a \circ T_b = T_{a\,b} \tag{2.10.5}$$

for every $a, b \in M_n(k)$. This means that (2.10.4) is an algebra isomorphism from $M_n(k)$ onto $\mathcal{L}(V)$, with respect to matrix multiplication on $M_n(k)$, and composition of linear mappings on V. It follows that (2.10.4) is also a Lie algebra isomorphism from $gl_n(k)$ onto $gl(V)$, with respect to their corresponding commutator brackets.

If $a = (a_{j,l}) \in M_n(k)$, then the *trace* of T_a is defined as an element of k by

$$\operatorname{tr} T_a = \operatorname{tr} a = \sum_{j=1}^{n} a_{j,j}, \tag{2.10.6}$$

where $\operatorname{tr} a$ refers to the trace of a as a matrix, as in the previous section. This defines the trace $\operatorname{tr} T$ of every linear mapping T from V into itself, by the remarks in the preceding paragraph. Note that the trace is a linear mapping from $\mathcal{L}(V)$ into k. If $T_1, T_2 \in \mathcal{L}(V)$, then

$$\operatorname{tr}(T_1 \circ T_2) = \operatorname{tr}(T_2 \circ T_1), \tag{2.10.7}$$

by (2.9.5) and (2.10.5). It is well known that the trace of $T \in \mathcal{L}(V)$ does not depend on the choice of basis $v_1, \ldots, v_n$ for V, because of (2.9.5) or (2.10.7).

Put

$$sl(V) = \{T \in gl(V) : \operatorname{tr} T = 0\}, \tag{2.10.8}$$

which is a linear subspace of $gl(V)$, or equivalently of $\mathcal{L}(V)$. If $T_1, T_2 \in gl(V)$, then

$$\operatorname{tr}[T_1, T_2] = 0, \tag{2.10.9}$$

by (2.10.7), and hence

$$[T_1, T_2] \in sl(V). \tag{2.10.10}$$

by (2.10.9). In particular, $sl(V)$ is a subalgebra of $gl(V)$ as a Lie algebra with respect to the commutator bracket. This is the *special linear algebra* associated to V. The mapping (2.10.4) defines a Lie algebra isomorphism from $sl_n(k)$ onto $sl(V)$.

2.11 Ideals and quotients

Let k be a commutative ring with a multiplicative identity element. If A and B are modules over k and ϕ is a module homomorphism from A into B, then the *kernel* of ϕ is the set of $a \in A$ such that $\phi(a) = 0$, as usual. Of course, this is a submodule of A.

If A is a module over k, and A_0 is a submodule of A, then the quotient A/A_0 can be defined as a module over k in the usual way. More precisely, one can consider the quotient A/A_0 initially as a commutative group with respect to addition, and check that scalar multiplication on A/A_0 by elements of k can be defined in a natural way. The corresponding quotient mapping is a module homomorphism from A onto A/A_0, with kernel equal to A_0.

Let A be an algebra over k in the strict sense, where multiplication of $a, b \in A$ is expressed as $a\,b$. Also let A_0 be a submodule of A, as a module over k. If

$$a\,b \in A_0 \tag{2.11.1}$$

for every $a \in A$ and $b \in A_0$, then A_0 is said to be a *left ideal* in A. Similarly, if (2.11.1) holds for every $a \in A_0$ and $b \in A$, then A_0 is said to be a *right ideal* in A. If A_0 is both a left and right ideal in A, then A is said to be a *two-sided ideal* in A. Of course, if A is a commutative algebra, then left and right ideals in A are the same. If B is another algebra over k in the strict sense, and ϕ is an algebra homomorphism from A into B, then the kernel of ϕ is a two-sided ideal in A.

If A_0 is a submodule of A, as a module over k, then the quotient A/A_0 can be defined as a module over k too, as before. Let q_0 be the corresponding quotient mapping from A onto A/A_0. Thus

$$(a, b) \mapsto q_0(a\,b) \tag{2.11.2}$$

is bilinear over k as a mapping from $A \times A$ into A/A_0. If A_0 is a left ideal in A, then

$$q_0(a\,b) = 0 \tag{2.11.3}$$

for every $a \in A$ and $b \in A_0$, and (2.11.2) leads to a bilinear mapping from $A \times (A/A_0)$ into A/A_0. More precisely, if $a, b \in A$, then $q_0(a\,b)$ only depends on a and $q_0(b)$ in this case. Similarly, if A_0 is a right ideal in A, then (2.11.3) holds for every $a \in A_0$ and $b \in A$, and (2.11.2) leads to a bilinear mapping from $(A/A_0) \times A$ into A/A_0. If A_0 is a two-sided ideal in A, then (2.11.3) holds when either a or b is in A_0, so that $q_0(a\,b)$ only depends on $q_0(a)$ and $q_0(b)$. In this situation, (2.11.2) leads to a bilinear mapping from $(A/A_0) \times (A/A_0)$ into A/A_0, which makes A/A_0 into an algebra over k in the strict sense, for which the quotient mapping q_0 is an algebra homomorphism.

Suppose for the moment that A is an associative algebra over k. If A_0 is a two-sided ideal in A, then A/A_0 is an associative algebra over k as well. If A_0 is a left ideal in A, then elements of A act on A/A_0 by multiplication on the left, as in the preceding paragraph. Associativity of multiplication on A implies that the action on A/A_0 by products of elements of A corresponds to the composition of the actions on A/A_0 of the individual elements of A. Similarly, if A_0 is a right ideal in A, then elements of A act on A/A_0 by multiplication on the right, with the appropriate relationship between products of elements of A and their actions on A/A_0.

Suppose now that $(A, [\cdot,\cdot]_A)$ is a Lie algebra over k, and let A_0 be a submodule of A as a module over k. If

$$[a, b]_A \in A_0 \tag{2.11.4}$$

for every $a \in A$ and $b \in A_0$, then A_0 is said to be an *ideal* in A as a Lie algebra. This is equivalent to saying that A_0 is a left, right, or two-sided ideal in A, as an algebra over k in the strict sense. In this case, if q_0 is the usual quotient mapping from A onto A_0, then $q_0([a, b]_A)$ depends only on $q_0(a)$ and $q_0(b)$, as before. It is easy to see that A/A_0 is also a Lie algebra over k with respect to the Lie bracket $[\cdot,\cdot]_{A/A_0}$ obtained from $[\cdot,\cdot]_A$ in this way.

Let A be an associative algebra over k again, where the product of $a, b \in A$ is denoted $a\,b$. Let A_0 be a two-sided ideal in A. Remember that A may also be considered as a Lie algebra over k with respect to the commutator bracket $[a, b]_A = a\,b - b\,a$. Under these conditions, A_0 may be considered an an ideal in A as a Lie algebra with respect to $[a, b]_A$ as well.

2.12 Bilinear forms

Let k be a commutative ring with a multiplicative identity element, and let A, C be modules over k. Also let β be a mapping from $A \times A$ into C that is bilinear over k. Of course, k may be considered as a module over itself as well, using multiplication on k as scalar multiplication. If $C = k$, as a module over itself, then β is said to be a *bilinear form* on A, as a module over k. As before, β is said to be *symmetric* on $A \times A$ when

$$\beta(b, a) = \beta(a, b) \tag{2.12.1}$$

for every $a, b \in A$, and *antisymmetric* on $A \times A$ when

$$\beta(b, a) = -\beta(a, b) \tag{2.12.2}$$

for every $a, b \in A$. It is sometimes better to ask that

$$\beta(a, a) = 0 \tag{2.12.3}$$

for every $a \in A$, instead of (2.12.2). Remember that (2.12.3) implies (2.12.2), because of bilinearity, as in Section 2.1. If $1 + 1 = 0$ in k, then (2.12.1) and (2.12.2) are the same. If $1 + 1$ is invertible in k, then (2.12.2) implies (2.12.3).

If β is any bilinear mapping from $A \times A$ into C, then

$$\beta(a, b) + \beta(b, a) \tag{2.12.4}$$

is symmetric on $A \times A$, and

$$\beta(a, b) - \beta(b, a) \tag{2.12.5}$$

is antisymmetric on $A \times A$. If $1 + 1 = 0$ in k, then (2.12.4) is the same as (2.12.5), and is equal to 0 when $a = b$. If $1 + 1$ is invertible in k, then every bilinear mapping from $A \times A$ into C can be expressed as the sum of a symmetric bilinear mapping and an antisymmetric bilinear mapping. In this case, a bilinear mapping from $A \times A$ into C that is both symmetric and antisymmetric on $A \times A$ is identically 0 on $A \times A$, which implies that the previous expression as a sum is unique.

Let β be a bilinear mapping from $A \times A$ into C, and let ϕ be a module homomorphism from A into itself. Let us say that ϕ is *symmetric* with respect to β on A if

$$\beta(\phi(a), b) = \beta(a, \phi(b)) \tag{2.12.6}$$

for every $a, b \in A$. Similarly, let us say that ϕ is *antisymmetric* with respect to β on A if

$$\beta(\phi(a), b) = -\beta(a, \phi(b)) \tag{2.12.7}$$

for every $a, b \in A$. The collections of module homomorphisms from A into itself that are symmetric or antisymmetric with respect to β are submodules of $\mathrm{Hom}_k(A, A)$. If $1+1 = 0$ in k, then (2.12.6) and (2.12.7) are the same, as usual.

Let ϕ and ψ be module homomorphisms from A into itself, and let $[\phi, \psi] = \phi \circ \psi - \psi \circ \phi$ be their commutator with respect to composition. If ϕ and ψ are both symmetric on A with respect to β, then

$$\begin{aligned} \beta(([\phi, \psi])(a), b) &= \beta(\phi(\psi(a)), b) - \beta(\psi(\phi(a)), b) \\ &= \beta(a, \psi(\phi(b))) - \beta(a, \phi(\psi(b))) = -\beta(a, ([\phi, \psi])(b))) \end{aligned} \tag{2.12.8}$$

for every $a, b \in A$. This also works when ϕ and ψ are both antisymmetric with respect to β on A, using antisymmetry twice in each term in the second step. In both cases, we get that $[\phi, \psi]$ is antisymmetric with respect to β on A. In particular, the collection of module homomorphisms from A into itself that are antisymmetric with respect to β is a Lie subalgebra of $\mathrm{Hom}_k(A, A)$, as a Lie algebra over k with respect to the commutator bracket.

2.13 Dual spaces and mappings

Let k be a field, and let V be a vector space over k. Remember that a linear functional on V is a linear mapping from V into k, where k is considered as a one-dimensional vector space over itself. The dual V' of V is the space of all linear functionals on V, which is a vector space over k with respect to pointwise addition and scalar multiplication. If V has finite dimension, then it is well known that the dimension of V' is the same as the dimension of V. This can be seen by expressing linear functionals on V in terms of a basis for V.

Let W be another vector space over k, and let T be a linear mapping from V into W. If μ is a linear functional on W, then

$$T'(\mu) = \mu \circ T \tag{2.13.1}$$

is a linear functional on V. This defines a linear mapping T' from W' into V', which is the dual mapping associated to T. We also have that

$$T \mapsto T' \tag{2.13.2}$$

is linear as a mapping from the space $\mathcal{L}(V, W)$ of linear mappings from V into W into the space $\mathcal{L}(W', V')$ of linear mappings from W' into V'. The dual of the identity mapping I_V on V, as a linear mapping from V into itself, is the identity mapping $I_{V'}$ on V'.

Let Z be a third vector space over k, let T_1 be a linear mapping from V into W, and let T_2 be a linear mapping from W into Z. Thus the composition $T_2 \circ T_1$ is a linear mapping from V into Z, whose dual maps Z' into V'. If $\nu \in Z'$, then

$$(T_2 \circ T_1)'(\nu) = \nu \circ (T_2 \circ T_1) = (\nu \circ T_2) \circ T_1 = T_1'(T_2'(\nu)). \tag{2.13.3}$$

This shows that

$$(T_2 \circ T_1)' = T_1' \circ T_2' \tag{2.13.4}$$

as mappings from Z' into V'.

Let $V'' = (V')'$ be the dual of V'. If $v \in V$ and $\lambda \in V'$, then

$$L_v(\lambda) = \lambda(v) \tag{2.13.5}$$

is an element of k. This defines L_v as a linear functional on V', and

$$v \mapsto L_v \tag{2.13.6}$$

is a linear mapping from V into V''. If $v \in V$ and $v \neq 0$, then one can find a $\lambda \in V'$ such that $\lambda(v) \neq 0$, using a basis for V. This implies that (2.13.6) is injective as a mapping from V into V''. If V has finite dimension, then V' has the same dimension as V, and hence V'' has the same dimension as well. In this case, (2.13.6) also maps V onto V''.

Let $\lambda_1, \ldots, \lambda_n$ be n linear functionals on V for some positive integer n, and put

$$\Lambda(v) = (\lambda_1(v), \ldots, \lambda_n(v)) \tag{2.13.7}$$

for each $v \in V$. This defines a linear mapping from V into the space k^n of n-tuples of elements of k, which is a vector space over k with respect to coordinatewise addition and scalar multiplication, as usual. Of course, the kernel of Λ is the same as the intersection of the kernels of $\lambda_1, \ldots, \lambda_n$. If Λ is injective, then the dimension of V is less than or equal to n, by standard results in linear algebra. In particular, if Λ is injective and the dimension of V is equal to n, then Λ maps V onto k^n.

2.14 Nondegenerate bilinear forms

Let k be a field, and let V be a finite-dimensional vector space over k. Also let $b(v, w)$ be a bilinear form on V. If $w \in V$, then

$$b_w(v) = b(v, w) \tag{2.14.1}$$

defines a linear functional on V as a function of v, and $w \mapsto b_w$ defines a linear mapping from V into its dual space V'. The image

$$\{b_w : w \in V\} \tag{2.14.2}$$

of this linear mapping is a linear subspace of V'. Note that (2.14.2) is equal to V' exactly when $w \mapsto b_w$ is injective as a linear mapping from V into V', because V and V' have the same dimension.

If for every $v \in V$ with $v \neq 0$ there is a $w \in V$ such that $b(v, w) \neq 0$, then b is said to be *nondegenerate* on V. This is the same as saying that the intersections of the kernels of the b_w's, $w \in V$, is the trivial subspace $\{0\}$ of V. One can check that this happens exactly when (2.14.2) is equal to V'.

Suppose that b is a nondegenerate bilinear form on V, and let T be a linear mapping from V into itself. If $w \in V$, then $b(T(v), w)$ defines a linear functional on V, as a function of v. This implies that there is a unique element $T^*(w)$ of V such that

$$b(T(v), w) = b(v, T^*(w)) \tag{2.14.3}$$

for every $v \in V$, because b is nondegenerate on V. This defines a mapping T^* from V into itself, which is the *adjoint* of T with respect to b. It is easy to see that T^* is a linear mapping from V into itself, because $T^*(w)$ is uniquely determined by (2.14.3).

Remember that the space $\mathcal{L}(V)$ of linear mappings from V into itself is an algebra over k with respect to composition of mappings. One can check that $T \mapsto T^*$ defines a linear mapping from $\mathcal{L}(V)$ into itself, because T^* is uniquely determined by (2.14.3). Clearly $I^* = I$, where I is the identity mapping on V.

If T is any linear mapping from V into itself, then $T^* = T$ exactly when T is symmetric with respect to b, as in Section 2.12. Similarly, $T^* = -T$ exactly when T is antisymmetric with respect to b.

If T is a linear mapping from V into itself and $T^* = 0$ on V, then $T = 0$ on V, because of (2.14.3) and the nondegeneracy of b on V. This implies that $T \mapsto T^*$ is a one-to-one mapping from $\mathcal{L}(V)$ onto itself, because $\mathcal{L}(V)$ is a finite-dimensional vector space over k.

Let T_1 and T_2 be linear mappings from V into itself. If $v, w \in V$, then

$$\begin{aligned} b((T_2 \circ T_1)(v), w) &= b(T_2(T_1(v)), w) = b(T_1(v), T_2^*(w)) \\ &= b(v, T_1^*(T_2^*(w))) = b(v, (T_1^* \circ T_2^*)(w)). \end{aligned} \tag{2.14.4}$$

This implies that

$$(T_2 \circ T_1)^* = T_1^* \circ T_2^*, \tag{2.14.5}$$

so that $T \mapsto T^*$ is an opposite algebra automorphism on $\mathcal{L}(V)$, as in Section 2.6.

Let T be a linear mapping from V into itself again, so that T^* and hence $(T^*)^*$ are defined as linear mappings from V into itself, as before. If b is symmetric on V, then

$$b(T(v), w) = b(T^*(w), v) = b(w, (T^*)^*(v)) = b((T^*)^*(v), w) \tag{2.14.6}$$

for every $v, w \in V$. Similarly, if b is antisymmetric on V, then

$$b(T(v), w) = -b(T^*(w), v) = -b(w, (T^*)^*(v)) = b((T^*)^*(v), w) \tag{2.14.7}$$

for every $v, w \in V$. In both cases, we get that

$$(T^*)^* = T. \tag{2.14.8}$$

It follows that $T \mapsto T^*$ defines an involution on $\mathcal{L}(V)$, as an algebra over k with respect to composition, when b is symmetric or antisymmetric on V.

2.15 Sesquilinear forms

Let V be a vector space over the field $\mathbf{C}$ of complex numbers. A complex-valued function b on $V \times V$ is said to be *sesquilinear* if $b(v, w)$ is complex-linear in v for each $w \in V$, and $b(v, w)$ is conjugate-linear in w for every $v \in V$. In particular, if we consider V and $\mathbf{C}$ as vector spaces over the real numbers, then it follows that b is bilinear over $\mathbf{R}$. If we also have that

$$b(w, v) = \overline{b(v, w)} \tag{2.15.1}$$

for every $v, w \in V$, then b is said to be *Hermitian-symmetric* on V, or equivalently b is a *Hermitian form* on V. The analogous Hermitian-antisymmetry condition

$$b(w, v) = -\overline{b(v, w)} \tag{2.15.2}$$

is the same as saying that $i\, b(v, w)$ is a Hermitian form on V. If b is any sesquilinear form on V, then $\overline{b(w, v)}$ is a sesquilinear form on V too,

$$b(v, w) + \overline{b(w, v)} \tag{2.15.3}$$

is a Hermitian form on V, and

$$b(v, w) - \overline{b(w, v)} \tag{2.15.4}$$

is Hermitian-antisymmetric on V. This permits us to express $b(v, w)$ in a unique way as $b_1(v, w) + i\, b_2(v, w)$, where $b_1(v, w)$ and $b_2(v, w)$ are Hermitian forms on V. Note that $b(v, v) \in \mathbf{R}$ for every $v \in V$ when b is a Hermitian form on V.

Let b be a sesquilinear form on V, and let T be a linear mapping from V into itself. Let us say that T is *self-adjoint* with respect to b on V if

$$b(T(v), w) = b(v, T(w)) \tag{2.15.5}$$

for every $v, w \in V$, and that T is *anti-self-adjoint* with respect to b on V if

$$b(T(v), w) = -b(v, T(w)) \tag{2.15.6}$$

for every $v, w \in V$. One can check that T is anti-self-adjoint with respect to b on V if and only if $i\,T$ is self-adjoint with respect to b on V. If we consider b as a real-bilinear mapping from $V \times V$ into $\mathbf{C}$, then these self-adjointness and anti-self-adjointness conditions correspond exactly to the symmetry and anti-symmetry conditions for module homomorphisms mentioned in Section 2.12. The space of self-adjoint linear mappings from V into itself with respect to b on V is a real-linear subspace of the space $\mathcal{L}(V)$ of linear mappings from V into itself, which is to say that it is a linear subspace of $\mathcal{L}(V)$ when $\mathcal{L}(V)$ is considered as a vector space over $\mathbf{R}$. If T_1, T_2 are self-adjoint linear mappings from V into itself with respect to b, then their commutator $[T_1, T_2] = T_1 \circ T_2 - T_2 \circ T_1$ with respect to composition is anti-self-adjoint with respect to b, as before. Similarly, if T_1, T_2 are anti-self-adjoint linear mappings from V into itself with respect to b, then $[T_1, T_2]$ is anti-self-adjoint with respect to b as well. It follows that the space of anti-self-adjoint linear mappings from V into itself with respect to b is a real Lie subalgebra of $\mathcal{L}(V)$, which is to say that it is a subalgebra of $\mathcal{L}(V)$ as a Lie algebra over $\mathbf{R}$ with respect to the commutator bracket.

Suppose from now on in this section that V has finite dimension as a complex vector space. If $w \in V$, then

$$b_w(v) = b(v, w) \tag{2.15.7}$$

defines a linear functional on V as a function of v, as before. In this situation, $w \mapsto b_w$ is a conjugate-linear mapping from V into its dual space V'. The image

$$\{b_w : w \in V\} \tag{2.15.8}$$

of this mapping is still a linear subspace of V', as a complex vector space. One can check that (2.15.8) is equal to V' exactly when $w \mapsto b_w$ is injective as a mapping from V into V', because V and V' have the same dimension as complex vector spaces.

If for every $v \in V$ with $v \neq 0$ there is a $w \in V$ such that $b(v, w) \neq 0$, then b is said to be *nondegenerate* as a sesquilinear form on V. This is the same as saying that the intersections of the kernels of the b_w's, $w \in V$, is trivial, as before. This happens exactly when (2.15.8) is equal to V', as in the previous section.

Let b be a nondegenerate sesquilinear form on V, and let T be a linear mapping from V into itself. Also let $w \in V$ be given, so that $b(T(v), w)$ defines a linear functional on V, as a function of v. It follows that there is a unique element $T^*(w)$ of V such that

$$b(T(v), w) = b(v, T^*(w)) \tag{2.15.9}$$

for every $v \in V$, because b is nondegenerate on V. The resulting mapping T^* from V into itself is called the *adjoint* of T with respect to b. One can check that T^* is a linear mapping from V into itself, using the sesquilinearity of b.

However, $T \mapsto T^*$ is conjugate-linear as a mapping from $\mathcal{L}(V)$ into itself in this situation. We still have that $I^* = I$, where I is the identity mapping on V. A linear mapping T from V into itself is self-adjoint with respect to b if and only if $T^* = T$. Similarly, T is anti-self-adjoint with respect to b if and only if $T^* = -T$.

If T is a linear mapping from V into itself and $T^* = 0$ on V, then $T = 0$ on V, because of (2.15.9) and nondegeneracy of b on V, as before. If T_1 and T_2 are linear mappings from V into itself, then one can verify that

$$(T_2 \circ T_1)^* = T_1^* \circ T_2^*, \tag{2.15.10}$$

in the same way as before. It follows that $T \mapsto T^*$ is a conjugate-linear opposite algebra automorphism on $\mathcal{L}(V)$, because $\mathcal{L}(V)$ is a finite-dimensional vector space over $\mathbf{C}$.

Suppose now that b is also Hermitian-symmetric on V. Let T be a linear mapping from V into itself, so that T^* and $(T^*)^*$ are defined as linear mappings from V into itself as well. If $v, w \in V$, then

$$b(T(v), w) = \overline{b(T^*(w), v)} = \overline{b(w, (T^*)^*(v))} = b((T^*)^*(v), w). \tag{2.15.11}$$

Thus

$$(T^*)^* = T, \tag{2.15.12}$$

so that $T \mapsto T^*$ is a conjugate-linear involution on $\mathcal{L}(V)$ in this case.

Chapter 3

Submultiplicativity and invertibility

3.1 Invertibility

Let k be a commutative ring with a multiplicative identity element, and let A be an associative algebra over k with a multiplicative identity element e, where multiplication of $a, b \in A$ is expressed as $a\,b$. An element a of A is said to be *invertible* in A if there is an element b of A such that

$$a\,b = b\,a = e. \tag{3.1.1}$$

It is easy to see that b is unique when it exists, using associativity of multiplication on A. In this case, b is called the multiplicative inverse of a in A, and is denoted a^{-1}. Of course, e is its own inverse in A. If x and y are invertible elements of A, then $x\,y$ is invertible in A too, with

$$(x\,y)^{-1} = y^{-1}\,x^{-1}. \tag{3.1.2}$$

Thus the collection of invertible elements in A is a group.

Let x and y be commuting elements of A, so that $x\,y = y\,x$. If x is invertible in A, then x^{-1} commutes with y too. Suppose that w and z are commuting elements of A, and $w\,z$ is invertible in A. Note that $w\,z$ commutes with w and z, so that $(w\,z)^{-1}$ commutes with w and z too. It follows that w and z are invertible in A, with $w^{-1} = (w\,z)^{-1}\,z$ and $z^{-1} = (w\,z)^{-1}\,w$.

Let $a \in A$ be given, and let n be a nonnegative integer. Using a standard computation, we get that

$$(e - a)\sum_{j=0}^{n} a^j = \Big(\sum_{j=0}^{n} a^j\Big)(e - a) = e - a^{n+1}, \tag{3.1.3}$$

where a^j is interpreted as being equal to e when $j = 0$. In particular, if $a^{n+1} = 0$, then it follows that $e - a$ is invertible in A, with

$$(e - a)^{-1} = \sum_{j=0}^{n} a^j. \tag{3.1.4}$$

If $e - a^{n+1}$ is invertible in A, then (3.1.3) implies that $e - a$ is invertible in A too, as in the previous paragraph.

Let n be a positive integer, and consider the algebra $M_n(A)$ of $n \times n$ matrices with entries in A. The group of invertible elements of $M_n(A)$ is denoted $GL_n(A)$, and is called the *nth general linear group* with entries in A.

Suppose for the moment that A is also commutative, so that the determinant of $a = (a_{j,l}) \in M_n(A)$ can be defined as an element of A in the usual way. If $a \in GL_n(A)$, then $\det a$ is an invertible element of A. Conversely, if $a \in M_n(A)$ and $\det a$ is an invertible element of A, then $a \in GL_n(A)$, by Cramer's rule. The *nth special linear group* $SL_n(A)$ with entries in A consists of the $a \in M_n(A)$ such that $\det a$ is the multiplicative identity element e in A. This is a normal subgroup of $GL_n(A)$, because $SL_n(A)$ is the kernel of the determinant as a group homomorphism from $GL_n(A)$ into the multiplicative group of invertible elements in A.

Let k be a field, and let V be a vector space over k. Remember that the space $\mathcal{L}(V)$ of linear mappings from V into itself is an associative algebra with respect to composition of mappings, and with the identity mapping $I = I_V$ on V as the multiplicative identity element in $\mathcal{L}(V)$. The group $GL(V)$ of one-to-one linear mappings from V onto itself with respect to composition of mappings is the same as the group of invertible elements in $\mathcal{L}(V)$, and may be called the *general linear group* associated to V.

Suppose that V has finite dimension $n \geq 1$, and let $v_1, \ldots, v_n$ be a basis for V. This leads to an algebra isomorphism from $M_n(k)$ onto $\mathcal{L}(V)$, as in Section 2.10. The restriction of this mapping to $GL_n(k)$ defines a group isomorphism from $GL_n(k)$ onto $GL(V)$.

The determinant of a linear mapping T from V into itself can be defined as an element of k as the determinant of the corresponding matrix in $M_n(k)$. It is well known that this does not depend on the choice of basis $v_1, \ldots, v_n$ of V. Note that $a \in M_n(k)$ is invertible exactly when $\det a \neq 0$, because k is a field. Thus $T \in \mathcal{L}(V)$ is invertible exactly when $\det T \neq 0$.

The *special linear group* $SL(V)$ associated to V consists of the linear mappings T from V into itself such that $\det T = 1$ in k. In particular, these linear mappings are invertible on V, and $SL(V)$ is a normal subgroup of $GL(V)$, because it is the kernel of the determinant as a group homomorphism from $GL(V)$ into the multiplicative group of non-zero elements of k. The restriction of the algebra isomorphism from $M_n(k)$ onto $\mathcal{L}(V)$ mentioned earlier to $SL_n(k)$ defines a group isomorphism from $SL_n(k)$ onto $SL(V)$.

3.2 Submultiplicative seminorms

Let k be a field with an absolute value function $|\cdot|$, and let A be an algebra over k in the strict sense, where multiplication of $a, b \in A$ is expressed as $a\,b$. Also let N_A be a seminorm on A, as a vector space over k, and with respect to $|\cdot|$ on k. As in Section 1.13, multiplication on A is bounded as a bilinear mapping from $A \times A$ into A with respect to N_A on A if there is a nonnegative real number C such that

$$N_A(a\,b) \le C\,N_A(a)\,N_A(b) \tag{3.2.1}$$

for every $a, b \in A$. If this holds with $C = 1$, then N_A is said to be *submultiplicative* on A. Similarly, if

$$N_A(a\,b) = N_A(a)\,N_A(b) \tag{3.2.2}$$

for every $a, b \in A$, then N_A is said to be *multiplicative* on A.

Suppose for the moment that A has a multiplicative identity element e. If (3.2.1) holds for some $C \ge 0$, then we get that

$$N_A(a) \le C\,N_A(a)\,N_A(e) \tag{3.2.3}$$

for every $a \in A$. If $N_A(a) > 0$ for some $a \in A$, then it follows that

$$1 \le C\,N_A(e). \tag{3.2.4}$$

Let V be a vector space over k, and let N_V be a seminorm on V with respect to $|\cdot|$ on k. Consider the space $\mathcal{BL}(V) = \mathcal{BL}(V, V)$ of bounded linear mappings from V into itself, with respect to N_V on V. This is a subalgebra of the algebra $\mathcal{L}(V)$ of all linear mappings from V into itself, with composition of mappings as multiplication. Let $\|\cdot\|_{op} = \|\cdot\|_{op,VV}$ be the operator seminorm on $\mathcal{BL}(V)$ corresponding to N_V on V, as in Section 1.9. This is a submultiplicative seminorm on $\mathcal{BL}(V)$ with respect to $|\cdot|$ on k, as before. It is easy to see that the identity mapping $I = I_V$ on V is bounded with respect to N_V, with

$$\|I\|_{op} = 1 \tag{3.2.5}$$

when $N_V(v) > 0$ for some $v \in V$, and $\|I\|_{op} = 0$ otherwise.

Let A be an algebra over k in the strict sense again, and let N_A be a seminorm on A with respect to $|\cdot|$ on k that satisfies (3.2.1) for some $C \ge 0$. If $a \in A$, then

$$M_a(x) = a\,x \tag{3.2.6}$$

defines a linear mapping from A into itself, as a vector space over k, as in Section 2.2. Using (3.2.1), we get that

$$N_A(M_a(x)) \le C\,N_A(a)\,N_A(x) \tag{3.2.7}$$

for every $x \in A$, so that M_a is bounded as a linear mapping from A into itself with respect to N_A. More precisely, we have that

$$\|M_a\|_{op} \le C\,N_A(a) \tag{3.2.8}$$

for every $a \in A$, where $\|\cdot\|_{op} = \|\cdot\|_{op,AA}$ is the operator seminorm on the space $\mathcal{BL}(A)$ of bounded linear mappings from A into itself with respect to N_A. If A has a multiplicative identity element e, then

$$N_A(a) = N_A(M_a(e)) \le \|M_a\|_{op}\, N_A(e) \tag{3.2.9}$$

for every $a \in A$.

Similarly, if $a \in A$, then

$$\widetilde{M}_a(x) = x\,a \tag{3.2.10}$$

defines a linear mapping from A into itself, as in Section 2.7. As before, we can use (3.2.1) to get that

$$N_A(\widetilde{M}_a(x)) \le C\, N_A(x)\, N_A(a) \tag{3.2.11}$$

for every $x \in A$. This implies that $\widetilde{M}_a$ is bounded as a linear mapping from A into itself with respect to N_A, with

$$\|\widetilde{M}_a\|_{op} \le C\, N_A(a) \tag{3.2.12}$$

for every $a \in A$. If A has a multiplicative identity element e, then

$$N_A(a) = N_A(\widetilde{M}_a(e)) \le \|\widetilde{M}_a\|_{op}\, N_A(e) \tag{3.2.13}$$

for every $a \in A$.

Let α be a positive real number, and put

$$\widehat{N}_A(a) = \alpha\, N_A(a) \tag{3.2.14}$$

for every $a \in A$. This defines a seminorm on A as a vector space over k too, with respect to $|\cdot|$ on k. Using (3.2.1), we get that

$$\widehat{N}_A(a\,b) \le (C/\alpha)\, \widehat{N}_A(a)\, \widehat{N}_A(b) \tag{3.2.15}$$

for every $a, b \in A$. In particular, this means that $\widehat{N}_A$ is submultiplicative on A when $\alpha \ge C$.

Alternatively, $\|M_a\|_{op}$ defines a seminorm on A as a vector space over k, with respect to $|\cdot|$ on k. Suppose that A is an associative algebra over k, so that $a \mapsto M_a$ is an algebra homomorphism from A into $\mathcal{BL}(A)$, as in Section 2.2. This implies that $\|M_a\|_{op}$ is submultiplicative as a seminorm on A, because $\|\cdot\|_{op}$ is submultiplicative on $\mathcal{BL}(A)$. If A has a multiplicative identity element e, then M_e is the identity operator on A, as before. Hence $\|M_e\|_{op}$ is equal to 1 when $N_A(a) > 0$ for some $a \in A$, and is equal to 0 otherwise.

3.3 Some matrix seminorms

Let k be a field with an absolute value function $|\cdot|$, and let A be an algebra over k in the strict sense again, where multiplication of $a, b \in A$ is expressed as $a\,b$.

Also let n be a positive integer, and let $M_n(A)$ be the space of $n \times n$ matrices with entries in A, which is an algebra over k in the strict sense with respect to matrix multiplication, as in Section 2.8. Suppose that N_A is a seminorm on A with respect to $|\cdot|$ on k that satisfies (3.2.1) for some $C \geq 0$. If $a = (a_{j,l}) \in M_n(A)$, then put

$$N_\infty(a) = \max_{1 \leq j,l \leq n} N_A(a_{j,l}), \tag{3.3.1}$$

$$N_{1,\infty}(a) = \max_{1 \leq l \leq n} \Big(\sum_{j=1}^n N_A(a_{j,l})\Big), \tag{3.3.2}$$

and

$$N_{\infty,1}(a) = \max_{1 \leq j \leq n} \Big(\sum_{l=1}^n N_A(a_{j,l})\Big). \tag{3.3.3}$$

It is easy to see that (3.3.1), (3.3.2), and (3.3.3) define seminorms on $M_n(A)$, as a vector space over k, and with respect to $|\cdot|$ on k. If N_A is a norm on A, then (3.3.1), (3.3.2), and (3.3.3) are norms on $M_n(A)$. Observe that

$$N_\infty(a) \leq N_{1,\infty}(a) \leq n\, N_\infty(a) \tag{3.3.4}$$

and

$$N_\infty(a) \leq N_{\infty,1}(a) \leq n\, N_\infty(a) \tag{3.3.5}$$

for every $a \in M_n(A)$. In addition,

$$N_\infty(a^t) = N_\infty(a) \tag{3.3.6}$$

and

$$N_{1,\infty}(a^t) = N_{\infty,1}(a) \tag{3.3.7}$$

for every $a \in M_n(A)$, where $a^t \in M_n(A)$ is the transpose of a, as before.

Suppose for the moment that A has a multiplicative identity element e. Remember that the corresponding identity matrix $I \in M_n(A)$ has diagonal entries equal to e, and all other entries equal to 0. Thus

$$N_\infty(I) = N_{1,\infty}(I) = N_{\infty,1}(I) = N_A(e). \tag{3.3.8}$$

Let $a, b \in M_n(A)$ be given, and let $c = a\, b$ be their product, so that

$$c_{j,r} = \sum_{l=1}^n a_{j,l}\, b_{l,r} \tag{3.3.9}$$

for every $j, r = 1, \ldots, n$. Observe that

$$N_A(c_{j,r}) \leq \sum_{l=1}^n N_A(a_{j,l}\, b_{l,r}) \leq C \sum_{l=1}^n N_A(a_{j,l})\, N_A(b_{l,r}) \tag{3.3.10}$$

for every $j, r = 1, \ldots, r$, using (3.2.1) in the second step. Thus

$$\begin{aligned} \sum_{j=1}^n N_A(c_{j,r}) &\le C \sum_{j=1}^n \sum_{l=1}^n N_A(a_{j,l})\, N_A(b_{l,r}) \\ &= C \sum_{l=1}^n \sum_{j=1}^n N_A(a_{j,l})\, N_A(b_{l,r}) \\ &\le C\, N_{1,\infty}(a) \sum_{l=1}^n N_A(b_{l,r}) \le C\, N_{1,\infty}(a)\, N_{1,\infty}(b) \end{aligned} \tag{3.3.11}$$

for every $l = 1, \ldots, n$, so that

$$N_{1,\infty}(c) \le C\, N_{1,\infty}(a)\, N_{1,\infty}(b). \tag{3.3.12}$$

Similarly,

$$\begin{aligned} \sum_{r=1}^n N_A(c_{j,r}) &\le C \sum_{r=1}^n \sum_{l=1}^n N_A(a_{j,l})\, N_A(b_{l,r}) \\ &= C \sum_{l=1}^n \sum_{r=1}^n N_A(a_{j,l})\, N_A(b_{l,r}) \\ &\le C \sum_{l=1}^n N_A(a_{j,l})\, N_{\infty,1}(b) \le C\, N_{\infty,1}(a)\, N_{\infty,1}(b) \end{aligned} \tag{3.3.13}$$

for every $j = 1, \ldots, n$, so that

$$N_{\infty,1}(c) \le C\, N_{\infty,1}(a)\, N_{\infty,1}(b). \tag{3.3.14}$$

Suppose now that N_A is a semi-ultranorm on A with respect to $|\cdot|$ on k. This implies that N_∞ is a semi-ultranorm on $M_n(A)$, as a vector space over k, and with respect to $|\cdot|$ on k. In this case, we have that

$$N_A(c_{j,r}) \le \max_{1 \le l \le n} N_A(a_{j,l}\, b_{l,r}) \le C \max_{1 \le l \le n} (N_A(a_{j,l})\, N_A(b_{l,r})) \tag{3.3.15}$$

for every $j, r = 1, \ldots, n$, using (3.2.1) in the second step. It follows that

$$N_\infty(c) \le C\, N_\infty(a)\, N_\infty(b). \tag{3.3.16}$$

3.4 Continuity of inverses

Let k be a field with an absolute value function $|\cdot|$, and let A be an associative algebra over k with a multiplicative identity element e. Also let N_A be a semi-norm on A as a vector space over k, with respect to $|\cdot|$ on k, and suppose that N_A satisfies the boundedness condition (3.2.1) with constant $C \ge 0$. If a is an invertible element of A, then

$$N_A(e) \le C\, N_A(a)\, N_A(a^{-1}). \tag{3.4.1}$$

Let x, y be invertible elements of A, and observe that

$$x^{-1} - y^{-1} = x^{-1}\,(y\,y^{-1}) - (x^{-1}\,x)\,y^{-1} = x^{-1}\,(y - x)\,y^{-1}. \tag{3.4.2}$$

It follows that

$$N_A(x^{-1} - y^{-1}) \le C^2\,N_A(x^{-1})\,N_A(y^{-1})\,N_A(x - y). \tag{3.4.3}$$

Hence

$$\begin{aligned} N_A(y^{-1}) &\le N_A(x^{-1}) + N_A(x^{-1} - y^{-1}) \\ &\le N_A(x^{-1}) + C^2\,N_A(x^{-1})\,N_A(y^{-1})\,N_A(x - y), \end{aligned} \tag{3.4.4}$$

so that

$$(1 - C^2\,N_A(x^{-1})\,N_A(x - y))\,N_A(y^{-1}) \le N_A(x^{-1}). \tag{3.4.5}$$

If

$$C^2\,N_A(x^{-1})\,N_A(x - y) < 1, \tag{3.4.6}$$

then we get that

$$N_A(y^{-1}) \le (1 - C^2\,N_A(x^{-1})\,N_A(x - y))^{-1}\,N_A(x^{-1}). \tag{3.4.7}$$

Combining this with (3.4.3), we obtain that

$$N_A(x^{-1} - y^{-1}) \le C^2\,(1 - C^2\,N_A(x^{-1}))^{-1}\,N_A(x^{-1})^2\,N_A(x - y) \tag{3.4.8}$$

when (3.4.6) holds.

Suppose for the moment that N_A is a semi-ultranorm on A, as a vector space over k. Let us check that

$$N_A(x^{-1}) = N_A(y^{-1}) \tag{3.4.9}$$

when (3.4.6) holds. Of course, this is trivial when $N_A \equiv 0$ on A. Otherwise, if $N_A \not\equiv 0$ on A, then $N_A(e) > 0$, and hence $N_A(y^{-1}) > 0$, by (3.4.1). In this case, (3.4.6) implies that

$$C^2\,N_A(x^{-1})\,N_A(y^{-1})\,N_A(x - y) < N_A(y^{-1}). \tag{3.4.10}$$

Combining this with (3.4.3), we get that

$$N_A(x^{-1} - y^{-1}) < N_A(y^{-1}). \tag{3.4.11}$$

This implies (3.4.9) in this situation, as in (1.8.7). It follows that

$$N_A(x^{-1} - y^{-1}) \le C^2\,N_A(x^{-1})^2\,N_A(x - y) \tag{3.4.12}$$

when (3.4.6) holds, by (3.4.3) and (3.4.9).

Let us now take $x = e$, for which there are some simplifications. If y is an invertible element of A, then

$$e - y^{-1} = (y - e)\,y^{-1}, \tag{3.4.13}$$

so that

$$N_A(e - y^{-1}) \le C\, N_A(y^{-1})\, N_A(y - e). \tag{3.4.14}$$

This implies that

$$N_A(y^{-1}) \le N_A(e) + N_A(e - y^{-1}) \le N_A(e) + C\, N_A(y^{-1})\, N_A(y - e), \tag{3.4.15}$$

and hence

$$(1 - C\, N_A(y - e))\, N_A(y^{-1}) \le N_A(e). \tag{3.4.16}$$

If

$$C\, N_A(y - e) < 1, \tag{3.4.17}$$

then it follows that

$$N_A(y^{-1}) \le (1 - C\, N_A(y - e))^{-1}\, N_A(e). \tag{3.4.18}$$

This implies that

$$N_A(e - y^{-1}) \le C\, (1 - C\, N_A(y - e))^{-1}\, N_A(e)\, N_A(y - e) \tag{3.4.19}$$

when (3.4.17) holds, because of (3.4.14).

Suppose now that N_A is a semi-ultranorm on A again, and let us verify that

$$N_A(y^{-1}) = N_A(e) \tag{3.4.20}$$

when (3.4.17) holds. This is trivial when $N_A \equiv 0$ on A, as before. Suppose instead that $N_A \not\equiv 0$ on A, so that $N_A(e) > 0$, and thus $N_A(y^{-1}) > 0$. We can multiply both sides of (3.4.17) by $N_A(y^{-1})$, to get that

$$C\, N_A(y^{-1})\, N_A(y - e) < N_A(y^{-1}). \tag{3.4.21}$$

This implies that

$$N_A(e - y^{-1}) < N_A(y^{-1}), \tag{3.4.22}$$

because of (3.4.14). This permits us to obtain (3.4.20) using (1.8.7), as before. Hence

$$N_A(e - y^{-1}) \le C\, N_A(e)\, N_A(y - e) \tag{3.4.23}$$

when (3.4.17) holds, by (3.4.14) and (3.4.20).

3.5 Banach algebras

Let k be a field with an absolute value function $|\cdot|$, and let A be an associative algebra over k. Also let $\|\cdot\|$ be a norm on A with respect to $|\cdot|$ on k such that

$$\|x\, y\| \le C\, \|x\|\, \|y\| \tag{3.5.1}$$

for some $C \ge 0$ and every $x, y \in A$. In this section, we ask that A be complete with respect to the metric associated to $\|\cdot\|$. Otherwise, one can pass to a completion of A, as usual. If (3.5.1) holds with $C = 1$, then A is said to be a *Banach algebra* with respect to $\|\cdot\|$.

Let us suppose too that A has a nonzero multiplicative identity element e, which is sometimes included in the definition of a Banach algebra. The condition

$$\|e\| = 1 \tag{3.5.2}$$

is sometimes included in the definition of a Banach algebra as well.

Let $a \in A$ be given, and remember that

$$(e - a) \sum_{j=0}^{n} a^j = \Big(\sum_{j=0}^{n} a^j\Big) (e - a) = e - a^{n+1} \tag{3.5.3}$$

for every nonnegative integer n, as in (3.1.3). Observe that

$$\|a^j\| \le C^{j-1} \|a\|^j \tag{3.5.4}$$

for every positive integer j, by (3.5.1). Suppose that

$$C \|a\| < 1, \tag{3.5.5}$$

so that

$$\lim_{j \to \infty} \|a^j\| \to 0, \tag{3.5.6}$$

by (3.5.4). We also get that

$$\sum_{j=0}^{\infty} \|a^j\| \tag{3.5.7}$$

converges as an infinite series of nonnegative real numbers, because

$$\sum_{j=0}^{\infty} C^j \|a\|^j \tag{3.5.8}$$

is a convergent geometric series. This means that $\sum_{j=0}^{\infty} a^j$ converges absolutely with respect to $\|\cdot\|$, and hence that $\sum_{j=0}^{\infty} a^j$ converges in A, because A is complete with respect to the metric associated to $\|\cdot\|$. The value of this sum satisfies

$$(e - a) \sum_{j=0}^{\infty} a^j = \Big(\sum_{j=0}^{\infty} a^j\Big) (a - e) = e, \tag{3.5.9}$$

by taking the limit as $n \to \infty$ in (3.5.3). Thus $e - a$ is invertible in A, with

$$(e - a)^{-1} = \sum_{j=0}^{\infty} a^j. \tag{3.5.10}$$

Let x be an invertible element of A, and let y be another element of A. Observe that

$$y = x - (x - y) = x\,(e - x^{-1}\,(x - y)). \tag{3.5.11}$$

Suppose that

$$C^2 \, \|x^{-1}\| \, \|x - y\| < 1, \tag{3.5.12}$$

so that

$$C \, \|x^{-1} \, (x - y)\| \le C^2 \, \|x^{-1}\| \, \|x - y\| < 1. \tag{3.5.13}$$

This implies that $e - x^{-1} \, (x - y)$ is invertible in A, as in the preceding paragraph. It follows that y is invertible in A, by (3.5.11).

Let a be an element of A again, and let j_0 be a positive integer. If $e - a^{j_0}$ is invertible in A, then $e - a$ is invertible in A, because of (3.5.3), with $n = j_0 - 1$. In particular, this holds when

$$C \, \|a^{j_0}\| < 1, \tag{3.5.14}$$

as before. Alternatively, one can use (3.5.1) to estimate $\|a^{j_0 \, l + r}\|$ in terms of $C^{l-1} \, \|a^{j_0}\|^l$ when $l \ge 1$ and $0 \le r < j_0$, to get that (3.5.6) holds and that (3.5.7) converges when (3.5.14) holds. This implies that $\sum_{j=0}^\infty a^j$ converges in A and satisfies (3.5.9) when (3.5.14) holds, as before.

3.6 Invertible linear mappings

Let k be a field with an absolute value function $|\cdot|$, and let V, W be vector spaces over k with seminorms N_V, N_W, respectively, with respect to $|\cdot|$ on k. If T is a one-to-one linear mapping from V onto W, then the corresponding inverse mapping T^{-1} is a linear mapping from W onto V. As usual, T^{-1} is bounded with respect to N_W, N_V if there is a nonnegative real number C such that

$$N_V(T^{-1}(w)) \le C \, N_W(w) \tag{3.6.1}$$

for every $w \in W$. This is the same as saying that

$$N_V(v) \le C \, N_W(T(v)) \tag{3.6.2}$$

for every $v \in V$.

Now let T be a linear mapping from V into W, and suppose that (3.6.2) holds for some $C \ge 0$. If N_V is a norm on V, then it follows that T is injective on V. Let T_1 be another linear mapping from V into W, and observe that

$$N_V(v) \le C \, N_W(T_1(v)) + C \, N_W(T_1(v) - T(v)) \tag{3.6.3}$$

for every $v \in V$. If $T_1 - T$ is bounded as a linear mapping from V into W, then we get that

$$N_V(v) \le C \, N_W(T_1(v)) + C \, \|T_1 - T\|_{op,VW} \, N_V(v) \tag{3.6.4}$$

for every $v \in V$, where the operator seminorm $\|\cdot\|_{op,VW}$ is as defined in Section 1.9. Thus

$$(1 - C \, \|T_1 - T\|_{op,VW}) \, N_V(v) \le C \, N_W(T_1(v)) \tag{3.6.5}$$

for every $v \in V$. If

$$C \, \|T_1 - T\|_{op,VW} < 1, \tag{3.6.6}$$

then it follows that

$$N_V(v) \le C \, (1 - C \, \|T_1 - T\|_{op,VW})^{-1} \, N_W(T_1(v)) \tag{3.6.7}$$

for every $v \in V$.

Suppose that N_W is a semi-ultranorm on W with respect to $|\cdot|$ on k. In this case, we have that

$$N_V(v) \le C \, \max(N_W(T_1(v)), N_W(T_1(v) - T(v))) \tag{3.6.8}$$

for every $v \in V$, by (3.6.2). Suppose for the moment that

$$C \, N_W(T_1(v) - T(v)) < N_V(v) \tag{3.6.9}$$

for every $v \in V$ with $N_V(v) > 0$. It follows that

$$N_V(v) \le C \, N_W(T_1(v)) \tag{3.6.10}$$

for every $v \in V$ with $N_V(v) > 0$. Of course, (3.6.10) holds trivially when $N_V(v) = 0$, so that (3.6.10) holds for all $v \in V$. If $T_1 - T$ is bounded as a linear mapping from V into W, then

$$N_W(T_1(v) - T(v)) \le \|T_1 - T\|_{op,VW} \, N_V(v) \tag{3.6.11}$$

for every $v \in V$. If (3.6.6) holds, then we get that (3.6.9) holds when $N_V(v) > 0$.

A bounded linear mapping T from V onto W is said to be *invertible* as a bounded linear mapping if T is a one-to-one mapping from V onto W whose inverse T^{-1} is bounded with respect to N_W, N_V. The bounded linear mappings from V onto itself with bounded inverses are the same as the invertible elements of $\mathcal{BL}(V)$, as an algebra with respect to composition of mappings.

Suppose that N_V and N_W are norms on V and W, respectively, and that T is a bounded linear mapping from V into W that satisfies (3.6.2) for some $C \ge 0$. If V is complete with respect to the metric associated to N_V, then it is easy to see that the image $T(V)$ of V under T is complete with respect to the restriction of the metric on W associated to N_W to $T(V)$. This implies that $T(V)$ is a closed set in W with respect to the metric associated to N_W, by a standard argument.

3.7 Isometric linear mappings

Let k be a field with an absolute value function $|\cdot|$ again, and let V, W be vector spaces over k with seminorms N_V, N_W, respectively, with respect to $|\cdot|$ on k. A linear mapping T from V into W is said to be an *isometry* with respect to N_V and N_W if

$$N_W(T(v)) = N_V(v) \tag{3.7.1}$$

for every $v \in V$. Of course, this is the same as saying that

$$N_W(T(v)) \le N_V(v) \tag{3.7.2}$$

and

$$N_V(v) \le N_W(T(v)) \tag{3.7.3}$$

for every $v \in V$. The first condition (3.7.2) means that T is a bounded linear mapping from V into W with respect to N_V and N_W, with

$$\|T\|_{op,VW} \le 1, \tag{3.7.4}$$

where the operator seminorm is as defined in Section 1.9. The second condition (3.7.3) is the same as (3.6.2), with $C = 1$.

Let Z be another vector space over k with a seminorm N_Z with respect to $|\cdot|$ on k. Also let T_1 be an isometric linear mapping from V into W with respect to N_V and N_W, and let T_2 be an isometric linear mapping from W into Z with respect to N_W and N_Z. Observe that

$$N_Z((T_2 \circ T_1)(v)) = N_Z(T_2(T_1(v))) = N_W(T_1(v)) = N_V(v) \tag{3.7.5}$$

for every $v \in V$, so that $T_2 \circ T_1$ is an isometric linear mapping from V into Z.

If T is a one-to-one linear mapping from V onto W, then (3.7.3) is equivalent to saying that T^{-1} is a bounded linear mapping from W into V with respect to N_W and N_V, with

$$\|T^{-1}\|_{op,WV} \le 1, \tag{3.7.6}$$

as in the previous section. Thus T is an isometric linear mapping if and only T and T^{-1} are bounded linear mappings that satisfy (3.7.4) and (3.7.6). In particular, T is an isometric linear mapping if and only if T^{-1} is an isometric linear mapping. Of course, the identity mapping on V is an isometric linear mapping from V onto itself with respect to N_V. The collection of one-to-one isometric linear mappings from V onto itself is a group with respect to composition of mappings.

Suppose now that N_W is a semi-ultranorm on W with respect to $|\cdot|$ on k. Let T be a linear mapping from V into W that satisfies (3.7.3) for every $v \in V$. Let T_1 be another linear mapping from V into W such that

$$N_W(T_1(v) - T(v)) < N_V(v) \tag{3.7.7}$$

for every $v \in V$ with $N_V(v) > 0$. Under these conditions, we have that

$$N_V(v) \le N_W(T_1(v)) \tag{3.7.8}$$

for every $v \in V$, as in (3.6.10), with $C = 1$.

Let T be an isometric linear mapping from V into W, and let T_1 be a bounded linear mapping from V into W. If

$$\|T_1 - T\|_{op,VW} \le 1, \tag{3.7.9}$$

then

$$\|T_1\|_{op,VW} \le 1, \tag{3.7.10}$$

because of (3.7.4) and the hypothesis that N_W be a semi-ultranorm on W. If

$$\|T_1 - T\|_{op,VW} < 1, \tag{3.7.11}$$

then (3.7.7) holds for every $v \in V$ with $N_V(v) > 0$, so that T_1 satisfies (3.7.8), as before. This shows that T_1 is also an isometric linear mapping from V into W when (3.7.11) holds.

3.8 Hilbert space isometries

Let $(V, \langle\cdot,\cdot\rangle_V)$ and $(W, \langle\cdot,\cdot\rangle_W)$ be inner product spaces, both real or both complex, and let $\|\cdot\|_V$ and $\|\cdot\|_W$ be the corresponding norms on V and W, respectively, as in Section 1.11. If a linear mapping T from V into W satisfies

$$\langle T(u), T(v)\rangle_W = \langle u, v\rangle_V \tag{3.8.1}$$

for every $u, v \in V$, then it is easy to see that T is an isometry with respect to $\|\cdot\|_V$ and $\|\cdot\|_W$, by taking $u = v$. Conversely, if T is an isometric linear mapping from V into W with respect to $\|\cdot\|_V$ and $\|\cdot\|_W$, then one can check that T satisfies (3.8.1), using polarization identities. An isometric linear mapping from V onto W is also known as an *orthogonal transformation* in the real case, and a *unitary transformation* in the complex case. The orthogonal or unitary transformations from V onto itself form a group with respect to composition of mappings.

Suppose that V and W are Hilbert spaces, and that T is a bounded linear mapping from V into W. Let T^* be the corresponding adjoint mapping from W into V, as in Section 1.11. Observe that

$$\langle T(u), T(v)\rangle_W = \langle u, T^*(T(v))\rangle_V \tag{3.8.2}$$

for every $u, v \in V$. Thus T is an isometric linear mapping from V into W if and only if

$$T^* \circ T = I_V, \tag{3.8.3}$$

where I_V is the identity mapping on V. This is the same as saying that

$$T^* = T^{-1} \tag{3.8.4}$$

when T maps V onto W.

If T is any bounded linear mapping from V into W, then it is well known that

$$\|T^* \circ T\|_{op,VV} = \|T\|^2_{VW}, \tag{3.8.5}$$

where these operator norms are taken with respect to $\|\cdot\|_V$ and $\|\cdot\|_W$, as appropriate. More precisely,

$$\|T^* \circ T\|_{op,VV} \le \|T\|_{op,VW}\,\|T^*\|_{op,WV} = \|T\|^2_{op,VW}, \tag{3.8.6}$$

using (1.11.15) in the second step. We also have that

$$\|T(v)\|_W^2 = \langle v, T^*(T(v))\rangle_V \le \|v\|_V \, \|T^*(T(v))\|_V \le \|T^* \circ T\|_{op,VV} \, \|v\|_V^2 \tag{3.8.7}$$

for every $v \in V$, by taking $u = v$ in (3.8.2) in the first step, and using the Cauchy–Schwarz inequality in the second step. This implies that

$$\|T\|_{op,VW}^2 \le \|T^* \circ T\|_{op,VV}, \tag{3.8.8}$$

as desired.

Observe that $w \in W$ satisfies $T^*(w) = 0$ if and only if

$$\langle T(v), w\rangle_W = 0 \tag{3.8.9}$$

for every $v \in V$, by the definition of T^*. If the image $T(V)$ of V under T is dense in W with respect to the metric associated to $\|\cdot\|_W$, then it follows that $T^*(w) = 0$. However, if $T(V)$ is not dense in W, then there is a $w \in W$ such that $w \neq 0$ and (3.8.9) holds for every $v \in V$, by standard results about Hilbert spaces. Thus $T(V)$ is dense in W if and only if the kernel of T^* is trivial.

Suppose that

$$\|v\|_V \le C \, \|T(v)\|_W \tag{3.8.10}$$

for some nonnegative real number C and every $v \in V$. This implies that $T(V)$ is a closed set in W with respect to the metric associated to $\|\cdot\|_W$, as in Section 3.6, because V is complete, by hypothesis. If $T(V)$ is dense in W, then it follows that $T(V) = W$.

3.9 Preserving bilinear forms

Let k be a commutative ring with a multiplicative identity element, and let A_1, A_2, and C be modules over k. Also let β_1, β_2 be bilinear mappings from $A_1 \times A_1$ and $A_2 \times A_2$ into C, respectively, as in Section 2.12. Let us say that a module homomorphism ϕ from A_1 into A_2 preserves these bilinear mappings if

$$\beta_2(\phi(a_1), \phi(b_1)) = \beta_1(a_1, b_1) \tag{3.9.1}$$

for every $a_1, b_1 \in A_1$. If ϕ is a one-to-one mapping from A_1 onto A_2, then (3.9.1) is equivalent to asking that

$$\beta_1(\phi^{-1}(a_2), \phi^{-1}(b_2)) = \beta_2(a_2, b_2) \tag{3.9.2}$$

for every $a_2, b_2 \in A_2$. Of course, this is the same as saying that ϕ^{-1} preserves β_2, β_1.

Let A_3 be another module over k, and let β_3 be a bilinear mapping from $A_3 \times A_3$ into C. Suppose that ϕ_1 is a module homomorphism from A_1 into A_2

that preserves β_1, β_2, and that ϕ_2 is a module homomorphism from A_2 into A_3 that preserves β_2, β_3. This implies that

$$\beta_3(\phi_2(\phi_1(a_1)), \phi_2(\phi_1(b_1))) = \beta_2(\phi_1(a_1), \phi_1(b_1)) = \beta_1(a_1, b_1) \tag{3.9.3}$$

for every $a_1, b_1 \in A_1$, so that $\phi_2 \circ \phi_1$ is a module homomorphism from A_1 into A_3 that preserves β_1, β_3.

Let ϕ be a module homomorphism from A_1 into A_2, and suppose that

$$\beta_2(\phi(a), \phi(a)) = \beta_1(a, a) \tag{3.9.4}$$

for every $a \in A_1$. If $a, b \in A_1$, then

$$\beta_1(a + b, a + b) = \beta_1(a, a) + \beta_1(a, b) + \beta_1(b, a) + \beta_1(b, b) \tag{3.9.5}$$

and

$$\begin{aligned} \beta_2(\phi(a + b), \phi(a + b)) &= \beta_2(\phi(a) + \phi(b), \phi(a) + \phi(b)) \\ &= \beta_2(\phi(a), \phi(a)) + \beta_2(\phi(a), \phi(b)) \\ &\quad + \beta_2(\phi(b), \phi(a)) + \beta_2(\phi(b), \phi(b)). \end{aligned} \tag{3.9.6}$$

It follows that

$$\beta_2(\phi(a), \phi(b)) + \beta_2(\phi(b), \phi(a)) = \beta_1(a, b) + \beta_1(b, a) \tag{3.9.7}$$

for every $a, b \in A_1$. If β_1 and β_2 are symmetric bilinear mappings, and if $1 + 1$ is invertible in k, then we get that ϕ preserves β_1, β_2. Of course, (3.9.4) holds when ϕ preserves β_1, β_2.

Let A be a module over k, and remember that the space $\mathrm{Hom}_k(A, A)$ of module homomorphisms from A into itself is an associative algebra over k with respect to composition of mappings. If ϕ is a one-to-one module homomorphism from A onto itself, then ϕ^{-1} is a module homomorphism from A into itself as well. In this case, ϕ may be called an *module automorphism* of A. The module automorphisms of A are the same as the invertible elements of $\mathrm{Hom}_k(A, A)$, and form a group with respect to composition of mappings.

A bilinear mapping β from $A \times A$ into C is said to be *invariant* under an module automorphism ϕ on A if

$$\beta(\phi(a), \phi(b)) = \beta(a, b) \tag{3.9.8}$$

for every $a, b \in A$, which is the same as saying that ϕ preserves β as a bilinear mapping from $A \times A$ into C for both the domain and range. The identity mapping on A obviously has this property. The collection of module automorphisms of A that preserve β is a subgroup of the group of all module automorphisms of A.

3.10 Preserving nondegenerate bilinear forms

Let k be a field, let V_1, V_2 be vector spaces over k, and let b_1, b_2 be bilinear forms on V_1, V_2, respectively. Suppose that V_1 has finite dimension, and that b_1 is nondegenerate on V_1, as in Section 2.14. Let T be a linear mapping from V_1 into V_2. If $w_2 \in V_2$, then $b_2(T(v_1), w_2)$ defines a linear functional on V_1, as a function of v_1. This implies that there is a unique element $T^*(w_2)$ of V_1 such that

$$b_2(T(v_1), w_2) = b_1(v_1, T^*(w_2)) \tag{3.10.1}$$

for every $v_1 \in V_1$. This defines a linear mapping T^* from V_2 into V_1, which is the *adjoint* of T with respect to b_1, b_2. The mapping $T \mapsto T^*$ is linear as a mapping from the space $\mathcal{L}(V_1, V_2)$ of linear mappings from V_1 into V_2 into the corresponding space $\mathcal{L}(V_2, V_1)$.

Let V_3 be another vector space over k with a bilinear form b_3, and suppose that V_2 also has finite dimension, and that b_2 is nondegenerate on V_2. If T_1 is a linear mapping from V_1 into V_2, and T_2 is a linear mapping from V_2 into V_3, then their adjoints T_1^* and T_2^* can be defined as in the preceding paragraph. Similarly, $T_2 \circ T_1$ is a linear mapping from V_1 into V_3, whose adjoint can be defined as in the previous paragraph as well. Observe that

$$\begin{aligned} b_3((T_2 \circ T_1)(v_1), w_3) &= b_3(T_2(T_1(v_1)), w_3) = b_2(T_1(v_1), T_2^*(w_3)) \\ &= b_1(v_1, T_1^*(T_2^*(w_3))) = b_1(v_1, (T_1^* \circ T_2^*)(w_3)) \end{aligned} \tag{3.10.2}$$

for every $v_1 \in V_1$ and $w_3 \in V_3$. This implies that

$$(T_2 \circ T_1)^* = T_1^* \circ T_2^* \tag{3.10.3}$$

as linear mappings from V_3 into V_1.

Let us continue to suppose for the moment that V_2 has finite dimension, and that b_2 is nondegenerate on V_2. If T is a linear mapping from V_1 into V_2 and $T^* = 0$ on V_2, then $T = 0$ on V_1, because of (3.10.1) and the nondegeneracy of b_2 on V_2. This implies that $T \mapsto T^*$ is a one-to-one mapping from $\mathcal{L}(V_1, V_2)$ onto $\mathcal{L}(V_2, V_1)$, because $\mathcal{L}(V_1, V_2)$ and $\mathcal{L}(V_2, V_1)$ are finite-dimensional vector spaces over k with the same dimension. Let T be a linear mapping from V_1 into V_2 again, and note that the adjoint $(T^*)^*$ of the adjoint T^* of T can be defined as a linear mapping from V_1 into V_2 in the same way in this situation. If b_1 and b_2 are symmetric on V_1 and V_2, respectively, then

$$\begin{aligned} b_2(T(v_1), w_2) = b_1(T^*(w_2), v_1) &= b_2(w_2, (T^*)^*(v_1)) \\ &= b_2((T^*)^*(v_1), w_2) \end{aligned} \tag{3.10.4}$$

for every $v_1 \in V_1$ and $w_2 \in V_2$. Similarly, if b_1 and b_2 are antisymmetric on V_1 and V_2, respectively, then

$$\begin{aligned} b_2(T(v_1), w_2) = -b_1(T^*(w_2), v_1) &= -b_2(w_2, (T^*)^*(v_1)) \\ &= b_2((T^*)^*(v_1), w_2) \end{aligned} \tag{3.10.5}$$

for every $v_1 \in V_1$ and $w_2 \in V_2$. In both cases, it follows that

$$(T^*)^* = T. \tag{3.10.6}$$

If one of b_1 and b_2 is symmetric, and the other is antisymmetric, then

$$(T^*)^* = -T, \tag{3.10.7}$$

by the analogous argument.

If T is any linear mapping from V_1 into V_2, then

$$b_2(T(v_1), T(w_1)) = b_1(v_1, T^*(T(w_1))) \tag{3.10.8}$$

for every $v_1, w_1 \in V_1$, by the definition of T^*. Thus T preserves b_1, b_2, as in the previous section, if and only if

$$T^* \circ T = I_{V_1}, \tag{3.10.9}$$

where I_{V_1} is the identity mapping on V_1. In particular, this implies that T is injective, which could also be obtained more directly from the nondegeneracy of b_1 on V_1. If V_2 has the same dimension as V_1, then it follows that T maps V_1 onto V_2. In this case, we get that

$$T^* = T^{-1}. \tag{3.10.10}$$

3.11 Preserving sesquilinear forms

Let V_1, V_2 be vector spaces over the complex numbers, and let b_1, b_2 be sesquilinear forms on V_1, V_2, respectively. Let us say that a linear mapping T from V_1 into V_2 preserves b_1, b_2 if

$$b_2(T(v_1), T(w_1)) = b_1(v_1, w_1) \tag{3.11.1}$$

for every $v_1, w_1 \in V_1$. If T is a one-to-one linear mapping from V_1 onto V_2, then this is the same as saying that

$$b_1(T^{-1}(v_2), T^{-1}(w_2)) = b_2(v_2, w_2) \tag{3.11.2}$$

for every $v_2, w_2 \in V_2$, which means that T^{-1} preserves b_2, b_1.

Let V_3 be another complex vector space with a sesquilinear form b_3. If T_1 is a linear mapping from V_1 into V_2 that preserves b_1, b_2, and T_2 is a linear mapping from V_2 into V_3 that preserves b_2, b_3, then it is easy to see that their composition $T_2 \circ T_1$ preserves b_1, b_3.

Let T be a linear mapping from V_1 into V_2 that satisfies

$$b_2(T(u_1), T(u_1)) = b_1(u_1, u_1) \tag{3.11.3}$$

for every $u_1 \in V$. One can check that T satisfies (3.11.1) for every $v_1, w_1 \in V_1$, by applying (3.11.3) to $u_1 = v_1 + w_1$ and to $u_1 = v_1 + i\, w_1$. Of course, (3.11.1) implies (3.11.3), by taking $v_1, w_1 = u_1$.

Let V be a complex vector space, and let T be a one-to-one linear mapping from V onto itself. A sesquilinear form b on V is said to be *invariant* under T if

$$b(T(v), T(w)) = b(v, w) \tag{3.11.4}$$

for every $v, w \in V$, which is to say that T preserves b as a sesquilinear form on both the domain and range. The collection of one-to-one linear mappings from V onto itself that preserve b is a group with respect to composition.

Let V_1, V_2 be complex vector spaces again, and let b_1, b_2 be sesquilinear forms on them, respectively. Let us suppose for the rest of the section that V_1 has finite dimension, and that b_1 is nondegenerate on V_1, as in Section 2.15. Let T be a linear mapping from V_1 into V_2, and let $w_2 \in V_2$ be given. Thus $b_2(T(v_1), w_2)$ is a linear functional on V_1, as a function of v_1, so that there is a unique element $T^*(w_2)$ of V_1 such that

$$b_2(T(v_1), w_2) = b_1(v_1, T^*(w_2)) \tag{3.11.5}$$

for every $v_1 \in V_1$. One can check that T^* is a linear mapping from V_2 into V_1, and that the mapping from T to its *adjoint* T^* is conjugate-linear as a mapping from $\mathcal{L}(V_1, V_2)$ into $\mathcal{L}(V_2, V_1)$.

Let V_3 be another complex vector space with a sesquilinear form b_3, and suppose that V_2 has finite dimension, and that b_2 is nondegenerate on b_2. If T_1 is a linear mapping from V_1 into V_2, and T_2 is a linear mapping from V_2 into V_3, then $T_2 \circ T_1$ is a linear mapping from V_1 into V_3, and the adjoints of T_1, T_2, and T_3 can be defined as in the preceding paragraph. Under these conditions, one can verify that

$$(T_2 \circ T_1)^* = T_1^* \circ T_2^*, \tag{3.11.6}$$

as linear mappings from V_3 into V_1.

Let us continue to ask for the moment that V_2 have finite dimension, and that b_2 be nondegenerate on V_2. If T is a linear mapping from V_1 into V_2 such that $T^* = 0$ on V_2, then $T = 0$ on V_1, because of (3.11.5) and the nondegeneracy of b_2 on V_2. It follows that $T \mapsto T^*$ is a one-to-one mapping from $\mathcal{L}(V_1, V_2)$ onto $\mathcal{L}(V_2, V_1)$, because $\mathcal{L}(V_1, V_2)$ and $\mathcal{L}(V_2, V_1)$ are finite-dimensional vector spaces over $\mathbf{C}$ with the same dimension. Let T be a linear mapping from V_1 into V_2 again, so that the adjoint $(T^*)^*$ of T^* is defined as a linear mapping from V_1 into V_2. Suppose that b_1 and b_2 are Hermitian-symmetric on V_1 and V_2, respectively. Under these conditions, we have that

$$\begin{aligned} b_2(T(v_1), w_2) = \overline{b_1(T^*(w_2), v_1)} &= \overline{b_2(w_2, (T^*)^*(v_1))} \\ &= b_2((T^*)^*(v_1), w_2) \end{aligned} \tag{3.11.7}$$

for every $v_1 \in V_1$ and $w_2 \in V_2$. This implies that

$$(T^*)^* = T \tag{3.11.8}$$

in this situation.

As before,

$$b_2(T(v_1), T(w_1)) = b_1(v_1, T^*(T(w_1))) \tag{3.11.9}$$

for every linear mapping T from V_1 into V_2 and $v_1, w_1 \in V_1$. This implies that T preserves b_1, b_2 if and only if

$$T^* \circ T = I_{V_1}, \tag{3.11.10}$$

because b_1 is nondegenerate on V_1. Note that T is injective in this case. If T maps V_1 onto V_2, then (3.11.10) is the same as saying that

$$T^* = T^{-1}. \tag{3.11.11}$$

Of course, surjectivity of T follows from injectivity when V_2 has the same dimension as V_1.

3.12 Bilinear forms and matrices

Let k be a commutative ring with a multiplicative identity element, and let n be a positive integer. The space k^n of n-tuples of elements of k is a (free) module over k with respect to coordinatewise addition and scalar multiplication. Let C be another module over k, and let $(\beta_{j,l})$ be an $n \times n$ matrix with entries in C. Put

$$\beta(x, y) = \sum_{j=1}^{n} \sum_{l=1}^{n} \beta_{j,l}\, x_l\, y_j \tag{3.12.1}$$

for every $x, y \in k^n$, where the terms of the sum are defined using multiplication on k and scalar multiplication on C. This defines a mapping from $k^n \times k^n$ into C that is bilinear over k, and it is easy to see that every bilinear mapping from $k^n \times k^n$ into C can be expressed as (3.12.1) in a unique way.

Observe that (3.12.1) is symmetric as a bilinear mapping from $k^n \times k^n$ into C if and only if $(\beta_{j,l})$ is symmetric as a matrix, which is to say that

$$\beta_{l,j} = \beta_{j,l} \tag{3.12.2}$$

for every $j, l = 1, \ldots, n$. Similarly, (3.12.1) is antisymmetric as a bilinear mapping from $k^n \times k^n$ into C if and only if $(\beta_{j,l})$ is antisymmetric as a matrix, in the sense that

$$\beta_{l,j} = -\beta_{j,l} \tag{3.12.3}$$

for every $j, l = 1, \ldots, n$. Remember that (3.12.1) is antisymmetric as a bilinear mapping from $k^n \times k^n$ into C when

$$\beta(x, x) = 0 \tag{3.12.4}$$

for every $x \in k^n$, as in Section 2.1. In this situation, one can check that (3.12.4) holds for every $x \in k^n$ if and only if $(\beta_{j,l})$ is antisymmetric and

$$\beta_{j,j} = 0 \tag{3.12.5}$$

for every $j = 1, \ldots, n$. If $1 + 1$ is invertible in k, then (3.12.3) implies (3.12.5), by taking $j = l$.

Let $a = (a_{j,l})$ be an $n \times n$ matrix with entries in k. If $x \in k^n$, then let $T_a(x)$ be the element of k^n whose jth coordinate is given by

$$(T_a(x))_j = \sum_{l=1}^{n} a_{j,l}\, x_l \tag{3.12.6}$$

for each $j = 1, \ldots, n$. This defines a module homomorphism from k^n into itself, and every module homomorphism from k^n into itself corresponds to a unique $a \in M_n(k)$ in this way. More precisely, $a \mapsto T_a$ is an isomorphism from $M_n(k)$ as an algebra over k with respect to matrix multiplication onto the algebra $\mathrm{Hom}_k(k^n, k^n)$ of module homomorphisms from k^n into itself with respect to composition of mappings. This corresponds to some of the remarks in Section 2.10 when k is a field.

Let $a \in M_n(k)$ be given again, and observe that

$$\beta(T_a(x), y) = \sum_{j=1}^{n} \sum_{l=1}^{n} \sum_{r=1}^{n} \beta_{r,j}\, a_{j,l}\, x_l\, y_r \tag{3.12.7}$$

for every $x, y \in k^n$, where the terms of the sum are again defined using multiplication on k and scalar multiplication on C. Similarly,

$$\beta(x, T_a(y)) = \sum_{j=1}^{n} \sum_{l=1}^{n} \sum_{r=1}^{n} \beta_{j,l}\, a_{j,r}\, x_l\, y_r \tag{3.12.8}$$

for every $x, y \in k^n$. It follows that T_a is symmetric with respect to β, as in Section 2.12, if and only if

$$\sum_{j=1}^{n} \beta_{r,j}\, a_{j,l} = \sum_{j=1}^{n} \beta_{j,l}\, a_{j,r} \tag{3.12.9}$$

for every $l, r = 1, \ldots, n$. Similarly, T_a is antisymmetric with respect to β if and only if

$$\sum_{j=1}^{n} \beta_{r,j}\, a_{j,l} = -\sum_{j=1}^{n} \beta_{j,l}\, a_{j,r} \tag{3.12.10}$$

for every $l, r = 1, \ldots, n$.

We also have that

$$\beta(T_a(x), T_a(y)) = \sum_{j=1}^{n} \sum_{l=1}^{n} \sum_{m=1}^{n} \sum_{r=1}^{n} \beta_{m,j}\, a_{j,l}\, a_{m,r}\, x_l\, y_r \tag{3.12.11}$$

for every $x, y \in k^n$, where the terms of the sum are defined using multiplication on k and scalar multiplication on C. Thus T_a preserves β, as in Section 3.9, if and only if

$$\sum_{j=1}^{n} \sum_{m=1}^{n} \beta_{m,j}\, a_{j,l}\, a_{m,r} = \beta_{r,l} \tag{3.12.12}$$

for every $l, r = 1, \ldots, n$. Note that T_a is a module automorphism of k^n exactly when a is invertible in $M_n(k)$.

Let $b \in M_n(k)$ be given, so that T_b can be defined as before, and

$$\beta(x, T_b(y)) = \sum_{j=1}^{n} \sum_{l=1}^{n} \sum_{r=1}^{n} \beta_{j,l}\, b_{j,r}\, x_l\, y_r \tag{3.12.13}$$

for every $x, y \in k^n$, as in (3.12.8). Comparing this with (3.12.7), we get that

$$\beta(T_a(x), y) = \beta(x, T_b(y)) \tag{3.12.14}$$

for every $x, y \in k^n$ if and only if

$$\sum_{j=1}^{n} \beta_{r,j}\, a_{j,l} = \sum_{j=1}^{n} \beta_{j,l} b_{j,r} \tag{3.12.15}$$

for every $l, r = 1, \ldots, n$.

The product of an $n \times n$ matrix with entries in C and an $n \times n$ matrix with entries in k, in either order, can be defined as an $n \times n$ matrix with entries in C in the usual way. Let us also use β to denote $(\beta_{j,l})$, as an element of $M_n(C)$. Thus (3.12.9) is the same as saying that

$$\beta\, a = a^t\, \beta \tag{3.12.16}$$

as elements of $M_n(C)$, where a^t is the transpose of a, as in Section 2.8. Similarly, (3.12.10) is the same as saying that

$$\beta\, a = -a^t\, \beta \tag{3.12.17}$$

as elements of $M_n(C)$. We can reexpress (3.12.12) as

$$a^t\, \beta\, a = \beta, \tag{3.12.18}$$

and (3.12.15) as

$$\beta\, a = b^t\, \beta. \tag{3.12.19}$$

Let us now take $C = k$, as a module over itself with respect to multiplication on k. If β is invertible in $M_n(k)$, then (3.12.19) is the same as saying that

$$b^t = \beta^{-1}\, a\, \beta. \tag{3.12.20}$$

If k is a field, then the invertibility of β in $M_n(k)$ is equivalent to the nondegeneracy of the corresponding bilinear form (3.12.1) on k^n as a vector space over k, as in Section 2.14. In this case, (3.12.20) characterizes T_b as the adjoint of T_a with respect to (3.12.1).

3.13 Sesquilinear forms and matrices

Let n be a positive integer, so that the space $\mathbf{C}^n$ of n-tuples of complex numbers is a vector space over $\mathbf{C}$ with respect to coordinatewise addition and scalar multiplication, as usual. Also let $(\beta_{j,l})$ be an $n \times n$ matrix with entries in $\mathbf{C}$, and put

$$\beta(z, w) = \sum_{j=1}^{n} \sum_{l=1}^{n} \beta_{j,l}\, z_l\, \overline{w_j} \tag{3.13.1}$$

for every $z, w \in \mathbf{C}^n$. This defines a sesquilinear form on $\mathbf{C}^n$, and one can check that every sesquilinear form on $\mathbf{C}^n$ corresponds to a unique matrix $(\beta_{j,l})$ in this way. Note that (3.13.1) is Hermitian-symmetric on $\mathbf{C}^n$ if and only if

$$\beta_{l,j} = \overline{\beta_{j,l}} \tag{3.13.2}$$

for every $j, l = 1, \ldots, n$.

If $a = (a_{j,l}) \in M_n(\mathbf{C})$ and $z \in \mathbf{C}^n$, then let $T_a(z)$ be the element of $\mathbf{C}^n$ whose jth coordinate is given by

$$(T_a(z))_j = \sum_{l=1}^{n} a_{j,l}\, z_l \tag{3.13.3}$$

for each $j = 1, \ldots, n$, as before. This defines a linear mapping from $\mathbf{C}^n$ into itself, and $a \mapsto T_a$ is an isomorphism from $M_n(\mathbf{C})$ as an algebra over $\mathbf{C}$ with respect to matrix multiplication onto the algebra $\mathcal{L}(\mathbf{C}^n)$ of linear mappings from $\mathbf{C}^n$ into itself with respect to composition of mappings, as in Section 2.10 and the previous section. Remember that $a^* = ((a^*)_{j,l}) \in M_n(\mathbf{C})$ is defined for each $a \in M_n(\mathbf{C})$ by

$$(a^*)_{j,l} = \overline{a_{l,j}}, \tag{3.13.4}$$

as in Section 2.8, and that $a \mapsto a^*$ is a conjugate-linear involution on $M_n(\mathbf{C})$.

Let $a \in M_n(\mathbf{C})$ be given, and observe that

$$\beta(T_a(z), w) = \sum_{j=1}^{n} \sum_{l=1}^{n} \sum_{r=1}^{n} \beta_{r,j}\, a_{j,l}\, z_l\, \overline{w_r} \tag{3.13.5}$$

for every $z, w \in \mathbf{C}^n$. Similarly,

$$\beta(z, T_a(w)) = \sum_{j=1}^{n} \sum_{l=1}^{n} \sum_{r=1}^{n} \beta_{j,l}\, \overline{a_{j,r}}\, z_l\, \overline{w_r} \tag{3.13.6}$$

for every $z, w \in \mathbf{C}^n$. Thus T_a is self-adjoint with respect to β, as in Section 2.15, if and only if

$$\sum_{j=1}^{n} \beta_{r,j}\, a_{j,l} = \sum_{j=1}^{n} \beta_{j,l}\, \overline{a_{j,r}} \tag{3.13.7}$$

for every $l, r = 1, \ldots, n$. If we also use β to denote $(\beta_{j,l})$ as an element of $M_n(\mathbf{C})$, then (3.13.7) is the same as saying that

$$\beta\, a = a^*\, \beta. \tag{3.13.8}$$

Observe that

$$\beta(T_a(z), T_a(w)) = \sum_{j=1}^n \sum_{l=1}^n \sum_{m=1}^n \sum_{r=1}^n \beta_{m,j}\, a_{j,l}\, \overline{a_{m,r}}\, z_l\, \overline{w_r} \tag{3.13.9}$$

for every $z, w \in \mathbf{C}^n$. It follows that T_a preserves $\beta(\cdot,\cdot)$, as in Section 3.11, if and only if

$$\sum_{j=1}^n \sum_{m=1}^n \beta_{m,j}\, a_{j,l}\, \overline{a_{m,r}} = \beta_{r,l} \tag{3.13.10}$$

for every $l, r = 1, \ldots, n$. This is the same as saying that

$$a^*\, \beta\, a = \beta \tag{3.13.11}$$

as elements of $M_n(\mathbf{C})$.

If $b \in M_n(\mathbf{C})$, then T_b can be defined as in (3.13.3), and

$$\beta(z, T_b(w)) = \sum_{j=1}^n \sum_{l=1}^n \sum_{r=1}^n \beta_{j,l}\, \overline{b_{j,r}}\, z_l\, \overline{w_r} \tag{3.13.12}$$

for every $z, w \in \mathbf{C}^n$, as before. Hence

$$\beta(T_a(z), w) = \beta(z, T_b(w)) \tag{3.13.13}$$

for every $z, w \in \mathbf{C}^n$ if and only if

$$\sum_{j=1}^n \beta_{r,j}\, a_{j,l} = \sum_{j=1}^n \beta_{j,l}\, \overline{b_{j,r}} \tag{3.13.14}$$

for every $l, r = 1, \ldots, n$. This is the same as saying that

$$\beta\, a = b^*\, \beta \tag{3.13.15}$$

as elements of $M_n(\mathbf{C})$. Suppose that $(\beta_{j,l})$ is invertible as an element of $M_n(\mathbf{C})$, which is equivalent to the nondegeneracy of $\beta(\cdot,\cdot)$ as a sesquilinear form on $\mathbf{C}^n$, as in Section 2.15. In this situation, (3.13.15) is the same as saying that

$$b^* = \beta\, a\, \beta^{-1}, \tag{3.13.16}$$

which characterizes T_b as the adjoint of T_a with respect to $\beta(\cdot,\cdot)$.

3.14 Invertibility and involutions

Let k be a commutative ring with a multiplicative identity element, and let A be an associative algebra over k with a multiplicative identity element e. Also let $x \mapsto x^*$ be an opposite algebra automorphism on A, as in Section 2.6. Thus $e^* = e$, as before. If x is an invertible element of A, then

$$x^* \, (x^{-1})^* = (x^{-1} \, x)^* = e^* = e \tag{3.14.1}$$

and

$$(x^{-1})^* \, x^* = (x \, x^{-1})^* = e^* = e. \tag{3.14.2}$$

This implies that x^* is invertible in A, with

$$(x^*)^{-1} = (x^{-1})^*. \tag{3.14.3}$$

Let β be an element of A, and let us say that $x \in A$ is *self-adjoint* with respect to β and the given opposite algebra automorphism on A if

$$\beta \, x = x^* \, \beta. \tag{3.14.4}$$

Similarly, let us say that x is *anti-self-adjoint* with respect to β and the given opposite algebra automorphism on A if

$$\beta \, x = -x^* \, \beta. \tag{3.14.5}$$

If $\beta = e$, then these reduce to the usual notions of self-adjointness and anti-self-adjointness with respect to the given opposite algebra automorphism on A, as in Section 2.6. The collections of self-adjoint and anti-self-adjoint elements of A with respect to β and the given opposite algebra automorphism on A are submodules of A, as a module over k.

Suppose for the moment that $x, y \in A$ are both anti-self-adjoint with respect to β and the given opposite algebra automorphism on A. This implies that

$$\beta \, x \, y = -x^* \, \beta \, y = x^* \, y^* \, \beta = (y \, x)^* \, \beta \tag{3.14.6}$$

and

$$\beta \, y \, x = -y^* \, \beta \, x = y^* \, x^* \, \beta = (x \, y)^* \, \beta. \tag{3.14.7}$$

If $[x, y] = x \, y - y \, x$ is the usual commutator of x and y in A, then we get that

$$\beta \, [x, y] = \beta \, x \, y - \beta \, y \, x = (y \, x)^* \, \beta - (x \, y)^* \, \beta = -([x, y])^* \, \beta. \tag{3.14.8}$$

Thus $[x, y]$ is anti-self-adjoint with respect to β and the given opposite algebra automorphism on A too.

Suppose that $x, y \in A$ satisfy

$$x^* \, \beta \, x = \beta \tag{3.14.9}$$

and

$$y^* \, \beta \, y = \beta. \tag{3.14.10}$$

This implies that

$$(x\,y)^*\,\beta\,x\,y = y^*\,x^*\,\beta\,x\,y = y^*\,\beta\,y = \beta. \tag{3.14.11}$$

Note that (3.14.9) holds when $x = e$, because $e^* = e$. If x is an invertible element of A that satisfies (3.14.9), then

$$\beta = (x^*)^{-1}\,\beta\,x^{-1} = (x^{-1})^*\,\beta\,x^{-1}, \tag{3.14.12}$$

using (3.14.3) in the second step. This shows that the collection of invertible elements x of A that satisfy (3.14.9) forms a group with respect to multiplication.

If β is an invertible element of A, then

$$\phi_\beta(x) = \beta^{-1}\,x^*\,\beta \tag{3.14.13}$$

defines an opposite algebra automorphism on A. In this case, (3.14.4) is equivalent to

$$\phi_\beta(x) = x, \tag{3.14.14}$$

which means that x is self-adjoint with respect to ϕ_β. Similarly, (3.14.5) is equivalent to

$$\phi_\beta(x) = -x, \tag{3.14.15}$$

which means that x is anti-self-adjoint with respect to ϕ_β. We also have that (3.14.9) is equivalent to

$$\phi_\beta(x)\,x = e, \tag{3.14.16}$$

which is the same as saying that

$$x^{-1} = \phi_\beta(x) \tag{3.14.17}$$

when x is invertible in A. Of course, (3.14.13) reduces to the given opposite algebra automorphism $x \mapsto x^*$ on A when $\beta = e$.

Suppose for the moment that $x \mapsto x^*$ is an involution on A, as in Section 2.6. If $x, \beta \in A$, then

$$(\beta\,x)^* = x^*\,\beta^* \tag{3.14.18}$$

and

$$(x^*\,\beta)^* = \beta^*\,(x^*)^* = \beta^*\,x. \tag{3.14.19}$$

It follows that x is self-adjoint or anti-self-adjoint with respect to β and the given involution on A if and only if x is self-adjoint or anti-self-adjoint, respectively, with respect to β^* and the given involution on A. We also have that

$$(x^*\,\beta\,x)^* = x^*\,\beta^*\,(x^*)^* = x^*\,\beta\,x \tag{3.14.20}$$

for every $x, \beta \in A$, so that (3.14.9) is equivalent to

$$x^*\,\beta^*\,x = \beta^*. \tag{3.14.21}$$

Let β be an invertible element of A again, so that ϕ_β can be defined on A as in (3.14.13). Observe that

$$(\phi_\beta(x))^* = (\beta^{-1}\, x^*\, \beta)^* = \beta^*\, (x^*)^*\, (\beta^{-1})^* = \beta^*\, x\, (\beta^*)^{-1} \tag{3.14.22}$$

for every $x \in A$, using the hypothesis that $x \mapsto x^*$ be an involution on A and (3.14.3) for β in the last step. Thus

$$\phi_\beta(\phi_\beta(x)) = \beta^{-1}\, \beta^*\, x\, (\beta^*)^{-1}\, \beta \tag{3.14.23}$$

for every $x \in A$. If β is either self-adjoint or anti-self-adjoint with respect to the given involution on A, then it follows that ϕ_β is an involution on A as well.

Suppose now that k is the field $\mathbf{C}$ of complex numbers, and that $x \mapsto x^*$ is a conjugate-linear opposite algebra automorphism on A, as in Section 2.6. Thus $x \mapsto x^*$ may be considered as a real-linear opposite algebra automorphism on A as an algebra over $\mathbf{R}$, as before. In particular, if $\beta \in A$, then the collections of elements of A that are self-adjoint or anti-self-adjoint with respect to β and $x \mapsto x^*$ are real-linear subspaces of A. In this situation, $x \in A$ is anti-self-adjoint with respect to β if and only if $i\,x$ is self-adjoint with respect to β.

3.15 Invertibility and seminorms

Let k be a field with an absolute value function $|\cdot|$, and let A be an associative algebra over k with a submultiplicative seminorm N_A with respect to $|\cdot|$ on k. Suppose that A has a multiplicative identity element e such that

$$N_A(e) = 1. \tag{3.15.1}$$

If x is an invertible element of A, then it follows that

$$N_A(x)\, N_A(x^{-1}) \geq 1. \tag{3.15.2}$$

In particular, if we have that

$$N_A(x),\ N_A(x^{-1}) \leq 1, \tag{3.15.3}$$

then

$$N_A(x) = N_A(x^{-1}) = 1. \tag{3.15.4}$$

Let y be another invertible element of A such that

$$N_A(y),\ N_A(y^{-1}) \leq 1. \tag{3.15.5}$$

Thus $x\,y$ is an invertible element of A too,

$$N_A(x, y) \leq N_A(x)\, N_A(y) \leq 1, \tag{3.15.6}$$

and

$$N_A((x\,y)^{-1}) = N_A(y^{-1}\, x^{-1}) \leq N_A(x^{-1})\, N_A(y^{-1}) \leq 1. \tag{3.15.7}$$

This shows that the collection of invertible elements x of A that satisfy (3.15.3) forms a group with respect to multiplication.

Suppose that N_A is a semi-ultranorm on A, and that x is an invertible element of A that satisfies (3.15.3). Let y be another invertible element of A such that

$$N_A(x - y) < 1. \tag{3.15.8}$$

This implies that

$$N_A(y) \le \max(N_A(x), N_A(x - y)) \le 1. \tag{3.15.9}$$

We also have that

$$N_A(y^{-1}) = N_A(x^{-1}) \le 1, \tag{3.15.10}$$

as in (3.4.9). Thus y satisfies (3.15.5) under these conditions.

Let A be an algebra over k in the strict sense, and let N_A be a seminorm on A with respect to $|\cdot|$ on k. Also let $x \mapsto x^*$ be an opposite algebra automorphism on A, as in Section 2.6. A basic compatibility condition between $x \mapsto x^*$ and N_A is that there be a nonnegative real number C_1 such that

$$N_A(x^*) \le C_1 \, N_A(x) \tag{3.15.11}$$

for every $x \in A$. This is the same as saying that $x \mapsto x^*$ is bounded as a linear mapping from A into itself, using N_A on the domain and range. Another compatibility condition is that there be a nonnegative real number C_2 such that

$$N_A(x) \le C_2 \, N_A(x^*) \tag{3.15.12}$$

for every $x \in A$. In particular, (3.15.11) and (3.15.12) hold with $C_1 = C_2 = 1$ if and only if

$$N_A(x^*) = N_A(x) \tag{3.15.13}$$

for every $x \in A$, which is to say that $x \mapsto x^*$ is an isometric linear mapping from A into itself with respect to N_A. If $x \mapsto x^*$ is an involution on A, then (3.15.11) and (3.15.12) are equivalent, and with the same constant. If k is the field of complex numbers with the standard absolute value function, then one can consider conjugate-linear opposite algebra automorphisms on A as well.

Chapter 4

Formal power series

4.1 Direct sums and products

Let k be a commutative ring with a multiplicative identity element, and let I be a nonempty set. Suppose that for each $j \in I$, A_j is a module over k. Under these conditions, the Cartesian product $\prod_{j \in I} A_j$ of the A_j's is a module over k too, with respect to coordinatewise addition and scalar multiplication. This is the *direct product* of the A_j's, $j \in I$. If $a \in \prod_{j \in I} A_j$ and $l \in I$, then we let a_l be the lth coordinate of a in A_l. Thus $a \mapsto a_l$ is the standard coordinate projection from $\prod_{j \in I} A_j$ onto A_l. Of course, this mapping is linear over k.

Let $\bigoplus_{j \in I} A_j$ be the set of $a \in \prod_{j \in I} A_j$ such that $a_l = 0$ for all but finitely many $l \in I$. This is the *direct sum* of A_j, $j \in I$. Note that $\bigoplus_{j \in I} A_j$ is a submodule of $\prod_{j \in I} A_j$, as a module over k. If I has only finitely many elements, then $\bigoplus_{j \in I} A_j$ is the same as $\prod_{j \in I} A_j$. If $I = \{1, \ldots, n\}$ for some $n \in \mathbf{Z}_+$, then we may use the notation $\bigoplus_{j=1}^n A_j$ or $\prod_{j=1}^n A_j$.

If A_j is an algebra over k in the strict sense for each $j \in I$, then $\prod_{j \in I} A_j$ is an algebra in the strict sense over k with respect to coordinatewise multiplication, and $\bigoplus_{j \in I} A_j$ is a two-sided ideal in $\prod_{j \in I} A_j$. If A_j is commutative for every $j \in I$, then $\prod_{j \in I} A_j$ is commutative as well. Similarly, if A_j is associative for every $j \in I$, then $\prod_{j \in I} A_j$ is associative. If A_j has a multiplicative identity element for every $j \in I$, then we get a multiplicative identity element in $\prod_{j \in I} A_j$. If A_j is a Lie algebra for every $j \in I$, then $\prod_{j \in I} A_j$ is a Lie algebra.

Now let k be a field with an absolute value function $|\cdot|$, and let I be a nonempty set again. Suppose that V_j is a vector space over k for each $j \in I$, so that the direct product $\prod_{j \in I} V_j$ is a vector space over k too. If N_l is a seminorm on V_l with respect to $|\cdot|$ on k for some $l \in I$, then it is easy to see that

$$\widetilde{N}_l(v) = N_l(v_l) \tag{4.1.1}$$

defines a seminorm on $\prod_{j \in I} V_j$ with respect to $|\cdot|$ on k. If N_l is a semi-ultranorm on V_l, then (4.1.1) is a semi-ultranorm on $\prod_{j \in I} V_j$.

As before, the direct sum $\bigoplus_{j \in I} V_j$ is a linear subspace of $\prod_{j \in I} V_j$. Suppose that N_j is a seminorm on V_j for each $j \in I$, and put

$$\widetilde{N}^1(v) = \sum_{j \in I} N_j(v_j) \tag{4.1.2}$$

for every $v \in \bigoplus_{j \in I} V_j$. More precisely, if $v \in \bigoplus_{j \in I} V_j$, then $v_j = 0$ for all but finitely many $j \in I$, so that the sum on the right side of (4.1.2) reduces to a finite sum of nonnegative real numbers. One can check that (4.1.2) defines a seminorm on $\bigoplus_{j \in I} V_j$ with respect to $|\cdot|$ on k, which is a norm when N_j is a norm on V_j for every $j \in I$.

Similarly, put

$$\widetilde{N}^\infty(v) = \max_{j \in I} N_j(v_j) \tag{4.1.3}$$

for every $v \in \bigoplus_{j \in I} V_j$, which reduces to the maximum of finitely many nonnegative real numbers. One can verify that this defines a seminorm on $\bigoplus_{j \in I} V_j$, which is a norm when N_j is a norm on V_j for every $j \in I$. If N_j is a semi-ultranorm on V_j for each $j \in I$, then (4.1.3) is a semi-ultranorm on $\bigoplus_{j \in I} V_j$. Observe that

$$\widetilde{N}^\infty(v) \le \widetilde{N}^1(v) \tag{4.1.4}$$

for every $v \in \bigoplus_{j \in I} V_j$. If I has only finitely many elements, then

$$\widetilde{N}^1(v) \le (\#I)\, \widetilde{N}^\infty(v) \tag{4.1.5}$$

for every $v \in \bigoplus_{j \in I} V_j$, where $\#I$ is the number of elements in I.

Let a_j be a positive real number for each $j \in I$. As before,

$$\widetilde{N}^1_a(v) = \sum_{j \in I} a_j\, N_j(v_j) \tag{4.1.6}$$

defines a seminorm on $\bigoplus_{j \in I} V_j$ with respect to $|\cdot|$ on k. Similarly,

$$\widetilde{N}^\infty_a(v) = \max_{j \in I} (a_j\, N_j(v_j)) \tag{4.1.7}$$

defines a seminorm on $\bigoplus_{j \in I} V_j$ with respect to $|\cdot|$ on k, which is a semi-ultranorm when N_j is a semi-ultranorm on V_j for each $j \in I$. Clearly

$$\widetilde{N}^\infty_a(v) \le \widetilde{N}^1_a(v) \tag{4.1.8}$$

for every $v \in \bigoplus_{j \in I} V_j$. If I has only finitely many elements, then

$$\widetilde{N}^1_a(v) \le \Big(\sum_{j \in I} a_j\Big)\, \widetilde{N}^\infty(v) \tag{4.1.9}$$

for every $v \in \bigoplus_{j \in I} V_j$. If I has infinitely many elements, then $\sum_{j \in I} a_j$ can be defined as an extended real number, as the supremum of the corresponding finite subsums. If the supremum is finite, then (4.1.9) still holds and is nontrivial.

4.2 Bilinear mappings and Cauchy products

Let k be a commutative ring with a multiplicative identity element, let A, B, and C be modules over k, and let β be a mapping from $A \times B$ into C that is bilinear over k. Also let $\sum_{j=0}^{\infty} a_j$ and $\sum_{l=0}^{\infty} b_l$ be infinite series with terms in A and B, respectively, considered formally for the moment. Put

$$c_n = \sum_{j=0}^{n} \beta(a_j, b_{n-j}) \tag{4.2.1}$$

for each nonnegative integer n. It is easy to see that

$$\sum_{n=0}^{\infty} c_n = \beta\Big(\sum_{j=0}^{\infty} a_j, \sum_{l=0}^{\infty} b_l\Big), \tag{4.2.2}$$

at least formally. More precisely, suppose for the moment that there are nonnegative integers J, L such that $a_j = 0$ when $j > J$ and $b_l = 0$ when $l > L$. If $n > J+L$, then it follows that $c_n = 0$. Thus the infinite series $\sum_{j=0}^{\infty} a_j$, $\sum_{l=0}^{\infty} b_l$, and $\sum_{n=0}^{\infty} c_n$ reduce to the finite sums $\sum_{j=0}^{J} a_j$, $\sum_{l=0}^{L} b_l$, and $\sum_{n=0}^{J+L} c_n$, respectively, and the formal argument for (4.2.2) works in this case.

In particular, if A is an algebra over k in the strict sense, then we can take β to be the corresponding mapping from $A \times A$ into A. Let $\sum_{j=0}^{\infty} a_j$ and $\sum_{l=0}^{\infty} b_l$ be infinite series with terms in A, and let us express multiplication of $a, b \in A$ as $a\,b$. The *Cauchy product* of these series is defined to be the series $\sum_{n=0}^{\infty} c_n$, where

$$c_n = \sum_{j=0}^{n} a_j\, b_{n-j}, \tag{4.2.3}$$

as in (4.2.1). Thus

$$\sum_{n=0}^{\infty} c_n = \Big(\sum_{j=0}^{\infty} a_j\Big)\Big(\sum_{l=0}^{\infty} b_l\Big), \tag{4.2.4}$$

at least formally, as before.

Suppose for the moment that $k = \mathbf{R}$ with the standard absolute value function, and that a_j, b_l are nonnegative real numbers for every $j, l \ge 0$. If c_n is as in (4.2.3), then c_n is a nonnegative real number for every $n \ge 0$. If J, L are nonnegative integers, then one can verify that

$$\Big(\sum_{j=0}^{J} a_j\Big)\Big(\sum_{l=0}^{L} b_l\Big) \le \sum_{n=0}^{J+L} c_n. \tag{4.2.5}$$

Similarly, if N is a nonnegative integer, then

$$\sum_{n=0}^{N} c_n \le \Big(\sum_{j=0}^{N} a_j\Big)\Big(\sum_{l=0}^{N} b_l\Big). \tag{4.2.6}$$

If $\sum_{j=0}^{\infty} a_j$ and $\sum_{l=0}^{\infty} b_l$ converge, then it follows that $\sum_{n=0}^{\infty} c_n$ converges, and that the sums satisfy (4.2.4).

Let k be any field with an absolute value function $|\cdot|$, and let A, B, and C be vector spaces over k with norms N_A, N_B, and N_C, respectively, with respect to $|\cdot|$ on k. Also let β be a bounded bilinear mapping from $A \times B$ into C with respect to these norms, so that there is a nonnegative real number $C(\beta)$ such that

$$N_C(\beta(a, b)) \le C(\beta)\, N_A(a)\, N_B(b) \tag{4.2.7}$$

for every $a \in A$ and $b \in B$. Suppose that A, B, and C are complete with respect to the metrics associated to N_A, N_B, and N_C, respectively. Let $\sum_{j=0}^{\infty} a_j$ and $\sum_{l=0}^{\infty} b_l$ be infinite series with terms in A and B that converge absolutely with respect to N_A and N_B, respectively, so that $\sum_{j=0}^{\infty} N_A(a_j)$ and $\sum_{l=0}^{\infty} N_B(b_l)$ converge as infinite series of nonnegative real numbers. If c_n is as in (4.2.1), then

$$N_C(c_n) \le \sum_{j=0}^{n} N_C(\beta(a_j, b_{n-j})) \le C(\beta) \sum_{j=0}^{n} N_A(a_j)\, N_B(b_{n-j}) \tag{4.2.8}$$

for every $n \ge 0$. The sum on the right side of (4.2.8) is the same as the nth term of the Cauchy product of $\sum_{j=0}^{\infty} N_A(a_j)$ and $\sum_{l=0}^{\infty} N_B(b_l)$. It follows that $\sum_{n=0}^{\infty} N_C(c_n)$ converges as an infinite series of nonnegative real numbers, with

$$\sum_{n=0}^{\infty} N_C(c_n) \le C(\beta) \Big(\sum_{j=0}^{\infty} N_A(a_j)\Big) \Big(\sum_{l=0}^{\infty} N_B(b_l)\Big). \tag{4.2.9}$$

Thus $\sum_{n=0}^{\infty} c_n$ converges absolutely with respect to N_C, and $\sum_{j=0}^{\infty} a_j$, $\sum_{l=0}^{\infty} b_l$, and $\sum_{n=0}^{\infty} c_n$ converge in A, B, and C, respectively, by completeness. One can check that (4.2.2) holds in this situation, by approximating these sums by finite sums.

Suppose now that N_A, N_B, and N_C are ultranorms on A, B, and C, respectively, and let $\sum_{j=0}^{\infty} a_j$ and $\sum_{l=0}^{\infty} b_l$ be infinite series with terms in A and B, respectively, such that

$$\lim_{j \to \infty} N_A(a_j) = \lim_{l \to \infty} N_B(b_l) = 0. \tag{4.2.10}$$

If c_n is as in (4.2.1) again, then

$$N_C(c_n) \le \max_{0 \le j \le n} N_C(\beta(a_j, b_{n-j})) \le C(\beta) \max_{0 \le j \le n} (N_A(a_j)\, N_B(b_l)) \tag{4.2.11}$$

for every $n \ge 0$. One can verify that

$$\lim_{n \to \infty} N_C(c_n) = 0, \tag{4.2.12}$$

using (4.2.10) and (4.2.11). It follows that $\sum_{j=0}^{\infty} a_j$, $\sum_{l=0}^{\infty} b_l$, and $\sum_{n=0}^{\infty} c_n$ converge in A, B, and C, respectively, because of completeness, as in Section 1.12. One can check that (4.2.2) holds in this situation too, by approximating these sums by finite sums, as before.

4.3 Formal power series and modules

Let k be a commutative ring with a multiplicative identity element, let A be a module over k, and let T be an indeterminate. As in [4, 11], we shall try to use upper-case letters like T for indeterminates, and lower-case letters for elements of k or A. A *formal power series* in T with coefficients in A can be expressed as

$$f(T) = \sum_{j=0}^{\infty} f_j\, T^j, \tag{4.3.1}$$

where f_j is an element of A for each nonnegative integer j. The space $A[[T]]$ of these formal power series can be defined as the space of functions on the set $\mathbf{Z}_+ \cup \{0\}$ of nonnegative integers with values in A, where (4.3.1) corresponds to $j \mapsto f_j$ as an A-valued function on $\mathbf{Z}_+ \cup \{0\}$. This is a module over k with respect to pointwise addition and scalar multiplication of A-valued functions on $\mathbf{Z}_+ \cup \{0\}$, which corresponds to termwise addition and scalar multiplication of formal power series as in (4.3.1).

Similarly, a *formal polynomial* in T with coefficients in A can be expressed as

$$f(T) = \sum_{j=0}^{n} f_j\, T^j \tag{4.3.2}$$

for some nonnegative integer n, where $f_j \in A$ for each $j = 0, \ldots, n$. This may be considered as a formal power series in T too, with $f_j = 0$ for $j > n$. The space $A[T]$ of these formal polynomials can be defined as the space of A-valued functions on $\mathbf{Z}_+ \cup \{0\}$ that are equal to 0 at all but finitely many nonnegative integers. Of course, $A[T]$ is a submodule of $A[[T]]$, as a module over k. Observe that $A[[T]]$ corresponds to the direct product of copies of A indexed by the set $\mathbf{Z}_+ \cup \{0\}$ of nonnegative integers, as a module over k, and that $A[T]$ corresponds to the analogous direct sum.

There is a natural mapping from A into $A[T]$, which sends $a \in A$ to the formal polynomial $f(T)$ with $f_0 = a$ and $f_j = 0$ when $j \geq 1$. This is an injective module homomorphism from A into $A[T]$, and it is sometimes convenient to think of A as a submodule of $A[T]$ in this way. Note that the mapping

$$f(T) \mapsto f_0 \tag{4.3.3}$$

is a module homomorphism from $A[[T]]$ onto A.

If $f(T) \in A[[T]]$ and l is a nonnegative integer, then

$$f(T)\, T^l = \sum_{j=0}^{\infty} f_j\, T^{j+l} = \sum_{j=l}^{\infty} f_{j-l}\, T^j \tag{4.3.4}$$

defines an element of $A[[T]]$, which is the same as $f(T)$ when $l = 0$. Of course, (4.3.4) is in $A[T]$ when $f(T) \in A[T]$. The mapping

$$f(T) \mapsto f(T)\, T^l \tag{4.3.5}$$

is an injective module homomorphism from $A[[T]]$ into itself for every $l \geq 0$.

Let us say that $f(T) \in A[[T]]$ *vanishes to order* n for some nonnegative integer n if $f_j = 0$ for every $j = 0, \ldots, n$. Equivalently, this means that $f(T) = g(T)\,T^{n+1}$ for some $g(T) \in A[[T]]$. The collection of $f(T) \in A[[T]]$ that vanishes to order n is a submodule of $A[[T]]$. This submodule is the same as the kernel of (4.3.3) when $n = 0$.

4.4 Sums and extensions

Let k be a commutative ring with a multiplicative identity element, let A be a module over k, and let T be an indeterminate again. Also let $f_l(T) = \sum_{j=0}^{\infty} f_{l,j}\,T^j$ be an element of $A[[T]]$ for each $l \in \mathbf{Z}_+$, and let $f(T)$ be another element of $A[[T]]$. Let us say that $\{f_l(T)\}_{l=1}^{\infty}$ *eventually agrees with* $f(T)$ *termwise* if for each nonnegative integer j there is a positive integer L_j such that

$$f_{l,j} = f_j \tag{4.4.1}$$

for every $l \geq L_j$. This implies that $f_l(T) - f(T)$ vanishes to order $n \geq 0$ when $l \geq \max(L_0, \ldots, L_n)$. As in the previous section, $A[[T]]$ can be defined as the space of A-valued functions on $\mathbf{Z}_+ \cup \{0\}$, which is the same as the Cartesian product of the family of copies of A indexed by $\mathbf{Z}_+ \cup \{0\}$. Consider the product topology on $A[[T]]$ as a Cartesian product, using the discrete topology on A in each factor. The condition that $\{f_l(T)\}_{l=1}^{\infty}$ eventually agree termwise with $f(T)$ is equivalent to the convergence of $\{f_l(T)\}_{l=1}^{\infty}$ to $f(T)$ with respect to this product topology.

Similarly, let us say that $\{f_l(T)\}_{l=1}^{\infty}$ is *termwise eventually constant* if for each nonnegative integer j there is an $L_j \in \mathbf{Z}_+$ such that $f_{l,j}$ does not depend on l when $l \geq L_j$. In this case, we can define $f_j \in A$ for each $j \geq 0$ by putting $f_j = f_{l,j}$ when $l \geq L_j$. This defines $f(T) = \sum_{j=0}^{\infty} f_j\,T^j$ as an element of $A[[T]]$, and we have that $\{f_l(T)\}_{l=1}^{\infty}$ eventually agrees termwise with $f(T)$. Conversely, if $\{f_l(T)\}_{l=1}^{\infty}$ eventually agrees termwise with some $f(T) \in A[[T]]$, then $\{f_l(T)\}_{l=1}^{\infty}$ is termwise eventually constant.

If $\{f_l(T)\}_{l=1}^{\infty}$ eventually agrees termwise with some $f(T) \in A[[T]]$ and $\alpha \in k$, then $\{\alpha\, f_l(T)\}_{l=1}^{\infty}$ eventually agrees termwise with $\alpha\, f(T)$. In this situation, we also have that $\{f_l(T)\,T^r\}_{l=1}^{\infty}$ eventually agrees termwise with $f(T)\,T^r$ for every nonnegative integer r. If $\{g_l(T)\}_{l=1}^{\infty}$ is another sequence of elements of $A[[T]]$ that eventually agrees termwise with $g(T) \in A[[T]]$, then $\{f_l(T) + g_l(T)\}_{l=1}^{\infty}$ eventually agrees termwise with $f(T) + g(T)$.

Let $a_l(T) = \sum_{j=0}^{\infty} a_{l,j}\,T^j$ be a formal power series in T with coefficients in A for each $l \in \mathbf{Z}_+$. Suppose that $\{a_l(T)\}_{l=1}^{\infty}$ eventually agrees termwise with 0, so that for each $j \geq 0$ there is an $L_j \in \mathbf{Z}_+$ such that $a_{l,j} = 0$ for every $l \geq L_j$ It follows that the coefficient of T^j in

$$\sum_{l=1}^{n} a_l(T) \tag{4.4.2}$$

does not depend on n when $n \geq L_j - 1$, so that the sequence of these sums is termwise eventually constant. Under these conditions, we can define

$$\sum_{l=1}^{\infty} a_l(T) \tag{4.4.3}$$

as a formal power series in T with coefficients in A, by taking the coefficient of T^j in (4.4.3) to be the coefficient of T^j in (4.4.2) when $l \geq L(n) - 1$, as before. By construction, the sequence of partial sums (4.4.2) eventually agrees termwise with (4.4.3).

If $\alpha \in k$, then $\{\alpha\, a_l(T)\}_{l=1}^{\infty}$ eventually agrees termwise with 0 too, and

$$\sum_{l=1}^{\infty} \alpha\, a_l(T) = \alpha \sum_{l=1}^{\infty} a_l(T). \tag{4.4.4}$$

If r is a nonnegative integer, then $\{a_l(T)\, T^r\}_{l=1}^{\infty}$ eventually agrees termwise with 0 as well, and

$$\sum_{l=1}^{\infty} a_l(T)\, T^r = \Big(\sum_{l=1}^{\infty} a_l(T)\Big)\, T^r. \tag{4.4.5}$$

If $\{b_l(T)\}_{l=1}^{\infty}$ is another sequence of elements of $A[[T]]$ that eventually agrees termwise with 0, then $\{a_l(T)+b_l(T)\}_{l=1}^{\infty}$ eventually agrees termwise with 0, and

$$\sum_{l=1}^{\infty}(a_l(T) + b_l(T)) = \sum_{l=1}^{\infty} a_l(T) + \sum_{l=1}^{\infty} b_l(T). \tag{4.4.6}$$

Of course, one can deal with sequences and series that start with $l = 0$ in the same way.

Let B be another module over k, so that $B[[T]]$ is a module over k too, as before. Also let ϕ be a module homomorphism from A into $B[[T]]$. Note that a module homomorphism from A into B may be considered as a module homomorphism from A into $B[[T]]$, by considering B as a submodule of $B[[T]]$. If $f(T) = \sum_{l=0}^{\infty} f_l\, T^l \in A[[T]]$, then $\phi(f_l) \in B[[T]]$ for each $l \geq 0$, and $\phi(f_l)\, T^l$ automatically vanishes to order $l-1$ for every $l \geq 1$. In particular, $\{\phi(f_l)\, T^l\}_{l=0}^{\infty}$ eventually agrees termwise with 0, and we put

$$\phi(f(T)) = \sum_{l=0}^{\infty} \phi(f_l)\, T^l, \tag{4.4.7}$$

where the sum is defined as an element of $B[[T]]$ as in (4.4.3). This defines a module homomorphism from $A[[T]]$ into $B[[T]]$, which agrees with the initial homomorphism from A into $B[[T]]$ when A is considered as a submodule of $A[[T]]$. If we start with a module homomorphism ϕ from A into $B[T]$, and if $f(T) \in A[T]$, then (4.4.7) reduces to a finite sum in $B[T]$.

If $f(T) \in A[[T]]$ vanishes to order n for some nonnegative integer n, then it is easy to see that $\phi(f(T))$ vanishes to order n as well. More precisely, one can check that

$$\phi(f(T)\, T^r) = \phi(f(T))\, T^r \tag{4.4.8}$$

for every $f(T) \in A[[T]]$ and nonnegative integer r. If $f(T) = \sum_{l=0}^\infty f_l\,T^l \in A[[T]]$ and j is a nonnegative integer, then the total coefficient of T^j in (4.4.7) is the sum of the coefficients of T^{j-l} in $\phi(f_l)$ for $l = 0, \ldots, j$, and in particular depends only on $\phi(f_l)$ for $l \le j$. If $\{f_r(T)\}_{r=1}^\infty$ is a sequence of elements of $A[[T]]$ that eventually agrees termwise with $f(T)$, then it follows that $\{\phi(f_r(T))\}_{r=1}^\infty$ eventually agrees termwise with $\phi(f(T))$.

4.5 Extending bilinear mappings

Let k be a commutative ring with a multiplicative identity element, let A, B, and C be modules over k, and let T be an indeterminate. As before, $C[[T]]$ is a module over k, and we let β be a mapping from $A \times B$ into $C[[T]]$ that is bilinear over k. There is a natural way to extend β to a mapping from $A[[T]] \times B[[T]]$ into $C[[T]]$, as follows. Let $f(T) = \sum_{j=0}^\infty f_j\,T^j$ and $g(T) = \sum_{l=0}^\infty g_l\,T^l$ be formal power series in T with coefficients in A and B, respectively. Put

$$h_n(T) = \sum_{j=0}^{n} \beta(f_j, g_{n-j}) \tag{4.5.1}$$

for each nonnegative integer n, which is an element of $C[[T]]$. Thus $h_n(T)\,T^n$ automatically vanishes to order $n-1$ for every $n \ge 1$, so that

$$h(T) = \sum_{n=0}^{\infty} h_n(T)\,T^n \tag{4.5.2}$$

defines an element of $C[[T]]$ too, as in the previous section. Put

$$\beta(f(T), g(T)) = h(T). \tag{4.5.3}$$

This defines a mapping from $A[[T]] \times B[[T]]$ into $C[[T]]$ that is bilinear over k and agrees with the initial mapping from $A \times B$ into $C[[T]]$, with A and B considered as submodules of $A[[T]]$ and $B[[T]]$, respectively.

If $f(T) \in A[T]$ and $g(T) \in B[T]$, then (4.5.1) is equal to 0 for all but finitely many n, so that (4.5.2) reduces to a finite sum. If the inital mapping β sends $A \times B$ into $C[T]$, then (4.5.1) is in $C[T]$ for every $n \ge 0$. In this case, it follows that (4.5.2) is an element of $C[T]$ when $f(T) \in A[T]$ and $g(T) \in B[T]$.

If $f(T) \in A[[T]]$ and $g(T) \in B[[T]]$ vanish to order r_1 and r_2, respectively, for some nonnegative integers r_1, r_2, then (4.5.1) is equal to 0 when $n \le r_1 + r_2$, so that (4.5.2) vanishes to order $r_1 + r_2$. More precisely, one can verify that

$$\beta(f(T)\,T^r, g(T)\,T^m) = \beta(f(T), g(T))\,T^{r+m} \tag{4.5.4}$$

for every $f(T) \in A[[T]]$, $g(T) \in B[[T]]$, and nonnegative integers r, m. If $f(T) = \sum_{j=0}^\infty f_j\,T^j \in A[[T]]$, $g(T) = \sum_{l=0}^\infty g_l\,T^l \in B[[T]]$, and r is a nonnegative integer, then the total coefficient of T^r in (4.5.2) is the sum of the coefficients of T^{r-n} in (4.5.1) for $n = 0, \ldots, r$. In particular, this only involves (4.5.1) for $n \le r$, and hence depends only on f_j and g_l for $j, l \le r$. If $\{f_m(T)\}_{m=1}^{\infty}$ and $\{g_m(T)\}_{m=1}^{\infty}$ are sequences of elements of $A[[T]]$ and $B[[T]]$ that eventually agree termwise with $f(T)$ and $g(T)$, respectively, then it follows that $\{\beta(f_m(T), g_m(T))\}_{m=1}^{\infty}$ eventually agrees termwise with $\beta(f(T), g(T))$.

Let $\{a_m(T)\}_{m=0}^{\infty}$ and $\{b_r(T)\}_{r=0}^{\infty}$ be sequences of elements of $A[[T]]$ and $B[[T]]$, respectively, that eventually agree termwise with 0. Thus $\sum_{m=0}^{\infty} a_m(T)$ and $\sum_{r=0}^{\infty} b_r(T)$ can be defined as elements of $A[[T]]$ and $B[[T]]$, respectively, as in the previous section. Using the extension of β to $A[[T]] \times B[[T]]$ defined earlier, we get that $\beta(a_m(T), b_r(T))$ is defined as an element of $C[[T]]$ for all $m, r \ge 0$. Put

$$c_N(T) = \sum_{m=0}^{N} \beta(a_m(T), b_{N-m}(T)) \tag{4.5.5}$$

for every nonnegative integer N, which is an element of $C[[T]]$. Note that $\beta(a_m(T), b_r(T))$ vanishes to arbitrarily large order when m or r is sufficiently large in this situation, by the remarks in the preceding paragraph. This implies that $\{c_N(T)\}_{N=0}^{\infty}$ eventually agrees termwise with 0, so that $\sum_{N=0}^{\infty} c_N(T)$ defines an element of $C[[T]]$, as in the previous section. One can check that

$$\sum_{N=0}^{\infty} c_N(T) = \beta\Big(\sum_{m=0}^{\infty} a_m(T), \sum_{r=0}^{\infty} b_r(T)\Big) \tag{4.5.6}$$

as elements of $C[[T]]$, as in Section 4.2. More precisely, this means that for each nonnegative integer j, the coefficients of T^j on both sides of (4.5.6) are the same. This reduces to an analogous statement for finite sums for each $j \ge 0$ in this situation.

Observe that (4.5.1) is the same as

$$\sum_{l=0}^{n} \beta(f_{n-l}, g_l). \tag{4.5.7}$$

Suppose now that $A = B$. If the initial mapping β from $A \times A$ into $C[[T]]$ is symmetric or antisymmetric, then it is easy to see that the extension of β to $A[[T]] \times A[[T]]$ has the same property, using the fact that (4.5.1) is the same as (4.5.7). Suppose that the initial mapping β on $A \times A$ satisfies

$$\beta(a, a) = 0 \tag{4.5.8}$$

for every $a \in A$, and let us check that the extension of β to $A[[T]] \times A[[T]]$ satisfies

$$\beta(f(T), f(T)) = 0 \tag{4.5.9}$$

for every $f(T) = \sum_{j=0}^{\infty} f_j\, T^j \in A[[T]]$. To do this, it suffices to verify that

$$\sum_{j=0}^{n} \beta(f_j, f_{n-j}) = 0 \tag{4.5.10}$$

for every nonnegative integer n. Remember that (4.5.8) implies that β is antisymmetric on $A \times A$, as in Section 2.1. If n is odd, then (4.5.10) reduces to the antisymmetry of β on $A \times A$. If n is even, then one can use the antisymmetry of β on $A \times A$ to reduce (4.5.10) to the condition that $\beta(f_{n/2}, f_{n/2}) = 0$, which follows from (4.5.8).

4.6 Formal power series and algebras

Let k be a commutative ring with a multiplicative identity element again, and let T be an indeterminate. Suppose that A is an algebra over k in the strict sense, where multiplication of $a, b \in A$ is expressed as $a\,b$. Let $f(T) = \sum_{j=0}^{\infty} f_j\,T^j$ and $g(T) = \sum_{l=0}^{\infty} g_l\,T^l$ be formal power series in T with coefficients in A, and put

$$h_n = \sum_{j=0}^{n} f_j\,g_{n-j} \tag{4.6.1}$$

for each nonnegative integer n. Thus $h(T) = \sum_{n=0}^{\infty} h_n\,T^n$ is a formal power series in T with coefficients in A too, and we put

$$f(T)\,g(T) = h(T). \tag{4.6.2}$$

This defines a mapping from $A[[T]] \times A[[T]]$ into $A[[T]]$, which is the same as the mapping obtained from multiplication on A as in the previous section. Using this definition of multiplication on $A[[T]]$, we get that $A[[T]]$ is an algebra over k in the strict sense. Note that $A[T]$ is a subalgebra of $A[[T]]$, and that A corresponds to a subalgebra of $A[T]$, using the identification mentioned in Section 4.3. The mapping $f(T) \mapsto f_0$ mentioned in Section 4.3 defines an algebra homomorphism from $A[[T]]$ onto A. If multiplication on A is commutative, then multiplication on $A[[T]]$ is commutative as well, as in the remark about symmetry of β in the previous section. Similarly, if multiplication on A is associative, then one can check that multiplication on $A[[T]]$ is associative too. If A has a multiplicative identity element e, then the corresponding formal polynomial in T is the multiplicative identity element in $A[[T]]$.

In particular, we can take $A = k$, considered as an algebra over itself. Thus $k[[T]]$ is a commutative associative algebra over k with a multiplicative identity element, and $k[T]$ is a subalgebra of $k[[T]]$. We can identify k with a subalgebra of $k[T]$, where the multiplicative identity element in k corresponds to the multiplicative identity element in $k[[T]]$.

If A is any module over k, then $A[[T]]$ may be considered as a module over $k[[T]]$. More precisely, if $f(T) \in k[[T]]$ and $g(T) \in A[[T]]$, then $f(T)\,g(T)$ can be defined as a formal power series in T with coefficients in A as in (4.6.2), where the terms in the sum on the right side of (4.6.1) are defined using scalar multiplication on A. Equivalently, scalar multiplication on A corresponds to a mapping from $k \times A$ into A that is bilinear over k, which can be extended to a mapping from $k[[T]] \times A[[T]]$ into $A[[T]]$ as in the previous section. Similarly, $A[T]$ may be considered as a module over $k[T]$.

Let A and B be modules over k, and let ϕ be a module homomorphism from A into $B[[T]]$, as modules over k. As in Section 4.4, there is a natural way to extend ϕ to a mapping from $A[[T]]$ into $B[[T]]$. It is easy to see that this mapping is a module homomorphism from $A[[T]]$ into $B[[T]]$, as modules over $k[[T]]$. If the initial mapping sends A into $B[T]$, then the restricton to $A[T]$ of the extension to $A[[T]]$ is a module homomorphism into $B[T]$, as modules over $k[T]$. Let C be another module over k, and let β be a mapping from $A \times B$ into $C[[T]]$ that is bilinear over k. One can check that the extension of β to a mapping from $A[[T]] \times B[[T]]$ into $C[[T]]$ defined in the previous section is bilinear over $k[[T]]$. If the initial mapping sends $A \times B$ into $C[T]$, then the restriction to $A[T] \times B[T]$ of the extension to $A[[T]] \times B[[T]]$ is bilinear over $k[T]$ as a mapping into $C[T]$. If A is an algebra over k in the strict sense, then $A[[T]]$ may be considered as an algebra over $k[[T]]$ in the strict sense, and $A[T]$ may be considered as an algebra over $k[T]$ in the strict sense.

Suppose that $(A, [\cdot,\cdot]_A)$ is a Lie algebra over k, and let $f(T)$ and $g(T)$ be formal power series in T with coefficients in A again. In this situation, (4.6.1) should be expressed as

$$h_n = \sum_{j=0}^{n} [f_j, g_{n-j}]_A \tag{4.6.3}$$

for each $n \geq 0$, and we put

$$[f(T), g(T)]_{A[[T]]} = h(T) = \sum_{n=0}^{\infty} h_n\, T^n. \tag{4.6.4}$$

One can verify that $A[[T]]$ is a Lie algebra over k with respect to (4.6.4). More precisely, one can use the fact that $[a, a]_A = 0$ for every $a \in A$ to get that $[f(T), f(T)]_{A[[T]]} = 0$ for every $f(T) \in A[[T]]$, as in the previous section. One can also get the Jacobi identity for $[\cdot,\cdot]_{A[[T]]}$ from the Jacobi identity for $[\cdot,\cdot]_A$. As before, $A[T]$ is a Lie subalgebra of $A[[T]]$, as a Lie algebra over k. One can consider $A[[T]]$ as a Lie algebra over $k[[T]]$, and $A[T]$ as a Lie algebra over $k[T]$.

4.7 Invertibility in $A[[T]]$

Let k be a commutative ring with a multiplicative identity element, and let A be an associative algebra over k with a multiplicative identity element e. Also let T be an indeterminate, so that $A[[T]]$ may be considered as an associative algebra over $k[[T]]$ as in the previous section. Let us identify e with the corresponding formal power series in T with coefficients in A, which is the multiplicative identity element in $A[[T]]$. If $a(T) \in A[[T]]$, then $a(T)^l$ can be defined as an element of $A[[T]]$ for every $l \in \mathbf{Z}_+$ using multiplication on $A[[T]]$, and we interpret $a(T)^l$ as being equal to e when $l = 0$. Observe that

$$(e - a(T)) \sum_{l=0}^{n} a(T)^l = \Big(\sum_{l=0}^{n} a(t)^l\Big)(e - a(T)) = e - a(T)^{n+1} \tag{4.7.1}$$

for every nonnegative integer n, by a standard computation.

Suppose that $a(T)$ vanishes to order 0, as in Section 4.3, so that the coefficient of T^0 in $a(T)$ is equal to 0. This implies that $a(T)^l$ vanishes to order $l-1$ for every $l \in \mathbf{Z}_+$. It follows that the coefficient of T^j in

$$\sum_{l=0}^{n} a(T)^l \tag{4.7.2}$$

is the same for $n \geq j$. As in Section 4.4, we define

$$\sum_{l=0}^{\infty} a(T)^l \tag{4.7.3}$$

as a formal power series in T with coefficients in A by taking the coefficient of T^j in (4.7.3) to be the same as the coefficient of T^j in (4.7.2) when $n \geq j$. In particular, $\{a(T)^l\}_{l=0}^{\infty}$ eventually agrees termwise with 0, as in Section 4.4, and the sequence of partial sums (4.7.2) eventually agrees termwise with (4.7.3).

Using (4.7.1), one can check that

$$(e - a(T)) \sum_{l=0}^{\infty} a(T)^l = \Big(\sum_{l=0}^{\infty} a(T)^l\Big)(e - a(T)) = e. \tag{4.7.4}$$

More precisely, for each nonnegative integer j, the coefficient of T^j in each of the three expressions in (4.7.4) is the same as in the corresponding expression in (4.7.1) when $n \geq j$. It follows that (4.7.3) is the multiplicative inverse of $e - a(T)$ in $A[[T]]$.

Let $f(T) = \sum_{j=0}^{\infty} f_j\, T^j$ be a formal power series in T with coefficients in A. If f_0 is invertible as an element of A, then $f(T)$ can be expressed as $f_0\,(e - a(T))$, where $a(T) \in A[[T]]$ vanishes to order 0. This implies that $f(T)$ is invertible in $A[[T]]$, because $e - a(T)$ is invertible in $A[[T]]$, as in the previous paragraph. Conversely, if $f(T)$ is invertible in $A[[T]]$, then f_0 is invertible in A, because $f(T) \mapsto f_0$ is an algebra homomorphism from $A[[T]]$ onto A.

Of course, the collection of invertible elements of $A[[T]]$ is a group with respect to multiplication of formal power series. The collection of $f(T) \in A[[T]]$ with $f_0 = e$ is a subgroup of this group.

4.8 Homomorphisms over $k[T]$

Let k be a commutative ring with a multiplicative identity element, let A, B be modules over k, and let T be an indeterminate. Also let ϕ be a homomorphism from $A[T]$ into $B[T]$, as modules over k. Suppose that

$$\phi(f(T)\,T) = \phi(f(T))\,T \tag{4.8.1}$$

for every $f(T) \in A[T]$. This implies that

$$\phi(f(T)\,T^r) = \phi(f(T))\,T^r \tag{4.8.2}$$

for every $f(T) \in A[T]$ and $r \in \mathbf{Z}_+$, by applying (4.8.1) repeatedly. Of course, (4.8.2) holds trivially when $r = 0$. It follows that ϕ is a homomorphism from $A[T]$ into $B[T]$ as modules over $k[T]$ under these conditions. Conversely, if ϕ is a homomorphism from $A[T]$ into $B[T]$ as modules over $k[T]$, then ϕ is a homomorphism from $A[T]$ into $B[T]$ as modules over k that satisfies (4.8.1).

Let ϕ be a homomorphism from $A[T]$ into $B[T]$ as modules over $k[T]$ again. It is easy to see that ϕ is uniquely determined on $A[T]$ by its restriction to A, considered as a submodule of $A[T]$ as a module over k, as in Section 4.3. Remember that every homomorphism from A into $B[T]$, as modules over k, can be extended to a homomorphism from $A[T]$ into $B[T]$ as modules over $k[T]$, as in Sections 4.4 and 4.6. This gives a natural isomorphism between $\mathrm{Hom}_k(A, B[T])$ and $\mathrm{Hom}_{k[T]}(A[T], B[T])$, as modules over k.

In fact, $\mathrm{Hom}_k(A, B[T])$ may be considered as a module over $k[T]$. More precisely, $\mathrm{Hom}_k(A, B[T])$ is a submodule of the space of all $B[T]$-valued functions on A, as a module over $k[T]$. The isomorphism between $\mathrm{Hom}_k(A, B[T])$ and $\mathrm{Hom}_{k[T]}(A[T], B[T])$ mentioned in the preceding paragraph is linear over $k[T]$.

Now let ϕ be a homomorphism from $A[[T]]$ into $B[[T]]$, as modules over k, that satisfies (4.8.1) for every $f(T) \in A[[T]]$. This implies that (4.8.2) holds for every $f(T) \in A[[T]]$ and nonnegative integer r, as before. If $f(T) \in A[[T]]$ vanishes to order n for some nonnegative integer n, then we get that $\phi(f(T))$ vanishes to order n as well, by expressing $f(T)$ as an element of $A[[T]]$ times T^{n+1}. Using this, one can check that ϕ is a homomorphism from $A[[T]]$ into $B[[T]]$, as modules over $k[[T]]$. Conversely, if ϕ is a homomorphism from $A[[T]]$ into $B[[T]]$ as modules over $k[[T]]$, then ϕ is a homomorphism from $A[[T]]$ into $B[[T]]$ as modules over $k[T]$, and hence ϕ is a homomorphism from $A[[T]]$ into $B[[T]]$ as modules over k that satisfies (4.8.1) for every $f(T) \in A[[T]]$.

Let ϕ be a homomorphism from $A[[T]]$ into $B[[T]]$ as modules over k that satisfies (4.8.1) for every $f(T) \in A[[T]]$ again. If $f(T) = \sum_{l=0}^{\infty} f_l\, T^l \in A[[T]]$ and j is a nonnegative integer, then

$$\phi\Big(\sum_{l=j+1}^{\infty} f_l\, T^l\Big) \tag{4.8.3}$$

vanishes to order j, as before. This implies that the total coefficient of T^j in $\phi(f(T))$ is the same as for

$$\phi\Big(\sum_{l=0}^{j} f_l\, T^l\Big) = \sum_{l=0}^{j} \phi(f_l)\, T^l. \tag{4.8.4}$$

It follows that ϕ is uniquely determined on $A[[T]]$ by its restriction to A, considered as a submodule of $A[[T]]$ as a module over k. We have also seen that every homomorphism from A into $B[[T]]$, as modules over k, can be extended to a homomorphism from $A[[T]]$ into $B[[T]]$ as modules over $k[[T]]$, as in Sections 4.4 and 4.6.

This gives a natural isomorphism between $\mathrm{Hom}_k(A, B[[T]])$ and

$$\mathrm{Hom}_{k[[T]]}(A[[T]], B[[T]]), \tag{4.8.5}$$

as modules over k. We may also consider $\mathrm{Hom}_k(A, B[[T]])$ as a module over $k[[T]]$, because it is a submodule of the space of all $B[[T]]$-valued functions on A, as a module over $k[[T]]$. It is easy to see that the isomorphism between $\mathrm{Hom}_k(A, B[[T]])$ and (4.8.5) is linear over $k[[T]]$.

Let C be another module over k, and let β be a mapping from $A[T] \times B[T]$ into $C[T]$. If β is bilinear over k and

$$\beta(f(T)\,T, g(T)) = \beta(f(T), g(T)\,T) = \beta(f(T), g(T))\,T \tag{4.8.6}$$

for every $f(T) \in A[T]$ and $g(T) \in B[T]$, then

$$\beta(f(T)\,T^r, g(T)\,T^m) = \beta(f(T), g(T))\,T^{r+m} \tag{4.8.7}$$

for all $f(T) \in A[T]$, $g(T) \in B[T]$, and nonnegative integers r, m, and hence β is bilinear over $k[T]$. Conversely, if β is bilinear over $k[T]$, then β is bilinear over k and satisfies (4.8.6). It is easy to see that β is uniquely determined on $A[T] \times B[T]$ by its restriction to $A \times B$ in this situation. We have seen that every mapping from $A \times B$ into $C[T]$ that is bilinear over k can be extended to a mapping from $A[T] \times B[T]$ into $C[T]$ that is bilinear over $k[T]$, as in Sections 4.5 and 4.6.

Let β be a mapping from $A[[T]] \times B[[T]]$ into $C[[T]]$. Suppose that β is bilinear over k and satisfies (4.8.6) for every $f(T) \in A[[T]]$ and $g(T) \in B[[T]]$, which implies that (4.8.7) holds for all $f(T) \in A[[T]]$, $g(T) \in B[[T]]$, and nonnegative integers r, m. If $f(T) \in A[[T]]$, $g(T) \in B[[T]]$ vanish to orders r_1, r_2 for some nonnegative integers r_1, r_2, respectively, then it follows that $\beta(f(T), g(T))$ vanishes to order $r_1 + r_2$. One can use this to verify that β is bilinear over $k[[T]]$. Conversely, if β is bilinear over $k[[T]]$, then β is bilinear over $k[T]$, and hence β is bilinear over k and satisfies (4.8.6) for every $f(T) \in A[[T]]$ and $g(T) \in B[[T]]$.

Suppose that β is bilinear over k and satisfies (4.8.6) for every $f(T) \in A[[T]]$ and $g(T) \in B[[T]]$ again. Let $f(T) = \sum_{j=0}^\infty f_j\,T^j \in A[[T]]$, and $g(T) = \sum_{l=0}^\infty g_l\,T^l \in B[[T]]$ be given. If r is any nonnegative integer, then the total coefficient of T^r in $\beta(f(T), g(T))$ is the same as for

$$\beta\Big(\sum_{j=0}^r f_j\,T^j, \sum_{l=0}^r g_l\,T^l\Big). \tag{4.8.8}$$

This implies that β is uniquely determined on $A[[T]] \times B[[T]]$ by its restriction to $A \times B$. We have seen that every mapping from $A \times B$ into $C[[T]]$ that is bilinear over k can be extended to a mapping from $A[[T]] \times B[[T]]$ into $C[[T]]$ that is bilinear over $k[[T]]$, as in Sections 4.5 and 4.6.

4.9 Formal power series and homomorphisms

Let k be a commutative ring with a multiplicative identity element again, let A, B be modules over k, and let T be an indeterminate. Remember that the space $\mathrm{Hom}_k(A, B)$ of module homomorphisms from A into B is a module over k with respect to pointwise addition and scalar multiplication, as in Section 2.1. Thus the corresponding spaces $(\mathrm{Hom}_k(A,B))[T]$ and $(\mathrm{Hom}_k(A,B))[[T]]$ of formal polynomials and power series in T with coefficients in $\mathrm{Hom}_k(A,B)$ can be defined as in Section 4.3. More precisely, $(\mathrm{Hom}_k(A,B))[T]$ and $(\mathrm{Hom}_k(A,B))[[T]]$ may be considered as modules over $k[T]$ and $k[[T]]$, respectively, as in Section 4.6. Let us see how elements of these modules are related to homomorphisms from A into $B[T]$ and $B[[T]]$, respectively.

Let

$$\phi(T) = \sum_{j=0}^{\infty} \phi_j \, T^j \tag{4.9.1}$$

be a formal power series in T with coefficients in $\mathrm{Hom}_k(A,B)$, so that ϕ_j is a homomorphism from A into B for every $j \ge 0$. If $a \in A$, then

$$(\phi(T))(a) = \sum_{j=0}^{\infty} \phi_j(a) \, T^j \tag{4.9.2}$$

defines a formal power series in T with coefficients in B, and the mapping from $a \in A$ to (4.9.2) is a homomorphism from A into $B[[T]]$, as modules over k. Conversely, every homomorphism from A into $B[[T]]$ as modules over k corresponds to a sequence $\{\phi_j\}_{j=0}^{\infty}$ of homomorphisms from A into B in this way, and hence to an element of $(\mathrm{Hom}_k(A,B))[[T]]$. This defines a natural isomorphism between $\mathrm{Hom}_k(A, B[[T]])$ and $(\mathrm{Hom}_k(A,B))[[T]]$, as modules over k. This isomorphism is linear over $k[[T]]$ as well, where $\mathrm{Hom}_k(A, B[[T]])$ is considered as a module over $k[[T]]$, as in the previous section.

Similarly, if

$$\phi(T) = \sum_{j=0}^{n} \phi_j \, T^j \tag{4.9.3}$$

is a formal polynomial in T with coefficients in $\mathrm{Hom}_k(A,B)$, then

$$(\phi(T))(a) = \sum_{j=0}^{n} \phi_j(a) \, T^j \tag{4.9.4}$$

is a formal polynomial in T with coefficients in B for every $a \in A$, and the mapping from $a \in A$ to (4.9.4) is a homomorphism from A into $B[T]$, as modules over k. In the other direction, a homomorphism from A into $B[T]$ as modules over k may be considered as a homomorphism from A into $B[[T]]$, and corresponds to a sequence $\{\phi_j\}_{j=0}^{\infty}$ of homomorphisms from A into B as in (4.9.2). The condition that this mapping sends A into $B[T]$ means that for each $a \in A$, we have that $\phi_j(a) = 0$ for all but finitely many j. In particular, this holds when $\phi_j = 0$ for all but finitely many j, as mappings from A into B. If for every $a \in A$ we have that $\phi_j(a) = 0$ for all but finitely many j, and if A is finitely generated as a module over k, then $\phi_j = 0$ for all but finitely many j.

Consider the mapping from (4.9.3) to (4.9.4), as a module homomorphism from A into $B[T]$. This defines a natural homomorphism from $(\mathrm{Hom}_k(A,B))[T]$

into $\mathrm{Hom}_k(A, B[T])$, as modules over k. It is easy to see that this mapping is injective. This mapping is also linear over $k[T]$, where $\mathrm{Hom}_k(A, B[T])$ is considered as a module over $k[T]$, as in the previous section. If A is finitely generated as a module over k, then this mapping is surjective, as in the preceding paragraph.

4.10 Extensions and compositions

Let us continue with the same notation and hypotheses as in the preceding section. Let $a(T) = \sum_{m=0}^{\infty} a_m\, T^m$ be a formal power series in T with coefficients in A. If $\phi(T)$ is a formal power series in T with coefficients in $\mathrm{Hom}_k(A, B)$ as in (4.9.1), then

$$(\phi(T))(a_m) = \sum_{j=0}^{\infty} \phi_j(a_m)\, T^j \tag{4.10.1}$$

defines a formal power series in T with coefficients in B for every nonnegative integer m, as in (4.9.2). Using this, we can define

$$(\phi(T))(a(T)) = \sum_{m=0}^{\infty} (\phi(T))(a_m)\, T^m \tag{4.10.2}$$

as a formal power series in T with coefficients in B, as in Section 4.4. This corresponds to extending the homomorphism from A into $B[[T]]$ associated to $\phi(T)$ to a homomorphism from $A[[T]]$ into $B[[T]]$, as modules over $k[[T]]$, as before. Of course, if $a(T)$ and $\phi(T)$ are formal polynomials in T with coefficients in A and $\mathrm{Hom}_k(A, B)$, respectively, then (4.10.1) is a formal polynomial in T with coefficients in B for each $m \geq 0$, and (4.10.2) is a formal polynomial in T with coefficients in B too. This corresponds to extending the homomorphism from A into $B[T]$ associated to $\phi(T)$ to a homomorphism from $A[T]$ into $B[T]$, as modules over $k[T]$.

Alternatively, put

$$E(\phi, a) = \phi(a) \tag{4.10.3}$$

for every $\phi \in \mathrm{Hom}_k(A, B)$ and $a \in A$, which is the natural evaluation mapping

$$\text{from} \quad \mathrm{Hom}_k(A, B) \times A \quad \text{into} \quad B. \tag{4.10.4}$$

This mapping is bilinear over k, and can be extended to a mapping

$$\text{from} \quad (\mathrm{Hom}_k(A, B))[[T]] \times A[[T]] \quad \text{into} \quad B[[T]], \tag{4.10.5}$$

as in Section 4.5. More precisely, let $\phi(T) \in (\mathrm{Hom}_k(A, B))[[T]]$ and $a(T)$ in $A[[T]]$ be given as before, and put

$$E_n(\phi(T), a(T)) = \sum_{j=0}^{n} \phi_j(a_{n-j}) \tag{4.10.6}$$

for each nonnegative integer n. This is an element of B for every $n \geq 0$, so that

$$E(\phi(T), a(T)) = \sum_{n=0}^{\infty} E_n(\phi(T), a(T))\, T^n \tag{4.10.7}$$

is an element of $B[[T]]$. It is easy to see that this is the same as (4.10.2). If $\phi(T) \in (\mathrm{Hom}_k(A, B))[T]$ and $a(T) \in A[T]$, then (4.10.6) is equal to 0 for all but finitely many $n \geq 0$, so that (4.10.6) is an element of $B[T]$. This corresponds to extending (4.10.3) to a mapping

$$\text{from} \quad (\mathrm{Hom}_k(A, B))[T] \times A[T] \quad \text{into} \quad B[T], \tag{4.10.8}$$

as before.

Let C be another module over k, let $\phi(T)$ be a formal power series in T with coefficients in $\mathrm{Hom}_k(A, B)$ as in (4.9.1), and let

$$\psi(T) = \sum_{l=0}^{\infty} \psi_l\, T^l \tag{4.10.9}$$

be a formal power series in T with coefficients in $\mathrm{Hom}_k(B, C)$. Note that the composition $\psi_l \circ \phi_j$ of ϕ_j and ψ_l defines a module homomorphism from A into C for all $j, l \geq 0$. Thus

$$(\psi(T) \circ \phi(T))_n = \sum_{l=0}^{n} \psi_l \circ \phi_{n-l} \tag{4.10.10}$$

is an element of $\mathrm{Hom}_k(A, C)$ for every nonnegative integer n. Put

$$\psi(T) \circ \phi(T) = \sum_{n=0}^{\infty} (\psi(T) \circ \phi(T))_n\, T^n, \tag{4.10.11}$$

which defines a formal power series in T with coefficients in $\mathrm{Hom}_k(A, C)$. If $\phi(T)$ and $\psi(T)$ are formal polynomials in T, then (4.10.10) is equal to 0 for all but finitely many $n \geq 0$, so that (4.10.11) is a formal polynomial in T as well.

The composition of module homomorphisms from A into B and from B into C defines a mapping

$$\text{from} \quad \mathrm{Hom}_k(A, B) \times \mathrm{Hom}_k(B, C) \quad \text{into} \quad \mathrm{Hom}_k(A, C) \tag{4.10.12}$$

that is bilinear over k. The definition of (4.10.11) corresponds to the extension of this bilinear mapping to mappings

$$\begin{aligned} &\text{from} \quad (\mathrm{Hom}_k(A, B))[[T]] \times (\mathrm{Hom}_k(B, C))[[T]] \\ &\text{into} \quad (\mathrm{Hom}_k(A, C))[[T]] \end{aligned} \tag{4.10.13}$$

and

$$\begin{aligned} &\text{from} \quad (\mathrm{Hom}_k(A, B))[T] \times (\mathrm{Hom}_k(B, C))[T] \\ &\text{into} \quad (\mathrm{Hom}_k(A, C))[T], \end{aligned} \tag{4.10.14}$$

as in Section 4.5.

As before, $\phi(T) \in (\mathrm{Hom}_k(A, B))[[T]]$ corresponds to a homomorphism from A into $B[[T]]$ as modules over k, which can be extended to a homomorphism from $A[[T]]$ into $B[[T]]$ as modules over $k[[T]]$. Similarly, $\psi(T)$ corresponds to a homomorphism from $B[[T]]$ into $C[[T]]$ as modules over $k[[T]]$, and (4.10.11) corresponds to a homomorphism from $A[[T]]$ into $C[[T]]$ as modules over $k[[T]]$. One can check that the homomorphism corresponding to (4.10.11) is the same as the composition of the homomorphisms corresponding to $\phi(T)$ and $\psi(T)$. If $\phi(T) \in (\mathrm{Hom}_k(A, B))[T]$ and $\psi(T) \in (\mathrm{Hom}_k(B, C))[T]$, then (4.10.11) is an element of $(\mathrm{Hom}_k(A, C))[T]$, as before. In this case, (4.10.11) corresponds to a homomorphism from $A[T]$ into $C[T]$, as modules over $k[T]$, which is the composition of the homomorphisms from $A[T]$ into $B[T]$ and from $B[T]$ into $C[T]$ corresponding to $\phi(T)$ and $\psi(T)$, respectively.

4.11 Two-step extensions

Let k be a commutative ring with a multiplicative identity element, let A, B, C be modules over k, and let T be an indeterminate. If β is a mapping from $A \times B$ into $C[[T]]$ that is bilinear over k, then β can be extended to a mapping from $A[[T]] \times B[[T]]$ into $C[[T]]$ that is bilinear over $k[[T]]$, as in Sections 4.5 and 4.6. One can also look at this in terms of extending module homomorphisms, as in Sections 4.4 and 4.6, in two steps. More precisely, if $a \in A$, then $\beta(a, b)$ defines a mapping from B into $C[[T]]$, as a function of b, that is linear over k. This can be extended to a mapping from $B[[T]]$ into $C[[T]]$ that is linear over $k[[T]]$, as before. If $b(T) \in B[[T]]$, then we can use the extension just mentioned to get $\beta(a, b(T))$ as a function of $a \in A$ with values in $C[[T]]$ that is linear over k. This can be extended to a mapping from $A[[T]]$ into $C[[T]]$ that is linear over $k[[T]]$, which extends β to a mapping from $A[[T]] \times B[[T]]$ into $C[[T]]$ that is bilinear over $k[[T]]$. Similarly, if β is a mapping from $A \times B$ into $C[T]$ that is bilinear over k, then β can be extended to a mapping from $A[T] \times B[T]$ into $C[T]$ that is bilinear over $k[T]$ in two steps.

Let β be a mapping from $A \times B$ into $C[[T]]$ that is bilinear over k again, and put

$$\rho_a(b) = \beta(a, b) \tag{4.11.1}$$

for every $a \in A$ and $b \in B$. If $a \in A$, then ρ_a defines a mapping from B into $C[[T]]$ that is linear over k, which is to say that $\rho_a \in \mathrm{Hom}_k(B, C[[T]])$. Thus

$$a \mapsto \rho_a \tag{4.11.2}$$

defines a mapping from A into $\mathrm{Hom}_k(B, C[[T]])$, which is linear over k. Remember that there are natural isomorphisms between $\mathrm{Hom}_k(B, C[[T]])$ and each of $\mathrm{Hom}_{k[[T]]}(B[[T]], C[[T]])$ and $(\mathrm{Hom}_k(B, C))[[T]]$, as modules over $k[[T]]$, as in Sections 4.8 and 4.9. The isomorphism with $\mathrm{Hom}_{k[[T]]}(B[[T]], C[[T]])$ gives the extension of ρ_a to $B[[T]]$, and the isomorphism with $(\mathrm{Hom}_k(B, C))[[T]]$ can be used to extend (4.11.2) to $A[[T]]$.

Now let β be a mapping from $A \times B$ into $C[T]$ that is bilinear over k. If $a \in A$, then (4.11.1) defines ρ_a as a mapping from B into $C[T]$ that is linear over k, and hence an element of $\mathrm{Hom}_k(B, C[T])$. Similarly, (4.11.2) defines a mapping from A into $\mathrm{Hom}_k(B, C[T])$ that is linear over k. There is a natural isomorphism between $\mathrm{Hom}_k(B, C[T])$ and $\mathrm{Hom}_{k[T]}(B[T], C[T])$, as modules over $k[T]$, as in Section 4.8. This permits one to identify ρ_a with a homomorphism from $B[T]$ into $C[T]$, as modules over $k[T]$.

As in Section 4.9, there is a natural injection from $(\mathrm{Hom}_k(B, C))[T]$ into $\mathrm{Hom}_k(B, C[T])$ that is linear over $k[T]$. If (4.11.2) corresponds to a mapping from A into $(\mathrm{Hom}_k(B, C))[T]$ that is linear over k, then this mapping can be extended to one from $A[T]$ into $(\mathrm{Hom}_k(B, C))[T]$ that is linear over $k[T]$ in the usual way. Otherwise, (4.11.2) can still be extended to a mapping from $A[T]$ into $\mathrm{Hom}_k(B, C[T])$ or equivalently $\mathrm{Hom}_{k[T]}(B[T], C[T])$ that is linear over $k[T]$. This basically just uses the fact that $\mathrm{Hom}_k(B, C[T])$ or equivalently $\mathrm{Hom}_{k[T]}(B[T], C[T])$ is a module over $k[T]$. Of course, one can also look at this in terms of extending (4.11.1) in a for b fixed, as mentioned at the beginning of the section.

4.12 Extending algebra homomorphisms

Let k be a commutative ring with a multiplicative identity element, let T be an indeterminate, and let A, B be algebras over k in the strict sense. As in Section 4.6, multiplication on A and B can be extended to $A[[T]]$ and $B[[T]]$, respectively, so that they become algebras over $k[[T]]$ in the strict sense. In particular, $A[[T]]$ and $B[[T]]$ may be considered as algebras over k.

Let ϕ be a homomorphism from A into $B[[T]]$, as modules over k. Thus ϕ can be expressed as

$$\phi(a) = \sum_{j=0}^{\infty} \phi_j(a)\, T^j \tag{4.12.1}$$

for each $a \in A$, where ϕ_j is a homomorphism from A into B, as modules over k, for every nonnegative integer j. In order for ϕ to be a homomorphism from A into $B[[T]]$, as algebras over k, we need to have that

$$\phi(a\, a') = \phi(a)\, \phi(a') \tag{4.12.2}$$

for every $a, a' \in A$. Of course,

$$\phi(a\, a') = \sum_{n=0}^{\infty} \phi_n(a\, a')\, T^n, \tag{4.12.3}$$

and

$$\begin{aligned} \phi(a)\, \phi(a') &= \Big(\sum_{j=0}^{\infty} \phi_j(a)\, T^j\Big) \Big(\sum_{l=0}^{\infty} \phi_l(a')\, T^l\Big) \\ &= \sum_{n=0}^{\infty} \Big(\sum_{j=0}^{n} \phi_j(a)\, \phi_{n-j}(a')\Big) T^n. \end{aligned} \tag{4.12.4}$$

It follows that (4.12.2) holds if and only if

$$\phi_n(a\,a') = \sum_{j=0}^{n} \phi_j(a)\,\phi_{n-j}(a') \tag{4.12.5}$$

for every nonnegative integer n.

As in Section 4.4, we can extend ϕ to a module homomorphism from $A[[T]]$ into $B[[T]]$ by putting

$$\phi(f(T)) = \sum_{j=0}^{\infty} \phi(f_j)\,T^j \tag{4.12.6}$$

for every $f(T) = \sum_{j=0}^{\infty} f_j\,T^j \in A[[T]]$. If $g(T) = \sum_{l=0}^{\infty} g_l\,T^l$ is another element of $A[[T]]$, then $h(T) = f(T)\,g(T)$ is defined by putting $h(T) = \sum_{n=0}^{\infty} h_n\,T^n$, where

$$h_n = \sum_{j=0}^{n} f_j\,g_{n-j} \tag{4.12.7}$$

for every $n \geq 0$, as in Section 4.6. Thus

$$\phi(f(T)\,g(T)) = \phi(h(T)) = \sum_{n=0}^{\infty} \phi(h_n)\,T^n, \tag{4.12.8}$$

where the sum on the right is defined as an element of $B[[T]]$ as in Section 4.4 again. If ϕ is an algebra homomorphism from A into $B[[T]]$, then

$$\phi(h_n) = \sum_{j=0}^{n} \phi(f_j\,g_{n-j}) = \sum_{j=0}^{n} \phi(f_j)\,\phi(g_{n-j}) \tag{4.12.9}$$

for each $n \geq 0$. This implies that

$$\phi(f(T)\,g(T)) = \sum_{n=0}^{\infty} \Big(\sum_{j=0}^{n} \phi(f_j)\,\phi(g_{n-j})\Big)\,T^n = \phi(f(T))\,\phi(g(T)). \tag{4.12.10}$$

More precisely, this follows from the definition of multiplication on $B[[T]]$ when ϕ maps A into B. Otherwise, if $\phi(f_j)$ and $\phi(g_l)$ are elements of $B[[T]]$, then the second step in (4.12.10) can be obtained as in (4.5.6). This shows that the extension of ϕ to a module homomorphism from $A[[T]]$ into $B[[T]]$ defined in (4.12.6) is an algebra homomorphism in this case.

Similarly, multiplication on A and B can be extended to $A[T]$ and $B[T]$, respectively, so that they become algebras in the strict sense over $k[T]$, as in Section 4.6. If ϕ is a homomorphism from A into $B[T]$, as modules over k, then we can extend ϕ to a module homomorphism from $A[T]$ into $B[T]$ as in (4.12.6). If ϕ is an algebra homomorphism from A into $B[T]$, then this extension is an algebra homomorphism from $A[T]$ into $B[T]$, as before. Of course, there are analogous statements for opposite algebra homomorphisms.

4.13 Some remarks about commutators

Let k be a commutative ring with a multiplicative identity element, and let A be an associative algebra over k with a multiplicative identity element e. Also let T be an indeterminate, and let us identify e with the corresponding formal power series in T with coefficients in A in the usual way, which is the multiplicative identity element in $A[[T]]$. Suppose that $a(T) = \sum_{j=0}^\infty a_j\,T^j$ and $b(T) = \sum_{j=0}^\infty b_j\,T^j$ are elements of $A[[T]]$ with $a_0 = b_0 = e$. Note that $a(T)$ and $b(T)$ are invertible in $A[[T]]$, as in Section 4.7.

Put $\alpha(T) = a(T) - e = \sum_{j=1}^\infty a_j\,T^j$ and $\beta(T) = b(T) - e = \sum_{j=1}^\infty b_j\,T^j$, so that $a(T) = e + \alpha(T)$ and $b(T) = e + \beta(T)$. Thus

$$a(T)\,b(T) = e + \alpha(T) + \beta(T) + \alpha(T)\,\beta(T). \tag{4.13.1}$$

As in Section 4.7,

$$a(T)^{-1} = \sum_{l=0}^\infty (-\alpha(T))^l = e + \sum_{l=1}^\infty (-\alpha(T))^l \tag{4.13.2}$$

and

$$b(T)^{-1} = \sum_{l=0}^\infty (-\beta(T))^l = e + \sum_{l=1}^\infty (-\beta(T))^l. \tag{4.13.3}$$

If $n \in \mathbf{Z}_+$, then we let $O(T^n)$ refer to any element of $A[[T]]$ that vanishes to order $n-1$, which means that it can be expressed as an element of $A[[T]]$ times T^n. Observe that

$$a(T)\,b(T)\,a(T)^{-1}\,b(T)^{-1} = e + O(T), \tag{4.13.4}$$

because $a(T), b(T), a(T)^{-1}, b(T)^{-1} = e + O(T)$. More precisely,

$$a(T)\,b(T)\,a(T)^{-1}\,b(T)^{-1} = e + O(T^2), \tag{4.13.5}$$

because

$$a(T) = e + a_1\,T + O(T^2), \quad b(T) = e + b_1\,T + O(T^2), \tag{4.13.6}$$

and

$$a(T)^{-1} = e - a_1\,T + O(T^2), \quad b(T)^{-1} = e - b_1\,T + O(T^2). \tag{4.13.7}$$

We also have that

$$a(T) = e + a_1\,T + a_2\,T^2 + O(T^3), \quad b(T) = e + b_1\,T + b_2\,T^2 + O(T^3), \tag{4.13.8}$$

and

$$a(T)\,b(T) = e + a_1\,T + b_1\,T + a_2\,T^2 + b_2\,T^2 + a_1\,b_1\,T^2 + O(T^3). \tag{4.13.9}$$

Using (4.13.2), we get that

$$\begin{aligned} a(T)^{-1} &= e - \alpha(T) + \alpha(T)^2 + O(T^3) \\ &= e - a_1\,T - a_2\,T^2 + a_1^2\,T^2 + O(T^3). \end{aligned} \tag{4.13.10}$$

Similarly,

$$b(T)^{-1} = e - b_1\,T - b_2\,T^2 + b_1^2\,T^2 + O(T^3). \tag{4.13.11}$$

It follows that

$$\begin{aligned} a(T)^{-1}\,b(T)^{-1} &= e - a_1\,T - b_1\,T - a_2\,T^2 - b_2\,T^2 \\ &\quad + a_1^2\,T^2 + b_2^2\,T^2 + a_1\,b_1\,T^2 + O(T^3). \end{aligned} \tag{4.13.12}$$

Combining (4.13.9) and (4.13.12), it is not difficult to verify that

$$\begin{aligned} a(T)\,b(T)\,a(T)^{-1}\,b(T)^{-1} &= e + a_1\,b_1\,T^2 - b_1\,a_1\,T^2 + O(T^3) \\ &= e + \alpha(T)\,\beta(T) - \beta(T)\,\alpha(T) + O(T^3). \end{aligned} \tag{4.13.13}$$

4.14 Formal power series and involutions

Let k be a commutative ring with a multiplicative identity element, and let T be an indeterminate. Also let A be an algebra over k in the strict sense, and let $x \mapsto x^*$ be an opposite algebra automorphism on A. If $k = \mathbf{C}$, then we may wish to consider opposite algebra automorphisms that are conjugate-linear, as usual. If $a(T) = \sum_{j=0}^{\infty} a_j\,T^j \in A[[T]]$, then

$$a(T)^* = \sum_{j=0}^{\infty} a_j^*\,T^j \tag{4.14.1}$$

defines an element of $A[[T]]$, which is in $A[T]$ when $a(T) \in A[T]$. Of course,

$$a(T) \mapsto a(T)^* \tag{4.14.2}$$

defines an opposite algebra automorphism on $A[[T]]$. Note that $a(T)$ is self-adjoint with respect to (4.14.2) if and only if a_j is self-adjoint for every $j \geq 0$, and similarly $a(T)$ is anti-self-adjoint with respect to (4.14.2) if and only if a_j is anti-self-adjoint for every $j \geq 0$. If $x \mapsto x^*$ is an involution on A, then (4.14.2) is an involution on $A[[T]]$.

Suppose now that A is an associative algebra over k with a multiplicative identity element e. Remember that $e^* = e$, as in Section 2.6. Let y be an element of A, and put $y_0 = y - e$, so that $y = e + y_0$, $y^* = e + y_0^*$, and

$$y^*\,y = (e + y_0^*)\,(e + y_0) = e + y_0 + y_0^* + y_0^*\,y_0. \tag{4.14.3}$$

Suppose that $y_1, y_2 \in A$ satisfy

$$y_0 = y_1 + y_2, \quad y_1^* = y_1, \quad y_2^* = -y_2, \quad \text{and} \quad y_1\,y_2 = y_2\,y_1. \tag{4.14.4}$$

Under these conditions, $y_0^* = y_1 - y_2$, and

$$y^*\,y = e + 2 \cdot y_1 + (y_1 - y_2)\,(y_1 + y_2) = e + 2 \cdot y_1 + y_1^2 - y_2^2. \tag{4.14.5}$$

Let $a(T) = \sum_{j=0}^{\infty} a_j\, T^j$ be an element of $A[[T]]$ with $a_0 = e$, and put $\alpha(T) = a(T) - e$. As in (4.14.3), we have that

$$a(T)^*\, a(T) = e + \alpha(T) + \alpha(T)^* + \alpha(T)^*\, \alpha(T). \tag{4.14.6}$$

In particular, a necessary condition for

$$a(T)^*\, a(T) = e \tag{4.14.7}$$

to hold is that

$$a_1^* = -a_1. \tag{4.14.8}$$

More precisely, (4.14.8) is equivalent to $a(T)^*\, a(T) = e + O(T^2)$, in the notation of the previous section. Of course, (4.14.7) is the same as saying that

$$a(T)^* = a(T)^{-1}, \tag{4.14.9}$$

which also implies that $a(T)$ commutes with $a(T)^*$.

Suppose that $\beta(T) = \sum_{j=0}^{\infty} \beta_j\, T^j, \gamma(T) = \sum_{j=0}^{\infty} \gamma_j\, T^j \in A[[T]]$ satisfy $\beta_0 = \gamma_0 = 0$, $\alpha(T) = \beta(T) + \gamma(T)$,

$$\beta(T)^* = \beta(T), \quad \gamma(T)^* = -\gamma(T), \quad \text{and} \quad \beta(T)\, \gamma(T) = \gamma(T)\, \beta(T). \tag{4.14.10}$$

Under these conditions, we have that

$$a(T)^*\, a(T) = e + 2 \cdot \beta(T) + \beta(T)^2 - \gamma(T)^2, \tag{4.14.11}$$

as in (4.14.5). In this situation, (4.14.7) holds exactly when

$$2 \cdot \beta(T) = -\beta(T)^2 + \gamma(T)^2. \tag{4.14.12}$$

Let us suppose from now on in this section that $1+1$ has a multiplicative inverse in k. It is easy to see that $\beta(T)$ is uniquely determined by $\gamma(T)$ and (4.14.12).

More precisely, if $\gamma(T) \in A[[T]]$ satisfies $\gamma_0 = 0$, then there is a unique $\beta(T) \in A[[T]]$ that satisfies $\beta_0 = 0$ and (4.14.12). Indeed, for each $j \in \mathbf{Z}_+$, one can use (4.14.12) to get β_j from β_l with $l < j$ and the coefficients of $\gamma(T)$. One can in fact approximate β in terms of polynomials in $\gamma(T)^2$ with coefficients in k, using (4.14.12). This implies that $\beta(T)$ commutes with $\gamma(T)$, which could also be verified more directly. If $\gamma(T)^* = -\gamma(T)$, as in (4.14.10), then

$$(\gamma(T)^2)^* = (\gamma(T)^*)^2 = (-\gamma(T))^2 = \gamma(T)^2. \tag{4.14.13}$$

In this case, one can check that $\beta(T)^* = \beta(T)$. If we take $\alpha(T) = \beta(T) + \gamma(T)$ and $a(T) = e + \alpha(T)$, as before, then (4.14.11) holds, which implies (4.14.7), by (4.14.12).

Chapter 5

Some related notions

5.1 Adjoining nilpotent elements

Let k be a commutative ring with a multiplicative identity element, and let A be a module over k. If $n \in \mathbf{Z}_+$, then we would like to define $A[\epsilon_n]$ as a module over k, where ϵ_n is an additional element that is considered to satisfy

$$\epsilon_n^{n+1} = 0. \tag{5.1.1}$$

The elements of $A[\epsilon_n]$ may be expressed as formal sums of the form

$$a = a_0 + a_1\,\epsilon_n + \cdots + a_n\,\epsilon_n^n, \tag{5.1.2}$$

where $a_0, a_1, \ldots, a_n \in A$. Addition and scalar multiplication on $A[\epsilon_n]$ are defined termwise, so that $A[\epsilon_n]$ becomes a module over k that contains A as a submodule. More precisely, $A[\epsilon_n]$ is isomorphic to the direct sum of $n+1$ copies of A, as a module over k. If $a \in A[\epsilon_n]$ is as in (5.1.2), then

$$a\,\epsilon_n = a_0\,\epsilon_n + \cdots + a_{n-1}\,\epsilon_n^n \tag{5.1.3}$$

defines an element of $A[\epsilon_n]$ as well. This defines

$$a \mapsto a\,\epsilon_n \tag{5.1.4}$$

as a module homomorphism from $A[\epsilon_n]$ into itself. It is sometimes convenient to consider the a_0 term on the right side of (5.1.2) as being $a_0\,\epsilon_n^0$, so that multiplication by ϵ_n^0 corresponds to the identity mapping on $A[\epsilon_n]$.

Let B be another module over k, so that $B[\epsilon_n]$ can be defined as in the previous paragraph. Also let ϕ be a homomorphism from A into $B[\epsilon_n]$, as modules over k. If $a \in A[\epsilon_n]$ is as in (5.1.2), then

$$\phi(a) = \phi(a_0) + \phi(a_1)\,\epsilon_n + \cdots + \phi(a_n)\,\epsilon_n^n \tag{5.1.5}$$

defines an element of $B[\epsilon_n]$. This defines an extension of ϕ to a homomorphism from $A[\epsilon_n]$ into $B[\epsilon_n]$, as modules over k. It is easy to see that

$$\phi(a\,\epsilon_n) = \phi(a)\,\epsilon_n \tag{5.1.6}$$

for every $a \in A[\epsilon_n]$, and that this extension of ϕ to $A[\epsilon_n]$ is uniquely determined by these properties.

Let C be another module over k, so that $C[\epsilon_n]$ can be defined as before. Also let β be a mapping from $A \times B$ into $C[\epsilon_n]$ that is bilinear over k. We can extend β to a mapping from $A[\epsilon_n] \times B[\epsilon_n]$ into $C[\epsilon_n]$, as follows. Let $a \in A[\epsilon_n]$ be as in (5.1.2), and let

$$b = b_0 + b_1\,\epsilon_n + \cdots + b_n\,\epsilon_n^n \tag{5.1.7}$$

be an element of $B[\epsilon_n]$, with $b_0, b_1, \ldots, b_n \in B$. Thus

$$\beta(a, b) = \sum_{j=0}^{n} \sum_{l=0}^{n} \beta(a_j, b_l)\,\epsilon_n^{j+l} \tag{5.1.8}$$

defines an element of $C[\epsilon_n]$, which extends β to a mapping from $A[\epsilon_n] \times B[\epsilon_n]$ into $C[\epsilon_n]$ that is bilinear over k. One can check that

$$\beta(a\,\epsilon_n, b) = \beta(a, b\,\epsilon_n) = \beta(a, b)\,\epsilon_n \tag{5.1.9}$$

for every $a \in A[\epsilon_n]$ and $b \in B[\epsilon_n]$, and that this extension of β to $A[\epsilon_n] \times B[\epsilon_n]$ is uniquely determined by the properties. One can also look at this in terms of extending β in each variable separately, as in the previous paragraph.

Suppose now that $A = B$, so that we start with a mapping β from $A \times A$ into $C[\epsilon_n]$. If β is symmetric or antisymmetric on $A \times A$, then the extension of β to $A[\epsilon_n] \times A[\epsilon_n]$ into $C[\epsilon_n]$ as in the preceding paragraph has the same property. Similarly, if

$$\beta(a, a) = 0 \tag{5.1.10}$$

for every $a \in A$, then (5.1.10) holds for every $a \in A[\epsilon_n]$. To see this, let $a \in A[\epsilon_n]$ be given as in (5.1.2), so that

$$\beta(a, a) = \sum_{j=0}^{n} \sum_{l=0}^{n} \beta(a_j, a_l)\,\epsilon_n^{j+l}, \tag{5.1.11}$$

as in (5.1.8). By hypothesis, $\beta(a_j, a_j) = 0$ for each j. Remember that β is antisymmetric on $A \times A$, as in Section 2.1. This implies that

$$\beta(a_j, a_l) + \beta(a_l, a_j) = 0 \tag{5.1.12}$$

when $j \neq l$, which can be used to get that (5.1.11) is equal to 0.

5.2 Adjoining nilpotent elements to algebras

Let k be a commutative ring with a multiplicative identity element, and let A be an algebra over k in the strict sense, where multiplication of $a, b \in A$ is expressed as $a\,b$. Also let n be a positive integer, and let ϵ_n be as in the previous section, so that $A[\epsilon_n]$ can be defined as a module over k as before. If $a, b \in A[\epsilon_n]$ are as in (5.1.2) and (5.1.7), respectively, then

$$a\, b = \sum_{j=0}^{n} \sum_{l=0}^{n} a_j\, b_l\, \epsilon_n^{j+l} \tag{5.2.1}$$

defines an element of $A[\epsilon_n]$ too. This extends multiplication on A to a mapping from $A[\epsilon_n] \times A[\epsilon_n]$ into $A[\epsilon_n]$ that is bilinear over k, as in the previous section. Thus $A[\epsilon_n]$ becomes an algebra over k in the strict sense as well.

If multiplication on A is commutative, then this extension of multiplication to $A[\epsilon_n]$ is commutative too. If multiplication on A is associative, then one can verify that multiplication on $A[\epsilon_n]$ is associative as well. If A has a multiplicative identity element e, then e is also the multiplicative identity element in $A[\epsilon_n]$. We can apply this to $A = k$, to get $k[\epsilon_n]$ as a commutative associative algebra over k with a multiplicative identity element.

Let A be a module over k, so that $A[\epsilon_k]$ can be defined as a module over k as in the previous section. In fact, $A[\epsilon_n]$ may be considered as a module over $k[\epsilon_n]$. More precisely, let $a \in k[\epsilon_n]$ be as in (5.1.2), with $a_0, a_1, \ldots, a_n \in k$, and let $b \in A[\epsilon_n]$ be as in (5.1.7), with $b_0, b_1, \ldots, b_n \in A$. Under these conditions, $a\, b$ can be defined as an element of $A[\epsilon_n]$ as in (5.2.1), where $a_j\, b_l$ is defined as an element of A using scalar multiplication with respect to k. This is the same as extending scalar multiplication on A as a bilinear mapping from $k \times A$ into A to a bilinear mapping from $k[\epsilon_n] \times A[\epsilon_n]$ into $A[\epsilon_n]$, as in the previous section.

Let B be another module over k, so that $B[\epsilon_n]$ can be defined as before. It is easy to see that a mapping ϕ from $A[\epsilon_n]$ into $B[\epsilon_n]$ is linear over $k[\epsilon_n]$ if and only if ϕ is linear over k and (5.1.6) holds for every $a \in A[\epsilon_n]$. Similarly, let C be a module over k, and let $C[\epsilon_n]$ be as before. One can check that a mapping β from $A[\epsilon_n] \times B[\epsilon_n]$ into $C[\epsilon_n]$ is bilinear over $k[\epsilon_n]$ if and only if β is bilinear over k and satisfies (5.1.9) for ever $a \in A[\epsilon_n]$ and $b \in B[\epsilon_n]$. If A is an algebra over k in the strict sense, then $A[\epsilon_n]$ may be considered as an algebra over $k[\epsilon_n]$ in the strict sense.

If $(A, [\cdot,\cdot]_A)$ is a Lie algebra over k, then $[\cdot,\cdot]_A$ can be extended to $A[\epsilon_n]$ as before. More precisely, if $a, b \in A[\epsilon_n]$ are as in (5.1.2) and (5.1.7), respectively, then

$$[a, b]_{A[\epsilon_n]} = \sum_{j=0}^{n} \sum_{l=0}^{n} [a_j, b_l]_A\, \epsilon_n^{j+l} \tag{5.2.2}$$

defines an element of $A[\epsilon_n]$ as well. As in the previous section, $[a, a]_{A[\epsilon_n]} = 0$ for every $a \in A[\epsilon_n]$, because of the analogous property of $[\cdot,\cdot]_A$ on A. One can verify that (5.2.2) satisfies the Jacobi identity on $A[\epsilon_n]$, using the Jacobi identity for $[\cdot,\cdot]_A$ on A. Thus $A[\epsilon_n]$ is a Lie algebra over k with respect to (5.2.2), which may be considered as a Lie algebra over $k[\epsilon_n]$.

Let A be a module over k again, and let T be an indeterminate, so that the space $A[[T]]$ of formal power series in T with coefficients in A can be defined as in Section 4.3. If $f(T) = \sum_{j=0}^{\infty} f_j\, T^j$ is an element of $A[[T]]$, then

$$f_0 + f_1\, \epsilon_n + \cdots + f_n\, \epsilon_n^n \tag{5.2.3}$$

defines an element of $A[\epsilon]$. This defines a homomorphism from $A[[T]]$ onto $A[\epsilon_n]$, as modules over k. This homomorphism also maps the space $A[T]$ of formal polynomials in T with coefficients in A onto $A[\epsilon_n]$. Note that multiplication by T on $A[[T]]$ corresponds to multiplication by ϵ_n on $A[\epsilon_n]$ with respect to this homomorphism.

If A is an algebra over k in the strict sense, then one can check that the mapping from $f(T)$ in $A[[T]]$ to (5.2.3) defines a homomorphism from $A[[T]]$ onto $A[\epsilon_n]$ as algebras over k. In particular, we can apply this to $A = k$.

5.3 Invertibility in $A[\epsilon_n]$

Let k be a commutative ring with a multiplicative identity element, and let A be an associative algebra over k with a multiplicative identity element e. Also let n be a positive integer, and let $A[\epsilon_n]$ be as in the previous two sections. Remember that $a \in A[\epsilon_n]$ can be expressed as

(5.3.1) $$a = a_0 + a_1\,\epsilon_n + \cdots + a_n\,\epsilon_n^n,$$

where $a_0, a_1, \ldots, a_n \in A$. The mapping

(5.3.2) $$a \mapsto a_0$$

defines an algebra homomorphism from $A[\epsilon_n]$ onto A. If a is invertible in $A[\epsilon_n]$, then it follows that a_0 is invertible in A.

Note that

(5.3.3) $$(e - a) \sum_{l=0}^{n} a^l = \Big(\sum_{l=0}^{n} a^l\Big)(e - a) = e - a^{n+1}$$

for every $a \in A[\epsilon_n]$, where a^l is interpreted as being equal to e when $l = 0$, as usual. If $a_0 = 0$, then $a^{n+1} = 0$, so that (5.3.3) reduces to

(5.3.4) $$(e - a) \sum_{l=0}^{n} a^l = \Big(\sum_{l=0}^{n} a^l\Big)(e - a) = e.$$

This means that $e - a$ is invertible in $A[\epsilon_n]$, with

(5.3.5) $$(e - a)^{-1} = \sum_{l=0}^{n} a^l.$$

If

(5.3.6) $$b = b_0 + b_1\,\epsilon_n + \cdots + b_n\,\epsilon_n$$

is an element of $A[\epsilon_n]$, where b_0 is an invertible element of A, then b can be expressed as $b_0\,(e - a)$, where $a \in A[\epsilon_n]$ is as in (5.3.1), with $a_0 = 0$. It follows that b is invertible in $A[\epsilon_n]$, because $e - a$ is invertible.

Suppose now that $a, b \in A[\epsilon_n]$ are as in (5.3.1) and (5.3.6), respectively, with $a_0 = b_0 = e$. Put $\alpha = a - e$ and $\beta = b - e$, so that $a = e + \alpha$, $b = e + \beta$,

$$a\,b = e + \alpha + \beta + \alpha\,\beta, \tag{5.3.7}$$

and α, β are multiples of ϵ_n. As in the preceding paragraph, a and b are invertible elements of $A[\epsilon_n]$, with

$$a^{-1} = \sum_{l=0}^{n} (-\alpha)^l = e + \sum_{l=1}^{n} (-\alpha)^l \tag{5.3.8}$$

and

$$b^{-1} = \sum_{l=0}^{n} (-\beta)^l = e + \sum_{l=1}^{n} (-\beta)^l. \tag{5.3.9}$$

We also have that

$$\begin{aligned} a\,b\,a^{-1}\,b^{-1} &= e + a_1\,b_1\,\epsilon_n^2 - b_1\,a_1\,\epsilon_n^2 + O(\epsilon_n^3) \\ &= e + \alpha\,\beta - \beta\,\alpha + O(\epsilon_n^3), \end{aligned} \tag{5.3.10}$$

where $O(\epsilon_n^3)$ refers to any element of $A[\epsilon_n]$ that is a multiple of ϵ_n^3. This can be verified in the same way as in Section 4.13, or reduced to that situation, using the homomorphism from $A[[T]]$ onto $A[[\epsilon_n]]$ mentioned in the previous section.

If $n = 1$, then $\alpha = a_1\,\epsilon_1$, $\beta = b_1\,\epsilon_1$, and (5.3.7) reduces to

$$a\,b = e + \alpha + \beta = e + a_1\,\epsilon_1 + b_1\,\epsilon_1. \tag{5.3.11}$$

In this case, (5.3.8) and (5.3.9) reduce to

$$a^{-1} = e - \alpha = e - a_1\,\epsilon_1 \tag{5.3.12}$$

and

$$b^{-1} = e - \beta = e - b_1\,\epsilon_1. \tag{5.3.13}$$

Note that a and b commute in this situation, so that $a\,b\,a^{-1}\,b^{-1} = e$.

If $n = 2$, then $\alpha = a_1\,\epsilon_2 + a_2\,\epsilon_2^2$, $\beta = b_1\,\epsilon_2 + b_2\,\epsilon_2^2$, and (5.3.7) reduces to

$$a\,b = e + a_1\,\epsilon_2 + a_2\,\epsilon_2^2 + b_1\,\epsilon_2 + b_2\,\epsilon_2^2 + a_1\,b_1\,\epsilon_2^2. \tag{5.3.14}$$

Similarly, (5.3.10) reduces to

$$a\,b\,a^{-1}\,b^{-1} = e + a_1\,b_1\,\epsilon_2^2 - b_1\,a_1\,\epsilon_2^2. \tag{5.3.15}$$

5.4 Adjoining two nilpotent elements

Let k be a commutative ring with a multiplicative identity element, and let A be a module over k. We would like to define $A[\epsilon_1, \eta_1]$ as a module over k, where ϵ_1 and η_1 are additional elements that are considered to satisfy

$$\epsilon_1^2 = \eta_1^2 = 0, \quad \epsilon_1\,\eta_1 = \eta_1\,\epsilon_1. \tag{5.4.1}$$

The elements of $A[\epsilon_1, \eta_1]$ can be expressed as formal sums of the form

$$a = a_{0,0} + a_{1,0}\,\epsilon_1 + a_{0,1}\,\eta_1 + a_{1,1}\,\epsilon_1\,\eta_1, \tag{5.4.2}$$

where $a_{0,0}, a_{1,0}, a_{0,1}, a_{1,1} \in A$. Addition and scalar multiplication on $A[\epsilon_1, \eta_1]$ are defined termwise, so that $A[\epsilon_1, \eta_1]$ becomes a module over k, which is isomorphic to the direct sum of four copies of A. By construction, $A[\epsilon_1, \eta_1]$ contains a copy of A, and in fact $A[\epsilon_1, \eta_1]$ contains copies of $A[\epsilon_1]$ and $A[\eta_1]$, which are defined as in Section 5.1. If $a \in A[\epsilon_1, \eta_1]$ is as in (5.4.2), then

$$a\,\epsilon_1 = a_{0,0}\,\epsilon_1 + a_{0,1}\,\epsilon_1\,\eta_1, \quad a\,\eta_1 = a_{0,0}\,\eta_1 + a_{1,0}\,\epsilon_1\,\eta_1 \tag{5.4.3}$$

define elements of $A[\epsilon_1, \eta_1]$. This defines

$$a \mapsto a\,\epsilon_1, \quad a \mapsto a\,\eta_1 \tag{5.4.4}$$

as module homomorphisms from $A[\epsilon_1, \eta_1]$ into itself. One can also look at $A[\epsilon_1, \eta_1]$ in terms of adjoining ϵ_1 and η_1 separately, as before.

Let B be another module over k, and let ϕ be a homomorphism from A into $B[\epsilon_1, \eta_1]$, as modules over k, where $B[\epsilon_1, \eta_1]$ is defined as in the previous paragraph. If $a \in A[\epsilon_1, \eta_1]$ is as in (5.4.2), then

$$\phi(a) = \phi(a_{0,0}) + \phi(a_{1,0})\,\epsilon_1 + \phi(a_{0,1})\,\eta_1 + \phi(a_{1,1})\,\epsilon_1\,\eta_1 \tag{5.4.5}$$

defines an element of $B[\epsilon_1, \eta_1]$. This extends ϕ to a homomorphism from $A[\epsilon_1, \eta_1]$ into $B[\epsilon_1, \eta_1]$, as modules over k. This extension satisfies

$$\phi(a\,\epsilon_1) = \phi(a)\,\epsilon_1, \quad \phi(a\,\eta_1) = \phi(a)\,\eta_1 \tag{5.4.6}$$

for every $a \in A[\epsilon_1, \eta_1]$, and is uniquely determined by these properties.

Similarly, let C be another module over k, and let β be a mapping from $A \times B$ into $C[\epsilon_1, \eta_1]$ that is bilinear over k, where $C[\epsilon_1, \eta_1]$ is defined as before. One can extend β to a mapping from $A[\epsilon_1, \eta_1] \times B[\epsilon_1, \eta_1]$ into $C[\epsilon_1, \eta_1]$ that is bilinear over k and satisfies

$$\beta(a\,\epsilon_1, b) = \beta(a, b\,\epsilon_1) = \beta(a, b)\,\epsilon_1 \tag{5.4.7}$$

and

$$\beta(a\,\eta_1, b) = \beta(a, b\,\eta_1) = \beta(a, b)\,\eta_1 \tag{5.4.8}$$

for every $a \in A[\epsilon_1, \eta_1]$ and $b \in B[\epsilon_1, \eta_1]$.

Now let A be an algebra over k in the strict sense. Multiplication on A can be extended to a mapping from $A[\epsilon_1, \eta_1] \times A[\epsilon_1, \eta_1]$ into $A[\epsilon_1, \eta_1]$ that is bilinear over k, as in the preceding paragraph, so that $A[\epsilon_1, \eta_1]$ becomes an algebra over k in the strict sense too. If multiplication on A is commutative, then multiplication on $A[\epsilon_1, \eta_1]$ is commutative as well. If multiplication on A is associative, then one can check that multiplication on $A[\epsilon_1, \eta_1]$ is associative. If A has a multiplicative identity element e, then e is the multiplicative identity element in $A[\epsilon_1, \eta_1]$ too. One can look at $A[\epsilon_1, \eta_1]$ as an algebra in terms adjoining ϵ_1 and η_1 separately, as before. Thus these and other properties of $A[\epsilon_1, \eta_1]$ can be obtained from the remarks in Sections 5.1 and 5.2.

5.5 Invertibility in $A[\epsilon_1, \eta_1]$

Let k be a commutative ring with a multiplicative identity element, and let A be an associative algebra over k with a multiplicative identity element e. Thus $A[\epsilon_1, \eta_1]$ is an associative algebra that contains A as a subalgebra, as in the previous section, and e is the multiplicative identity element of $A[\epsilon_1, \eta_1]$. As before, $a \in A[\epsilon_1, \eta_1]$ as in (5.4.2), with $a_{0,0}, a_{1,0}, a_{0,1}, a_{1,1} \in A$. The mapping

$$a \mapsto a_{0,0} \tag{5.5.1}$$

defines an algebra homomorphism from $A[\epsilon_1, \eta_1]$ onto A. If a is invertible in $A[\epsilon_1, \eta_1]$, then $a_{0,0}$ is invertible in A.

As usual,

$$(e - a) \sum_{l=0}^{2} a^l = \Big(\sum_{l=0}^{2} a^l\Big) (e - a) = e - a^3 \tag{5.5.2}$$

for every $a \in A[\epsilon_1, \eta_1]$, where a^l is interpreted as being e when $l = 0$. If a is as in (5.4.2), with $a_{0,0} = 0$, then $a^3 = 0$, and hence

$$(e - a) \sum_{l=0}^{2} a^l = \Big(\sum_{l=0}^{2} a^l\Big) (e - a) = e. \tag{5.5.3}$$

It follows that $e - a$ is invertible in $A[\epsilon_1, \eta_1]$, with

$$(e - a)^{-1} = \sum_{l=0}^{2} a^l = e + a + a^2. \tag{5.5.4}$$

If

$$b = b_{0,0} + b_{1,0}\, \epsilon_1 + b_{0,1}\, \eta_1 + b_{1,1}\, \epsilon_1\, \eta_1 \tag{5.5.5}$$

is an element of $A[\epsilon_1, \eta_1]$, where $b_{0,0}$ is an invertible element of A, then b can be expressed as $b_{0,0}\,(e - a)$, where $a \in A[\epsilon_1, \eta_1]$ is as in (5.4.2), with $a_{0,0} = 0$. This implies that b is invertible in $A[\epsilon_1, \eta_1]$, because $e - a$ is invertible.

Suppose that $a, b \in A[\epsilon_1, \eta_1]$ are as in (5.4.2) and (5.5.5), respectively, with $a_{0,0} = b_{0,0} = e$. Put

$$\alpha = a - e = a_{1,0}\, \epsilon_1 + a_{0,1}\, \eta_1 + a_{1,1}\, \epsilon_1\, \eta_1 \tag{5.5.6}$$

and

$$\beta = b - e = b_{1,0}\, \epsilon_1 + b_{0,1}\, \eta_1 + b_{1,1}\, \epsilon_1\, \eta_1. \tag{5.5.7}$$

Thus $a = e + \alpha$, $b = e + \beta$, and

$$a\, b = e + \alpha + \beta + \alpha\, \beta = e + \alpha + \beta + a_{1,0}\, b_{0,1}\, \epsilon_1\, \eta_1 + a_{0,1}\, b_{1,0}\, \epsilon_1\, \eta_1. \tag{5.5.8}$$

We also have that a and b are invertible elements of $A[\epsilon_1, \eta_1]$, as in the preceding paragraph, with

$$a^{-1} = \sum_{l=0}^{2} (-\alpha)^l = e - \alpha + \alpha^2 = e - \alpha + 2 \cdot a_{1,0}\, a_{0,1}\, \epsilon_1\, \eta_1 \tag{5.5.9}$$

and

$$(5.5.10) \qquad b^{-1} = \sum_{l=0}^{2} (-\beta)^l = e - \beta + \beta^2 = e - \beta + 2 \cdot b_{1,0}\, b_{0,1}\, \epsilon_1\, \eta_1.$$

Here $2 \cdot x$ denotes $x + x$ for any element x of A or $A[\epsilon_1, \eta_1]$.

Suppose now that $a_{0,1} = a_{1,1} = b_{1,0} = b_{1,1} = 0$, so that

$$(5.5.11) \qquad a = e + a_{1,0}\, \epsilon_1, \quad b = e + b_{0,1}\, \eta_1$$

and $\alpha = a_{1,0}\, \epsilon_1$, $\beta = b_{0,1}\, \eta_1$. In this case, (5.5.8) reduces to

$$(5.5.12) \qquad a\, b = e + a_{1,0}\, \epsilon_1 + b_{0,1}\, \eta_1 + a_{1,0}\, b_{0,1}\, \epsilon_1\, \eta_1.$$

Similarly, (5.5.9) and (5.5.10) reduce to

$$(5.5.13) \qquad a^{-1} = e - a_{1,0}\, \epsilon_1, \quad b^{-1} = e - b_{0,1}\, \eta_1.$$

Thus

$$(5.5.14) \qquad a^{-1}\, b^{-1} = e - a_{1,0}\, \epsilon_1 - b_{0,1}\, \eta_1 + a_{1,0}\, b_{0,1}\, \epsilon_1\, \eta_1.$$

Combining (5.5.12) and (5.5.14), one can verify that

$$(5.5.15) \qquad a\, b\, a^{-1}\, b^{-1} = e + a_{1,0}\, b_{0,1}\, \epsilon_1\, \eta_1 - b_{0,1}\, a_{1,0}\, \epsilon_1\, \eta_1.$$

5.6 Differentiation

Let k be a commutative ring with a multiplicative identity element, and let T be an indeterminate. Also let A be a module over k, so that the spaces $A[T]$ and $A[[T]]$ of formal polynomials and power series in T with coefficients in A can be defined as in Section 4.3. If $f(T) = \sum_{j=0}^{\infty} f_j\, T^j \in A[[T]]$, then the formal *derivative* of $f(T)$ is defined by

$$(5.6.1) \qquad f'(T) = \sum_{j=1}^{\infty} j \cdot f_j\, T^{j-1} = \sum_{j=0}^{\infty} (j+1) \cdot f_{j+1}\, T^j,$$

where $j \cdot a$ is the sum of j a's in A for every $j \in \mathbf{Z}_+$ and $a \in A$. Thus $f'(T) \in A[[T]]$ too, and

$$(5.6.2) \qquad f(T) \mapsto f'(T)$$

is a homomorphism from $A[[T]]$ into itself, as a module over k. If $f(T) \in A[T]$, then $f'(T) \in A[T]$ as well.

Let B and C be two more modules over k, and let β be a mapping from $A \times B$ into C that is bilinear over k. Let $f(T) \in A[[T]]$ be given as before, as well as $g(T) = \sum_{l=0}^{\infty} g_l\, T^l \in B[[T]]$. Put

$$(5.6.3) \qquad h_n = \sum_{j=0}^{n} \beta(f_j, g_{n-j})$$

for every nonnegative integer n, and

$$\beta(f(T), g(T)) = h(T) = \sum_{n=0}^{\infty} h_n\, T^n, \tag{5.6.4}$$

as in Section 4.5. We would like to verify that

$$h'(T) = \beta(f'(T), g(T)) + \beta(f(T), g'(T)). \tag{5.6.5}$$

This is the same as saying that

$$\begin{aligned}(n+1)\cdot h_{n+1} &= \sum_{j=0}^{n} \beta((j+1)\cdot f_{j+1}, g_{n-j}) \\ &\quad + \sum_{j=0}^{n} \beta(f_j, (n-j+1)\cdot g_{n-j+1})\end{aligned} \tag{5.6.6}$$

for every $n \ge 0$. By the definition (5.6.3) of h_n, we have that

$$\begin{aligned}(n+1)\cdot h_{n+1} &= \sum_{j=0}^{n+1} (n+1)\cdot \beta(f_j, g_{n+1-j}) \\ &= \sum_{j=0}^{n+1} j\cdot \beta(f_j, g_{n+1-j}) + \sum_{j=0}^{n+1} (n+1-j)\cdot \beta(f_j, g_{n+1-j}) \\ &= \sum_{j=1}^{n+1} j\cdot \beta(f_j, g_{n+1-j}) + \sum_{j=0}^{n} (n+1-j)\cdot \beta(f_j, g_{n+1-j}) \\ &= \sum_{j=0}^{n} (j+1)\cdot \beta(f_{j+1}, g_{n-j}) + \sum_{j=0}^{n} (n-j+1)\cdot \beta(f_j, g_{n-j+1})\end{aligned} \tag{5.6.7}$$

for each $n \ge 0$. This implies (5.6.6), as desired.

Let A be an algebra over k in the strict sense, where multiplication of $a, b \in A$ is expressed as $a\, b$. As in Section 4.6, multiplication on A can be extended to $A[[T]]$, so that $A[[T]]$ becomes an algebra over k in the strict sense too. If $f(T)$ and $g(T)$ are elements of $A[[T]]$ and $h(T) = f(T)\, g(T)$, then

$$h'(T) = f'(T)\, g(T) + f(T)\, g'(T), \tag{5.6.8}$$

as in (5.6.5). Thus (5.6.2) defines a derivation on $A[[T]]$, as an algebra over k. Similarly, the restriction of (5.6.2) to $A[T]$ defines a derivation on $A[T]$, as an algebra over k.

Let A be a module over k again, and remember that $A[[T]]$ may be considered as a module over $k[[T]]$, as in Section 4.6. Let $f(T) \in k[[T]]$ and $g(T) \in A[[T]]$ be given, so that $h(T) = f(T)\, g(T)$ defines an element of $A[[T]]$ as well. Under these conditions, $f'(T) \in k[[T]]$, $g'(T), h'(T) \in A[[T]]$, and (5.6.8) holds in $A[[T]]$. This may be considered as another instance of (5.6.5). More precisely, this uses scalar multiplication on A as a bilinear mapping from $k \times A$ into A, and its extension to $k[[T]] \times A[[T]]$.

5.7 Polynomial functions

Let k be a commutative ring with multiplicative identity element, let A be a module over k, and let T be an indeterminate. Also let $f(T) = \sum_{j=0}^{n} f_j\, T^j$ be a formal polynomial in T with coefficients in A, as in Section 4.3. If $t \in k$, then

$$f(t) = \sum_{j=0}^{n} f_j\, t^j \tag{5.7.1}$$

defines an element of A, where $f_j\, t^j$ is defined using scalar multiplication on A, and t^j is interpreted as being the multiplicative identity element 1 in k when $j = 0$. The mapping

$$f(T) \mapsto f(t) \tag{5.7.2}$$

defines a homomorphism from $A[T]$ into A, as modules over k.

Let B and C be modules over k as well, and let β be a mapping from $A \times B$ into C that is bilinear over k. If $f(T) \in A[T]$ and $g(T) \in B[T]$, then

$$h(T) = \beta(f(T), g(T)) \tag{5.7.3}$$

can be defined as an element of $C[T]$ as in Section 4.5. Under these conditions, one can check that

$$h(t) = \beta(f(t), g(t)) \tag{5.7.4}$$

for every $t \in k$.

Now let A be an algebra over k in the strict sense, where multiplication of $a, b \in A$ is expressed as $a\, b$. Remember that multiplication on A can be extended to $A[T]$, so that $A[T]$ becomes an algebra over k in the strict sense, as in Section 4.6. If $f(T), g(T) \in A[T]$ and $h(T) = f(T)\, g(T)$, then

$$h(t) = f(t)\, g(t) \tag{5.7.5}$$

for every $t \in k$, as in (5.7.4). Thus (5.7.2) defines a homomorphism from $A[T]$ into A, as algebras over k.

Let A be a module over k again, so that $A[T]$ may be considered as a module over $k[T]$, as in Section 4.6. Let $f(T) \in k[T]$ and $g(T) \in A[T]$ be given, and let $h(T) = f(T)\, g(T)$ be their product in $A[T]$. If $t \in k$, then $f(t)$ is defined as an element of k, $g(t)$ and $h(t)$ are defined as elements of A, and (5.7.5) holds, as in (5.7.4).

Let $t \in k$ be given, and suppose that $\epsilon \in k$ satisfies

$$\epsilon^2 = 0. \tag{5.7.6}$$

Noe that

$$(t + \epsilon)^j = t^j + j \cdot t^{j-1}\, \epsilon \tag{5.7.7}$$

for every positive integer j. If $f(T) = \sum_{j=0}^{n} f_j\, T^j \in A[T]$, then

$$f(t+\epsilon) = \sum_{j=0}^{n} f_j\,(t+\epsilon)^j = \sum_{j=0}^{n} f_j\, t^j + \sum_{j=1}^{n} j \cdot f_j\, t^{j-1}\,\epsilon = f(t) + f'(t)\,\epsilon. \tag{5.7.8}$$

Here $f'(T) \in A[T]$ is as defined in the previous section, so that $f'(t)$ is defined as an element of A as before.

Let A be an associative algebra over k with a multiplicative identity element e. If $f(T) = \sum_{j=0}^{n} f_j\, t^j \in k[T]$ and $a \in A$, then

$$f(a) = \sum_{j=0}^{n} f_j\, a^j \tag{5.7.9}$$

is defined as an element of A, where a^j is interpreted as being equal to e when $j = 0$. Let $g(T)$ be another element of $k[T]$, so that $h(T) = f(T)\,g(T)$ is defined as an element of $k[T]$ too. It is easy to see that

$$h(a) = f(a)\,g(a), \tag{5.7.10}$$

so that

$$f(T) \mapsto f(a) \tag{5.7.11}$$

defines a homomorphism from $k[T]$ into A, as algebras over k.

Suppose that $a, \epsilon \in A$ satisfy

$$a\,\epsilon = \epsilon\,a \tag{5.7.12}$$

and $\epsilon^2 = 0$. As in (5.7.7), we have that

$$(a+\epsilon)^j = a^j + j \cdot a^{j-1}\,\epsilon \tag{5.7.13}$$

for every $j \in \mathbf{Z}_+$. Using this, we get that

$$f(a+\epsilon) = f(a) + f'(a)\,\epsilon, \tag{5.7.14}$$

as in (5.7.8).

5.8 Several commuting indeterminates

Let k be a commutative ring with a multiplicative identity element, and let A be a module over k. Also let n be a positive integer, and let $T_1, \ldots, T_n$ be n commuting indeterminates. As usual, a *multi-index* of length n is an n-tuple $\alpha = (\alpha_1, \ldots, \alpha_n)$ of nonnegative integers, and we put

$$|\alpha| = \alpha_1 + \cdots + \alpha_n. \tag{5.8.1}$$

The corresponding formal monomial

$$T^\alpha = T_1^{\alpha_1} \cdots T_n^{\alpha_n} \tag{5.8.2}$$

in $T_1, \ldots, T_n$ has degree $|\alpha|$. A *formal power series* in $T_1, \ldots, T_n$ with coefficients in A can be expressed as

$$f(T) = f(T_1, \ldots, T_n) = \sum_{\alpha \in (\mathbf{Z}_+ \cup \{0\})^n} f_\alpha \, T^\alpha, \tag{5.8.3}$$

where $f_\alpha \in A$ for every multi-index α. The space $A[[T_1, \ldots, T_n]]$ of all such formal power series can be defined as the space of all A-valued functions on the set $(\mathbf{Z}_+ \cup \{0\})^n$ of all multi-indices of length n. This is a module over k with respect to pointwise addition and scalar multiplication of A-valued functions on $(\mathbf{Z}_+ \cup \{0\})^n$, which corresponds to termwise addition and scalar multiplication of formal power series as in (5.8.3). As a module over k, $A[[T_1, \ldots, T_n]]$ corresponds to the direct product of copies of A indexed by $(\mathbf{Z}_+ \cup \{0\})^n$.

A *formal polynomial* in $T_1, \ldots, T_n$ with coefficients in A can be expressed as

$$f(T) = f(T_1, \ldots, T_n) = \sum_{|\alpha| \le N} f_\alpha \, T^\alpha, \tag{5.8.4}$$

where the sum is taken over multi-indices α with $|\alpha| \le N$ for some nonnegative integer N, and $f_\alpha \in A$ for each such α. Of course, we can take $f_\alpha = 0$ when $|\alpha| > N$, so that (5.8.4) may be considered as a formal power series in $T_1, \ldots, T_n$ with coefficients in A. The space $A[T_1, \ldots, T_n]$ of all such formal polynomials can be defined as the space of all A-valued functions on $(\mathbf{Z}_+ \cup \{0\})^n$ that are equal to 0 for all but finitely many α, which is a submodule of $A[[T_1, \ldots, T_n]]$. As a module over k, $A[T_1, \ldots, T_n]$ corresponds to the direct sum of copies of A indexed by $(\mathbf{Z}_+ \cup \{0\})^n$. We can identify A with the submodule of $A[T_1, \ldots, T_n]$ consisting of $f(T)$ as in (5.8.4) with $N = 0$.

Suppose that A is an algebra over k in the strict sense, where multiplication of $a, b \in A$ is expressed as $a\,b$. Let $f(T) \in A[[T_1, \ldots, T_n]]$ be as in (5.8.3), and let

$$g(T) = \sum_{\beta \in (\mathbf{Z}_+ \cup \{0\})^n} g_\beta \, T^\beta \tag{5.8.5}$$

be another element of $A[[T_1, \ldots, T_n]]$. If α and β are multi-indices of length n, then $\alpha + \beta$ can be defined as a multi-index of length n by coordinatewise addition, and we have that

$$|\alpha + \beta| = |\alpha| + |\beta|. \tag{5.8.6}$$

Put

$$h_\gamma = \sum_{\alpha + \beta = \gamma} f_\alpha \, g_\beta \tag{5.8.7}$$

for every multi-index γ of length n, where the sum is taken over all pairs of multi-indices α, β such that $\alpha + \beta = \gamma$. There are only finitely many such pairs, so that the sum on the right side of (5.8.7) is a finite sum of elements of A. Thus

(5.8.8) $$h(T) = \sum_{\gamma \in (\mathbf{Z}_+ \cup \{0\})^n} h_\gamma \, T^\gamma$$

defines an element of $A[[T_1, \ldots, T_n]]$, and we put

(5.8.9) $$f(T)\, g(T) = h(T).$$

This extends multiplication on A to $A[[T_1, \ldots, T_n]]$, so that the latter becomes an algebra over k in the strict sense too. It is easy to see that $A[T_1, \ldots, T_n]$ is a subalgebra of $A[[T_1, \ldots, T_n]]$ with respect to this definition of multiplication. If multiplication on A is commutative or associative, then one can check that multiplication on $A[[T_1, \ldots, T_n]]$ has the same property. If A has a multiplicative identity element e, then the corresponding formal polynomial in $T_1, \ldots, T_n$ is the multiplicative identity element in $A[[T_1, \ldots, T_n]]$. In particular, $k[[T_1, \ldots, T_n]]$ is a commutative associative algebra over k.

Let A be a module over k again, let $f(T) \in k[[T_1, \ldots, T_n]]$ be as in (5.8.3), and let $g(T) \in A[[T_1, \ldots, T_n]]$ be as in(5.8.5). Thus $f_\alpha\, g_\beta$ is defined as an element of A for all multi-indices α, β, using scalar multiplication on A. If γ is a multi-index of length n, then h_γ can be defined as an element of A as in (5.8.7). This permits us to define $h(T)$ as an element of $A[[T_1, \ldots, T_n]]$ as in (5.8.8), which can be used to define $f(T)\, g(T)$. One can verify that $A[[T_1, \ldots, T_n]]$ is a module over $k[[T_1, \ldots, T_n]]$ in this way. Similarly, if $f(T) \in k[T_1, \ldots, T_n]$ and $g(T) \in A[T_1, \ldots, T_n]$, then $h(T) \in A[T_1, \ldots, T_n]$. Using this definition of scalar multiplication, $A[T_1, \ldots, T_n]$ becomes a module over $k[T_1, \ldots, T_n]$.

Let l and m be positive integers, and let $X_1, \ldots, X_l, Y_1, \ldots, Y_m$ be commuting indeterminates. If β and γ are multi-indices of length l and m, respectively, then let us identify (β, γ) with a multi-index of length $l + m$. This corresponds to identifying $(\mathbf{Z}_+ \cup \{0\})^l \times (\mathbf{Z}_+ \cup \{0\})^m$ with $(\mathbf{Z}_+ \cup \{0\})^{l+m}$. We may consider

(5.8.10) $$X^\beta \, Y^\gamma = X_1^{\beta_1} \cdots X_l^{\beta_l} \, Y_1^{\gamma_1} \cdots Y_m^{\gamma_m}$$

as a formal monomial in the variables $X_1, \ldots, X_l$, $Y_1, \ldots, Y_m$ of degree $|\beta| + |\gamma|$. As before, $A[[X_1, \ldots, X_l]]$ is a module over k, so that

(5.8.11) $$(A[[X_1, \ldots, X_l]])[[Y_1, \ldots, Y_m]]$$

can be defined as a module over k as well. There is a simple one-to-one correspondence between the elements of (5.8.11) and

(5.8.12) $$A[[X_1, \ldots, X_l, Y_1, \ldots, Y_m]],$$

which defines an isomorphism between these modules over k. This correspondence takes

(5.8.13) $$(A[X_1, \ldots, X_l])[Y_1, \ldots, Y_m]$$

onto

(5.8.14) $$A[X_1, \ldots, X_l, Y_1, \ldots, Y_m].$$

If A is an algebra over k in the strict sense, then we get an isomorphism between (5.8.11) and (5.8.12) as algebras over k. In particular, we get an isomorphism between

$$(k[[X_1, \ldots, X_l]])[[Y_1, \ldots, Y_m]] \tag{5.8.15}$$

and

$$k[[X_1, \ldots, X_l, Y_1, \ldots, Y_m]] \tag{5.8.16}$$

as algebras over k. Similarly, if A is a module over k, then scalar multiplication on (5.8.11) by elements of (5.8.15) corresponds to scalar multiplication on (5.8.12) by elements of (5.8.16).

5.9 Polynomial functions in several variables

Let k be a commutative ring with a multiplicative identity element, and let n be a positive integer. As usual, we let k^n be the space of n-tuples of elements of k. If $t = (t_1, \ldots, t_n) \in k^n$ and α is a multi-index of length n, then t^α is defined as an element of k by

$$t^\alpha = t_1^{\alpha_1} \cdots t_n^{\alpha_n}. \tag{5.9.1}$$

Here $t_j^{\alpha_j}$ is interpreted as being the multiplicative identity element 1 in k when $\alpha_j = 0$, as before. If β is another multi-index of length n, then

$$t^{\alpha+\beta} = t^\alpha \, t^\beta. \tag{5.9.2}$$

Let A be a module over k, and let $T_1, \ldots, T_n$ be n commuting indeterminates. Also let $f(T)$ be a formal polynomial in $T_1, \ldots, T_n$ with coefficients in A, as in (5.8.4). If $t \in k^n$, then

$$f(t) = \sum_{|\alpha| \le N} f_\alpha \, t^\alpha \tag{5.9.3}$$

defines an element of A, where $f_\alpha \, t^\alpha$ is defined using scalar multiplication on A for each multi-index α. The mapping

$$f(T) \mapsto f(t) \tag{5.9.4}$$

defines a homomorphism from $A[T_1, \ldots, T_n]$ into A, as modules over k.

Let A be an algebra over k in the strict sense, where multiplication of $a, b \in A$ is expressed as $a\,b$. Remember that multiplication on A can be extended to $A[T_1, \ldots, T_n]$, as in the previous section. Let $f(T), g(T) \in A[T_1, \ldots, T_n]$ be given, and put $h(T) = f(T)\,g(T)$. If $t \in k^n$, then one can check that

$$h(t) = f(t)\,g(t). \tag{5.9.5}$$

This means that (5.9.4) defines a homomorphism from $A[T_1, \ldots, T_n]$ into A, as algebras over k.

Let A be a module over k again, and remember that $A[T_1, \ldots, T_n]$ may be considered as a module over $k[T_1, \ldots, T_n]$, as in the previous section. Let $f(T)$

in $k[T_1, \ldots, T_n]$ and $g(T) \in A[T_1, \ldots, T_n]$ be given, so that $h(T) = f(T)\,g(T)$ is defined as an element of $A[T_1, \ldots, T_n]$ as well. If $t \in k^n$, then $f(t) \in k$, $g(t)$ and $h(t)$ are elements of A, and one can verify that (5.9.5) holds.

Let A be an associative algebra over k with a multiplicative identity element e, and let A^n be the space of n-tuples of elements of A. Suppose that $a = (a_1, \ldots, a_n) \in A^n$ has commuting coordinates, so that

$$a_j\, a_l = a_l\, a_j \tag{5.9.6}$$

for all $j, l = 1, \ldots, n$. Of course, this condition holds trivially when $n = 1$. If α is a multi-index of length n, then a^α is defined as an element of A by

$$a^\alpha = a_1^{\alpha_1} \cdots a_n^{\alpha_n}, \tag{5.9.7}$$

where $a_j^{\alpha_j}$ is interpreted as being equal to e when $\alpha_j = 0$. Note that

$$a^{\alpha+\beta} = a^\alpha\, a^\beta \tag{5.9.8}$$

for all multi-indices α, β under these conditions. Let $f(T)$ be a formal polynomial in $T_1, \ldots, T_n$ with coefficients in k, as in (5.8.4) again. As before, $f(a)$ is defined as an element of A by

$$f(a) = \sum_{|\alpha| \le N} f_\alpha\, a^\alpha, \tag{5.9.9}$$

where $f_\alpha\, a^\alpha$ is defined using scalar multiplication on A. If $g(T) \in k[T_1, \ldots, T_n]$ too and $h(T) = f(T)\,g(T)$, then one can verify that

$$h(a) = f(a)\,g(a). \tag{5.9.10}$$

It follows that $f(T) \mapsto f(a)$ is a homomorphism from $k[T_1, \ldots, T_n]$ into A, as algebras over k, since this mapping is clearly linear over k.

5.10 Partial derivatives

Let n be a positive integer, let α be a multi-index of length n, and let l be a positive integer with $l \le n$. The multi-index $\alpha(l)$ of length n is defined by

$$\alpha_j(l) = \alpha_j \quad \text{when } j \ne l \tag{5.10.1}$$

and

$$\begin{aligned} \alpha_l(l) &= \alpha_l - 1 \quad \text{when } \alpha_l \ge 1 \\ &= 0 \qquad\quad\ \text{when } \alpha_l = 0. \end{aligned} \tag{5.10.2}$$

Similarly, let $\alpha^+(l)$ be the multi-index of length n defined by

$$\begin{aligned} \alpha_j^+(l) &= \alpha_j \qquad\ \text{when } j \ne l \\ &= \alpha_l + 1 \quad \text{when } j = l. \end{aligned} \tag{5.10.3}$$

Let k be a commutative ring with a multiplicative identity element, let A be a module over k, and let $T_1, \ldots, T_n$ be n commuting indeterminates. Also let $f(T)$ be a formal power series in $T_1, \ldots, T_n$ with coefficients in A, as in (5.8.3). The formal *partial derivative* of $f(T)$ in T_l can be defined as a formal power series in $T_1, \ldots, T_n$ with coefficients in A by

$$\partial_l f(T) = \frac{\partial}{\partial T_l} f(T) = \sum_{\alpha \in (\mathbf{Z}_+ \cup \{0\})^n} (\alpha_l + 1) \cdot f_{\alpha^+(l)} \, T^\alpha. \tag{5.10.4}$$

This is basically the same as

$$\sum_{\alpha \in (\mathbf{Z}_+ \cup \{0\})^n} \alpha_l \cdot f_\alpha \, T^{\alpha(l)} = \sum_{\alpha_l \geq 1} \alpha_l \cdot f_\alpha \, T^{\alpha(l)}, \tag{5.10.5}$$

where the second sum is taken over all multi-indices α with $\alpha_l \geq 1$. Note that

$$f(T) \mapsto \partial_l f(T) \tag{5.10.6}$$

defines a homomorphism from $A[[T_1, \ldots, T_n]]$ into itself, as a module over k. Of course, if $f(T) \in A[T_1, \ldots, T_n]$, then the previous sums reduce to finite sums, and $\partial_l f(T) \in A[T_1, \ldots, T_n]$. One can check that

$$\partial_l(\partial_m f(T)) = \partial_m(\partial_l f(T)) \tag{5.10.7}$$

for every $l, m = 1, \ldots, n$ and $f(T) \in A[[T_1, \ldots, T_n]]$.

If $n = 1$, then (5.10.4) reduces to the definition of the derivative in Section 5.6. If $n > 1$, then we can identify $f(T) \in A[[T_1, \ldots, T_n]]$ with a formal power series in T_l whose coefficients are formal power series in the other variables T_j, $j \neq l$, with coefficients in A, as in Section 5.8. The derivative of this formal power series in T_l can be defined as in Section 5.6, as a formal power series in T_l whose coefficients are formal power series in the other variables. This differentiated formal power series can be identified with a formal power series in $T_1, \ldots, T_n$, as before, which is the same as (5.10.4).

Suppose that A is an algebra over k in the strict sense, so that $A[[T_1, \ldots, T_n]]$ is an algebra over k in the strict sense as well, as in Section 5.8. Under these conditions, (5.10.6) defines a derivation on $A[[T_1, \ldots, T_n]]$. This can be reduced to the analogous statement for polynomials in one variable in Section 5.6, as in the preceding paragraph, or verified directly as in the $n = 1$ case.

Let A be a module over k again, and remember that $A[[T_1, \ldots, T_n]]$ may be considered as a module over $k[[T_1, \ldots, T_n]]$, as in Section 5.8. If $f(T)$ is an element of $k[[T_1, \ldots, T_n]]$ and $g(T) \in A[[T_1, \ldots, T_n]]$, then

$$\partial_l(f(T)\, g(T)) = (\partial_l f(T))\, g(T) + f(T)\, (\partial_l g(T)), \tag{5.10.8}$$

as elements of $A[[T_1, \ldots, T_n]]$. This can be reduced to the analogous statement for polynomials in one variable in Section 5.6, as before, or verified directly in a similar way.

Let $t \in k^n$ be given, and suppose that $u \in k^n$ satisfies

$$u_j \, u_l = 0 \tag{5.10.9}$$

for all $j, l = 1, \ldots, n$. Of course, $t + u$ is defined as an element of k^n, using coordinatewise addition. Let α be a multi-index of length n, so that t^α and $(t+u)^\alpha$ are defined as elements of k, as in (5.9.1). As in (5.7.7),

$$(t_l + u_l)^{\alpha_l} = t_l^{\alpha_l} + \alpha_l \cdot t_l^{\alpha_l - 1} \, u_l \tag{5.10.10}$$

for each $l = 1, \ldots, n$ when $\alpha_l \geq 1$, because $u_l^2 = 0$. If $\alpha_l = 0$, then $(t_l + u_l)^{\alpha_l} = t_l^{\alpha_l} = 1$. Thus

$$(t_l + u_l)^{\alpha_l} = t_l^{\alpha_l} + \alpha_l \cdot t_l^{\alpha_l(l)} \, u_l \tag{5.10.11}$$

for every $l = 1, \ldots, n$. Using this, one can check that

$$(t + u)^\alpha = t^\alpha + \sum_{l=1}^n \alpha_l \cdot t^{\alpha(l)} \, u_l. \tag{5.10.12}$$

If $f(T) \in A[T_1, \ldots, T_n]$, then it follows that

$$f(t + u) = f(t) + \sum_{l=1}^n (\partial_l f)(t) \, u_l. \tag{5.10.13}$$

Let A be an associative algebra over k with a multiplicative identity element e, and suppose that $a \in A^n$ has commuting coordinates, as in the previous section. Also let u be an element of A^n that satisfies (5.10.9), and whose coordinates commute with the coordinates of a, so that

$$a_j \, u_l = u_l \, a_j \tag{5.10.14}$$

for all $j, l = 1, \ldots, n$. Note that u has commuting coordinates, and hence $a + u$ has commuting coordinates. Let α be a multi-index of length n again, so that a^α and $(a + u)^\alpha$ are defined as elements of A as before. As in (5.10.11),

$$(a_l + u_l)^{\alpha_l} = a_l^{\alpha_l} + \alpha_l \cdot a_l^{\alpha_l(l)} \, u_l \tag{5.10.15}$$

for every $l = 1, \ldots, n$. This implies that

$$(a + u)^\alpha = a^\alpha + \sum_{l=1}^n \alpha_l \cdot a^{\alpha(l)} \, u_l, \tag{5.10.16}$$

as before. If $f(T) \in k[T_1, \ldots, T_n]$, then we get that

$$f(a + u) = f(a) + \sum_{l=1}^n (\partial_l f)(a) \, u_l. \tag{5.10.17}$$

5.11 Formal differential operators

Let k be a commutative ring with a multiplicative identity element, and let n be a positive integer. Also let $\partial_1, \ldots, \partial_n$ be commuting formal symbols, which may be used to represent partial derivatives, as in the previous section. If α is a multi-index of length n, then let

$$\partial^\alpha = \partial_1^{\alpha_1} \cdots \partial_n^{\alpha_n} \tag{5.11.1}$$

be the corresponding formal product of ∂_l's.

Let $T_1, \ldots, T_n$ be n commuting indeterminates, as before. A *formal differential operator* in $\partial_1, \ldots, \partial_n$ with coefficients in $k[[T_1, \ldots, T_n]]$ can be expressed as

$$\sum_{|\alpha| \le N} a^\alpha(T)\, \partial^\alpha, \tag{5.11.2}$$

where N is a nonnegative integer, the sum is taken over all multi-indices α of length n with $|\alpha| \le N$, and $a^\alpha(T) \in k[[T_1, \ldots, T_n]]$ for each such α. As usual, we can take $a^\alpha(T) = 0$ when $|\alpha| > N$, so that $a^\alpha(T)$ is defined for every multi-index α. The space of these formal differential operators can be defined as the space of functions $\alpha \mapsto a^\alpha(T)$ from $(\mathbf{Z}_+ \cup \{0\})^n$ into $k[[T_1, \ldots, T_n]]$ such that $a^\alpha(T) = 0$ for all but finitely many α. This is a module over k with respect to pointwise addition and scalar multiplication, which corresponds to termwise addition and scalar multiplication of sums as in (5.11.2). As a module over k, this corresponds to the direct sum of copies of $k[[T_1, \ldots, T_n]]$ indexed by $(\mathbf{Z}_+ \cup \{0\})^n$. We can identify elements of $k[[T_1, \ldots, T_n]]$ with sums of the form (5.11.2) with $N = 0$.

Multiplication on $k[[T_1, \ldots, T_n]]$ can be extended to these formal differential operators, with

$$\partial_l (b^\beta(T)\, \partial^\beta) = (\partial_l\, b^\beta(T))\, \partial^\beta + b^\beta(T)\, \partial_l\, \partial^\beta \tag{5.11.3}$$

for every $l = 1, \ldots, n$, multi-index β, and $b^\beta(T) \in k[[T_1, \ldots, T_n]]$. Note that

$$\partial_l\, \partial^\beta = \partial^{\beta^+(l)}, \tag{5.11.4}$$

in the notation of the previous section. The space of these formal differential operators is an associative algebra over k in this way, which contains $k[[T_1, \ldots, T_n]]$ as a subalgebra. The multiplicative identity element of k is also the multiplicative identity element in the space of these formal differential operators, when considered as an element of $k[[T_1, \ldots, T_n]]$ and hence a formal differential operator, as before.

A formal differential operator in $\partial_1, \ldots, \partial_n$ with coefficients in $k[T_1, \ldots, T_n]$ can be expressed as in (5.11.2), with $a^\alpha(T) \in k[T_1, \ldots, T_n]$ for each α. The space of these formal differential operators is a subalgebra of the space of formal differential operators in $\partial_1, \ldots, \partial_n$ with coefficients in $k[[T_1, \ldots, T_n]]$. The space of formal differential operators in $\partial_1, \ldots, \partial_n$ with coefficients in $k[T_1, \ldots, T_n]$ contains $k[T_1, \ldots, T_n]$ as a subalgebra, as before.

Let A be a module over k. If α is a multi-index of length n and $f(T)$ is a formal power series in $T_1, \ldots, T_n$ with coefficients in A, then

$$\partial^\alpha f(T) = \partial_1^{\alpha_1} \cdots \partial_n^{\alpha_n} f(T) \tag{5.11.5}$$

defines an element of $A[[T_1, \ldots, T_n]]$ as well, where partial derivatives are defined on $A[[T_1, \ldots, T_n]]$ as in the previous section. This is interpreted as being equal to $f(T)$ when $\alpha = 0$. Similarly, if (5.11.2) is a formal differential operator in $\partial_1, \ldots, \partial_n$ with coefficients in $k[[T_1, \ldots, T_n]]$, then

$$\Big(\sum_{|\alpha| \le N} a^\alpha(T)\, \partial^\alpha\Big) f(T) = \sum_{|\alpha| \le N} a^\alpha(T)\, \partial^\alpha f(T) \tag{5.11.6}$$

defines an element of $A[[T_1, \ldots, T_n]]$. Thus (5.11.2) induces a mapping from $A[[T_1, \ldots, T_n]]$ into itself, which is linear over k. If the coefficients $a^\alpha(T)$ of (5.11.2) are elements of $k[T_1, \ldots, T_n]$ and $f(T) \in A[T_1, \ldots, T_n]$, then (5.11.6) is in $A[T_1, \ldots, T_n]$ too.

Remember that the space

$$\mathrm{Hom}_k(A[[T_1, \ldots, T_n]], A[[T_1, \ldots, T_n]]) \tag{5.11.7}$$

of homomorphisms from $A[[T_1, \ldots, T_n]]$ into itself, as a module over k, is an associative algebra over k with respect to composition of mappings. The remarks in the preceding paragraph define a mapping from the space of formal differential operators in $\partial_1, \ldots, \partial_n$ with coefficients in $k[[T_1, \ldots, T_n]]$ into (5.11.7). One can check that this mapping is an algebra homomorphism, with respect to multiplication of formal differential operators, as mentioned earlier.

Suppose now that $A = k$, as a module over itself. Let us also suppose for the moment that if m is a positive integer, $t \in k$, and $m \cdot t = 0$ in k, then $t = 0$. In particular, this holds when $k = \mathbf{Z}$, or k is a field of characteristic 0, or at least an algebra over $\mathbf{Q}$. In this case, one can verify that a formal differential operator (5.11.2) in $\partial_1, \ldots, \partial_n$ with coefficients in $k[[T_1, \ldots, T_n]]$ is uniquely determined by the corresponding mapping from $k[[T_1, \ldots, T_n]]$ into itself. More precisely, (5.11.2) is uniquely determined by the restriction of this mapping to $k[T_1, \ldots, T_n]$. This uses the fact that

$$\partial^\alpha T^\beta = 0 \tag{5.11.8}$$

when α, β are multi-indices such that $\alpha_j > \beta_j$ for some $j = 1, \ldots, n$. This also uses the fact that

$$\partial^\alpha\, T^\alpha = \prod_{j=1}^n (\alpha_j!) \tag{5.11.9}$$

for every multi-index α.

5.12 First-order differential operators

Let k be a commutative ring with a multiplicative identity element, let n be a positive integer, and let $\partial_1, \ldots, \partial_n$ be commuting formal symbols, as in the previous section. Also let $T_1, \ldots, T_n$ be commuting indeterminates, and let

$$a(T) = (a^1(T), \ldots, a^n(T)) \tag{5.12.1}$$

be an n-tuple of formal power series in $T_1, \ldots, T_n$ with coefficients in k. Put

$$D_{a(T)} = \sum_{j=1}^{n} a^j(T)\, \partial_j, \tag{5.12.2}$$

which defines a formal partial differential operator in $\partial_1, \ldots, \partial_n$ with coefficients in $k[[T_1, \ldots, T_n]]$, as in the previous section.

Let $b(T) = (b^1(T), \ldots, b^n(T))$ be another n-tuple of formal power series in $T_1, \ldots, T_n$ with coefficients in k, so that $D_{b(T)}$ can be defined as before. The products $D_{a(T)}\, D_{b(T)}$ and $D_{b(T)}\, D_{a(T)}$ can be defined as formal differential operators in $\partial_1, \ldots, \partial_n$ with coefficients in $k[[T_1, \ldots, T_n]]$ as well, as in the previous section. It is easy to see that

$$\begin{aligned} &D_{a(T)}\, D_{b(T)} - D_{b(T)}\, D_{a(T)} \\ &\quad = \sum_{j=1}^{n} \sum_{l=1}^{n} (a^j(T)\, \partial_j b^l(T) - b^j(T)\, \partial_j a^l(T))\, \partial_l, \end{aligned} \tag{5.12.3}$$

using (5.11.3). Put $c(T) = (c^1(T), \ldots, c^n(T))$, where

$$c^l(T) = \sum_{j=1}^{n} (a^j(T)\, \partial_j b^l(T) - b^j(T)\, \partial_j a^l(T)) \tag{5.12.4}$$

for each $l = 1, \ldots, n$. Thus $c(T)$ is another n-tuple of elements of $k[[T_1, \ldots, T_n]]$, and

$$D_{a(T)}\, D_{b(T)} - D_{b(T)}\, D_{a(T)} = D_{c(T)}. \tag{5.12.5}$$

If $f(T) \in k[[T_1, \ldots, T_n]]$, then

$$D_{a(T)} f(T) = \sum_{j=1}^{n} a^j(T)\, \partial_j f(T) \tag{5.12.6}$$

defines an element of $k[[T_1, \ldots, T_n]]$ too, as in the previous section. One can check that this defines a derivation on $k[[T_1, \ldots, T_n]]$, because partial derivatives define derivations on $k[[T_1, \ldots, T_n]]$.

If $a^j(T) \in k[T_1, \ldots, T_n]$ for each $j = 1, \ldots, n$, and $f(T) \in k[T_1, \ldots, T_n]$, then (5.12.6) defines an element of $k[T_1, \ldots, T_n]$, as before. In this case, we get a derivation on $k[T_1, \ldots, T_n]$. If $b^j(T) \in k[T_1, \ldots, T_n]$ for each $j = 1, \ldots, n$ as well, then (5.12.4) is an element of $k[T_1, \ldots, T_n]$ for every $l = 1, \ldots, n$.

Let δ be any derivation on $k[T_1, \ldots, T_n]$, as an algebra over k. Note that T_j may be considered as an element of $k[T_1, \ldots, T_n]$ for each $j = 1, \ldots, n$, where more precisely the coefficient of T_j is the multiplicative identity element in k. Thus

$$a^j(T) = \delta(T_j) \tag{5.12.7}$$

defines an element of $k[T_1, \ldots, T_n]$ for each $j = 1, \ldots, n$. This permits us to define $a(T)$ as an n-tuple of elements of $k[T_1, \ldots, T_n]$ as in (5.12.1), so that $D_{a(T)}$ can be defined as in (5.12.2). If $f(T) \in k[T_1, \ldots, T_n]$, then one can verify that

$$\delta(f(T)) = D_{a(T)} f(T), \tag{5.12.8}$$

where the right side is defined as in (5.12.6).

Now let δ be a derivation on $k[[T_1, \ldots, T_n]]$, as an algebra over k. In this case, (5.12.7) defines an element of $k[[T_1, \ldots, T_n]]$ for each $j = 1, \ldots, n$, so that we can define $a(T)$ as an n-tuple of elements of $k[[T_1, \ldots, T_n]]$ as in (5.12.1). Thus $D_{a(T)}$ can be defined as in (5.12.2), and (5.12.8) holds for every $f(T) \in k[T_1, \ldots, T_n]$, as in the preceding paragraph. Of course, we would like to extend this to $f(T) \in k[[T_1, \ldots, T_n]]$.

Let us say that $f(T) \in \sum_{\alpha \in (\mathbf{Z}_+ \cup \{0\})^n} f_\alpha \, T^\alpha \in k[[T_1, \ldots, T_n]]$ *vanishes to order* L for some nonnegative integer L if $f_\alpha = 0$ for every multi-index α with $|\alpha| \le L$. If $g(T) \in k[[T_1, \ldots, T_n]]$, then

$$g(T) \, T^\beta \tag{5.12.9}$$

vanishes to order $|\beta| - 1$ for every nonzero multi-index β. If $f(T)$ vanishes to order L for some $L \ge 0$, then $f(T)$ can be expressed as a finite sum of elements of $k[[T_1, \ldots, T_n]]$ of the form (5.12.9), with $|\beta| = L + 1$.

If $f(T)$ vanishes to order L for some $L \ge 1$, then $\delta(f(T))$ vanishes to order $L - 1$. This can be verified directly when $f(T)$ is of the form (5.12.9) with $|\beta| = L + 1$, and otherwise one can reduce to that case, as in the preceding paragraph. One can use this to get that (5.12.8) holds for every $f(T) \in k[[T_1, \ldots, T_n]]$, as desired.

5.13 Homogeneous formal polynomials

Let k be a commutative ring with a multiplicative identity element, let $T_1, \ldots, T_n$ be n commuting indeterminates for some positive integer n, and let A be a module over k. A formal polynomial $f(T)$ in $T_1, \ldots, T_n$ with coefficients in A is said to be *homogeneous of degree* d for some nonnegative integer d if $f(T)$ can be expressed as

$$f(T) = \sum_{|\alpha| = d} f_\alpha \, T^\alpha, \tag{5.13.1}$$

where the sum is taken over all multi-indices α of length n with $|\alpha| = d$, and f_α is an element of A for all such α. Equivalently, this means that the coefficient f_α of T^α in $f(T)$ is equal to 0 when $|\alpha| \ne d$. The space $A_d[T_1, \ldots, T_n]$ of these formal polynomials is a submodule of $A[T_1, \ldots, T_n]$, as a module over k. Note that $A_d[T_1, \ldots, T_n]$ corresponds to a direct sum of copies of A indexed by multi-indices α with $|\alpha| = d$, and that $A[T_1, \ldots, T_n]$ can be viewed as the direct sum of $A_d[T_1, \ldots, T_n]$ over all nonnegative integers d. Similarly, $A[[T_1, \ldots, T_n]]$ can be viewed as the direct product of $A_d[T_1, \ldots, T_n]$ over all nonnegative integers

d. If $f(T) \in A_d[T_1, \ldots, T_n]$ for some $d \geq 1$, then it is easy to see that $\partial_l f(T)$ is homogeneous of degree $d - 1$ for every $l = 1, \ldots, n$.

Suppose that A is an algebra over k in the strict sense. If $f(T)$, $g(T)$ are homogeneous formal polynomials in $T_1, \ldots, T_n$ with coefficients in A for some nonnegative integers d_1, d_2, respectively, then one can check that $f(T)\, g(T)$ is homogeneous of degree $d_1 + d_2$.

Let us now take $A = k$, and let

$$a^j(T) = \sum_{l=1}^{n} a_l^j\, T_l \tag{5.13.2}$$

be elements of $k_1[T_1, \ldots, T_n]$ for $j = 1, \ldots, n$, so that $a_l^j \in k$ for all $j, l = 1, \ldots, n$. Thus $\partial_l a^j(T) = a_l^j$ for every $j, l = 1, \ldots, n$. Put $a(T) = (a^1(T), \ldots, a^n(T))$, and let $\partial_1, \ldots, \partial_n$ be commuting formal symbols, as in the previous two sections. Consider the corresponding formal differential operator $D_{a(T)}$ in $\partial_1, \ldots, \partial_n$, as before. If $f(T)$ is a formal polynomial in $T_1, \ldots, T_n$ with coefficients in k, then $D_{a(T)} f(T)$ is defined as an element of $k[T_1, \ldots, T_n]$ too. More precisely, if $f(T)$ is homogeneous of degree d, then $D_{a(T)} f(T)$ is homogeneous of degree d as well. In particular, if

$$f(T) = \sum_{j=1}^{n} f_j\, T_j \tag{5.13.3}$$

is homogeneous of degree 1, so that $f_j \in k$ for $j = 1, \ldots, n$, then

$$D_{a(T)} f(T) = \sum_{j=1}^{n} a^j(T)\, \partial_j f(T) = \sum_{j=1}^{n} \sum_{l=1}^{n} a_l^j\, f_j\, T_l. \tag{5.13.4}$$

Let

$$b^j(T) = \sum_{l=1}^{n} b_l^j\, T_l \tag{5.13.5}$$

be elements of $k_1[T_1, \ldots, T_n]$ for $j = 1, \ldots, n$, and put $b(T) = (b^1(T), \ldots, b^n(T))$. Put

$$c^j(T) = \sum_{l=1}^{n} (a^l(T)\, b_l^j - b^l(T)\, a_l^j) = \sum_{l=1}^{n} \sum_{m=1}^{n} (a_m^l\, b_l^j - b_m^l\, a_l^j)\, T_m \tag{5.13.6}$$

for each $j = 1, \ldots, n$, and $c(T) = (c^1(T), \ldots, c^n(T))$. Note that $c^j(T)$ is an element of $k_1[T_1, \ldots, T_n]$ for $j = 1, \ldots, n$. If $D_{b(T)}$ and $D_{c(T)}$ are the formal differential operators in $\partial_1, \ldots, \partial_n$ corresponding to $b(T)$ and $c(T)$, respectively, then

$$D_{a(T)}\, D_{b(T)} - D_{b(T)}\, D_{a(T)} = D_{c(T)}, \tag{5.13.7}$$

as in (5.12.5).

5.14 Homogeneous differential operators

Let k be a commutative ring with a multiplicative identity element, and let n be a positive integer. Also let $T_1, \ldots, T_n$ be commuting indeterminates, and let $\partial_1, \ldots, \partial_n$ be commuting formal symbols, as in Section 5.11. Consider a formal differential operator

$$L = \sum_{|\alpha| \le N} a^\alpha(T)\, \partial^\alpha \tag{5.14.1}$$

in $\partial_1, \ldots, \partial_n$ with coefficients in $k[T_1, \ldots, T_n]$. Let us say that L is *homogeneous* of degree d for some integer d if the following conditions hold. If α is a multi-index such that $d \ge -|\alpha|$, then $a^\alpha(T)$ should be homogeneous of degree $d + |\alpha|$ as a formal polynomial in $T_1, \ldots, T_n$ with coefficients in k. Otherwise, if d is strictly less than $-|\alpha|$, then $a^\alpha(T) = 0$. The space of these formal differential operators that are homogeneous of degree d is a submodule of the space of all formal differential operators in $\partial_1, \ldots, \partial_n$ with coefficients in $k[T_1, \ldots, T_n]$, as a module over k.

Let L_1 and L_2 be formal differential operators in $\partial_1, \ldots, \partial_n$ with coefficients in $k[T_1, \ldots, T_n]$, so that their product $L_1\, L_2$ can be defined as a formal differential operator with coefficients in $k[T_1, \ldots, T_n]$ as well. If L_1, L_2 are homogeneous of degrees $d_1, d_2 \in \mathbf{Z}$, respectively, then one can check that $L_1\, L_2$ is homogeneous of degree $d_1 + d_2$. More precisely, one can start with the case where $L_1 = \partial_j$ for some $j = 1, \ldots, n$, so that $d_1 = -1$. Using this, one can obtain the analogous statement for $L_1 = \partial^\alpha$ for some multi-index α, so that $d_1 = -|\alpha|$. One can use this to obtain the analogous statement when L_1 is homogeneous of any degree d_1.

Let L_1 be a formal differential operator in $\partial_1, \ldots, \partial_n$ with coefficients in $k[T_1, \ldots, T_n]$ again, and let A be a module over k. Also let $f(T)$ be a formal polynomial in $T_1, \ldots, T_n$ with coefficients in A, so that $L_1 f(T)$ is defined as an element of $A[T_1, \ldots, T_n]$ too. Suppose that L_1 is homogeneous of degree $d_1 \in \mathbf{Z}$, and that $f(T)$ is homogeneous of degree d for some nonnegative integer d. One can verify that $L_1 f(T)$ is homogeneous of degree $d_1 + d$ when $d_1 \ge -d$, and that $L_1 f(T) = 0$ otherwise. Indeed, if $L_1 = \partial_j$ for some $j = 1, \ldots, n$, then this was mentioned in the previous section. As before, one can use this to obtain the analogous statement when $L_1 = \partial^\alpha$ for some multi-index α. The analogous statement for any L_1 follows easily from this.

Remember that the space of formal differential operators in $\partial_1, \ldots, \partial_n$ with coefficients in $k[T_1, \ldots, T_n]$ is an algebra over k. The collection of such formal differential operators that are homogeneous of degree 0 is a subalgebra of this algebra. This subalgebra is generated as an an algebra over k by homogeneous differential operators of degree 0 as in (5.14.1) with $N = 1$. To see this, one can start with a homogeneous differential operator of degree 0 of the form $T^\alpha\, \partial^\beta$, where α, β are multi-indices with $|\alpha| = |\beta| \ge 2$. This can be approximated by a product of $|\alpha| = |\beta|$ operators of the form $T_j\, \partial_l$ for some $j, l = 1, \ldots, n$. More precisely, one can choose the approximation so that the difference is a formal differential operator of lower order. One can repeat the process to express any homogeneous differential operator of degree 0 as a finite sum of products of homogeneous differential operators of degree 0 and order less than or equal to 1, as desired.

5.15 Some algebras of differential operators

Let k be a commutative ring with a multiplicative identity element, let n be a positive integer, let $T_1, \ldots, T_n$ be commuting indeterminates, and let $\partial_1, \ldots, \partial_n$ be commuting formal symbols, as before. Remember that

(5.15.1) the space of formal differential operators in $\partial_1, \ldots, \partial_n$ with coefficients in $k[[T_1, \ldots, T_n]]$

is an associative algebra over k, as in Section 5.11. Similarly,

(5.15.2) the space of formal differential operators in $\partial_1, \ldots, \partial_n$ with coefficients in $k[T_1, \ldots, T_n]$

is a subalgebra of (5.15.1). We also have that

(5.15.3) the space of formal differential operators in $\partial_1, \ldots, \partial_n$ with coefficients in $k[T_1, \ldots, T_n]$ that are homogeneous of degree 0

is a subalgebra of (5.15.2), as in the previous section.

If $a(T) = (a^1(T), \ldots, a^n(T))$ is an element of the space $(k[[T_1, \ldots, T_n]])^n$ of n-tuples of formal power series in $T_1, \ldots, T_n$ with coefficients in k, then put $D_{a(T)} = \sum_{j=1}^n a^j(T)\, \partial_j$, as in Section 5.12. Note that

$$\{D_{a(T)} : a(T) \in (k[[T_1, \ldots, T_n]])^n\} \tag{5.15.4}$$

is a submodule of (5.15.1), as a module over k. Remember that the commutator of two elements of (5.15.4) is an element of (5.15.4) too, as in Section 5.12. Thus (5.15.4) is a Lie subalgebra of (5.15.1), as a Lie algebra over k with respect to the commutator bracket. Similarly,

$$\{D_{a(T)} : a(T) \in (k[T_1, \ldots, T_n])^n\} \tag{5.15.5}$$

is a submodule of (5.15.2), as a module over k, and a Lie subalgebra of (5.15.2), as a Lie algebra over k with respect to the commutator bracket.

Remember that $k_1[T_1, \ldots, T_n]$ is the space of homogeneous formal polynomials in $T_1, \ldots, T_n$ of degree one with coefficients in k, as in Section 5.13. Put

$$g_n(k) = \{D_{a(T)} : a(T) \in (k_1[T_1, \ldots, T_n])^n\}, \tag{5.15.6}$$

which is a submodule of (5.15.3), as a module over k. In fact, (5.15.6) is a Lie subalgebra of (5.15.3), as a Lie algebra over k with respect to the commutator bracket.

Of course, $a(T) \in (k_1[T_1, \ldots, T_n])^n$ can be expressed as $a^j(T) = \sum_{l=1}^n a_l^j \, T_l$ for $j = 1, \ldots, n$, where $a_l^j \in k$ for every $j, l = 1, \ldots, n$. Thus the elements of $(k_1[T_1, \ldots, T_n])^n$ correspond to $n \times n$ matrices with entries in k in an obvious way. Using this, it is easy to see that $g_n(k)$ is isomorphic to $gl_n(k)$ as a Lie algebra over k, as in Section 5.13.

Put

$$s_n(k) = \Big\{ D_{a(T)} : a(T) \in (k_1[T_1, \ldots, T_n])^n, \, \sum_{j=1}^n a_j^j = 0 \Big\}, \tag{5.15.7}$$

where a_l^j, $1 \le j, l \le n$, corresponds to $a(T) \in (k_1[T_1, \ldots, T_n])^n$ as in the preceding paragraph. This is a Lie subalgebra of $g_n(k)$, as a Lie algebra over k, which corresponds to $sl_n(k)$ under the isomorphism between $g_n(k)$ and $gl_n(k)$ mentioned before. More precisely,

$$[g_n(k), g_n(k)] \subseteq s_n(k), \tag{5.15.8}$$

as in Section 2.9.

If $a(T) \in (k_1[T_1, \ldots, T_n])^n$, then $D_{a(T)}$ defines a mapping from $k_1[T_1, \ldots, T_n]$ into itself that is linear over k, as in the previous two sections. Multiplication of differential operators corresponds to composition of the associated linear mappings on $k_1[T_1, \ldots, T_n]$, so that commutators of differential operators correspond to commutators of the associated linear mappings on $k_1[T_1, \ldots, T_n]$. Of course, $k_1[T_1, \ldots, T_n]$ is freely generated by $T_1, \ldots, T_n$, as a module over k. The linear mapping on $k_1[T_1, \ldots, T_n]$ associated to $D_{a(T)}$ corresponds to an $n \times n$ matrix whose entries are determined by the coefficients of the components of $a(T)$, as before.

Remember that formal polynomials in $T_1, \ldots, T_n$ with coefficients in k determine k-valued polynomial functions on k^n, as in Section 5.9. In particular, elements of $k_1[T_1, \ldots, T_n]$ correspond exactly to mappings from k^n into k that are linear over k. Similarly, elements of $(k_1[T_1, \ldots, T_n])^n$ correspond exactly to mappings from k^n into itself that are linear over k.

Of course, mappings from k^n into itself that are linear over k correspond to $n \times n$ matrices with entries in k in the usual way. Using this, matrix multiplication corresponds to composition of mappings on k^n. Thus commutators of matrices correspond to commutators of linear mappings on k^n.

If $a(T) \in (k_1[T_1, \ldots, T_n])^n$, then we get a linear mapping from k^n into itself, and an $n \times n$ matrix with entries in k, as in the previous two paragraphs. One can check that the $n \times n$ matrix associated to $D_{a(T)}$ as mentioned earlier is the same as the transpose of the matrix associated to the linear mapping from k^n into itself. This means that commutators of these differential operators correspond to -1 times the commutators of the linear mappings on k^n associated to the same elements of $(k_1[T_1, \ldots, T_n])^n$.

Chapter 6

Bilinear actions and representations

6.1 Bilinear actions

Let k be a commutative ring with a multiplicative identity element, and let A, V be modules over k. Also let β be a mapping from $A \times V$ into V that is bilinear over k. This may be described as a *bilinear action* of A on V over k, or more precisely as a bilinear action of A on V *on the left*. It is sometimes convenient to consider a mapping from $V \times A$ into V that is bilinear over k as a bilinear action of A on V *on the right*. If A is an associative algebra over k, or a Lie algebra over k, then we may be interested in bilinear actions that satisfy additional conditions, as in Sections 6.4 and 6.5.

Alternatively, we may use the notation

$$\rho_a(v) = \beta(a, v), \tag{6.1.1}$$

where $a \in A$ and $v \in V$. The bilinearity of β means that ρ_a is a module homomorphism from V into itself for each $a \in A$, and that $a \mapsto \rho_a$ defines a module homomorphism from A into the space $\mathrm{Hom}_k(V, V)$ of module homomorphisms from V into itself. We may use ρ to denote a module homomorphism from A into $\mathrm{Hom}_k(V, V)$ in this way, which defines a bilinear action of A on V as in (6.1.1). We may also use the notation

$$a \cdot v = \beta(a, v) \tag{6.1.2}$$

for $a \in A$ and $v \in V$. A bilinear action of A on V on the right may be expressed by $v \cdot a$ for $a \in A$ and $v \in V$.

Let T be an indeterminate, and remember that $k[T]$, $A[T]$, and $V[T]$ are the corresponding spaces of formal polynomials in T with coefficients in k, A, and V, respectively. A bilinear action of A on V over k can be extended to a bilinear action of $A[T]$ on $V[T]$ over $k[T]$. More precisely, one could start with a mapping from $A \times V$ into $V[T]$ that is bilinear over k. This can be extended to a mapping from $A[T] \times V[T]$ into $V[T]$ that is bilinear over $k[T]$, as in Sections 4.5 and 4.6.

Remember that $k[[T]]$, $A[[T]]$, and $V[[T]]$ are the corresponding spaces of formal power series in T with coefficients in k, A, and T, respectively. A bilinear action of A on V over k can be extended to a bilinear action of $A[[T]]$ on $V[[T]]$ over $k[[T]]$. As before, one could start with a mapping from $A \times V$ into $V[[T]]$ that is bilinear over k, which can be extended to a mapping from $A[[T]] \times V[[T]]$ into $V[[T]]$ that is bilinear over $k[[T]]$.

Suppose now that k is a field with an absolute value function $|\cdot|$, and that A, V are vector spaces over k with seminorms N_A, N_V, respectively, with respect to $|\cdot|$ on V. Remember that a bilinear mapping β from $A \times V$ into V is said to be bounded with respect to these seminorms if there is a nonnegative real number C such that

$$N_V(\beta(a, v)) \leq C\, N_A(a)\, N_V(v) \tag{6.1.3}$$

for every $a \in A$ and $v \in V$, as in Section 1.13. Let ρ_a be as in (6.1.1), so that (6.1.3) can be reformulated as saying that

$$N_V(\rho_a(v)) \leq C\, N_A(a)\, N_V(v) \tag{6.1.4}$$

for every $a \in A$ and $v \in V$. This is the same as saying that for each $a \in A$, ρ_a is bounded as a linear mapping from V into itself with respect to N_V, with

$$\|\rho_a\|_{op,VV} \leq C\, N_A(a). \tag{6.1.5}$$

This can also be reformulated as saying that $a \mapsto \rho_a$ is bounded as a linear mapping from A into the space $\mathcal{BL}(V)$ of bounded linear mappings from V into itself with respect to N_V, with the corresponding operator seminorm of this mapping being less than or equal to C.

6.2 Subactions and homomorphisms

Let k be a commutative ring with a multiplicative identity element, let A and V be modules over k, and let β be a mapping from $A \times V$ into V that is bilinear over k. Also let W be a submodule of V, as a module over k, and suppose that

$$\beta(a, w) \in W \tag{6.2.1}$$

for every $a \in A$ and $w \in W$. This means that the restriction of β to $A \times W$ defines a mapping into W that is bilinear over k, and hence a bilinear action of A on W. Equivalently, if ρ_a is as in (6.1.1), then (6.2.1) says that

$$\rho_a(W) \subseteq W \tag{6.2.2}$$

for every $a \in A$. Thus the restriction of ρ_a to W defines a module homomorphism from W into itself for every $a \in A$, and the mapping from $a \in A$

to the restriction of ρ_a to W defines a module homomorphism from A into $\mathrm{Hom}_k(W, W)$. If the bilinear action of A on V is expressed as in (6.1.2), then (6.2.1) can be reformulated as saying that

$$a \cdot w \in W \tag{6.2.3}$$

for every $a \in A$ and $w \in W$. If A acts on V on the right, then the corresponding condition is that

$$w \cdot a \in W \tag{6.2.4}$$

for every $a \in A$ and $w \in W$. In this case, A acts on W on the right, as before.

As a basic class of examples, suppose that A is an algebra over k in the strict sense, where multiplication of $a\,b \in A$ is expressed as $a\,b$. We can use multiplication on A to define bilinear actions of A on itself, on the left and on the right. Let A_0 be a submodule of A, as a module over k. The condition that A_0 be a left ideal in A says exactly that the action of A on itself on the left maps A_0 into itself. Similarly, the condition that A_0 be a right ideal in A says that the action of A on itself on the right maps A_0 into itself.

Let A and V be modules over k again, and let β^V be a mapping from $A \times V$ into V that is bilinear over k. Let Z be another module over k, let β^Z be a mapping from $A \times Z$ into Z that is bilinear over k, and let ϕ be a homomorphism from V into Z, as modules over k. If

$$\phi(\beta^V(a, v)) = \beta^Z(a, \phi(v)) \tag{6.2.5}$$

for every $a \in A$ and $v \in V$, then we say that ϕ *intertwines* the actions of A on V and Z. Equivalently, if $a \in A$, then let ρ_a^V and ρ_a^Z be the module homomorphisms from V and Z into themselves, respectively, associated to β^V and β^Z as in (6.1.1). It is easy to see that (6.2.5) is the same as saying that

$$\phi \circ \rho_a^V = \rho_a^Z \circ \phi \tag{6.2.6}$$

for every $a \in A$, as mappings from V into Z. If these bilinear actions of A on V and Z are expressed as in (6.1.2), then (6.2.5) can be reexpressed as

$$\phi(a \cdot v) = a \cdot \phi(v) \tag{6.2.7}$$

for every $a \in A$ and $v \in V$. If A acts on V and Z on the right, then ϕ intertwines these actions when

$$\phi(v \cdot a) = \phi(v) \cdot a \tag{6.2.8}$$

for every $a \in A$ and $v \in V$.

6.3 Quotient actions

Let k be a commutative ring with a multiplicative identity element, let V be a module over k, and let W be a submodule of V. Remember that the quotient

V/W can be defined as a module over k too, as in Section 2.11. Let q be the corresponding quotient mapping from V onto V/W.

Suppose that ϕ is a homomorphism from V into itself, as a module over k, such that

(6.3.1) $$\phi(W) \subseteq W.$$

Thus $q \circ \phi$ is a homomorphism from V into V/W, as modules over k, whose kernel contains W. Under these conditions, there is a unique mapping ψ from V/W into itself such that

(6.3.2) $$\psi \circ q = q \circ \phi$$

as mappings from V into W, by standard arguments. Equivalently, this means that

(6.3.3) $$\psi(q(v)) = q(\phi(v))$$

for every $v \in V$. Of course, ψ is a homomorphism from V/W into itself, as a module over k.

Let A be another module over k, and let β^V be a mapping from $A \times V$ into V that is bilinear over k. Suppose that the action of A on V maps W into itself, as in (6.2.1), with $\beta = \beta^V$. This implies that $q(\beta^V(a, w)) = 0$ for every $a \in A$ and $w \in W$. It follows that for $a \in A$ and $v \in V$, $q(\beta^V(a, v))$ actually depends only on a and $q(v)$. This permits us to define a mapping $\beta^{V/W}$ from $A \times (V/W)$ into V/W that is bilinear over k and satisfies

(6.3.4) $$\beta^{V/W}(a, q(v)) = q(\beta^V(a, v))$$

for every $a \in A$ and $v \in V$. Equivalently, if $a \in A$, then let ρ_a^V be the module homomorphism from V into itself associated to β^V as in (6.1.1). There is a unique mapping $\rho_a^{V/W}$ from V/W into itself such that

(6.3.5) $$\rho_a^{V/W} \circ q = q \circ \rho_a^V,$$

as in (6.3.2). More precisely, ρ_a^{VW} is a module homomorphism from V/W into itself, as before, and one can check that $a \mapsto \rho_a^{V/W}$ is a module homomorphism from A into $\mathrm{Hom}_k(V/W, V/W)$. If the bilinear action of A on V is expressed as in (6.1.2), then the induced bilinear action of A on V/W can be expressed in the same way, with

(6.3.6) $$a \cdot q(v) = q(a \cdot v)$$

for every $a \in A$ and $v \in V$. Similarly, if A acts on V on the right, then we get a bilinear action of A on V/W on the right, with

(6.3.7) $$q(v) \cdot a = q(v \cdot a)$$

for every $a \in A$ and $v \in V$. Note that q intertwines the actions of A on V and V/W, by construction.

Let A be an algebra over k in the strict sense, so that multiplication on A defines bilinear actions of A on itself, on the left and on the right, as in the previous section. If A_0 is a left ideal in A, then the action of A on itself on the left maps A_0 into itself, and we get a bilinear action of A on the quotient A/A_0 on the left, as in the preceding paragraph. Similarly, if A_0 is a right ideal in A, then the action of A on itself on the right maps A_0 into itself, and we get a bilinear action of A on A/A_0 on the right. This was mentioned earlier in Section 2.11, in terms of bilinear mappings.

6.4 Representations of associative algebras

Let k be a commutative ring with a multiplicative identity element, let A be an associative algebra over k, and let V be a module over k. Remember that the space $\mathrm{Hom}_k(V, V)$ of module homomorphisms from V into itself is an associative algebra over k with respect to composition of mappings. A *representation* of A on V is an algebra homomorphism from A into $\mathrm{Hom}_k(V, V)$. If A has a multiplicative identity element e, then one may also require that the representation send e to the identity mapping on V. In this case, if $a \in A$ has a multiplicative inverse in A, then the representation sends a to an invertible mapping on V.

A representation of A on V may be denoted ρ, where for each $a \in A$, ρ_a denotes the corresponding module homomorphism from V into itself. Thus $\rho_a(v)$ is the image of $v \in V$ under ρ_a. Note that $\rho_a(v)$ is linear over k in a and v, because the representation is linear over k as a mapping from A into $\mathrm{Hom}_k(V, V)$, and elements of $\mathrm{Hom}_k(V, V)$ are linear over k by definition. The multiplicative property of an algebra homomorphism can be expressed as

$$\rho_a \circ \rho_b = \rho_{a\,b} \tag{6.4.1}$$

for every $a, b \in A$, which is the same as saying that

$$\rho_a(\rho_b(v)) = \rho_{a\,b}(v) \tag{6.4.2}$$

for every $a, b \in A$ and $v \in V$. If A has a multiplicative identity element e, then one may require that ρ_e be the identity mapping on V, as before, so that

$$\rho_e(v) = v \tag{6.4.3}$$

for every $v \in V$.

It is sometimes convenient to express a representation ρ of A on V by

$$\rho_a(v) = a \cdot v \tag{6.4.4}$$

for every $a \in A$ and $v \in V$. As before, $a \cdot v$ should be linear over k in a and v, so that $a \cdot v$ corresponds to a mapping from $A \times V$ into V that is bilinear over k. The multiplicative property (6.4.2) can be reexpressed in this notation as

$$a \cdot (b \cdot v) = (a\,b) \cdot v \tag{6.4.5}$$

for every $a, b \in A$ and $v \in V$. If A has a multiplicative identity element e, then (6.4.3) can be reexpressed as

$$e \cdot v = v \tag{6.4.6}$$

for every $v \in V$. We may also call V a *(left) module over* A, as an associative algebra over k, with respect to this representation.

Suppose now that we have an action of A on V on the right, so that for each $a \in A$ and $v \in V$, $v \cdot a$ is defined as an element of V. Suppose that $v \cdot a$ is linear over k in a and v, so that $v \cdot a$ corresponds to a mapping from $V \times A$ into V that is bilinear over k. If we also have that

$$(v \cdot a) \cdot b = v \cdot (a\,b) \tag{6.4.7}$$

for every $a, b \in A$ and $v \in V$, then V is said to be a *right module over* A, as an associative algebra over k. If A has a multiplicative identity element e, then one may require that

$$v \cdot e = v \tag{6.4.8}$$

for every $v \in V$, as usual.

If V is a right module over A, as in the preceding paragraph, then

$$\rho_a(v) = v \cdot a \tag{6.4.9}$$

defines a module homomorphism from V into itself for each $a \in A$, because $v \cdot a$ is linear over k in v. The mapping from $a \in A$ to $\rho_a \in \mathrm{Hom}_k(V, V)$ is linear over k, because $v \cdot a$ is linear over k in a. The multiplicativity condition (6.4.7) is the same as saying that

$$\rho_b(\rho_a(v)) = \rho_{a\,b}(v) \tag{6.4.10}$$

for every $a, b \in A$ and $v \in V$, which means that

$$\rho_b \circ \rho_a = \rho_{a\,b} \tag{6.4.11}$$

for every $a, b \in A$. Thus $a \mapsto \rho_a$ is an opposite algebra homomorphism from A into $\mathrm{Hom}_k(V, V)$. If A has a multiplicative identity element e, then (6.4.8) says that ρ_e is the identity mapping on V.

Remember that A is a module over k in particular. We may also consider A as both a right and left module over itself, where the actions of A on itself as a module over k on the left and the right are given by multiplication on A. The linearity conditions for these actions correspond to the definition of an algebra over k in the strict sense. Similarly, the conditions (6.4.5) and (6.4.7) correspond in this situation to associativity of multiplication on A. If A has a multiplicative identity element e, then (6.4.6) and (6.4.8) hold automatically.

Equivalently, the representation of A on itself as in (6.4.4) corresponds to the multiplication operators discussed in Section 2.2. Similarly, if $V = A$, then (6.4.9) corresponds to the right multiplication operators discussed in Section 2.7.

6.5 Representations of Lie algebras

Let k be a commutative ring with a multiplicative identity element, let $(A, [\cdot,\cdot]_A)$ be a Lie algebra over k, and let V be a module over k. The space $\mathrm{Hom}_k(V, V)$ of module homomorphisms from V into itself is an associative algebra over k with respect to compositions of mappings, and hence a Lie algebra over k with respect to the corresponding commutator bracket. A Lie algebra homomorphism from A into $\mathrm{Hom}_k(V, V)$, as a Lie algebra over k, is also known as a Lie algebra *representation* of A on V.

As before, a Lie algebra representation of A on V may be denoted ρ, where ρ_a is the module homomorphism from V into itself corresponding to $a \in A$, and $\rho_a(v)$ is the image of $v \in V$ under ρ_a. Thus $\rho_a(v)$ is linear over k in a and v, and

$$\rho_{[a,b]_A} = \rho_a \circ \rho_b - \rho_b \circ \rho_a \tag{6.5.1}$$

for every $a, b \in A$. Equivalently, this means that

$$\rho_{[a,b]_A}(v) = \rho_a(\rho_b(v)) - \rho_b(\rho_a(v)) \tag{6.5.2}$$

for every $a, b \in A$ and $v \in V$.

Let ρ be a Lie algebra representation of A on V, and put

$$\rho_a(v) = a \cdot v \tag{6.5.3}$$

for every $a \in A$ and $v \in V$. This is linear over k in a and v, so that it corresponds to a mapping from $A \times V$ into V that is bilinear over k. Using this notation, (6.5.2) can be reexpressed as saying that

$$([a, b]_A) \cdot v = a \cdot (b \cdot v) - b \cdot (a \cdot v) \tag{6.5.4}$$

for every $a, b \in A$ and $v \in V$. We may also call V a *module* over A, as a Lie algebra over k, with respect to this representation.

Suppose for the moment that A is an associative algebra over k, where multiplication of $a, b \in A$ is expressed as $a\,b$. Thus A may be considered as a Lie algebra over k with respect to the corresponding commutator bracket $[a, b] = a\,b - b\,a$. If ρ is a representation of A on V, where A is considered as an associative algebra over k, then ρ is a Lie algebra representation of A on V too. Equivalently, if V is a left module over A as an associative algebra over k, then V is a module over A as a Lie algebra over k as well. Suppose now that V is a right module over A as an associative algebra over k, and let ρ be as in (6.4.9). This means that $a \mapsto \rho_a$ is an opposite algebra homomorphism from A into $\mathrm{Hom}_k(V, V)$, as before. If $a, b \in A$, then

$$\rho_{[a,b]} = \rho_{a\,b} - \rho_{b\,a} = \rho_b \circ \rho_a - \rho_a \circ \rho_b. \tag{6.5.5}$$

It follows that $-\rho_a$ defines a Lie algebra representation of A on V in this case.

Let A be any Lie algebra over k, and remember that the corresponding adjoint representation was defined in Section 2.4. This defines a representation of A on itself, as a module over k.

6.6 Subrepresentations

Let k be a commutative ring with a multiplicative identity element, and let A be an associative algebra over k. Also let ρ be a representation of A on a module V over k. Suppose that W is a submodule of V such that

$$\rho_a(W) \subseteq W \tag{6.6.1}$$

for every $a \in A$. Thus, for each $a \in A$, the restriction of ρ_a to W defines a module homomorphism from W into itself. This defines a representation of A on W, which is a *subrepresentation* of ρ on V.

As before, V may be considered as a left module over A, with $a \cdot v = \rho_a(v)$ for every $a \in A$ and $v \in V$. Using this notation, (6.6.1) is the same as saying that

$$a \cdot w \in W \tag{6.6.2}$$

for every $a \in A$ and $w \in W$. Under these conditions, we may also say that W is a *(left) submodule* of V, as a left module over A.

Similarly, suppose that V is a right module over A. If W is a submodule of V as a module over k, and if

$$w \cdot a \in W \tag{6.6.3}$$

for every $a \in A$ and $w \in W$, then we say that W is a *(right) submodule* of V, as a right module over A.

As a basic class of examples, let V be a module over k, and let A be a subalgebra of $\mathrm{Hom}_k(V, V)$, as an associative algebra over k with respect to composition of mappings. There is an obvious representation of A on V, because the elements of A are already module homomorphisms from V into itself. Let W be a submodule of V, as a module over k, such that

$$a(W) \subseteq W \tag{6.6.4}$$

for every $a \in A$. The restrictions of the elements of A to W defines a subrepresentation of the obvious representation of A on V just mentioned. Equivalently, V is a left module over A in an obvious way, and W is a left submodule of V as a left module over A.

As another basic class of examples, let A be any associative algebra over k. We may consider A as both a left and right module over itself, using multiplication on the left and on the right, as in Section 6.4. A left ideal in A is the same as a left submodule of A as a left module over itself, and similarly a right ideal in A is the same as a right submodule of A as a right module over itself.

Now let $(A, [\cdot, \cdot]_A)$ be a Lie algebra over k, and let ρ be a representation of A as a Lie algebra on a module V over k. Suppose that W is a submodule of V, as a module over k, such that (6.6.1) holds for every $a \in A$. Hence the restriction of ρ_a to W defines a homomorphism from W into itself, as a module over k, for every $a \in A$. This defines a representation of A as a Lie algebra on W, which is a *subrepresentation* of ρ on V.

As usual, V may be considered as a module over A as a Lie algebra, with $a \cdot v = \rho_a(v)$ for every $a \in A$ and $v \in V$. The condition (6.6.1) on W can be reexpressed in this notation as (6.6.2), as before. In this case, W may be called a *submodule* of V, as a module over A, as a Lie algebra over k.

Let V be a module over k, and let A be a Lie subalgebra of $\mathrm{Hom}_k(V, V)$, as a Lie algebra with respect to the usual commutator bracket. As before, there is an obvious representation of A as a Lie algebra over k on V, because the elements of A are already homomorphisms from V into itself, as a module over k. If W is a submodule of V, as a module over k, that satisfies (6.6.4) for every $a \in A$, then the restrictions of the elements of A to W defines a subrepresentation of this representation of A as a Lie algebra over k on V. This is the same as saying that V is a module over A as a Lie algebra over k in an obvious way, and that W is a submodule of V as a module over A.

If A is any Lie algebra over k, then subrepresentations of the adjoint representation of A correspond exactly to ideals in A.

6.7 Homomorphisms between representations

Let k be a commutative ring with a multiplicative identity element, and let A be an associative algebra over k again. Also let V, W be modules over k, and let ρ^V, ρ^W be representations of A on V, W, respectively. Suppose that ϕ is a homomorphism from V into W, as modules over k, such that

$$\phi \circ \rho^V_a = \rho^W_a \circ \phi \tag{6.7.1}$$

for every $a \in A$, which is the same as saying that

$$\phi(\rho^V_a(v)) = \rho^W_a(\phi(v)) \tag{6.7.2}$$

for every $a \in A$ and $v \in V$. In this case, we say that ϕ *intertwines* the representations ρ^V and ρ^W, or that ϕ is a *homomorphism* between these representations. If ϕ is a one-to-one mapping from V onto W, then ϕ^{-1} intertwines ρ^W and ρ^V as a mapping from W onto V, and we say that ϕ defines an *isomorphism* between ρ^V and ρ^W.

Let us consider V and W as left modules over A, with

$$a \cdot v = \rho^V_a(v), \quad a \cdot w = \rho^W_a(w) \tag{6.7.3}$$

for every $a \in A$, $v \in V$, and $w \in W$. Thus (6.7.2) may be reexpressed as

$$\phi(a \cdot v) = a \cdot \phi(v) \tag{6.7.4}$$

for every $a \in A$ and $v \in V$. We may also say that ϕ defines a *homomorphism* from V into W as left modules over A in this situation. If ϕ is a one-to-one mapping from V onto W, then it follows that ϕ^{-1} is a homomorphism from W into V, as left modules over A. Under these conditions, ϕ is said to be an *isomorphism* from V onto W, as left modules over A.

Suppose now that V and W are right modules over A, so that $v \cdot a$ and $w \cdot a$ are defined as elements of V and W, respectively, for every $a \in A$, $v \in V$, and $w \in W$. Let ϕ be a homomorphism from V into W, as modules over k. If

$$\phi(v \cdot a) = \phi(v) \cdot a \tag{6.7.5}$$

for every $a \in A$ and $v \in V$, then ϕ is said to be a *homomorphism* from V into W, as right modules over A. If ϕ is also a one-to-one mapping from V onto W, then ϕ^{-1} is a homomorphism from W into V, as right modules over A. As before, ϕ is said to be an *isomorphism* from V onto W, as right modules over A, under these conditions.

Let $(A, [\cdot, \cdot]_A)$ be a Lie algebra over k, and let ρ^V, ρ^W be representations of A as a Lie algebra on modules V, W over k, respectively. Also let ϕ be a homomorphism from V into W, as modules over k. If ϕ satisfies (6.7.1) for every $a \in A$, then ϕ is said to *intertwine* ρ^V and ρ^W, or equivalently be a *homomorphism* between these representations. We may consider V and W as modules over A as a Lie algebra over k, as in (6.7.3). Using this notation, we can reexpress (6.7.2) as (6.7.4), and we say that ϕ is a *homomorphism* from V into W as modules over A, as a Lie algebra over k. If ϕ is a one-to-one mapping from V onto W, then ϕ^{-1} is a homomorphism from W into V, as modules over A. In this case, ϕ is an *isomorphism* between these representations of A, or equivalently an *isomorphism* from V onto W, as modules over A.

6.8 Quotient representations

Let k be a commutative ring with a multiplicative identity element, and let A be an associative algebra over k. Also let V be a module over k, and let ρ^V be a representation of A on V. Suppose that

$$\rho_a^V(W) \subseteq W \tag{6.8.1}$$

for every $a \in A$, as in Section 6.6. This implies that for each $a \in A$ there is a unique mapping $\rho_a^{V/W}$ from V/W into itself such that

$$\rho_a^{V/W} \circ q = q \circ \rho_a^V \tag{6.8.2}$$

as mappings from V into V/W, as in Section 6.3. One can check that this defines $\rho^{V/W}$ as a representation of A on V/W.

Equivalently, suppose that V is a left module over A, and that W is a left submodule of V. If $a \in A$ and $v \in V$, then $q(a \cdot v)$ defines an element of V/W that is equal to 0 when $v \in W$. This permits us to define an action of A on V/W on the left, with

$$a \cdot q(v) = q(a \cdot v) \tag{6.8.3}$$

for every $a \in A$ and $v \in V$. This defines V/W as a left module over A, as before. If A_0 is a left ideal in A, then note that the quotient A/A_0 is a left module over A.

Similarly, suppose that V is a right module over A, and that W is a right submodule of V. If $a \in A$ and $v \in V$, then $q(v \cdot a)$ is an element of V/W that is equal to 0 when $v \in W$. Using this, we can define an action of A on V/W on the right, with

$$q(v) \cdot a = q(v \cdot a) \tag{6.8.4}$$

for every $a \in A$ and $v \in V$. One can verify that this defines V/W as a right module over A. If A_0 is a right ideal in A, then the quotient A/A_0 is a right module over A.

Suppose now that A is a Lie algebra over k, and that ρ^V is a representation of A on V. If W satisfies (6.8.1) for every $a \in A$, then one can define $\rho^{V/W}$ on V/W as in (6.8.2). One can check that $\rho^{V/W}$ is a representation of A on V/W. Equivalently, if V is a module over A, and if W is a submodule of V as a module over A, then we can define the action of A on V/W as in (6.8.3). This makes V/W a module over A, as a Lie algebra over k, as before.

In each of these situations, the quotient mapping q intertwines the actions of A on V and V/W, by construction.

6.9 Sums of representations

Let k be a commutative ring with a multiplicative identity element, and let I be a nonempty set. Also let V_j be a module over k for every $j \in I$. Thus the direct product $\prod_{j \in I} V_j$ of the V_j's defines a module over k, and the direct sum $\bigoplus_{j \in I} V_j$ is a submodule of $\prod_{j \in I} V_j$, as in Section 4.1. If $v \in \prod_{j \in I} V_j$ and $j \in I$, then v_j denotes the jth coordinate of v in V_j, as before.

Let A be a module over k, and suppose that for each $j \in I$, β^{V_j} is a mapping from $A \times V_j$ into V_j that is bilinear over k. If $a \in A$ and $v \in \prod_{j \in I} V_j$, then $\beta(a, v)$ can be defined as an element of $\prod_{j \in I} V_j$ by putting

$$(\beta(a, v))_j = \beta^{V_j}(a, v_j) \tag{6.9.1}$$

for every $j \in I$. It is easy to see that this defines β as a mapping from $A \times \prod_{j \in I} V_j$ into $\prod_{j \in I} V_j$ that is bilinear over k. If $v \in \bigoplus_{j \in I} V_j$, then

$$\beta(a, v) \in \bigoplus_{j \in I} V_j \tag{6.9.2}$$

for every $a \in A$.

Equivalently, if the bilinear action of A on V_j is given by ρ^{V_j} for each $j \in I$, as in Section 6.1, then the corresponding bilinear action ρ of A on $\prod_{j \in I} V_j$ is defined by

$$(\rho_a(v))_j = \rho_a^{V_j}(v_j). \tag{6.9.3}$$

Similarly, if the bilinear action of A on V_j is expressed as $a \cdot v_j$ for every $a \in A$, $v_j \in V_j$, and $j \in I$, then the corresponding bilinear action of A on $\prod_{j \in I} V_j$ can be expressed by $a \cdot v$ for every $a \in A$ and $v \in \prod_{j \in I} V_j$, where

$$(a \cdot v)_j = a \cdot v_j \tag{6.9.4}$$

for each $j \in I$. If A acts on V_j on the right for each $j \in I$, so that the bilinear action is expressed as $v_j \cdot a$ for every $a \in A$, $v_j \in V_j$, and $j \in I$, then the corresponding bilinear action of A on $\prod_{j \in I} V_j$ on the right can be expressed as $v \cdot a$ for every $a \in A$ and $v \in \prod_{j \in I} V_j$, where

$$(v \cdot a)_j = v_j \cdot a \tag{6.9.5}$$

for each $j \in I$.

Let A be an associative algebra over k. If ρ^{V_j} is a representation of A on V_j for each $j \in I$, then one can check that (6.9.3) defines ρ as a representation of A on $\prod_{j \in I} V_j$. Equivalently, if V_j is a left module over A for every $j \in I$, then $\prod_{j \in I} V_j$ is a left module over A with respect to (6.9.4). Note that $\bigoplus_{j \in I} V_j$ is a left submodule of $\prod_{j \in I} V_j$, as a left module over A, as in (6.9.2). Similarly, if V_j is a right module over A for every $j \in I$, then $\prod_{j \in I} V_j$ a right module over A with respect to (6.9.5), and $\bigoplus_{j \in I} V_j$ is a right submodule of $\prod_{j \in I} V_j$, as a right module over A.

Now let A be a Lie algebra over k. If ρ^{V_j} is a representation of A on V_j for every $j \in I$, then one can verify that (6.9.3) defines ρ as a representation of A on $\prod_{j \in I} V_j$. Equivalently, if V_j is a module over A for every $j \in I$, then $\prod_{j \in I} V_j$ is a module over A with respect to (6.9.4). As before, $\bigoplus_{j \in I} V_j$ is a submodule of $\prod_{j \in I} V_j$, as a module over A.

Let V be a module over k, and let V_1, V_2 be submodules of V. Observe that

$$V_1 + V_2 = \{v_1 + v_2 : v_1 \in V_1,\ v_2 \in V_2\} \tag{6.9.6}$$

is a submodule of V too. The direct sum $V_1 \oplus V_2$ of V_1 and V_2 can be defined as a module over k as in Section 4.1, with $I = \{1, 2\}$. More precisely, $V_1 \oplus V_2$ can be defined as a set as the Cartesian product $V_1 \times V_2$ of V_1 and V_2, consisting of all ordered pairs (v_1, v_2) with $v_1 \in V_1$ and $v_2 \in V_2$. Addition and scalar multiplication can be defined on $V_1 \oplus V_2$ coordinatewise, as usual. Observe that

$$(v_1, v_2) \mapsto v_1 + v_2 \tag{6.9.7}$$

defines a homomorphism from $V_1 \oplus V_2$ onto $V_1 + V_2$, as modules over k. If

$$V_1 \cap V_2 = \{0\}, \tag{6.9.8}$$

then (6.9.7) is injective as a mapping from $V_1 \oplus V_2$ into V.

Let A be a module over k again, and suppose that we have a bilinear action of A on V. If this action maps V_1 and V_2 into themselves, then it maps $V_1 + V_2$ into itself as well. In this case, we also get a corresponding bilinear action of A on $V_1 \oplus V_2$, as before. Of course, (6.9.7) intertwines the bilinear actions of A on $V_1 \oplus V_2$ and $V_1 + V_2$.

6.10 Compatible bilinear mappings

Let k be a commutative ring with a multiplicative identity element, and let A and V be modules over k. Also let ρ be a bilinear action of A on V, so that

ρ_a is a module homomorphism from V into itself for every $a \in A$, and $a \mapsto \rho_a$ is a module homomorphism from A into $\mathrm{Hom}_k(V, V)$, as in Section 6.1. Let W be another module over k, and let μ be a mapping from $V \times V$ into W that is bilinear over k. Suppose that for every $a \in A$ there is an $\widetilde{a} \in A$ such that

$$\mu(\rho_a(u), v) = \mu(u, \rho_{\widetilde{a}}(v)) \tag{6.10.1}$$

for every $u, v \in V$. If $k = \mathbf{C}$, then one may consider a sesquilinear form μ on V.

Let V_0 be a submodule of V, and put

$$(V_0)^\perp = (V_0)^{\perp,\mu} = \{u \in V : \text{ for every } v \in V_0,\ \mu(u, v) = 0\}. \tag{6.10.2}$$

Suppose that ρ satisfies the compatibility condition with μ in the preceding paragraph, and that

$$\rho_a(V_0) \subseteq V_0 \tag{6.10.3}$$

for every $a \in A$. Let $a \in A$, $u \in (V_0)^\perp$, and $v \in V_0$ be given, and let $\widetilde{a} \in A$ be as in (6.10.1). Observe that

$$\mu(\rho_a(u), v) = \mu(u, \rho_{\widetilde{a}}(v)) = 0, \tag{6.10.4}$$

because $\rho_{\widetilde{a}}(v) \in V_0$, by (6.10.3). This means that $\rho_a(u) \in (V_0)^\perp$, so that

$$\rho_a((V_0)^\perp) \subseteq (V_0)^\perp. \tag{6.10.5}$$

Now let A be an associative algebra over k, and suppose that ρ is a representation of A on V. Also let $a \mapsto a^*$ be an opposite algebra automorphism on A. One way that (6.10.1) can hold is with $\widetilde{a} = a^*$, so that

$$\mu(\rho_a(u), v) = \mu(u, \rho_{a^*}(v)) \tag{6.10.6}$$

for every $a \in A$ and $u, v \in V$. If $k = \mathbf{C}$ and μ is a sesquilinear form on V, then one may consider a conjugate-linear opposite algebra automorphism on A.

If ρ satisfies (6.10.6), then

$$\mu(\rho_a(u), \rho_a(v)) = \mu(u, \rho_{a^*}(\rho_a(v))) = \mu(u, \rho_{a^*\,a}(v)) \tag{6.10.7}$$

for every $a \in A$ and $u, v \in V$. Suppose that A has a multiplicative identity element e, and that ρ_e is the identity mapping on V. If $a \in A$ satisfies $a^*\,a = e$, then (6.10.7) implies that ρ_a preserves μ.

In some situations there may be an opposite algebra automorphism $T \mapsto T^\star$ on the algebra $\mathrm{Hom}_k(V, V)$ of module homomorphisms from V into itself such that

$$\mu(T(u), v) = \mu(u, T^\star(v)) \tag{6.10.8}$$

for every $u, v \in V$ and $T \in \mathrm{Hom}_k(V, V)$. In this case, one can ask that ρ be compatible with these opposite algebra automorphisms on A and $\mathrm{Hom}_k(V, V)$, in the sense that

$$(\rho_a)^\star = \rho_{a^*} \tag{6.10.9}$$

for every $a \in A$. Note that (6.10.6) follows from (6.10.8) and (6.10.9). More precisely, one might have an opposite algebra automorphism on a subalgebra of $\mathrm{Hom}_k(V, V)$ that satisfies (6.10.8), and a representation ρ of A on V with values in this subalgebra of $\mathrm{Hom}_k(V, V)$. If $k = \mathbf{C}$, then one may consider conjugate-linear opposite algebra automorphisms and a sesquilinear form on V again.

Suppose now that $(A, [\cdot, \cdot]_A)$ is a Lie algebra over k, and that ρ is a representation of A as a Lie algebra on V. A natural compatibility condition for ρ with μ is that ρ_a be antisymmetric with respect to μ for every $a \in A$, so that

$$\mu(\rho_a(u), v) = -\mu(u, \rho_a(v)) \tag{6.10.10}$$

for every $u, v \in V$. This means that (6.10.1) holds with $\widetilde{a} = -a$.

Let us take $V = A$, as a module over k, and ρ to be the adjoint representation on A. Thus, for each $x \in A$, $\rho_x = \mathrm{ad}\, x = \mathrm{ad}_x$ is the module homomorphism from A into itself defined by

$$\mathrm{ad}_x(z) = [x, z]_A, \tag{6.10.11}$$

as in Section 2.4. In this situation, (6.10.10) is the same as saying that

$$\mu(\mathrm{ad}_w(x), y) = -\mu(x, \mathrm{ad}_w(y)) \tag{6.10.12}$$

for every $w, x, y \in A$. Equivalently, this means that

$$\mu([w, x]_A, y) = -\mu(x, [w, y]_A) \tag{6.10.13}$$

for every $w, x, y \in A$, which can also be expressed as

$$\mu([x, w]_A, y) = \mu(x, [w, y]_A). \tag{6.10.14}$$

This property is sometimes described by saying that μ is *associative* on $A \times A$, as on p21 of [14].

6.11 Representations and formal power series

Let k be a commutative ring with a multiplicative identity element, let V be a module over k, and let T be an indeterminate. Remember that there are natural isomorphisms between $\mathrm{Hom}_k(V, V[[T]])$,

$$\mathrm{Hom}_{k[[T]]}(V[[T]], V[[T]]), \tag{6.11.1}$$

and

$$(\mathrm{Hom}_k(V, V))[[T]], \tag{6.11.2}$$

as modules over $k[[T]]$, as in Sections 4.8 and 4.9. Of course, $\mathrm{Hom}_k(V, V)$ and (6.11.1) are associative algebras over k and $k[[T]]$, respectively, with composition of mappings as multiplication. Similarly, (6.11.2) is an associative algebra over

$k[[T]]$, as in Section 4.6. In fact, the natural isomorphism between (6.11.2) and (6.11.1) preserves multiplication, as in Section 4.10.

As before, there is also a natural isomorphism between $\mathrm{Hom}_k(V, V[T])$ and

$$\mathrm{Hom}_{k[T]}(V[T], V[T]), \tag{6.11.3}$$

and a natural injective homomorphism from

$$(\mathrm{Hom}_k(V, V))[T] \tag{6.11.4}$$

into (6.11.3), as modules over $k[T]$. Note that (6.11.3) is an associative algebra over $k[T]$ with respect to composition of mappings, and that (6.11.4) is an associative algebra over $k[T]$ too, as in Section 4.6. The natural injective homomorphism from (6.11.4) into (6.11.3) preserves multiplication, as in Section 4.10.

Let A be an associative algebra over k, so that $A[[T]]$ and $A[T]$ are associative algebras over $k[[T]]$ and $k[T]$, respectively, as in Section 4.6. Remember that a representation of A on V corresponds to an algebra homomorphism from A into $\mathrm{Hom}_k(V, V)$, as in Section 6.4. This can be extended to an algebra homomorphism from $A[[T]]$ into (6.11.2), as algebras over $k[[T]]$, as in Section 4.12. This corresponds to an algebra homomorphism from $A[[T]]$ into (6.11.1), which is to say a representation of $A[[T]]$ on $V[[T]]$. Similarly, we get an algebra homomorphism from $A[T]$ into (6.11.4), as algebras over $k[T]$, as in Section 4.12. This leads to an algebra homomorphism from $A[T]$ into (6.11.3), which gives a representation of $A[T]$ on $V[T]$. If V is a right module over A, then we can get $V[[T]]$ as a right module over $A[[T]]$, and $V[T]$ as a right module over $A[T]$, in the same way.

Remember that an associative algebra is automatically a Lie algebra with respect to the corresponding commutator bracket. The natural algebra isomorphism between (6.11.2) and (6.11.1) mentioned earlier automatically preserves commutator brackets. Similarly, the natural injective algebra homomorphism from (6.11.4) into (6.11.3) automatically preserves commutator brackets. Let A be a Lie algebra over k, so that $A[[T]]$ and $A[T]$ are Lie algebras over $k[[T]]$ and $k[T]$, as in Section 4.6. A representation of A on V is the same as a homomorphism from A into $\mathrm{Hom}_k(V, V)$, as a Lie algebra over k with respect to the commutator bracket. This can be extended to a Lie algebra homomorphism from $A[[T]]$ into (6.11.2), as in Section 4.12. This corresponds to a Lie algebra homomorphism from $A[[T]]$ into (6.11.1), which is a representation of $A[[T]]$ as a Lie algebra over $k[[T]]$ on $V[[T]]$. We also get a Lie algebra homomorphism from $A[T]$ into (6.11.4), as in Section 4.12. This leads to a Lie algebra homomorphism from $A[T]$ into (6.11.3), and hence a representation of $A[T]$ as a Lie algebra over $k[T]$ on $V[T]$.

6.12 Opposite algebras

Let k be a commutative ring with a multiplicative identity element, and let A be an algebra over k in the strict sense, where multiplication of $a, b \in A$ is expressed as $a\,b$. The corresponding *opposite algebra* A^{op} is defined as an algebra over k in the strict sense as follows. As a module over k, A^{op} is the same as A. The product of $a, b \in A^{op}$ is defined to be the product $b\,a$ of b and a in A. Thus multiplication in A^{op} is the same as multiplication in A exactly when A is commutative. If A has a multiplicative identity element e, then e is also the multiplicative identity element in A^{op}. If A is associative, then it is easy to see that A^{op} is associative as well. By construction, the identity mapping on A is an opposite algebra isomorphism between A and A^{op}.

Let B be another algebra over k in the strict sense. An algebra homomorphism from A into B may also be considered as an algebra homomorphism from A^{op} into B^{op}. An opposite algebra homomorphism from A into B corresponds to an algebra homomorphism from A^{op} into B, or from A into B^{op}.

Suppose that A is an associative algebra over k, and let V be a module over k. A bilinear action of A on V makes V into a left module over A exactly when it makes V into a right module over A^{op}. Similarly, a bilinear action of A on V makes V into a right module over A exactly when it makes V into a left module over A^{op}. Equivalently, this corresponds to a representation of A^{op} on V.

Let n be a positive integer, and let $M_n(A)$ and $M_n(A^{op})$ be the corresponding spaces of $n \times n$ matrices with entries in A and A^{op}, respectively, as in Section 2.8. Thus $M_n(A)$ and $M_n(A^{op})$ are the same as modules over k, using entrywise addition and scalar multiplication. Remember that $M_n(A)$ and $M_n(A^{op})$ are algebras over k with respect to matrix multiplication. Let a, b be $n \times n$ matrices with entries in A, which can also be considered as $n \times n$ matrices with entries in A^{op}. The product c of a and b in $M_n(A)$ is given by

$$c_{j,r} = \sum_{l=1}^{n} a_{j,l}\, b_{l,r} \tag{6.12.1}$$

for every $j, r = 1, \ldots, n$, as usual. Let $\widetilde{c}$ be the product of a and b in $M_n(A^{op})$. This means that

$$\widetilde{c}_{j,r} = \sum_{l=1}^{n} b_{l,r}\, a_{j,l} \tag{6.12.2}$$

for every $j, r = 1, \ldots, n$, where the terms in the sum on the right use multiplication in A.

Let a^t, b^t, and c^t be the transposes of a, b, and c, respectively, as in Section 2.8. Thus

$$c^t_{j,r} = c_{r,j} = \sum_{l=1}^{n} a_{r,l}\, b_{l,j} \tag{6.12.3}$$

for every $j, r = 1, \ldots, n$. This is the same as the product of b^t and a^t in $M_n(A^{op})$. This means that

$$a \mapsto a^t \tag{6.12.4}$$

is an opposite algebra homomorphism from $M_n(A)$ into $M_n(A^{op})$. More precisely, (6.12.4) is an opposite algebra isomorphism from $M_n(A)$ onto $M_n(A^{op})$, because (6.12.4) is a one-to-one mapping from $M_n(A)$ onto $M_n(A^{op})$.

6.13 Matrices and associative algebras

Let k be a commutative ring with a multiplicative identity element, and let A be an associative algebra over k. Also let n be a positive integer, and let A^n be the space of n-tuples of elements of A, as usual. Of course, A^n is a module over k with respect to coordinatewise addition and scalar multiplication. Similarly, A^n may be considered as both a left and right module over A, with respect to coordinatewise multiplication. More precisely, if $a \in A$ and $x = (x_1, \ldots, x_n)$ is an element of A^n, then $a \cdot x$ and $x \cdot a$ are defined as elements of A^n by

$$a \cdot x = (a\,x_1, \ldots, a\,x_n) \tag{6.13.1}$$

and

$$x \cdot a = (x_1\,a, \ldots, x_n\,a), \tag{6.13.2}$$

respectively. If A is commutative, then (6.13.1) and (6.13.2) are the same. Note that

$$(a \cdot x) \cdot b = a \cdot (x \cdot b) \tag{6.13.3}$$

for every $a, b \in A$ and $x \in A^n$.

Let $\alpha = (\alpha_{j,l})$ be an $n \times n$ matrix with entries in A, which is to say an element of $M_n(A)$. If $x \in A^n$, then let $T^L_\alpha(x)$ be the element of A^n whose jth coordinate is given by

$$(T^L_\alpha(x))_j = \sum_{l=1}^n \alpha_{j,l}\,x_l \tag{6.13.4}$$

for every $j = 1, \ldots, n$. Similarly, let $T^R_\alpha(x)$ be the element of A^n whose jth coordinate is given by

$$(T^R_\alpha(x))_j = \sum_{l=1}^n x_l\,\alpha_{j,l} \tag{6.13.5}$$

for every $j = 1, \ldots, n$. If A is commutative, then (6.13.4) and (6.13.5) are the same. It is easy to see that T^L_α and T^R_α are homomorphisms from A^n into itself, as a module over k. Observe that

$$(T^L_\alpha(x)) \cdot a = T^L_\alpha(x \cdot a) \tag{6.13.6}$$

and

$$a \cdot (T^R_\alpha(x)) = T^R_\alpha(a \cdot x) \tag{6.13.7}$$

for every $a \in A$ and $x \in A^n$. Thus T^L_α is a homomorphism from A^n into itself as a right module over A, and T^R_α is a homomorphism from A^n into itself as a left module over A.

If $t \in k$, then $t\,\alpha = (t\,\alpha_{j,l}) \in M_n(A)$, as in Section 2.8. Clearly

$$T^L_{t\,\alpha}(x) = t\,T^L_\alpha(x) \tag{6.13.8}$$

and

$$T^R_{t\,\alpha}(x) = t\,T^R_\alpha(x) \tag{6.13.9}$$

for every $x \in A^n$. Let $\beta = (\beta_{j,l})$ be another $n \times n$ matrix with entries in A, so that $\alpha + \beta \in M_n(A)$ too. Of course,

$$T^L_{\alpha+\beta}(x) = T^L_\alpha(x) + T^L_\beta(x) \tag{6.13.10}$$

and

$$T^R_{\alpha+\beta}(x) = T^R_\alpha(x) + T^R_\beta(x) \tag{6.13.11}$$

for every $x \in A^n$. One can check that

$$T^L_\alpha(T^L_\beta(x)) = T^L_{\alpha\,\beta}(x) \tag{6.13.12}$$

for every $x \in A^n$, where $\alpha\,\beta \in M_n(A)$ is defined using matrix multiplication, as in Section 2.8. Let γ be the product of α and β as elements of $M_n(A^{op})$, where A^{op} is the opposite algebra associated to A, as in the previous section. One can verify that

$$T^R_\alpha(T^R_\beta(x)) = T^R_\gamma(x) \tag{6.13.13}$$

for every $x \in A^n$.

Suppose that A has a multiplicative identity element e. Remember that the corresponding identity matrix in $M_n(A)$ has diagonal entries equal to e and all other entries equal to 0, as in Section 2.8. If α is the identity matrix, then T^L_α and T^R_α are equal to the identity mapping on A^n. Let $u^1, \ldots, u^n$ be the elements of A^n with $u^l_j = e$ when $j = l$ and $u^l_j = 0$ when $j \neq l$. Thus

$$x = \sum_{l=1}^n x_l \cdot u^l = \sum_{l=1}^n u^l \cdot x_l \tag{6.13.14}$$

for every $x \in A^n$.

If T is any homomorphism from A^n into itself, as a right module over A, then

$$T(x) = T\Big(\sum_{l=1}^n u^l \cdot x_l\Big) = \sum_{l=1}^n T(u^l) \cdot x_l \tag{6.13.15}$$

for every $x \in A^n$. This means that T can be represented in a unique way as T^L_α, with $\alpha \in M_n(A)$. More precisely, $\alpha_{j,l}$ is the jth coordinate of $T(u^l)$ for each $j, l = 1, \ldots, n$. Similarly, if T is a homomorphism from A^n into itself, as a left module over A, then

$$T(x) = T\Big(\sum_{l=1}^n x_l \cdot u^l\Big) = \sum_{l=1}^n x_l \cdot T(u^l) \tag{6.13.16}$$

for every $x \in A^n$. This implies that T can be represented in a unique way as T^R_α, where $\alpha_{j,l}$ is the jth coordinate of $T(u^l)$ for every $j, l = 1, \ldots, n$.

6.14 Irreducibility

Let k be a commutative ring with a multiplicative identity element, let A, V be modules over k, and let ρ be a bilinear action of A on V. Thus ρ_a is a homomorphism from V into itself, as a module over k, for every $a \in A$, and $a \mapsto \rho_a$ is a homomorphism from A into the space $\mathrm{Hom}_k(V, V)$ of module homomorphisms from V into itself, as modules over k, as in Section 6.1. Suppose that there is no submodule W of V, as a module over k, such that $W \neq \{0\}, V$ and

$$\rho_a(W) \subseteq W \tag{6.14.1}$$

for every $a \in A$. In this case, one may say that ρ is *irreducible* on V, or equivalently that V is *simple* with respect to the action of ρ. The condition that $V \neq \{0\}$ is typically included in the definition of irreducibility or simplicity as well.

Let V_1, V_2 be modules over k, and let ρ^1, ρ^2 be bilinear actions of A on V_1, V_2, respectively. Suppose that ϕ is a homomorphism from V_1 into V_2, as modules over k, that intertwines ρ^1 and ρ^2, as in Section 6.2. If $v_1 \in V_1$ is in the kernel of ϕ and $a \in A$, then

$$\phi(\rho^1_a(v_1)) = \rho^2_a(\phi(v_1)) = 0, \tag{6.14.2}$$

so that $\rho^1_a(v_1)$ is in the kernel of ϕ too. If ρ^1 is irreducible on V_1, then it follows that the kernel of ϕ is either trivial or equal to V_1, so that ϕ is either injective or equal to 0 on V_1. This is part of *Schur's lemma.*

Similarly,

$$\rho^2_a(\phi(V_1)) = \phi(\rho^1_a(V_1)) \subseteq \phi(V_1) \tag{6.14.3}$$

for every $a \in A$. If ρ^2 is irreducible on V_2, then it follows that $\phi(V_1) = \{0\}$ or V_2, so that either $\phi = 0$ on V_1 or ϕ is surjective. This is another part of Schur's lemma.. If ρ^1 and ρ^2 are both irreducible, then either $\phi = 0$ or ϕ is a bijection.

Let V be a module over k again, and let ρ be a bilinear action of A on V. Remember that $\mathrm{Hom}_k(V, V)$ is an associative algebra over k with respect to composition of mappings. Consider the space $\mathrm{Hom}_{k,\rho}(V, V)$ of $\phi \in \mathrm{Hom}_k(V, V)$ that intertwine ρ. It is easy to see that $\mathrm{Hom}_{k,\rho}(V, V)$ is a subalgebra of $\mathrm{Hom}_k(V, V)$, and that $\mathrm{Hom}_{k,\rho}(V, V)$ contains the identity mapping on V. If ρ is irreducible, then every nonzero element of $\mathrm{Hom}_{k,\rho}(V, V)$ is invertible, as in the preceding paragraph.

Suppose that k is an algebraically closed field, and that V has positive finite dimension as a vector space over k. If ϕ is any linear mapping from V into itself, then it is well known that there is a $\lambda \in k$ such that ϕ has a nonzero eigenvector in V with eigenvalue λ. Let E_λ be the corresponding eigenspace of eigenvectors of ϕ in V with eigenvalue λ. Let ρ be a bilinear action of A on V again, and suppose that ϕ intertwines ρ. If $a \in A$, then ρ_a maps E_λ into itself, by a standard argument. If ρ is irreducible on V, then it follows that $E_\lambda = V$. This is another part of Schur's lemma.

6.15 Representations and differential operators

Let k be a commutative ring with a multiplicative identity element, let A be a module over k, and let n be a positive integer. Also let $T_1, \ldots, T_n$ be n commuting indeterminates, and let let $\partial_1, \ldots, \partial_n$ be n commuting formal symbols, which may be used to represent partial derivatives, as before. Remember that the space $A[[T_1, \ldots, T_n]]$ of formal power series in $T_1, \ldots, T_n$ with coefficients in A is a module over k, with respect to termwise addition and scalar multiplication, as in Section 5.8.

The space of formal differential operators in $\partial_1, \ldots, \partial_n$ with coefficients in $k[[T_1, \ldots, T_n]]$ is an associative algebra over k, as in Section 5.11. These formal differential operators determine mappings from $A[[T_1, \ldots, T_n]]$ into itself that are linear over k, as before. This defines a representation of the algebra of formal differential operators in $\partial_1, \ldots, \partial_n$ with coefficients in $k[[T_1, \ldots, T_n]]$ on $A[[T_1, \ldots, T_n]]$.

The space of formal differential operators in $\partial_1, \ldots, \partial_n$ with coefficients in $k[T_1, \ldots, T_n]$ is a subalgebra of the algebra of formal differential operators in $\partial_1, \ldots, \partial_n$ with coefficients in $k[[T_1, \ldots, T_n]]$. Thus $A[[T_1, \ldots, T_n]]$ may be considered as a left module over the algebra of formal differential operators in $\partial_1, \ldots, \partial_n$ with coefficients in $k[T_1, \ldots, T_n]$. The mappings from $A[[T_1, \ldots, T_n]]$ into itself corresponding to formal differential operators in $\partial_1, \ldots, \partial_n$ with coefficients in $k[T_1, \ldots, T_n]$ map the space $A[T_1, \ldots, T_n]$ of formal polynomials in $T_1, \ldots, T_n$ with coefficients in A into itself, as in Section 5.11. This means that

(6.15.1) $\qquad A[T_1, \ldots, T_n]$ is a submodule of $A[[T_1, \ldots, T_n]]$,

as a left module over the algebra of formal differential operators in $\partial_1, \ldots, \partial_n$ with coefficients in $k[T_1, \ldots, T_n]$.

Similarly, the space of formal differential operators in $\partial_1, \ldots, \partial_n$ with coefficients in $k[T_1, \ldots, T_n]$ that are homogeneous of degree 0 is a subalgebra of the algebra of formal differential operators in $\partial_1, \ldots, \partial_n$ with coefficients in $k[T_1, \ldots, T_n]$, as in Section 5.14. This permits us to consider $A[T_1, \ldots, T_n]$ as a left module over the algebra of formal differential operators in $\partial_1, \ldots, \partial_n$ with coefficients in $k[T_1, \ldots, T_n]$ that are homogeneous of degree 0. If d is a nonnegative integer, then the space $A_d[T_1, \ldots, T_n]$ of formal polynomials in $T_1, \ldots, T_n$ with coefficients in A that are homogeneous of degree d is a submodule of $A[T_1, \ldots, T_n]$, as a module over k, as in Section 5.13. In fact,

(6.15.2) $\qquad A_d[T_1, \ldots, T_n]$ is a submodule of $A[T_1, \ldots, T_n]$,

as a left module over the algebra of formal differential operators in $\partial_1, \ldots, \partial_n$ with coefficients in $k[T_1, \ldots, T_n]$ that are homogeneous of degree 0, as in Section 5.14.

If $a(T) = (a^1(T), \ldots, a^n(T))$ is in the space $(k[[T_1, \ldots, T_n]])^n$ of n-tuples of elements of $k[[T_1, \ldots, T_n]]$, then put $D_{a(T)} = \sum_{j=1}^n a^j(T)\, \partial_j$, as in Section 5.12. The space of these formal differential operators is a Lie subalgebra of the space of all formal differential operators in $\partial_1, \ldots, \partial_n$ with coefficients in

$k[[T_1, \ldots, T_n]]$, as a Lie algebra over k with respect to the commutator bracket, as in Section 5.15. Thus we may consider $A[[T_1, \ldots, T_n]]$ as a module over the Lie algebra consisting of $D_{a(T)}$, $a(T) \in (k[[T_1, \ldots, T_n]])^n$.

Similarly, the space of $D_{a(T)}$, $a(T) \in (k[T_1, \ldots, T_n])^n$, is a Lie subalgebra of the Lie algebra consisting of $D_{a(T)}$, $a(T) \in (k[[T_1, \ldots, T_n]])^n$. This permits us to consider $A[[T_1, \ldots, T_n]]$ as a module over the Lie algebra consisting of $D_{a(T)}$, $a(T) \in (k[T_1, \ldots, T_n])^n$. We may also consider $A[T_1, \ldots, T_n]$ as a submodule of $A[[T_1, \ldots, T_n]]$, as a module over the Lie algebra consisting of $D_{a(T)}$, with $a(T) \in (k[T_1, \ldots, T_n])^n$.

The space $g_n(k)$ consisting of $D_{a(T)}$, $a(T) \in (k_1[T_1, \ldots, T_n])^n$, is a Lie subalgebra of the Lie algebra of $D_{a(T)}$, $a(T) \in (k[T_1, \ldots, T_n])$, as in Section 5.15. Thus

(6.15.3) we may consider $A[T_1, \ldots, T_n]$ as a module over $g_n(k)$,

as a Lie algebra over k. If d is a nonnegative integer, then

(6.15.4) $A_d[T_1, \ldots, T_n]$ is a submodule of $A[T_1, \ldots, T_n]$, as a module over $g_n(k)$.

Remember that $s_n(k)$ is the Lie subalgebra of $g_n(k)$ consisting of $D_{a(T)}$ where the matrix of coefficients of the components of $a(T) \in (k_1[T_1, \ldots, T_n])^n$ has trace 0. We may consider $A_d[T_1, \ldots, T_n]$ as a module over $s_n(k)$ too, as a Lie algebra over k, for each $d \geq 0$.

Chapter 7

Representations and multilinear mappings

7.1 Some remarks about subalgebras

Let k be a commutative ring with a multiplicative identity element, and let A_1, A_2 be algebras over k in the strict sense. The direct sum $A_1 \oplus A_2$ of A_1 and A_2 can be defined as an algebra over k in the strict sense as in Section 4.1, with $I = \{1, 2\}$. More precisely, $A_1 \oplus A_2$ can be defined as a set as the Cartesian product of A_1 and A_2, consisting of all ordered pairs (a_1, a_2) with $a_1 \in A_1$ and $a_2 \in A_2$. Addition, scalar multiplication, and multiplication on $A_1 \oplus A_2$ are defined coordinatewise, as usual. In particular, if multiplication of $a_1, b_1 \in A_1$ and $a_2, b_2 \in A_2$ are expressed as $a_1\, b_1$ and $a_2\, b_2$, respectively, then

(7.1.1) $$(a_1, 0)\,(0, a_2) = 0$$

in $A_1 \oplus A_2$ for every $a_1 \in A_1$ and $a_2 \in A_2$.

If A is a module over k and $A_1, A_2 \subseteq A$ are submodules of A, then

(7.1.2) $$A_1 + A_2 = \{a_1 + a_2 : a_1 \in A_1,\ a_2 \in A_2\}$$

is a submodule of A, as before. Suppose that A is an algebra over k in the strict sense. If A_1, A_2 are left ideals in A, then (7.1.2) is a left ideal in A. Similarly, if A_1, A_2 are right ideals in A, then (7.1.2) is a right ideal in A. If A_1, A_2 are two-sided ideals in A, then it follows that (7.1.2) is a two-sided ideal in A.

Let A_1, A_2 be subalgebras of A. If

(7.1.3) $$a_1\, a_2 = a_2\, a_1 = 0$$

for every $a_1 \in A_1$ and $a_2 \in A_2$, then it is easy to see that (7.1.2) is a subalgebra of A. In this situation,

(7.1.4) $$(a_1, a_2) \mapsto a_1 + a_2$$

defines a homomorphism from $A_1 \oplus A_2$ into A, as algebras over k in the strict sense. If $(A, [\cdot,\cdot]_A)$ is a Lie algebra over k, then (7.1.3) is the same as saying that

$$[a_1, a_2]_A = 0 \tag{7.1.5}$$

for every $a_1 \in A_1$ and $a_2 \in A_2$.

Let A and B be algebras over k in the strict sense, and let ϕ, ψ be algebra homomorphisms from A into B. Suppose that

$$\phi(x)\,\psi(y) = \psi(y)\,\phi(x) = 0 \tag{7.1.6}$$

for every $x, y \in A$. This implies that

$$\begin{aligned}(\phi(x) + \psi(x))\,(\phi(y) + \psi(y)) \\ &= \phi(x)\,\phi(y) + \phi(x)\,\psi(y) + \psi(x)\,\phi(y) + \psi(x)\,\psi(y) \\ &= \phi(x)\,\phi(y) + \psi(x)\,\psi(y) = \phi(x\,y) + \psi(x\,y)\end{aligned} \tag{7.1.7}$$

for every $x, y \in A$, so that $\phi + \psi$ defines an algebra homomorphism from A into B as well. If $(B, [\cdot,\cdot]_B)$ is a Lie algebra over k, then (7.1.6) is the same as saying that

$$[\phi(x), \psi(y)]_B = 0 \tag{7.1.8}$$

for every $x, y \in A$.

Let A be a Lie algebra over k, and let ρ^1, ρ^2 be Lie algebra representations of A on a module V over k. Let us say that that ρ^1 and ρ^2 are commuting representations of A on V if

$$\rho^1_a \circ \rho^2_b = \rho^2_b \circ \rho^1_a \tag{7.1.9}$$

for every $a, b \in A$. Under these conditions,

$$(\rho^1 + \rho^2)_a = \rho^1_a + \rho^2_a \tag{7.1.10}$$

defines a Lie algebra representation of A on V too, as in the preceding paragraph.

7.2 Representations on linear mappings

Let k be a commutative ring with a multiplicative identity element, and let V, W be modules over k. Remember that the space $\mathrm{Hom}_k(V, W)$ of module homomorphisms from V into W is a module over k too, with respect to pointwise addition and scalar multiplication. Let T be a module homomorphism from V into itself, and let ϕ be a module homomorphism from V into W. Thus

$$\widetilde{T}(\phi) = \phi \circ T \tag{7.2.1}$$

defines another module homomorphism from V into W. This defines $\widetilde{T}$ as a homomorphism from $\mathrm{Hom}_k(V, W)$ into itself, as a module over k.

Let R be another module homomorphism from V into itself, so that the composition $T \circ R$ is a module homomorphism from V into itself as well. In particular, $\widetilde{R}$ and $(\widetilde{T \circ R})$ can be defined as homomorphisms from $\mathrm{Hom}_k(V, W)$, as a module over k, as in the preceding paragraph. If ϕ is a module homomorphism from V into W, then

$$(\widetilde{T \circ R})(\phi) = \phi \circ (T \circ R) = (\phi \circ T) \circ R = \widetilde{R}(\widetilde{T}(\phi)). \tag{7.2.2}$$

This means that

$$(\widetilde{T \circ R}) = \widetilde{R} \circ \widetilde{T} \tag{7.2.3}$$

as mappings from $\mathrm{Hom}_k(V, W)$. Note that

$$T \mapsto \widetilde{T} \tag{7.2.4}$$

is linear over k, as a mapping from $\mathrm{Hom}_k(V, V)$ into the space of mappings from $\mathrm{Hom}_k(V, W)$ into itself. More precisely, this defines an opposite algebra homomorphism from $\mathrm{Hom}_k(V, V)$ into the algebra of module homomorphisms from $\mathrm{Hom}_k(V, W)$ into itself. If T is the identity mapping on V, then $\widetilde{T}$ is the identity mapping on $\mathrm{Hom}_k(V, W)$.

Let A be an associative algebra over k, and let ρ be a representation of A on V. If $a \in A$, then ρ_a is a module homomorphism from V into itself, so that $\widetilde{\rho_a}$ can be defined as before, as a module homomorphism from $\mathrm{Hom}_k(V, W)$ into itself. By hypothesis, $a \mapsto \rho_a$ is an algebra homomorphism from A into $\mathrm{Hom}_k(V, V)$, which implies that $\widetilde{\rho_a}$ is an opposite algebra homomorphism from A into the algebra of module homomorphisms from $\mathrm{Hom}_k(V, W)$ into itself. Similarly, if $a \mapsto \rho_a$ is an opposite algebra homomorphism from A into $\mathrm{Hom}_k(V, V)$, then $a \mapsto \widetilde{\rho_a}$ is an algebra homomorphism from A into the algebra of module homomorphisms from $\mathrm{Hom}_k(V, W)$ into itself. Equivalently, if V is a left module over A, then $\mathrm{Hom}_k(V, W)$ becomes a right module over A in this way, and if V is a right module over A, then $\mathrm{Hom}_k(V, W)$ becomes a left module over A.

Now let A be a Lie algebra over k, and let ρ be a representation of A on V. As before, $\widetilde{\rho_a}$ is defined as a module homomorphism from V into W for every $a \in A$. Under these conditions, one can check that $a \mapsto -\widetilde{\rho_a}$ defines a representation of A as a Lie algebra on $\mathrm{Hom}_k(V, W)$.

7.3 Multilinear mappings

Let k be a commutative ring with a multiplicative identity element, and let n be a positive integer. Also let $V_1, \ldots, V_n$ be n modules over k, and let W be another module over k. A mapping μ from $V_1 \times \cdots \times V_n$ into W is said to be *multilinear over* k if μ is linear over k in each variable separately. This reduces to ordinary linearity over k when $n = 1$, and to bilinearity over k when $n = 2$.

The space of mappings μ from $\prod_{j=1}^n V_j$ into W that are multilinear over k may be denoted $L(V_1, \ldots, V_n; W)$, or $L_k(V_1, \ldots, V_n; W)$ to indicate the role of k. It is easy to see that $L_k(V_1, \ldots, V_n; W)$ is a module over k with respect to pointwise addition and scalar multiplication of mappings from $\prod_{j=1}^n V_j$ into W. More precisely, $L_k(V_1, \ldots, V_n; W)$ may be considered as a submodule of the module of all W-valued functions on $\prod_{j=1}^n V_j$. Of course, $L_k(V_1, \ldots, V_n; W)$ reduces to $\mathrm{Hom}_k(V_1, W)$ when $n = 1$.

Suppose for the moment that $V_1, \ldots, V_n$ are the same module V over k, and that $n \geq 2$. Let us say that $\mu \in L_k(V_1, \ldots, V_n; W)$ is *symmetric* if $\mu(v_1, \ldots, v_n)$ is invariant under permutations of the variables $v_1, \ldots, v_n$. This reduces to the earlier notion of symmetry for bilinear mappings when $n = 2$. Similarly, let us say that $\mu \in L_k(V_1, \ldots, V_n; W)$ is *antisymmetric* if

$$\begin{aligned} \mu(v_1, \ldots, v_{j-1}, v_l, v_{j+1}, \ldots, v_{l-1}, v_j, v_{l+1}, \ldots, v_n) \\ = -\mu(v_1, \ldots, v_{j-1}, v_j, v_{j+1}, \ldots, v_{l-1}, v_l, v_{l+1}, \ldots, v_n) \end{aligned} \tag{7.3.1}$$

for every $v_1, \ldots, v_n \in V$ and $1 \leq j < l \leq n$, which is to say that interchanging two of the variables corresponds to taking the additive inverse of the value of μ. This reduces to the earlier notion of antisymmetry for bilinear mappings when $n = 2$. As usual, it is sometimes better to ask that

$$\mu(v_1, \ldots, v_n) = 0 \tag{7.3.2}$$

whenever $v_j = v_l$ for some $j \neq l$. This implies that μ is antisymmetric, by the same type of argument as for bilinear mappings. If $1 + 1$ is invertible in k, then this condition holds when μ is antisymmetric, as before.

Let $V_1, \ldots, V_n$ be n modules over k for some $n \geq 1$ again, and let j be an integer with $1 \leq j \leq n$. Also let A_j be a module homomorphism from V_j into itself, and let μ be a mapping from $\prod_{j=1}^n V_j$ into W that is multilinear over k. If $v_1 \in V_1, \ldots, v_n \in V_n$, then put

$$(\widetilde{A_j}(\mu))(v_1, \ldots, v_n) = \mu(v_1, \ldots, v_{j-1}, A_j(v_j), v_{j+1}, \ldots, v_n). \tag{7.3.3}$$

This defines a mapping $\widetilde{A_j}(\mu)$ from $\prod_{j=1}^n V_j$ into W, which corresponds to composing μ with A_j in the jth variable. Note that $\widetilde{A_j}(\mu)$ is multilinear over k, because A_j is linear over k. It is easy to see that $\widetilde{A_j}$ is linear over k, as a mapping from $L(V_1, \ldots, V_n; W)$ into itself. The mapping

$$A_j \mapsto \widetilde{A_j} \tag{7.3.4}$$

is linear over k as well, as a mapping from $\mathrm{Hom}_k(V_j, V_j)$ into the space of module homomorphisms from $L(V_1, \ldots, V_n; W)$ into itself.

Let B_j be another module homomorphism from V_j into itself, and let μ be a mapping from $\prod_{j=1}^n V_j$ into W that is multilinear over k again. The composition $B_j \circ A_j$ of A_j and B_j is a module homomorphism from V_j into itself too, so that $(\widetilde{B_j \circ A_j})(\mu)$ can be defined as a multilinear mapping from $\prod_{j=1}^n V_j$ into W as before. More precisely, if $v_1 \in V_1, \ldots, v_n \in V_n$, then

$$\begin{aligned} ((\widetilde{B_j \circ A_j})(\mu))(v_1, \ldots, v_n) \\ = \mu(v_1, \ldots, v_{j-1}, (B_j \circ A_j)(v_j), v_{j+1}, \ldots, v_n) \\ = \mu(v_1, \ldots, v_{j-1}, B_j(A_j(v_j)), v_{j+1}, \ldots, v_n). \end{aligned} \tag{7.3.5}$$

This is the same as

$$(\widetilde{B_j}(\mu))(v_1, \ldots, v_{j-1}, A_j(v_j), v_{j+1}, \ldots, v_n) \\ = (\widetilde{A_j}(\widetilde{B_j}(\mu)))(v_1, \ldots, v_n), \tag{7.3.6}$$

so that

$$(\widetilde{B_j \circ A_j}) = \widetilde{A_j} \circ \widetilde{B_j} \tag{7.3.7}$$

as mappings from $L(V_1, \ldots, V_n; W)$ into itself. Of course, this was mentioned in Section 7.2 when $n = 1$.

7.4 Boundedness and multilinearity

Let k be a field with an absolute value function $|\cdot|$, let n be a positive integer, and let $V_1, \ldots, V_n$ and W be vector spaces over k. Also let $N_{V_1}, \ldots, N_{V_n}$ and N_W be seminorms on $V_1, \ldots, V_n$ and W, respectively, and with respect to $|\cdot|$ on k. A multilinear mapping μ from $V_1 \times \cdots \times V_n$ into W is said to be *bounded* with respect to $N_{V_1}, \ldots, N_{V_n}$ and N_W if there is a nonnegative real number C such that

$$N_W(\mu(v_1, \ldots, v_n)) \le C\, N_{V_1}(v_1) \cdots N_{V_n}(v_n) \tag{7.4.1}$$

for every $v_1 \in V_1, \ldots, v_n \in V_n$. This reduces to the earlier definitions of boundedness for linear and bilinear mappings when $n = 1$ and $n = 2$, respectively, as in Sections 1.9 and 1.13.

Let $BL(V_1, \ldots, V_n; W)$ be the space of bounded multilinear mappings from $\prod_{j=1}^n V_j$ into W, with respect to $N_{V_1}, \ldots, N_{V_n}$ and N_W. It is easy to see that this is a linear subspace of the space of all multilinear mappings from $\prod_{j=1}^n V_j$ into W. If $\mu \in BL(V_1, \ldots, V_n; W)$, then put

$$\|\mu\| = \|\mu\|_{V_1,\ldots,V_n;W} = \inf\{C \ge 0 : (7.4.1) \text{ holds}\}, \tag{7.4.2}$$

where more precisely the infimum is taken over all nonnegative real numbers C such that (7.4.1) holds for every $v_1 \in V_1, \ldots, v_n \in V_n$. This reduces to the operator seminorm of a bounded linear mapping when $n = 1$, as in (1.9.3). As before, the infimum in (7.4.2) is automatically attained, so that (7.4.1) holds with $C = \|\mu\|$. One can check that (7.4.2) defines a seminorm on $BL(V_1, \ldots, V_n; W)$ with respect to $|\cdot|$, and that (7.4.2) is a norm on $BL(V_1, \ldots, V_n; W)$ when N_W is a norm on W. Similarly, if N_W is a semi-ultranorm on W, then (7.4.2) is a semi-ultranorm on $BL(V_1, \ldots, V_n; W)$.

Suppose for the moment that $n \ge 2$, and let μ be a multilinear mapping from $\prod_{j=1}^n V_j$ into W. If $v_n \in V_n$, then

$$\mu_{v_n}(v_1, \ldots, v_{n-1}) = \mu(v_1, \ldots, v_{n-1}, v_n) \tag{7.4.3}$$

defines a multilinear mapping from $V_1 \times \cdots \times V_{n-1}$ into W. In addition,

$$T_\mu(v_n) = \mu_{v_n} \tag{7.4.4}$$

defines a linear mapping from V_n into $L(V_1, \ldots, V_{n-1}; W)$. Note that every linear mapping from V_n into $L(V_1, \ldots, V_{n-1}; W)$ corresponds to a multilinear mapping from $\prod_{j=1}^n V_j$ into W in this way. If μ is also bounded as a multilinear mapping, then

$$\begin{aligned} N_W(\mu_{v_n}(v_1, \ldots, v_{n-1})) &= N_W(\mu(v_1, \ldots, v_n)) \\ &\le \|\mu\|_{V_1,\ldots,V_n;W}\, N_{V_1}(v_1) \cdots N_{V_{n-1}}(v_{n-1})\, N_{V_n}(v_n) \end{aligned} \tag{7.4.5}$$

for every $v_1 \in V_1, \ldots, v_{n-1} \in V_{n-1}, v_n \in V_n$. This implies that μ_{v_n} is bounded as a multilinear mapping for each $v_n \in V_n$, with

$$\|\mu_{v_n}\|_{V_1,\ldots,V_{n-1};W} \le \|\mu\|_{V_1,\ldots,V_n;W}\, N_{V_n}(v_n). \tag{7.4.6}$$

Using $\|\cdot\|_{V_1,\ldots,V_{n-1};W}$ on $BL(V_1, \ldots, V_{n-1}; W)$, we get that (7.4.4) is bounded as a linear mapping from V_n into $BL(V_1, \ldots, V_{n-1}; W)$, with

$$\|T_\mu\|_{op} \le \|\mu\|_{V_1,\ldots,V_n;W}. \tag{7.4.7}$$

Conversely, suppose that (7.4.4) is a bounded linear mapping from V_n into $BL(V_1, \ldots, V_{n-1}; W)$. If $v_n \in V$, then $\mu_{v_n} \in BL(V_1, \ldots, V_{n-1}; W)$, with

$$\|\mu_{v_n}\|_{V_1,\ldots,V_{n-1};W} \le \|T_\mu\|_{op}\, N_{V_n}(v_n). \tag{7.4.8}$$

If $v_1 \in V_1, \ldots, v_{n-1} \in V_{n-1}$, then we get that

$$\begin{aligned} N_W(\mu(v_1, \ldots, v_{n-1}, v_n)) &= N_W(\mu_{v_n}(v_1, \ldots, v_{n-1})) \\ &\le \|\mu_{v_n}\|_{V_1,\ldots,V_{n-1};W}\, N_{V_1}(v_1) \cdots N_{V_{n-1}}(v_{n-1}) \\ &\le \|T_\mu\|_{op}\, N_{V_1}(v_1) \cdots N_{V_{n-1}}(v_{n-1})\, N_{V_n}(v_n). \end{aligned} \tag{7.4.9}$$

This implies that $\mu \in BL(V_1, \ldots, V_n; W)$, with

$$\|\mu\|_{V_1,\ldots,V_n;W} \le \|T_\mu\|_{op}. \tag{7.4.10}$$

It follows that

$$\|T_\mu\|_{op} = \|\mu\|_{V_1,\ldots,V_n;W}, \tag{7.4.11}$$

by (7.4.7).

Suppose now that $n \ge 1$, $1 \le j \le n$, and that A_j is a bounded linear mapping from V_j into itself, with respect to N_{V_j} on V_j. Let μ be a bounded multilinear mapping from $\prod_{j=1}^n V_j$ into W, and let $\widetilde{A_j}(\mu)$ be the multilinear mapping from $\prod_{j=1}^n V_j$ into W corresponding to μ and A_j as in the previous section. If $v_1 \in V_1, \ldots, v_n \in V_n$, then

$$\begin{aligned} & N_W((\widetilde{A_j}(\mu))(v_1, \ldots, v_n)) \\ &\quad = N_W(\mu(v_1, \ldots, v_{j-1}, A_j(v_j), v_{j+1}, v_n)) \\ &\quad \le \|\mu\|_{V_1,\ldots,V_n;W}\, N_{V_1}(v_1) \cdots N_{V_{j-1}}(v_{j-1})\, N_{V_j}(A_j(v_j)) \\ &\qquad\qquad N_{V_{j+1}}(v_{j+1}) \cdots N_{V_n}(v_n) \\ &\quad \le \|A_j\|_{op,V_jV_j}\, \|\mu\|_{V_1,\ldots,V_n;W}\, N_{V_1}(v_1) \cdots N_{V_n}(v_n), \end{aligned} \tag{7.4.12}$$

where $\|A_j\|_{op,V_j V_j}$ is the usual operator seminorm of A_j associated to N_{V_j} on V_j. This shows that $\widetilde{A_j}(\mu)$ is also bounded as a multilinear mapping, with

$$\|\widetilde{A_j}(\mu)\|_{V_1,\ldots,V_n;W} \le \|A_j\|_{op,V_j V_j} \, \|\mu\|_{V_1,\ldots,V_n;W}. \tag{7.4.13}$$

Similarly, let A be a bounded linear mapping from W into itself, with respect to N_W on W. It is easy to see that the composition $A \circ \mu$ of μ with A is multilinear over k, as a mapping from $\prod_{j=1}^n V_j$ into W. If $v_1 \in V_1, \ldots, v_n \in V_n$, then

$$\begin{aligned} N_W(A(\mu(v_1, \ldots, v_n))) &\le \|A\|_{op,WW} \, N_W(\mu(v_1, \ldots, v_n)) \\ &\le \|A\|_{op,WW} \, \|\mu\|_{V_1,\ldots,V_n;W} \, N_{V_1}(v_1) \cdots N_{V_n}(v_n), \end{aligned} \tag{7.4.14}$$

where $\|A\|_{op,WW}$ is the operator seminorm of A associated to N_W on W. Thus $A \circ \mu$ is bounded as a multilinear mapping too, with

$$\|A \circ \mu\|_{V_1,\ldots,V_n;W} \le \|A\|_{op,WW} \, \|\mu\|_{V_1,\ldots,V_n;W}. \tag{7.4.15}$$

7.5 Representations on multilinear mappings

Let k be a commutative ring with a multiplicative identity element, and let $V_1, \ldots, V_n$ and W be modules over k. The space $L_k(V_1, \ldots, V_n; W)$ of mappings from $\prod_{j=1}^n V_j$ into W that are multilinear over k is a module over k with respect to pointwise addition and scalar multiplication of mappings, as in Section 7.3. Let A be an associative algebra over k, and suppose for the moment that W is a left module over A. If $a \in A$ and $\mu \in L(V_1, \ldots, V_n; W)$, then

$$a \cdot (\mu(v_1, \ldots, v_n)) \tag{7.5.1}$$

defines a multilinear mapping from $\prod_{j=1}^n V_j$ into W as well. It is easy to see that this makes $L(V_1, \ldots, V_n; W)$ into a left module over A.

Suppose that V_j is a left module over A for some j, $1 \le j \le n$. If $a \in A$ and $\mu \in L(V_1, \ldots, V_n; W)$, then

$$\mu(v_1, \ldots, v_{j-1}, a \cdot v_j, v_{j+1}, \ldots, v_n) \tag{7.5.2}$$

defines another multilinear mapping from $\prod_{j=1}^n V_j$ into W. This defines an opposite algebra homomorphism from A into the algebra of module homomorphisms from $L(V_1, \ldots, V_n; W)$ into itself, as in Section 7.3. Equivalently, $L(V_1, \ldots, v_n; W)$ may be considered as a right module over A in this way. This was mentioned in Section 7.2 when $n = 1$.

Suppose from now on in this section that A is a Lie algebra over k. If W is a module over A as a Lie algebra over k, $a \in A$, and $\mu \in L(V_1, \ldots, V_n; W)$, then (7.5.1) defines an element of $L(V_1, \ldots, V_n; W)$, as before. This makes $L(V_1, \ldots, V_n; W)$ into a module over A as a Lie algebra over k. Similarly, if V_j is a module over A as a Lie algebra over k for some j, $a \in A$, and μ is in $L(V_1, \ldots, V_n; W)$, then (7.5.2) is an element of $L(V_1, \ldots, V_n; W)$, and hence

$$-\mu(v_1, \ldots, v_{j-1}, a \cdot v_j, v_{j+1}, \ldots, v_n) \tag{7.5.3}$$

is an element of $L(V_1, \ldots, V_n; W)$. One can check that $L(V_1, \ldots, V_n; W)$ is a module over A as a Lie algebra over k with respect to (7.5.3), which was mentioned in Section 7.2 when $n = 1$.

Suppose that $V_1, \ldots, V_n$ and W are all modules over A as a Lie algebra. Let $a \in A$ and $\mu \in L_k(V_1, \ldots, V_n; W)$ be given, and let us define $a \cdot \mu$ as a mapping from $\prod_{j=1}^n V_j$ into W, as follows. If $v_j \in V_j$ for each $j = 1, \ldots, n$, then we put

$$(7.5.4) \qquad \begin{aligned} (a \cdot \mu)(v_1, \ldots, v_n) &= a \cdot (\mu(v_1, \ldots, v_n)) \\ &\quad + \sum_{j=1}^{n} (-\mu(v_1, \ldots, v_{j-1}, a \cdot v_j, v_{j+1}, \ldots, v_n)). \end{aligned}$$

It is easy to see that (7.5.4) is multilinear over k as a mapping from $\prod_{j=1}^n V_j$ into W, and that (7.5.4) is linear in a over k. One can verify that this makes $L(V_1, \ldots, V_n; W)$ into a module over A as a Lie algebra over k, using the remarks in the preceding paragraph. More precisely, each term on the right side of (7.5.4) defines a Lie algebra representation of A on $L(V_1, \ldots, V_n; W)$, as before. One can check directly that these $n + 1$ representations of A on $L(V_1, \ldots, V_n; W)$ commute with each other. Hence their sum defines a Lie algebra representation of A on $L(V_1, \ldots, V_n; W)$ too, as in Section 6.5.

Suppose that $V_1, \ldots, V_n$ are the same module V over k, with the same Lie algebra representation of A. Let $a \in A$ and $\mu \in L(V_1, \ldots, V_n; W)$ be given again. If μ is a symmetric multilinear mapping, then (7.5.4) is symmetric as well. If μ is antisymmetric, then one can verify that (7.5.4) is antisymmetric too. If

$$(7.5.5) \qquad \mu(v_1, \ldots, v_n) = 0$$

whenever $v_j = v_l$ for some $j \neq l$, then one can check that (7.5.4) satisfies the same condition. More precisely, if $v_j = v_l$ for some $j \neq l$, then this uses the antisymmetry of μ for the two terms on the right side of (7.5.4) that involve $a \cdot v_j$ and $a \cdot v_l$. Otherwise, one can apply the hypothesis on μ directly to the other terms on the right side of (7.5.4).

7.6 Centralizers and invariant elements

Let k be a commutative ring with a multiplicative identity element, and let A be an algebra over k in the strict sense, where multiplication of $a, b \in A$ is denoted $a\,b$. The *centralizer* of a set $E \subseteq A$ in A is the set of $a \in A$ that commute with every $x \in E$, which is to say that

$$(7.6.1) \qquad a\,x = x\,a$$

for every $x \in E$. This is a submodule of A as a module over k, and a subalgebra of A when A is associative. The *center* of A is the centralizer of A in itself.

Now let $(A, [\cdot, \cdot]_A)$ be a Lie algebra over k. The *centralizer* of a set $E \subseteq A$ in A as a Lie algebra is given by

$$(7.6.2) \qquad C_A(E) = \{a \in A : [a, x]_A = 0 \text{ for every } x \in E\}.$$

It is easy to see that this is a Lie subalgebra of A, using the Jacobi identity. The *center* of A as a Lie algebra is given by

$$Z(A) = C_A(A) = \{a \in A : [a, x]_A = 0 \text{ for every } x \in A\}, \tag{7.6.3}$$

which is automatically an ideal in A.

Note that (7.6.2) is contained in the centralizer of A as an algebra in the strict sense, and that (7.6.3) is contained in the center of A as an algebra in the strict sense. If $1 + 1$ is invertible in k, then (7.6.2) is the same as the centralizer of E in A as an algebra in the strict sense, and (7.6.3) is the same as the center of A as an algebra in the strict sense.

If A is an associative algebra over k, then A is a Lie algebra over k with respect to the corresponding commutator bracket $[x, y] = x\,y - y\,x$. Of course, (7.6.1) is the same as saying that $[a, x] = 0$. In this case, the centralizer of $E \subseteq A$ in A as an associative algebra is the same as the centralizer of E in A as a Lie algebra with respect to the commutator bracket. In particular, the center of A as an associative algebra is the same as the center of A as a Lie algebra.

Let $(A, [\cdot, \cdot]_A)$ be a Lie algebra over k again, and let ρ be a representation of A as a Lie algebra over k on a module V over k. An element v of V is said to be *invariant* under ρ if

$$\rho_a(v) = 0 \tag{7.6.4}$$

for every $a \in A$, as on p31 of [25]. As usual, V may be considered as a module over A as a Lie algebra over k, with $a \cdot v = \rho_a(v)$ for every $a \in A$ and $v \in V$. Thus (7.6.4) can be reexpressed as saying that

$$a \cdot v = 0 \tag{7.6.5}$$

for every $a \in A$.

If every $v \in V$ is invariant under ρ, then ρ is said to act trivially on V. It is easy to see that the collection of $v \in V$ that are invariant under ρ is a submodule of V, as a module over k. This defines a subrepresentation of ρ on V, on which ρ acts trivially.

If A_0 is any Lie subalgebra of A, then the restriction of ρ_a to $a \in A_0$ defines a representation of A_0 on V, as a Lie algebra over k. If v is any element of V, then the collection of $a \in A$ such that (7.6.4) or equivalently (7.6.5) holds is a Lie subalgebra of A.

Remember that the adjoint representation of A is a representation of A as a Lie algebra on itself, as a module over k. The collection of elements of A that are invariant under the adjoint representation is the same as the center of A as a Lie algebra.

7.7 Invariant multilinear mappings

Let k be a commutative ring with a multiplicative identity element, and let $(A, [\cdot, \cdot]_A)$ be a Lie algebra over k. Also let V, W be modules over k, and let ρ^V, ρ^W be representations of A as a Lie algebra over k on V, W, respectively.

Remember that the space $\mathrm{Hom}_k(V, W)$ of homomorphisms from V into W as modules over k is a module over k too, with respect to pointwise addition and scalar multiplication of mappings. If $a \in A$, then ρ_a^V and ρ_a^W are homomorphisms from V and W into themselves, as modules over k. If $\phi \in \mathrm{Hom}_k(V, W)$, then it follows that $\phi \circ \rho_a^V$ and $\rho_a^W \circ \phi$ are homomorphisms from V into W as well, as modules over k. The mappings

$$\phi \mapsto \rho_a^W \circ \phi \tag{7.7.1}$$

and

$$\phi \mapsto -\phi \circ \rho_a^V \tag{7.7.2}$$

define homomorphisms from $\mathrm{Hom}_k(V, W)$ into itself, as a module over k. These define representations of A as a Lie algebra over k on $\mathrm{Hom}_k(V, W)$, as in Section 7.5. We also saw that

$$\rho_a(\phi) = \rho_a^W \circ \phi - \phi \circ \rho_a^V \tag{7.7.3}$$

defines a representation of A as a Lie algebra over k on $\mathrm{Hom}_k(V, W)$. Remember that $\phi \in \mathrm{Hom}_k(V, W)$ is said to be invariant under ρ when (7.7.3) is equal to 0 for every $a \in A$, as in the previous section. This happens exactly when ϕ intertwines the representations ρ^V, ρ^W of A on V, W, respectively, as in Section 6.7.

Let V, W be modules over k again, and let ρ^V be a respresentation of A as a Lie algebra over k on V. Remember that the space $L_k(V, V; W)$ of mappings from $V \times V$ into W that are bilinear over k is a module over k with respect to pointwise addition and scalar multiplication. If $a \in A$ and $\beta \in L_k(V, V; W)$, then ρ_a^V is a homomorphism from V into itself, as a module over k, and

$$\beta(\rho_a^V(u), v), \quad \beta(u, \rho_a^V(v)) \tag{7.7.4}$$

define elements of $L_k(V, V; W)$. The mappings

$$\beta(u, v) \mapsto -\beta(\rho_a^V(u), v) \tag{7.7.5}$$

and

$$\beta(u, v) \mapsto -\beta(u, \rho_a^V(v)) \tag{7.7.6}$$

define homomorphisms from $L_k(V, V; W)$ into itself, as a module over k. These define representations of A as a Lie algebra over k on $L_k(V, V; W)$, as in Section 7.5, and

$$(\rho_a(\beta))(u, v) = -\beta(\rho_a^V(u), v) - \beta(u, \rho_a^V(v)) \tag{7.7.7}$$

defines a representation of A as a Lie algebra over k on $L_k(V, V; W)$ too. The condition that

$$\rho_a(\beta) = 0 \tag{7.7.8}$$

as an element of $L_k(V, V; W)$ is the same as saying that (7.7.7) is equal to 0 for every $u, v \in V$, which means that ρ_a^V is antisymmetric on V with respect to β. Thus β is invariant under the representation (7.7.7) of A on $L_k(V, V; W)$ exactly when ρ_a^V is antisymmetric on V with respect to β for every $a \in A$.

Let $V_1, \ldots, V_n$ and W be modules over k, and let μ be a mapping from $\prod_{j=1}^n V_j$ into W that is multilinear over k. Also let $l \in \{1, \ldots, n\}$ be given, and let V_l^μ be the set of $v_l \in V_l$ such that

$$\mu(v_1, \ldots, v_{l-1}, v_l, v_{l+1}, \ldots, v_n) = 0 \tag{7.7.9}$$

for every $v_j \in V_j$ with $1 \le j \le n$ and $j \ne l$. Note that V_l^μ is a submodule of V_l, as a module over k. Let A be a Lie algebra over k, and suppose that $V_1, \ldots, V_n$ and W are modules over A. Thus, for each $a \in A$, $a \cdot \mu$ can be defined as a mapping from $\prod_{j=1}^n V_j$ into W that is multilinear over k, as in Section 7.5. If $a \cdot \mu = 0$ as a mapping on $\prod_{j=1}^n V_j$, and if $v_l \in V_l^\mu$, then it is easy to see that $a \cdot v_l \in V_l^\mu$ too. This means that V_l^μ is a submodule of V_l, as a module over A, when $a \cdot \mu = 0$ for every $a \in A$.

Let V be a module over k, and let β be a mapping from $V \times V$ into V that is bilinear over k. Thus V is an algebra in the strict sense over k, with respect to β. Let A be a Lie algebra over k, and suppose that V is a module over A. If $a \in A$, then $a \cdot \beta$ is defined as a mapping from $V \times V$ into V that is bilinear over k by

$$(a \cdot \beta)(v, w) = a \cdot (\beta(v, w)) - \beta(a \cdot v, w) - \beta(v, a \cdot w) \tag{7.7.10}$$

for every $v, w \in V$, as in Section 7.5. Observe that $a \cdot \beta = 0$ as a mapping on $V \times V$ exactly when $\delta_a(v) = a \cdot v$ defines a derivation on V with respect to β.

7.8 Traces of linear mappings

Let k be a commutative ring with a multiplicative identity element, let A_0 be a commutative associative algebra over k, and let n be a positive integer. Remember that the space $M_n(A_0)$ of $n \times n$ matrices with entries in A_0 is an associative algebra over k, using entrywise addition and scalar multiplication, and matrix multiplication. The trace of an element of $M_n(A_0)$ defines a homomorphism from $M_n(A_0)$ into A_0 as modules over k, which satisfies

$$\operatorname{tr}(a\,b) = \operatorname{tr}(b\,a) \tag{7.8.1}$$

for every $a, b \in M_n(A_0)$. Put

$$B_0(a, b) = \operatorname{tr}(a\,b) \tag{7.8.2}$$

for every $a, b \in M_n(A_0)$, which defines a mapping from $M_n(A_0) \times M_n(A_0)$ into A_0. This mapping is bilinear over k, and symmetric in a, b.

Let $a, b, x \in M_n(A_0)$ be given, and observe that

$$B_0(a\,x, b) = \operatorname{tr}((a\,x)\,b) = \operatorname{tr}(a\,(x\,b)) = B_0(a, x\,b). \tag{7.8.3}$$

We also have that

$$\begin{aligned} B_0(x\,a, b) = \operatorname{tr}((x\,a)\,b) &= \operatorname{tr}(x\,(a\,b)) \\ &= \operatorname{tr}((a\,b)\,x) = \operatorname{tr}(a\,(b\,x)) = B_0(a, b\,x). \end{aligned} \tag{7.8.4}$$

Of course,

$$a \mapsto a\,x, \quad a \mapsto x\,a \tag{7.8.5}$$

define homomorphisms from $M_n(A_0)$ into itself, as a module over k. Similarly,

$$C_x(a) = [x, a] = x\,a - a\,x \tag{7.8.6}$$

defines C_x as a homomorphism from $M_n(A_0)$ into itself, as a module over k. It is easy to see that

$$B_0(C_x(a), b) = -B_0(a, C_x(b)), \tag{7.8.7}$$

using (7.8.3) and (7.8.4).

Let k^n be the space of n-tuples of elements of k, which is a (free) module over k with respect to coordinatewise addition and scalar multiplication. If $a = (a_{j,l})$ is an $n \times n$ matrix with entries in k, then

$$(T_a(v))_j = \sum_{l=1}^{n} a_{j,l}\,v_l \tag{7.8.8}$$

defines a module homomorphism from k^n into itself, as usual. The mapping $a \mapsto T_a$ defines an isomorphism from $M_n(k)$ onto $\mathrm{Hom}_k(k^n, k^n)$, as associative algebras over k. The *trace* of T_a is defined as an element of k to be the trace of a, which defines the trace as a homomorphism from $\mathrm{Hom}_k(k^n, k^n)$ into k, as modules over k. If $R, T \in \mathrm{Hom}_k(k^n, k^n)$, then we have that

$$\mathrm{tr}(R \circ T) = \mathrm{tr}(T \circ R), \tag{7.8.9}$$

as in (7.8.1).

Let V be a module over k that is isomorphic to k^n as a module over k, so that $\mathrm{Hom}_k(V, V)$ is isomorphic to $\mathrm{Hom}_k(k^n, k^n)$ as associative algebras over k. The trace can be defined as a homomorphism from $\mathrm{Hom}_k(V, V)$ into k, as modules over k, as before. One can check that this definition of the trace does not depend on the module isomorphism between V and k^n, because of (7.8.9). Of course, if k is a field, then an n-dimensional vector space V over k is isomorphic to k^n as a vector space over k. This corresponds to choosing a basis for V, and the trace of a linear mapping from V into itself does not depend on the choice of the basis.

Put

$$B(T_1, T_2) = \mathrm{tr}(T_1 \circ T_2) \tag{7.8.10}$$

for every $T_1, T_2 \in \mathrm{Hom}_k(V, V)$, which defines a symmetric bilinear form on $\mathrm{Hom}_k(V, V)$. If $R \in \mathrm{Hom}_k(V, V)$, then

$$C_R(T) = [R, T] = R \circ T - T \circ R \tag{7.8.11}$$

defines a homomorphism from $\mathrm{Hom}_k(V, V)$ into itself, as a module over k. As in (7.8.7), we have that

$$B(C_R(T_1), T_2) = -B(T_1, C_R(T_2)) \tag{7.8.12}$$

for every $T_1, T_2 \in \mathrm{Hom}_k(V, V)$, so that C_R is antisymmetric on $\mathrm{Hom}_k(V, V)$ with respect to (7.8.10).

7.9 The Killing form

Let k be a commutative ring with a multiplicative identity element, and let $(A, [\cdot,\cdot]_A)$ be a Lie algebra over k. Also let V be a module over k, and let ρ be a representation of A as a Lie algebra on k. Suppose that V is isomorphic to k^n as a module over k for some positive integer n. If T is a homomorphism from V into itself, as a module over k, then the trace $\operatorname{tr} T = \operatorname{tr}_V T$ of T can be defined as an element of k as in the previous section. Put

$$B_\rho(x, y) = \operatorname{tr}_V(\rho_x \circ \rho_y) \tag{7.9.1}$$

for every $x, y \in A$, which is the trace of $\rho_x \circ \rho_y$ as a module homomorphism from V into itself. This defines a mapping from $A \times A$ into k that is bilinear over k. Note that (7.9.1) is symmetric in x and y.

Let $w, x, y \in A$ be given, and observe that

$$B_\rho([w, x]_A, y) = \operatorname{tr}_V(\rho_{[w,x]_A} \circ \rho_y) = \operatorname{tr}_V([\rho_w, \rho_x] \circ \rho_y). \tag{7.9.2}$$

The right side is equal to

$$-\operatorname{tr}_V(\rho_x \circ [\rho_w, \rho_y]), \tag{7.9.3}$$

as in the previous section. It follows that

$$B_\rho([w, x]_A, y) = -B_\rho(x, [w, y]_A). \tag{7.9.4}$$

If $x \in A$, then $\operatorname{ad} x = \operatorname{ad}_x$ is defined as a module homomorphism from A into itself by

$$\operatorname{ad}_x(z) = [x, z]_A \tag{7.9.5}$$

for every $z \in A$, as in Section 2.4. Thus (7.9.4) can be reformulated as saying that

$$B_\rho(\operatorname{ad}_w(x), y) = -B_\rho(x, \operatorname{ad}_w(y)) \tag{7.9.6}$$

for every $w, x, y \in A$.

Remember that the space of bilinear forms on A may be considered as a module over A, with respect to the adjoint representation on A and the trivial representation of A on k, as in Section 7.5. Using this, (7.9.6) is the same as saying that (7.9.1) is invariant under this action of A on bilinear forms on A, as in Section 7.7. This corresponds to Proposition 1.1 on p32 of [25], which was formulated for a field k. Equivalently, (7.9.4) means that (7.9.1) is associative as a bilinear mapping on $A \times A$, as in Section 6.10. See also p27 of [14].

If A is isomorphic to k^n as a module over k for some positive integer n, then we can take $V = A$ and $\rho_x = \operatorname{ad}_x$ in the previous paragraphs. In this case, (7.9.1) becomes

$$b(x, y) = \operatorname{tr}_A(\operatorname{ad}_x \circ \operatorname{ad}_y) \tag{7.9.7}$$

for $x, y \in A$. This is known as the *Killing form* on A, as on p21 of [14], and Definition 1.2 on p32 of [25].

7.10 Invariant subspaces and traces

Let k be a commutative ring with a multiplicative identity element, and let V be a module over k. Remember that the collection $\mathrm{Hom}_k(V, V)$ of all homomorphisms from V into itself, as a module over k, is an associative algebra over k with respect to composition of mappings. Let W be a submodule of V, and let $\mathcal{A}_W$ be the collection of all $T \in \mathrm{Hom}_k(V, V)$ such that

$$T(W) \subseteq W. \tag{7.10.1}$$

Note that $\mathcal{A}_W$ is a subalgebra of $\mathrm{Hom}_k(V, V)$. If $T \in \mathcal{A}_W$, then let T_W be the restriction of T to W, which defines a module homomorphism from W into itself. Of course,

$$T \mapsto T_W \tag{7.10.2}$$

defines an algebra homomorphism from $\mathcal{A}_W$ into the algebra $\mathrm{Hom}_k(W, W)$ of all module homomorphisms from W into itself. Let q be the canonical quotient mapping from V onto the quotient module V/W. If $T \in \mathcal{A}_W$, then there is a unique module homomorphism $T_{V/W}$ from V/W into itself such that

$$T_{V/W} \circ q = q \circ T. \tag{7.10.3}$$

It is easy to see that

$$T \mapsto T_{V/W} \tag{7.10.4}$$

defines an algebra homomorphism from $\mathcal{A}_W$ into the algebra $\mathrm{Hom}_k(V/W, V/W)$ of all module homomorphisms from V/W into itself.

Suppose that V/W is isomorphic to k^n as a module over k for some positive integer n, so that V/W is a free module over k of rank n. This means that there are n elements $z_1, \ldots, z_n$ of V such that every element of V/W can be expressed in a unique way as a linear combination of $q(z_1), \ldots, q(z_n)$ with coefficients in k. Let Z be the submodule of V consisting of linear combinations of $z_1, \ldots, z_n$ with coefficients in k. More precisely, every element of Z can be expressed in a unique way as a linear combination of $z_1, \ldots, z_n$ with coefficients in k, because of the analogous property of $q(z_1), \ldots, q(z_n)$ in V/W. Note that the restriction of q to Z defines an isomorphism from Z onto V/W, as modules over k. It is easy to see that every element of V can be expressed in a unique way as the sum of elements of W and Z, so that V may be identified with the direct sum of W and Z, as a module over k. Suppose that W is isomorphic to k^m as a module over k for some positive integer m as well. Under these conditions, V is isomorphic to k^{m+n} as a module over k.

If $T \in \mathcal{A}_W$, then the traces of T, T_W, and $T_{V/W}$ on V, W, and V/W, respectively, can be defined as elements of k, as in Section 7.8. Observe that

$$\mathrm{tr}_V T = \mathrm{tr}_W T_W + \mathrm{tr}_{V/W} T_{V/W}, \tag{7.10.5}$$

where the subscripts indicate the spaces on which the traces are taken. In particular, if

$$T(V) \subseteq W, \tag{7.10.6}$$

then $T_{V/W} = 0$, and

$$\mathrm{tr}_V T = \mathrm{tr}_W T_W. \tag{7.10.7}$$

If $T_1, T_2 \in \mathrm{Hom}_k(V, V)$, then put

$$B_V(T_1, T_2) = \mathrm{tr}_V(T_1 \circ T_2), \tag{7.10.8}$$

as in Section 7.8. Let $B_W(\cdot, \cdot)$ and $B_{V/W}(\cdot, \cdot)$ be the analogous bilinear forms on $\mathrm{Hom}_k(W, W)$ and $\mathrm{Hom}_k(V/W, V/W)$, respectively. Suppose that $T_1, T_2 \in \mathcal{A}_W$, and let $T_{1,W}, T_{2,W} \in \mathrm{Hom}_k(W, W)$ and $T_{1,V/W}, T_{2,V/W} \in \mathrm{Hom}_k(V/W, V/W)$ be as before. Note that

$$(T_1 \circ T_2)_W = T_{1,W} \circ T_{2,W}, \quad (T_1 \circ T_2)_{V/W} = T_{1,V/W} \circ T_{2,V/W}, \tag{7.10.9}$$

because (7.10.2) and (7.10.4) are algebra homomorphisms. It follows that

$$B_V(T_1, T_2) = B_W(T_{1,W}, T_{2,W}) + B_{V/W}(T_{1,V/W}, T_{2,V/W}), \tag{7.10.10}$$

by applying (7.10.5) to $T = T_1 \circ T_2$.

Let $(A, [\cdot, \cdot])$ be a Lie algebra over k, and let B be an ideal in A, so that the quotient A/B is defined as a Lie algebra over k too. If $x \in A$, then $\mathrm{ad}_x = \mathrm{ad}_{A,x}$ is defined as a module homomorphism from A into itself by

$$\mathrm{ad}_x(z) = \mathrm{ad}_{A,x}(z) = [x, z] \tag{7.10.11}$$

for every $z \in A$, as in Section 2.4. Let $(\mathrm{ad}_x)_B$ be the restriction of ad_x to B, which maps B into itself, because B is an ideal in A. Similarly, let $(\mathrm{ad}_x)_{A/B}$ be the mapping from A/B into itself which is induced by ad_x on A. Suppose that B and A/B are isomorphic as modules over k to k^m and k^n, respectively, for some positive integers m and n. This implies that A is isomorphic to k^{m+n} as a module over k, as before. If $x, y \in A$, then

$$\begin{aligned} \mathrm{tr}_A(\mathrm{ad}_x \circ \mathrm{ad}_y) &= \mathrm{tr}_B((\mathrm{ad}_x)_B \circ (\mathrm{ad}_y)_B) \\ &\quad + \mathrm{tr}_{A/B}((\mathrm{ad}_x)_{A/B} \circ (\mathrm{ad}_y)_{A/B}), \end{aligned} \tag{7.10.12}$$

as in (7.10.10).

7.11 Radicals of bilinear mappings

Let k be a commutative ring with a multiplicative identity element, and let V, W be modules over k. Also let β be a mapping from $V \times V$ into W that is bilinear over k. Note that

$$V^\beta = \{u \in V : \beta(u, v) = 0 \text{ for every } v \in V\} \tag{7.11.1}$$

is a submodule of V. This may be called the *radical* of β in V, as on p22 of [14].

Let $(A, [\cdot, \cdot])$ be a Lie algebra over k, and let β be a mapping from $A \times A$ into W that is bilinear over k. Thus we take $V = A$ in the preceding paragraph, as a module over k. If $x \in A$, then $\mathrm{ad}_x = \mathrm{ad}_{A,x}$ is the module homomorphism from A into itself defined by (7.10.11), as before. Suppose that

$$\beta(\mathrm{ad}_w(x), y) = -\beta(x, \mathrm{ad}_w(y)) \tag{7.11.2}$$

for every $w, x, y \in A$, which is the same as saying that

$$\beta([x, w], y) = \beta(x, [w, y]) \tag{7.11.3}$$

for every $w, x, y \in A$, as in Section 6.10. In this case, we may say that β is associative as a bilinear form on A, as in Section 6.10. Equivalently, β is invariant with respect to the representation on the space of bilinear mappings from $A \times A$ into W corresponding to the adjoint representation on A and the trivial representation on W, as in Section 7.7. It is easy that the radical A^β of β in A is an ideal in A as a Lie algebra over k, as on p22 of [14], and p44 of [25]. This may be considered as a particular case of statements in Sections 6.10 and 7.7.

Suppose that A is isomorphic to k^r as a module over k for some positive integer r. If $x, y \in A$, then

$$\beta(x, y) = \mathrm{tr}_A(\mathrm{ad}_x \circ \mathrm{ad}_y) \tag{7.11.4}$$

is defined as an element of k, as in Section 7.8. This defines a symmetric bilinear mapping from $A \times A$ into k that satisfies (7.11.2), as in Section 7.9. Thus the radical A^β of (7.11.4) in A is an ideal in A as a Lie algebra over k, as in the preceding paragraph.

Let B be an ideal in A as a Lie algebra over k, so that the quotient A/B is a Lie algebra over k as well. Suppose that B and A/B are isomorphic to k^m and k^n, respectively, as modules over k for some positive integers m and n. This implies that A is isomorphic to k^{m+n} as a module over k, as in the previous section. If $x, y \in A$, then let $(\mathrm{ad}_x)_B$, $(\mathrm{ad}_y)_B$ be the restrictions of ad_x, ad_y to B, and let $(\mathrm{ad}_x)_{A/B}$, $(\mathrm{ad}_y)_{A/B}$ be the mappings from A/B into itself induced by ad_x, ad_y, as before. If $x \in B$, then ad_x maps A into B, so that the induced mapping $(\mathrm{ad}_x)_{A/B}$ is equal to 0. This implies that the second term on the right side of (7.10.12) is equal to 0 for every $y \in A$. It follows that

$$\mathrm{tr}_A(\mathrm{ad}_x \circ \mathrm{ad}_y) = \mathrm{tr}_B((\mathrm{ad}_x)_B \circ (\mathrm{ad}_y)_B) \tag{7.11.5}$$

for every $x \in B$ and $y \in A$.

If $x \in B$ and B is commutative as a Lie algebra, then $(\mathrm{ad}_x)_B$ is equal to 0. This implies that the right side of (7.11.5) is equal to 0 for every $y \in A$. Under these conditions, we get that

$$\beta(x, y) = \mathrm{tr}_A(\mathrm{ad}_x \circ \mathrm{ad}_y) = 0 \tag{7.11.6}$$

for every $x \in B$ and $y \in A$. This means that

$$B \subseteq A^\beta \tag{7.11.7}$$

in this situation.

7.12 Tensor products

Let k be a commutative ring with a multiplicative identity element, let $n \geq 2$ be an integer, and let $V_1, \ldots, V_n$ be n modules over k. The *tensor product*

$$\bigotimes_{j=1}^{n} V_j = V_1 \bigotimes \cdots \bigotimes V_n \tag{7.12.1}$$

of these modules over k is a module over k with the following two properties. First, the tensor product comes equipped with a mapping from $\prod_{j=1}^n V_j$ into $\bigotimes_{j=1}^n V_j$ that is multilinear over k. The image of $(v_1, \ldots, v_n) \in \prod_{j=1}^n V_j$ in $\bigotimes_{j=1}^n V_j$ under this mapping is often expressed as $v_1 \otimes \cdots \otimes v_n$. Second, let W be any module over k, and let μ be any mapping from $\prod_{j=1}^n V_j$ into W that is multilinear over k. Under these conditions, μ can be expressed in a unique way as the composition of the mapping from $\prod_{j=1}^n V_j$ into $\bigotimes_{j=1}^n V_j$ just mentioned with a homomorphism from $\bigotimes_{j=1}^n V_j$ into W, as modules over k. Equivalently, this means that there is a unique module homomorphism $\widetilde{\mu}$ from $\bigotimes_{j=1}^n V_j$ into W such that

$$\widetilde{\mu}(v_1 \otimes \cdots \otimes v_n) = \mu(v_1, \ldots, v_n) \tag{7.12.2}$$

for every $(v_1, \ldots, v_n) \in \prod_{j=1}^n V_j$. The tensor product is unique up to a suitable isomorphic equivalence.

Note that $\bigotimes_{j=1}^n V_j$ is generated as a module over k by the associated image of $\prod_{j=1}^n V_j$. This means that every element of $\bigotimes_{j=1}^n V_j$ can be expressed as a finite sum of terms of the form $v_1 \otimes \cdots \otimes v_n$, where $v_j \in V_j$ for each $j = 1, \ldots, n$. This is clear from the standard construction of the tensor product, and it can also be obtained from the uniqueness of the tensor product.

Let $W_1, \ldots, W_n$ another collection of n modules over k, and suppose that ϕ_j is a homomorphism from V_j into W_j for each $j = 1, \ldots, n$, as modules over k. Consider the mapping from $\prod_{j=1}^n V_j$ into $\bigotimes_{j=1}^n W_j$ that sends $(v_1, \ldots, v_n)$ in $\prod_{j=1}^n V_j$ to

$$\phi_1(v_1) \otimes \cdots \otimes \phi_n(v_n). \tag{7.12.3}$$

It is easy to see that this mapping is multilinear over k. This leads to a unique module homomorphism ϕ from $\bigotimes_{j=1}^n V_j$ into $\bigotimes_{j=1}^n W_j$ such that

$$\phi(v_1 \otimes \cdots \otimes v_n) \tag{7.12.4}$$

is equal to (7.12.3) for every $(v_1, \ldots, v_n) \in \prod_{j=1}^n V_j$.

Let $Z_1, \ldots, Z_n$ be another collection of n modules over k, and let ψ_j be a homomorphism from W_j into Z_j for each $j = 1, \ldots, n$, as modules over k. This leads to a module homomorphism ψ from $\bigotimes_{j=1}^n W_j$ into $\bigotimes_{j=1}^n Z_j$, as in the preceding paragraph. Note that $\psi_j \circ \phi_j$ is a module homomorphism from V_j into Z_j for each $j = 1, \ldots, n$. One can check that $\psi \circ \phi$ is the same as the module homomorphism from $\bigotimes_{j=1}^n V_j$ into $\bigotimes_{j=1}^n Z_j$ obtained from $\psi_j \circ \phi_j$, $1 \leq j \leq n$, as in the previous paragraph.

Let A be an associative algebra over k, and suppose that V_l is also a left or right module over A for some $l \in \{1, \ldots, n\}$. One can define an action of A on $\bigotimes_{j=1}^n V_j$ on the left or the right, as appropriate, so that $\bigotimes_{j=1}^n V_j$ becomes a left or right module over A too. More precisely, if $a \in A$, then the corresponding module homomorphism from V_l into itself leads to a module homomorphism from $\bigotimes_{j=1}^n V_j$ into itself as before, using the identity mapping on V_j when $j \neq l$.

Similarly, let A be a Lie algebra over k, and suppose that V_l is a module over A for some $l \in \{1, \ldots, n\}$. One can define an action of A on $\bigotimes_{j=1}^n V_j$ in the same way as in the preceding paragraph, so that $\bigotimes_{j=1}^n V_j$ becomes a module over A.

Suppose now that V_l is a module over A as a Lie algebra for each $l = 1, \ldots, n$, which leads to an action of A on $\bigotimes_{j=1}^n V_j$ for each $l = 1, \ldots, n$, as in the previous paragraph. It is easy to see that these actions commute with each other on $\bigotimes_{j=1}^n V_j$. It follows that $\bigotimes_{j=1}^n V_j$ is a module over A with respect to the sum of these actions, as in Section 7.1.

7.13 Functions on sets

Let k be a commutative ring with a multiplicative identity element, and let W be a module over k. Also let X be a nonempty set, and let $c(X, W)$ be the space of W-valued functions on X. It is easy to see that $c(X, W)$ is a module over k with respect to pointwise addition and scalar multiplication of functions. This is the same as the direct product of the family of copies of W indexed by X.

If f is a W-valued function on X, then the *support* of f on X is defined to be the set of $x \in X$ such that $f(x) \neq 0$. Let $c_{00}(X, W)$ be the subset of $c(X, W)$ consisting of functions with finite support. This is a submodule of $c(X, W)$, as a module over k, which corresponds to the direct sum of the family of copies of W indexed by X. Of course, $c_{00}(X, W)$ is the same as $c(X, W)$ when X has only finitely many elements.

In particular, we can take $W = k$, considered as a module over itself. If $x \in X$, then let δ_x be the k-valued function on X equal to 1 at x and to 0 elsewhere. Every element of $c_{00}(X, k)$ can be expressed in a unique way as a linear combination of finitely many δ_x's with coefficients in k.

Let Z be another module over k. If ϕ is a homomorphism from $c_{00}(X, k)$ into Z, as modules over k, then $f(x) = \phi(\delta_x)$ defines a mapping from X into Z. It is easy to see that ϕ is uniquely determined by f, and that every Z-valued function f on X corresponds to a module homomorphism ϕ from $c_{00}(X, k)$ into Z in this way. The mapping $\phi \mapsto f$ defines an isomorphism from the space $\mathrm{Hom}_k(c_{00}(X, k), Z)$ of module homomorphisms from $c_{00}(X, k)$ into Z onto $c(X, Z)$, as modules over k.

Similarly, let ϕ be a homomorphism from $c_{00}(X, W)$ into Z, as modules over k. If $x \in X$ and $w \in W$, then $\delta_x\, w \in c_{00}(X, W)$, so that

$$\phi_x(w) = \phi(\delta_x\, w) \tag{7.13.1}$$

defines an element of Z. This defines ϕ_x as a module homomorphism from W into Z, so that $x \mapsto \phi_x$ is an element of $c(X, \mathrm{Hom}_k(W, Z))$. One can check that ϕ is uniquely determined by $x \mapsto \phi_x$, and that every mapping from X into $\mathrm{Hom}_k(W, Z)$ corresponds to a module homomorphism ϕ from $c_{00}(X, W)$ into Z in this way. This defines an isomorphism between the space $\mathrm{Hom}_k(c_{00}(X, W), Z)$ of module homomorhisms from $c_{00}(X, W)$ into Z and $c(X, \mathrm{Hom}_k(W, Z))$, as modules over k.

If $f \in c(X, k)$ and $w \in W$, then $f(x)\, w$ defines a W-valued function on X. This defines a mapping from $c(X, k) \times W$ into $c(X, W)$ that is bilinear over k. The restriction of this mapping to $c_{00}(X, k) \times W$ maps into $c_{00}(X, W)$.

Let μ be a mapping from $c_{00}(X, k) \times W$ into Z that is bilinear over k. If $x \in X$, then put

$$\mu_x(w) = \mu(\delta_x, w) \tag{7.13.2}$$

for every $w \in W$, which defines a module homomorphism from W into Z. If $f \in c_{00}(X, W)$, then

$$\sum_{x \in X} \mu_x(f(x)) \tag{7.13.3}$$

defines an element of Z, where all but finitely many terms in the sum are equal to 0. This defines a homomorphism from $c_{00}(X, W)$ into Z, as modules over k. One can use this to check that $c_{00}(X, W)$ satisfies the requirements of the tensor product of $c_{00}(X, k)$ and W, as modules over k.

Let V be another module over k, and suppose that ϕ is a homomorphism from V into $c(X, Z)$, as modules over k. If $x \in X$ and $v \in V$, then let $\phi_x(v)$ be the value of $\phi(v)$ at x, as a Z-valued function on X. This defines ϕ_x as a module homomorphism from V into Z for each $x \in X$, so that $x \mapsto \phi_x$ is an element of $c(X, \mathrm{Hom}_k(V, Z))$. Clearly ϕ is uniquely determined by $x \mapsto \phi_x$, and every mapping from X into $\mathrm{Hom}_k(V, Z)$ corresponds to a module homomorphism ϕ from V into $c(X, Z)$ in this way. This defines an isomorphism between the space $\mathrm{Hom}_k(V, c(X, Z))$ of module homomorphisms from V into $c(X, Z)$ and $c(X, \mathrm{Hom}_k(V, Z))$, as modules over k.

7.14 Some remarks about sums, products

Let k be a commutative ring with a multiplicative identity element, and let W be a module over k. Of course, k may be considered as a module over itself, and

$$(t, w) \mapsto t\, w \tag{7.14.1}$$

defines a mapping from $k \times W$ into W that is bilinear over k. Using this mapping, one can check that W satisfies the requirements of $k \bigotimes W$.

Let I be a nonempty set, and let V_j be a module over k for every $j \in I$. Thus $\bigoplus_{j \in I} V_j$ is a module over k, and one can verify that

$$\Big(\bigoplus_{j \in I} V_j\Big) \bigotimes W = \bigoplus_{j \in I} (V_j \bigotimes W) \tag{7.14.2}$$

in a natural way. Of course, there is an analogous statement for tensor products with a direct sum in any factor.

If Z is a module over k, then

$$\mathrm{Hom}_k(k, Z) = Z \tag{7.14.3}$$

in a natural way, because a mapping from k into Z that is linear over k corresponds to multiplication by an element of Z. If I and V_j, $j \in I$, are as in the previous paragraph, then

$$\mathrm{Hom}_k\Big(\bigoplus_{j\in I} V_j, Z\Big) = \prod_{j\in I} \mathrm{Hom}_k(V_j, Z) \tag{7.14.4}$$

in a natural way. More precisely, any module homomorphism from $\bigoplus_{j\in I} V_j$ into Z leads to a module homomorphism from V_l into Z for every $l \in I$, using the natural inclusion of V_l into $\bigoplus_{j\in I} V_j$. Conversely, if one has a module homomorphism from V_l into Z for every $l \in I$, then one can get a module homomorphism from $\bigoplus_{j\in I} V_j$ into Z using the given homomorphisms on each coordinate of an element of $\bigoplus_{j\in I} V_j$, and adding the results in Z.

Similarly, let V be a module over k, and let Z_j be a module over k for every $j \in I$. It is easy to see that

$$\mathrm{Hom}_k\Big(V, \prod_{j\in I} Z_j\Big) = \prod_{j\in I} \mathrm{Hom}_k(V, Z_j) \tag{7.14.5}$$

in a natural way.

7.15 Some natural isomorphisms

Let k be a commutative ring with a multiplicative identity element, and let $V_1, \ldots, V_n$ be modules over k for some integer $n \ge 2$. Also let σ be a permutation on $\{1, \ldots, n\}$, which is to say a one-to-one mapping from $\{1, \ldots, n\}$ onto itself. Thus the tensor products $\bigotimes_{j=1}^n V_j$ and $\bigotimes_{j=1}^n V_{\sigma(j)}$ can be defined as modules over k as in Section 7.12. There is a unique module homomorphism from $\bigotimes_{j=1}^n V_j$ into $\bigotimes_{j=1}^n V_{\sigma(j)}$ with

$$v_1 \otimes \cdots \otimes v_n \mapsto v_{\sigma(1)} \otimes \cdots \otimes v_{\sigma(n)} \tag{7.15.1}$$

for every $(v_1, \ldots, v_n) \in \prod_{j=1}^n V_j$. More precisely, one can start with the mapping from $\prod_{j=1}^n V_j$ into $\bigotimes_{j=1}^n V_{\sigma(j)}$ defined by

$$(v_1, \ldots, v_n) \mapsto v_{\sigma(1)} \otimes \cdots \otimes v_{\sigma(n)}, \tag{7.15.2}$$

which is multilinear over k.

Let τ be another permutation on $\{1, \ldots, n\}$, which leads to a unique module homomorphism from $\bigotimes_{j=1}^n V_{\sigma(j)}$ into $\bigotimes_{j=1}^n V_{\tau(\sigma(j))}$ with

$$v_{\sigma(1)} \otimes \cdots \otimes v_{\sigma(n)} \mapsto v_{\tau(\sigma(1))} \otimes \cdots \otimes v_{\tau(\sigma(n))} \tag{7.15.3}$$

for every $(v_1, \ldots, v_n) \in \prod_{j=1}^n V_j$, as before. The composition of this module homomorphism with the previous one that satisfies (7.15.1) is a module homomorphism from $\bigotimes_{j=1}^n V_j$ into $\bigotimes_{j=1}^n V_{\tau(\sigma(j))}$ with

$$v_1 \otimes \cdots \otimes v_n \mapsto v_{\tau(\sigma(1))} \otimes \cdots \otimes v_{\tau(\sigma(n))} \tag{7.15.4}$$

for every $(v_1, \ldots, v_n) \in \prod_{j=1}^n V_j$. This is the same as the homomorphism associated to $\tau \circ \sigma$, by uniqueness. In particular, if $\tau \circ \sigma$ is the identity mapping on $\{1, \ldots, n\}$, then we get the identity mapping on $\bigotimes_{j=1}^n V_j$. It follows that the module homomorphism from $\bigotimes_{j=1}^n V_j$ into $\bigotimes_{j=1}^n V_{\sigma(j)}$ that satisfies (7.15.1) is an isomorphism, whose inverse is the analogous homomorphism from $\bigotimes_{j=1}^n V_{\sigma(j)}$ into $\bigotimes_{j=1}^n V_j$ associated to the inverse of σ.

Now let n_1 and n_2 be positive integers with $n_1 + n_2 = n$. The tensor products $\bigotimes_{j=1}^{n_1} V_j$ and $\bigotimes_{l=1}^{n_2} V_{n_1+l}$ can be defined as before when $n_1, n_2 \geq 2$, and otherwise they may be interpreted as being the given module over k when n_1 or n_2 is equal to 1. Thus the tensor product

$$\Big(\bigotimes_{j=1}^{n_1} V_j\Big) \bigotimes \Big(\bigotimes_{l=1}^{n_2} V_{n_1+l}\Big) \tag{7.15.5}$$

is defined as a module over k as well. It is well known that there is a natural isomorphism between $\bigotimes_{j=1}^n V_j$ and (7.15.5), as modules over k. More precisely, if $(v_1, \ldots, v_n) \in \prod_{j=1}^n V_j$, then $v_1 \otimes \cdots \otimes v_n$ corresponds to

$$(v_1 \otimes \cdots \otimes v_{n_1}) \otimes (v_{n_1+1} \otimes \cdots \otimes v_n) \tag{7.15.6}$$

under this isomorphism.

Let V be a module over k, and suppose that $V_j = V$ for each $j = 1, \ldots, n$. In this case,

$$T^n V = \bigotimes_{j=1}^n V_j \tag{7.15.7}$$

is called the *nth tensor power* of V. We can interpret $T^1 V$ as being equal to V, as in the preceding paragraph. If σ is a permutation on $\{1, \ldots, n\}$, then we get a module automorphism on $T^n V$, as before. The elements of $T^n V$ that are invariant under the module automorphisms associated to all permutations on $\{1, \ldots, n\}$ are said to be *symmetric*, and form a submodule of $T^n V$, as a module over k.

If V_1, V_2, V_3 are modules over k, then $(V_1 \bigotimes V_2) \bigotimes V_3$ and $V_1 \bigotimes (V_2 \bigotimes V_3)$ are both isomorphic to $V_1 \bigotimes V_2 \bigotimes V_3$, as modules over k, as before. This leads to a natural isomorphism between $(V_1 \bigotimes V_2) \bigotimes V_3$ and $V_1 \bigotimes (V_2 \bigotimes V_3)$, as modules over k. More precisely, if $v_1 \in V_1$, $v_2 \in V_2$, and $v_3 \in V_3$, then $(v_1 \otimes v_2) \otimes v_3$ corresponds to $v_1 \otimes (v_2 \otimes v_3)$ under this isomorphism.

Chapter 8

Formal series and ordered rings

8.1 Poles of finite order

Let k be a commutative ring with a multiplicative identity element, let A be a module over k, and let T be an indeterminate. Consider the space $A((T))$ of formal series of the form

$$f(T) = \sum_{j=j_0}^{\infty} f_j \, T^j, \tag{8.1.1}$$

where $j_0 \in \mathbf{Z}$ and $f_j \in A$ for each $j \geq j_0$. More precisely, $A((T))$ may be defined as the space of A-valued functions on $\mathbf{Z}$ that are equal to 0 for all but finitely many negative integers. Thus (8.1.1) corresponds to $j \mapsto f_j$ as an A-valued function on $\mathbf{Z}$, where $f_j = 0$ when $j < j_0$. As in [4], elements of $A((T))$ may also be expressed as

$$f(T) = \sum_{j>>-\infty} f_j \, T^j, \tag{8.1.2}$$

to indicate that $f_j = 0$ for all but finitely many $j < 0$.

Note that $A((T))$ is a module over k with respect to termwise addition and scalar multiplication of these formal series, which corresponds to pointwise addition and scalar multiplication of the associated A-valued functions on $\mathbf{Z}$. The space $A[[T]]$ of formal power series in T with coefficients in A can be identified with the submodule of $A((T))$ consisting of formal series $f(T)$ such that $f_j = 0$ for all $j < 0$. In particular, A can be identified with the submodule of $A((T))$ consisting of formal series $f(T)$ with $f_j = 0$ when $j \neq 0$.

If $f(T) \in A((T))$ and $l \in \mathbf{Z}$, then

$$f(T)\, T^l = \sum_{j>>-\infty} f_j \, T^{j+l} = \sum_{j>>-\infty} f_{j-l} \, T^j \tag{8.1.3}$$

defines an element of $A((T))$ as well. This is the same as $f(T)$ when $l = 0$, and agrees with the analogous definition on $A[[T]]$ in Section 4.3 when $l \geq 0$. In this situation, $f(T) \mapsto f(T)\,T^l$ is a module automorphism on $A((T))$ for every $l \in \mathbf{Z}$.

Let $n \in \mathbf{Z}$ be given, and let $(A[[T]])\,T^n$ be the subset of $A((T))$ of formal series of the form $g(T)\,T^n$, where $g(T) \in A[[T]]$ is identified with an element of $A[[T]]$ as before. Equivalently, this is the set of $f(T) \in A((T))$ that can be expressed as in (8.1.1), with $j_0 \geq n$. If $n \geq 1$, then the elements of $(A[[T]])\,T^n$ correspond to formal power series in T with coefficients in A that vanish to order $n-1$, as in Section 4.3. Clearly $(A[[T]])\,T^n$ is a submodule of $A((T))$ for every $n \in \mathbf{Z}$, with

$$(A[[T]])\,T^n \subseteq (A[[T]])\,T^{n+1} \tag{8.1.4}$$

and

$$A((T)) = \bigcup_{n=-\infty}^{\infty} (A[[T]])\,T^n. \tag{8.1.5}$$

Let us say that the elements of a subset E of $A((T))$ have *poles of bounded order* if $E \subseteq (A[[T]])\,T^n$ for some $n \in \mathbf{Z}$. Of course, if E has only finitely many elements, then the elements of E have poles of bounded order. Suppose that E is a submodule of $A((T))$, as a module over k. If E is finitely generated, as a module over k, then it is easy to see that the elements of E have poles of bounded order.

8.2 Sequences and series

Let us continue with the same notation and hypotheses as in the previous section. Let $l_0 \in \mathbf{Z}$ be given, and let

$$f_l(T) = \sum_{j>>-\infty} f_{l,j}\,T^j \tag{8.2.1}$$

be an element of $A((T))$ for each integer $l \geq l_0$. As in Section 4.4, let us say that the sequence $\{f_l(T)\}_{l=l_0}^{\infty}$ is *termwise eventually constant* if for each $j \in \mathbf{Z}$ there is an integer $L_j \geq l_0$ such that $f_{l,j}$ does not depend on l when $l \geq L_j$. Similarly, let us say that $\{f_l(T)\}_{l=l_0}^{\infty}$ *eventually agrees with* $f(T) \in A((T))$ *termwise* if for every $j \in \mathbf{Z}$ there is an integer $L \geq l_0$ such that

$$f_{l,j} = f_j \tag{8.2.2}$$

for every $l \geq L_j$. Of course, this implies that $\{f_l(T)\}_{l=l_0}^{\infty}$ is termwise eventually constant. If $\{f_l(T)\}_{l=l_0}^{\infty}$ is termwise eventually constant, and if the $f_l(T)$'s have poles of bounded order, then $\{f_l(T)\}_{l=l_0}^{\infty}$ eventually agrees with an element of $A((T))$ termwise. However, a sequence of elements of $A((T))$ may eventually agree termwise with an element of $A((T))$ without having poles of bounded order.

Let $\alpha \in k$ and $r \in \mathbf{Z}$ be given, as well as another sequence $\{g_l(T)\}_{l=l_0}^{\infty}$ of elements of $A((T))$. If $\{f_l(T)\}_{l=l_0}^{\infty}$ and $\{g_l(T)\}_{l=l_0}^{\infty}$ are termwise eventually constant, then so are $\{\alpha\, f_l(T)\}_{l=l_0}^{\infty}$, $\{f_l(T)\, T^r\}_{l=l_0}^{\infty}$, and $\{f_l(T) + g_l(T)\}_{l=l_0}^{\infty}$. If the $f_l(T)$'s and $g_l(T)$'s have poles of bounded order, then the $\alpha\, f_l(T)$'s and $f_l(T) + g_l(T)$'s have the same property. In this case, if $r_0 \in \mathbf{Z}$, then the $f_l(T)\, T^r$'s have poles of bounded order for $l \geq l_0$ and $r \geq r_0$. If $\{f_l(T)\}_{l=l_0}^{\infty}$ and $\{g_l(T)\}_{l=l_0}^{\infty}$ eventually agree with $f(T), g(T) \in A((T))$ termwise, respectively, then $\{\alpha\, f_l(T)\}_{l=l_0}^{\infty}$, $\{f_l(T)\, T^r\}_{l=l_0}^{\infty}$, and $\{f_l(T) + g_l(T)\}_{l=l_0}^{\infty}$ eventually agree with $\alpha\, f(T)$, $f(T)\, T^r$, and $f(T) + g(T)$ termwise, respectively.

Let

$$a_l(T) = \sum_{j>>-\infty} a_{l,j}\, T^j \tag{8.2.3}$$

be an element of $A((T))$ for every integer $l \geq l_0$. Suppose that $\{a_l(T)\}_{l=l_0}^{\infty}$ eventually agrees with 0 termwise, and that the poles of the $a_l(T)$'s have bounded order. Under these conditions, the partial sums

$$\sum_{l=l_0}^{n} a_l(T) \tag{8.2.4}$$

are termwise eventually constant and have poles of bounded order. This implies that the partial sums (8.2.4) eventually agree termwise with an element of $A((T))$, as before. Let us denote this element of $A((T))$ by

$$\sum_{l=l_0}^{\infty} a_l(T). \tag{8.2.5}$$

If $\alpha \in k$, then $\{\alpha\, a_l(T)\}_{l=l_0}^{\infty}$ eventually agrees with 0 termwise, the $\alpha\, a_l(T)$'s have poles of bounded order, and

$$\sum_{l=l_0}^{\infty} \alpha\, a_l(T) = \alpha \sum_{l=l_0}^{\infty} a_l(T). \tag{8.2.6}$$

Similarly, if $r \in \mathbf{Z}$, then $\{a_l(T)\, T^r\}_{l=l_0}^{\infty}$ eventually agrees with 0 termwise, the $a_l(T)\, T^r$'s have poles of bounded order (in l), and

$$\sum_{l=l_0}^{\infty} a_l(T)\, T^r = \Big(\sum_{l=l_0}^{\infty} a_l(T)\Big)\, T^r. \tag{8.2.7}$$

Let $\{b_l(T)\}_{l=l_0}^{\infty}$ be another sequence of elements of $A((T))$ that eventually agrees termwise with 0, and whose terms have poles of bounded order. This implies that $\{a_l(T) + b_l(T)\}_{l=l_0}^{\infty}$ eventually agrees termwise with 0 too, and that the $a_l(T) + b_l(T)$'s have poles of bounded order. It is easy to see that

$$\sum_{l=l_0}^{\infty} (a_l(T) + b_l(T)) = \sum_{l=l_0}^{\infty} a_l(T) + \sum_{l=l_0}^{\infty} b_l(T) \tag{8.2.8}$$

in this situation.

8.3 Formal series and module homomorphisms

Let k be a commutative ring with a multiplicative identity element, let A, B be modules over k, and let T be an indeterminate. Thus $B((T))$ can be defined as a module over k as in Section 8.1. Let ϕ be a homomorphism from A into $B((T))$, as modules over k. If $a \in A$, then $\phi(a)$ can be expressed as

$$\phi(a) = \sum_{j=-\infty}^{\infty} \phi_j(a)\, T^j, \tag{8.3.1}$$

where $\phi_j(a) \in B$ for every $j \in \mathbf{Z}$, and $\phi_j(a) = 0$ for all but finitely many $j < 0$. More precisely, for each $j \in \mathbf{Z}$, ϕ_j is a homomorphism from A into B, as modules over k. Conversely, let ϕ_j be a module homomorphism from A into B for every $j \in \mathbf{Z}$, and suppose that for each $a \in A$, $\phi_j(a) = 0$ for all but finitely many $j < 0$. Under these conditions, (8.3.1) defines an element of $B((T))$ for every $a \in A$, and this defines ϕ as a homomorphism from A into $B((T))$, as modules over k.

Let ϕ be a module homomorphism from A into $B((T))$ again. Let us say that ϕ has *poles of bounded order* if the set of $\phi(a)$ with $a \in A$ has poles of bounded order, as a subset of $B((T))$. Equivalently, this means that there is an integer $n(\phi)$ such that $\phi_j(a) = 0$ for every $a \in A$ and $j < n(\phi)$. This is the same as saying that $\phi_j = 0$ for all but finitely many $j < 0$, as homomorphisms from A into B. If A is finitely generated as a module over k, then this follows automatically from the fact that $\phi(a) \in B((T))$ for every $a \in A$.

Remember that the space $\mathrm{Hom}_k(A, B)$ of module homomorphisms from A into B is a module over k too, with respect to pointwise addition and scalar multiplication of mappings. Thus $(\mathrm{Hom}_k(A, B))((T))$ can be defined as a module over k as before. Let

$$\phi(T) = \sum_{l=l_0}^{\infty} \phi_l\, T^l \tag{8.3.2}$$

be an element of $(\mathrm{Hom}_k(A, B))((T))$, so that $l_0 \in \mathbf{Z}$ and $\phi_l \in \mathrm{Hom}_k(A, B)$ for every $l \geq l_0$. If $a \in A$, then

$$(\phi(T))(a) = \sum_{l=l_0}^{\infty} \phi_l(a)\, T^l \tag{8.3.3}$$

defines an element of $B((T))$, and the mapping from $a \in A$ to (8.3.3) is a homomorphism from A into $B((T))$, as modules over k. This homomorphism has poles of finite order, and every module homomorphism from A into $B((T))$ with poles of finite order corresponds to an element of $(\mathrm{Hom}_k(A, B))((T))$ in this way.

The space $\mathrm{Hom}_k(A, B((T)))$ of module homomorphisms from A into $B((T))$ is a module over k as well. It is easy to see that the collection of module homomorphisms from A into $B((T))$ with poles of finite order is a submodule of $\mathrm{Hom}_k(A, B((T)))$. The mapping from (8.3.2) to (8.3.3) defines an injective module homomorphism from $(\mathrm{Hom}_k(A, B))((T))$ onto this submodule of

$\mathrm{Hom}_k(A, B((T)))$. If $\phi(T) \in (\mathrm{Hom}_k(A, B))((T))$ and $r \in \mathbf{Z}$, then $\phi(T)\, T^r$ defines an element of $(\mathrm{Hom}_k(A, B))((T))$ too, as in Section 8.1. Note that for every $a \in A$,

(8.3.4) $$(\phi(T)\, T^r)(a) = (\phi(T))(a)\, T^r,$$

as elements of $B((T))$.

8.4 Extending module homomorphisms

Let us continue with the notation and hypotheses in the previous section. Let $\phi(T)$ be an element of $(\mathrm{Hom}_k(A, B))((T))$ as in (8.3.2) again, and let

(8.4.1) $$a(T) = \sum_{m=m_0}^{\infty} a_m\, T^m$$

be an element of $A((T))$, where $m_0 \in \mathbf{Z}$. Thus

(8.4.2) $$(\phi(T))(a_m) = \sum_{l=l_0}^{\infty} \phi_l(a_m)\, T^l$$

defines an element of $B((T))$ for every $m \in \mathbf{Z}$, as in (8.3.3). Put

(8.4.3) $$(\phi(T))(a(T)) = \sum_{m=m_0}^{\infty} (\phi(T))(a_m)\, T^m,$$

where the series on the right can be defined as an element of $B((T))$ as in Section 8.2. This defines a homomorphism from $A((T))$ into $B((T))$, as modules over k, associated to $\phi(T)$.

It is easy to see that

(8.4.4) $$(\phi(T))(a(T)\, T^r) = (\phi(T))(a(T))\, T^r$$

for every $a(T) \in A((T))$ and $r \in \mathbf{Z}$. We also have that

(8.4.5) $$(\phi(T))((A[[T]])\, T^n) \subseteq (B[[T]])\, T^{n+l_0}$$

for every $n \in \mathbf{Z}$. Note that (8.4.3) is linear over k in $\phi(T)$. If $r \in \mathbf{Z}$, then $\phi(T)\, T^r$ defines an element of $(\mathrm{Hom}_k(A, B))((T))$, as before. One can verify that

(8.4.6) $$(\phi(T)\, T^r)(a(T)) = (\phi(T))(a(T))\, T^r$$

as elements of $B((T))$ for every $a(T) \in A((T))$.

Let $a(T) \in A((T))$ be given as in (8.4.1) again. As before, we take $\phi_l = 0$ when $l < l_0$, and $a_m = 0$ when $m < m_0$. Let $n \in \mathbf{Z}$ be given, and observe that

(8.4.7) $$\phi_l(a_{n-l}) = 0$$

when $l < l_0$ and when $n - l < m_0$, which is to say that $n - m_0 < l$. In particular, (8.4.7) holds for all but finitely many $l \in \mathbf{Z}$, so that

$$((\phi(T))(a(T)))_n = \sum_{l=-\infty}^{\infty} \phi_l(a_{n-l}) \tag{8.4.8}$$

defines an element of B. If $n < l_0 + m_0$, then (8.4.7) holds for every $l \in \mathbf{Z}$, so that (8.4.8) is equal to 0. Consider

$$(\phi(T))(a(T)) = \sum_{n=l_0+m_0}^{\infty} ((\phi(T))(a(T)))_n \, T^n \tag{8.4.9}$$

as an element of $B((T))$. One can check that this is equivalent to (8.4.3).

Let C be a third module over k, and let

$$\psi(T) = \sum_{r=r_0}^{\infty} \psi_r \, T^r \tag{8.4.10}$$

be an element of $(\mathrm{Hom}_k(B, C))((T))$, where $r_0 \in \mathbf{Z}$. As usual, we take $\psi_r = 0$ when $r < r_0$. The composition $\psi_r \circ \phi_l$ is defined as a module homomorphism from A into C for every $l, r \in \mathbf{Z}$. Let $n \in \mathbf{Z}$ be given, and note that

$$\psi_r \circ \phi_{n-r} = 0 \tag{8.4.11}$$

when $r < r_0$ and when $n - r < l_0$, which means that $n - l_0 < r$. It follows that (8.4.11) holds for all but finitely many $r \in \mathbf{Z}$, so that

$$(\psi(T) \circ \phi(T))_n = \sum_{r=-\infty}^{\infty} \psi_r \circ \phi_{n-r} \tag{8.4.12}$$

defines a module homomorphism from A into C. If $n < l_0 + r_0$, then (8.4.11) holds for every $r \in \mathbf{Z}$, and (8.4.12) is equal to 0. Put

$$\psi(T) \circ \phi(T) = \sum_{n=l_0+r_0}^{\infty} (\psi(T) \circ \phi(T))_n \, T^n, \tag{8.4.13}$$

which defines an element of $(\mathrm{Hom}_k(A, C))((T))$. One can verify that the module homomorphism from $A((T))$ into $C((T))$ corresponding to (8.4.13) as before is the same as the composition of the homomorphisms from $A((T))$ into $B((T))$ and from $B((T))$ into $C((T))$ corresponding to $\phi(T)$ and $\psi(T)$, respectively.

8.5 Homomorphisms from $A((T))$ into $B((T))$

Let k be a commutative ring with a multiplicative identity element again, let A, B be modules over k, and let T be an indeterminate. Also let ϕ be a homomorphism from $A((T))$ into $B((T))$, as modules over k, and suppose that

$$\phi(f(T)\, T) = \phi(f(T))\, T \tag{8.5.1}$$

for every $f(T) \in A((T))$. This implies that

$$\phi(f(T)\,T^r) = \phi(f(T))\,T^r \tag{8.5.2}$$

for every $f(T) \in A((T))$ and $r \in \mathbf{Z}$. Remember that $A[[T]]$ can be identified with the set of $f(T) \in A((T))$ such that $f_j = 0$ for every $j < 0$. Using (8.5.2), we get that ϕ is uniquely determined by its restriction to this subset of $A((T))$ corresponding to $A[[T]]$.

Suppose in addition that there is an integer $l_0(\phi)$ such that

$$\phi((A[[T]])\,T^n) \subseteq (B[[T]])\,T^{n+l_0(\phi)} \tag{8.5.3}$$

for every $n \in \mathbf{Z}$. Note that this condition holds automatically when ϕ is obtained from an element of $(\mathrm{Hom}_k(A, B))((T))$ as in the previous section. In order to verify this condition for any ϕ as in the preceding paragraph, it suffices to consider the case where $n = 0$, because of (8.5.2). The case where $n = 0$ can be reformulated as saying that if $f(T)$ corresponds to an element of $A[[T]]$, then $\phi(f(T))\,T^{-l_0(\phi)}$ corresponds to an element of $B[[T]]$. This means that

$$\widetilde{\phi}(f(T)) = \phi(f(T))\,T^{-l_0(\phi)} \tag{8.5.4}$$

maps the subset of $A((T))$ corresponding to $A[[T]]$ into the subset of $B((T))$ corresponding to $B[[T]]$. Equivalently, the $n = 0$ case says that the collection of $\phi(f(T))$ with $f(T) \in A[[T]]$ has poles of bounded order in $B((T))$. Thus we may simply say that ϕ has *poles of bounded order* on $A[[T]]$ in this situation.

Under these conditions, one can check that ϕ is uniquely determined by its restriction to the subset of $A((T))$ corresponding to A. This can also be obtained from the analogous statement in Section 4.8, applied to the mapping from the subset of $A((T))$ corresponding to $A[[T]]$ into the subset of $B((T))$ corresponding to $B[[T]]$ given by (8.5.4). In this situation, the restriction of ϕ to the subset of $A((T))$ corresponding to A has poles of bounded order, as in Section 8.3, and hence corresponds to an element of $(\mathrm{Hom}_k(A, B))((T))$, as before. This element of $(\mathrm{Hom}_k(A, B))((T))$ determines a homomorphism from $A((T))$ into $B((T))$, as in Section 8.4. In fact, ϕ is equal to this homomorphism on all of $A((T))$.

Let $\{a_l(T)\}_{l=l_0}^{\infty}$ be a sequence of elements of $A((T))$ starting at some $l_0 \in \mathbf{Z}$, and suppose that the set of $a_l(T)$'s, $l \ge l_0$, has poles of bounded order in $A((T))$. This implies that the set of $\phi(a_l(T))$'s, $l \ge l_0$, has poles of finite order in $B((T))$, by (8.5.3). Suppose that $\{a_l(T)\}_{l=l_0}^{\infty}$ also eventually agrees with some $a(T)$ in $A((T))$ termwise, as in Section 8.2. Under these conditions, one can check that $\{\phi(a_l(T))\}_{l=l_0}^{\infty}$ eventually agrees with $\phi(a(T))$ termwise. In particular, if $\{a_l(T)\}_{l=l_0}^{\infty}$ eventually agrees termwise with 0, then $\{\phi(a_l(T))\}_{l=l_0}^{\infty}$ eventually agrees termwise with 0. In this situation, $\sum_{l=l_0}^{\infty} a_l(T)$ and $\sum_{l=l_0}^{\infty} \phi(a_l(T))$ can be defined as elements of $A((T))$ and $B((T))$, respectively, as in Section 8.2. It is easy to see that

$$\phi\Big(\sum_{l=l_0}^{\infty} a_l(T)\Big) = \sum_{l=l_0}^{\infty} \phi(a_l(T)), \tag{8.5.5}$$

using the previous statement for the partial sums of these series.

8.6 Formal series and bilinear mappings

Let k be a commutative ring with a multiplicative identity element, let A, B, C be modules over k, and let T be an indeterminate. Thus $C((T))$ can be defined as a module over k as in Section 8.1, and we let β be a mapping from $A \times B$ into $C((T))$ that is bilinear over k. If $a \in A$ and $b \in B$, then $\beta(a, b)$ can be expressed as

$$\beta(a,b) = \sum_{r=-\infty}^{\infty} \beta_r(a,b)\, T^r, \tag{8.6.1}$$

where $\beta_r(a, b) \in C$ for every $r \in \mathbf{Z}$, and

$$\beta_r(a,b) = 0 \tag{8.6.2}$$

for all but finitely many $r < 0$. This defines β_r as a mapping from $A \times B$ into C that is bilinear over k for every $r \in \mathbf{Z}$. Conversely, if β_r is a mapping from $A \times B$ into C that is bilinear over k for every $r \in \mathbf{Z}$, and if for every $a \in A$ and $b \in B$ we have that (8.6.2) holds for all but finitely many $r < 0$, then (8.6.1) defines an element of $C((T))$ for every $a \in A$ and $b \in B$, and this defines a mapping from $A \times B$ into $C((T))$ that is bilinear over k.

Let β be a mapping from $A \times B$ into $C((T))$ that is bilinear over k again. Let us say that β has *poles of bounded order* if the set of $\beta(a, b)$ with $a \in A$ and $b \in B$ has poles of bounded order in $C((T))$. This means that there is an integer $r(\beta)$ such that (8.6.2) holds for every $a \in A$, $b \in B$, and $r < r(\beta)$. One can check that this holds automatically when A and B are finitely generated as modules over k. If β has poles of bounded order, then β corresponds to a formal series in T with poles of finite order whose coefficients are bilinear mappings from $A \times B$ into C.

Let β be a mapping from $A \times B$ into $C((T))$ that is bilinear over k and has poles of bounded order, so that there is an $r(\beta) \in \mathbf{Z}$ such that (8.6.2) holds for every $a \in A$, $b \in B$, and $r < r(\beta)$. Also let $f(T) = \sum_{j=j_0}^{\infty} f_j\, T^j \in A((T))$ and $g(T) = \sum_{l=l_0}^{\infty} g_l\, T^l \in B((T))$ be given, where $j_0, l_0 \in \mathbf{Z}$. As before, we take $f_j = 0$ when $j < j_0$, and $g_l = 0$ when $l < l_0$. Let $n \in \mathbf{Z}$ be given, and observe that

$$\beta(f_j, g_{n-j}) = 0 \tag{8.6.3}$$

when $j < j_0$, and when $n - j < l_0$, which means that $n - l_0 < j$. In particular, (8.6.3) holds for all but finitely many $j \in \mathbf{Z}$, so that

$$h_n = \sum_{j=-\infty}^{\infty} \beta(f_j, g_{n-j}) \tag{8.6.4}$$

defines an element of $C((T))$. Equivalently,

$$\beta(f_{n-l}, g_l) = 0 \tag{8.6.5}$$

when $l < l_0$ and when $n - l < j_0$, which means that $n - j_0 < l$. Thus (8.6.5) holds for all but finitely many $l \in \mathbf{Z}$, and (8.6.4) is the same as

$$h_n = \sum_{l=-\infty}^{\infty} \beta(f_{n-l}, g_l). \tag{8.6.6}$$

If $n < j_0 + l_0$, then (8.6.3) holds for every $j \in \mathbf{Z}$, which is the same as saying that (8.6.5) holds for every $l \in \mathbf{Z}$, so that $h_n = 0$. Note that the coefficient of T^r in h_n is equal to 0 when $r < r(\beta)$, because of the corresponding hypothesis on β. Put

$$h(T) = \sum_{n=j_0+l_0}^{\infty} h_n\, T^n, \tag{8.6.7}$$

where the series on the right defines an element of $C((T))$ as in Section 8.2.

Put

$$\beta(f(T), g(T)) = h(T), \tag{8.6.8}$$

which defines a mapping from $A((T)) \times B((T))$ into $C((T))$ that is bilinear over k. This mapping agrees with the initial mapping from $A \times B$ into $C((T))$, when A and B are identified with submodules of $A((T))$ and $B((T))$, respectively, as in Section 8.1. One can verify that

$$\beta(f(T)\, T^{m_1}, g(T)\, T^{m_2}) = \beta(f(T), g(T))\, T^{m_1+m_2} \tag{8.6.9}$$

for every $f(T) \in A((T))$, $g(T) \in B((T))$, and $m_1, m_2 \in \mathbf{Z}$. The coefficient of T^r in (8.6.7) is equal to 0 when

$$r < j_0 + l_0 + r(\beta), \tag{8.6.10}$$

because of the analogous statement for h_n. Equivalently, if $f(T) \in (A[[T]])\, T^{m_1}$ and $g(T) \in (B[[T]])\, T^{m_2}$ for some $m_1, m_2 \in \mathbf{Z}$, then

$$\beta(f(T), g(T)) \in (C[[T]])\, T^{m_1+m_2+r(\beta)}. \tag{8.6.11}$$

Suppose that $A = B$. If the initial mapping β from $A \times A$ into $C((T))$ is symmetric or antisymmetric, then the extension of β to $A((T)) \times A((T))$ just defined has the same property, because (8.6.4) and (8.6.6) are the same. Similarly, if $\beta(a, a) = 0$ for every $a \in A$, then

$$\beta(f(T), f(T)) = 0 \tag{8.6.12}$$

for every $f(T) \in A((T))$. To see this, it suffices to verify that

$$\sum_{j=-\infty}^{\infty} \beta(f_j, f_{n-j}) = 0 \tag{8.6.13}$$

for every $n \in \mathbf{Z}$. Remember that β is antisymmetric on $A \times A$ in this situation, as in Section 2.1. If n is odd, then (8.6.13) follows from the antisymmetry of β on $A \times A$. If n is even, then (8.6.13) follows from the antisymmetry of β and the fact that $\beta(f_{n/2}, f_{n/2}) = 0$, by hypothesis.

8.7 Bilinear mappings on $A((T)) \times B((T))$

Let k be a commutative ring with a multiplicative identity element again, let A, B, and C be modules over k, and let T be an indeterminate. Suppose that β is a mapping from $A((T)) \times B((T))$ into $C((T))$ that is bilinear over k and satisfies

(8.7.1) $$\beta(f(T)\,T, g(T)) = \beta(f(T), g(T)\,T) = \beta(f(T), g(T))\,T$$

for every $f(T) \in A((T))$ and $g(T) \in B((T))$. This implies that

(8.7.2) $$\beta(f(T)\,T^{m_1}, g(T)\,T^{m_2}) = \beta(f(T), g(T))\,T^{m_1+m_2}$$

for every $f(T) \in A((T))$, $g(T) \in B((T))$, and $m_1, m_2 \in \mathbf{Z}$. It is easy to see that β is uniquely determined by its restriction to the subset of $A((T)) \times B((T))$ corresponding to $A[[T]] \times B[[T]]$, using (8.7.2).

As before, let us ask in addition that there be an integer $r(\beta)$ such that if $f(T) \in (A[[T]])\,T^{m_1}$ and $g(T) \in (B[[T]])\,T^{m_2}$ for some $m_1, m_2 \in \mathbf{Z}$, then

(8.7.3) $$\beta(f(T), g(T)) \in (C[[T]])\,T^{m_1+m_2+r(\beta)}.$$

Remember that this condition holds when β is obtained from a bilinear mapping from $A \times B$ into $C((T))$ with poles of bounded order as in the previous section. To verify this condition for any β as in the preceding paragraph, it is enough to consider the case where $m_1 = m_2 = 0$, because of (8.7.2). This case can be reformulated as saying that if $f(T)$ and $g(T)$ correspond to elements of $A[[T]]$ and $B[[T]]$, respectively, then $\beta(f(T), g(T))\,T^{-r(\beta)}$ corresponds to an element of $C[[T]]$. Equivalently, this means that

(8.7.4) $$\widetilde{\beta}(f(T), g(T)) = \beta(f(T), g(T))\,T^{-r(\beta)}$$

maps the subset of $A((T)) \times B((T))$ corresponding to $A[[T]] \times B[[T]]$ into the subset of $C((T))$ corresponding to $C[[T]]$. The $m_1 = m_2 = 0$ case of (8.7.3) is the same as saying that the collection of $\beta(f(T), g(T))$ with $f(T) \in A[[T]]$ and $g(T) \in B[[T]]$ has poles of bounded order in $C((T))$. In this situation, we may simply say that β has *poles of bounded order* on $A[[T]] \times B[[T]]$.

One can check that β is uniquely determined by its restriction to the subset of $A((T)) \times B((T))$ that corresponds to $A \times B$ under these conditions. This can also be seen using the analogous statement in Section 4.8 for mappings from $A[[T]] \times B[[T]]$ into $C[[T]]$, applied to the mapping that corresponds to (8.7.4). Of course, the restriction of β to $A \times B$ has poles of bounded order on $A \times B$. Thus the restriction of β to $A \times B$ can be extended to $A((T)) \times B((T))$ as in the previous section. This extension agrees with β on all of $A((T)) \times B((T))$ in this situation.

Let $\{a_m(T)\}_{m=m_0}^{\infty}$ and $\{b_r(T)\}_{r=r_0}^{\infty}$ be sequences of elements of $A((T))$ and $B((T))$, respectively. Suppose that the sets of $a_m(T)$'s, $m \geq m_0$, and $b_r(T)$'s, $r \geq r_0$, have poles of bounded order in $A((T))$ and $B((T))$, respectively. This implies that the set of $\beta(a_m(T), b_r(T))$'s, $m \geq m_0, r \geq r_0$, has poles of bounded order in $C((T))$, by (8.7.3). Suppose that $\{a_m(T)\}_{m=m_0}^{\infty}$ and $\{b_r(T)\}_{r=r_0}^{\infty}$ eventually agree with some $a(T) \in A((T))$ and $b(T) \in B((T))$ termwise, respectively, as in Section 8.2. One can verify that $\{\beta(a_r(T), b_r(T))\}_{r=\max(m_0,r_0)}^{\infty}$ eventually agrees termwise with $\beta(a(T), b(T))$.

Suppose now that $\{a_m(T)\}_{m=m_0}^{\infty}$ and $\{b_r(T)\}_{r=r_0}^{\infty}$ eventually agree termwise with 0 in $A((T))$ and $B((T))$, respectively, in addition to having poles of bounded order. This implies that $\sum_{m=m_0}^{\infty} a_m(T)$ and $\sum_{r=r_0}^{\infty} b_r(T)$ define elements of $A((T))$ and $B((T))$, respectively, as in Section 8.2. If N is an integer with $N \geq m_0 + r_0$, then put

$$c_N(T) = \sum_{m=m_0}^{N-r_0} \beta(a_m(T), b_{N-m}(T)), \tag{8.7.5}$$

which is an element of $C((T))$. Equivalently, this is the sum of

$$\beta(a_m(T), b_r(T)) \tag{8.7.6}$$

over $m \geq m_0$ and $r \geq r_0$ with $m + r = N$. Note that the set of $c_N(T)$'s, $N \geq m_0 + r_0$, has poles of bounded order in $C((T))$, because of the analogous statement for (8.7.6) in the preceding paragraph. One can check that (8.7.6) vanishes to arbitrarily large order in T when m or r is sufficiently large, because of (8.7.3). In particular, $\{c_N(T)\}_{N=m_0+r_0}^{\infty}$ eventually agrees termwise with 0. Thus $\sum_{N=m_0+r_0}^{\infty} c_N(T)$ defines an element of $C((T))$, as in Section 8.2. One can verify that

$$\sum_{N=m_0+r_0}^{\infty} c_N(T) = \beta\Big(\sum_{m=m_0}^{\infty} a_m(T), \sum_{r=r_0}^{\infty} b_r(T)\Big), \tag{8.7.7}$$

as in Section 4.2.

8.8 Algebras and modules over $k((T))$

Let k be a commutative ring with a multiplicative identity element, and let A be an algebra over k in the strict sense, where multiplication of $a, b \in A$ is expressed as $a\,b$. Also let T be an indeterminate, and let $f(T) = \sum_{j=j_0}^{\infty} f_j\, T^j$ and $g(T) = \sum_{l=l_0}^{\infty} g_l\, T^l$ be elements of $A((T))$, where $j_0, l_0 \in \mathbf{Z}$. As usual, we take $f_j = 0$ when $j < j_0$, and $g_l = 0$ when $l < l_0$. Let $n \in \mathbf{Z}$ be given, and observe that

$$f_j\, g_{n-j} = 0 \tag{8.8.1}$$

when $j < j_0$ and when $n - j < l_0$, which means that $n - l_0 < j$. In particular, (8.8.1) holds for all but finitely many $j \in \mathbf{Z}$, so that

$$h_n = \sum_{j=-\infty}^{\infty} f_j\, g_{n-j} \tag{8.8.2}$$

reduces to a finite sum in A. Equivalently,

$$f_{n-l}\, g_l = 0 \tag{8.8.3}$$

when $l < l_0$ and when $n - l < j_0$, which means that $n - j_0 < l$. Thus (8.8.3) holds for all but finitely many $l \in \mathbf{Z}$, and (8.8.2) is the same as

$$h_n = \sum_{l=-\infty}^{\infty} f_{n-l}\, g_l. \tag{8.8.4}$$

If $n < j_0 + l_0$, then (8.8.1) holds for every $j \in \mathbf{Z}$, which is the same as saying that (8.8.3) holds for every $l \in \mathbf{Z}$, so that $h_n = 0$. Put

$$f(T)\, g(T) = h(T) = \sum_{n=j_0+l_0}^{\infty} h_n\, T^n, \tag{8.8.5}$$

which defines another element of $A((T))$. Of course, this is the same as in (8.6.7), with the bilinear mapping β given by multiplication on A. As before, one can check that

$$(f(T)\, T^{m_1})\, (g(T)\, T^{m_2}) = (f(T)\, g(T))\, T^{m_1+m_2} \tag{8.8.6}$$

for every $m_1, m_2 \in \mathbf{Z}$. If $f(T) \in (A[[T]])\, T^{m_1}$ and $g(T) \in (A[[T]])\, T^{m_2}$ for some $m_1, m_2 \in \mathbf{Z}$, then

$$f(T)\, g(T) \in (A[[T]])\, T^{m_1+m_2}. \tag{8.8.7}$$

This extends multiplication on A to a mapping from $A((T)) \times A((T))$ into $A((T))$ that is bilinear over k, which makes $A((T))$ into an algebra over k in the strict sense. In particular, this agrees with the extension of multiplication on A to $A[[T]]$ discussed in Section 4.6, so that $A[[T]]$ may be considered as a subalgebra of $A((T))$. If A is a commutative algebra over k, then $A((T))$ is commutative as well, by the remark about symmetry of β in the previous section. Similarly, if A is an associative algebra over k, then one can verify that $A((T))$ is an associative algebra. If A has a multiplicative identity element e, then e corresponds to the multiplicative identity element in $A((T))$ too.

Suppose that A is an associative algebra over k with a multiplicative identity element e, and let $f(T) = \sum_{j=j_0}^{\infty} f_j\, T^j$ be an element of $A((T))$. Thus $f(T)\, T^{-j_0}$ corresponds to an element of $A[[T]]$. If f_{j_0} is invertible in A, then $f(T)\, T^{-j_0}$ is invertible in $A[[T]]$, as in Section 4.7. This implies that $f(T)$ is invertible in $A((T))$.

Applying the earlier remarks to k as a commutative associative algebra over itself, we get that $k((T))$ is a commutative associative algebra over k with a multiplicative identity element. Let A be a module over k, and let $f(T) \in k((T))$ and $g(T) \in A((T))$ be given. Under these conditions, $f(T)\, g(T)$ can be defined as an element of $A((T))$ as in (8.8.5), where the terms on the right side of (8.8.2) are defined using scalar multiplication on A. This is the same as extending scalar multiplication on A, as a mapping from $k \times A$ into A that is bilinear over k, to a mapping from $k((T)) \times A((T))$ into $A((T))$, as in the previous section. One can check that this makes $A((T))$ into a module over $k((T))$. Note that (8.8.6) holds for every $m_1, m_2 \in \mathbf{Z}$ in this situation. Similarly, if $f(T) \in (k[[T]])\, T^{m_1}$ and $g(T) \in (A[[T]])\, T^{m_2}$ for some $m_1, m_2 \in \mathbf{Z}$, then (8.8.7) holds.

Let B be another module over k, and let $\phi(T) \in (\mathrm{Hom}_k(A, B))((T))$ be given. This leads to a homomorphism from $A((T))$ into $B((T))$ as modules over k, as in Section 8.4. More precisely, one can verify that this is a homomorphism from $A((T))$ into $B((T))$ as modules over $k((T))$. One can also look at this in terms of k-linear mappings satisfying (8.5.1) and (8.5.3).

Similarly, let C be a third module over k, and let β be a mapping from $A \times B$ into $C((T))$ that is bilinear over k and has poles of bounded order. One can check that the extension of β to a mapping from $A((T)) \times B((T))$ into $C((T))$ defined in Section 8.6 is bilinear over $k((T))$. One can also look at this in terms of mappings from $A((T)) \times B((T))$ into $C((T))$ that are bilinear over k and satisfy (8.7.1) and (8.7.3). In particular, if A is an algebra over k in the strict sense, then $A((T))$ may be considered as an algebra over $k((T))$ in the strict sense.

Let $(A, [\cdot,\cdot]_A)$ be a Lie algebra over k. If $f(T), g(T) \in A((T))$, then (8.8.2) should be expressed as

$$h_n = \sum_{j=-\infty}^{\infty} [f_j, g_{n-j}]_A \tag{8.8.8}$$

for each $n \in \mathbf{Z}$, so that (8.8.5) corresponds to

$$[f(T), g(T)]_{A((T))} = h(T) = \sum_{n=-\infty}^{\infty} h_n\, T^n. \tag{8.8.9}$$

As in Section 8.6, $[f(T), f(T)]_{A((T))} = 0$ for every $f(T) \in A((T))$, because $[a, a]_A = 0$ for every $a \in A$. One can also check that $[\cdot,\cdot]_{A((T))}$ satisfies the Jacobi identity on $A((T))$, using the Jacobi identity for $[\cdot,\cdot]_A$ on A. Thus $A((T))$ is a Lie algebra with respect to (8.8.9) over k, and in fact over $k((T))$.

8.9 Absolute values on $k((T))$

Let k be a field, and let T be an indeterminate. If $f(T)$ is a nonzero element of $k((T))$, then $f(T)$ is invertible in $k((T))$, because nonzero elements of k are invertible in k, and using the remark about invertibility in the previous section. Thus $k((T))$ is a field. Let $f(T) = \sum_{j>>-\infty} f_j\, T^j \in k((T))$ be given. If $f(T) \neq 0$, then there is a unique minimal integer $j_0(f(T))$ such that $f_{j_0(f(T))} \neq 0$, which is to say that $f_j = 0$ when $j < j_0(f(T))$. If $f(T) = 0$, then it is convenient to put $j_0(f) = +\infty$. Observe that

$$j_0(f(T) + g(T)) \geq \min(j_0(f(T)), j_0(g(T))) \tag{8.9.1}$$

and

$$j_0(f(T)\, g(T)) = j_0(f(T)) + j_0(g(T)) \tag{8.9.2}$$

for every $f(T), g(T) \in k((T))$, with suitable interpretations when any of these terms is $+\infty$.

Let r be a positive real number with $r \le 1$. If $f(T) \in k((T))$, then put

$$|f(T)|_r = r^{j_0(f(T))} \tag{8.9.3}$$

when $f(T) \neq 0$, and $|f(T)|_r = 0$ when $f(T) = 0$. Using (8.9.1) and (8.9.2), we get that

$$|f(T) + g(T)|_r \le \max(|f(T)|_r, |g(T)|_r) \tag{8.9.4}$$

and

$$|f(T)\, g(T)|_r = |f(T)|_r\, |g(T)|_r \tag{8.9.5}$$

for every $f(T), g(T) \in k((T))$. Thus $|f(T)|_r$ defines an ultrametric absolute value function on $k((T))$, which is the same as the trivial absolute value function on $k((T))$ when $r = 1$. If a is a positive real number, then $0 < r^a \le 1$, and

$$|f(T)|_r^a = |f(T)|_{r^a} \tag{8.9.6}$$

for every $f(T) \in k((T))$.

It follows that

$$d_r(f(T), g(T)) = |f(T) - g(T)|_r \tag{8.9.7}$$

is an ultrametric on $k((T))$, which is the discrete metric when $r = 1$. Let us suppose from now on in this section that $r < 1$. If $l \in \mathbf{Z}$, then the closed ball in $k((T))$ centered at 0 with radius r^l with respect to (8.9.7) is given by

$$\begin{aligned} \overline{B}(0, r^l) &= \{f(T) \in k((T)) : |f(T)|_r \le r^l\} \\ &= \{f(T) \in k((T)) : j_0(f(T)) \ge l\} = (k[[T]])\, T^l. \end{aligned} \tag{8.9.8}$$

Let $l \in \mathbf{Z}$ be given, so that (8.9.8) can be identified with the space of k-valued functions on the set of integers $j \ge l$. This may be considered as the Cartesian product of copies of k indexed by integers $j \ge l$. One can check that the topology determined on (8.9.8) by the restriction of the ultrametric (8.9.7) to (8.9.8) corresponds to the product topology on the Cartesian product just mentioned, using the discrete topology on k.

One can verify that $k((T))$ is complete with respect to the ultrametric (8.9.7), as follows. Any Cauchy sequence in $k((T))$ with respect to (8.9.7) is contained in (8.9.8) for some $l \in \mathbf{Z}$, because a Cauchy sequence in any metric space is bounded. It is easy to see that for each $j \in \mathbf{Z}$, the corresponding sequence of coefficients of T^j in the terms of the Cauchy sequence is eventually constant, as a sequence of elements of k. This leads to an element of (8.9.8), for which the coefficient of T^j is the eventual constant value of the sequence in k just mentioned, for each $j \in \mathbf{Z}$. The given Cauchy sequence in $k((T))$ converges to this element of (8.9.8) with respect to the ultrametric (8.9.7), by the description of the topology determined on (8.9.8) by the restriction of the ultrametric (8.9.7) in the preceding paragraph.

8.10 Formal series and algebra homomorphisms

Let k be a commutative ring with a multiplicative identity element, and let T be an indeterminate. Also let A, B be algebras over k in the strict sense, where multiplication of x, y is expressed as $x\,y$. Remember that multiplication on A and B can be extended to $A((T))$ and $B((T))$, respectively, so that $A((T))$ and $B((T))$ become algebras in the strict sense over $k((T))$, as in Section 8.8. In particular, they may be considered as algebras over k.

Let ϕ be a homomorphism from A into $B((T))$, as modules over k for the moment. As in Section 8.3, ϕ can be expressed as

$$\phi(a) = \sum_{j=-\infty}^{\infty} \phi_j(a)\, T^j \tag{8.10.1}$$

for each $a \in A$, where ϕ_j is a module homomorphism from A into B for every $j \in \mathbf{Z}$, and for every $a \in A$ we have that $\phi_j(a) = 0$ for all but finitely many $j < 0$. Of course, ϕ is a homomorphism from A into $B((T))$ as algebras over k when

$$\phi(a\,a') = \phi(a)\,\phi(a') \tag{8.10.2}$$

for every $a, a' \in A$. Let $a, a' \in A$ be given, so that

$$\phi(a\,a') = \sum_{n=-\infty}^{\infty} \phi_n(a\,a')\, T^n, \tag{8.10.3}$$

as in (8.10.1), where $\phi_n(a\,a') = 0$ for all but finitely many $n < 0$. We also have that

$$\begin{aligned} \phi(a)\,\phi(a') &= \Big(\sum_{j=-\infty}^{\infty} \phi_j(a)\, T^j\Big)\Big(\sum_{l=-\infty}^{\infty} \phi_l(a')\, T^l\Big) \\ &= \sum_{n=-\infty}^{\infty} \Big(\sum_{j=-\infty}^{\infty} \phi_j(a)\,\phi_{n-j}(a')\Big)\, T^n, \end{aligned} \tag{8.10.4}$$

as in Section 8.8. Remember that for each $n \in \mathbf{Z}$, $\phi_j(a)\,\phi_{n-j}(a') = 0$ for all but finitely many $j \in \mathbf{Z}$, and that for all but finitely many $n < 0$, this condition holds for every $j \in \mathbf{Z}$. Comparing (8.10.3) and (8.10.4), we get that (8.10.2) holds if and only if

$$\phi_n(a\,a') = \sum_{j=-\infty}^{\infty} \phi_j(a)\,\phi_{n-j}(a') \tag{8.10.5}$$

for every $n \in \mathbf{Z}$.

Suppose that ϕ has poles of bounded order on A, so that there is an integer $r(\phi)$ such that $\phi_j = 0$ on A when $j < r(\phi)$. Let $f(T) = \sum_{j=j_0}^{\infty} f_j\, T^j$ be an element of $A((T))$. As in Section 8.4, ϕ can be extended to a module homomorphism from $A((T))$ into $B((T))$, by putting

$$\phi(f(T)) = \sum_{j=j_0}^{\infty} \phi(f_j)\, T^j, \tag{8.10.6}$$

where the sum on the right is defined as an element of $B((T))$ as in Section 8.2. Let $g(T) = \sum_{l=l_0}^{\infty} g_l\, T^l$ be another element of $A((T))$, so that

$$\phi(g(T)) = \sum_{l=l_0}^{\infty} \phi(g_l)\, T^l. \tag{8.10.7}$$

Remember that $f(T)\, g(T) = h(T) = \sum_{n=j_0+l_0}^{\infty} h_n\, T^n$ is defined in $A((T))$ by putting

$$h_n = \sum_{j=-\infty}^{\infty} f_j\, g_{n-j} \tag{8.10.8}$$

for each n, which reduces to a finite sum in A. Thus

$$\phi(f(T)\, g(T)) = \phi(h(T)) = \sum_{n=j_0+l_0}^{\infty} \phi(h_n)\, T^n, \tag{8.10.9}$$

where the sum on the right is defined as an element of $B((T))$ as in Section 8.2 again. If ϕ is an algebra homomorphism from A into $B((T))$, then

$$\phi(h_n) = \sum_{j=-\infty}^{\infty} \phi(f_j\, g_{n-j}) = \sum_{j=-\infty}^{\infty} \phi(f_j)\, \phi(g_{n-j}) \tag{8.10.10}$$

for each n, where the sums reduce to finite sums in $B((T))$. We would like to say that

$$\sum_{n=j_0+l_0}^{\infty} \Big(\sum_{j=-\infty}^{\infty} \phi(f_j)\, \phi(g_{n-j}) \Big)\, T^n = \Big(\sum_{j=j_0}^{\infty} \phi(f_j)\, T^j \Big) \Big(\sum_{l=l_0}^{\infty} \phi(g_l)\, T^l \Big), \tag{8.10.11}$$

as elements of $B((T))$. If ϕ maps A into B, then this follows from the definition of the extension of multiplication on B to $B((T))$, as in Section 8.8. Otherwise, the $\phi(f_j)$'s, $j \ge j_0$, and $\phi(g_l)$'s, $l \ge l_0$, are elements of $B((T))$ with poles of bounded order, and (8.10.11) can be obtained from (8.7.7). It follows that

$$\phi(f(T)\, g(T)) = \phi(f(T))\, \phi(g(T)), \tag{8.10.12}$$

so that the extension of ϕ to $A((T))$ is an algebra homomorphism as well.

There are analogous statements for opposite algebra homomorphisms, as usual.

8.11 Involutions and formal series

Let k be a commutative ring with a multiplicative identity element, and let T be an indeterminate. Also let A, B be modules over k, and let ϕ be a module homomorphism from A into B. If $f(T) = \sum_{j>>-\infty} f_j\, T^j \in A((T))$, then

$$\phi(f(T)) = \sum_{j>>-\infty} \phi(f_j)\, T^j \tag{8.11.1}$$

defines an element of $B((T))$. This defines a homomorphism from $A((T))$ into $B((T))$, as modules over $k((T))$. This may be seen as a simple case of the situation discussed in Section 8.4, by identifying ϕ with an element of $(\mathrm{Hom}_k(A, B))((T))$. In particular, we have that

$$\phi(f(T)\, T^r) = \phi(f(T))\, T^r \tag{8.11.2}$$

for every $f(T) \in A((T))$ and $r \in \mathbf{Z}$. Of course, if $f(T)$ corresponds to an element of $A[T]$ or $A[[T]]$, then $\phi(f(T))$ corresponds to an element of $B[T]$ or $B[[T]]$, as appropriate. If ϕ is a one-to-one mapping from A onto B, then (8.11.1) defines a one-to-one mapping from $A((T))$ onto $B((T))$.

Now let A, B be algebras over k in the strict sense, where multiplication of x, y is expressed as $x\, y$. If ϕ is an algebra homomorphism from A into B, then (8.11.1) defines an algebra homomorphism from $A((T))$ into $B((T))$, as in the previous section. Similarly, if ϕ is an opposite algebra homomorphism from A into B, then (8.11.1) defines an opposite algebra homomorphism from $A((T))$ into $B((T))$.

Let $x \mapsto x^*$ be an algebra involution on A, and put

$$f(T)^* = \sum_{j>>-\infty} f_j^*\, T^j \tag{8.11.3}$$

for every $f(T) \in A((T))$. This defines an algebra involution on $A((T))$, as before. Clearly $f(T) \in A((T))$ is self-adjoint with respect to this involution if and only if f_j is self-adjoint in A for every j. Similarly, $f(T)$ is anti-self-adjoint with respect to this involution if and only if f_j is anti-self-adjoint in A for every j.

If k is the field $\mathbf{C}$ of complex numbers, then there are analogous statements for conjugate-linear mappings. More precisely, if A and B are vector spaces over $\mathbf{C}$, then $A((T))$ and $B((T))$ may be considered as vector spaces over $\mathbf{C}$ too. If ϕ is a conjugate-linear mapping from A into B, then (8.11.1) defines a conjugate-linear mapping from $A((T))$ into $B((T))$, as vector spaces over $\mathbf{C}$. Remember that complex vector spaces may be considered as real vector spaces, and that conjugate-linear mappings between complex vector spaces may be considered as real-linear mappings between the corresponding real vector spaces. This can be used to reduce statements about conjugate-linear mappings to the analogous statements for real-linear mappings, as before.

In particular, if $a(T) = \sum_{j>>-\infty} a_j\, T^j \in \mathbf{C}((T))$, then

$$\overline{a(T)} = \sum_{j>>-\infty} \overline{a_j}\, T^j \tag{8.11.4}$$

defines an element of $\mathbf{C}((T))$ too, and this defines a conjugate-linear automorphism of $\mathbf{C}((T))$ as an algebra over $\mathbf{C}$. If $a(T)$ corresponds to an element of $\mathbf{C}[T]$ or $\mathbf{C}[[T]]$, then $\overline{a(T)}$ corresponds to an element of $\mathbf{C}[T]$ or $\mathbf{C}[[T]]$, as appropriate. One can use this to define conjugate-linearity over $\mathbf{C}[T]$, $\mathbf{C}[[T]]$, and $\mathbf{C}((T))$. These conjugate-linearity conditions amount to ordinary conjugate-linearity over $\mathbf{C}$, together with the appropriate "real" linearity condition over $\mathbf{R}[T]$, $\mathbf{R}[[T]]$, or $\mathbf{R}((T))$, respectively.

8.12 Ordered rings

Let R be a ring with a nonzero multiplicative identity element e. Of course, R may be considered as an associative algebra over $\mathbf{Z}$, and in particular as a module over $\mathbf{Z}$. Suppose that certain nonzero elements x of R have been designated as *positive*, which may be expressed by

$$x > 0. \tag{8.12.1}$$

We say that R is an *ordered ring* if the following conditions are satisfied. First, if x and y are positive elements of R, then

$$x + y > 0, \quad x\,y > 0. \tag{8.12.2}$$

Second, if x is any nonzero element of R, then either x or $-x$ is positive. This corresponds to the definition on p261 of [19].

Let R be an ordered ring. If x, y are nonzero elements of R, then $x\,y \neq 0$. More precisely,

$$x\,y = (-x)\,(-y) > 0 \tag{8.12.3}$$

when $x, y > 0$, and when $-x, -y > 0$. Similarly,

$$-x\,y = (-x)\,y = x\,(-y) > 0 \tag{8.12.4}$$

when $-x, y > 0$, and when $x, -y > 0$.

If R is commutative, then it follows that R is an integral domain. This corresponds to the definition of an ordered integral domain on p9 of [3]. Similarly, an *ordered field* is an ordered ring that is also a field, as in [3, 19].

Let R be an ordered ring again. Note that $x \in R$ and $-x$ cannot both be positive, because that would imply that $x + (-x) = 0$ is positive. If $x \in R$ and $x \neq 0$, then

$$x^2 > 0, \tag{8.12.5}$$

because x or $-x$ is positive, and $x^2 = (-x)^2$. Of course, this corresponds to (8.12.3), with $y = x$. In particular,

$$e = e^2 > 0 \tag{8.12.6}$$

in R. If $x, y \in R$, then put

$$x < y \tag{8.12.7}$$

when $y - x > 0$. This defines a linear ordering on R, which is invariant under translations on R.

Alternatively, one might start with a translation-invariant linear ordering on R, and define $x \in R$ to be positive when $x > 0$ with respect to this ordering. One can check that the sum of positive elements of R is positive in this situation. If products of positive elements of R are positive too, then R is an ordered ring. This is how ordered fields are defined on p7 in [20].

Clearly $\mathbf{Z}$ is an ordered ring with respect to the standard ordering. In fact, this is the only ordering on $\mathbf{Z}$ for which $\mathbf{Z}$ is an ordered ring. More precisely, if **Z** is an ordered ring with respect to some ordering, then 1 has to be positive in **Z** with respect to that ordering, by (8.12.6). This implies that all sums of 1 have to be positive with respect to this ordering on **Z**. One can check that these are the only elements of **Z** that can be positive, so that this ordering on **Z** is the same as the usual one.

Let R be an ordered ring, and let R_0 be a subring of R that contains e. It is easy to see that R_0 is an ordered ring too, with respect to the restriction of the restriction of the ordering on R to R_0.

8.13 Some additional features

Let R be a ring, with multiplicative identity element e. If n is a positive integer, then $n \cdot e$ is the sum of n e's in R, as usual. We can extend this to integers $n \le 0$ in the obvious way, by putting $0 \cdot e = 0$ in R, and $n \cdot e = -((-n) \cdot e)$ when $n < 0$. This defines a ring homomorphism from **Z** into R.

Suppose that R is an ordered ring. If $n \in \mathbf{Z}_+$, then

$$n \cdot e > 0 \tag{8.13.1}$$

in R, by (8.12.6). Of course, this implies that

$$-(n \cdot e) = (-n) \cdot e > 0 \tag{8.13.2}$$

when $-n \in \mathbf{Z}_+$. Thus $n \mapsto n \cdot e$ is an injective order-preserving mapping from **Z** into R, with respect to the standard ordering on **Z**.

If $x \in R$, $x > 0$, and x has a multiplicative inverse x^{-1} in R, then

$$x^{-1} > 0. \tag{8.13.3}$$

Otherwise, if $-x^{-1} > 0$, then $-e = x\,(-x^{-1}) > 0$, contradicting (8.12.6).

If $x \in R$, then the *absolute value* $|x|$ of x may be defined as an element of R by

$$\begin{aligned} |x| &= x \quad \text{when } x \ge 0 \\ &= -x \quad \text{when } -x \ge 0, \end{aligned} \tag{8.13.4}$$

as on p10 of [3], and p264 of [19]. Note that $|x| \ge 0$ and

$$-|x| \le x \le |x| \tag{8.13.5}$$

for every $x \in R$. One can check that

$$|x\,y| = |x|\,|y| \tag{8.13.6}$$

and

$$|x + y| \le |x| + |y| \tag{8.13.7}$$

for every $x, y \in R$. More precisely, (8.13.6) is basically the same as (8.12.3) and (8.12.4). To get (8.13.7), and one can use (8.13.5) and its analogue for y.

Let T be an indeterminate, and let $R((T))$ be as before. More precisely, R may be considered as an associative algebra over $\mathbf{Z}$, so that $R((T))$ is an associative algebra over $\mathbf{Z}$ too. If $f(T) \in R((T))$ can be expressed as $\sum_{j=j_0}^{\infty} f_j\, T^j$, where $f_{j_0} > 0$ in R, then let us say that $f(T)$ is *positive* as an element of $R((T))$. Let us check that this makes $R((T))$ into an ordered ring, as in the discussion on p284-5 in [19]. Note that the elements of $R((T))$ are called *extended formal power series* in [19].

Let $f(T)$ be as in the preceding paragraph, and let $g(T) = \sum_{l=l_0}^{\infty} g_l\, T^l$ be another positive element of $R((T))$, with $g_{l_0} > 0$. Put $h(T) = f(T)\, g(T)$, so that $h(T) = \sum_{n=j_0+l_0}^{\infty} h_n\, T^n$, with

$$h_{j_0+l_0} = f_{j_0}\, g_{l_0}. \tag{8.13.8}$$

This implies that $h_{j_0+l_0} > 0$ in R, so that $h(T) > 0$ in $R((T))$.

One can verify that

$$f(T) + g(T) > 0 \tag{8.13.9}$$

in $R((T))$, directly from the definitions. More precisely, if $l_0 > j_0$, then (8.13.9) holds when $f_{j_0} > 0$ in R, without additional conditions on $g(T)$. Similarly, if $j_0 > l_0$, then (8.13.9) holds when $g_{l_0} > 0$ in R, without additional conditions on $f(T)$.

If $a(T)$ is any nonzero element of $R((T))$, then $a(T)$ can be expressed as $\sum_{r=r_0}^{\infty} a_r\, T^r$, where $a_{r_0} \neq 0$. Because R is an ordered ring, either $a_{r_0} > 0$ or $-a_{r_0} > 0$ in R. This implies that $a(T) > 0$ or $-a(T) > 0$ in $R((T))$, as appropriate.

8.14 Ordered fields

Note that $\mathbf{Q}$ is an ordered field with respect to the standard ordering. One can check that this is the only ordering on $\mathbf{Q}$ for which $\mathbf{Q}$ is an ordered field. Indeed, if $\mathbf{Q}$ is an ordered field with respect to some ordering, then every $n \in \mathbf{Z}_+$ is positive with respect to this ordering on $\mathbf{Q}$, as before. This implies that $1/n$ is positive with respect to this ordering on $\mathbf{Q}$, as in the previous section, and hence that quotients of elements of $\mathbf{Z}_+$ are positive with respect to this ordering on $\mathbf{Q}$. One can verify that these are the only elements of $\mathbf{Q}$ that can be positive, so that this ordering on $\mathbf{Q}$ is the standard ordering.

Let k be an ordered field. Note that k has characteristic 0, because sums of 1 are positive in k. The usual homomorphism from $\mathbf{Z}$ into k extends to a field isomorphism from $\mathbf{Q}$ onto a subfield of k. This isomorphism is also compatible with the standard ordering on $\mathbf{Q}$, as in the preceding paragraph. This corresponds to the corollary on p266 of [19].

The classical version of the *archimedean property* can be stated for k as follows: if x, y are positive elements of k, then there is a positive integer n such that

$$n \cdot x > y. \tag{8.14.1}$$

Of course, $\mathbf{R}$ has the archimedean property with respect to the standard ordering. If k has the archimedean property, then every subfield of k has the archimedean property.

Let k_1 and k_2 be ordered fields. To say that k_1 and k_2 are *isomorphic* as ordered fields means that there is a field isomorphism from k_1 onto k_2 that preserves order as well. Clearly the archimedean property is invariant under order-preserving field isomorphisms.

Suppose that k_1 is an ordered field with the archimedean property. It is well known that k_1 is isomorphic as an ordered field to a subfield of $\mathbf{R}$, with the ordering induced by the standard ordering on $\mathbf{R}$. This corresponds to Exercise 10 on p286 of [19].

Let k be an ordered field again, and let T be an indeterminate. Thus $k((T))$ is an ordered field with respect to the ordering obtained from the one on k described in the previous section. It is easy to see that $k((T))$ does not have the archimedean property with respect to this ordering, even if k has the archimedean property, as on p285 of [19]. More precisely, T is a positive element of $k((T))$, because $1 > 0$ in k. However,

$$n \cdot T < 1 \tag{8.14.2}$$

for every positive integer n.

Some topics related to inner products on vector spaces over ordered fields will be discussed in Section 11.9.

Part II

Solvability, nilpotence, and semisimplicity

Chapter 9

Solvability and nilpotence

9.1 Some basic isomorphism theorems

Let k be a commutative ring with a multiplicative identity element, and let A be an algebra over k in the strict sense. If A_0 is a two-sided ideal in A, then the quotient A/A_0 can be defined as an algebra over k in the strict sense too, as in Section 2.11. Let q_0 be the canonical quotient mapping from A onto A/A_0, which is an algebra homomorphism.

Suppose that B is another algebra over k in the strict sense, and that ϕ is an algebra homomorphism from A into B. The kernel $\ker \phi$ of ϕ is a two-sided ideal in A, as mentioned in Section 2.11. If $A_0 \subseteq \ker \phi$, then there is a unique algebra homomorphism ψ from A/A_0 onto $\phi(A) \subseteq B$ such that

$$\psi \circ q_0 = \phi. \tag{9.1.1}$$

If $A_0 = \ker \phi$, then ψ is injective.

Let A_1, A_2 be two-sided ideals in A such that $A_1 \subseteq A_2$, and let q_1, q_2 be the canonical quotient mappings from A onto A/A_1, A/A_2, respectively. There is a natural algebra homomorphism Ψ from A/A_1 onto A/A_2 such that

$$\Psi \circ q_1 = q_2, \tag{9.1.2}$$

as in the preceding paragraph.

Note that A_1 may be considered as a two-sided ideal in A_2, so that A_2/A_1 can be defined as an algebra over k in the strict sense. Of course, A_2/A_1 is essentially the same as $q_1(A_2) \subseteq A/A_1$. It is easy to see that $q_1(A_2)$ is a two-sided ideal in A/A_1, because A_2 is a two-sided ideal in A.

The kernel of Ψ is equal to $q_1(A_2)$, by construction. Thus Ψ can be identified with the quotient mapping from A/A_1 onto $(A/A_1)/q_1(A_2)$, which is the same as $(A/A_1)/(A_2/A_1)$. This leads to a natural algebra isomorphism between this quotient and A/A_2.

Let A_3, A_4 be two-sided ideals in A, and observe that $A_3 \cap A_4$ is a two-sided ideal in A as well. Remember that $A_3 + A_4$ is a two-sided ideal in A too, as in

Section 7.1. Let q_4 be the canonical quotient mapping from A onto A/A_4. The restriction of q_4 to $A_3 + A_4$ is essentially the same as the canonical quotient mapping from $A_3 + A_4$ onto $(A_3 + A_4)/A_4$, as before.

Observe that $q_4(A_3) = q_4(A_3 + A_4)$. The kernel of the restriction of q_4 to A_3 is equal to $A_3 \cap A_4$. The restriction of q_4 to A_3, as an algebra homomorphism from A_3 onto $q_4(A_3)$, can be identified with the quotient mapping from A_3 onto $A_3/(A_3 \cap A_4)$. This leads to a natural algebra isomorphism between this quotient and $q_4(A_3 + A_4)$, which is essentially the same as $(A_3 + A_4)/A_4$.

These isomorphism theorems are stated for Lie algebras (over fields) on p7-8 of [14].

9.2 Products of ideals

Let k be a commutative ring with a multiplicative identity element, and let A be an algebra over k in the strict sense, where multiplication of $a, b \in A$ is expressed as $a\,b$. Also let A_1 and A_2 be submodules of A, as a module over k. The *product* $A_1 \cdot A_2$ of A_1 and A_2 is defined to be the subset of A consisting of all finite sums of elements of A of the form $a_1\,a_2$, where $a_1 \in A_1$ and $a_2 \in A_2$. It is easy to see that $A_1 \cdot A_2$ is a submodule of A as well, as a module over k. If multiplication on A is commutative or anti-commutative, then

$$A_1 \cdot A_2 = A_2 \cdot A_1. \tag{9.2.1}$$

If A_1 is a right ideal in A, then

$$A_1 \cdot A_2 \subseteq A_1. \tag{9.2.2}$$

Similarly, if A_2 is a left ideal in A, then

$$A_1 \cdot A_2 \subseteq A_2. \tag{9.2.3}$$

Suppose for the moment that A is an associative algebra over k. If A_1 is a left ideal in A, then $A_1 \cdot A_2$ is a left ideal in A too. If A_2 is a right ideal in A, then $A_1 \cdot A_2$ is a right ideal in A.

Let B be a subalgebra of A, as an algebra over k in the strict sense. If B_1 and B_2 are submodules of B, as a module over k, then B_1 and B_2 are submodules of A too, so that $[B_1, B_2]$ can be defined as a submodule of A as before. This is the same as defining $[B_1, B_2]$ as a submodule of B in the analogous way.

Let C be another algebra over k in the strict sense, and let ϕ be an algebra homomorphism from A into C. If A_1 and A_2 are submodules of A, as a module over k, then $\phi(A_1)$ and $\phi(A_2)$ are submodules of C, so that $\phi(A_1) \cdot \phi(A_2)$ can be defined as a submodule of C as before. Observe that

$$\phi(A_1 \cdot A_2) = \phi(A_1) \cdot \phi(A_2). \tag{9.2.4}$$

Suppose now that $(A, [\cdot, \cdot]_A)$ is a Lie algebra over k. In this situation, $A_1 \cdot A_2$ may be denoted $[A_1, A_2]$, and consists of finite sums of elements of A of the form $[a_1, a_2]_A$, where $a_1 \in A_1$ and $a_2 \in A_2$, as before. Note that

$$[A_1, A_2] = [A_2, A_1], \tag{9.2.5}$$

as in (9.2.1), because of anticommutativity of the Lie bracket on A. If A_1 and A_2 are ideals in A, then it is easy to see that $[A_1, A_2]$ is an ideal in A, using the Jacobi identity.

In particular, we can apply this to $A_1 = A_2 = A$, to get that $[A, A]$ is an ideal in A. This is known as the *derived algebra* associated to A. By construction, $A/[A, A]$ is commutative as a Lie algebra over k.

Let A_0 be an ideal in A, and suppose that A/A_0 is commutative as a Lie algebra over k. If $a_1, a_2 \in A$, then the image of $[a_1, a_2]_A$ in A/A_0 is the same as the Lie bracket of the images of a_1 and a_2 in A/A_0, which is equal to 0. This means that $[a_1, a_2] \in A_0$, so that

$$[A, A] \subseteq A_0. \tag{9.2.6}$$

Equivalently, if ϕ is a homomorphism from A into a commutative Lie algebra over k, then one can take A_0 to be the kernel of ϕ.

Let B be a Lie subalgebra of A, so that B may be considered as a Lie algebra over k too. If B_1, B_2 are ideals in B, then $[B_1, B_2]$ is an ideal in B, as before. In particular, $[B, B]$ is an ideal in B, and

$$[B, B] \subseteq [A, A]. \tag{9.2.7}$$

9.3 Solvable Lie algebras

Let k be a commutative ring with a multiplicative identity element, and let $(A, [\cdot, \cdot]_A)$ be a Lie algebra over k. If j is a nonnegative integer, then $A^{(j)}$ is defined inductively by putting $A^{(0)} = A$, $A^{(1)} = [A, A]$, and

$$A^{(j+1)} = [A^{(j)}, A^{(j)}] \tag{9.3.1}$$

for each $j \geq 0$, where the right side is as defined in the preceding section. It is easy to see that $A^{(j)}$ is an ideal in A for every $j \geq 0$, using induction and a remark in the previous section. This sequence of ideals is called the *derived series* of A. Here we use the notation on p10 of [14], while on p35 of [25] the notation $D^j A$ is used for $A^{(j-1)}$ when $j \geq 1$.

Observe that

$$A^{(j+1)} \subseteq A^{(j)} \tag{9.3.2}$$

for every $j \geq 0$. Of course, $A^{(1)} = \{0\}$ exactly when A is commutative as a Lie algebra. If $A^{(j)} = \{0\}$ for some $j \geq 0$, then A is said to be *solvable* as a Lie algebra.

If B is a Lie subalgebra of A, then $B^{(j)}$ can be defined as an ideal in B for each $j \geq 0$ as before. One can check that

$$B^{(j)} \subseteq A^{(j)} \tag{9.3.3}$$

for every $j \geq 0$, using (9.2.7) and induction. In particular, if A is solvable, then B is solvable.

By construction,

$$A^{(j+l)} = (A^{(j)})^{(l)} \tag{9.3.4}$$

for every $j, l \geq 0$. If $A^{(j)}$ is solvable for some $j \geq 0$, then it follows that A is solvable.

Let C be another Lie algebra over k, and let ϕ be a Lie algebra homomorphism from A onto C. One can verify that

$$\phi(A^{(j)}) = C^{(j)} \tag{9.3.5}$$

for every $j \geq 0$, using (9.2.4) and induction. If A is solvable, then it follows that C is solvable.

Suppose that C is solvable, so that $C^{(n)} = \{0\}$ for some nonnegative integer n. This implies that

$$\phi(A^{(n)}) = C^{(n)} = \{0\}, \tag{9.3.6}$$

as in (9.3.5), which means that

$$A^{(n)} \subseteq \ker \phi. \tag{9.3.7}$$

Suppose that the kernel of ϕ is solvable as a Lie algebra over k as well, so that $(\ker \phi)^{(l)} = \{0\}$ for some nonnegative integer l. Under these conditions, we get that

$$A^{(n+l)} = (A^{(n)})^{(l)} \subseteq (\ker \phi)^{(l)} = \{0\}, \tag{9.3.8}$$

and hence that A is solvable.

These properties correspond to parts (a) and (b) of the proposition on p11 of [14], and to part of Exercise 1 on p43 of [25]. Alternatively, let $A_0, A_1, \ldots, A_n$ be finitely many Lie subalgebras of A, with $A_0 = A$, and A_{j+1} an ideal in A_j for $j = 0, \ldots, n-1$. Suppose that A_j/A_{j+1} is commutative as a Lie algebra for each $j = 0, \ldots, n-1$, which is the same as saying that

$$[A_j, A_j] \subseteq A_{j+1} \tag{9.3.9}$$

for every $j = 0, \ldots, n-1$. This implies that

$$A^{(j)} \subseteq A_j \tag{9.3.10}$$

for each $j = 0, 1, \ldots, n$, by induction. In particular, if $A_n = \{0\}$, then it follows that A is solvable. Conversely, if A is solvable, then $A^{(n)} = \{0\}$ for some $n \geq 0$, and one can simply take $A_j = A^{(j)}$ for $j = 0, 1, \ldots, n$. This characterization of solvability is mentioned on p35-6 of [25], and in Exercise 2 on p14 of [14].

9.4 The solvable radical

Let k be a commutative ring with a multiplicative identity element, and let $(A, [\cdot,\cdot]_A)$ be a Lie algebra over k. Also let A_1 and A_2 be ideals in A, so that

$A_1 \cap A_2$ and $A_1 + A_2$ are ideals in A as well. If A_1 and A_2 are solvable as Lie algebras over k, then it is well known that $A_1 + A_2$ is solvable as a Lie algebra too. To see this, it suffices to check that $(A_1 + A_2)/A_2$ is solvable as a Lie algebra over k, because A_2 is solvable, as in the previous section. Remember that $(A_1 + A_2)/A_2$ is isomorphic to $A_1/(A_1 \cap A_2)$, as in Section 9.1. Of course, $A_1/(A_1 \cap A_2)$ is solvable as a Lie algebra, because A_1 is solvable, as in the previous section. Thus $(A_1 + A_2)/A_2$ is solvable, as desired. This is part (c) of the proposition on p11 of [14], which is mentioned on p44 of [25].

One often considers Lie algebras A over a field, with finite dimension as a vector space over the field. In this case, it is easy to see that there is a maximal solvable ideal in A, by taking a solvable ideal in A of maximal dimension, as a linear subspace of A. The remarks in the previous paragraph imply that a maximal solvable ideal in A is unique, and in fact contains every other solvable ideal in A. This maximal solvable ideal is called the *(solvable) radical* of A, and may be denoted $\operatorname{Rad} A$.

Let A be a Lie algebra over a commutative ring k with a multiplicative identity element again. It may still happen that A has a maximal solvable ideal, which can still be called the radical of A, and denoted $\operatorname{Rad} A$. In particular, A has a maximal solvable ideal when solvable ideals in A satisfy an ascending chain condition. If a maximal solvable ideal exists, then it is unique, and contains all other solvable ideals in A, as before. If

$$\operatorname{Rad} A = \{0\}, \tag{9.4.1}$$

then A may be called *semisimple* as a Lie algebra. More precisely, let us say that A is semisimple as a Lie algebra if $\{0\}$ is the only solvable ideal in A, in which case it is automatically maximal. Equivalently, A is not semisimple when A contains a nonzero solvable ideal, without asking for a maximal solvable ideal.

Suppose that A is not semisimple, and let B be a nonzero solvable ideal in A. Note that the derived subalgebra $B^{(j)}$ is an ideal in A for every nonnegative integer j. This follows from a remark in Section 9.2 when $j = 1$, and can be verified using induction otherwise. Because $B \neq \{0\}$ is solvable, there is a nonnegative integer j_0 such that $B^{(j_0)} \neq \{0\}$ and $B^{(j_0+1)} = \{0\}$. This means that $B^{(j_0)}$ is commutative as a Lie algebra, since $[B^{(j_0)}, B^{(j_0)}] = B^{(j_0+1)} = \{0\}$. Of course, if A has a nonzero ideal that is commutative as a Lie algebra, then A is not semisimple, because commutative Lie algebras are solvable. Thus A is not semisimple exactly when A has a nonzero ideal that is commutative as a Lie algebra, as on p22 of [14] and p44 of [25].

Suppose that the radical of A exists, so that the quotient $A/\operatorname{Rad} A$ can be defined as a Lie algebra over k, and let q be the canonical quotient mapping from A onto $A/\operatorname{Rad} A$. In this situation, $A/\operatorname{Rad} A$ is automatically semisimple, as on p11 of [14]. Indeed, if C is any ideal in $A/\operatorname{Rad} A$, then $q^{-1}(C)$ is an ideal in A. If C is solvable as a Lie algebra over k, then $q^{-1}(C)$ is solvable as a Lie algebra too, because $\operatorname{Rad} A$ is solvable, as in the previous section. This implies that $q^{-1}(C) = \operatorname{Rad} A$, so that $C = \{0\}$, as desired.

9.5 Nilpotent Lie algebras

Let k be a commutative ring with a multiplicative identity element, and let $(A, [\cdot,\cdot]_A)$ be a Lie algebra over k. If j is a nonnegative integer, then A^j is defined inductively by putting $A^0 = A$, $A^1 = [A, A]$, and

$$A^{j+1} = [A, A^j] \tag{9.5.1}$$

for every $j \geq 0$, where the right side is as defined in Section 9.2. One can check that A^j is an ideal in A for every $j \geq 0$, using induction and a remark in Section 9.2. This sequence of ideals is called the *descending central series* or *lower central series* in A. This uses the notation on p11 in [14], and the notation $C^j A$ is used on p32 of [25] for A^{j-1} when $j \geq 1$.

The fact that A^j is an ideal in A says exactly that

$$A^{j+1} \subseteq A^j \tag{9.5.2}$$

for every $j \geq 0$. If $A^j = \{0\}$ for some $j \geq 0$, then A is said to be *nilpotent* as a Lie algebra.

Observe that

$$A^{(j)} \subseteq A^j \tag{9.5.3}$$

for every $j \geq 0$, with equality when $j = 0, 1$. It follows that nilpotent Lie algebras are solvable. If A is a commutative Lie algebra, then $A^1 = A^{(1)} = \{0\}$, and hence A is nilpotent.

If B is a Lie subalgebra of A, then B^j can be defined as an ideal in B in the same way as before, so that $B^0 = B$ and

$$B^{j+1} = [B, B^j] \tag{9.5.4}$$

for every $j \geq 0$. It is easy to see that

$$B^j \subseteq A^j \tag{9.5.5}$$

for every $j \geq 0$, by induction. If A is nilpotent, then it follows that B is nilpotent.

Let ϕ be a Lie algebra homomorphism from A onto another Lie algebra C over k. One can check that

$$\phi(A^j) = C^j \tag{9.5.6}$$

for every $j \geq 0$, using (9.2.4) and induction. If A is nilpotent, then it follows that C is nilpotent as well.

Remember that $Z(A)$ is the center of A as a Lie algebra, as in Section 7.6. If B is a submodule of A, as a module over k, then

$$B \subseteq Z(A) \tag{9.5.7}$$

if and only if

$$[A, B] = \{0\}. \tag{9.5.8}$$

If

$$A^j \subseteq Z(A) \tag{9.5.9}$$

for some $j \geq 0$, then it follows that

$$A^{j+1} = [A, A^j] = \{0\}, \tag{9.5.10}$$

so that A is nilpotent as a Lie algebra. If $A/Z(A)$ is nilpotent as a Lie algebra, then (9.5.9) holds for some $j \geq 0$, because of (9.5.6). This implies that A is nilpotent as a Lie algebra, as before.

Let B be a submodule of A again, as a module over k, and let B_0 be an ideal in A. It is easy to see that

$$[A, B] \subseteq B_0 \tag{9.5.11}$$

if and only if the image of B in A/B_0 is contained in the center of A/B_0, as a Lie algebra.

Let $A_0, A_1, \ldots, A_n$ be finitely many ideals in A, with $A_0 = A$, and

$$A_{j+1} \subseteq A_j \tag{9.5.12}$$

for each $j = 0, \ldots, n-1$. Suppose that A_j/A_{j+1} is contained in the center of A/A_{j+1} for each $j = 0, \ldots, n-1$, which is the same as saying that

$$[A, A_j] \subseteq A_{j+1} \tag{9.5.13}$$

for every $j = 0, \ldots, n-1$, as in the preceding paragraph. Under these conditions, we get that

$$A^j \subseteq A_j \tag{9.5.14}$$

for each $j = 0, \ldots, n$, by induction. If $A_n = \{0\}$, then it follows that A is nilpotent as a Lie algebra. Conversely, if A is nilpotent as a Lie algebra, then $A^n = \{0\}$ for some nonnegative integer n, and one can take $A_j = A^j$ for $j = 0, \ldots, n$.

These basic properties of nilpotent Lie algebras correspond to parts (a) and (b) of the proposition on p12 of [14], part of Theorem 2.1 on p32 in [25], and part of Exercise 1 on p43 of [25].

Suppose that A is nilpotent as a Lie algebra, and that $A \neq \{0\}$. Let j be the largest nonnegative integer such that $A^j \neq \{0\}$, which means that $A^{j+1} = \{0\}$. This implies that $A^j \subseteq Z(A)$, and in particular that $Z(A) \neq \{0\}$. This is part (c) of the proposition on p12 of [14].

9.6 Two-dimensional Lie algebras

Let k be a commutative ring with a multiplicative identity element, and let $(A, [\cdot,\cdot]_A)$ be a Lie algebra over k. If A is generated, as a module over k, by a single element, then it is easy to see that A is commutative as a Lie algebra. Suppose now that A is generated by $a_0, b_0 \in A$, as a module over k, so that every element of A can be expressed as

$$\alpha\, a_0 + \beta\, b_0 \tag{9.6.1}$$

for some $\alpha, \beta \in k$. This implies that $A^{(1)} = [A, A]$ consists of elements of A of the form

$$\gamma\,[a_0, b_0]_A, \tag{9.6.2}$$

where $\gamma \in k$. It follows that $A^{(2)} = [A^{(1)}, A^{(1)}] = \{0\}$, and in particular that A is solvable.

By hypothesis,

$$[a_0, b_0]_A = \alpha_0\, a_0 + \beta_0\, b_0 \tag{9.6.3}$$

for some $\alpha_0, \beta_0 \in k$. Of course, if $[a_0, b_0]_A = 0$, then A is commutative as a Lie algebra. Suppose that $[a_0, b_0]_A \neq 0$, and that (9.6.1) is not equal to 0 in A when $\alpha, \beta \in k$ satisfy $\alpha \neq 0$ or $\beta \neq 0$. If k has no nonzero nilpotent elements, then one can check that A is not nilpotent as a Lie algebra. This corresponds to the first part of Exercise 5 on p14 of [14], and part of Exercise 2 on p43 of [25]. Suppose for the moment that k is a field, so that A is a two-dimensional vector space over k. One can choose a basis a, b for A such that

$$[a, b]_A = a, \tag{9.6.4}$$

as on p5 of [14], and the other part of Exercise 2 on p43 of [25].

Let A be a module over k, and let $[a, b]_A$ be a mapping from $A \times A$ into A that is bilinear over k and satisfies

$$[a, a]_A = 0 \tag{9.6.5}$$

for every $a \in A$. In order for $[\cdot, \cdot]_A$ to define a Lie bracket on A, one should verify that the Jacobi identity holds for any triple of elements x, y, and z of A. If $x = y = z$, then each of the three terms in the Jacobi identity is equal to 0, because of (9.6.5). If any two of x, y, and z are the same element of A, then one of the terms in the Jacobi identity is automatically equal to 0, by (9.6.5) again. In this case, the Jacobi identity can be obtained using the antisymmetry of $[\cdot, \cdot]_A$, which follows from (9.6.5), as usual.

Suppose that A is generated as a module over k by $a_0, b_0 \in A$, so that every element of A can be expressed as in (9.6.1). In order to show that $[\cdot, \cdot]_A$ satisfies the Jacobi identity on A, it suffices to consider triples of elements x, y, and z of A where each of x, y, and z is equal to either a_0 or b_0, because of bilinearity. This means that at least two of the elements x, y, and z are the same. In this situation, the Jacobi identity can be obtained from (9.6.5), as in the preceding paragraph.

9.7 Nilpotency conditions

Let k be a commutative ring with a multiplicative identity element, and let $(A, [\cdot, \cdot]_A)$ be a Lie algebra over k. Remember that if $x \in A$, then $\operatorname{ad} x = \operatorname{ad}_x$ is the homomorphism from A into itself, as a module over k, defined by

$$\operatorname{ad}_x(y) = [x, y]_A \tag{9.7.1}$$

for every $y \in A$, as in Section 2.4. Let n be a positive integer, and let $x_1, \ldots, x_n$ be n elements of A. Thus ad_{x_j} is a module homomorphism from A into itself for each $j = 1, \ldots, n$, so that compositions of the ad_{x_j}'s are defined as module homomorphisms from A into itself. If $y \in A$, then

$$(\mathrm{ad}_{x_1} \circ \mathrm{ad}_{x_2} \circ \cdots \circ \mathrm{ad}_{x_n})(y) = [x_1, [x_2, [\ldots, [x_n, y]_A \ldots]_A]_A]_A. \tag{9.7.2}$$

This is an element of the ideal A^n defined in Section 9.5. If $A^n = \{0\}$, then (9.7.2) is equal to 0 for every $y \in A$, so that

$$\mathrm{ad}_{x_1} \circ \mathrm{ad}_{x_2} \circ \cdots \circ \mathrm{ad}_{x_n} = 0 \tag{9.7.3}$$

as a mapping from A into itself. Conversely, if (9.7.3) holds for every $x_1, \ldots, x_n$ in A, then (9.7.2) is equal to 0 for all $x_1, \ldots, x_n, y \in A$, and which implies that $A^n = \{0\}$. This corresponds to part of Theorem 2.1 on p32 of [25], and is also mentioned on p12 of [14].

Let B be an associative algebra over k, where multiplication of $b, b' \in B$ is expressed as $b\,b'$. An element b of B is said to be *nilpotent* if $b^l = 0$ for some positive integer l. If b_1 and b_2 are commuting nilpotent elements of B, then it is easy to see that $b_1 + b_2$ is nilpotent as well. More precisely, if $b_1^{l_1} = 0$ and $b_2^{l_2} = 0$ for some positive integers l_1 and l_2, then

$$(b_1 + b_2)^{l_1 + l_2 - 1} = 0. \tag{9.7.4}$$

Indeed, the left side of (9.7.4) can be expressed as a sum of terms of the form $b_1^{j_1}\, b_2^{j_2}$, where j_1 and j_2 are nonnegative integers with $j_1 + j_2 = l_1 + l_2 - 1$, which implies that either $j_1 \geq l_1$ or $j_2 \geq l_2$.

Let B_{Lie} be B as a Lie algebra over k, with respect to the commutator bracket $[b, b']_B = b\,b' - b'\,b$ corresponding to multiplication on B. Let n be a positive integer, and suppose that

$$b_1\, b_2\, \cdots\, b_n\, b_{n+1} = 0 \tag{9.7.5}$$

for every $b_1, b_2, \ldots, b_n, b_{n+1} \in B$. This implies that

$$[b_1, [b_2, [\ldots, [b_n, b_{n+1}]_B \ldots]_B]_B]_B = 0 \tag{9.7.6}$$

for every $b_1, b_2, \ldots, b_n, b_{n+1} \in B$, because the left side of (9.7.6) can be expanded into a sum of products of $n+1$ elements of B. It follows that $B_{Lie}^n = \{0\}$, where B_{Lie}^n is defined as in Section 9.5. In particular, this means that B_{Lie} is nilpotent as a Lie algebra.

Let A be a Lie algebra over k again. An element x of A is said to be ad-*nilpotent* if ad_x is nilpotent as an element of the algebra of module homomorphisms from A into itself, as on p12 of [14]. If $A^n = \{0\}$ for some positive integer n, then $(\mathrm{ad}_x)^n = 0$ as a module homomorphism from A into itself for every $x \in A$, as in (9.7.3). In particular, if A is nilpotent as a Lie algebra, then every element of A is ad-nilpotent.

Let B be an associative algebra over k again, with corresponding Lie algebra B_{Lie}. If $b \in B$, then ad_b is defined as a module homomorphism from B into itself, by

(9.7.7) $$\mathrm{ad}_b(c) = [b, c]_B = b\,c - c\,b$$

for every $c \in B$. Equivalently,

(9.7.8) $$\mathrm{ad}_b = M_b - \widetilde{M}_b,$$

where M_b and $\widetilde{M}_b$ are the operators of left and right multiplication by b on B, respectively, as in Sections 2.2 and 2.7. Remember that M_b and $\widetilde{M}_b$ commute as module homomorphisms from B into itself. If $b^l = 0$ for some positive integer l, then $(M_b)^l = M_{b^l} = 0$ and $(\widetilde{M}_b)^l = \widetilde{M}_{b^l} = 0$, as module homomorphisms from B into itself. This implies that $(\mathrm{ad}_b)^{2\,l-1} = 0$, as a module homomorphism from B into itself, as in (9.7.4). Thus b is ad-nilpotent as an element of B_{Lie} when b is nilpotent in B. This corresponds to the lemma on p12 of [14], and Step 2 on p34 of [25].

9.8 Maximal Lie subalgebras

Let k be a commutative ring with a multiplicative identity element, and let $(A, [\cdot,\cdot]_A)$ be a Lie algebra over k. If $x \in A$, then

(9.8.1) $$\{\alpha\, x : \alpha \in k\}$$

is a Lie subalgebra of A that contains x as an element. If $x \neq 0$ and k is a field, then (9.8.1) is one-dimensional as a linear subspace of A.

Let B be a Lie subalgebra of A that is proper, so that $B \neq A$. As usual, B is said to be *maximal* as a proper Lie subalgebra of A with respect to inclusion if any proper Lie subalgebra of A that contains B is equal to B. If B_0 is any proper Lie subalgebra of A, then in some situations one can get the existence of a maximal proper Lie subalgebra B of A that contains B_0. In particular, if k is a field and A is finite-dimensional as a vector space over k, then one can take B to be a Lie subalgebra of A that contains B_0 and whose dimension is strictly less than the dimension of A and maximal. One can also get such maximal proper Lie subalgebras of A when Lie subalgebras of A satisfy an ascending chain condition.

Let B_0 be a submodule of A, as a module over k. The *normalizer* $N_A(B_0)$ of B_0 in A is defined to be the set of $x \in A$ such that

(9.8.2) $$[x, y]_A \in B_0$$

for every $y \in B_0$. It is easy to see that $N_A(B_0)$ is a submodule of A, as a module over k, because B_0 is a submodule of A. One can check that $N_A(B_0)$ is a Lie subalgebra of A, using the Jacobi identity. If B_0 is a Lie subalgebra of A, then

(9.8.3) $$B_0 \subseteq N_A(B_0),$$

and in fact B_0 is an ideal in $N_A(B_0)$, as a Lie algebra over k. In this case, $N_A(B_0)$ may be described as the largest Lie subalgebra of A that contains A as an ideal, as on p7 of [14]. If $B_0 = N_A(B_0)$, then B_0 is said to be *self-normalizing* in A. If B_0 is a maximal Lie subalgebra of A, then it follows that B_0 is either self-normalizing in A, or B_0 is an ideal in A.

Let B be an ideal in A. If $x \in A$, then it is easy to see that

$$\{\alpha\, x + y : \alpha \in k,\, y \in B\} \tag{9.8.4}$$

is a Lie subalgebra of A. Of course, (9.8.4) contains B and x. If B is a maximal proper Lie subalgebra of A, and $x \in A \setminus B$, then (9.8.4) is equal to A.

Suppose that $A \neq \{0\}$, and that $\{0\}$ is maximal as a proper Lie subalgebra of A. Let x be a nonzero element of A, so that (9.8.1) is equal to A. Observe that

$$\{\alpha \in k : \alpha\, x = 0\} \tag{9.8.5}$$

is a proper ideal in k, because $x \neq 0$. One can check that (9.8.5) is a maximal ideal in k in this situation. This uses the fact that ideals in k correspond to submodules of (9.8.1), which are Lie subalgebras of A.

9.9 Nilpotent linear mappings

Let k be a field, and let V be a vector space over k of positive finite dimension. Remember that the space $\mathcal{L}(V)$ of linear mappings from V into itself is an associative algebra over k with respect to composition of mappings. In particular, a linear mapping T from V into itself is said to be *nilpotent* if $T^n = 0$ for some positive integer n, which is to say that T is nilpotent as an element of $\mathcal{L}(V)$. As in Section 2.10, we may use $gl(V)$ to denote the space of linear mappings from V into itself as a Lie algebra over k, with respect to the corresponding commutator bracket. Let A be a Lie subalgebra of $gl(V)$, and suppose that every element of A is nilpotent as an element of $\mathcal{L}(V)$. Under these conditions, it is well known that there is a $v \in V$ such that $v \neq 0$ and

$$a(v) = 0 \tag{9.9.1}$$

for every $a \in A$. This is the theorem stated at the bottom of p12 in [14], which corresponds to Theorem 3.2' on p33 in [25], as in Step 1 on p34 in [25].

Note that A is a finite-dimensional vector space over k. The theorem is proved using induction on the dimension of A. Of course, the theorem is trivial when $A = \{0\}$. If the dimension of A is equal to 1, then the theorem reduces to the fact that a nilpotent linear mapping from V into itself has a nontrivial kernel.

Suppose now that A has positive dimension, and that the theorem holds for Lie algebras over k of smaller dimension. Let B be a proper Lie subalgebra of A, which has dimension less than the dimension of A.

If $x \in gl(V)$, then let ad_x be the linear mapping from $gl(V)$ into itself defined by

$$\mathrm{ad}_x(y) = [x, y] \tag{9.9.2}$$

for every $y \in gl(V)$, as in Section 2.4. If x is nilpotent as an element of $\mathcal{L}(V)$, then ad_x is nilpotent as a linear mapping from $gl(V)$ into itself, as in Section 9.7. If $x \in A$, then ad_x maps A into itself, because A is a Lie subalgebra of $gl(V)$, by hypothesis. More precisely, ad_x is nilpotent as a linear mapping from A into itself, because x is nilpotent as an element of $\mathcal{L}(V)$, by hypothesis.

If $x \in B$, then ad_x maps B into itself, because B is a Lie subalgebra of A. In particular, B is a linear subspace of A, so that the quotient A/B can be defined as a vector space over k. Let q be the canonical quotient mapping from A onto A/B. If T is a linear mapping from A into itself that maps B into itself, then $q \circ T$ is a linear mapping from A into A/B whose kernel contains B. This means that for $a \in A$, $q(T(a))$ only depends on $q(a)$, so that there is a unique linear mapping $T^{A/B}$ from A/B into itself such that

$$T^{A/B} \circ q = q \circ T. \tag{9.9.3}$$

Note that $T^{A/B}$ is nilpotent on A/B when T is nilpotent on A. Of course, $A/B \neq \{0\}$, because $B \neq A$, by hypothesis.

If $x \in B$, then we can apply this to $T = \mathrm{ad}_x$, to get a linear mapping $\mathrm{ad}_x^{A/B}$ from A/B into itself. More precisely, $\mathrm{ad}_x^{A/B}$ is nilpotent on A/B, because ad_x is nilpotent on A, as before. Let C be the collection of $\mathrm{ad}_x^{A/B}$, with $x \in B$. This is a Lie subalgebra of $gl(A/B)$. The dimension of C, as a vector space over k, is less than or equal to the dimension of B.

Hence the dimension of C is strictly less than the dimension of A. The induction hypothesis permits us to apply the theorem to C, to get that there is a nonzero element $q(a_0)$ of A/B, $a_0 \in A$, such that

$$\mathrm{ad}_x^{A/B}(q(a_0)) = 0 \tag{9.9.4}$$

for every $x \in B$. Equivalently, this means that $q(\mathrm{ad}_x(a_0)) = 0$ for every $x \in B$, which is the same as saying that

$$[x, a_0] = \mathrm{ad}_x(a_0) \in B \tag{9.9.5}$$

for every $x \in B$. This shows that a_0 is an element of the normalizer $N_A(B)$ of B in A. Note that $a_0 \notin B$, because $q(a_0) \neq 0$ in A/B.

Let us now take B to be a maximal proper Lie subalgebra of A. In this case, we get that B is an ideal in A, as in the previous section. Put

$$W = \{v \in V : x(v) = 0 \text{ for every } x \in B\}, \tag{9.9.6}$$

which is a linear subspace of V. Using the induction hypothesis again, we get that $W \neq 0$. Let us check that

$$a(W) \subseteq W \tag{9.9.7}$$

for every $a \in A$. If $x \in B$ and $v \in W$, then

$$x(a(v)) = a(x(v)) - ([a, x])(v) = 0, \tag{9.9.8}$$

because $[a, x] \in B$, as before. This implies that $a(v) \in W$, as desired.

Let a_1 be any element of $A \setminus B$. The restriction of a_1 to W is a nilpotent linear mapping from W into itself, and hence there is a $v_1 \in W$ such that $v_1 \neq 0$ and $a_1(v_1) = 0$. If a is any element of A, then a can be expressed as the sum of an element of B and a scalar multiple of a_1, as in the previous section. It follows that $a(v_1) = 0$, because $v_1 \in W$. Thus (9.9.1) holds, as desired.

9.10 Engel's theorem

Let k be a field, and let V be a vector space over k of positive finite dimension n. A finite sequence $\mathcal{F} = \{V_j\}_{j=0}^n$ of n linear subspaces in V is said to be a *flag* in V if $V_0 = \{0\}$, $V_n = V$, $V_j \subsetneq V_{j+1}$ for $j = 0, \ldots, n-1$, and the dimension of V_j is equal to j for each $j = 0, \ldots, n$. If l is a nonnegative integer with $l \leq n$, then let $\mathcal{U}_l(\mathcal{F})$ be the collection of linear mappings T from V into itself such that

$$T(V_j) \subseteq V_{j-l} \tag{9.10.1}$$

for each $j = l, \ldots, n$. This is a subalgebra of the algebra $\mathcal{L}(V)$ of all linear mappings from V into itself, as an associative algebra over k with respect to composition of mappings. Note that $\mathcal{U}_0(\mathcal{F})$ contains the identity mapping $I = I_V$ on V, $\mathcal{U}_n(\mathcal{F}) = 0$, and

$$\mathcal{U}_{l_2}(\mathcal{F}) \subseteq \mathcal{U}_{l_1}(\mathcal{F}) \tag{9.10.2}$$

when $l_1 \leq l_2$.

More precisely, if l_1, l_2 are nonnegative integers with $l_1 + l_2 \leq n$, $T_1 \in \mathcal{U}_{l_1}(\mathcal{F})$, and $T_2 \in \mathcal{U}_{l_2}(\mathcal{F})$, then

$$T_1 \circ T_2 \in \mathcal{U}_{l_1+l_2}(\mathcal{F}). \tag{9.10.3}$$

In particular, $\mathcal{U}_l(\mathcal{F})$ is an ideal in $\mathcal{U}_0(\mathcal{F})$ for each l. If $T_1, T_2, \ldots, T_n \in \mathcal{U}_1(\mathcal{F})$, then

$$T_1 \circ T_2 \circ \cdots \circ T_n = 0, \tag{9.10.4}$$

because the n-fold composition on the left is an element of $\mathcal{U}_n(\mathcal{F})$. We may consider $\mathcal{U}_l(\mathcal{F})$ as a Lie subalgebra of the Lie algebra $gl(V)$ of linear mappings from V into itself with respect to the commutator bracket for each $l = 0, 1, \ldots, n$. It follows from (9.10.4) that $\mathcal{U}_1(\mathcal{F})$ is nilpotent as a Lie algebra over k, with respect to the commutator bracket, as in Section 9.7.

Let A be a Lie subalgebra of $gl(V)$, and suppose that every element of A is nilpotent as a linear mapping on V, as in the previous section. Under these conditions, it is well known that there is a flag $\mathcal{F}$ in V such that

$$A \subseteq \mathcal{U}_1(\mathcal{F}). \tag{9.10.5}$$

This is the corollary stated on p13 of [14], which corresponds to Theorem 3.2 on p33 of [25]. If $V \neq \{0\}$, then one can first get a one-dimensional linear subspace V_1 of V on which the elements of A vanish, as in the previous section. In order to repeat the process, one can look at the induced linear mappings on the quotient V/V_1.

Now let A be any finite-dimensional Lie algebra over k. If every element of A is ad-nilpotent, as in Section 9.7, then it is well known that A is nilpotent as a Lie algebra. This is the theorem stated on the middle of p12 in [14], which corresponds to Theorem 3.1 on p33 of [25]. In the argument on the bottom of p34 of [25], one applies the theorem mentioned in the preceding paragraph to the image of A under the adjoint representation, as a Lie algebra of linear mappings from A into itself. This leads to a flag of linear subspaces of A, which are in fact ideals in A, and which can be used to show that A is nilpotent as a Lie algebra, as in Section 9.5. Alternatively, one can use the previous theorem to get that the image of A under the adjoint representation is nilpotent as a Lie algebra. This implies that A is nilpotent as a Lie algebra, because the kernel of the adjoint representation is the center $Z(A)$ of A, as a Lie algebra. The proof on the middle of p13 in [14] applies the theorem mentioned in the previous section to the image of the adjoint representation of A when $A \neq \{0\}$ to get that $Z(A) \neq \{0\}$. One can repeat the process on $A/Z(A)$ to get that A is nilpotent.

Let A be a finite-dimensional nipotent Lie algebra over k, and let B be an ideal in A with $B \neq \{0\}$. If $x \in A$, then ad_x is a linear mapping from A into itself that maps B into itself, because B is an ideal in A. Consider the collection $\mathcal{A}_B$ of linear mappings from B into itself obtained by restricting ad_x to B for each $x \in A$. This is a Lie subalgebra of $gl(B)$, because of the usual properties of the adjoint representation on A, as in Section 2.4. Remember that ad_x is nilpotent as a Lie mapping from A into itself for each $x \in A$, because A is nilpotent as a Lie algebra, as in Section 9.7. This implies that the elements of $\mathcal{A}_B$ are nilpotent as linear mappings from B into itself. It follows that there is a $y \in B$ such that $y \neq 0$ and $\mathrm{ad}_x(y) = 0$ for every $x \in A$, as in the previous section. Equivalently, this means that $B \cap Z(A) \neq \{0\}$, as in the lemma on p13 of [14].

9.11 Flags and matrices

Let k be a field, let V be a vector space of positive finite dimension n, and let $\mathcal{F} = \{V_j\}_{j=0}^n$ be a flag in V. If T is an element of the algebra $\mathcal{U}_0(\mathcal{F})$ defined in the previous section, then T induces a linear mapping from V_j/V_{j-1} into itself for each $j = 1, \ldots, n$. This linear mapping corresponds to multiplication by an element $\phi_j(T)$ of k, because V_j/V_{j-1} is a one-dimensional vector space over k. This defines an algebra homomorphism ϕ_j from $\mathcal{U}_0(\mathcal{F})$ into k for each $j = 1, \ldots, n$. Let us consider k^n as a commutative associative algebra over k, with respect to coordinatewise addition and multiplication. Thus we get an algebra homomorphism ϕ from $\mathcal{U}_0(\mathcal{F})$ into k^n, whose jth coordinate is the algebra homomorphism ϕ_j from $\mathcal{U}_0(\mathcal{F})$ into k just mentioned. The kernel of ϕ is the ideal $\mathcal{U}_1(\mathcal{F})$ of $\mathcal{U}_0(\mathcal{F})$ defined in the previous section. In particular, if $T_1, T_2 \in \mathcal{U}_0(\mathcal{F})$, then

$$T_1 \circ T_2 - T_2 \circ T_1 \in \mathcal{U}_1(\mathcal{F}). \tag{9.11.1}$$

Remember that $\mathcal{U}_0(\mathcal{F})$ is a Lie subalgebra of $gl(V)$, so that $\mathcal{U}_0(\mathcal{F})$ may be considered as a Lie algebra over k with respect to the commutator bracket associated to composition of linear mappings on V. Using (9.11.1), we get that

$$[\mathcal{U}_0(\mathcal{F}), \mathcal{U}_0(\mathcal{F})] \subseteq \mathcal{U}_1(\mathcal{F}). \tag{9.11.2}$$

This implies that $\mathcal{U}_0(\mathcal{F})$ is solvable as a Lie algebra, because $\mathcal{U}_1(\mathcal{F})$ is nilpotent as a Lie algebra.

Now let k be a commutative ring with a multiplicative identity element, let n be a positive integer, and let A be an associative algebra over k, where multiplication of $x, y \in A$ is expressed as $x\,y$. Remember that the space $M_n(A)$ of $n \times n$ matrices with entries in A is an associative algebra over k with respect to matrix multiplication, as in Section 2.8. If r is a nonnegative integer with $r \leq n$, then let $T_{n,r}(A)$ be the collection of $a = (a_{j,l}) \in M_n(A)$ such that

$$a_{j,l} = 0 \tag{9.11.3}$$

when $l \leq j + r - 1$. Equivalently, this means that $a_{j,l}$ may be nonzero only when $l \geq j + r$. Thus $T_{n,0}(A)$ consists of upper-triangular matrices, $T_{n,1}(A)$ consists of strictly upper-triangular matrices, and $T_{n,n}(A) = \{0\}$. Clearly

$$T_{n,r_2}(A) \subseteq T_{n,r_1}(A) \tag{9.11.4}$$

when $r_1 \leq r_2$. If $a \in T_{n,r_1}(A)$ and $b \in T_{n,r_2}(A)$ for some nonnegative integers r_1, r_2 with $r_1 + r_2 \leq n$, then

$$a\,b \in T_{n,r_1+r_2}(A). \tag{9.11.5}$$

In particular, $T_{n,0}(A)$ is a subalgebra of $M_n(A)$, $T_{n,r}(A)$ is an ideal in $T_{n,0}(A)$ for each $0 \leq r \leq n$, and the product of n elements of $T_{n,1}(A)$ is equal to 0.

If j is a positive integer with $j \leq n$ and $a \in T_{n,0}(A)$, then put $\psi_j(a) = a_{j,j}$, which defines an algebra homomorphism from $T_{n,0}(A)$ onto A. Let ψ be the mapping from $T_{n,0}(A)$ into A^n such that the jth coordinate of $\psi(a)$ is equal to $\psi_j(a)$ for every $j = 1, \ldots, n$ and $a \in T_{n,0}(A)$. This defines an algebra homomorphism from $T_{n,0}(A)$ onto A^n, where A^n is considered as an associative algebra over k with respect to coordinatewise addition and multiplication. The kernel of ψ is equal to $T_{n,1}(A)$. If A is a commutative algebra over k, then

$$a\,b - b\,a \in T_{n,1}(A) \tag{9.11.6}$$

for every $a, b \in T_{n,0}(A)$.

Remember that $gl_n(A)$ is the same as $M_n(A)$, but considered as a Lie algebra over k with respect to the commutator bracket. Similarly, we may use $t_{n,r}(A)$ for $T_{n,r}(A)$, considered as a Lie subalgebra of $gl_n(A)$. As in Section 9.7, $t_{n,1}(A)$ is nilpotent as a Lie algebra, because the product of n elements of $T_{n,1}(A)$ is equal to 0. If A is commutative, then

$$[t_{n,0}(A), t_{n,0}(A)] \subseteq t_{n,1}(A), \tag{9.11.7}$$

by (9.11.6). This implies that $t_{n,0}(A)$ is solvable as a Lie algebra, because $t_{n,1}(A)$ is nilpotent.

Let k be a field again, and let V be a vector space over k of dimension $n \in \mathbf{Z}_+$. If $v_1, \ldots, v_n$ is a basis for V, then we can get a flag $\mathcal{F} = \{V_j\}_{j=0}^n$ in V by taking V_j to be the linear span of $v_1, \ldots, v_j$ for each $j = 1, \ldots, n$. Of course, every flag in V corresponds to a basis for V in this way. Using this basis for V, elements of $M_n(k)$ correspond to linear mappings from V into itself, as in Section 2.10. Similarly, $T_{n,r}(k)$ corresponds to $\mathcal{U}_r(\mathcal{F})$ for each $r = 0, 1, \ldots, n$.

9.12 A useful lemma

Let k be a field of characteristic 0, let $(A, [\cdot, \cdot])$ be a Lie algebra over k, and let B be an ideal in A. Also let V be a finite-dimensional vector space over k, and suppose that V is a module over A, as a Lie algebra over k. Let v be a nonzero element of V, and suppose that χ is a mapping from B into k such that

$$b \cdot v = \chi(b)\, v \tag{9.12.1}$$

for every $b \in B$. If $a \in A$ and $b \in B$, then $[a, b] \in B$, and in fact

$$\chi([a, b]) = 0. \tag{9.12.2}$$

This is the Main Lemma stated on p36 of [25], which corresponds to part of the proof of Step (3) on p16 of [14].

Equivalently, let ρ be the representation of A on V, which makes V into a module over A as a Lie algebra over k. The hypothesis (9.12.1) says that for each $b \in B$, v is an eigenvector of ρ_b, with eigenvalue $\chi(b)$. The conclusion (9.12.2) says that

$$([a, b]) \cdot v = \rho_{[a,b]}(v) = 0 \tag{9.12.3}$$

for every $a \in A$ and $b \in B$. One could also reduce to the case where A is a Lie subalgebra of $gl(V)$, by considering the Lie algebra of linear mappings from V into itself of the form ρ_a for some $a \in A$. In particular, the discussion in [14] is given in this setting.

Let $a \in A$ be given, and put $V_0 = \{0\}$. If j is a positive integer, then let V_j be the linear span of

$$v,\ \rho_a(v), \ldots, (\rho_a)^{j-1}(v) \tag{9.12.4}$$

in V. Thus V_j is a linear subspace of V for every $j \geq 0$, with $V_j \subseteq V_{j+1}$. Let n be the smallest positive integer such that

$$V_n = V_{n+1}. \tag{9.12.5}$$

This uses the finite-dimensionality of V, to get that this condition holds for some positive integer. Note that V_n has dimension equal to n as a vector space over k, and that

$$\rho_a(V_n) \subseteq V_{n+1} = V_n. \tag{9.12.6}$$

In particular, n is less than or equal to the dimension of V.

If $b \in B$, then we would like to show that

$$\rho_b((\rho_a)^j(v)) = \chi(b)\,(\rho_a)^j(v) \quad \text{modulo } V_j \tag{9.12.7}$$

for each $j \geq 0$, using induction on j. This is the same as (9.12.1) when $j = 0$. If $j \geq 1$, then

$$\begin{aligned} \rho_b((\rho_a)^j(v)) &= \rho_b(\rho_a((\rho_a)^{j-1}(v))) \\ &= \rho_a(\rho_b((\rho_a)^{j-1}(v))) - ([\rho_a, \rho_b])((\rho_a)^{j-1}(v)) \\ &= \rho_a(\rho_b((\rho_a)^{j-1}(v))) - \rho_{[a,b]}((\rho_a)^{j-1}(v)). \end{aligned} \tag{9.12.8}$$

Of course,

$$\rho_b((\rho_a)^{j-1}(v)) = \chi(b)\,(\rho_a)^{j-1}(v) \quad \text{modulo } V_{j-1}, \tag{9.12.9}$$

by the induction hypothesis. This implies that

$$\rho_a(\rho_b((\rho_a)^{j-1}(v))) = \chi(b)\,(\rho_a)^j(v) \quad \text{modulo } V_j, \tag{9.12.10}$$

because $\rho_a(V_{j-1}) \subseteq V_j$ by construction. Similarly,

$$\rho_{[a,b]}((\rho_a)^{j-1}(v)) = \chi([a,b])\,(\rho_a)^{j-1}(v) \quad \text{modulo } V_{j-1}, \tag{9.12.11}$$

by the induction hypothesis, because $[a, b] \in B$. It follows that the left side of (9.12.11) is an element of V_j. Combining this with (9.12.8) and (9.12.10), we get that (9.12.7) holds, as desired.

In particular, (9.12.7) implies that ρ_b maps V_n into itself when $b \in B$. Observe that

$$\mathrm{tr}_{V_n} \rho_b = n \cdot \chi(b) \tag{9.12.12}$$

for every $b \in B$, by (9.12.7), where more precisely the left side is the trace of the restriction of ρ_b to V_n. We also have that

$$\mathrm{tr}_{V_n} \rho_{[a,b]} = \mathrm{tr}_{V_n}([\rho_a, \rho_b]) = 0 \tag{9.12.13}$$

for every $b \in B$, using the fact that ρ_a and ρ_b both map V_n into itself in the second step. Thus

$$n \cdot \chi([a, b]) = 0 \tag{9.12.14}$$

for every $b \in B$, by (9.12.12) applied to $[a, b]$. This implies (9.12.2), because k is supposed to have characteristic 0. Note that this also works when k has positive characteristic and the dimension of V is strictly less than the characteristic of k, because n is less than or equal to the dimension of V. This is related to Exercise 2 on p20 of [14].

9.13 Lie's theorem

Let k be an algebraically closed field of characteristic 0, let $(A, [\cdot, \cdot])$ be a solvable Lie algebra over k, and let ρ be a representation of A as a Lie algebra on a finite-dimensional vector space V over k. If $V \neq \{0\}$, then there exists a $v \in V$ such that $v \neq 0$ and v is an eigenvector for ρ_a for every $a \in A$. This corresponds to Theorem 5.1' on p36 of [25], and the theorem on p15 of [14]. As before, one can reduce to the case where A is a Lie subalgebra of $gl(V)$, by considering the Lie algebra of linear mappings from V into itself of the form ρ_a for some $a \in A$. The theorem on p15 of [14] is stated in this way, so that A is finite-dimensional as a vector space over k in particular. The finite-dimensionality of A is implicit in Theorem 5.1' in [25], as mentioned at the beginning of Chapter 5 in [25]. Let us suppose now that A is finite-dimensional as a vector space over k too.

The proof uses induction on the dimension of A, as a vector space over k. Of course, if $A = \{0\}$, then the statement is trivial. Suppose now that $A \neq \{0\}$, and note that $[A, A] \neq A$, because A is solvable. Let B be a linear subspace of V of codimension 1 that contains $[A, A]$, which implies that B is an ideal in A. The induction hypothesis implies that there is a $v \in V$ with $v \neq 0$ and a mapping χ from B into k such that

$$\rho_b(v) = \chi(b)\, v \tag{9.13.1}$$

for every $b \in B$. Put

$$W = \{w \in V : \rho_b(w) = \chi(b)\, w \quad \text{for every } b \in B\}, \tag{9.13.2}$$

which is a linear subspace of V with $v \in W$, so that $W \neq \{0\}$. We would like to verify that

$$\rho_a(W) \subseteq W \tag{9.13.3}$$

for every $a \in A$. If $a \in A$, $b \in B$, and $w \in W$, then

$$\rho_b(\rho_a(w)) = \rho_a(\rho_b(w)) - \rho_{[a,b]}(w) = \chi(b)\, \rho_a(w) - \chi([a, b])\, w, \tag{9.13.4}$$

using the fact that $[a, b] \in B$ in the second step. Combining this with (9.12.2), we obtain that

$$\rho_b(\rho_a(w)) = \chi(b)\, \rho_a(w), \tag{9.13.5}$$

as desired.

Let a_0 be any element of A not in B. Because k is algebraically closed, there is a $w_0 \in W$ such that $w_0 \neq 0$ and w_0 is an eigenvector for ρ_{a_0}. If a is any element of A, then a can be expressed as the sum of a multiple of a_0 and an element b of B, because B has codimension 1 in A. It follows that w_0 is an eigenvector for ρ_a, as desired, because w_0 is an eigenvector for ρ_b, by definition of W. Note that this also works when k has positive characteristic strictly larger than the dimension of V, as in Exercise 2 on p20 of [14].

Under these conditions, *Lie's theorem* states that there is a flag $\mathcal{F} = \{V_j\}_{j=0}^n$ in V such that $\rho_a(V_j) \subseteq V_j$ for every $a \in A$ and $j = 0, 1, \ldots, n$. This is Theorem

5.1 on p36 of [25], which corresponds to Corollary A on p16 of [14]. More precisely, one can get V_1 as in the previous paragraphs. One can repeat the process, by considering the induced linear mappings on V/V_1.

In particular, if A is a solvable Lie algebra over k that is finite-dimensional as a vector space over k, then there is a flag in A consisting of ideals in A. This is Corollary 5.2 on p37 of [25], and Corollary B on p16 of [14]. This follows from the statement in the preceding paragraph, applied to the adjoint representation of A.

9.14 Structure constants

Let k be a commutative ring with a multiplicative identity element, and let n be a positive integer. Remember that the space k^n of n-tuples of elements of k is a (free) module over k with respect to coordinatewise addition and scalar multiplication. Let $u_1, \ldots, u_n$ be the "standard basis" elements of k^n, so that the jth coordinate of u_l is equal to 1 when $j = l$ and to 0 otherwise. If $x = (x_1, \ldots, x_n) \in k^n$, then

$$x = \sum_{l=1}^{n} x_l \, u_l. \tag{9.14.1}$$

Of course, if k is a field and V is an n-dimensional vector space over k, then V can be identified with k^n by choosing a basis for V.

Let $[\cdot,\cdot]_{k^n}$ be a mapping from $k^n \times k^n$ into k^n that is bilinear over k. We can express $[u_j, u_l]_{k^n}$ as

$$[u_j, u_l]_{k^n} = \sum_{r=1}^{n} c_{j,l}^r \, u_r \tag{9.14.2}$$

for each $j, l = 1, \ldots, n$, where $c_{j,l}^r$ are elements of k for every $j, l, r = 1, \ldots, n$. This implies that

$$([x, y]_{k^n})_r = \sum_{j=1}^{n} \sum_{l=1}^{n} c_{j,l}^r \, x_j \, y_l \tag{9.14.3}$$

for every $x, y \in k^n$ and $r = 1, \ldots, n$, where the left side is the rth coordinate of $[x, y]_{k^n}$. More precisely, this uses (9.14.1) and the bilinearity of $[\cdot,\cdot]_{k^n}$ over k. Conversely, if $c_{j,l}^r \in k$ for every $j, l, r = 1, \ldots, n$, then (9.14.3) defines a mapping from $k^n \times k^n$ into k^n that is bilinear over k.

Clearly

$$[x, y]_{k^n} = -[y, x]_{k^n} \tag{9.14.4}$$

for every $x, y \in k^n$ if and only if

$$c_{j,l}^r = -c_{l,j}^r \tag{9.14.5}$$

for every $j, l, r = 1, \ldots, n$. One can check that

$$[x, x]_{k^n} = 0 \tag{9.14.6}$$

for every $x \in k^n$ if and only if (9.14.5) holds and

$$c_{j,j}^r = 0 \tag{9.14.7}$$

for every $j, r = 1, \ldots, n$. If $1 + 1$ has a multiplicative inverse in k, then (9.14.4) implies (9.14.6), and (9.14.5) implies (9.14.7), as usual. The Jacobi identity for $[\cdot, \cdot]_{k^n}$ holds if and only if

$$\sum_{h=1}^{n} (c_{j,l}^h \, c_{h,m}^r + c_{l,m}^h \, c_{h,j}^r + c_{m,j}^h \, c_{h,l}^r) = 0 \tag{9.14.8}$$

for every $j, l, m, r = 1, \ldots, n$, as on p5 of [14]. Let us suppose from now on in this section that the $c_{j,l}^r$'s satisfy these conditions, so that $[\cdot, \cdot]_{k^n}$ defines a Lie bracket on k^n.

Let A be a commutative associative algebra over k. Note that the space A^n of n-tuples of elements of A is a module over k with respect to coordinatewise addition and scalar multiplication. If $a, b \in A^n$, then define $[a, b]_{A^n}$ as an element of A^n by

$$([a, b]_{A^n})_r = \sum_{j=1}^{n} \sum_{l=1}^{n} c_{j,l}^r \, a_j \, b_l \tag{9.14.9}$$

for each $r = 1, \ldots, n$, where the left side is the rth coordinate of $[a, b]_{A^n}$. The conditions on the $c_{j,l}^r$'s in the preceding paragraph imply that A^n is a Lie algebra over k with respect to (9.14.9). If k^n is solvable or nilpotent as a Lie algebra with respect to $[\cdot, \cdot]_{k^n}$, then one can check that A^n has the same property with respect to $[\cdot, \cdot]_{A^n}$.

Suppose that A has a multiplicative identity element e. In this case, A^n may be considered as a module over A with respect to coordinatewise addition and scalar multiplication, and as a Lie algebra over A with respect to (9.14.9). Of course,

$$t \mapsto t\, e \tag{9.14.10}$$

defines a ring homomorphism from k into A, which leads to a Lie algebra homomorphism from k^n into A^n, as Lie algebras over k. Suppose that (9.14.10) is injective, which implies that the corresponding Lie algebra homomorphism from k^n into A^n is injective. If A^n is solvable or nilpotent as a Lie algebra, then it follows that k^n has the same property.

9.15 Another corollary

Let k be a commutative ring with a multiplicative identity element, and let $(A, [\cdot, \cdot])$ be a Lie algebra over k. If $x \in A$, then we may use $\mathrm{ad}_A\, x = \mathrm{ad}_{A,x}$ to denote the usual mapping

$$(\mathrm{ad}_A x)(y) = \mathrm{ad}_{A,x}(y) = [x, y] \tag{9.15.1}$$

from A into itself. Similarly, if B is a Lie subalgebra of A and $x \in B$, then $\mathrm{ad}_B\, x = \mathrm{ad}_{B,x}$ is a module homomorphism from B into itself. In this situation, $\mathrm{ad}_{B,x}$ is the same as the restriction of (9.15.1) to $y \in B$.

Suppose that k is an algebraically closed field of characteristic 0, and that $(A, [\cdot, \cdot])$ be a solvable Lie algebra over k that is finite-dimensional as a vector space over k. Under these conditions, $[A, A]$ is nilpotent as a Lie algebra over k. This is Corollary C on p16 of [14], and part of Corollary 5.3 on p37 of [25]. Remember that there is a flag of ideals in A, as a consequence of Lie's theorem in Section 9.13. If $x \in A$, then $\mathrm{ad}_{A,x}$ maps these ideals into themselves. If $x \in [A, A]$, then $\mathrm{ad}_{A,x}$ maps the nonzero ideals in the flag into the next smaller one, as in Section 9.11. This implies that $\mathrm{ad}_{A,x}$ is nilpotent as a mapping from A into itself. It follows that $\mathrm{ad}_{[A,A],x}$ is nilpotent as a mapping from $[A, A]$ into itself, because this mapping is the same as the restriction of $\mathrm{ad}_{A,x}$ to $[A, A]$, as in the preceding paragraph. This implies that $[A, A]$ is nilpotent as a Lie algebra, as in Section 9.10.

Alternatively, one can use the same type of argument to get that the image of $[A, A]$ under the adjoint representation of A is nilpotent as a Lie algebra over k. One can use this to get that $[A, A]$ is nipotent as a Lie algebra, because the kernel of the adjoint representation of A is the center of A.

Suppose now that k is a field of characteristic 0, and that A is a finite-dimensional solvable Lie algebra over k. Corollary 5.3 on p37 of [25] states that $[A, A]$ is still nilpotent as a Lie algebra over k, without asking k to be algebraically closed. To see this, let k_1 be an algebraically closed field that contains k. The statement is trivial when $A = \{0\}$, and so we may suppose that the dimension n of A as a vector space over k is positive. Thus A is isomorphic to k^n as a vector space over k, and we may as well suppose that $A = k^n$ with some Lie bracket. This leads to a Lie bracket on k_1^n, as in the previous section. If k^n is solvable as a Lie algebra, then k_1^n is solvable as a Lie algebra too, as before. This implies that $[k_1^n, k_1^n]$ is nilpotent as a Lie algebra, by the earlier arguments for algebraically closed fields. Note that $[k^n, k^n]$ may be considered as a Lie subalgebra of $[k_1^n, k_1^n]$, as a Lie algebra over k. It follows that $[k^n, k^n]$ is solvable as a Lie algebra over k, as desired.

Chapter 10

Matrices and traces

10.1 Some remarks about $gl_n(k)$

Let k be a commutative ring with a multiplicative identity element, and let n be a positive integer. The space k^n of n-tuples of elements of k is a (free) module over k with respect to coordinatewise addition and scalar multiplication, as usual. If $a = (a_{j,l})$ is an $n \times n$ matrix with entries in k and $x \in k^n$, then $T_a(x)$ is defined as the element of k^n whose jth coordinate is given by

$$(T_a(x))_j = \sum_{l=1}^{n} a_{j,l}\, x_l \tag{10.1.1}$$

for each $j = 1, \ldots, n$. This defines a module homomorphism from k^n into itself, and $a \mapsto T_a$ is an algebra isomorphism from the algebra $M_n(k)$ of $n \times n$ matrices with entries in k with respect to matrix multiplication onto the algebra $\mathrm{Hom}_k(k^n, k^n)$ of module homomorphisms from k^n into itself with respect to composition of mappings.

Let $u_1, \ldots, u_n$ be the n "standard basis" elements of k^n, so that the lth coordinate of u_r is equal to 1 when $l = r$, and to 0 otherwise. Thus

$$x = \sum_{r=1}^{n} x_r\, u_r \tag{10.1.2}$$

for every $x = (x_1, \ldots, x_n) \in k^n$. If $a \in M_n(k)$, then

$$(T_a(u_r))_j = a_{j,r} \tag{10.1.3}$$

for every $j, r = 1, \ldots, n$.

Similarly, if $h, m \in \{1, \ldots, n\}$, then let $e_{h,m}$ be the element of $M_n(k)$ whose (h, m) entry is equal to 1, and all of whose other entries are equal to 0. If $a = (a_{j,l})$ is any element of $M_n(k)$, then a can be expressed as

$$a = \sum_{h=1}^{n} \sum_{m=1}^{n} a_{h,m}\, e_{h,m}. \tag{10.1.4}$$

It is sometimes convenient to let $T_{h,m}$ be the module homomorphism from k^n into itself associated to $e_{h,m}$ as in (10.1.1) for each $h, m = 1, \ldots, n$, so that

$$T_{h,m} = T_{e_{h,m}}. \tag{10.1.5}$$

If $a = (a_{j,l}) \in M_n(k)$, then T_a can be expressed as

$$T_a = \sum_{h=1}^{n} \sum_{m=1}^{n} a_{h,m} \, T_{h,m}. \tag{10.1.6}$$

If $q, r \in \{1, \ldots, n\}$, then let $\delta_{q,r} \in k$ be equal to 1 when $q = r$, and to 0 otherwise, as usual. Observe that

$$T_{h,m}(u_r) = \delta_{m,r} \, u_h \tag{10.1.7}$$

for every $h, m, r = 1, \ldots, n$. We also have that

$$e_{h,m} \, e_{q,r} = \delta_{m,q} \, e_{h,r} \tag{10.1.8}$$

for every $h, m, q, r = 1, \ldots, n$. Equivalently,

$$T_{h,m} \circ T_{q,r} = \delta_{m,q} \, T_{h,r} \tag{10.1.9}$$

for every $h, m, q, r = 1, \ldots, n$. It follows from (10.1.8) that

$$[e_{h,m}, e_{q,r}] = e_{h,m} \, e_{q,r} - e_{q,r} \, e_{h,m} = \delta_{m,q} \, e_{h,r} - \delta_{r,h} \, e_{q,m} \tag{10.1.10}$$

for every $h, m, q, r = 1, \ldots, n$. In particular, if $h \neq r$ and $m \neq q$, then

$$[e_{h,m}, e_{q,r}] = 0, \tag{10.1.11}$$

because each of the two terms on the right side of (10.1.10) is equal to 0. Otherwise,

$$[e_{h,m}, e_{m,r}] = e_{h,r} \tag{10.1.12}$$

when $h \neq r$, and

$$[e_{h,m}, e_{q,h}] = -e_{q,m} \tag{10.1.13}$$

when $m \neq q$. Of course, these two cases are equivalent, because of the antisymmetry of the commutator bracket. Similarly,

$$[e_{h,m}, e_{m,h}] = e_{h,h} - e_{m,m} \tag{10.1.14}$$

for every $h, m = 1, \ldots, n$.

Remember that $gl_n(k)$ is the same as $M_n(k)$ as a module over k, but considered as a Lie algebra over k with respect to the corresponding commutator bracket, as in Section 2.9. Similarly, $sl_n(k)$ is the ideal in $gl_n(k)$ consisting of matrices with trace 0, as before. In fact,

$$[gl_n(k), gl_n(k)] = sl_n(k), \tag{10.1.15}$$

where the left side is as defined in Section 9.2. More precisely, the inclusion of the left side of (10.1.15) in the right side follows from basic properties of the trace, as in Section 2.9. The opposite inclusion can be obtained from (10.1.12) and (10.1.14). This corresponds to Exercise 2 on p9 of [14]. One can also verify that

(10.1.16) $$[gl_n(k), sl_n(k)] = sl_n(k),$$

using the same argument.

10.2 Some basic properties of $sl_2(k)$

Let k be a commutative ring with a multiplicative identity element, and remember that $sl_2(k)$ is the space of 2×2 matrices with entries in k and trace 0. This is a Lie algebra over k with respect to the usual commutator bracket. Consider the elements of $sl_2(k)$ given by

(10.2.1) $$x = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}, \quad y = \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix}, \quad \text{and} \quad h = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}.$$

It is easy to see that every element of $sl_2(k)$ can be expressed in a unique way as a linear combination of x, y, and h with coefficients in k. Thus $sl_2(k)$ is isomorphic to the free module k^3 of rank 3 over k, as a module over k.

Equivalently, using the notation in the previous section, with $n = 2$, we have that

(10.2.2) $$x = e_{1,2}, \quad y = e_{2,1}, \quad \text{and} \quad h = e_{1,1} - e_{2,2}.$$

One can check that

(10.2.3) $$[x, y] = h, \quad [h, x] = 2 \cdot x, \quad [h, y] = -2 \cdot y,$$

as on p6 of [14]. Here $2 \cdot a = a + a$ for each $a \in sl_2(k)$, as usual. If $1 + 1 = 0$ in k, then h is the same as the identity matrix, so that

(10.2.4) $$[h, x] = [h, y] = 0,$$

as in (10.2.3). In this case, it follows that $sl_2(k)$ is nilpotent as a Lie algebra over k, as in Exercise 3 on p14 of [14].

Suppose for the moment that k is a field with characteristic 2. Elements of $sl_2(k)$ correspond to linear mappings from k^2 into itself, as a two-dimensional vector space over k, as before. It is well known and not difficult to check that the linear mappings on k^2 corresponding to elements of $sl_2(k)$ do not have a (nonzero) simultaneous eigenvector. This shows that the results discussed in Section 9.13 can fail in positive characteristic, as mentioned on p37 of [25].

If $1 + 1$ has a multiplicative inverse in k, then we get that

(10.2.5) $$[sl_2(k), sl_2(k)] = sl_2(k),$$

where the left side is as defined in Section 9.2. This corresponds to part of Exercise 9 on p5 of [14]. Similarly, if $2^j \cdot 1 = 0$ in k for some $j \in \mathbf{Z}_+$, then one can check that $sl_2(k)$ is nilpotent as a Lie algebra over k. However, if for each $j \in \mathbf{Z}_+$, $2^j \cdot 1 \neq 0$ in k, then $sl_2(k)$ is not solvable as a Lie algebra over k.

If n is any positive integer with $n \geq 3$, then

$$[sl_n(k), sl_n(k)] = sl_n(k). \tag{10.2.6}$$

This corresponds to part of Exercise 9 on p5 of [14] again. Of course, the left side of (10.2.6) is contained in the right side, as in (10.1.15). To get the opposite inclusion, one can verify that

$$e_{h,r} \in [sl_n(k), sl_n(k)] \tag{10.2.7}$$

for every $h, r \in \{1, \ldots, n\}$ with $h \neq r$, using (10.1.12) with $m \neq h, r$. We also have that

$$e_{h,h} - e_{m,m} \in [sl_n(k), sl_n(k)] \tag{10.2.8}$$

for every $h, m = 1, \ldots, n$ with $h \neq m$, by (10.1.14).

10.3 Scalar and diagonal matrices

Let k be a commutative ring with a multiplicative identity element, let n be a positive integer, and let A be an associative algebra over k, where multiplication of $x, y \in A$ is expressed as $x\,y$. As usual, an $n \times n$ matrix $a = (a_{j,l})$ with entries in A is said to be a *diagonal matrix* if $a_{j,l} = 0$ when $j \neq l$. Let $D_n(A)$ be the space of these diagonal matrices, which is a subalgebra of the algebra $M_n(A)$ of $n \times n$ matrices with entries in A, as an associative algebra over k with respect to matrix multiplication. If multiplication on A is commutative, then matrix multiplication is commutative on $D_n(A)$.

An element a of $D_n(A)$ is said to be a *scalar matrix* if the diagonal entries $a_{j,j}$ of a are all equal to each other. Let $S_n(A)$ be the space of these scalar matrices, which is a subalgebra of $D_n(A)$. If multiplication on A is commutative, then the elements of $S_n(A)$ commute with all other elements of $M_n(A)$, with respect to matrix multiplication.

As before, $gl_n(A)$ is the same as $M_n(A)$, but considered as a Lie algebra over k with respect to the corresponding commutator bracket. Similarly, let $d_n(A)$ and $s_n(A)$ be the same as $D_n(A)$ and $S_n(A)$, respectively, considered as Lie subalgebras of $gl_n(A)$.

Let us now simply take $A = k$. Remember that the identity matrix I in $M_n(k)$ is the diagonal matrix with diagonal entries equal to the multiplicative identity element 1 in k, which is the multiplicative identity element in $M_n(k)$. The scalar matrices in $M_n(k)$ are the same as scalar multiples of I by elements of k.

Using the notation in Section 10.1, we have that

$$e_{h,m} \in sl_n(k) \tag{10.3.1}$$

for every $h, m = 1, \ldots, n$ with $h \neq m$, and

$$e_{h,h} - e_{m,m} \in sl_n(k) \tag{10.3.2}$$

for every $h, m = 1, \ldots, n$. As on p2 of [14], we may consider the $e_{h,m}$'s with $h \neq m$, together with the matrices $e_{h,h} - e_{h+1,h+1}$ for $h = 1, \ldots, n-1$ when $n \geq 2$, as the "standard basis elements" of $sl_n(k)$. One can check that every element of $sl_n(k)$ can be expressed in a unique way as a linear combination of these standard basis elements with coefficients in k. Note that there are $(n^2 - n) + (n - 1) = n^2 - 1$ of these standard basis elements in $sl_n(k)$. Thus $sl_n(k)$ is isomorphic to the free module k^{n^2-1} of rank $n^2 - 1$ over k, as a module over k.

Of course, every element of $gl_n(k)$ can be expressed in a unique way as a linear combination of the $e_{h,m}$'s, $h, m = 1, \ldots, n$, with coefficients in k, so that $gl_n(k)$ is isomorphic to the free module k^{n^2} of rank n^2 over k, as a module over k. Alternatively, one can verify that every element of $gl_n(k)$ can be expressed in a unique way as a linear combination of the standard basis elements for $sl_n(k)$ mentioned in the preceding paragraph together with $e_{1,1}$, with coefficients in k. In particular, every element of $gl_n(k)$ can be expressed in a unique way as the sum of an element of $sl_n(k)$ and a multiple of $e_{1,1}$ by an element of k, so that $gl_n(k)$ is isomorphic to the direct sum of $sl_n(k)$ and k, as modules over k. Indeed, if $a \in gl_n(k)$, then

$$a - (\operatorname{tr} a)\, e_{1,1} \in sl_n(k), \tag{10.3.3}$$

because $\operatorname{tr} e_{1,1} = 1$. Thus a can be expressed as the sum of (10.3.3) and $(\operatorname{tr} a)\, e_{1,1}$, and one can use the trace again to see that this is unique.

Note that $\operatorname{tr} I = n \cdot 1$, as an element of k. If $n \cdot 1 = 0$ in k, then $n \times n$ scalar matrices with entries in k have trace equal to 0. Suppose for the moment that $n \cdot 1$ has a multiplicative inverse in k. If $a \in gl_n(k)$, then

$$a - \frac{\operatorname{tr} a}{n \cdot 1}\, I \in sl_n(k), \tag{10.3.4}$$

and $\operatorname{tr} a/(n \cdot 1)$ is the unique element of k with this property. This implies that every element of $gl_n(k)$ can be expressed in a unique way as the sum of elements of $sl_n(k)$ and $s_n(k)$, as in Exercise 7 on p5 in [14].

10.4 Centrality in $gl_n(k)$, $sl_n(k)$

Let k be a commutative ring with a multiplicative identity element, and let n be a positive integer. Remember that $a = (a_{j,l}) \in gl_n(k)$ can be expressed as

$$a = \sum_{h=1}^{n} \sum_{m=1}^{n} a_{h,m}\, e_{h,m}, \tag{10.4.1}$$

as in (10.1.4). If $q, r \in \{1, \ldots, n\}$, then

$$\begin{aligned} [a, e_{q,r}] &= \sum_{h=1}^{n} \sum_{m=1}^{n} a_{h,m}\, [e_{h,m}, e_{q,r}] \\ &= \sum_{h \neq r} a_{h,q}\, e_{h,r} - \sum_{m \neq q} a_{r,m}\, e_{q,m} + a_{r,q}\, (e_{r,r} - e_{q,q}), \end{aligned} \tag{10.4.2}$$

by (10.1.11), (10.1.12) with $m = q$, (10.1.13) with $h = r$, and (10.1.14) with $h = r$ and $m = q$. More precisely, the two sums on the right side of (10.4.2) are taken over $h, m = 1, \ldots, n$ with $h \neq r$ and $m \neq q$, respectively. If $q \neq r$, then we get that

$$\begin{aligned}[a, e_{q,r}] &= \sum_{h \neq q,r} a_{h,q}\, e_{h,r} - \sum_{m \neq q,r} a_{r,m}\, e_{q,m} + (a_{q,q} - a_{r,r})\, e_{q,r} \\ &\quad + a_{r,q}\, (e_{r,r} - e_{q,q}), \end{aligned} \tag{10.4.3}$$

where the sums are taken over $h, m = 1, \ldots, n$ with $h, m \neq q, r$, respectively.

Suppose that $[a, e_{q,r}] = 0$ for every $q, r \in \{1, \ldots, n\}$ with $q \neq r$. In this case, one can use (10.4.3) to get that a is a diagonal matrix whose diagonal entries are equal to each other, so that a is a scalar matrix. In particular, the center of $gl_n(k)$ as a Lie algebra over k is the Lie subalgebra $s_n(k)$ of scalar matrices. This corresponds to the first part of Exercise 3 on p10 of [14].

Similarly, the center $Z(sl_n(k))$ of $sl_n(k)$ as a Lie algebra over k is the intersection of $s_n(k)$ with $sl_n(k)$. This consists of matrices of the form $t\, I$, where $t \in k$ satisfies $n \cdot t = 0$. If $n \cdot 1$ has a multiplicative inverse in k, then $Z(sl_n(k)) = \{0\}$. If $n \cdot 1 = 0$ in k, then $Z(sl_n(k)) = s_n(k)$. This corresponds to the second part of Exercise 3 on p10 of [14].

If $r \in \{1, \ldots, n\}$, then

$$[a, e_{r,r}] = \sum_{h \neq r} a_{h,r}\, e_{h,r} - \sum_{m \neq r} a_{r,m}\, e_{r,m}, \tag{10.4.4}$$

by (10.4.2) with $q = r$. Let $d_n(k)$ be the Lie subalgebra of $gl_n(k)$ consisting of diagonal matrices, as in the previous section. Remember that $a \in gl_n(k)$ is in the normalizer of $d_n(k)$ in $gl_n(k)$ if $[a, b] \in d_n(k)$ for every $b \in d_n(k)$, as in Section 9.8. In this case, it is easy to see that $a \in d_n(k)$, using (10.4.4). This corresponds to part of Exercise 7 on p10 of [14].

If $a \in d_n(k)$, then

$$[a, e_{q,r}] = (a_{q,q} - a_{r,r})\, e_{q,r} \tag{10.4.5}$$

for every $q, r \in \{1, \ldots, n\}$ with $q \neq r$, by (10.4.3). This also works when $q = r$, in which the right side is equal to 0, by (10.4.4). This corresponds to Exercise 6 on p5 of [14].

10.5 Solvability and traces

Let k be a field of characteristic 0, and let V be a vector space over k of positive finite dimension n. Remember that the space $gl(V)$ of linear mappings from V into itself is a Lie algebra over k, with respect to the usual commutator bracket. Let A be a Lie subalgebra of $gl(V)$, and suppose that A is solvable as a Lie algebra over k. If $T \in A$ and $R \in [A, A]$, then

$$\mathrm{tr}(T \circ R) = 0, \tag{10.5.1}$$

as in Theorem 7.1 on p42 of [25]. Here $[A, A]$ is the derived algebra of A, as in Section 9.2, as usual.

Suppose for the moment that k is algebraically closed. Lie's theorem implies that there is a flag $\mathcal{F} = \{V_j\}_{j=0}^n$ in V such that $T(V_j) \subseteq V_j$ for every $T \in A$ and $j = 0, 1, \ldots, n$, as in Section 9.13. If $R \in [A, A]$, then $R(V_j) \subseteq V_{j-1}$ for $j = 1, \ldots, n$, as in Section 9.11. This implies (10.5.1), using a basis for V that is compatible with $\mathcal{F}$. This corresponds to Exercise 7 on p21 of [14].

Now let k be any field of characteristic 0. Of course, V is isomorphic to k^n as a vector space over k, and we may as well take $V = k^n$. We can reformulate (10.5.1) in terms of matrices, as follows. If A_0 is a Lie subalgebra of $gl_n(k)$ that is solvable as a Lie algebra over k, then

$$\mathrm{tr}(T_0\, R_0) = 0 \tag{10.5.2}$$

for every $T_0 \in A_0$ and $R_0 \in [A_0, A_0]$. More precisely, this uses matrix multiplication and the trace on the space $M_n(k)$ of $n \times n$ matrices with entries in k.

Let k_1 be an algebraically closed field that contains k as a subfield, so that $gl_n(k)$ is contained in $gl_n(k_1)$. Let A_1 be the linear span of A_0 in $gl_n(k_1)$, as a vector space over k_1. It is easy to see that A_1 is a Lie subalgebra of $gl_n(k_1)$, as a Lie algebra over k_1, because A_0 is a Lie subalgebra of $gl_n(k)$. Similarly, one can check that A_1 is solvable as a Lie algebra over k_1, because A_0 is solvable as a Lie algebra over k. It follows that

$$\mathrm{tr}(T_1\, R_1) = 0 \tag{10.5.3}$$

for every $T_1 \in A_1$ and $R_1 \in [A_1, A_1]$, by the earlier argument for algebraically closed fields. This uses matrix multiplication and the trace on $M_n(k_1)$, which contains $M_n(k)$. This implies (10.5.2), because $A_0 \subseteq A_1$, and hence $[A_0, A_0]$ is contained in $[A_1, A_1]$.

Let k be a commutative ring with a multiplicative identity element, and remember that $[gl_2(k), gl_2(k)] = sl_2(k)$, as in Section 10.1. Suppose that $1+1 = 0$ in k, so that the identity matrix in $gl_2(k)$ is in $sl_2(k)$. Remember that $sl_2(k)$ is nilpotent as a Lie algebra over k in this case, as in Section 10.2, so that $gl_2(k)$ is solvable as a Lie algebra over k. In this situation, (10.5.2) would say that every element of $gl_2(k)$ has trace 0, which is of course not the case.

10.6 Diagonalizable linear mappings

Let k be a field, let V be a vector space over k, and let T be a linear mapping from V into itself. If $\lambda \in k$, then put

$$E_\lambda(T) = \{v \in V : T(v) = \lambda(v)\}, \tag{10.6.1}$$

which is a linear subspace of V. As usual, λ is said to be an eigenvalue of T when $E_\lambda(T) \neq \{0\}$, in which case the elements of $E_\lambda(T)$ are said to be eigenvectors of T corresponding to λ. If R is another linear mapping from V into itself that commutes with T and $v \in E_\lambda(T)$, then

$$T(R(v)) = R(T(v)) = \lambda\, R(v). \tag{10.6.2}$$

This means that $R(v) \in E_\lambda(T)$, so that

$$R(E_\lambda(T)) \subseteq E_\lambda(T). \tag{10.6.3}$$

Suppose that $\lambda_1, \ldots, \lambda_l$ are finitely many distinct elements of k, and let $r \in \{1, \ldots, n\}$ be given. Consider the linear mapping

$$\prod_{j \ne r} (T - \lambda_j\, I) \tag{10.6.4}$$

on V, where more precisely I is the identity mapping on V, and the product is the composition of $T_j - \lambda_j\, I$ for $j = 1, \ldots, n$ and $j \ne r$. This linear mapping is equal to 0 on $E_{\lambda_j}(T)$ when $j \ne r$, and it is equal to

$$\prod_{j \ne r} (\lambda_r - \lambda_j) \tag{10.6.5}$$

times the identity mapping on $E_{\lambda_r}(T)$. As before, (10.6.5) is the product of $\lambda_r - \lambda_j$ for $j = 1, \ldots, n$ and $j \ne r$, which is a nonzero element of k. If $v_j \in E_{\lambda_j}(T)$ for each $j = 1, \ldots, l$ and

$$\sum_{j=1}^{l} v_j = 0, \tag{10.6.6}$$

then it is easy to see that $v_r = 0$ for every $r = 1, \ldots, l$, by applying (10.6.4) to the sum on the left.

Suppose from now on in this section that V has positive finite dimension, as a vector space over k. Note that T can have only finitely many distinct eigenvalues, and that the sum of the dimensions of the nontrivial eigenspaces of T is less than or equal to the dimension of V, by the remark at the end of the preceding paragraph. If every element of V can be expressed as a sum of eigenvectors of T, then T is said to be *diagonalizable* on V. This means that V is the direct sum of the nontrivial eigenspaces of T, and hence that there is a basis for V consisting of eigenvectors for T.

Suppose that T is diagonalizable on V, with distinct eigenvalues $\lambda_1, \ldots, \lambda_l$. If $r \in \{1, \ldots, n\}$, then (10.6.4) maps V onto $E_{\lambda_r}(T)$. Let W be a linear subspace of V such that

$$T(W) \subseteq W. \tag{10.6.7}$$

Observe that (10.6.4) maps W into itself for each $r = 1, \ldots, n$. Of course, every $w \in W$ can be expressed as a sum of eigenvectors of T, by hypothesis. In this situation, these eigenvectors of T are also elements of W, because (10.6.4) maps W into itself for each r. This implies that the restriction of T to W is diagonalizable.

Let R be another linear mapping from V into itself that commutes with T again. Thus R maps $E_{\lambda_j}(T)$ into itself for each $j = 1, \ldots, n$, as in (10.6.3). If R is diagonalizable on V, then the restriction of R to $E_{\lambda_j}(T)$ is diagonalizable for every $r = 1, \ldots, n$, as in the previous paragraph. This implies that R and T are simultaneously diagonalizable on V, which is to say that there is a basis of V consisting of vectors that are eigenvectors for both R and T. In particular, it follows that $R + T$ and $R \circ T$ are diagonalized by the same basis for V.

10.7 Nilpotent vectors

Let k be a field, and let A be an associative algebra over k with a multiplicative identity element e, where multiplication of $a, b \in A$ is expressed as $a\,b$. If $a \in A$ is nilpotent, $\lambda \in k$, and $\lambda \neq 0$, then $\lambda\, e + a$ has a multiplicative inverse in A. This follows from a remark in Section 3.1 when $\lambda = 1$, and otherwise one can reduce to that case.

Let V be a vector space over k, and let T be a linear mapping from V into itself. Remember that

$$(I - T) \sum_{j=0}^{n} T^j = \Big(\sum_{j=0}^{n} T^j\Big)(I - T) = I - T^{n+1} \tag{10.7.1}$$

for every nonnegative integer n, as in Section 3.1, where I is the identity mapping on V. Suppose for the moment that for each $v \in V$ we have that $T^l(v) = 0$ for some nonnegative integer l, which implies that $T^j(v) = 0$ when $j \geq l$. This permits us to define

$$\sum_{j=0}^{\infty} T^j(v) \tag{10.7.2}$$

as an element of V for every $v \in V$, so that $\sum_{j=0}^{\infty} T^j$ is defined as a linear mapping from V into itself. One can check that

$$(I - T) \sum_{j=0}^{\infty} T^j = \Big(\sum_{j=0}^{\infty} T^j\Big)(I - T) = I, \tag{10.7.3}$$

using (10.7.1). This implies that $I - T$ is invertible on V, with

$$(I - T)^{-1} = \sum_{j=0}^{\infty} T^j. \tag{10.7.4}$$

If $\lambda \in k$ and $\lambda \neq 0$, then $\lambda\, I - T = \lambda\,(I - (1/\lambda)\,T)$ is invertible on V too, because $(1/\lambda)\,T$ satisfies the same condition on V.

Let T be any linear mapping from V into itself again, and put

$$\mathcal{E}_0(T) = \{v \in V : T^l(v) = 0 \text{ for some } l \in \mathbf{Z}_+\}. \tag{10.7.5}$$

This is a linear subspace of V that contains the kernel of T. If $v \in \mathcal{E}_0(T)$ and $v \neq 0$, and if j is the smallest positive integer such that $T^j(v) = 0$, then $T^{j-1}(v)$

is a nonzero element of the kernel of T. Thus $\mathcal{E}_0(T) \neq \{0\}$ if and only if the kernel of T is nontrivial. Note that T maps $\mathcal{E}_0(T)$ into itself. If $\lambda \in k$ and $\lambda \neq 0$, then $\lambda\, I - T$ is invertible as a linear mapping on $\mathcal{E}_0(T)$, by the remarks in the previous paragraph. If R is a linear mapping from V into itself that commutes with T and $v \in \mathcal{E}_0(T)$, then

$$T^l(R(v)) = R(T^l(v)) = 0 \tag{10.7.6}$$

for some $l \in \mathbf{Z}_+$. This means that $R(v) \in \mathcal{E}_0(T)$, and hence

$$R(\mathcal{E}_0(T)) \subseteq \mathcal{E}_0(T). \tag{10.7.7}$$

Let $\lambda \in k$ be given, and put

$$\mathcal{E}_\lambda(T) = \mathcal{E}_0(T - \lambda\, I) = \{v \in V : (T - \lambda\, I)^l(v) = 0 \text{ for some } l \in \mathbf{Z}_+\}. \tag{10.7.8}$$

This is a linear subspace of V, which reduces to (10.7.5) when $\lambda = 0$. Of course,

$$E_\lambda(T) \subseteq \mathcal{E}_\lambda(T), \tag{10.7.9}$$

where $E_\lambda(T)$ is as in (10.6.1). As before, $\mathcal{E}_\lambda(T) \neq \{0\}$ if and only if the kernel of $T - \lambda\, I$ is nontrivial, which means that λ is an eigenvalue of T. If R is a linear mapping from V into itself that commutes with T, then

$$R(\mathcal{E}_\lambda(T)) \subseteq \mathcal{E}_\lambda(T), \tag{10.7.10}$$

as in (10.7.7). In particular, T maps $\mathcal{E}_\lambda(T)$ into itself. If $\mu \in k$ and $\mu \neq \lambda$, then

$$\mu\, I - T = (\mu - \lambda)\, I - (T - \lambda\, I) \tag{10.7.11}$$

is invertible as a linear mapping from $\mathcal{E}_\lambda(T)$ into itself, by the analogous statement in the preceding paragraph.

Let $\lambda_1, \ldots, \lambda_m$ be finitely many distinct eigenvalues of T, and let $v_j \in \mathcal{E}_{\lambda_j}(T)$ be given for $j = 1, \ldots, m$. If

$$\sum_{j=1}^m v_j = 0, \tag{10.7.12}$$

then $v_r = 0$ for each $r = 1, \ldots, m$. To see this, one can apply suitable powers of $T - \lambda_j\, I$ to the sum on the left side of (10.7.12) for $j \neq r$, to get a product of powers of $T - \lambda_j\, I$ with $j \neq r$ applied to v_r. This can only be 0 when $v_r = 0$, because of the invertibility of $T - \lambda_j\, I$ on $\mathcal{E}_{\lambda_r}(T)$ when $j \neq r$.

10.8 Jordan–Chevalley decompositions

Let k be a field, and let V be a vector space over k of positive finite dimension. If T is a linear mapping from V into itself, then one may wish to be able to express T as

$$T = T_1 + T_2, \tag{10.8.1}$$

where T_1 is a diagonalizable linear mapping from V into itself, T_2 is a nilpotent linear mapping from V into itself, and T_1, T_2 commute with each other, and hence with T. Suppose that this is possible, so that V corresponds to the direct sum of the eigenspaces of T_1, as in Section 10.6, and T_2 maps each of these eigenspaces into itself, because T_1 and T_2 commute. Let λ be an eigenvalue of T_1, and let $E_\lambda(T_1)$ be the corresponding eigenspace of T_1, as before. On $E_\lambda(T_1)$, $T - \lambda I = T_2$, so that $T - \lambda I$ is nilpotent on $E_\lambda(T)$. This implies that

$$E_\lambda(T_1) \subseteq \mathcal{E}_\lambda(T), \tag{10.8.2}$$

where the right side is as in (10.7.8). In particular, λ is an eigenvalue of T as well.

Let $\lambda_1, \ldots, \lambda_m$ be a list of all of the distinct eigenvalues of T_1, so that every element of V can be expressed as a sum of elements of the corresponding eigenspaces $E_{\lambda_j}(T_1)$, $j = 1, \ldots, m$. An element of V can be expressed in at most one way as a sum of elements of the $\mathcal{E}_{\lambda_j}(T)$'s, $j = 1, \ldots, m$, as in the previous section. Using this and (10.8.2), we get that

$$E_{\lambda_j}(T_1) = \mathcal{E}_{\lambda_j}(T) \tag{10.8.3}$$

for each $j = 1, \ldots, m$. One can also verify that $\lambda_1, \ldots, \lambda_m$ are all of the eigenvalues of T. If one already knows that every element of V can be expressed as a sum of elements of the $\mathcal{E}_\lambda(T)$'s, where λ is an eigenvalue of T, then one can get T_1 and T_2 using the remarks in the previous section. It is well known that this holds when the characteristic polynomial of T can be factored into a product of linear factors. In particular, this happens when k is algebraically closed.

Note that T_1 and T_2 can be expressed as polynomials in T with coefficients in k and no constant term, as in part (b) of the proposition on p17 of [14], and Lemma 6.1 on p40 of [25]. Equivalently, this means that T_1 and T_2 can be expressed as linear combinations of positive powers of T. In particular, if R is any linear mapping from V into itself that commutes with T, then R commutes with T_1 and T_2. Alternatively, if R commutes with T, then one can check that R commutes with T_1, using (10.7.10) and (10.8.3). This implies that R commutes with T_2 as well, by (10.8.1).

Suppose that T_3 and T_4 are commuting linear mappings from V into itself such that

$$T = T_3 + T_4, \tag{10.8.4}$$

T_3 is diagonalizable on V, and T_4 is nilpotent on V. Note that T_3 and T_4 commute with T, and hence with T_1 and T_2, as in the preceding paragraph. Of course,

$$T_1 - T_3 = T_4 - T_2, \tag{10.8.5}$$

by (10.8.1) and (10.8.4). In this situation, $T_1 - T_3$ is diagonalizable on V, as in Section 10.6. We also have that $T_4 - T_2$ is nilpotent on V, as in Section 9.7. The only linear mapping from V into itself that is both diagonalizable and nilpotent is equal to 0 on V, so that $T_1 = T_3$ and $T_2 = T_4$. This is the uniqueness statement in [14, 25]. One could obtain $T_1 = T_3$ from (10.8.3) too.

Suppose that W_0 and W are linear subspaces of V with

$$T(W) \subseteq W_0 \subseteq W. \tag{10.8.6}$$

Under these conditions,

$$T_1(W),\, T_2(W) \subseteq W_0, \tag{10.8.7}$$

as in part (c) of the proposition on p17 of [14], and Consequence 6.2 on p40 of [25]. This follows from the expressions for T_1 and T_2 in terms of polynomials in T mentioned earlier.

10.9 Some related situations

Let k be a field, and let V be a vector space over k of positive finite dimension. If A and B are linear mappings from V into itself, then put

$$\mathrm{ad}_A(B) = [A, B] = A \circ B - B \circ A, \tag{10.9.1}$$

as before. This defines ad_A as a linear mapping from $\mathcal{L}(V)$ into itself, where $\mathcal{L}(V)$ is the space of linear mappings from V into itself. If A is diagonalizable on V, then ad_A is diagonalizable on $\mathcal{L}(V)$. This can be seen using a basis for V consisting of eigenvectors for A, to reduce to the analogous statement for matrices, as in Section 10.4. Similarly, if A is nilpotent on V, then ad_A is nilpotent on $\mathcal{L}(V)$, as in Section 9.7. Let T, T_1, and T_2 be as in (10.8.1), so that

$$\mathrm{ad}_T = \mathrm{ad}_{T_1} + \mathrm{ad}_{T_2}. \tag{10.9.2}$$

Note that ad_{T_1} is diagonalizable on $\mathcal{L}(V)$, and that ad_{T_2} is nilpotent on $\mathcal{L}(V)$, by the corresponding properties of T_1 and T_2 on V, and the previous remarks. We also have that

$$[\mathrm{ad}_{T_1}, \mathrm{ad}_{T_2}] = \mathrm{ad}_{[T_1,T_2]} = 0, \tag{10.9.3}$$

so that ad_{T_1} and ad_{T_2} commute on $\mathcal{L}(V)$, because T_1 and T_2 commute on V. Thus (10.9.2) is the analogue of (10.8.1) for ad_T, as in Lemma A on p18 of [14]. This also corresponds to Lemma 6.3 on p41 of [25], with $p = q = 1$.

Let A be an algebra over k in the strict sense, where multiplication of $a, b \in A$ is expressed as $a\,b$. Also let δ be a derivation on A. If $a, b \in A$ are eigenvectors of δ with eigenvalues $\lambda, \mu \in k$, respectively, then

$$\delta(a\,b) = \delta(a)\,b + a\,\delta(b) = (\lambda\,a)\,b + a\,(\mu\,b) = (\lambda + \mu)\,(a\,b), \tag{10.9.4}$$

so that $a\,b$ is an eigenvector of A with eigenvalue $\lambda + \mu$ when $a\,b \neq 0$. It follows that the linear span in A of the eigenvectors of δ forms a subalgebra of A. This is stated in Exercise 12 on p6 of [14] for derivations on Lie algebras that come from the adjoint representation.

If $\lambda \in k$, then put

$$\mathcal{E}_\lambda(\delta) = \{a \in A : (\delta - \lambda\,I)^l(a) = 0 \text{ for some } l \in \mathbf{Z}_+\}, \tag{10.9.5}$$

as in Section 10.7, where I is the identity mapping on A. This is a linear subspace of A which is nontrivial exactly when λ is an eigenvalue of δ on A, as before. Let $a, b \in A$ and $\lambda, \mu \in k$ be given, and observe that

$$(10.9.6) \quad \begin{aligned}(\delta - (\lambda + \mu)\, I)(a\, b) &= \delta(a)\, b + a\, \delta(b) - \lambda\, a\, b - \mu\, a\, b \\ &= ((\delta - \lambda\, I)(a))\, b + a\, ((\delta - \mu\, I)(b)).\end{aligned}$$

If $a \in \mathcal{E}_\lambda(\delta)$ and $b \in \mathcal{E}_\mu(\delta)$, then one can use this repeatedly to get that

$$(10.9.7) \qquad (\delta - (\lambda + \mu)\, I)^j(a\, b) = 0$$

when j is sufficiently large, so that $a\, b \in \mathcal{E}_{\lambda+\mu}(\delta)$. If $a\, b \neq 0$, then $\mathcal{E}_{\lambda+\mu}(\delta) \neq \{0\}$, which implies that $\lambda + \mu$ is an eigenvalue of δ, as before.

Suppose that k is algebraically closed, and that A has positive finite dimension as a vector space over k. As in the previous section, there are linear mappings δ_1, δ_2 from A into itself such that

$$(10.9.8) \qquad \delta = \delta_1 + \delta_2,$$

δ_1 is diagonalizable on A, δ_2 is nilpotent on A, and δ_1, δ_2 commute on A. More precisely,

$$(10.9.9) \qquad E_\lambda(\delta_1) = \mathcal{E}_\lambda(\delta)$$

for every $\lambda \in k$, and in particular the eigenvalues of δ and δ_1 are the same. If $a \in E_\lambda(\delta_1) = \mathcal{E}_\lambda(\delta)$ and $b \in E_\mu(\delta_1) = \mathcal{E}_\mu(\delta)$ for some $\lambda, \mu \in k$, then $a\, b$ is an element of $\mathcal{E}_{\lambda+\mu}(\delta) = E_{\lambda+\mu}(\delta_1)$, as in the preceding paragraph. Note that $a\, b$ may be equal to 0, in which case $\lambda + \mu$ need not be an eigenvalue of δ, δ_1. In this situation,

$$(10.9.10) \quad \delta_1(a\, b) = (\lambda + \mu)\, a\, b = (\lambda\, a)\, b + a\, (\mu\, b) = \delta_1(a)\, b + a\, \delta_1(b).$$

One can use this to get that δ_1 is a derivation on A, because A is spanned by the eigenspaces of δ_1. It follows that δ_2 is a derivation on A as well, by (10.9.8). This corresponds to Lemma B on p18-19 of [14].

10.10 Replicas

Let k be a field, let V be a vector space over k of positive finite dimension n, and let A be a diagonalizable linear mapping from V into itself. Thus V corresponds to the direct sum of the nontrivial eigenspaces of A. If ϕ is a k-valued function on the set of eigenvalues of A, then $\phi(A)$ can be defined as a linear mapping from V into itself by putting $\phi(A) = \lambda\, I$ on $E_\lambda(A)$ for each eigenvalue $\lambda \in k$ of A. This corresponds to Definition 6.4 on p41 of [25], but with fewer conditions on ϕ for the moment, as in a remark just after Definition 6.4 in [25]. Note that $\phi(A)$ can be expressed as a polynomial in A with coefficients in k, using a polynomial whose values at the eigenvalues of A are the same as the values of ϕ.

Equivalently, let $v_1, \ldots, v_n$ be a basis of V consisting of eigenvectors of A with eigenvalues $a_1, \ldots, a_n \in k$, so that

$$A(v_j) = a_j\, v_j \tag{10.10.1}$$

for every $j = 1, \ldots, n$. Using this basis, $\phi(A)$ can be characterized by

$$(\phi(A))(v_j) = \phi(a_j)\, v_j \tag{10.10.2}$$

for each $j = 1, \ldots, n$. If $h, m \in \{1, \ldots, n\}$, then let $E_{h,m}$ be the linear mapping from V into itself such that

$$E_{h,m}(v_j) = \delta_{m,j}\, v_h \tag{10.10.3}$$

for every $j = 1, \ldots, n$, where $\delta_{m,j}$ is as in Section 10.1. The $E_{h,m}$'s form a basis for the space $\mathcal{L}(V)$ of linear mappings from V into itself, as a vector space over k. Let ad_A be the linear mapping from $\mathcal{L}(V)$ into itself corresponding to A as in (10.9.1). One can check that

$$\mathrm{ad}_A(E_{h,m}) = (a_h - a_m)\, E_{h,m} \tag{10.10.4}$$

for every $h, m = 1, \ldots, n$, as in (10.4.5). Similarly,

$$\mathrm{ad}_{\phi(A)}(E_{h,m}) = (\phi(a_h) - \phi(a_m))\, E_{h,m} \tag{10.10.5}$$

for every $h, m = 1, \ldots, n$.

Suppose now that ϕ is defined on a subgroup of k, as a commutative group with respect to addition, that contains the eigenvalues of A. Suppose also that ϕ is a group homomorphism from this subgroup of k into k, with respect to addition. Under these conditions, (10.10.5) implies that

$$\mathrm{ad}_{\phi(A)}(E_{h,m}) = \phi(a_h - a_m)\, E_{h,m} \tag{10.10.6}$$

for every $h, m = 1, \ldots, n$. This means that

$$\mathrm{ad}_{\phi(A)} = \phi(\mathrm{ad}_A), \tag{10.10.7}$$

where the right side is obtained from ad_A as a diagonalizable linear mapping from $\mathcal{L}(V)$ into itself in the same way as before. This corresponds to Lemma 6.5 on p41 of [25], with $p = q = 1$, using a remark near the top of p41 in [25].

If 0 is not an eigenvalue of A, then $\phi(A)$ can be expressed as a polynomial in A with coefficients in k and constant term equal to 0, using a polynomial whose values at the eigenvalues of A are the same as the values of ϕ, and whose value at 0 is equal to 0. We can also do this when 0 is an eigenvalue of A, as long as $\phi(0) = 0$. Of course, $\phi(0) = 0$ automatically when ϕ is a homomorphism from an additive subgroup of k into k, as in the preceding paragraph. In this case, we can apply the same argument to (10.10.7) on $\mathcal{L}(V)$, to get that (10.10.7) can be expressed as a polynomial in ad_A with coefficients in k and constant term equal to 0.

If k has characteristic 0, then k may be considered as a vector space over the field $\mathbf{Q}$ rational numbers. In this case, we may consider mappings from the linear span of the set of eigenvalues of A in k, as a vector space over $\mathbf{Q}$, into k that are linear over $\mathbf{Q}$, as in the proof of the lemma on p19 of [14]. In [25], one simply considers mappings ϕ from k into itself that are linear over $\mathbf{Q}$. The corresponding linear mappings $\phi(A)$ are called *replicas* of A by Chevalley, as mentioned on p42 of [25].

10.11 Two lemmas about traces

Let k be an algebraically closed field of characteristic 0, and let V be a vector space over k of positive finite dimension n. Also let T be a linear mapping from V into itself, and let T_1, T_2 be the corresponding linear mappings from V into itself discussed in Section 10.8, so that

$$T = T_1 + T_2, \tag{10.11.1}$$

T_1 is diagonalizable on V, T_2 is nilpotent on V, and T_1, T_2 commute. If ϕ is a mapping from the linear span of the eigenvalues of T_1 in k, as a vector space over $\mathbf{Q}$, into k that is linear over $\mathbf{Q}$, then $\phi(T_1)$ can be defined as a linear mapping from V into itself, as in the previous section. If

$$\mathrm{tr}(T \circ \phi(T_1)) = 0 \tag{10.11.2}$$

for all such ϕ, then $T_1 = 0$, so that $T = T_2$ is nilpotent on V. This corresponds to Lemma 6.7 on p42 of [25], rephrased a bit in the way that it is used in the proof of the lemma on p19 of [14].

Remember that T_2 maps the eigenspaces of T_1 into themselves, because T_1 and T_2 commute. If ϕ is as in the preceding paragraph, then it follows that T_2 commutes with $\phi(T_1)$, by definition of $\phi(T_1)$. In particular, $T_2 \circ \phi(T_1)$ is nilpotent, and

$$\mathrm{tr}(T_2 \circ \phi(T_1)) = 0. \tag{10.11.3}$$

Thus (10.11.2) is the same as saying that

$$\mathrm{tr}(T_1 \circ \phi(T_1)) = 0. \tag{10.11.4}$$

Let $\lambda_1, \ldots, \lambda_l \in k$ be a list of the eigenvalues of T_1, and let $m_1, \ldots, m_l \in \mathbf{Z}_+$ be the dimensions of the corresponding eigenspaces of T_1 in V. Using (10.11.4) we get that

$$\sum_{j=1}^{l} m_j \cdot \lambda_j \, \phi(\lambda_j) = 0, \tag{10.11.5}$$

because $\phi(T_1) = \phi(\lambda_j)\, I$ on $E_{\lambda_j}(T_1)$ for each $j = 1, \ldots, l$, by construction. If we also ask that $\phi(\lambda_j)$ be in the subfield of k corresponding to $\mathbf{Q}$ for each $j = 1, \ldots, l$, then we can apply ϕ to (10.11.5), to obtain that

$$\sum_{j=1}^{l} m_j \cdot \phi(\lambda_j)^2 = 0. \tag{10.11.6}$$

This means that $\phi(\lambda_j) = 0$ for each $j = 1, \ldots, n$, because $\phi(\lambda_j)$ is in the subfield of k corresponding to $\mathbf{Q}$. This implies that 0 is the only eigenvalue of T_1, because the previous statement holds for all mappings ϕ from the linear span of the eigenvalues of T_1 in k as a vector space over $\mathbf{Q}$ into the subfield of k corresponding to $\mathbf{Q}$ that are linear over $\mathbf{Q}$. Thus $T_1 = 0$ on V, because T_1 is diagonalizable on V, by hypothesis, as desired.

If k is the field $\mathbf{C}$ of complex numbers, then a variant of this argument was remarked by Bergman, as mentioned on p42 of [25]. Namely, if (10.11.5) holds with ϕ equal to complex conjugation on $\mathbf{C}$, then

$$\sum_{j=1}^{l} m_j\, |\lambda_j|^2 = 0. \tag{10.11.7}$$

This implies directly that 0 is the only eigenvalue of T_1, as desired.

Let $\mathcal{A}$ and $\mathcal{B}$ be linear subspaces of the space $\mathcal{L}(V)$ of all linear mappings from V into itself, with

$$\mathcal{A} \subseteq \mathcal{B}. \tag{10.11.8}$$

Put

$$\mathcal{M} = \{T \in \mathcal{L}(V) : [T, B] \in \mathcal{A} \text{ for every } B \in \mathcal{B}\}. \tag{10.11.9}$$

If $T \in \mathcal{M}$ satisfies

$$\operatorname{tr}(T \circ R) = 0 \tag{10.11.10}$$

for every $R \in \mathcal{M}$, then T is nilpotent on V. This is the lemma stated on p19 of [14].

Let $T \in \mathcal{M}$ be given, and let $T_1, T_2 \in \mathcal{L}(V)$ be as in (10.11.1) again. Also let ϕ be a mapping from the linear span of the eigenvalues of T_1 in k, as a vector space over $\mathbf{Q}$, into k that is linear over $\mathbf{Q}$, as before. Thus $\phi(T_1)$ can be defined as a linear mapping from V into itself as in the previous section, and we would like to check that

$$\phi(T_1) \in \mathcal{M}. \tag{10.11.11}$$

This means that (10.11.2) follows from (10.11.10), so that we can reduce to the previous statement.

If A is a linear mapping from V into itself, then ad_A denotes the corresponding linear mapping from $\mathcal{L}(V)$ into itself, as in (10.9.1). The condition that $T \in \mathcal{M}$ means exactly that

$$\mathrm{ad}_T(\mathcal{B}) \subseteq \mathcal{A}. \tag{10.11.12}$$

Remember that

$$\mathrm{ad}_T = \mathrm{ad}_{T_1} + \mathrm{ad}_{T_2} \tag{10.11.13}$$

is the analogue of (10.11.1) for ad_T as a linear mapping from $\mathcal{V}$ into itself, as in Section 10.9. This implies that ad_{T_1} can be expressed as a polynomial in ad_T with coefficients in k and constant term equal to 0, as in Section 10.8. It follows from this and (10.11.12) that

$$\mathrm{ad}_{T_1}(\mathcal{B}) \subseteq \mathcal{A}, \tag{10.11.14}$$

so that $T_1 \in \mathcal{M}$.

We also have that

$$\mathrm{ad}_{\phi(T_1)} = \phi(\mathrm{ad}_{T_1}), \tag{10.11.15}$$

as in (10.10.7). Remember that (10.11.15) can be expressed as a polynomial in ad_{T_1} with coefficients in k and constant term equal to 0, as in the previous section. This implies that

$$\mathrm{ad}_{\phi(T_1)}(\mathcal{B}) \subseteq \mathcal{A}, \tag{10.11.16}$$

because of (10.11.14). Thus (10.11.11) holds, as desired.

10.12 Cartan's criterion

Let k be a field of characteristic 0, and let V be a vector space over k of positive finite dimension n. Also let A be a Lie subalgebra of $gl(V)$, and suppose that

$$\mathrm{tr}(T \circ R) = 0 \tag{10.12.1}$$

for every $T \in A$ and $R \in [A, A]$. Under these conditions, A is solvable as a Lie algebra over k. This is part of Theorem 7.1 on p42 of [25]. Note that the converse was discussed in Section 10.5.

Suppose first that k is algebraically closed, which corresponds to the theorem on p20 in [14]. In order to show that A is solvable as a Lie algebra, it suffices to show that $[A, A]$ is nilpotent as a Lie algebra over k. To do this, it is enough to show that every element of $[A, A]$ is nilpotent as a linear mapping on V, as in Section 9.10.

Put

$$\mathcal{M} = \{Z \in gl(V) : [Z, T] \in [A, A] \text{ for every } T \in A\}, \tag{10.12.2}$$

and observe that $A \subseteq \mathcal{M}$. We would like to show that

$$\mathrm{tr}(R \circ Z) = 0 \tag{10.12.3}$$

for every $R \in [A, A]$ and $Z \in \mathcal{M}$. This will imply that every $R \in [A, A]$ is nilpotent as a linear mapping on V, as in the previous section.

In order to get (10.12.3), it is enough to check that

$$\mathrm{tr}(([T_1, T_2]) \circ Z) = 0 \tag{10.12.4}$$

for every $T_1, T_2 \in A$ and $Z \in \mathcal{M}$. Remember that

$$\mathrm{tr}(([T_1, T_2]) \circ Z) = -\,\mathrm{tr}(T_2 \circ ([T_1, Z])), \tag{10.12.5}$$

as in Section 7.8. If $T_1 \in A$ and $Z \in \mathcal{M}$, then $[T_1, Z] \in [A, A]$, by the definition (10.12.2) of $\mathcal{M}$. If we also have that $T_2 \in A$, then it follows that the right side of (10.12.5) is equal to 0, by (10.12.1). This implies (10.12.4), as desired.

Now let k be any field of characteristic 0. We may as well take $V = k^n$, because V is isomorphic to k^n as a vector space over k. The earlier statement can be reformulated in terms of matrices as saying that if A_0 is a Lie subalgebra of $gl_n(k)$ such that

$$\mathrm{tr}(T_0\, R_0) = 0 \tag{10.12.6}$$

for every $T_0 \in A_0$ and $R_0 \in [A_0, A_0]$, then A_0 is solvable as a Lie algebra over k. This uses matrix multiplication and the trace on the space $M_n(k)$ of $n \times n$ matrices with entries in k.

Let k_1 be an algebraically closed field that contains k as a subfield, so that $gl_n(k)$ may be considered as a subset of $gl_n(k_1)$. If A_1 is the linear span of A_0 in $gl_n(k_1)$, as a vector space over k_1, then A_1 is a Lie subalgebra of $gl_n(k_1)$, as a Lie algebra over k_1, as mentioned in Section 10.5. Note that $[A_0, A_0]$ is an ideal in A_0 as a Lie algebra over k, and that $[A_1, A_1]$ is defined analogously as an ideal in A_1, as a Lie algebra over k_1, as in Section 9.2. One can check that $[A_1, A_1]$ is the same as the linear span of $[A_0, A_0]$ in A_1, as a vector space over k_1.

It follows that

$$\mathrm{tr}(T_1\, R_1) = 0 \tag{10.12.7}$$

for every $T_1 \in A_1$ and $R_1 \in [A_1, A_1]$, because of (10.12.6). This uses matrix multiplication and the trace on $M_n(k_1)$. Thus A_1 is solvable as a Lie algebra over k_1, by the earlier argument for algebraically closed fields of characteristic 0. This implies that A_0 is solvable as a Lie algebra over k, as desired.

10.13 Comparing radicals

Let k be a field, and let $(A, [\cdot,\cdot])$ be a Lie algebra over k. If $x \in A$, then $\mathrm{ad}_x = \mathrm{ad}_{A,x}$ is the linear mapping from A into itself defined by

$$\mathrm{ad}_x(z) = \mathrm{ad}_{A,x}(z) = [x, z] \tag{10.13.1}$$

for every $z \in A$, as in Section 2.4. Suppose that A has positive finite dimension as a vector space over k, so that the Killing form

$$\beta(x, y) = \mathrm{tr}_A(\mathrm{ad}_x \circ \mathrm{ad}_y) \tag{10.13.2}$$

is defined as an element of k for every $x, y \in A$. Remember that the radical

$$A^\beta = \{x \in A : \beta(x, y) = 0 \text{ for every } y \in A\} \tag{10.13.3}$$

of (10.13.2) in A is an ideal in A as a Lie algebra over k, as in Section 7.11.

Of course, the space of linear mappings from A into itself, as a vector space over k, is an associative algebra over k with respect to composition of mappings, and hence a Lie algebra over k with respect to the corresponding commutator bracket. Let A_0 be a Lie subalgebra of A. The image

$$\{\mathrm{ad}_x : x \in A_0\} \tag{10.13.4}$$

of A_0 under the adjoint representation of A is a Lie subalgebra of the Lie algebra of all linear mappings from A into itself. Suppose that $\beta(x, y) = 0$ for every

$x \in [A_0, A_0]$ and $y \in A_0$. If k has characteristic 0, then Cartan's criterion implies that (10.13.4) is solvable as a Lie algebra over k. It follows that A_0 is solvable as a Lie algebra over k, because the kernel of the adjoint representation on A is the center of A. This corresponds to the corollary on p20 of [14] when $A_0 = A$.

The radical (10.13.3) of β in A automatically satisfies the conditions on A_0 mentioned in the preceding paragraph. If k has characteristic 0, then we get that A^β is solvable as a Lie algebra over k. Let $\operatorname{Rad} A$ be the solvable radical of A, as in Section 9.4. It follows that

$$A^\beta \subseteq \operatorname{Rad} A \tag{10.13.5}$$

when k has characteristic 0, because A^β is an ideal in A as a Lie algebra.

Remember that A is said to be semisimple as a Lie algebra when $\operatorname{Rad} A = \{0\}$. If A is semisimple and k has characteristic 0, then $A^\beta = \{0\}$, by (10.13.5), which means that the Killing form (10.13.2) on A is nondegenerate. This corresponds to parts of the theorem on p22 of [14] and Theorem 2.1 on p44 of [25].

If B is an ideal in A and B is commutative as a Lie algebra over k, then B is contained in the radical (10.13.3) of β in A, as in Section 7.11. If the Killing form on A is nondegenerate, then it follows that $B = \{0\}$. Remember that A is semisimple as a Lie algebra when $\{0\}$ is the only ideal in A that is commutative as a Lie algebra, as in Section 9.4. This means that A is semisimple as a Lie algebra when the Killing form on A is nondegenerate. This corresponds to the other parts of the theorem on p22 of [14] and Theorem 2.1 on p44 of [25].

10.14 Complementary ideals

Let k be a commutative ring with a multiplicative identity element, and let $(A, [\cdot,\cdot])$ be a Lie algebra over k. Suppose that A is isomorphic to k^r as a module over k for some positive integer r, so that the Killing form β can be defined on A as in (10.13.2). Remember that β has the associativity or invariance property

$$\beta([x, w], y) = \beta(x, [w, y]) \tag{10.14.1}$$

for every $w, x, y \in A$, as in Section 7.11. If B is a submodule of A, as a module over k, then put

$$B^\perp = B^{\perp,\beta} = \{x \in A : \beta(x, y) = 0 \text{ for every } y \in B\}. \tag{10.14.2}$$

This is a submodule of A, as a module over k, which is the same as the radical of β in A when $B = A$. If B is an ideal in A as a Lie algebra over k, then it is easy to see that (10.14.2) is an ideal in A, using (10.14.1). This can also be obtained from statements in Sections 6.10 and 7.7.

Let us suppose from now on in this section that k is a field, and that A has positive finite dimension as a vector space over k. Let B be a linear subspace of A, so that (10.14.2) is a linear subspace of A too, as before. If the Killing form

β is nondegenerate as a bilinear form on A, then the sum of the dimensions of B and $B^\perp$ is equal to the dimension of A, by standard arguments.

Now let B be an ideal in A as a Lie algebra over k, so that (10.14.2) is an ideal in A too, as before. Thus

$$A_0 = B \cap B^\perp \tag{10.14.3}$$

is an ideal in A as well, and $\beta(x, y) = 0$ for every $x, y \in A_0$, by construction. If k has characteristic 0, then it follows that A_0 is solvable as a Lie algebra over k, as in the previous section. If A is semisimple as a Lie algebra over k, then we get that $A_0 = \{0\}$. This implies that

$$[x, y] = 0 \tag{10.14.4}$$

for every $x \in B$ and $y \in B^\perp$, because $[x, y] \in B \cap B^\perp$.

If k has characteristic 0 and A is semisimple as a Lie algebra over k, then the Killing form β is nondegenerate on A, as in the previous section. Under these conditions, we have that

$$B + B^\perp = \{x + y : x \in B, y \in B^\perp\} = A. \tag{10.14.5}$$

More precisely, the dimension of $B + B^\perp$ is equal to the sum of the dimensions of B and $B^\perp$, because $B \cap B^\perp = \{0\}$, as in the preceding paragraph. We have also seen that the sum of the dimensions of B and $B^\perp$ is equal to the dimension of A, because β is nondegenerate on A. This implies (10.14.5), and hence that A is isomorphic to the direct sum of B and $B^\perp$ as a Lie algebra over k, because of (10.14.4).

This corresponds to the first step in the proof of the theorem on p23 in [14], and to Theorem 2.2 on p44 of [25]. Note that ideals in B and $B^\perp$ are ideals in A in this situation, because of (10.14.4) and (10.14.5). This implies that B and $B^\perp$ are semisimple as Lie algebras over k, because A is semisimple. It follows that A/B is semisimple as a Lie algebra over k, because it is isomorphic to $B^\perp$.

10.15 Simple Lie algebras

Let k be a field. A Lie algebra $(A, [\cdot, \cdot])$ over k is said to be *simple* if A is not commutative as a Lie algebra, and if the only ideals in A are A itself and $\{0\}$. See p6 of [14], and Definition 2.3 on p44 of [25]. Note that the trivial Lie algebra $\{0\}$ is not considered to be simple, nor is the one-dimensional Lie algebra k with respect to the trivial Lie bracket. If A is a simple Lie algebra over k, then the center $Z(A)$ of A as a Lie algebra is trivial, because $Z(A)$ is an ideal in A, and A is not commutative as a Lie algebra. Similarly, if A is simple and $[A, A]$ is as in Section 9.2, then $[A, A] = A$, because $[A, A]$ is an ideal in A, and A is not commutative. In particular, this means that A is not solvable as a Lie algebra, and in fact that A is semisimple as a Lie algebra.

Let $(A, [\cdot, \cdot])$ be a Lie algebra over A again, and let $A_1, \ldots, A_n$ be finitely many ideals in A. Suppose that every element of A can be expressed in a unique way as the sum of elements of $A_1, \ldots, A_n$, so that A corresponds to the direct sum of $A_1, \ldots, A_n$, as a vector space over k. Let $j, l \in \{1, \ldots, n\}$ be given, with $j \neq l$, so that $A_j \cap A_l = \{0\}$. If $a_j \in A_j$ and $a_l \in A_l$, then $[a_j, a_l] \in A_j \cap A_l$, because A_j and A_l are ideals in A. This implies that

$$[a_j, a_l] = 0, \tag{10.15.1}$$

because $A_j \cap A_l = \{0\}$. This means that A corresponds to the direct sum of $A_1, \ldots, A_n$ as a Lie algebra over k, as remarked on p22 of [14]. Note that ideals in any A_j as a Lie algebra over k are ideals in A, because of (10.15.1).

Suppose from now on in this section that k has characteristic 0, and that A is a semisimple Lie algebra over k with positive finite dimension as a vector space over k. Under these conditions, there are finitely many ideals $A_1, \ldots, A_n$ in A such that A corresponds to the direct sum of the A_j's, as in the preceding paragraph, and A_j is simple as a Lie algebra over k for each $j = 1, \ldots, n$. Of course, if A is already simple as a Lie algebra over k, then this holds with $n = 1$. Otherwise, A corresponds to the direct sum of two proper ideals, each of which is semisimple as a Lie algebra over k, as in the previous section. One can repeat the process as needed until all of the ideals are simple as Lie algebras over k. At each step, any ideal in any of the ideals already obtained in A is an ideal in A too, as in the previous paragraph. This corresponds to the first part of the first theorem on p23 of [14], and to Corollary 1 on p45 of [25].

Remember that $[A_j, A_j] = A_j$ for each $j = 1, \ldots, n$, because the A_j's are simple Lie algebras. This implies that $[A, A] = A$, as in the corollary on p32 in [14], and Corollary 2 on p45 of [25].

Let C be a simple Lie algebra over k, and suppose that ϕ is a Lie algebra homomorphism from A onto C. Note that $\phi(A_j)$ is an ideal in C for each $j = 1, \ldots, n$, because A_j is an ideal in A and $\phi(A) = C$. It follows that for each $j = 1, \ldots, n$, $\phi(A_j)$ is either trivial or equal to C, because C is simple. Clearly $\phi(A_{j_1}) \neq \{0\}$ for some $j_1 \in \{1, \ldots, n\}$, because $\phi(A) = C$. This can happen for at most one element of $\{1, \ldots, n\}$, by (10.15.1) and the noncommutativity of C. The restriction of ϕ to A_{j_1} is injective, because A_{j_1} is simple as a Lie algebra over k. This is the uniqueness property discussed on p45 of [25].

Let B_0 be a simple ideal in A. Note that the center $Z(A)$ of A is trivial, because A is semisimple. This implies that $[A, B_0] \neq \{0\}$, because $B_0 \neq \{0\}$. It follows that $[A_{j_0}, B_0] \neq \{0\}$ for some $j_0 \in \{1, \ldots, n\}$. Remember that $[A_{j_0}, B_0]$ is an ideal in A that is contained in A_{j_0} and B_0, because A_{j_0} and B_0 are ideals in A, as in Section 9.2. Thus $A_{j_0} = [A_{j_0}, B_0] = B_0$, because A_{j_0} and B_0 are simple. This is the uniqueness part of the first theorem on p23 of [14]. See also Theorem 4' on p6 of [24].

If B is a nontrivial proper ideal in A, then one can start the process for expressing A as a direct sum of simple ideals using B, as before. Thus B is also expressed as a direct sum of some of these ideals, as in the corollary on p23 of [14], and Corollary 3 on p45 of [25].

Chapter 11

Some examples and related properties

11.1 Simplicity and solvability

Let k be a field, and remember that $x = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}$, $y = \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix}$, and $h = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$ form a basis for $sl_2(k)$, as a vector space over k. We also have that $[x, y] = h$, $[h, x] = 2 \cdot x$, and $[h, y] = -2 \cdot y$, as in Section 10.2. It is not difficult to check directly that $sl_2(k)$ is simple as a Lie algebra over k when the characteristic of k is different from 2, as on p6-7 of [14]. More precisely, suppose that A is a nonzero ideal in $sl_2(k)$. Let

$$a\,x + b\,y + c\,h \tag{11.1.1}$$

be a nonzero element of A, where $a, b, c \in k$. One can take the commutator of (11.1.1) with x twice to get that $-2 \cdot b\,x \in A$, and similarly one can take the commutator of (11.1.1) with y twice to get that $-2 \cdot a\,y \in A$. This implies that $x \in A$ when $b \neq 0$, and that $y \in A$ when $a \neq 0$, because the characteristic of A is not 2. Otherwise, if $a = b = 0$, then $c \neq 0$, and it follows that $h \in A$. Thus A contains at least one of x, y, or h. One can use this to get that A contains each of x, y, and h, because the characteristic of k is not 2. This means that $A = sl_2(k)$, as desired.

Let k be any field, and let $(A, [\cdot, \cdot]_A)$ be a Lie algebra over k. Suppose that the dimension of A is 3, as a vector space over k, and that $[A, A] = A$, where $[A, A]$ is as in Section 9.2. Under these conditions, A is simple as a Lie algebra over k, as in Exercise 5 on p10 of [14]. To see this, let A_0 be an ideal in A, so that the quotient A/A_0 is a Lie algebra over k too. It is easy to see that

$$[A/A_0, A/A_0] = A/A_0 \tag{11.1.2}$$

in this situation, as in Section 9.3. However, if A/A_0 has dimension 1 as a vector space over k, then the left side of (11.1.2) is $\{0\}$. Similarly, if A/A_0 has dimension 2 as a vector space over k, then the left side of (11.1.2) has dimension less than or equal to 1. It follows that A/A_0 has dimension 0 or 3, which is to say that $A_0 = \{0\}$ or A, as desired.

Let k be a commutative ring with a multiplicative identity element, and let $(A, [\cdot, \cdot]_A)$ be a Lie algebra over k again. Suppose that the derived subalgebra $A^{(1)} = [A, A]$ is generated by two elements a, b as a module over k, so that every element of $A^{(1)}$ can be expressed as a linear combination of a and b, with coefficients in k. This implies that $A^{(2)} = [A^{(1)}, A^{(1)}]$ consists of multiples of $[a, b]_A$, with coefficients in k. It follows that $A^{(3)} = \{0\}$, so that A is solvable as a Lie algebra. Of course, if $A^{(1)}$ consists of the multiples of a single element of A with coefficients in k, then $A^{(2)} = \{0\}$.

Suppose that k is a field, and that A has dimension 3 as a vector space over k. If $[A, A]$ is a proper subset of A, then $[A, A]$ has dimension less than or equal to 2, as a vector space over k. This implies that A is solvable as a Lie algebra, as in the preceding paragraph.

11.2 Traces on $M_n(k)$

Let k be a commutative ring with a multiplicative identity element, and let n be a positive integer. Remember that the space $M_n(k)$ of $n \times n$ matrices with entries in k is an associative algebra over k with respect to matrix multiplication, as in Section 2.8. If $a, x \in M_n(k)$, then

$$L_a(x) = a\,x \tag{11.2.1}$$

is defined as an element of $M_n(k)$ using matrix multiplication. This defines L_a as a homomorphism from $M_n(k)$ into itself, as a module over k. If $b \in M_n(k)$ too, then

$$L_a \circ L_b = L_{a\,b}, \tag{11.2.2}$$

as in Section 2.8. It is not difficult to see that

$$\mathrm{tr}_{M_n(k)} L_a = n \cdot \mathrm{tr}\, a \tag{11.2.3}$$

for every $a \in M_n(k)$, where $\mathrm{tr}\, a$ is the ordinary trace of a, as an $n \times n$ matrix with entries in k. The left side of (11.2.3) is the trace of L_a as a module homomorphism from $M_n(k)$ into itself, as in Section 7.8. More precisely, the definition of $\mathrm{tr}_{M_n(k)}$ uses the fact that $M_n(k)$ is isomorphic to k^{n^2}, as a module over k. It follows that

$$\mathrm{tr}_{M_n(k)}(L_a \circ L_b) = \mathrm{tr}_{M_n(k)} L_{a\,b} = n \cdot \mathrm{tr}(a\,b) \tag{11.2.4}$$

for every $a, b \in M_n(k)$, using (11.2.2) in the first step.

Similarly, if $a \in M_n(k)$, then

$$R_a(x) = x\,a \tag{11.2.5}$$

defines R_a as a module homomorphism from $M_n(k)$ into itself. If $b \in M_n(k)$ too, then

$$R_a \circ R_b = R_{b\,a}, \tag{11.2.6}$$

as in Section 2.7. One can check that

$$\mathrm{tr}_{M_n(k)} R_a = n \cdot \mathrm{tr}\, a \tag{11.2.7}$$

for every $a \in M_n(k)$. This implies that

$$\mathrm{tr}_{M_n(k)}(R_a \circ R_b) = \mathrm{tr}_{M_n(k)}(R_{b\,a}) = n \cdot \mathrm{tr}(b\,a) = n \cdot \mathrm{tr}(a\,b) \tag{11.2.8}$$

for every $a, b \in M_n(k)$, using (11.2.6) in the first step.

Remember that L_a and R_b commute with each other on $M_n(k)$ for every $a, b \in M_n(k)$, as in Section 2.7. One can verify that

$$\mathrm{tr}_{M_n(k)}(L_a \circ R_b) = (\mathrm{tr}\, a)\,(\mathrm{tr}\, b) \tag{11.2.9}$$

for every $a, b \in M_n(k)$.

If $a \in M_n(k)$, then

$$\mathrm{ad}_a(x) = [a, x] = a\,x - x\,a = L_a(x) - R_a(x) \tag{11.2.10}$$

defines a module homomorphism from $M_n(k)$ into itself, as usual. Equivalently,

$$\mathrm{ad}_a = L_a - R_a. \tag{11.2.11}$$

If $b \in M_n(k)$ too, then

$$\begin{aligned} \mathrm{ad}_a \circ \mathrm{ad}_b &= (L_a - R_a) \circ (L_b - R_b) \\ &= L_a \circ L_b - L_a \circ R_b - L_b \circ R_a + R_a \circ R_b \\ &= L_{a\,b} - L_a \circ R_b - L_b \circ R_a + R_{b\,a}. \end{aligned} \tag{11.2.12}$$

It follows that

$$\begin{aligned} \mathrm{tr}_{M_n(k)}(\mathrm{ad}_a \circ \mathrm{ad}_b) &= \mathrm{tr}_{M_n(k)} L_{a\,b} - \mathrm{tr}_{M_n(k)}(L_a \circ R_b) \\ &\quad - \mathrm{tr}_{M_n(k)}(L_b \circ R_a) + \mathrm{tr}_{M_n(k)} R_{b\,a} \\ &= n \cdot \mathrm{tr}(a\,b) - 2 \cdot (\mathrm{tr}\, a)\,(\mathrm{tr}\, b) + n \cdot \mathrm{tr}(b\,a) \\ &= 2\,n \cdot \mathrm{tr}(a\,b) - 2 \cdot (\mathrm{tr}\, a)\,(\mathrm{tr}\, b). \end{aligned} \tag{11.2.13}$$

Note that the right side is automatically equal to 0 when either a or b is a multiple of the identity matrix.

Of course, $gl_n(k)$ is the same as $M_n(k)$ as a module over k, so that traces over $gl_n(k)$ are the same as traces over $M_n(k)$. If $a \in sl_n(k)$, then let $\mathrm{ad}_{sl_n(k),a}$ be the mapping from $sl_n(k)$ into itself defined in the usual way, which is the same as the restriction of ad_a to $sl_n(k)$. Remember that $sl_n(k)$ is isomorphic to k^{n^2-1} as a module over k, and that $gl_n(k)$ is isomorphic to the direct sum of $sl_n(k)$ and k, as modules over k, as in Section 10.3. If $a, b \in sl_n(k)$, then we have that

$$\mathrm{tr}_{sl_n(k)}(\mathrm{ad}_{sl_n(k),a} \circ \mathrm{ad}_{sl_n(k),b}) = \mathrm{tr}_{M_n(k)}(\mathrm{ad}_a \circ \mathrm{ad}_b), \tag{11.2.14}$$

as in Section 7.10. This implies that

$$\mathrm{tr}_{sl_n(k)}(\mathrm{ad}_{sl_n(k),a} \circ \mathrm{ad}_{sl_n(k),b}) = 2\,n \cdot \mathrm{tr}(a\,b), \tag{11.2.15}$$

by (11.2.13).

11.3 A nice criterion

Let k be a commutative ring with a multiplicative identity element, and let $(A, [\cdot, \cdot]_A)$ be a Lie algebra over k. Of course, the center $Z(A)$ of A as a Lie algebra is a solvable ideal in A. If every solvable ideal in A is contained in $Z(A)$, then A is said to be *reductive* as a Lie algebra over k, as in Exercise 5 on p30 and p102 of [14]. This means that the solvable radical $\operatorname{Rad} A$ of A is equal to $Z(A)$, as in Section 9.4. In particular, this holds when A is commutative or semisimple as a Lie algebra.

Now let k be an algebraically closed field of characteristic 0, and let V be a vector space over k of positive finite dimension. Also let A be a Lie subsalgebra of the Lie algebra $gl(V)$ of linear mappings from V into itself. Thus V may be considered as a module over A, as a Lie algebra over k. Suppose that V is irreducible as a module over A. Under these conditions, A is reductive as a Lie algebra over k, and every element of the center $Z(A)$ of A is a scalar multiple of the identity mapping $I = I_V$ on V. In particular, the dimension of $Z(A)$ as a vector space over k is less than or equal to 1. If $A \subseteq sl(V)$, then A is semisimple as a Lie algebra over k. This corresponds to part (b) of the proposition on p102 of [14], and is related to Theorem 5.1 on p50 of [25].

Remember that the solvable radical $\operatorname{Rad} A$ of A is the maximal solvable ideal in A, as in Section 9.4. Lie's theorem implies that there is a $v_0 \in V$ such that $v_0 \neq 0$ and v_0 is an eigenvector of every element of $\operatorname{Rad} A$, as in Section 9.13. This means that there is a linear functional λ on $\operatorname{Rad} A$ such that

$$T(v_0) = \lambda(T)\, v_0 \tag{11.3.1}$$

for every $T \in \operatorname{Rad} A$.

If $R \in A$ and $T \in \operatorname{Rad} A$, then $[R, T] = R \circ T - T \circ R \in \operatorname{Rad} A$, because $\operatorname{Rad} A$ is an ideal in A. Under these conditions,

$$\lambda([R, T]) = 0, \tag{11.3.2}$$

as in Section 9.12.

Put

$$V_\lambda = \{v \in V : T(v) = \lambda(T)\, v \quad \text{for every } T \in \operatorname{Rad} A\}. \tag{11.3.3}$$

This is a linear subspace of V that contains v_0. Let $R \in A$, $T \in \operatorname{Rad} A$, and $v \in V_\lambda$ be given, and observe that

$$\begin{aligned} T(R(v)) = R(T(v)) - ([R, T])(v) &= R(\lambda(T)\, v) - \lambda([R, T])\, v \\ &= \lambda(T)\, R(v). \end{aligned} \tag{11.3.4}$$

This uses the fact that $[R, T] \in \operatorname{Rad} A$ in the second step, and (11.3.2) in the third step. It follows that $R(v) \in V_\lambda$, so that $R(V_\lambda) \subseteq V_\lambda$.

Because V is irreducible as a module over A, we get that $V_\lambda = V$. This means that every $T \in \operatorname{Rad} A$ is equal to $\lambda(T)\, I$. In particular, $\operatorname{Rad} A \subseteq Z(A)$, which implies that $\operatorname{Rad} A = Z(A)$, as desired.

A basic property of reductive Lie algebras will be discussed in Section 13.9.

11.4 Ideals and structure constants

Let k be a commutative ring with a multiplicative identity element, and let n be a positive integer. Thus the space k^n of n-tuples of elements of k is a (free) module over k with respect to coordinatewise addition and scalar multiplication. Let $c_{j,l}^r$ be an element of k for every $j, l, r = 1, \ldots, n$. If $x, y \in k^n$, then let $[x, y]_{k^n}$ be the element of k^n whose rth coordinate is given by

$$([x, y]_{k^n})_r = \sum_{j=1}^{n} \sum_{l=1}^{n} c_{j,l}^r x_j \, y_l \tag{11.4.1}$$

for every $r = 1, \ldots, n$. This defines a mapping from $k^n \times k^n$ into k^n that is bilinear over k. Suppose that

$$c_{j,l}^r = -c_{l,j}^r \quad \text{and} \quad c_{j,j}^r = 0 \tag{11.4.2}$$

for every $j, l, r = 1, \ldots, n$, so that $[x, x]_{k^n} = 0$ for every $x \in k^n$. Suppose also that the $c_{j,l}^r$'s satisfy (9.14.8), so that (11.4.1) satisfies the Jacobi identity, as before. This means that k^n is a Lie algebra over k with respect to (11.4.1).

Let $m < n$ be a positive integer, and let us use $k^m \times \{0\}$ to denote the space of $x \in k^n$ such that $x_j = 0$ when $j \geq m+1$. Suppose that for every $r = 1, \ldots, n$,

$$c_{j,l}^r = 0 \quad \text{when } j \geq m+1 \text{ or } l \geq m+1. \tag{11.4.3}$$

This implies that $k^m \times \{0\}$ is an ideal in k^n, as a Lie algebra over k with respect to (11.4.1). Note that this condition is necessary for $k^m \times \{0\}$ to be an ideal in k^n with respect to (11.4.1).

Let K be a commutative associative algebra over k, and note that the space K^n of n-tuples of elements of K may be considered as a module over k with respect to coordinatewise addition and scalar multiplication. If $a, a' \in K^n$, then let $[a, a']_{K^n}$ be the element of K^n whose rth coordinate is equal to

$$([a, a']_{K^n})_r = \sum_{j=1}^{n} \sum_{l=1}^{n} c_{j,l}^r \, a_j \, a'_l \tag{11.4.4}$$

for each $r = 1, \ldots, n$. As in Section 9.14, K^n is a Lie algebra over k with respect to (11.4.4). We also have that $K^m \times \{0\}$ is an ideal in K^n with respect to (11.4.4), because of (11.4.3). If $k^m \times \{0\}$ is solvable as a Lie algebra over k, then $K^m \times \{0\}$ is solvable as a Lie algebra over k too, as before.

Suppose that K has a multiplicative identity element e, so that K^n may be considered as a module over K, and as a Lie algebra over K with respect to (11.4.4). Remember that $t \mapsto t\,e$ defines a ring homomorphism from k into K, which leads to a homomorphism from k^n into K^n, as Lie algebras over k. If $t \mapsto t\,e$ is injective as a mapping from k into K, then the corresponding mapping from k^n into K^n is injective.

Now let k be a field, and let $(A, [\cdot, \cdot]_A)$ be a Lie algebra over k of positive finite dimension n, as a vector space over k. Any choice of basis for A, as a vector space over k, leads to an isomorphism between A and k^n, as vector spaces over k. As in Section 9.14, there are structure constants $c^r_{j,l} \in k$ such that (11.4.1) corresponds to $[\cdot, \cdot]_A$ with respect to this isomorphism.

Let K be a field that contains k as a subfield. Using the structure constants $c^r_{j,l}$ just mentioned, K^n becomes a Lie algebra over K with respect to (11.4.4). Any other choice of basis for A will lead to isomorphic Lie algebra structures on k^n and K^n.

Suppose that A_0 is a proper nonzero ideal in A, of dimension m. We can choose a basis for A that contains a basis for A_0, so that A_0 corresponds to $k^m \times \{0\}$ in k^n. If A_0 is solvable as a Lie algebra over k, then $k^m \times \{0\}$ is solvable as a Lie algebra over k, and $K^m \times \{0\}$ is solvable as a Lie algebra over K.

If K^n is semisimple as a Lie algebra over K, then it follows that A is semisimple as a Lie algebra over k. Similarly, if K^n is simple as a Lie algebra over K, then A is simple as a Lie algebra over k. This corresponds to part of Theorem 9 on p9 of [24] and the remark following it when $k = \mathbf{R}$ and $K = \mathbf{C}$.

11.5 Nondegeneracy and bilinear forms

Let k be a field, and let V be a vector space over k of finite positive dimension n. If $v_1, \ldots, v_n$ is a basis for V and $l \in \{1, \ldots, n\}$, then there is a unique linear functional λ_l on V such that $\lambda_l(v_j)$ is equal to 1 when $j = l$ and to 0 when $j \neq l$. If μ is any linear functional on V, then it is easy to see that

$$\mu = \sum_{l=1}^{n} \mu(v_l)\, \lambda_l. \tag{11.5.1}$$

In fact, $\lambda_1, \ldots, \lambda_n$ forms a basis for the dual space V' of all linear functionals on V, as a vector space over k.

Let β be a bilinear form on V, so that

$$\beta_w(v) = \beta(v, w) \tag{11.5.2}$$

is a linear functional on V for each $w \in W$. Observe that

$$\beta_{v_l} = \sum_{j=1}^{n} \beta_{v_l}(v_j)\, \lambda_j = \sum_{j=1}^{n} \beta(v_j, v_l)\, \lambda_j \tag{11.5.3}$$

for each $l = 1, \ldots, n$, using (11.5.1) in the first step. Of course, $w \mapsto \beta_w$ defines a linear mapping from V into V', and (11.5.3) expresses this linear mapping in terms of a matrix. In particular, β is nondegenerate as a bilinear form on V if and only if $(\beta(v_j, v_l))$ is invertible as an $n \times n$ matrix with entries in k.

Now let $(A, [\cdot, \cdot]_A)$ be a Lie algebra over k with finite positive dimension n as a vector space over k. Using a basis for A, we get an isomorphism between A and k^n, as vector spaces over k. As before, there are structure constants $c^r_{j,l} \in k$ for $j, l, r = 1, \ldots, n$ that satisfy (11.4.2) and (9.14.8) such that (11.4.1) corresponds to $[\cdot,\cdot]_A$ with respect to the isomorphism just mentioned. If $x \in k^n$, then

$$\mathrm{ad}_{k^n,x}(z) = [x,z]_{k^n} \tag{11.5.4}$$

defines a linear mapping from k^n into itself, as in Section 2.4. The Killing form on k^n is defined by

$$b_{k^n}(x,y) = \mathrm{tr}_{k^n}(\mathrm{ad}_{k^n,x} \circ \mathrm{ad}_{k^n,y}) \tag{11.5.5}$$

for every $x, y \in k^n$, as in Section 7.9.

Let K be a field that contains k as a subfield, so that K^n becomes a Lie algebra over K with respect to (11.4.4). As before,

$$\mathrm{ad}_{K^n,x} = [x,z]_{K^n} \tag{11.5.6}$$

defines a linear mapping from K^n into itself for each $x \in K^n$, and the Killing form on K^n is defined by

$$b_{K^n}(x,y) = \mathrm{tr}_{K^n}(\mathrm{ad}_{K^n,x} \circ \mathrm{ad}_{K^n,y}) \tag{11.5.7}$$

for every $x, y \in K^n$. If $x \in k^n$, then (11.5.4) and (11.5.6) are the same on k^n, because (11.4.1) and (11.4.4) are the same on k^n. This implies that (11.5.5) and (11.5.7) are the same when $x, y \in k^n$.

Let $u_1, \ldots, u_n$ be the standard basis elements of k^n, so that the jth coordinate of u_l is equal to 1 when $j = l$ and to 0 when $j \neq l$. Note that $u_1, \ldots, u_n$ form a basis for K^n as well, as a vector space over K. As in the preceding paragraph,

$$b_{k^n}(u_j, u_l) = b_{K^n}(u_j, u_l) \tag{11.5.8}$$

for every $j, l = 1, \ldots, n$. It follows that (11.5.5) is nondegenerate as a bilinear form on k^n if and only if (11.5.7) is nondegenerate as a bilinear form on K^n. More precisely, this happens exactly when the determinant of (11.5.8), as an $n \times n$ matrix with entries in k, is not 0. Remember that nondegeneracy of the Killing form is equivalent to semisimplicity of a finite-dimensional Lie algebra over a field of characteristic 0, as in Section 10.13. If k has characteristic 0, then K has characteristic 0, and we get that k^n is semisimple as a Lie algebra over k if and only if K^n is semisimple as a Lie algebra over K. This corresponds to part of Theorem 9 on p9 of [24] when $k = \mathbf{R}$ and $K = \mathbf{C}$.

11.6 Bilinear forms and adjoints

Let k be a commutative ring with a multiplicative identity element, and let n be a positive integer. The space k^n of n-tuples of elements of k is a module over k with respect to coordinatewise addition and scalar multiplication, as usual. Let $\beta(\cdot,\cdot)$ be a bilinear form on k^n, which is to say a mapping from $k^n \times k^n$ into k that is bilinear over k. Remember that there is a unique $n \times n$ matrix $(\beta_{j,l})$ with entries in k such that

$$\beta(x,y) = \sum_{j=1}^{n} \sum_{l=1}^{n} \beta_{j,l}\, x_j\, y_l \tag{11.6.1}$$

for every $x, y \in k^n$, as in Section 3.12. It is easy to see that $\beta(\cdot,\cdot)$ is symmetric or antisymmetric as a bilinear form on k^n if and only if $(\beta_{j,l})$ is symmetric or antisymmetric as a matrix, respectively, as before. Similarly, $\beta(x,x) = 0$ for every $x \in k^n$ if and only if $(\beta_{j,l})$ is antisymmetric and $\beta_{j,j} = 0$ for every $j = 1, \ldots, n$. If $1+1$ has a multiplicative inverse in k, then this is equivalent to the antisymmetry of $\beta(\cdot,\cdot)$ or $(\beta_{j,l})$.

Remember that $M_n(k)$ is the space of $n \times n$ matrices with entries in k, which is an associative algebra over k with respect to matrix multiplication. If $a \in M_n(k)$, then a^t denotes the transpose of a, as usual. Let us also use β to denote $(\beta_{j,l})$ as an element of $M_n(k)$, and let us suppose for the rest of the section that β is invertible in $M_n(k)$. Put

$$a^* = (\beta^{-1}\, a\, \beta)^t = \beta^t\, a^t\, (\beta^t)^{-1} \tag{11.6.2}$$

for each $a \in M_n(k)$. It is easy to see that $a \mapsto a^*$ defines an opposite algebra automorphism on $M_n(k)$, because of the same property of $a \mapsto a^t$.

If $a = (a_{j,l}) \in M_n(k)$, then

$$(T_a(x))_j = \sum_{l=1}^n a_{j,l}\, x_l \tag{11.6.3}$$

defines a module homomorphism T_a from k^n into itself, as before. Remember that $a \mapsto T_a$ defines an isomorphism from the space $M_n(k)$ of $n \times n$ matrices with entries in k onto the space of module homomorphisms from k^n into itself, as algebras over k. By construction,

$$\beta(T_a(x), y) = \beta(x, T_{a^*}(y)) \tag{11.6.4}$$

for every $a \in M_n(k)$ and $x, y \in k^n$, as in Section 3.12. More precisely, a^* is uniquely determined by this property, and we may call $(T_a)^* = T_{a^*}$ the *adjoint* of T_a with respect to β. This defines an opposite algebra automorphism on the space of module homomorphisms from k^n into itself.

Observe that

$$\begin{aligned}(a^*)^* = \beta^t\, (a^*)^t\, (\beta^t)^{-1} &= \beta^t\, (\beta^t\, a^t\, (\beta^t)^{-1})^t\, (\beta^t)^{-1} \\ &= \beta^t\, ((\beta)^t)^{-1})^t\, (a^t)^t\, (\beta^t)^t\, (\beta^t)^{-1} \\ &= \beta^t\, \beta^{-1}\, a\, \beta\, (\beta^t)^{-1}\end{aligned} \tag{11.6.5}$$

for every $a \in M_n(k)$. If β is either symmetric or antisymmetric, then we get that

$$(a^*)^* = a \tag{11.6.6}$$

for every $a \in M_n(k)$, and (11.6.2) is the same as

$$a^* = \beta\, a^t\, \beta^{-1}. \tag{11.6.7}$$

Thus $a \mapsto a^*$ defines an algebra involution on $M_n(k)$ in each of these two cases. Equivalently, $T \mapsto T^*$ is an algebra involution on the space of module homomorphisms from k^n into itself in both cases. This may be considered as an instance of a remark in Section 3.14 as well.

11.7 Bilinear forms and symmetry conditions

Let us continue with the same notation and hypotheses as in the previous section, so that $\beta = (\beta_{j,l})$ is an invertible element of $M_n(k)$, and $\beta(\cdot,\cdot)$ is the corresponding bilinear form on k^n, as in (11.6.1). Remember that $a \in M_n(k)$ is invertible exactly when the determinant $\det a$ of a is invertible in k, and that the determinant of the transpose of a is the same as $\det a$. If a is antisymmetric, then

$$\det a = \det a^t = \det(-a) = (-1)^n \det a. \tag{11.7.1}$$

If a is invertible too, then it follows that $(-1)^n = 1$ in k. This implies that $-1 = 1$ in k when n is odd.

Let $a \in M_n(k)$ be given, and let T_a be the corresponding module homomorphism from k^n into itself, as in (11.6.3). Observe that

$$\beta(T_a(x), y) \tag{11.7.2}$$

defines another bilinear form on k^n. One can check that every bilinear form on k^n corresponds to a unique $a \in M_n(k)$ in this way, because β is supposed to be invertible. This defines an isomorphism between $M_n(k)$ and the space of bilinear forms on k^n, as modules over k. Equivalently, this defines an isomorphism between the space of module homomorphisms from k^n into itself and the space of bilinear forms on k^n, as modules over k.

Remember that T_a is said to be symmetric with respect to β when

$$\beta(T_a(x), y) = \beta(x, T_a(y)) \tag{11.7.3}$$

for every $x, y \in k^n$. This is equivalent to asking that a be self-adjoint with respect to (11.6.2), which is to say that $a^* = a$. If $\beta(\cdot,\cdot)$ is symmetric as a bilinear form on k^n, then (11.7.3) holds if and only if

$$\beta(T_a(x), y) = \beta(T_a(y), x) \tag{11.7.4}$$

for every $x, y \in k^n$, which means that (11.7.2) is symmetric as a bilinear form on k^n. If $\beta(\cdot,\cdot)$ is antisymmetric as a bilinear form on k^n, then (11.7.3) holds if and only if

$$\beta(T_a(x), y) = -\beta(T_a(y), x) \tag{11.7.5}$$

for every $x, y \in k^n$, which means that (11.7.2) is antisymmetric as a bilinear form on k^n.

Similarly, T_a is antisymmetric with respect to β when

$$\beta(T_a(x), y) = -\beta(x, T_a(y)) \tag{11.7.6}$$

for every $x, y \in k^n$. This is equivalent to asking that a be anti-self-adjoint with respect to (11.6.2), so that $a^* = -a$. If $\beta(\cdot,\cdot)$ is symmetric as a bilinear form on k^n, then (11.7.6) holds if and only if (11.7.5) holds, so that (11.7.2) is antisymmetric as a bilinear form on k^n. If $\beta(\cdot,\cdot)$ is antisymmetric as a bilinear form on k^n, then (11.7.6) holds if and only if (11.7.4) holds, so that (11.7.2) is symmetric as a bilinear form on k^n.

Of course, if $\gamma = (\gamma_{j,l}) \in M_n(k)$, then

$$\gamma(x, y) = \sum_{j=1}^{n} \sum_{l=1}^{n} \gamma_{j,l} \, x_j \, y_l \tag{11.7.7}$$

defines a bilinear form on k^n. As usual, $\gamma(\cdot, \cdot)$ is symmetric or antisymmetric as a bilinear form on k^n exactly when γ is symmetric or antisymmetric as a matrix, respectively. Note that (11.7.2) corresponds to (11.7.7) with

$$\gamma = \beta \, a. \tag{11.7.8}$$

Thus (11.7.2) is symmetric or antisymmetric as a bilinear form on k^n exactly when (11.7.8) is symmetric or antisymmetric as a matrix, respectively.

11.8 Traces and involutions

Let k be a commutative ring with a multiplicative identity element, and let n be a positive integer. Also let $a \mapsto a^*$ be an algebra involution on the algebra $M_n(k)$ of $n \times n$ matrices with entries in k. Suppose that

$$\operatorname{tr} a^* = \operatorname{tr} a \tag{11.8.1}$$

for every $a \in M_n(k)$ too, where $\operatorname{tr} a \in k$ is the usual trace of a. Note that this condition holds automatically when a^* is as in (11.6.2). Remember that $a \mapsto a^*$ is an involution on $M_n(k)$ in that situation when β is symmetric or antisymmetric.

Put

$$(a, b)_{M_n(k)} = \operatorname{tr}(a \, b^*) \tag{11.8.2}$$

for every $a, b \in M_n(k)$, which defines a bilinear form on $M_n(k)$. Observe that

$$(a, b)_{M_n(k)} = \operatorname{tr}(a \, b^*)^* = \operatorname{tr}((b^*)^* \, a^*) = \operatorname{tr}(b \, a^*) = (b, a)_{M_n(k)} \tag{11.8.3}$$

for every $a, b \in M_n(k)$, using (11.8.1) in the first step. If $c \in M_n(k)$, then let

$$L_c(a) = c \, a \quad \text{and} \quad R_c(a) = a \, c \tag{11.8.4}$$

be the corresponding operators of left and right multiplication on $M_n(k)$ by c, respectively. Thus

$$\begin{aligned} (L_c(a), b)_{M_n(k)} = \operatorname{tr}(c \, a \, b^*) &= \operatorname{tr}(a \, b^* \, c) \\ &= \operatorname{tr}(a \, (c^* \, b)^*) = (a, L_{c^*}(b))_{M_n(k)} \end{aligned} \tag{11.8.5}$$

for every $a, b \in M_n(k)$. Similarly,

$$(R_c(a), b)_{M_n(k)} = \operatorname{tr}(a \, c \, b^*) = \operatorname{tr}(a \, (b \, c^*)^*) = (a, R_{c^*}(b))_{M_n(k)} \tag{11.8.6}$$

for every $a, b \in M_n(k)$.

Let a and b be elements of $M_n(k)$ again. If b is self-adjoint with respect to the given involution on $M_n(k)$, so that $b^* = b$, then

$$(a, b)_{M_n(k)} = \operatorname{tr}(a\,b). \tag{11.8.7}$$

If a is self-adjoint and b is arbitrary, then

$$(a, b)_{M_n(k)} = (b, a)_{M_n(k)} = \operatorname{tr}(b\,a) = \operatorname{tr}(a\,b). \tag{11.8.8}$$

If a is arbitrary and b is anti-self-adjoint, so that $b^* = -b$, then

$$(a, b)_{M_n(k)} = -\operatorname{tr}(a\,b). \tag{11.8.9}$$

If a is anti-self-adjoint and b is arbitrary, then

$$(a, b)_{M_n(k)} = (b, a)_{M_n(k)} = -\operatorname{tr}(b\,a) = -\operatorname{tr}(a\,b). \tag{11.8.10}$$

If $c \in M_n(k)$, then put

$$C_c(a) = [c, a] = c\,a - a\,c = L_c(a) - R_c(a) \tag{11.8.11}$$

for every $a \in M_n(k)$, so that C_c is a homomorphism from $M_n(k)$ into itself, as a module over k. Note that

$$(C_c(a), b)_{M_n(k)} = (a, C_{c^*}(b))_{M_n(k)} \tag{11.8.12}$$

for every $a, b \in M_n(k)$, by (11.8.5) and (11.8.6). Of course,

$$(C_c(a))^* = ([c, a])^* = -[c^*, a^*] = -C_{c^*}(a^*) \tag{11.8.13}$$

for every $a \in M_n(k)$.

Suppose that $1 + 1$ has a multiplicative inverse in k. If $a \in M_n(k)$ is self-adjoint and $b \in M_n(k)$ is anti-self-adjoint, then

$$(a, b)_{M_n(k)} = 0, \tag{11.8.14}$$

by (11.8.8) and (11.8.9). This also holds when a is anti-self-adjoint and b is self-adjoint, by (11.8.3).

11.9 Inner products over ordered fields

Let k be an ordered field, as in Section 8.12, and let V be a vector space over k. Also let $\langle v, w\rangle_V$ be an *inner product* on V, which is to say a symmetric bilinear form on V that is positive definite, in the sense that

$$\langle v, v\rangle_V > 0 \tag{11.9.1}$$

for every $v \in V$ with $v \neq 0$. As usual, $v, w \in V$ are said to be *orthogonal* with respect to $\langle \cdot, \cdot\rangle_V$ when

$$\langle v, w\rangle_V = 0. \tag{11.9.2}$$

Suppose that $e_1, \ldots, e_n$ are finitely many nonzero vectors in V that are pairwise orthogonal, so that

$$\langle e_j, e_l \rangle_V = 0 \tag{11.9.3}$$

when $j \neq l$. If $v \in V$, then put

$$w = \sum_{j=1}^{n} \frac{\langle v, e_j \rangle_V}{\langle e_j, e_j \rangle_V} \, e_j, \tag{11.9.4}$$

which is an element of the linear span of $e_1, \ldots, e_n$. Observe that

$$\langle w, e_l \rangle_V = \langle v, e_l \rangle_V \tag{11.9.5}$$

for every $l = 1, \ldots, n$. Equivalently, $\langle w - v, e_l \rangle_V = 0$ for each $l = 1, \ldots, n$, so that

$$\langle w - v, u \rangle_V = 0 \tag{11.9.6}$$

for every u in the linear span of $e_1, \ldots, e_n$ in V. If v is in the linear span of $e_1, \ldots, e_n$ in V, then we get that

$$v = w, \tag{11.9.7}$$

because w is in the linear span of $e_1, \ldots, e_n$ in V, by construction.

Suppose from now on in this section that V has positive finite dimension n, as a vector space over k. In this case, there are nonzero pairwise-orthogonal vectors $e_1, \ldots, e_n$ in V whose linear span is equal to V, so that they form a basis for V as a vector space over k. This can be obtained from the Gram–Schmidt process, using the remarks in the preceding paragraph. If $v \in V$, then we get that

$$v = \sum_{j=1}^{n} \frac{\langle v, e_j \rangle_V}{\langle e_j, e_j \rangle_V} \, e_j, \tag{11.9.8}$$

as before. Of course, if $k = \mathbf{R}$, then we can take the e_j's to be orthonormal in V, so that $\langle e_j, e_j \rangle_V = 1$ for every $j = 1, \ldots, n$.

Remember that $\mathcal{L}(V)$ denotes the algebra of linear mappings from V into itself. If $T \in \mathcal{L}(V)$, then there is a unique adjoint mapping $T^* \in \mathcal{L}(V)$ such that

$$\langle T(v), w \rangle_V = \langle v, T^*(w) \rangle_V \tag{11.9.9}$$

for every $v, w \in V$, as usual. We have also seen that $T \mapsto T^*$ is an algebra involution on $\mathcal{L}(V)$. Observe that

$$T(e_l) = \sum_{j=1}^{n} \frac{\langle T(e_l), e_j \rangle_V}{\langle e_j, e_j \rangle_V} \, e_j \tag{11.9.10}$$

for each $l = 1, \ldots, n$, so that

$$\mathrm{tr}_V T = \sum_{j=1}^{n} \frac{\langle T(e_j), e_j \rangle_V}{\langle e_j, e_j \rangle_V}. \tag{11.9.11}$$

This implies that

$$\mathrm{tr}_V T^* = \sum_{j=1}^{n} \frac{\langle T^*(e_j), e_j\rangle_V}{\langle e_j, e_j\rangle_V} = \sum_{j=1}^{n} \frac{\langle e_j, T(e_j)\rangle_V}{\langle e_j, e_j\rangle_V} = \mathrm{tr}_V T. \tag{11.9.12}$$

If $T_1, T_2 \in \mathcal{L}(V)$, then put

$$\langle T_1, T_2\rangle_{\mathcal{L}(V)} = \mathrm{tr}_V(T_1 \circ T_2^*) = \mathrm{tr}_V(T_2^* \circ T_1), \tag{11.9.13}$$

which defines a bilinear form on $\mathcal{L}(V)$. Using (11.9.12), we get that

$$\langle T_1, T_2\rangle_{\mathcal{L}(V)} = \mathrm{tr}_V(T_1 \circ T_2^*)^* = \mathrm{tr}_V(T_2 \circ T_1^*) = \langle T_2, T_1\rangle_{\mathcal{L}(V)}, \tag{11.9.14}$$

as in the previous section. Observe that

$$\begin{aligned} \langle T, T\rangle_{\mathcal{L}(V)} = \mathrm{tr}_V(T^* \circ T) &= \sum_{j=1}^{n} \frac{\langle (T^*(T(e_j)), e_j\rangle_V}{\langle e_j, e_j\rangle_V} \\ &= \sum_{j=1}^{n} \frac{\langle T(e_j), T(e_j)\rangle_V}{\langle e_j, e_j\rangle_V} \end{aligned} \tag{11.9.15}$$

for every $T \in \mathcal{L}(V)$. If $T \neq 0$, then it follows that

$$\langle T, T\rangle_{\mathcal{L}(V)} > 0, \tag{11.9.16}$$

because each of the terms on the right side of (11.9.15) is greater than or equal to 0 in k, and at least one term is strictly positive. Thus (11.9.13) defines an inner product on $\mathcal{L}(V)$, as a vector space over k.

Suppose that $T_1 \in \mathcal{L}(V)$ is self-adjoint and $T_2 \in \mathcal{L}(V)$ is anti-self-adjoint, so that $T_1^* = T_1$ and $T_2^* = -T_2$. Under these conditions, we have that

$$\langle T_1, T_2\rangle_{\mathcal{L}(V)} = -\mathrm{tr}_V(T_2 \circ T_1) = -\langle T_2, T_1\rangle_{\mathcal{L}(V)}. \tag{11.9.17}$$

This means that

$$\langle T_1, T_2\rangle_{\mathcal{L}(V)} = 0. \tag{11.9.18}$$

If $A \in \mathcal{L}(V)$, then put

$$L_A(T) = A \circ T \quad \text{and} \quad R_A(T) = T \circ A \tag{11.9.19}$$

for every $T \in \mathcal{L}(V)$, as before. Observe that

$$\begin{aligned} \langle L_A(T_1), T_2\rangle_{\mathcal{L}(V)} &= \mathrm{tr}_V(A \circ T_1 \circ T_2^*) = \mathrm{tr}_V(T_1 \circ T_2^* \circ A) \\ &= \mathrm{tr}_V(T_1 \circ (A^* \circ T_2)^*) = \langle T_1, L_{A^*}(T_2)\rangle_{\mathcal{L}(V)} \end{aligned} \tag{11.9.20}$$

and

$$\begin{aligned} \langle R_A(T_1), T_2\rangle_{\mathcal{L}(V)} &= \mathrm{tr}_V(T_1 \circ A \circ T_2^*) = \mathrm{tr}_V(T_1 \circ (T_2 \circ A^*)^*) \\ &= \langle T_1, R_{A^*}(T_2)\rangle_{\mathcal{L}(V)} \end{aligned} \tag{11.9.21}$$

for every $T_1, T_2 \in \mathcal{L}(V)$. Put

$$C_A(T) = [A, T] = A \circ T - T \circ A = L_A(T) - R_A(T) \tag{11.9.22}$$

for every $T \in \mathcal{L}(V)$. Thus

$$\langle C_A(T_1), T_2 \rangle_{\mathcal{L}(V)} = \langle T_1, C_{A^*}(T_2) \rangle_{\mathcal{L}(V)} \tag{11.9.23}$$

for every $T_1, T_2 \in \mathcal{L}(V)$, by (11.9.21) and (11.9.22).

11.10 Self-adjoint Lie subalgebras

Let us continue with the same notation and hypotheses as in the previous section. As before, we use $gl(V)$ to denote $\mathcal{L}(V)$, considered as a Lie algebra over k with respect to the corresponding commutator bracket. If $R \in gl(V)$, then put

$$C_R(T) = [R, T] = R \circ T - T \circ R \tag{11.10.1}$$

for every $T \in gl(V)$, as in (11.9.22), which is the same as $\mathrm{ad}_{gl(V),R}(T)$. Remember that

$$\langle C_R(T_1), T_2 \rangle_{\mathcal{L}(V)} = \langle T_1, C_{R^*}(T_2) \rangle_{\mathcal{L}(V)} \tag{11.10.2}$$

for every $T_1, T_2 \in gl(V)$, as in (11.9.23). This means that C_{R^*} is the adjoint of C_R as a linear mapping from $gl(V) = \mathcal{L}(V)$ into itself, with respect to the inner product (11.9.13).

Let $\mathcal{A}$ be a Lie subalgebra of $gl(V)$, as a Lie algebra over k.. If $R \in \mathcal{A}$, then C_R maps $\mathcal{A}$ into itself, and the restriction of C_R to $\mathcal{A}$ is the same as $\mathrm{ad}_{\mathcal{A},R}$. If $R_1, R_2 \in \mathcal{A}$, then

$$\mathrm{tr}_{\mathcal{A}}(\mathrm{ad}_{\mathcal{A},R_1} \circ \mathrm{ad}_{\mathcal{A},R_2}) = \mathrm{tr}_{\mathcal{A}}(C_{R_1} \circ C_{R_2}) \tag{11.10.3}$$

is the same as the Killing form on $\mathcal{A}$ evaluated at R_1, R_2. This is the trace of $\mathrm{ad}_{\mathcal{A},R_1} \circ \mathrm{ad}_{\mathcal{A},R_2}$ as a linear mapping from $\mathcal{A}$ into itself, where $\mathcal{A}$ is considered as a finite-dimensional vector space over k. In the right side of (11.10.3), one should use the restrictions of C_{R_1} and C_{R_2} to $\mathcal{A}$, as indicated by taking the trace is taken over $\mathcal{A}$.

If $\mathcal{A}$ is any subset of $\mathcal{L}(V)$, then put

$$\mathcal{A}^* = \{T^* : T \in \mathcal{A}\}, \tag{11.10.4}$$

which is a subset of $\mathcal{L}(V)$ as well. Let us say that $\mathcal{A}$ is *self-adjoint* as a subset of $\mathcal{L}(V)$ when $\mathcal{A}^* = \mathcal{A}$. Let $\mathcal{A}$ be a Lie subalgebra of $gl(V)$ again, and suppose that $\mathcal{A}$ is self-adjoint as a subset of $\mathcal{L}(V)$. If $R \in \mathcal{A}$, then $R^* \in \mathcal{A}$, so that C_R and C_{R^*} both map $\mathcal{A}$ into itself. The restriction of C_{R^*} to $\mathcal{A}$ is the same as the adjoint of the restriction of C_R to $\mathcal{A}$, with respect to the restriction of the inner product (11.9.13) on $\mathcal{L}(V)$ to $\mathcal{A}$.

Let $\mathcal{L}(\mathcal{A})$ be the space of all linear mappings from $\mathcal{A}$ into itself, as usual. The restriction of the inner product (11.9.13) on $\mathcal{L}(V)$ to $\mathcal{A}$ defines an inner product on $\mathcal{A}$, as a vector space over k. If $Z \in \mathcal{L}(\mathcal{A})$, then let $Z^{\mathcal{A},*} \in \mathcal{L}(\mathcal{A})$ be the adjoint of Z with respect to the inner product on $\mathcal{A}$ just mentioned. Put

$$\langle Z_1, Z_2 \rangle_{\mathcal{L}(\mathcal{A})} = \mathrm{tr}_{\mathcal{A}}(Z_1 \circ Z_2^{\mathcal{A},*}) \tag{11.10.5}$$

for every $Z_1, Z_1 \in \mathcal{L}(\mathcal{A})$. This defines an inner product on $\mathcal{L}(\mathcal{A})$, as a vector space over k, as in the previous section.

Let $R_1, R_2 \in \mathcal{A}$ be given, and remember that $\mathrm{ad}_{\mathcal{A},R_2^*}$ is the same as the adjoint of $\mathrm{ad}_{\mathcal{A},R_2}$ with respect to the inner product on $\mathcal{A}$ mentioned in the preceding paragraph. It follows that

$$\mathrm{tr}_{\mathcal{A}}(\mathrm{ad}_{\mathcal{A},R_1} \circ \mathrm{ad}_{\mathcal{A},R_2}) = \langle \mathrm{ad}_{\mathcal{A},R_1}, \mathrm{ad}_{\mathcal{A},R_2^*} \rangle_{\mathcal{L}(\mathcal{A})}, \tag{11.10.6}$$

where the right side is as in (11.10.5). In particular,

$$\mathrm{tr}_{\mathcal{A}}(\mathrm{ad}_{\mathcal{A},R} \circ \mathrm{ad}_{\mathcal{A},R^*}) = \langle \mathrm{ad}_{\mathcal{A},R}, \mathrm{ad}_{\mathcal{A},R} \rangle_{\mathcal{L}(\mathcal{A})} \tag{11.10.7}$$

for every $R \in \mathcal{A}$. The right side is automatically greater than or equal to 0 in k, because (11.10.5) is an inner product on $\mathcal{L}(\mathcal{A})$. More precisely, the right side of (11.10.7) is equal to 0 exactly when $\mathrm{ad}_{\mathcal{A},R} = 0$ as a linear mapping from $\mathcal{A}$ into itself.

11.11 Comparing involutions

Let $\mathcal{A}$ be a commutative group, where the group operations are expressed additively, and let

$$x \mapsto x^{*,1} \tag{11.11.1}$$

and

$$x \mapsto x^{*,2} \tag{11.11.2}$$

be group homomorphisms from $\mathcal{A}$ into itself. Suppose for the moment that these two group homomorphisms commute on $\mathcal{A}$, so that

$$(x^{*,1})^{*,2} = (x^{*,2})^{*,1} \tag{11.11.3}$$

for every $x \in \mathcal{A}$. Of course, one can define self-adjointness and anti-self-adjointness of elements of $\mathcal{A}$ with respect to (11.11.1) and (11.11.2) in the usual way. If $x \in \mathcal{A}$ is self-adjoint with respect to (11.11.2), then it follows that $x^{*,1}$ is self-adjoint with respect to (11.11.2) as well. Similarly, if x is anti-self-adjoint with respect to (11.11.2), then $x^{*,1}$ is anti-self-adjoint with respect to (11.11.2).

Now let k be a commutative ring with a multiplicative identity element, and let $\mathcal{A}$ be an associative algebra over k with a multiplicative identity element e, where multiplication of $a, b \in \mathcal{A}$ is expressed as $a\,b$. Suppose that (11.11.1) is an algebra involution on $\mathcal{A}$, and let c be an invertible element of $\mathcal{A}$. Put

$$x^{*,2} = c^{-1}\, x^{*,1}\, c \tag{11.11.4}$$

for every $x \in \mathcal{A}$. This defines (11.11.2) as an opposite algebra automorphism on $\mathcal{A}$. Let us suppose from now on in this section that

$$c^{*,1} = c \tag{11.11.5}$$

or

$$c^{*,1} = -c. \tag{11.11.6}$$

In either case, (11.11.2) is an algebra involution on $\mathcal{A}$ as well, as in Section 3.14. Note that

$$c^{*,2} = c \tag{11.11.7}$$

when (11.11.5) holds, and that

$$c^{*,2} = -c \tag{11.11.8}$$

when (11.11.6) holds.

If $x \in \mathcal{A}$, then

$$(x^{*,1})^{*,2} = c^{-1}\,(x^{*,1})^{*,1}\,c = c^{-1}\,x\,c \tag{11.11.9}$$

and

$$(x^{*,2})^{*,1} = (c^{-1}\,x^{*,1}\,c)^{*,1} = c^{*,1}\,(x^{*,1})^{*,1}\,(c^{*,1})^{-1} = c^{*,1}\,x\,(c^{*,1})^{-1}. \tag{11.11.10}$$

This reduces to

$$(x^{*,2})^{*,1} = c\,x\,c^{-1} \tag{11.11.11}$$

when c satisfies (11.11.5) or (11.11.6). If

$$c^2 = t\,e \tag{11.11.12}$$

for some $t \in k$ with a multiplicative inverse in k, then we get that (11.11.3) holds. If $k = \mathbf{C}$, then (11.11.1) may be conjugate-linear, as usual.

Let $\mathcal{A}_1$ be a subalgebra of $\mathcal{A}$, and suppose that (11.11.1) maps $\mathcal{A}_1$ into itself. There are some situations where c is not necessarily in $\mathcal{A}_1$, but $c^{-1}\,x\,c \in \mathcal{A}_1$ for every $x \in \mathcal{A}_1$. If $x \in \mathcal{A}_1$, then it follows that (11.11.4) is an element of $\mathcal{A}_1$ as well.

11.12 Some projections

Let k be a field, let V be a vector space over k, and let $b(v, w)$ be a bilinear form on V. Also let V_0 be a finite-dimensional linear subspace of V, and suppose that the restriction of $b(v, w)$ to $v, w \in V_0$ is nondegenerate on V_0. If $z \in V$, then put

$$\lambda_z(v) = b(v, z) \tag{11.12.1}$$

for every $v \in V_0$, which defines a linear functional on V_0. Because $b(\cdot, \cdot)$ is nondegenerate on V_0, there is a unique element $P_0(z)$ of V_0 such that

$$\lambda_z(v) = b(v, P_0(z)) \tag{11.12.2}$$

for every $v \in V_0$. Equivalently, this means that

$$b(v, z - P_0(z)) = 0 \tag{11.12.3}$$

for every $v \in V$. It is easy to see that P_0 defines a linear mapping from V into V_0. More precisely,

$$P_0(z) = z \tag{11.12.4}$$

when $z \in V_0$, so that P_0 maps V onto V_0. It follows that

$$P_0 \circ P_0 = P_0 \tag{11.12.5}$$

on V, so that P_0 is a projection on V.

Let Z_0 be the kernel of P_0, which is a linear subspace of V. Note that

$$V_0 \cap Z_0 = \{0\}, \tag{11.12.6}$$

by (11.12.4). If $z \in V$, then

$$z - P_0(z) \in Z_0, \tag{11.12.7}$$

by (11.12.5). Thus $z \in V_0 + Z_0$, so that $V = V_0 + Z_0$. This shows that V corresponds to the direct sum of V_0 and Z_0, as a vector space over k. If $z \in Z_0$, then

$$b(v, z) = 0 \tag{11.12.8}$$

for every $v \in V_0$, by (11.12.3). This is equivalent to (11.12.3), because of (11.12.7).

Suppose that $b(\cdot, \cdot)$ is either symmetric or antisymmetric on V. This implies that

$$b(z, v) = 0 \tag{11.12.9}$$

for every $v \in V_0$ and $z \in Z_0$, by (11.12.8). If $u, w \in V$, then $P_0(u), P_0(w) \in V_0$, $u - P_0(u), w - P_0(w) \in Z_0$, and hence

$$b(P_0(u), w - P_0(w)) = b(u - P_0(u), P_0(w)) = 0, \tag{11.12.10}$$

by (11.12.8) and (11.12.9). It follows that

$$b(u, w) = b(P_0(u), P_0(w)) + b(u - P_0(u), w - P_0(w)). \tag{11.12.11}$$

Thus $b(\cdot, \cdot)$ corresponds, as a bilinear form on V, to the bilinear form on the direct sum of V_0 and Z_0 obtained from the restrictions of $b(\cdot, \cdot)$ to V_0 and Z_0.

Suppose for the moment that

$$b(w, w) = 0 \tag{11.12.12}$$

for every $v \in V$. Remember that this implies that $b(\cdot, \cdot)$ is antisymmetric on V, and that the converse holds when the characteristic of k is different from 2, as in Section 2.1. Let x, y be elements of V such that

$$b(x, y) \neq 0. \tag{11.12.13}$$

This implies that x and y are linearly independent in V, because of (11.12.12). Thus the linear span V_0 of x and y in V is a two-dimensional linear subspace of V. It is easy to see that the restriction of $b(\cdot,\cdot)$ to V_0 is nondegenerate on V_0. It follows that there is a complementary linear subspace Z_0 of V_0 with the properties discussed in the previous paragraphs.

Suppose that V has finite dimension as a vector space over k. If $b(\cdot,\cdot) \not\equiv 0$ on V, then there are $x, y \in V$ as in the preceding paragraph. Repeating the process, we get that V corresponds to the direct sum of finitely many two-dimensional linear subspaces on which $b(\cdot,\cdot)$ is nondegenerate, and possibly an additional linear subspace on which $b(\cdot,\cdot) \equiv 0$. This additional linear subspace is not needed when $b(\cdot,\cdot)$ is nondegenerate on V. By construction, $b(\cdot,\cdot)$ corresponds to the bilinear form on this direct sum obtained from the restrictions of $b(\cdot,\cdot)$ to these linear subspaces.

Let V be any vector space over k again, and suppose that $b(\cdot,\cdot)$ is symmetric on V. Let x be an element of V such that

$$b(x,x) \neq 0, \tag{11.12.14}$$

and let V_0 be the linear span of x in V. Clearly V_0 is a one-dimensional linear subspace of V, and the restriction of $b(\cdot,\cdot)$ to V_0 is nondegenerate on V_0. This leads to a complementary subspace Z_0 of V_0 in V as before, so that $b(\cdot,\cdot)$ corresponds to the bilinear form on the direct sum of V_0 and Z_0 obtained from the restrictions of $b(\cdot,\cdot)$ to V_0 and Z_0.

Suppose that V has finite dimension as a vector space over k again. Repeating the argument from the preceding pagraph, we get that V can be expressed as the direct sum of finitely many one-dimensional linear subspaces on which $b(\cdot,\cdot) \not\equiv 0$, and possibly an additional linear subspace W such that (11.12.12) holds for every $w \in W$. As before, $b(\cdot,\cdot)$ corresponds to the bilinear form on the direct sum obtained from the restrictions of $b(\cdot,\cdot)$ to these linear subspaces. If the characteristic of k is different from 2, then $b(\cdot,\cdot) \equiv 0$ on W, because $b(\cdot,\cdot)$ is both symmetric and antisymmetric on W. In this case, the additional subspace W is not needed when $b(\cdot,\cdot)$ is nondegenerate on V.

11.13 Antisymmetric bilinear forms

Let k be a field with characteristic different from 2, and let V be a vector space over k of positive finite dimension. Also let $\beta(\cdot,\cdot)$ be a nondegenerate antisymmetric bilinear form on V. Under these conditions, there is a basis for V consisting of vectors $x_1, \ldots, x_n$, $y_1, \ldots, y_n$ for some positive integer n with the following properties. First,

$$\beta(x_j, x_l) = \beta(y_j, y_l) = 0 \tag{11.13.1}$$

for every $j, l = 1, \ldots, n$, and

$$\beta(x_j, y_l) = 0 \tag{11.13.2}$$

when $j \neq l$. Second, for each $j = 1, \ldots, n$,

$$\beta(x_j, y_j) \neq 0. \tag{11.13.3}$$

This well-known representation for $\beta(\cdot, \cdot)$ follows from some of the remarks in the previous section. More precisely, we may ask that

$$\beta(x_j, y_j) = 1 \tag{11.13.4}$$

for every $j = 1, \ldots, n$, by multiplying the x_j's or y_j's by suitable nonzero elements of k, if necessary.

If $v \in V$, then v can be expressed in a unique way as

$$v = \sum_{j=1}^{n} v_{x_j}\, x_j + \sum_{j=1}^{n} v_{y_j}\, y_j, \tag{11.13.5}$$

where $v_{x_j}, v_{y_j} \in k$ for every $j = 1, \ldots, n$. Put

$$\langle v, w \rangle_V = \sum_{j=1}^{n} v_{x_j}\, w_{x_j} + \sum_{j=1}^{n} v_{y_j}\, w_{y_j} \tag{11.13.6}$$

for every $v, w \in V$, where $w_{x_j}, w_{y_j} \in k$ correspond to w as in (11.13.5). This defines a symmetric bilinear form on V, with

$$\langle v, v \rangle_V = \sum_{j=1}^{n} v_{x_j}^2 + \sum_{j=1}^{n} v_{y_j}^2 \tag{11.13.7}$$

for every $v \in V$. If k is an ordered field, then (11.13.7) is strictly positive when $v \neq 0$, and hence (11.13.6) defines an inner product on V. Of course, $x_1, \ldots, x_n, y_1, \ldots, y_n$ is an orthonormal basis for V with respect to (11.13.6).

Let B be the unique linear mapping from V into itself that satisfies

$$B(x_j) = y_j, \quad B(y_j) = -x_j \tag{11.13.8}$$

for every $j = 1, \ldots, n$. It is easy to see that

$$B^2 = -I_V, \tag{11.13.9}$$

where I_V is the identity mapping on V. One can check that

$$\beta(v, w) = \langle B(v), w \rangle_V \tag{11.13.10}$$

for every $v, w \in V$, by reducing to the cases where $v = x_j$ or y_j and $w = x_l$ or y_l, $1 \leq j, l \leq n$. We also have that

$$B^* = -B, \tag{11.13.11}$$

where B^* is the adjoint of B with respect to (11.13.6). This corresponds to the antisymmetry of $\beta(\cdot, \cdot)$ on V, because of (11.13.10).

If T is a linear mapping from V into itself, then the adjoint $T^{*,\beta}$ of T with respect to $\beta(\cdot,\cdot)$ is the unique linear mapping from V into itself such that

$$\beta(T(v), w) = \beta(v, T^{*,\beta}(w)) \tag{11.13.12}$$

for every $v, w \in V$. This is the same as saying that

$$\langle B(T(v)), w\rangle_V = \langle B(v), T^{*,\beta}(w)\rangle_V \tag{11.13.13}$$

for every $v, w \in V$, by (11.13.10). This is equivalent to

$$\langle B(T(v)), w\rangle_V = -\langle v, B(T^{*,\beta}(w))\rangle_V \tag{11.13.14}$$

for every $v, w \in V$, because of (11.13.11). This means that

$$(B \circ T)^* = -B \circ T^{*,\beta}, \tag{11.13.15}$$

where the left side is the adjoint of $B \circ T$ with respect to the inner product (11.13.6). Thus

$$T^{*,\beta} = -B^{-1} \circ (B \circ T)^* = -B^{-1} \circ T^* \circ B^* = B^{-1} \circ T^* \circ B. \tag{11.13.16}$$

11.14 Symmetric bilinear forms

Let k be an ordered field, and let V be a vector space over k of positive finite dimension n. In this section, we consider a nondegenerate symmetric bilinear form $\beta(\cdot,\cdot)$ on V. It is well known that there is a basis $e_1, \ldots, e_n$ for V such that

$$\beta(e_j, e_l) = 0 \tag{11.14.1}$$

when $j \neq l$, and for each $j = 1, \ldots, n$,

$$\beta(e_j, e_j) \neq 0, \tag{11.14.2}$$

as in Section 11.12. Remember that the absolute value $|t|$ of $t \in k$ can be defined as an element of k, as in Section 8.13. If $k = \mathbf{R}$, then one can choose the e_j's so that $\beta(e_j, e_j) = \pm 1$ for each $j = 1, \ldots, n$.

If $v \in V$, then let

$$v = \sum_{j=1}^{n} v_j\, e_j \tag{11.14.3}$$

be the unique representation of v as a linear combination of the e_j's with coefficients $v_j \in k$. Put

$$\langle v, w\rangle_V = \sum_{j=1}^{n} |\beta(e_j, e_j)|\, v_j\, w_j \tag{11.14.4}$$

for every $v, w \in V$, where $w_j \in k$ corresponds to w as in (11.14.3). This defines a symmetric bilinear form on V, and

$$\langle v, v\rangle_V = \sum_{j=1}^{n} |\beta(e_j, e_j)|\, v_j^2 \tag{11.14.5}$$

for every $v \in V$. If $v \neq 0$, then (11.14.5) is strictly positive in k, so that (11.14.4) is an inner product on V. Note that the e_j's are pairwise orthogonal with respect to (11.14.4).

Let B be the unique linear mapping from V into itself that satisfies

$$\begin{aligned} B(e_j) &= e_j \quad \text{when } \beta(e_j, e_j) > 0 \\ &= -e_j \quad \text{when } -\beta(e_j, e_j) > 0. \end{aligned} \tag{11.14.6}$$

Clearly

$$B^2 = I_V, \tag{11.14.7}$$

where I_V is the identity mapping on V. It is easy to see that

$$B^* = B, \tag{11.14.8}$$

where B^* is the adjoint of B with respect to the inner product (11.14.4). Of course,

$$\langle B(v), w\rangle_V = \sum_{j=1}^{n} \beta(e_j, e_j)\, v_j\, w_j \tag{11.14.9}$$

for every $v, w \in V$, by construction. One can check that

$$\beta(v, w) = \langle B(v), w\rangle_V \tag{11.14.10}$$

for every $v, w \in V$, by reducing to the case where $v = e_j$ and $w = e_l$, $1 \leq j, l \leq n$.

If T is a linear mapping from V into itself, then the adjoint $T^{*,\beta}$ of T with respect to β is the unique linear mapping from V into itself such that

$$\beta(T(v), w) = \beta(v, T^{*,\beta}(w)) \tag{11.14.11}$$

for every $v, w \in V$, as before. This means that

$$\langle B(T(v)), w\rangle_V = \langle B(v), T^{*,\beta}(w)\rangle_V \tag{11.14.12}$$

for every $v, w \in V$, because of (11.14.10). This is the same as saying that

$$\langle B(T(v)), w\rangle_V = \langle v, B(T^{*,\beta}(w))\rangle_V \tag{11.14.13}$$

for every $v, w \in V$, by (11.14.8). This is equivalent to asking that

$$(B \circ T)^* = B \circ T^{*,\beta}, \tag{11.14.14}$$

where the left side is the adjoint of $B \circ T$ with respect to the inner product (11.14.4). This shows that

$$T^{*,\beta} = B^{-1} \circ (B \circ T)^* = B^{-1} \circ T^* \circ B^* = B^{-1} \circ T^* \circ B. \tag{11.14.15}$$

Chapter 12

Some complex versions

12.1 Complexifying ordered fields

Let k be a ordered ring, as in Section 8.12, and suppose that k is commutative and has a multiplicative identity element $1 = 1_k$. Also let a be an element of k such that $a > 0$. Thus, for each $x \in k$, we have that $x^2 \neq -a$, because $x^2 \geq 0$. As usual, we can get a commutative ring $k[\sqrt{-a}]$ by adjoining a square root $\sqrt{-a}$ of $-a$ to k. More precisely, we can define $k[\sqrt{-a}]$ to be the space k^2 of ordered pairs of elements of k. An element of $k[\sqrt{-a}]$ may be expressed in a unique way as

$$z = x + y\,\sqrt{-a}, \tag{12.1.1}$$

with $x, y \in k$, which corresponds to $(x, y) \in k^2$. Let us identify $x \in k$ with $x + 0\,\sqrt{-a}$ in $k[\sqrt{-a}]$, so that k corresponds to a subset of $k[\sqrt{-a}]$. Let

$$w = u + v\,\sqrt{-a} \tag{12.1.2}$$

be another element of $k[\sqrt{-a}]$, with $u, v \in k$. Addition and multiplication on k can be extended to $k[\sqrt{-a}]$ by putting

$$z + w = (x + u) + (y + v)\,\sqrt{-a} \tag{12.1.3}$$

and

$$z\,w = (x\,u - y\,v\,a) + (x\,v + y\,u)\,\sqrt{-a}, \tag{12.1.4}$$

as usual. One can verify that $k[\sqrt{-a}]$ is a commutative ring, and that k corresponds to a subring of $k[\sqrt{-a}]$. The multiplicative identity element 1 in k corresponds to the multiplicative identity element in $k[\sqrt{-a}]$. Of course, $(\sqrt{-a})^2 = -a$ in $k[\sqrt{-a}]$, by construction.

If $z \in k[\sqrt{-a}]$ is as in (12.1.1), then the *conjugate* $\overline{z}$ of z in $k[\sqrt{-a}]$ is defined as usual by

$$\overline{z} = x - y\,\sqrt{-a}. \tag{12.1.5}$$

One can verify that

$$\overline{z + w} = \overline{z} + \overline{w} \tag{12.1.6}$$

and

(12.1.7) $$\overline{z\,w} = \overline{z}\,\overline{w}$$

for every $z, w \in k[\sqrt{-a}]$. Clearly

(12.1.8) $$\overline{(\overline{z})} = z$$

for every $z \in k[\sqrt{-a}]$, and $\overline{z} = z$ exactly when z corresponds to an element of k. If $z \in k[\sqrt{-a}]$ is as in (12.1.1) again, then

(12.1.9) $$z + \overline{z} = 2 \cdot x$$

and

(12.1.10) $$z\,\overline{z} = x^2 + a\,y^2$$

correspond to elements of k. Note that

(12.1.11) $$z\,\overline{z} > 0$$

in k when $z \neq 0$.

Suppose now that k is an ordered field. If $z \in k[\sqrt{-a}]$ and $z \neq 0$, then $z\,\overline{z}$ corresponds to a nonzero element of k, which has a multiplicative inverse in k. This implies that z has a multiplicative inverse in $k[\sqrt{-a}]$, which is $\overline{z}\,(1/(z\,\overline{z}))$. Thus $k[\sqrt{-a}]$ is a field in this case as well. If k is a subfield of $\mathbf{R}$, then we can take $\sqrt{-a}$ to be $i\,\sqrt{a} \in \mathbf{C}$, so that $k[\sqrt{-a}]$ corresponds to a subfield of $\mathbf{C}$.

Let k be an ordered field again, let a be a positive element of k, and let $k[\sqrt{-a}]$ be as before. Also let V and W be vector spaces over $k[\sqrt{-a}]$, which may be considered as vector spaces over k too. A linear mapping T from V into W, as vector spaces over $k[\sqrt{-a}]$, may be called $k[\sqrt{-a}]$-linear, or linear over $k[\sqrt{-a}]$, as usual. Similarly, if T is a linear mapping from V into W as vector spaces over k, the we may say that T is k-linear, or linear over k. Thus a mapping T from V into W is $k[\sqrt{-a}]$-linear if and only if T is k-linear and

(12.1.12) $$T(\sqrt{-a}\,v) = \sqrt{-a}\;T(v)$$

for every $v \in V$. A k-linear mapping T from V into W is said to be *conjugate-linear* if

(12.1.13) $$T(\sqrt{-a}\,v) = -\sqrt{-a}\;T(v)$$

for every $v \in V$. This implies that

(12.1.14) $$T(t\,v) = \overline{t}\,T(v)$$

for every $t \in k[\sqrt{-a}]$ and $v \in V$.

12.2 Sesquilinearity over $k[\sqrt{-a}]$

Let k be an ordered field, let a be a positive element of k, and let $k[\sqrt{-a}]$ be as in the previous section. Also let V be a vector space over k, and let $b(v, w)$

be a function defined for $v, w \in V$ with values in $k[\sqrt{-a}]$. We say that $b(\cdot, \cdot)$ is *sesquilinear* if $b(v, w)$ is $k[\sqrt{-a}]$-linear in v for every $w \in V$, and conjugate-linear in w for every $v \in V$. In particular, this means that $b(\cdot, \cdot)$ is bilinear over k, where V and $k[\sqrt{-a}]$ are considered as vector spaces over k. As before, $b(\cdot, \cdot)$ is said to be *Hermitian-symmetric* on V if

$$b(w, v) = \overline{b(v, w)} \tag{12.2.1}$$

for every $v, w \in V$.

Let $b(\cdot, \cdot)$ be a sesquilinear form on V, and let T be a $k[\sqrt{-a}]$-linear mapping from V into itself. As before, we say that T is *self-adjoint* with respect to $b(\cdot, \cdot)$ if

$$b(T(v), w) = b(v, T(w)) \tag{12.2.2}$$

for every $v, w \in V$, and we say that T is *anti-self-adjoint* with respect to $b(\cdot, \cdot)$ if

$$b(T(v), w) = -b(v, T(w)) \tag{12.2.3}$$

for every $v, w \in V$. It is easy to see that T is anti-self-adjoint with respect to $b(\cdot, \cdot)$ if and only if $\sqrt{-a}\, T$ is self-adjoint with respect to $b(\cdot, \cdot)$. Remember that the space $\mathcal{L}(V)$ of $k[\sqrt{-a}]$-linear mappings from V into itself is a vector space over $k[\sqrt{-a}]$, and thus may be considered as a vector space over k too. The spaces of self-adjoint and anti-self-adjoint linear mappings from V into itself with respect to $b(\cdot, \cdot)$ are k-linear subspaces of $\mathcal{L}(V)$, which is to say that they are linear subspaces of $\mathcal{L}(V)$, as a vector space over k. If $T_1, T_2 \in \mathcal{L}(V)$ are anti-self-adjoint with respect to $b(\cdot, \cdot)$, then their commutator $[T_1, T_2] = T_1 \circ T_2 - T_2 \circ T_1$ with respect to composition is anti-self-adjoint with respect to $b(\cdot, \cdot)$ as well. This means that the space of anti-self-adjoint linear mappings from V into itself with respect to $b(\cdot, \cdot)$ is a Lie subalgebra of $gl(V)$ as a Lie algebra over k with respect to the commutator bracket.

Suppose from now on in this section that V has finite dimension as a vector space over $k[\sqrt{-a}]$. If $w \in V$, then

$$b_w(v) = b(v, w) \tag{12.2.4}$$

defines a linear functional on V, and $w \mapsto b_w$ is a conjugate-linear mapping from V into its dual space V'. The image

$$\{b_w : w \in V\} \tag{12.2.5}$$

of this mapping is a linear subspace of V', as a vector space over $k[\sqrt{-a}]$. As before, one can verify that (12.2.5) is equal to V' exactly when $w \mapsto b_w$ is injective, because V and V' have the same dimension as vector spaces over $k[\sqrt{-a}]$.

We say that $b(\cdot, \cdot)$ is *nondegenerate* as a sesquilinear form on V if for every $v \in V$ with $v \neq 0$ there is a $w \in V$ such that $b(v, w) \neq 0$. Equivalently, this means that the intersections of the kernels of the b_w's, $w \in V$, is the trivial subspace of V. This holds exactly when (12.2.5) is equal to V', as in the complex case.

Let $b(\cdot,\cdot)$ be a nondegenerate sesquilinear form on V, let T be a $k[\sqrt{-a}]$-linear mapping from V into itself, and let $w \in V$ be given. Thus $b(T(v), w)$ defines a linear functional on V, as a function of v, so that there is a unique element $T^*(w)$ of V such that

$$b(T(v), w) = b(v, T^*(w)) \tag{12.2.6}$$

for every $v \in V$. One can check that T^* is a $k[\sqrt{-a}]$-linear mapping from V into itself, which is called the *adjoint* of T with respect to $b(\cdot,\cdot)$. However, $T \mapsto T^*$ is conjugate-linear as a mapping from $\mathcal{L}(V)$ into itself, as a vector space over $k[\sqrt{-a}]$. Note that T is self-adjoint with respect to $b(\cdot,\cdot)$ when $T^* = T$, and that T is anti-self-adjoint with respect to $b(\cdot,\cdot)$ when $T^* = -T$. If $T_1, T_2 \in \mathcal{L}(V)$, then one can check that

$$(T_2 \circ T_1)^* = T_1^* \circ T_2^*, \tag{12.2.7}$$

as usual. If $b(\cdot,\cdot)$ is Hermitian-symmetric on V, then one can verify that

$$(T^*)^* = T \tag{12.2.8}$$

for every $T \in \mathcal{L}(V)$, as in Section 2.15.

12.3 Inner products over $k[\sqrt{-a}]$

Let k be an ordered field again, let a be a positive element of k, and let $k[\sqrt{-a}]$ be as in Section 12.1. Also let V be a vector space over $k[\sqrt{-a}]$, and let $\langle\cdot,\cdot\rangle_V$ be a Hermitian form on V, which is to say a Hermitian-symmetric sesquilinear form on V. Note that

$$\langle v, v\rangle_V \in k \tag{12.3.1}$$

for every $v \in V$, because $\overline{\langle v, v\rangle_V} = \langle v, v\rangle_V$, by Hermitian symmetry. Suppose that

$$\langle v, v\rangle_V > 0 \tag{12.3.2}$$

for every $v \in V$ with $v \neq 0$, in which case $\langle\cdot,\cdot\rangle_V$ is said to be an *inner product* on V. If $v, w \in V$ satisfy

$$\langle v, w\rangle_V = 0, \tag{12.3.3}$$

then v and w are said to be *orthogonal* with respect to $\langle\cdot,\cdot\rangle_V$, as usual.

Let $e_1, \ldots, e_n$ be finitely many pairwise-orthogonal nonzero vectors in V, and let $v \in V$ be given. Thus

$$w = \sum_{j=1}^{n} \frac{\langle v, e_j\rangle_V}{\langle e_j, e_j\rangle_V}\, e_j \tag{12.3.4}$$

is an element of the linear span of $e_1, \ldots, e_n$ in V, and

$$\langle w, e_l\rangle_V = \langle v, e_l\rangle_V \tag{12.3.5}$$

for every $l = 1, \ldots, n$. This means that $\langle w - v, e_l \rangle_V = 0$ for each $l = 1, \ldots, n$, so that

$$\langle w - v, u \rangle_V = 0 \tag{12.3.6}$$

for every element u of the linear span of $e_1, \ldots, e_n$ in V. If v is an element of the linear span of $e_1, \ldots, e_n$ in V, then it follows that $v = w$.

Let us suppose from now on in this section that V has positive finite dimension n, as a vector space over $k[\sqrt{-a}]$. Using the Gram–Schmidt process, one can get nonzero pairwise-orthogonal vectors $e_1, \ldots, e_n$ in V that form a basis for V. If $v \in V$, then

$$v = \sum_{j=1}^{n} \frac{\langle v, e_j \rangle_V}{\langle e_j, e_j \rangle_V} \, e_j, \tag{12.3.7}$$

as in the preceding paragraph. Let T be a linear mapping from V into itself, so that there is a unique $T^* \in \mathcal{L}(V)$ such that

$$\langle T(v), w \rangle_V = \langle v, T^*(w) \rangle_V \tag{12.3.8}$$

for every $v, w \in V$, as before. Of course,

$$T(e_l) = \sum_{j=1}^{n} \frac{\langle T(e_l), e_j \rangle_V}{\langle e_j, e_j \rangle_V} \, e_j \tag{12.3.9}$$

for every $l = 1, \ldots, n$, as in (12.3.7). This implies that

$$\mathrm{tr}_V T = \sum_{j=1}^{n} \frac{\langle T(e_j), e_j \rangle_V}{\langle e_j, e_j \rangle_V}. \tag{12.3.10}$$

Thus

$$\begin{aligned} \mathrm{tr}_V T^* = \sum_{j=1}^{n} \frac{\langle T^*(e_j), e_j \rangle_V}{\langle e_j, e_j \rangle_V} &= \sum_{j=1}^{n} \frac{\langle e_j, T(e_j) \rangle_V}{\langle e_j, e_j \rangle_V} \\ &= \sum_{j=1}^{n} \frac{\overline{\langle T(e_j), e_j \rangle_V}}{\langle e_j, e_j \rangle_V} = \overline{\mathrm{tr}_V T}. \end{aligned} \tag{12.3.11}$$

Put

$$\langle T_1, T_2 \rangle_{\mathcal{L}(V)} = \mathrm{tr}_V(T_1 \circ T_2^*) = \mathrm{tr}_V(T_2^* \circ T_1) \tag{12.3.12}$$

for every $T_1, T_2 \in \mathcal{L}(V)$. This defines a sesquilinear form on $\mathcal{L}(V)$, because $T \mapsto T^*$ is conjugate-linear on $\mathcal{L}(V)$. Observe that

$$\begin{aligned} \overline{\langle T_1, T_2 \rangle_{\mathcal{L}(V)}} = \overline{\mathrm{tr}_V(T_1 \circ T_2^*)} &= \mathrm{tr}_V(T_1 \circ T_2^*)^* \\ &= \mathrm{tr}_V(T_2 \circ T_1^*) = \langle T_2, T_1 \rangle_{\mathcal{L}(V)} \end{aligned} \tag{12.3.13}$$

for every $T_1, T_2 \in \mathcal{L}(V)$, using (12.3.11) in the second step. Thus (12.3.12) is Hermitian-symmetric on $\mathcal{L}(V)$. If $T \in \mathcal{L}(V)$, then

$$\langle T, T\rangle_{\mathcal{L}(V)} = \mathrm{tr}_V(T^* \circ T) = \sum_{j=1}^{n} \frac{\langle T^*(T(e_j))\rangle_V}{\langle e_j, e_j\rangle_V} = \sum_{j=1}^{n} \frac{\langle T(e_j), T(e_j)\rangle_V}{\langle e_j, e_j\rangle_V}. \tag{12.3.14}$$

This implies that $\langle T, T\rangle_{\mathcal{L}(V)} > 0$ when $T \neq 0$, because each of the terms on the right side of (12.3.14) is greater than or equal to 0 in k, and at least one term is strictly positive. It follows that (12.3.12) defines an inner product on $\mathcal{L}(V)$, as a vector space over $k[\sqrt{-a}]$.

Let $A \in \mathcal{L}(V)$ be given, and put

$$L_A(T) = A \circ T, \quad R_A(T) = T \circ A \tag{12.3.15}$$

for every $T \in \mathcal{L}(V)$, as before. As in Sections 11.8 and 11.9, we have that

$$\begin{aligned} \langle L_A(T_1), T_2\rangle_{\mathcal{L}(V)} &= \mathrm{tr}_V(A \circ T_1 \circ T_2^*) = \mathrm{tr}_V(T_1 \circ T_2^* \circ A) \\ &= \mathrm{tr}_V(T_1 \circ (A^* \circ T_2)^*) = \langle T_1, L_{A^*}(T_2)\rangle_{\mathcal{L}(V)} \end{aligned} \tag{12.3.16}$$

and

$$\begin{aligned} \langle R_A(T_1), T_2\rangle_{\mathcal{L}(V)} &= \mathrm{tr}_V(T_1 \circ A \circ T_2^*) = \mathrm{tr}_V(T_1 \circ (T_2 \circ A^*)^*) \\ &= \langle T_1, R_{A^*}(T_2)\rangle_{\mathcal{L}(V)} \end{aligned} \tag{12.3.17}$$

for every $T_1, T_2 \in \mathcal{L}(V)$. If we put

$$C_A(T) = [A, T] = L_A(T) - R_A(T) \tag{12.3.18}$$

for each $T \in \mathcal{L}(V)$, then we get that

$$\langle C_A(T_1), T_2\rangle_{\mathcal{L}(V)} = \langle T_1, C_{A^*}(T_2)\rangle_{\mathcal{L}(V)} \tag{12.3.19}$$

for every $T_1, T_2 \in \mathcal{L}(V)$, as before.

12.4 Self-adjointness in $gl(V)$

Let us continue with the same notation and hypotheses as in the previous section. We would like to consider the analogues of the remarks in Section 11.10 in this situation. Remember that $gl(V)$ is the same as $\mathcal{L}(V)$, considered as a Lie algebra over $k[\sqrt{-a}]$ with respect to the corresponding commutator bracket. If $R, T \in gl(V)$, then

$$C_R(T) = [R, T] = R \circ T - T \circ R \tag{12.4.1}$$

is the same as $\mathrm{ad}_{gl(V),R}(T)$. As before,

$$\langle C_R(T_1), T_2\rangle_{\mathcal{L}(V)} = \langle T_1, C_{R^*}(T_2)\rangle_{\mathcal{L}(V)} \tag{12.4.2}$$

for every $R, T_1, T_2 \in gl(V)$.

Let $\mathcal{A}$ be a Lie subalgebra of $gl(V)$, as a Lie algebra over $k[\sqrt{-a}]$. Thus, for each $R \in \mathcal{A}$, C_R maps $\mathcal{A}$ into itself, and the restriction of C_R to $\mathcal{A}$ is the same as $\mathrm{ad}_{\mathcal{A},R}$. Let $R_1, R_2 \in \mathcal{A}$ be given, so that

$$\mathrm{tr}_{\mathcal{A}}(\mathrm{ad}_{\mathcal{A},R_1} \circ \mathrm{ad}_{\mathcal{A},R_2}) = \mathrm{tr}_{\mathcal{A}}(C_{R_1} \circ C_{R_2}) \tag{12.4.3}$$

is the same as the Killing form on $\mathcal{A}$ evaluated at R_1, R_2, as before. This uses the trace on $\mathcal{A}$, as a finite-dimensional vector space over $k[\sqrt{-a}]$. More precisely, one should use the restrictions of C_{R_1} and C_{R_2} to $\mathcal{A}$ on the right side of (12.4.3).

If $\mathcal{A}$ is any subset of $\mathcal{L}(V)$, then let $\mathcal{A}^*$ be the subset of $\mathcal{L}(V)$ defined by

$$\mathcal{A}^* = \{T^* : T \in \mathcal{A}\}, \tag{12.4.4}$$

as before. Let us say that $\mathcal{A}$ is *self-adjoint* in $\mathcal{L}(V)$ when $\mathcal{A}^* = \mathcal{A}$. Let $\mathcal{A}$ be a Lie subalgebra of $gl(V)$ again, as a Lie algebra over $k[\sqrt{-a}]$, and suppose that $\mathcal{A}$ is self-adjoint in $\mathcal{L}(V)$. Let $R \in \mathcal{A}$ be given, so that $R^* \in \mathcal{A}$ too, and C_R and C_{R^*} both map $\mathcal{A}$ into itself. The restriction of C_{R^*} to $\mathcal{A}$ is the adjoint of the restriction of C_R to $\mathcal{A}$, as an inner product space over $k[\sqrt{-a}]$ with respect to the restriction of the inner product (12.3.12) on $\mathcal{L}(V)$ to $\mathcal{A}$.

Let $\mathcal{L}(A)$ be the space of all linear mappings from $\mathcal{A}$ into itself, which is in particular a vector space over $k[\sqrt{-a}]$. The restriction of the inner product (12.3.12) on $\mathcal{L}(V)$ to $\mathcal{A}$ defines an inner product on $\mathcal{A}$ as a vector space over $k[\sqrt{-a}]$, as before. If $Z \in \mathcal{L}(\mathcal{A})$, then let $Z^{\mathcal{A},*} \in \mathcal{L}(\mathcal{A})$ be the adjoint of Z with respect to this inner product. If $Z_1, Z_2 \in \mathcal{L}(\mathcal{A})$, then put

$$\langle Z_1, Z_2 \rangle_{\mathcal{L}(\mathcal{A})} = \mathrm{tr}_{\mathcal{A}}(Z_1 \circ Z_2^{\mathcal{A},*}). \tag{12.4.5}$$

This defines an inner product on $\mathcal{L}(\mathcal{A})$, as a vector space over $k[\sqrt{-a}]$, as in the previous section.

Let $R_1, R_2 \in \mathcal{A}$ be given, so that $R_2^* \in \mathcal{A}$ as well, and $\mathrm{ad}_{\mathcal{A},R_2^*}$ is the same as the adjoint of $\mathrm{ad}_{\mathcal{A},R_2}$ with respect to the inner product on $\mathcal{A}$ mentioned in the preceding paragraph. This implies that

$$\mathrm{tr}_{\mathcal{A}}(\mathrm{ad}_{\mathcal{A},R_1} \circ \mathrm{ad}_{\mathcal{A},R_2}) = \langle \mathrm{ad}_{\mathcal{A},R_1}, \mathrm{ad}_{\mathcal{A},R_2^*} \rangle_{\mathcal{L}(\mathcal{A})}, \tag{12.4.6}$$

where the right side is as in (12.4.5). If $R \in \mathcal{A}$, then we can take $R_1 = R$ and $R_2 = R^*$, to get that

$$\mathrm{tr}_{\mathcal{A}}(\mathrm{ad}_{\mathcal{A},R} \circ \mathrm{ad}_{\mathcal{A},R^*}) = \langle \mathrm{ad}_{\mathcal{A},R}, \mathrm{ad}_{\mathcal{A},R} \rangle_{\mathcal{L}(\mathcal{A})}. \tag{12.4.7}$$

The right side is automatically greater than or equal to 0 in k, because (12.4.5) is an inner product on $\mathcal{L}(\mathcal{A})$. Similarly, the right side is strictly positive when $\mathrm{ad}_{\mathcal{A},R} \neq 0$ on $\mathcal{A}$.

12.5 Projections and sesquilinear forms

Let k be an ordered field, let a be a positive element of k again, and let $k[\sqrt{-a}]$ be as in Section 12.1. Also let V be a vector space over the complex numbers, and let $b(v, w)$ be a sesquilinear form on V, as in Section 12.2. Suppose that V_0 is a finite-dimensional linear subspace of V, and that the restriction of $b(v, w)$ to $v, w \in V_0$ is nondegenerate on V_0. Let $z \in V$ be given, and put

$$\lambda_z(v) = b(v, z) \tag{12.5.1}$$

for every $v \in V_0$, so that λ_z defines a linear functional on V_0. As in Section 11.12, there is a unique element $P_0(z)$ of V_0 such that

$$\lambda_z(v) = b(v, P_0(z)) \tag{12.5.2}$$

for every $v \in V_0$, because $b(\cdot, \cdot)$ is nondegenerate on V_0. Equivalently,

$$b(v, z - P_0(z)) = 0 \tag{12.5.3}$$

for every $v \in V$. Of course,

$$P_0(z) = z \tag{12.5.4}$$

when $z \in V_0$. One can check that P_0 defines a linear mapping from V onto V_0, as before. Note that $P_0 \circ P_0 = P_0$, so that P_0 is a projection on V.

Let Z_0 be the kernel of P_0, and observe that

$$V_0 \cap Z_0 = \{0\}, \tag{12.5.5}$$

by (12.5.4). We also have that $z - P_0(z) \in Z_0$ for every $z \in V$, so that

$$V = V_0 + Z_0. \tag{12.5.6}$$

Thus V corresponds to the direct sum of V_0 and Z_0, as a vector space over $k[\sqrt{-a}]$. Note that Z_0 is the same as the set of $z \in V$ such that

$$b(v, z) = 0 \tag{12.5.7}$$

for every $v \in V_0$.

Suppose from now on in this section that $b(\cdot, \cdot)$ is Hermitian-symmetric on V. Using this and (12.5.7), we get that

$$b(z, v) = 0 \tag{12.5.8}$$

for every $v \in V_0$ and $z \in Z_0$. Let $u, w \in V$ be given, so that $P_0(u), P_0(w) \in V_0$, $u - P_0(u), w - P_0(w) \in Z_0$, and

$$b(P_0(u), w - P_0(w)) = b(u - P_0(u), P_0(w)) = 0. \tag{12.5.9}$$

Thus

$$b(u, w) = b(P_0(u), P_0(w)) + b(u - P_0(u), w - P_0(w)). \tag{12.5.10}$$

This means that $b(\cdot,\cdot)$ corresponds to the sesquilinear form on the direct sum of V_0 and Z_0 obtained from the restrictions of $b(\cdot,\cdot)$ to V_0 and Z_0.

Suppose that $x \in V$ satisfies

$$b(x,x) \neq 0, \tag{12.5.11}$$

and let V_0 be the linear span of x in V. Thus V_0 is a one-dimensional linear subspace of V, and the restriction of $b(\cdot,\cdot)$ to V_0 is nondegenerate on V_0. It follows that V corresponds to the direct sum of V_0 and another linear subspace Z_0, in such a way that $b(\cdot,\cdot)$ corresponds to the sesquilinear form on the direct sum obtained from the restrictions of $b(\cdot,\cdot)$ to V_0 and Z_0.

Suppose now that V has finite dimension as a vector space over $k[\sqrt{-a}]$. Repeating the previous argument, we can express V as the direct sum of finitely many one-dimensional subspaces on which $b(\cdot,\cdot) \not\equiv 0$, and perhaps an additional linear subspace W such that

$$b(w,w) = 0 \tag{12.5.12}$$

for every $w \in W$. We also have that $b(\cdot,\cdot)$ corresponds to the sesquilinear form on the direct sum obtained from the restrictions of $b(\cdot,\cdot)$ to these linear subspaces. One can check that $b(\cdot,\cdot) \equiv 0$ on W, using polarization arguments. If $b(\cdot,\cdot)$ is nondegenerate on V, then this additional subspace W is not needed.

12.6 Nondegenerate Hermitian forms

Let k be an ordered field, let a be a positive element of k, and let $k[\sqrt{-a}]$ be as in Section 12.1 again. Also let V be a vector space over $k[\sqrt{-a}]$ of positive finite dimension n, and let $\beta(\cdot,\cdot)$ be a nondegenerate Hermitian form on V. Under these conditions, there is a basis $e_1,\ldots,e_n$ for V such that

$$\beta(e_j,e_l) = 0 \tag{12.6.1}$$

when $j \neq l$, and for each $j = 1,\ldots,n$,

$$\beta(e_j,e_j) \neq 0, \tag{12.6.2}$$

as in the previous section. Note that

$$\beta(e_j,e_j) \in k \tag{12.6.3}$$

for each $j = 1,\ldots,n$, by Hermitian symmetry. If $k = \mathbf{R}$, then one choose the e_j's so that $\beta(e_j,e_j) = \pm 1$ for each $j = 1,\ldots,n$.

Each $v \in V$ can be expressed in a unique way as

$$v = \sum_{j=1}^{n} v_j\, e_j, \tag{12.6.4}$$

where $v_j \in k[\sqrt{-a}]$ for every $j = 1, \ldots, n$. Remember that the absolute value $|t|$ of $t \in k$ is defined as an element of k as in Section 8.13. If $v, w \in V$, then put

$$\langle v, w \rangle_V = \sum_{j=1}^{n} |\beta(e_j, e_j)|\, v_j\, \overline{w_j}, \tag{12.6.5}$$

where $w_j \in k[\sqrt{-a}]$ corresponds to w as in (12.6.4). This defines a Hermitian form on V, as a vector space over $k[\sqrt{-a}]$. In particular,

$$\langle v, v \rangle_V = \sum_{j=1}^{n} |\beta(e_j, e_j)|\, v_j\, \overline{v_j} \tag{12.6.6}$$

is an element of k for each $v \in V$. If $v \neq 0$, then it is easy to see that (12.6.6) is positive in k. Thus (12.6.5) defines an inner product on V, as a vector space over $k[\sqrt{-a}]$. Of course, the e_j's are orthogonal with respect to (12.6.5), by construction.

Let B be the unique linear mapping from V into itself such that

$$\begin{aligned} B(e_j) &= e_j \quad \text{when } \beta(e_j, e_j) > 0 \\ &= -e_j \quad \text{when } -\beta(e_j, e_j) > 0. \end{aligned} \tag{12.6.7}$$

Note that B^2 is the identity mapping $I = I_V$ on V. One can check that B is self-adjoint with respect to (12.6.5). It is easy to see that

$$\beta(v, w) = \langle B(v), w \rangle_V \tag{12.6.8}$$

when $v = e_j$ and $w = e_l$, $1 \leq j, l \leq n$. This implies that (12.6.8) holds for every $v, w \in V$.

Let T be a linear mapping from V into itself, and remember that the adjoint $T^{*,\beta} \in \mathcal{L}(V)$ of T with respect to $\beta(\cdot, \cdot)$ is characterized by the condition that

$$\beta(T(v), w) = \beta(v, T^{*,\beta}(w)) \tag{12.6.9}$$

for every $v, w \in V$. This is the same as saying that

$$\langle B(T(v)), w \rangle_V = \langle B(v), T^{*,\beta}(w) \rangle_V \tag{12.6.10}$$

for every $v, w \in V$, by (12.6.8). Equivalently, this means that

$$\langle B(T(v)), w \rangle_V = \langle v, B(T^{*,\beta}(w)) \rangle_V \tag{12.6.11}$$

for every $v, w \in V$, because B is self-adjoint with respect to (12.6.5). This is the same as asking that

$$(B \circ T)^* = B \circ T^{*,\beta}, \tag{12.6.12}$$

where the left side is the adjoint of $B \circ T$ with respect to the inner product (12.6.5). Thus

$$T^{*,\beta} = B^{-1} \circ (B \circ T)^* = B^{-1} \circ T^* \circ B^* = B^{-1} \circ T^* \circ B. \tag{12.6.13}$$

12.7 Real parts

Let k be an ordered field, let a be a positive element of k, and let $k[\sqrt{-a}]$ be as in Section 12.1, as before. If $z = x + y\sqrt{-a} \in k[\sqrt{-a}]$, with $x, y \in k$, then let us call

(12.7.1) $$\mathrm{Re}_{k[\sqrt{-a}]}\, z = x = (1/2)\,(z + \overline{z})$$

the *real part* of z. Note that

(12.7.2) $$\mathrm{Re}_{k[\sqrt{-a}]}(\sqrt{-a}\, z) = -a\, y = (\sqrt{-a}/2)\,(z - \overline{z}).$$

Let $V = V_{k[\sqrt{-a}]}$ be a finite-dimensional vector space over $k[\sqrt{-a}]$, and let $\langle \cdot, \cdot \rangle_{V_{k[\sqrt{-a}]}}$ be an inner product on V. We shall use V_k to denote V considered as a vector space over k. It is easy to see that

(12.7.3) $$\langle v, w \rangle_{V_k} = \mathrm{Re}_{k[\sqrt{-a}]}\,(\langle v, w \rangle_{V_{k[\sqrt{-a}]}})$$

defines an inner product on V_k, as a vector space over k.

Let $\mathcal{L}(V) = \mathcal{L}_{k[\sqrt{-a}]}(V_{k[\sqrt{-a}]})$ be the algebra of $k[\sqrt{-a}]$-linear mappings from V into itself, as usual, and let $\mathcal{L}_k(V_k)$ be the algebra of k-linear mappings from V into itself. If $T \in \mathcal{L}_{k[\sqrt{-a}]}(V_{k[\sqrt{-a}]})$, then its adjoint with respect to $\langle \cdot, \cdot \rangle_{V_{k[\sqrt{-a}]}}$ is the unique $k[\sqrt{-a}]$-linear mapping $T^{*, V_{k[\sqrt{-a}]}}$ from V into itself such that

(12.7.4) $$\langle T(v), w \rangle_{V_{k[\sqrt{-a}]}} = \langle v, T^{*, V_{k[\sqrt{-a}]}}(w) \rangle_{V_{k[\sqrt{-a}]}}$$

for every $v, w \in V$. Similarly, if $T \in \mathcal{L}_k(V_k)$, then its adjoint with respect to (12.7.3) is the unique k-linear mapping T^{*, V_k} from V into itself such that

(12.7.5) $$\langle T(v), w \rangle_{V_k} = \langle v, T^{*, V_k}(w) \rangle_{V_k}$$

for every $v, w \in V$. If $T \in \mathcal{L}_{k[\sqrt{-a}]}(V_{k[\sqrt{-a}]})$, then T may be considered as an element of $\mathcal{L}_k(V_k)$, and

(12.7.6) $$T^{*, V_k} = T^{*, V_{k[\sqrt{-a}]}}.$$

Put

(12.7.7) $$J_a(v) = \sqrt{-a}\, v$$

for every $v \in V$, which defines a $k[\sqrt{-a}]$-linear mapping from V into itself. By construction,

(12.7.8) $$J_a^2 = -a\, I,$$

where I is the identity mapping on V, and

(12.7.9) $$\langle J_a(v), w \rangle_{V_k} = \mathrm{Re}_{k[\sqrt{-a}]}\,(\sqrt{-a}\, \langle v, w \rangle_{V_{k[\sqrt{-a}]}})$$

for every $v, w \in V$. One can check that

(12.7.10) $$J_a^{*, V_k} = J_a^{*, V_{k[\sqrt{-a}]}} = -J_a.$$

This means that (12.7.9) is an antisymmetric bilinear form on V_k. Remember that a k-linear mapping from V into itself is linear over $k[\sqrt{-a}]$ exactly when it commutes with J_a.

Let $\beta_{V_{k[\sqrt{-a}]}}(\cdot,\cdot)$ be a sesquilinear form on $V_{k[\sqrt{-a}]}$, and put

$$\beta_{V_k}(v,w) = \mathrm{Re}_{k[\sqrt{-a}]}\,(\beta_{V_{k[\sqrt{-a}]}}(v,w)) \tag{12.7.11}$$

for every $v, w \in V$. This defines a bilinear form on V_k, which is to say a k-valued function on $V \times V$ that is bilinear over k. Observe that

$$\beta_{V_k}(J_a(v),w) = -\beta_{V_k}(v,J_a(w)) = \mathrm{Re}_{k[\sqrt{-a}]}\,(\sqrt{-a}\,\beta_{V_{\mathbf{C}}}(v,w)) \tag{12.7.12}$$

for every $v, w \in V$. If $\beta_{V_{k[\sqrt{-a}]}}(\cdot,\cdot)$ is Hermitian-symmetric on $V_{\mathbf{C}}$, then (12.7.11) is symmetric on $V_{\mathbf{R}}$, and (12.7.12) is antisymmetric on $V_{\mathbf{R}}$. Of course, (12.7.11) and (12.7.12) correspond to (12.7.3) and (12.7.9) when $\beta_{V_{\mathbf{C}}}(\cdot,\cdot) = \langle\cdot,\cdot\rangle_{V_{\mathbf{C}}}$.

Suppose now that $\beta_{V_{k[\sqrt{-a}]}}(\cdot,\cdot)$ is nondegenerate as a sesquilinear form on $V_{k[\sqrt{-a}]}$, which implies that (12.7.11) and (12.7.12) are nondegenerate as bilinear forms on V_k. If $T \in \mathcal{L}_{k[\sqrt{-a}]}(V_{k[\sqrt{-a}]})$, then there is a unique $T^{*,\beta_{V_{k[\sqrt{-a}]}}}$ in $\mathcal{L}_{k[\sqrt{-a}]}(V_{k[\sqrt{-a}]})$ such that

$$\beta_{V_{k[\sqrt{-a}]}}(T(v),w) = \beta_{V_{k[\sqrt{-a}]}}(v,T^{*,\beta_{V_{k[\sqrt{-a}]}}}(w)) \tag{12.7.13}$$

for every $v, w \in V$, as usual. Similarly, if $T \in \mathcal{L}_k(V_k)$, then there is a unique $T^{*,\beta_{V_k}} \in \mathcal{L}_k(V_k)$ such that

$$\beta_{V_k}(T(v),w) = \beta_{V_k}(v,T^{*,\beta_{V_k}}(w)) \tag{12.7.14}$$

for every $v, w \in V$. If $T \in \mathcal{L}_{k[\sqrt{-a}]}(V_{k[\sqrt{-a}]})$, then $T \in \mathcal{L}_k(V_k)$, and

$$T^{*,\beta_{V_{\mathbf{R}}}} = T^{*,\beta_{V_{\mathbf{C}}}}, \tag{12.7.15}$$

as before. In particular, $J_a^{*,\beta_{V_k}} = J_a^{*,\beta_{V_{k[\sqrt{-a}]}}} = -J_a$.

Let $\alpha_{V_k}(\cdot,\cdot)$ be a bilinear form on V_k such that

$$\alpha_{V_k}(J_a(v),w) = -\alpha_{V_k}(v,J_a(w)) \tag{12.7.16}$$

for every $v, w \in V$. Put

$$\alpha_{V_{k[\sqrt{-a}]}}(v,w) = \alpha_{V_k}(v,w) + (1/\sqrt{-a})\,\alpha_{V_k}(J_a(v),w) \tag{12.7.17}$$

for every $v, w \in V$. One can check that this defines a sesquilinear form on $V_{k[\sqrt{-a}]}$. If $\alpha_{V_k}(\cdot,\cdot)$ is symmetric on V_k, then (12.7.16) is antisymmetric on V_k, and (12.7.17) is Hermitian-symmetric on $V_{k[\sqrt{-a}]}$. If $\alpha_{V_k}(\cdot,\cdot)$ is nondegenerate on V_k, then (12.7.16) is nondegenerate on V_k, and (12.7.17) is nondegenerate on $V_{k[\sqrt{-a}]}$. If $\alpha_{V_k}(\cdot,\cdot)$ is an inner product on V_k, then (12.7.17) is an inner product on $V_{k[\sqrt{-a}]}$. If $\alpha_{V_k}(\cdot,\cdot)$ is equal to (12.7.11), then (12.7.17) is equal to $\beta_{V_{\mathbf{C}}}(\cdot,\cdot)$, by (12.7.12).

12.8 Bilinear forms over $k[\sqrt{-a}]$

Let k be an ordered field, let a be a positive element of k, and let $k[\sqrt{-a}]$ be as in Section 12.1, as usual. Also let $V = V_{k[\sqrt{-a}]}$ be a finite-dimensional vector space over $k[\sqrt{-a}]$ again, and let $\gamma_{V_{k[\sqrt{-a}]}}(\cdot,\cdot)$ be a bilinear form on $V_{k[\sqrt{-a}]}$, which is to say a $k[\sqrt{-a}]$-valued function on $V \times V$ that is bilinear over $k[\sqrt{-a}]$. It follows that

$$\gamma_{V_k}(v,w) = \mathrm{Re}_{k[\sqrt{-a}]}\,(\gamma_{V_{k[\sqrt{-a}]}}(v,w)) \tag{12.8.1}$$

defines a bilinear form on V_k, which is to say a k-valued function on $V \times V$ that is bilinear over k. Put $J_a(v) = \sqrt{-a}\,v$ for every $v \in V$, as in the previous section. Observe that

$$\gamma_{V_k}(J_a(v),w) = \gamma_{V_k}(v,J_a(w)) = \mathrm{Re}_{k[\sqrt{-a}]}\,(\sqrt{-a}\,\gamma_{V_{k[\sqrt{-a}]}}(v,w)) \tag{12.8.2}$$

for every $v,w \in V$. If $\gamma_{V_{k[\sqrt{-a}]}}(\cdot,\cdot)$ is symmetric or antisymmetric on $V_{k[\sqrt{-a}]}$, then (12.8.1) and (12.8.2) have the same property on V_k. If $\gamma_{V_{k[\sqrt{-a}]}}(\cdot,\cdot)$ is nondegenerate as a bilinear form on $V_{k[\sqrt{-a}]}$, then (12.8.1) and (12.8.2) are nondegenerate as bilinear forms on V_k.

Let $\alpha_{V_k}(\cdot,\cdot)$ be a bilinear form on V_k such that

$$\alpha_{V_k}(J_a(v),w) = \alpha_{V_k}(v,J_a(w)) \tag{12.8.3}$$

for every $v,w \in V$. Put

$$\alpha_{V_{k[\sqrt{-a}]}}(v,w) = \alpha_{V_k}(v,w) + (1/\sqrt{-a})\,\alpha_{V_k}(J_a(v),w) \tag{12.8.4}$$

for every $v,w \in V$. One can check that this defines a bilinear form on $V_{k[\sqrt{-a}]}$. If $\alpha_{V_k}(\cdot,\cdot)$ is symmetric or antisymmetric, then (12.8.3) and (12.8.4) have the same property. Similarly, if $\alpha_{V_k}(\cdot,\cdot)$ is nondegenerate, then (12.8.3) and (12.8.4) are nondegenerate.

Suppose for the moment that $\gamma_{V_{k[\sqrt{-a}]}}(\cdot,\cdot)$ is nondegenerate on $V_{k[\sqrt{-a}]}$, so that $\gamma_{V_k}(\cdot,\cdot)$ is nondegenerate on V_k. If $T \in \mathcal{L}_{k[\sqrt{-a}]}(V_{k[\sqrt{-a}]})$, then there is a unique $T^{*,\gamma_{V_{k[\sqrt{-a}]}}} \in \mathcal{L}_{k[\sqrt{-a}]}(V_{k[\sqrt{-a}]})$ such that

$$\gamma_{V_{k[\sqrt{-a}]}}(T(v),w) = \gamma_{V_{k[\sqrt{-a}]}}(v,T^{*,\gamma_{V_{k[\sqrt{-a}]}}}(w)) \tag{12.8.5}$$

for every $v,w \in V$. Similarly, if $T \in \mathcal{L}_k(V_k)$, then there is a unique $T^{*,\gamma_{V_k}}$ in $\mathcal{L}_k(V_k)$ such that

$$\gamma_{V_k}(T(v),w) = \gamma_{V_k}(v,T^{*,\gamma_{V_k}}(w)) \tag{12.8.6}$$

for every $v,w \in V$. If $T \in \mathcal{L}_{k[\sqrt{-a}]}(V_{k[\sqrt{-a}]})$, then $T \in \mathcal{L}_k(V_k)$, and

$$T^{*,\gamma_{V_k}} = T^{*,\gamma_{V_{k[\sqrt{-a}]}}}. \tag{12.8.7}$$

Note that

$$J_a^{*,\gamma_{V_k}} = J_a^{*,\gamma_{V_{k[\sqrt{-a}]}}} = J_a. \tag{12.8.8}$$

Let $\langle \cdot, \cdot \rangle_{V_{k[\sqrt{-a}]}}$ be an inner product on $V_{k[\sqrt{-a}]}$. If $w \in V$, then there is a unique element $C(w)$ of V such that

$$\gamma_{V_{k[\sqrt{-a}]}}(v, w) = \langle v, C(w) \rangle_{V_{k[\sqrt{-a}]}} \tag{12.8.9}$$

for every $v \in V$, by standard arguments. More precisely, the left side may be considered as a linear functional on $V_{k[\sqrt{-a}]}$ as a function of v, which can be represented in terms of the inner product as on the right side. It is easy to see that C is conjugate-linear as a mapping from V into itself, because the left side of (12.8.9) is linear over $k[\sqrt{-a}]$ in w, and the inner product $\langle \cdot, \cdot \rangle_{V_{k[\sqrt{-a}]}}$ is conjugate-linear in the second variable.

Suppose that $\gamma_{V_{k[\sqrt{-a}]}}(\cdot, \cdot)$ is nondegenerate on $V_{k[\sqrt{-a}]}$ again, which implies that C is a one-to-one mapping from V onto itself. If T is a $k[\sqrt{-a}]$-linear mapping from V into itself, then

$$\langle T(v), C(w) \rangle_{V_{k[\sqrt{-a}]}} = \langle v, C(T^{*, \gamma_{V_{k[\sqrt{-a}]}}}(w)) \rangle_{V_{k[\sqrt{-a}]}} \tag{12.8.10}$$

for every $v, w \in V$, by (12.8.5) and (12.8.9). We also have that

$$\langle T(v), C(w) \rangle_{V_{k[\sqrt{-a}]}} = \langle v, T^{*, V_{k[\sqrt{-a}]}}(C(w)) \rangle_{V_{k[\sqrt{-a}]}} \tag{12.8.11}$$

for every $v, w \in V$, where $T^{*, V_{k[\sqrt{-a}]}}$ is the adjoint of T with respect to the inner product $\langle \cdot, \cdot \rangle_{V_{k[\sqrt{-a}]}}$ on $V_{k[\sqrt{-a}]}$. It follows that

$$C \circ T^{*, \gamma_{V_{k[\sqrt{-a}]}}} = T^{*, V_{k[\sqrt{-a}]}} \circ C. \tag{12.8.12}$$

12.9 Conjugate-linearity and adjoints

Let k be an ordered field, let a be a positive element of k, and let $k[\sqrt{-a}]$ be as in Section 12.1. Also let $V = V_{k[\sqrt{-a}]}$ be a finite-dimensional vector space over $k[\sqrt{-a}]$, and let V_k be V considered as a vector space over k, as before. Note that the composition of two conjugate-linear mappings from V into itself is linear over $k[\sqrt{-a}]$. Similarly, the composition of a conjugate-linear mapping from V into itself with a $k[\sqrt{-a}]$-linear mapping from V into itself, in either order, is conjugate-linear.

Let $\langle \cdot, \cdot \rangle_{V_{k[\sqrt{-a}]}}$ be an inner product on $V_{k[\sqrt{-a}]}$, and let $\langle \cdot, \cdot \rangle_{V_k}$ be its real part, as in (12.7.3). Thus $\langle \cdot, \cdot \rangle_{V_k}$ is an inner product on V_k as a vector space over k, as before. Let C be a conjugate-linear mapping from V into itself, which is linear over k in particular. The adjoint C^{*, V_k} of C with respect to $\langle \cdot, \cdot \rangle_{V_k}$ is defined as a k-linear mapping from V into itself in the usual way. Remember that J_a is the mapping from V into itself defined by multiplication by $\sqrt{-a}$, as in (12.7.7). Conjugate-linearity of C means that

$$C \circ J_a = -J_a \circ C, \tag{12.9.1}$$

as in Section 12.1. This implies that

$$C^{*,V_k} \circ J_a = -J_a \circ C^{*,V_k}, \tag{12.9.2}$$

because $J_a^{*,V_k} = -J_a$, as in (12.7.10). This shows that C^{*,V_k} is conjugate-linear on V as well.

Observe that

$$\langle v, C(w) \rangle_{V_k} = \langle C^{*,V_k}(v), w \rangle_{V_k} = \langle w, C^{*,V_k}(v) \rangle_{V_k} \tag{12.9.3}$$

for every $v, w \in V$, by definition of the adjoint. In fact, we have that

$$\langle v, C(w) \rangle_{V_{k[\sqrt{-a}]}} = \langle w, C^{*,V_k}(v) \rangle_{V_{k[\sqrt{-a}]}} \tag{12.9.4}$$

for every $v, w \in V$. More precisely, the real parts of both sides are the same, by (12.9.3). One can get (12.9.4) using this and the fact that both sides are $k[\sqrt{-a}]$-linear in w. This gives another way to see the conjugate-linearity of C^{*,V_k} on V too.

Put

$$\gamma_{V_{k[\sqrt{-a}]}}(v, w) = \langle v, C(w) \rangle_{V_{k[\sqrt{-a}]}} \tag{12.9.5}$$

for every $v, w \in V$. This defines a bilinear form on $V_{k[\sqrt{-a}]}$, because C is conjugate-linear, and $\langle \cdot, \cdot \rangle_{V_{k[\sqrt{-a}]}}$ is sesquilinear. Similarly, put

$$\gamma_{V_k}(v, w) = \langle v, C(w) \rangle_{V_k} \tag{12.9.6}$$

for every $v, w \in V$, which is the same as the real part of (12.9.5). Thus

$$\gamma_{V_{k[\sqrt{-a}]}}(v, w) = \langle w, C^{*,V}(v) \rangle_{V_{k[\sqrt{-a}]}} \tag{12.9.7}$$

and

$$\gamma_{V_k}(v, w) = \langle w, C^{*,V_k}(v) \rangle_{V_k} \tag{12.9.8}$$

for every $v, w \in V$. It follows that the self-adjointness or anti-self-adjointness of C with respect to $\langle \cdot, \cdot \rangle_{V_k}$ is equivalent to the symmetry or anti-symmetry of (12.9.5), (12.9.6), as appropriate.

12.10 Antisymmetric forms over $k[\sqrt{-a}]$

Let k be an ordered field, let a be a positive element of k, and let $k[\sqrt{-a}]$ be as in Section 12.1. Also let V be a vector space over $k[\sqrt{-a}]$ of positive finite dimension, and let $\gamma(\cdot, \cdot)$ be a nondegenerate antisymmetric bilinear form on V. As in Section 11.13, there is a basis for V consisting of vectors $x_1, \ldots, x_n$, $y_1, \ldots, y_n$ for some positive integer n such that

$$\gamma(x_j, x_l) = \gamma(y_j, y_l) = 0 \tag{12.10.1}$$

for every $j, l = 1, \ldots, n$,

$$\gamma(x_j, y_l) = 0 \tag{12.10.2}$$

when $j \neq l$, and

$$\gamma(x_j, y_j) = 1 \tag{12.10.3}$$

for every $j = 1, \ldots, n$. It is easy to define an inner product on V, as a vector space over $k[\sqrt{-a}]$, for which $x_1, \ldots, x_n$, $y_1, \ldots, y_n$ are orthonormal, as in the next paragraph. Using this, we can express $\gamma(\cdot, \cdot)$ in terms of a conjugate-linear mapping C from V into itself, as in the previous sections.

Each $v \in V$ can be expressed in a unique way as

$$v = \sum_{j=1}^{n} v_{x_j}\, x_j + \sum_{j=1}^{n} v_{y_j}\, y_j, \tag{12.10.4}$$

where $v_{x_j}, v_{y_j} \in k[\sqrt{-a}]$ for every $j = 1, \ldots, n$. Similarly, if $w \in V$, then let $w_{x_j}, w_{y_j} \in k[\sqrt{-a}]$ be as in (12.10.4). Put

$$\langle v, w\rangle_V = \sum_{j=1}^{n} v_{x_j}\, \overline{w_{x_j}} + \sum_{j=1}^{n} v_{y_j}\, \overline{w_{y_j}} \tag{12.10.5}$$

for every $v, w \in V$. It is easy to see that this defines an inner product on V, as a vector space over $k[\sqrt{-a}]$. Note that $x_1, \ldots, x_n$, $y_1, \ldots, y_n$ are orthonormal in V with respect to (12.10.5), by construction.

Let C be the unique conjugate-linear mapping from V into itself such that

$$C(x_j) = -y_j, \quad C(y_j) = x_j \tag{12.10.6}$$

for each $j = 1, \ldots, n$. Thus, if $v \in V$ is as in (12.10.4), then

$$C(v) = -\sum_{j=1}^{n} \overline{v_j}\, y_j + \sum_{j=1}^{n} \overline{w_j}\, x_j. \tag{12.10.7}$$

One can verify that

$$\gamma(v, w) = \langle v, C(w)\rangle_V \tag{12.10.8}$$

for every $v, w \in V$. More precisely, one can first check that this holds when v, w are among the basis vectors $x_1, \ldots, x_n$, $y_1, \ldots, y_n$. This implies that (12.10.8) holds for all $v, w \in V$, because both sides of (12.10.8) are $k[\sqrt{-a}]$-linear in v and w.

Observe that

$$C^2 = -I_V, \tag{12.10.9}$$

where I_V is the identity mapping on V. Let V_k be V considered as a vector space over k, as before. Also let $\langle v, w\rangle_{V_k}$ be the real part of (12.10.5), which defines an inner product on V_k. One can check that C is anti-self-adjoint as a k-linear mapping from V into itself with respect to $\langle \cdot, \cdot\rangle_{V_k}$. This corresponds to the antisymmetry of (12.10.8) as a bilinear form on V, as in the previous section.

12.11 Symmetric forms over $k[\sqrt{-a}]$

Let k be an ordered field, let a be a positive element of k, and let $k[\sqrt{-a}]$ be as in Section 12.1 again. Also let V be a vector space over $k[\sqrt{-a}]$ of positive finite dimension n, and let $e_1, \ldots, e_n$ be a basis for V. Suppose that $\gamma(\cdot, \cdot)$ is a bilinear form on V such that

$$\gamma(e_j, e_l) = 0 \tag{12.11.1}$$

when $j \neq l$, and for each $j = 1, \ldots, n$,

$$\gamma(e_j, e_j) \neq 0 \tag{12.11.2}$$

and

$$\gamma(e_j, e_j) \in k. \tag{12.11.3}$$

Note that $\gamma(\cdot, \cdot)$ is symmetric and nondegenerate on V, because of (12.11.1) and (12.11.2). Conversely, it is well known that for any nondegenerate symmetric bilinear form on V, there is a basis for V for which (12.11.1) and (12.11.2) hold, as in Sections 11.12 and 11.14. Because of (12.11.3), we can reduce further to the case where

$$\gamma(e_j, e_j) > 0 \tag{12.11.4}$$

for every $j = 1, \ldots, n$, using scalar multiplication by $\sqrt{-a}$, when needed. If $k = \mathbf{R}$, so that $k[\sqrt{-a}] = \mathbf{C}$, then we can reduce directly to the case where

$$\gamma(e_j, e_j) = 1 \tag{12.11.5}$$

for every $j = 1, \ldots, n$, without asking that (12.11.3) hold.

Every $v \in V$ can be expressed in a unique way as

$$v = \sum_{j=1}^{n} v_j \, e_j, \tag{12.11.6}$$

where $v_j \in k[\sqrt{-a}]$ for each $j = 1, \ldots, n$. If $v, w \in V$, then put

$$\langle v, w \rangle_V = \sum_{j=1}^{n} |\gamma(e_j, e_j)| \, v_j \, \overline{w_j}, \tag{12.11.7}$$

where $w_j \in k[\sqrt{-a}]$ corresponds to w as in (12.11.6). Remember that the absolute value $|\gamma(e_j, e_j)|$ of $\gamma(e_j, e_j)$ is defined as an element of k as in Section 8.13. Of course, this is the same as $\gamma(e_j, e_j)$ when (12.11.4) holds. It is easy to see that (12.11.7) defines an inner product on V, for which the e_j's are pairwise orthogonal.

Let C be the unique conjugate-linear mapping from V into itself such that

$$\begin{aligned} C(e_j) &= e_j \quad \text{when } \gamma(e_j, e_j) > 0 \\ &= -e_j \quad \text{when } -\gamma(e_j, e_j) > 0. \end{aligned} \tag{12.11.8}$$

If (12.11.4) holds, then $C(e_j) = e_j$ for every $j = 1, \dots, n$, so that

$$C(v) = \sum_{j=1}^{n} \overline{v_j}\, e_j \tag{12.11.9}$$

for every $v \in V$ as in (12.11.6). Observe that

$$\langle v, C(w)\rangle_V = \sum_{j=1}^{n} \gamma(e_j, e_j)\, v_j\, w_j \tag{12.11.10}$$

for every $v, w \in V$. Using this, one can check that

$$\gamma(v, w) = \langle v, C(w)\rangle_V \tag{12.11.11}$$

for every $v, w \in V$. One can also verify that

$$C^2 = I_V, \tag{12.11.12}$$

where I_V is the identity mapping on V.

Let V_k be V considered as a vector space over k, as usual. The real part $\langle v, w\rangle_{V_k}$ of (12.11.7) defines an inner product on V_k, as before. One can check that C is self-adjoint with respect to $\langle \cdot, \cdot \rangle_{V_k}$, as a k-linear mapping from V into itself. This corresponds to the fact that (12.11.11) is symmetric on V, as in Section 12.9.

12.12 Nonnegative self-adjoint operators

Let $(V, \langle \cdot, \cdot \rangle_V)$ and $(W, \langle \cdot, \cdot \rangle_W)$ be finite-dimensional inner product spaces, both defined over the real numbers or both defined over the complex numbers, and let $\|\cdot\|_V$, $\|\cdot\|_W$ be the corresponding norms on V, W, respectively. Also let T be a linear mapping from V into W, and let T^* be the corresponding adjoint mapping from W into V. Thus $T^* \circ T$ maps V into itself, and it is easy to see that $T^* \circ T$ is self-adjoint. Observe that

$$\langle (T^* \circ T)(v), v\rangle_V = \langle T(v), T(v)\rangle_W = \|T(v)\|_W^2 \tag{12.12.1}$$

for every $v \in V$. Of course, one could consider infinite-dimensional Hilbert spaces as well.

Let A be a linear mapping from V into itself that is self-adjoint with respect to the inner product $\langle \cdot, \cdot \rangle$, so that

$$\langle A(v), w\rangle = \langle v, A(w)\rangle \tag{12.12.2}$$

for every $v, w \in V$. In the complex case, (12.12.2) implies that

$$\langle A(v), v\rangle = \langle v, A(v)\rangle = \overline{\langle A(v), v\rangle} \tag{12.12.3}$$

for every $v \in V$, so that $\langle A(v), v\rangle \in \mathbf{R}$ for every $v \in V$. In both the real and complex cases, A is said to be *nonnegative* on V if

$$\langle A(v), v\rangle \geq 0 \tag{12.12.4}$$

for every $v \in V$. Similarly, A is said to be *strictly positive* on V if

$$\langle A(v), v\rangle_V > 0 \tag{12.12.5}$$

for every $v \in V$ with $v \neq 0$. In particular, this implies that the kernel of A is trivial. If T is a linear mapping from V into W, as before, then $T^* \circ T$ is automatically nonnegative, by (12.12.1). More precisely, $T^* \circ T$ is strictly positive exactly when the kernel of T is trivial.

If A is any self-adjoint linear mapping from V into itself, then there is an orthonormal basis for V consisting of eigenvectors for A, because V has finite dimension. Note that the eigenvalues of A are real, even in the complex case. It is easy to see that A is nonnegative on V if and only if the eigenvalues of A are nonnegative real numbers. Similarly, A is strictly positive on V if and only if the eigenvalues of A are positive real numbers. If A is nonnegative on V and the kernel of A is trivial, then it follows that A is strictly positive on V.

If A is nonnegative on V, then there is a nonnegative self-adjoint linear mapping B from V into itself such that $B^2 = A$. This can be obtained using a diagonalization for A, as in the preceding paragraph. If A is strictly positive on V, then B is strictly positive on V as well. Note that B automatically commutes with A in this situation. More precisely, B commutes with any linear mapping C from V into itself that commutes with A. Indeed, if C commutes with A, then C maps the eigenspaces of A into themselves. On each eigenspace of A, B is equal to a nonnegative multiple of the identity, by construction.

Let B_1 be any nonnegative self-adjoint linear mapping from V into itself such that $B_1^2 = A$. Thus B_1 commutes with A, so that B_1 maps the eigenspaces of A into themselves. One can check that the restriction of B_1 to each eigenspace of A is a nonnegative multiple of the identity. This can be obtained using a diagonalization of B_1 with respect to an orthonormal basis for each eigenspace of A. It follows that B_1 is uniquely determined by A under these conditions.

12.13 Polar decompositions

Let us continue with the same notation and hypotheses as in the previous section. Let T be a linear mapping from V into W again, so that $T^* \circ T$ is a nonnegative self-adjoint linear mapping from V into itself. It follows that there is a unique nonnegative self-adjoint linear mapping R from V into itself such that

$$R^2 = T^* \circ T, \tag{12.13.1}$$

as in the previous section. If $u, v \in V$, then

$$\langle (T^* \circ T)(u), v\rangle_V = \langle T(u), T(v)\rangle_W \tag{12.13.2}$$

and

$$\langle R^2(u), v\rangle_V = \langle R(u), R(v)\rangle_V. \tag{12.13.3}$$

This implies that

$$\langle R(u), R(v)\rangle_V = \langle T(u), T(v)\rangle_W, \tag{12.13.4}$$

by (12.13.1). In particular,

$$\|R(v)\|_V = \|T(v)\|_W \tag{12.13.5}$$

for every $v \in V$, by taking $u = v$ in (12.13.4). Let us suppose from now on in this section that the kernel of T is trivial. This implies that the kernel of R is trivial too, by (12.13.5). Thus R is invertible as a mapping from V into itself, because V has finite dimension.

Put

$$U = T \circ R^{-1}, \tag{12.13.6}$$

which defines a linear mapping from V into W. If $v, v' \in V$, then

$$\langle U(R(v)), U(R(v'))\rangle_V = \langle T(v), T(v')\rangle_W = \langle R(v), R(v')\rangle_V, \tag{12.13.7}$$

using the definition of U in the first step, and (12.13.4) in the second step. This means that

$$\langle U(v), U(v')\rangle_W = \langle v, v'\rangle_V \tag{12.13.8}$$

for every $v, v' \in V$, because R is invertible on V. It follows that

$$\|U(v)\|_W = \|v\|_V \tag{12.13.9}$$

for every $v \in V$, by taking $v' = v$ in (12.13.8). Let us suppose from now on in this section that $V = W$. This implies that T maps V onto itself, because V has finite dimension. Thus U is a one-to-one mapping from V onto itself. More precisely,

$$U^{-1} = U^*, \tag{12.13.10}$$

because of (12.13.8), as in Section 3.8.

Suppose that T is *normal* on V, in the sense that T commutes with T^*. Of course, this implies that T commutes with $T^* \circ T$. It follows that R commutes with T, as in the previous section. This means that U commutes with R and T, by the definition of U.

Suppose for the moment that T is self-adjoint on V, which implies that T is normal in particular. In this case, we get that

$$U^2 = T^2 \circ R^{-2} = I, \tag{12.13.11}$$

the identity operator on V. Equivalently, one can check that U is self-adjoint in this situation.

Similarly, if T is anti-self-adjoint on V, then T is normal, and $T^* \circ T = -T^2$. This implies that

$$U^2 = T^2 \circ R^{-2} = -I. \tag{12.13.12}$$

Alternatively, one can verify directly that U is anti-self-adjoint in this case.

12.14 Bilinear forms and inner products

Let $(V, \langle \cdot, \cdot \rangle)$ be a finite-dimensional inner product space over the real numbers. If B is a linear mapping from V into itself, then

$$\beta(v, w) = \langle B(v), w \rangle \tag{12.14.1}$$

defines a bilinear form on V. Every bilinear form on V corresponds to a unique linear mapping on V in this way. Note that β is symmetric or antisymmetric on V exactly when B is self-adjoint or anti-self-adjoint on V with respect to $\langle \cdot, \cdot \rangle$, as appropriate. Let us suppose from now on that B is invertible on V, so that β is nondegenerate on V.

Of course, the adjoint B^* of B with respect to $\langle \cdot, \cdot \rangle$ is invertible on V too, because B is invertible. Note that $B \circ B^*$ is a strictly positive self-adjoint linear mapping from V into itself, which corresponds to taking $T = B^*$ in the previous section. As before, there is a unique nonnegative self-adjoint linear mapping A from V into itself such that

$$A^2 = B \circ B^*. \tag{12.14.2}$$

More precisely, A is invertible on V, so that A is strictly positive on V. Put

$$B_0 = A^{-1} \circ B, \tag{12.14.3}$$

which is invertible on V as well. By construction,

$$B_0 \circ B_0^* = A^{-1} \circ B \circ B^* \circ A^{-1} = I, \tag{12.14.4}$$

so that

$$B_0^{-1} = B_0^*. \tag{12.14.5}$$

If we take $T = B^*$ in the previous section, then A corresponds to R, and B_0 corresponds to U^*.

If B is normal on V, then A commutes with B, and hence B_0 commutes with A and B, as before. If B is self-adjoint on V, and normal in particular, then

$$B_0^2 = A^{-2} \circ B^2 = I. \tag{12.14.6}$$

Equivalently, one can check that B_0 is self-adjoint on V. Similarly, if B is anti-self-adjoint on V, then B is normal, and

$$B_0^2 = A^{-2} \circ B^2 = -I. \tag{12.14.7}$$

Alternatively, one can verify that B_0 is anti-self-adjoint in this case.

Clearly

$$B = A \circ B_0, \tag{12.14.8}$$

by (12.14.3). Put

$$\langle v, w \rangle_A = \langle A(v), w \rangle \tag{12.14.9}$$

for every $v, w \in V$. This defines an inner product on V, because A is strictly positive and self-adjoint on V. Observe that

$$\beta(v, w) = \langle B_0(v), w\rangle_A \tag{12.14.10}$$

for every $v, w \in V$. If B is normal with respect to $\langle \cdot, \cdot \rangle$ on V, then

$$\begin{aligned} \langle B_0(v), w\rangle_A = \langle A(B_0(v)), w\rangle &= \langle B_0(A(v)), w\rangle \\ &= \langle A(v), B_0^*(w)\rangle = \langle v, B_0^*(w)\rangle_A \end{aligned} \tag{12.14.11}$$

for every $v, w \in V$, because B_0 commutes with A.

Now let $(V, \langle \cdot, \cdot \rangle)$ be a finite-dimensional inner product space over the complex numbers. If B is a linear mapping from V into itself, then (12.14.1) defines a sesquilinear form β on V, and every sesquilinear form on V corresponds to a unique linear mapping from V into itself in this way. One can check that β is Hermitian-symmetric on V exactly when B is self-adjoint on V with respect to $\langle \cdot, \cdot \rangle$. Suppose from now on in this section that B is invertible on V, so that β is nondegenerate on V. This implies that the adjoint B^* of B with respect to $\langle \cdot, \cdot \rangle$ is invertible on V as well.

As before, $B \circ B^*$ is a strictly positive self-adjoint linear mapping from V into itself. Hence there is a unique nonnegative self-adjoint linear mapping A from V into itself that satisfies (12.14.2). In fact, A is invertible on V, and strictly positive. Let B_0 be as in (12.14.3), which is invertible on V, with inverse equal to B_0^*, as in (12.14.5). If B is normal on V, then A commutes with B, and B_0 commutes with A and B. If B is self-adjoint on V, then B is normal, and

$$B_0^2 = I. \tag{12.14.12}$$

Alternatively, one can check directly that B_0 is self-adjoint in this case.

Let $\langle v, w\rangle_A$ be defined for $v, w \in V$ as in (12.14.9), which defines an inner product on V, because A is strictly positive and self-adjoint on V. Thus (12.14.10) holds for every $v, w \in V$ again, by construction. If B is normal on V with respect to $\langle \cdot, \cdot \rangle$, then the adjoint of B_0 with respect to $\langle \cdot, \cdot \rangle_A$ is the same as the adjoint with respect to $\langle \cdot, \cdot \rangle$, as in (12.14.11).

12.15 Complex bilinear forms

Let $(V, \langle \cdot, \cdot \rangle)$ be a finite-dimensional inner product space over the complex numbers again. If C is a conjugate-linear mapping from V into itself, then

$$\gamma(v, w) = \langle v, C(w)\rangle \tag{12.15.1}$$

is a bilinear form on V, as before. Every bilinear form on V corresponds to a conjugate-linear mapping C on V in this way, as in Section 12.8.

Let $V_{\mathbf{R}}$ be V considered as a vector space over the real numbers, and let $\langle \cdot, \cdot \rangle_{V_{\mathbf{R}}}$ be the real part of $\langle \cdot, \cdot \rangle$, which is an inner product on $V_{\mathbf{R}}$. Also let C be a conjugate-linear mapping from V into itself, and let $C^{*, V_{\mathbf{R}}}$ be the adjoint of C, as a real-linear mapping from V into itself, with respect to $\langle \cdot, \cdot \rangle_{V_{\mathbf{R}}}$. Thus $C^{*,V_{\mathbf{R}}}$ is conjugate-linear on V too, as in Section 12.9. It follows that $C \circ C^{*,V_{\mathbf{R}}}$ is a complex-linear mapping from V into itself, as before.

Note that $C \circ C^{*,V_{\mathbf{R}}}$ is nonnegative and self-adjoint with respect to $\langle \cdot, \cdot \rangle_{V_{\mathbf{R}}}$. This implies that there is a unique real-linear mapping A from V into itself that is nonnegative and self-adjoint with respect $\langle \cdot, \cdot \rangle_{V_{\mathbf{R}}}$ and satisfies

$$A^2 = C \circ C^{*,V_{\mathbf{R}}}. \tag{12.15.2}$$

Remember that A commutes with any real-linear mapping from V into itself that commutes with $C \circ C^{*,V_{\mathbf{R}}}$. In particular, A commutes with the mapping J from V into itself that corresponds to multiplication by i, because $C \circ C^{*,V_{\mathbf{R}}}$ is complex linear. This means that A is complex linear on V as well, and one can check that A is self-adjoint and nonnegative with respect to $\langle \cdot, \cdot \rangle$.

Alternatively, $C \circ C^{*,V_{\mathbf{R}}}$ is self-adjoint as a complex-linear mapping from V into itself with respect to $\langle \cdot, \cdot \rangle$, because $C \circ C^{*,V_{\mathbf{R}}}$ is complex linear and self-adjoint as a real-linear mapping from V into itself with respect to $\langle \cdot, \cdot \rangle_{V_{\mathbf{R}}}$, as in Section 12.7. Similarly, it is easy to see that $C \circ C^{*,V_{\mathbf{R}}}$ is nonnegative as a self-adjoint complex-linear mapping from V into itself with respect to $\langle \cdot, \cdot \rangle$, because $C \circ C^{*,V_{\mathbf{R}}}$ is nonnegative as a self-adjoint real-linear mapping from V into itself with respect to $\langle \cdot, \cdot \rangle_{V_{\mathbf{R}}}$. Thus one can take A to be the unique complex-linear mapping from V into itself that is nonnegative and self-adjoint with respect to $\langle \cdot, \cdot \rangle$ and satisfies (12.15.2).

Suppose from now on in this section that C is invertible on V, so that (12.15.1) is nondegenerate as a bilinear form on V. This implies that $C^{*,V_{\mathbf{R}}}$ is invertible on V too, and that $C \circ C^{*,V_{\mathbf{R}}}$ is strictly positive on V with respect to $\langle \cdot, \cdot \rangle_{V_{\mathbf{R}}}$, and hence with respect to $\langle \cdot, \cdot \rangle$. It follows that A is invertible on V, and strictly positive with respect to $\langle \cdot, \cdot \rangle_{V_{\mathbf{R}}}$, $\langle \cdot, \cdot \rangle$. Thus

$$\langle v, w \rangle_{V_{\mathbf{R}},A} = \langle A(v), w \rangle_{V_{\mathbf{R}}} \tag{12.15.3}$$

defines an inner product on $V_{\mathbf{R}}$, and

$$\langle v, w \rangle_A = \langle A(v), w \rangle \tag{12.15.4}$$

defines an inner product on V. Of course,

$$\langle v, w \rangle_{V_{\mathbf{R}},A} = \operatorname{Re} \langle v, w \rangle_A \tag{12.15.5}$$

for every $v, w \in V$, by construction.

Put

$$C_0 = A^{-1} \circ C, \tag{12.15.6}$$

which is invertible as a real-linear mapping on V. In fact, C_0 is conjugate-linear on V, because A is complex-linear and C is conjugate-linear. As before, $C_0 \circ C_0^{*,V_{\mathbf{R}}} = I$, so that

$$C_0^{-1} = C_0^{*,V_{\mathbf{R}}}. \tag{12.15.7}$$

Of course, $C = A \circ C_0$, so that

$$\begin{aligned} \gamma(v,w) = \langle v, C(w)\rangle &= \langle v, A(C_0(w))\rangle \\ &= \langle A(v), C_0(w)\rangle = \langle v, C_0(w)\rangle_A \end{aligned} \tag{12.15.8}$$

for every $v, w \in V$.

Suppose for the moment that C is normal with respect to $\langle \cdot, \cdot \rangle_{V_{\mathbf{R}}}$, so that C commutes with $C^{*,V_{\mathbf{R}}}$. This implies that C commutes with $C \circ C^{*,V_{\mathbf{R}}}$, and hence that A commutes with C. It follows that C_0 commutes with A and C in this situation. Thus

$$\begin{aligned} \langle C_0(v), w\rangle_{V_{\mathbf{R}},A} &= \langle A(C_0(v)), w\rangle_{V_{\mathbf{R}}} = \langle C_0(A(v)), w\rangle_{V_{\mathbf{R}}} \\ &= \langle A(v), C_0^{*,V_{\mathbf{R}}}(w)\rangle_{V_{\mathbf{R}}} = \langle v, C_0^{*,V_{\mathbf{R}}}(w)\rangle_{V_{\mathbf{R}},A} \end{aligned} \tag{12.15.9}$$

for every $v, w \in V$. This means that the adjoint of C_0 with respect to $\langle \cdot, \cdot \rangle_{V_{\mathbf{R}},A}$ is the same as $C_0^{*,V_{\mathbf{R}}}$ in this case.

If $\gamma(\cdot, \cdot)$ is symmetric or antisymmetric on V, then

$$\gamma_{\mathbf{R}}(v,w) = \operatorname{Re}\gamma(v,w) = \langle v, C(w)\rangle_{V_{\mathbf{R}}} \tag{12.15.10}$$

has the analogous property as a bilinear form on $V_{\mathbf{R}}$. This means that C is self-adjoint or antiself-adjoint with respect to $\langle \cdot, \cdot \rangle_{V_{\mathbf{R}}}$. In both cases, C is normal with respect to $\langle \cdot, \cdot \rangle_{V_{\mathbf{R}}}$. If C is self-adjoint with respect to $\langle \cdot, \cdot \rangle_{V_{\mathbf{R}}}$, then C_0 is self-adjoint with respect to $\langle \cdot, \cdot \rangle_{V_{\mathbf{R}}}$, and

$$C_0^2 = I, \tag{12.15.11}$$

as in the previous section. Similarly, if C is anti-self-adjoint with respect to $\langle \cdot, \cdot \rangle_{V_{\mathbf{R}}}$, then C_0 is anti-self-adjoint with respect to $\langle \cdot, \cdot \rangle_{V_{\mathbf{R}}}$, and

$$C_0^2 = -I. \tag{12.15.12}$$

Chapter 13

Semisimplicity

13.1 Semisimple modules

Let k be a commutative ring with a multiplicative identity element, let A, V be modules over k, and let ρ be a bilinear action of A on V, as in Section 6.1. Suppose that V corresponds to the direct sum of a family of submodules, as a module over k, where each of these submodules is mapped into itself by the action of ρ. Suppose also that the action of ρ on each of these submodules is irreducible, or equivalently that each of these submodules is simple with respect to the action of ρ, as in Section 6.14. Under these conditions, ρ is said to be *completely reducible* on V, or equivalently V is said to be *semisimple* with respect to the action of ρ.

In particular, these notions may be applied to representations of associative algebras over k, or to Lie algebras over k. Equivalently, one may consider modules over associative algebras over k, or Lie algebras over k. One can always reduce to the case of a representation of an associative algebra, using the algebra of homomorphisms from V into itself, as a module over k, generated by the mappings on V defined by the bilinear action. Of course, one may include the identity mapping on V in this algebra, without affecting the invariant submodules.

Let V_0 be a submodule of V, as a module over k, that is mapped into itself by the action of ρ on V. Consider the following condition on V_0:

(13.1.1) V corresponds to the direct sum of V_0 and another submodule V_1, as a module over k, where V_1 is also invariant under the action of ρ on V.

In fact, ρ is completely reducible on V exactly when this condition holds for all such V_0. This is Proposition 4.1 on p11 of [5] for modules over rings. This corresponds to a remark at the bottom of p45 of [25] for representations of Lie algebras as well.

Indeed, suppose that V corresponds to the direct sum of a family $\{V_j\}_{j \in I}$ of submodules, as a module over k, where for each $j \in I$, V_j is mapped into itself by the action of ρ on V, and V_j is irreducible under the action of ρ. If $I_0 \subseteq I$, then let $V(I_0)$ be the submodule of V generated by V_j, $j \in I_0$. Let W be a submodule of V, as a module over k, that is mapped into itself by the action of ρ on V. Under these conditions, there is an $I_1 \subseteq I$ such that

$$V(I_1) \cap W = \{0\}, \tag{13.1.2}$$

and I_1 is maximal with respect to inclusion. More precisely, one can find such an I_1 in a fairly straightforward way when I has only finitely or countably many elements, and otherwise one can use Zorn's lemma or Hausdorff's maximality principle.

If $j \in I \setminus I_1$, then

$$V(I_1 \cup \{j\}) \cap W \neq \{0\}, \tag{13.1.3}$$

by the maximality of I_1. Thus there is a nonzero element of W that can be expressed as the sum of elements of $V(I_1)$ and V_j, and this element of V_j has to be nonzero, by (13.1.2). This means that there is a nonzero element of V_j that can be expressed as a sum of elements of $V(I_1)$ and W, so that

$$V_j \cap (V(I_1) + W) \neq \{0\}. \tag{13.1.4}$$

It follows that

$$V_j \subseteq V(I_1) + W, \tag{13.1.5}$$

because $V_j \cap (V(I_1) + W)$ is a submodule of V, as a module over k, that is invariant under the action of ρ, and V_j is irreducible with respect to the action of ρ. This implies that

$$V = V(I_1) + W, \tag{13.1.6}$$

so that V corresponds to the direct sum of $V(I_1)$ and W, as a module over k, by (13.1.2).

Before considering the converse, note that (13.1.1) holds for a submodule V_0 of V, as a module over k, that is mapped into itself by the action of ρ on V, if and only if

(13.1.7) there is a homomorphism ϕ_0 from V onto V_0, as modules over k, that intertwines the action of ρ on V, and is equal to the identity mapping on V_0.

Of course, if (13.1.1) holds, then one can take ϕ_0 to be the corresponding projection from V onto V_0. If (13.1.7) holds, then one can take V_1 to be the kernel of ϕ_0 in (13.1.1).

Suppose now that (13.1.1) holds for every submodule V_0 of V, as a module over k, that is mapped into itself by the action of ρ on V, so that (13.1.7) holds for every such V_0. Let W be a submodule of V, and let W_0 be a submodule of W, as modules over k, such that W and W_0 are mapped into themselves by the action of ρ on V. Using (13.1.7) with $V_0 = W_0$, we get a homomorphism from V onto W_0, as modules over k, that intertwines the action of ρ on V, and is equal to the identity mapping on W_0. The restriction of this homomorphism to W is a homomorphism from W onto W_0, as modules over k, that intertwines the action of ρ on W, and is equal to the identity mapping on W_0. This implies that W corresponds to the direct sum of W_0 and another submodule W_1, as a module over k, where W_1 is also mapped into itself by the action of ρ, as before.

If k is a field, and V has finite dimension, as a vector space over k, then it is easy to get that ρ is completely reducible on V, using the remarks in the preceding paragraph. Otherwise, complete reducibility can be obtained as in Proposition 4.1 on p11 of [5].

13.2 Complete reducibility

Let k be a field of characteristic 0, and let A be a Lie algebra over k with finite dimension as a vector space over k. Suppose that A is semisimple as a Lie algebra over k.

Remember that $[A, A] = A$, as in Section 10.15. This implies that any representation of A on a one-dimensional vector space over k is trivial, as in the lemma on p28 of [14], and remarked on p47 of [25].

A famous theorem going back to Weyl states that every finite-dimensional representation of A is completely reducible, as on p28 of [14] and p46 of [25]. In order to prove this, we shall begin with the following splitting principle. Weyl's theorem will be obtained from this in Section 13.7.

Let V be a finite-dimensional module over A, and suppose that W is a submodule of V, as a module over A, such that W has codimension one in V as a vector space over k. This means that the quotient space V/W has dimension one as a vector space over k, so that the induced action of A on V/W is trivial, as before. Equivalently, the action of A on V actually maps V into W. Under these conditions, we would like to show that V corresponds to the direct sum of W and a one-dimensional submodule of V, as a module over A.

The case where W is irreducible as a module over A will be discussed in Section 13.6. This will use a suitable Casimir element, which will be discussed in the next two sections.

To reduce to the case where W is irreducible, we use induction on the dimension of W. Suppose that W is not irreducible as a module over A, so that there is a proper nonzero submodule Z of W, as a module over A. Under these conditions, V/Z is an module over A too, W/Z is a submodule of V/Z, as a module over A, and W/Z has codimension one in V/Z, as a vector space over k. The dimension of W/Z is strictly less than the dimension of W, as vector spaces over k. Using induction, we get that V/Z corresponds to the direct sum of W/Z and a one-dimensional submodule of V/Z, as a module over A.

This one-dimensional submodule of V/Z can be expressed as U/Z, where U is a linear subspace of V that contains Z as a codimension-one subspace, and U is a submodule of V, as a module over A. Note that the dimension of Z

is strictly less than the dimension of W, as vector spaces over k. Using the induction hypothesis again, we get that U corresponds to the direct sum of Z and a one-dimensional submodule of U, as a module over A. One can check that V corresponds to the direct sum of W and this one-dimensional submodule of U, as desired.

13.3 Casimir elements

Let k be a field, and let $(A, [\cdot, \cdot]_A)$ be a Lie algebra over k. Suppose that A has positive finite dimension n as a vector space over k, and let β be a nondegenerate symmetric bilinear form on A. Suppose also that β is associative on A, or equivalently that β is invariant with respect to the adjoint representation on A, so that

$$\beta([x, w]_A, y) = \beta(x, [w, y]_A) \tag{13.3.1}$$

for every $w, x, y \in A$, as in Sections 6.10 and 7.11. Let $u_1, \ldots, u_n$ be a basis for A, as a vector space over k. Under these conditions, there is a basis $w_1, \ldots, w_n$ for A such that

$$\beta(u_j, w_l) = \delta_{j,l} \tag{13.3.2}$$

for every $j, l = 1, \ldots, n$. Here $\delta_{j,l} \in k$ is equal to 1 when $j = l$, and to 0 when $j \neq l$, as usual. This is the dual basis for A with respect to β.

Let $x \in A$ be given, and let $(a_{j,l})$ and $(b_{j,l})$ be the $n \times n$ matrices with entries in k such that

$$[x, u_j]_A = \sum_{l=1}^{n} a_{j,l}\, u_l \tag{13.3.3}$$

and

$$[x, w_j]_A = \sum_{l=1}^{n} b_{j,l}\, w_l \tag{13.3.4}$$

for every $j = 1, \ldots, n$. Observe that

$$\beta([x, u_j]_A, w_r) = \sum_{l=1}^{n} a_{j,l}\, \beta(u_l, w_r) = a_{j,r} \tag{13.3.5}$$

for every $j, r = 1, \ldots, n$, and similarly

$$\beta(u_j, [x, w_r]_A) = \sum_{l=1}^{n} b_{r,l}\, \beta(u_j, w_l) = b_{r,j} \tag{13.3.6}$$

for every $j, r = 1, \ldots, n$. Using (13.3.1), we get that

$$a_{j,r} = -b_{r,j} \tag{13.3.7}$$

for every $j, r = 1, \ldots, n$.

Let V be a vector space over k, and let ρ be a representation of A on V. Put

$$c_\rho(\beta) = \sum_{j=1}^n \rho_{u_j} \circ \rho_{w_j}, \tag{13.3.8}$$

which defines a linear mapping from V into itself. This is the *Casimir element* of the space $\mathcal{L}(V)$ of linear mappings from V into itself associated to β and ρ. If $x \in A$ is as in the preceding paragraph, then

$$[\rho_x, c_\rho(\beta)] = \sum_{j=1}^n [\rho_x, \rho_{u_j} \circ \rho_{w_j}], \tag{13.3.9}$$

using the commutator bracket on $\mathcal{L}(V)$ corresponding to composition of linear mappings on V. It follows that

$$[\rho_x, c_\rho(\beta)] = \sum_{j=1}^n [\rho_x, \rho_{u_j}] \circ \rho_{w_j} + \sum_{j=1}^n \rho_{u_j} \circ [\rho_x, \rho_{w_j}], \tag{13.3.10}$$

as in Section 2.5. Because ρ is a Lie algebra representation, we get that

$$\begin{aligned} [\rho_x, c_\rho(\beta)] &= \sum_{j=1}^n \rho_{[x,u_j]_A} \circ \rho_{w_j} + \sum_{j=1}^n \rho_{u_j} \circ \rho_{[x,w_j]_A} \\ &= \sum_{j=1}^n \sum_{l=1}^n a_{j,l}\, \rho_{u_l} \circ \rho_{w_j} + \sum_{j=1}^n \sum_{l=1}^n b_{j,l}\, \rho_{u_j} \circ \rho_{w_l} = 0, \end{aligned} \tag{13.3.11}$$

using (13.3.3) and (13.3.4) in the second step, and (13.3.7) in the third step. This corresponds to part of the discussion on p27 of [14].

Let $u_1', \ldots, u_n'$ and $w_1', \ldots, w_n'$ be bases for A as a vector space over k. We can express these bases in terms of the u_j's and w_l's, so that

$$u_h' = \sum_{j=1}^n \mu_{h,j}\, u_j \tag{13.3.12}$$

for every $h = 1, \ldots, n$ and

$$w_r' = \sum_{l=1}^n \nu_{r,l}\, w_l \tag{13.3.13}$$

for every $r = 1, \ldots, n$, where $\mu = (\mu_{h,j})$ and $\nu = (\nu_{r,l})$ are invertible $n \times n$ matrices with entries in k. Thus

$$\begin{aligned} \beta(u_h', w_r') &= \sum_{j=1}^n \sum_{l=1}^n \mu_{h,j}\, \nu_{r,l}\, \beta(u_j, w_l) \\ &= \sum_{j=1}^n \sum_{l=1}^n \mu_{h,j}\, \nu_{r,l}\, \delta_{j,l} = \sum_{j=1}^n \mu_{h,j}\, \nu_{r,j} \end{aligned} \tag{13.3.14}$$

for every $h, r = 1, \ldots, n$, using (13.3.2) in the second step. It follows that

$$\beta(u'_h, w'_r) = \delta_{h,r} \tag{13.3.15}$$

for every $h, r = 1, \ldots, n$ if and only if

$$\sum_{j=1}^{n} \mu_{h,j}\, \nu_{r,j} = \delta_{h,r} \tag{13.3.16}$$

for every $h, r = 1, \ldots, n$. Of course, (13.3.16) is the same as saying that μ times the transpose of ν is the identity matrix. This is equivalent to the condition that the transpose of ν times μ be the identity matrix, which means that

$$\sum_{h=1}^{n} \nu_{h,l}\, \mu_{h,j} = \delta_{l,j} \tag{13.3.17}$$

for every $j, l = 1, \ldots, n$. If ρ is as in the previous paragraph, then

$$\sum_{h=1}^{n} \rho_{u'_h} \circ \rho_{w'_h} = \sum_{h=1}^{n} \sum_{j=1}^{n} \sum_{l=1}^{n} \mu_{h,j}\, \nu_{h,l}\, \rho_{u_j} \circ \rho_{w_l}. \tag{13.3.18}$$

If (13.3.17) holds, then we get that

$$\sum_{h=1}^{n} \rho_{u'_h} \circ \rho_{w'_h} = \sum_{j=1}^{n} \sum_{l=1}^{n} \delta_{l,j}\, \rho_{u_j} \circ \rho_{w_l} = \sum_{j=1}^{n} \rho_{u_j} \circ \rho_{w_j}, \tag{13.3.19}$$

which is the same as (13.3.8).

The hypothesis that β be symmetric on A does not seem to have been used so far, but it does give some additional properties. If β is symmetric on A, then the conditions on $u_1, \ldots, u_n$ and $w_1, \ldots, w_n$ are symmetric in these two bases for A.

13.4 Another perspective

Let us continue with the same notation and hypotheses as in the previous section. Let A' be the space of linear functionals on A, as a vector space over k. Remember that the tensor products $A \bigotimes A$ and $A \bigotimes A'$ can be defined as vector spaces over k, as in Section 7.12. The product of an element of A and a linear functional on A defines a linear mapping from A into itself. This defines a bilinear mapping from $A \times A'$ into the space $\mathcal{L}(A)$ of linear mappings from A into itself, as a vector space over k. This leads to a linear mapping from $A \bigotimes A'$ into $\mathcal{L}(A)$, which is an isomorphism in this case, because A has finite dimension as a vector space over k. If $z \in A$, then

$$\beta_z(x) = \beta(x, z) \tag{13.4.1}$$

defines a linear functional on A, and $z \mapsto \beta_z$ is a linear mapping from A into A'. More precisely, $z \mapsto \beta_z$ is a one-to-one linear mapping from A onto A', because β is nondegenerate on A. This leads to a one-to-one linear mapping from $A \bigotimes A$ onto $A \bigotimes A'$.

The condition (13.3.2) on the bases $u_1, \ldots, u_n$ and $w_1, \ldots, w_n$ for A is the same as saying that

$$\sum_{j=1}^{n} u_j \, \beta(x, w_j) = x \tag{13.4.2}$$

for every $x \in A$. Consider

$$\sum_{j=1}^{n} u_j \otimes w_j, \tag{13.4.3}$$

as an element of $A \bigotimes A$. This corresponds to the identity mapping on A under the isomorphisms mentioned in the preceding paragraph, because of (13.4.2). Remember that A may be considered as a module over itself, as a Lie algebra over k, using the adjoint representation. It follows that A', $\mathcal{A}$, and the related tensor products may be considered as modules over A too, in the usual way. The invariance condition on β implies that $z \mapsto \beta_z$ is a homomorphism from A into A', as modules over A. One can use this to get that (13.4.3) is invariant under the corresponding representation of A on $A \bigotimes A$, because the identity mapping on A is invariant under the respresentation of A on $\mathcal{L}(A)$. This can also be verified using (13.3.3), (13.3.4), and (13.3.7), as before.

The image of (13.4.3) in the universal eveloping algebra of A is called the *Casimir element* associated to β, as on p46 of [25]. One can get (13.3.8) from (13.4.3) using the action of the universal enveloping algebra on V associated to the representation ρ, as in [25]. This amounts to using ρ to get a bilinear mapping from $A \times A$ into $\mathcal{L}(V)$, and thus a linear mapping from $A \bigotimes A$ into $\mathcal{L}(V)$. Related matters are discussed on p118-9 of [14].

Let $u_1', \ldots, u_n'$ and $w_1', \ldots, w_n'$ be bases for A again, which can be expressed in terms of the u_j's and w_l's as in (13.3.12) and (13.3.13), respectively. Thus

$$\sum_{h=1}^{n} u_h' \otimes w_h' = \sum_{h=1}^{n} \sum_{j=1}^{n} \sum_{l=1}^{n} \mu_{h,j} \, \nu_{h,l} \, u_j \otimes w_l. \tag{13.4.4}$$

If (13.3.17) holds, then it follows that

$$\sum_{h=1}^{n} u_h' \otimes w_h' = \sum_{j=1}^{n} \sum_{l=1}^{n} \delta_{l,j} \, u_j \otimes w_l = \sum_{j=1}^{n} u_j \otimes w_j. \tag{13.4.5}$$

This can also be obtained from the fact that (13.4.3) corresponds to the identity mapping on A under the isomorphisms mentioned earlier.

If β is symmetric on A, then (13.4.3) is symmetric as an element of $A \bigotimes A$, as in Section 7.15. This follows from (13.4.5), because (13.3.2) is symmetric in $u_1, \ldots, u_n$ and $w_1, \ldots, w_n$ in this case.

13.5 A more particular situation

Let k be a field of characteristic 0, and let $(A, [\cdot,\cdot]_A)$ be a Lie algebra over k with positive finite dimension n as a vector space over k. Also let V be a finite-dimensional vector space over k, and let ρ be a representation of A on V. Put

$$\beta_\rho(x,y) = \mathrm{tr}_V(\rho_x \circ \rho_y) \tag{13.5.1}$$

for every $x, y \in A$, which defines a symmetric bilinear form on A. Remember that (13.5.1) satisfies the associativity or invariance condition (13.3.1), as in Section 7.9. Suppose from now on in this section that A is semisimple as a Lie algebra over k, and that ρ is injective as a Lie algebra homomorphism from A into $gl(V)$.

Remember that the radical of (13.5.1) in A is defined by

$$A^{\beta_\rho} = \{x \in A : \beta_\rho(x,y) = 0 \text{ for every } y \in A\}, \tag{13.5.2}$$

as in Section 7.11. This is an ideal in A, because (13.5.1) is associative on A, as before. The image

$$\{\rho_x : x \in A^{\beta_\rho}\} \tag{13.5.3}$$

of A^{β_ρ} under ρ is a Lie subalgebra of $gl(V)$. Using Cartan's criterion, we get that (13.5.3) is solvable as a Lie algebra over k. This implies that (13.5.2) is solvable, because ρ is injective. It follows that $A^{\beta_\rho} = \{0\}$, because A is semisimple. This shows that (13.5.1) is nondegenerate on A under these conditions.

Let $u_1, \ldots, u_n$ be a basis for A, as a vector space over k. As in Section 13.3, there is a basis $w_1, \ldots, w_n$ for A that satisfies (13.3.2), with $\beta = \beta_\rho$. This leads to a *Casimir element* $c_\rho = c_\rho(\beta_\rho)$ of $\mathcal{L}(V)$ associated to ρ as in (13.3.8). Observe that

$$\mathrm{tr}_V c_\rho = \sum_{j=1}^n \mathrm{tr}_V(\rho_{u_j} \circ \rho_{w_j}) = \sum_{j=1}^n \beta_\rho(u_j, w_j) = n. \tag{13.5.4}$$

In particular, this means that $c_\rho \neq 0$, because we are assuming for convenience that $A \neq \{0\}$.

Remember that c_ρ commutes with the action of ρ on V, as in (13.3.11). If ρ is irreducible on V, then it follows that c_ρ is a one-to-one mapping from V onto itself, by Schur's lemma, as in Section 6.14. Otherwise, if W is a linear subspace of V that is invariant under the action of ρ, then c_ρ maps W into itself as well. This corresponds to parts of the discussions on p27 of [14] and p46 of [25].

13.6 A splitting theorem

Let k be a field of characteristic 0, and let A be a finite-dimensional semisimple Lie algebra over k. Also let V be a finite-dimensional vector space over k, and let ρ^V be a representation of A on V. Suppose that W is a codimension-one linear subspace of V, and that the action of ρ^V on V maps W into itself. We would like to show that V is the direct sum of W and a one-dimensional subspace that is mapped to itself by ρ^V, as in Section 13.2. Remember that the induced action of ρ^V on V/W is trivial, as before.

Let ρ^W be the representation of A on W obtained by restricting ρ^V from V to W. In this section, we consider the case where W is irreducible with respect to ρ^W. This corresponds to arguments on p28-9 of [14], and p47 of [25]. These arguments focus on V and W, respectively, as we shall see. Note that the roles of V and W are exchanged in the notation used on p47 of [25].

If $x, y \in A$, then put

$$\beta_{\rho^V}(x, y) = \mathrm{tr}_V(\rho_x^V \circ \rho_y^V) \tag{13.6.1}$$

and

$$\beta_{\rho^W}(x, y) = \mathrm{tr}_W(\rho_x^W \circ \rho_y^W), \tag{13.6.2}$$

as in (13.5.1). In this situation, (13.6.1) and (13.6.2) are the same, because the action induced on V/W by ρ^V is trivial. This also uses the remarks in Section 7.10.

Let us begin with the argument in [14]. Without loss of generality, we may suppose that ρ^V is injective as a Lie algebra homomorphism from A into $gl(V)$. Otherwise, we can replace A with its quotient by the kernel of ρ^V. This quotient of A is semisimple as a Lie algebra over k too, as in Section 10.14. We may suppose that $A \neq \{0\}$ as well, since otherwise the problem is very easy.

Let c_{ρ^V} be the Casimir element of $\mathcal{L}(V)$ associated to ρ^V as in the previous section. Thus c_{ρ^V} maps W into itself, because W is invariant under ρ^V, by hypothesis. The kernel of c_{ρ^V} in V is invariant under the action of ρ^V, because c_{ρ^V} commutes with the action of ρ^V on V, as in (13.3.11).

Because $c_{\rho^V}(W) \subseteq W$, c_{ρ^V} induces a linear mapping from V/W into itself. This induced mapping is equal to 0, because of the corresponding statement for ρ^V, and the definition of c_{ρ^V}. If $c_{\rho^V} \equiv 0$ on W, then it follows that $\mathrm{tr}_V\, c_{\rho^V} = 0$, as in Section 7.10. This contradicts (13.5.4), because $A \neq \{0\}$.

Thus $c_{\rho^V} \not\equiv 0$ on W, so that the restriction of c_{ρ^V} to W is a one-to-one mapping onto W, by Schur's lemma, as in Section 6.14. However, c_{ρ^V} is not invertible on V, because the induced mapping on V/W is equal to 0. Hence the kernel of c_{ρ^V} is a one-dimensional linear subspace of V whose intersection with W is trivial. This gives an invariant complement of W in V, as desired.

Now let us consider the argument in [25]. Let A_0 be the kernel of ρ^W, as a Lie algebra homomorphism from A into $gl(W)$. Thus A_0 is an ideal in A. If $x \in A_0$, then $\rho_x^V = \rho_x^W = 0$ on W, and $\rho_x^V(V) \subseteq W$, because the mapping on V/W induced by ρ_x^V is equal to 0. If $y \in [A_0, A_0]$, then it follows that $\rho_y^V = 0$ on V. Remember that A_0 is semisimple as a Lie algebra over k, because A is semisimple, as in Section 10.14. This implies that $A_0 = [A_0, A_0]$, as in Section 10.15. It follows that $\rho_y^V = 0$ on V for every $y \in A_0$. Note that A/A_0 is semisimple as a Lie algebra over k, as in Section 10.14 again. This permits us to reduce to the case where ρ^W is injective as a Lie algebra homomorphism from A into $gl(W)$, since otherwise we could replace A with A/A_0.

We may suppose that $A \neq \{0\}$ too, as before. Because ρ^W is injective as a Lie algebra homomorphism from A into $gl(W)$, (13.6.2) is nondegenerate on A, as in the previous section. Let $c_{\rho^V}(\beta_{\rho^W})$ be the Casimir element of $\mathcal{L}(V)$ that corresponds to ρ^V and (13.6.2), as in Section 13.3. Note that $c_{\rho^V}(\beta_{\rho^W})$ maps V into W, because of the corresponding property of ρ^V. The restriction of $c_{\rho^V}(\beta_{\rho^W})$ to W is the same as the Casimir element $c_{\rho^W} = c_{\rho^W}(\beta_{\rho^W})$ of $\mathcal{L}(W)$ that corresponds to ρ^W and (13.6.2), by the definitions of $c_{\rho^V}(\beta_{\rho^W})$ and ρ^W. The trace of c_{ρ^W} on W is equal to the dimension of A, as in (13.5.4). Thus $c_{\rho^W} \neq 0$, because $A \neq \{0\}$. This implies that c_{ρ^W} is invertible on W, by Schur's lemma, because ρ^W is irreducible on W. It follows that the kernel of $c_{\rho^V}(\beta_{\rho^W})$ is a one-dimensional subspace of V complementary to W, as before.

More precisely, the argument in [25] is formulated in terms of the Casimir element of the universal enveloping algebra of A associated to (13.6.2), as in Section 13.3. This is used again in the remarks following the proof, with the roles of V and W interchanged in the notation of [25], as before.

13.7 Weyl's theorem

Let k be a field of characteristic 0 again, let A be a finite-dimensional semisimple Lie algebra over k, and let V be a module over A that is finite-dimensional as a vector space over k. Also let W be a nonzero proper submodule of V. We would like to show that V corresponds to a direct sum of W and another submodule of V. This will imply Weyl's theorem, as in Section 13.2.

Remember that the space $\mathcal{L}(V, W)$ of all linear mappings from V into W may be considered as a module over A too, as in Section 7.5. More precisely, if $a \in A$ and $T \in \mathcal{L}(V, W)$, then $a \cdot T$ is defined as a linear mapping from V into W by putting

$$(a \cdot T)(v) = a \cdot (T(v)) - T(a \cdot v) \tag{13.7.1}$$

for every $v \in V$. This uses the action of A on V in both terms on the right, and the fact that this action sends W into itself, by hypothesis.

Let Z be the collection of linear mappings T from V into W for which there is an $\alpha(T) \in k$ such that

$$T(w) = \alpha(T)\, w \tag{13.7.2}$$

for every $w \in W$. It is easy to see that Z is a linear subspace of $\mathcal{L}(V, W)$, and that α defines a linear mapping from Z onto k. If $a \in A$, $T \in Z$, and $w \in W$, then

$$(a \cdot T)(w) = a \cdot (T(w)) - T(a \cdot w) = a \cdot (\alpha(T)\, w) - \alpha(T)\,(a \cdot w) = 0. \tag{13.7.3}$$

This implies that $a \cdot T \in Z$, with $\alpha(a \cdot T) = 0$. In particular, Z is a submodule of $\mathcal{L}(V, W)$, as a module over A.

Let Z_0 be the collection of linear mappings T from V into W such that $T \equiv 0$ on W. Equivalently, this means that $T \in Z$, with $\alpha(T) = 0$. Note that Z_0 is a submodule of Z, as a module over A. More precisely, if $a \in A$ and $T \in Z$, then

$a \cdot T \in Z_0$, as in the preceding paragraph. The codimension of Z_0 in Z is equal to one, because Z_0 is the kernel of α on Z.

The splitting theorem discussed in Section 13.2 and the previous section implies that there is a one-dimensional submodule of Z, as a module over A, that is complementary to Z_0. Let R be a nonzero element of this one-dimensional complementary submodule. Note that $\alpha(R) \neq 0$, since otherwise $R \in Z_0$, which would imply that $R = 0$. We may as well suppose that $\alpha(R) = 1$, by multiplying R by $1/\alpha(R)$. If $a \in A$, then $a \cdot R \in Z_0$, as before, which implies that $a \cdot R = 0$, because $a \cdot R$ is in the submodule of Z complementary to Z_0. This means that R commutes with the actions of A on V and W. Thus the kernel of R is a submodule of V, as a module over A. The kernel of R is also complementary to W in V, as desired.

13.8 Symmetric forms and tensors

Let k be a field, let A be a finite-dimensional vector space over k, and let $\beta(\cdot, \cdot)$ be a bilinear form on A. Thus

$$\beta_z(x) = \beta(x, z) \tag{13.8.1}$$

defines a linear functional on A for each $z \in A$, and $z \mapsto \beta_z$ defines a linear mapping from A into the dual space A' of all linear functionals on A. Let $y, z \in A$ be given, and put

$$T_{y,z}(x) = \beta_z(x)\, y = \beta(x, z)\, y \tag{13.8.2}$$

for every $x \in A$, which defines $T_{y,z}$ as a linear mapping from A into itself. Observe that

$$\beta(T_{y,z}(x), w) = \beta(x, z)\, \beta(y, w) \tag{13.8.3}$$

and

$$\beta(x, T_{z,y}(w)) = \beta(x, z)\, \beta(w, y) \tag{13.8.4}$$

for every $w, x, y, z \in A$. If $\beta(\cdot, \cdot)$ is symmetric as a bilinear form on A, then we get that

$$\beta(T_{y,z}(x), w) = \beta(x, T_{z,y}(w)) \tag{13.8.5}$$

for every $w, x, y, z \in A$.

Let us suppose from now on in this section that $\beta(\cdot, \cdot)$ is nondegenerate on A. If T is any linear mapping from A into itself, then there is a unique adjoint linear mapping T^* from A into itself such that

$$\beta(T(x), w) = \beta(x, T^*(w)) \tag{13.8.6}$$

for every $w, x \in A$, as in Section 2.14. If $\beta(\cdot, \cdot)$ is symmetric on A, then

$$(T_{y,z})^* = T_{z,y} \tag{13.8.7}$$

for every $y, z \in A$, by (13.8.5). Remember that $A \bigotimes A$ and $A \bigotimes A'$ are defined as vector spaces over k, as in Section 7.12. Clearly

$$(y, z) \mapsto T_{y,z} \tag{13.8.8}$$

defines a mapping from $A \times A$ into the space $\mathcal{L}(A)$ of linear mappings from A into itself that is bilinear over k. This leads to a linear mapping from $A \bigotimes A$ into $\mathcal{L}(A)$, with

$$y \otimes z \mapsto T_{y,z} \tag{13.8.9}$$

for every $y, z \in A$. More precisely, we have seen that there is a natural isomorphism from $A \bigotimes A'$ onto $\mathcal{L}(A)$, as vector spaces over k, as in Section 13.4. Because $\beta(\cdot, \cdot)$ is nondegenerate on A, $z \mapsto \beta_z$ is an isomorphism from A onto A', as vector spaces over k. This leads to an isomorphism from $A \bigotimes A$ onto $A \bigotimes A'$, as vector spaces over k, as before. We can compose these mappings to get an isomorphism from $A \bigotimes A$ onto $\mathcal{L}(A)$, as vector spaces over k. This is the same as the mapping determined by (13.8.9), by construction.

There is a natural automorphism on $A \bigotimes A$, as a vector space over k, with

$$y \otimes z \mapsto z \otimes y \tag{13.8.10}$$

for every $y, z \in A$, as in Section 7.15. Let us suppose from now on in this section that $\beta(\cdot, \cdot)$ is symmetric on A. Of course,

$$(y, z) \mapsto T_{z,y} = (T_{y,z})^* \tag{13.8.11}$$

defines a mapping from $A \times A$ into $\mathcal{L}(A)$, which is bilinear over k. This leads to a linear mapping from $A \bigotimes A$ into $\mathcal{L}(A)$, with

$$y \otimes z \mapsto T_{z,y} = (T_{y,z})^* \tag{13.8.12}$$

for every $y, z \in A$. This is the same as the composition of the mapping from $A \bigotimes A$ into $\mathcal{L}(A)$ determined by (13.8.9) with $T \mapsto T^*$, as a linear mapping from $\mathcal{L}(A)$ onto itself. This is also the same as the composition of the automorphism on $A \bigotimes A$ determined by (13.8.10) with the linear mapping from $A \bigotimes A$ into $\mathcal{L}(A)$ determined by (13.8.9). More precisely, these linear mappings from $A \bigotimes A$ into $\mathcal{L}(A)$ are the same, because they correspond to the same bilinear mapping from $A \times A$ into $\mathcal{L}(A)$.

An element of $T^2 A = A \bigotimes A$ is said to be symmetric if it is invariant under the automorphism determined by (13.8.10), as in Section 7.15. Symmetric elements of $A \bigotimes A$ correspond exactly to linear mappings from A into itself that are self-adjoint with respect to $\beta(\cdot, \cdot)$, under the vector space isomorphism from $A \bigotimes A$ onto $\mathcal{L}(A)$ determined by (13.8.9), as in the preceding paragraph. Note that the identity mapping on A is automatically self-adjoint with respect to $\beta(\cdot, \cdot)$. Thus the element of $A \bigotimes A$ that corresponds to the identity mapping on A under the isomorphism just mentioned is symmetric in $A \bigotimes A$ under these conditions. This gives another way to look at the symmetry condition mentioned at the end of Section 13.4.

13.9 Reductive Lie algebras

Let k be a commutative ring with a multiplicative identity element, and let $(A, [\cdot,\cdot]_A)$ be a Lie algebra over k. Remember that A may be considered as a module over itself, using the adjoint representation. The kernel of the adjoint representation, as a Lie algebra homomorphism from A into $gl(A)$, is the same as the center $Z(A)$ of A as a Lie algebra. Of course, the quotient $A/Z(A)$ may be considered as a Lie algebra over k too, because $Z(A)$ is an ideal in A. Thus A may be considered as a module over $A/Z(A)$, as a Lie algebra over k.

An ideal in A as a Lie algebra is the same as a submodule of A, as a module over itself with respect to the adjoint representation. Similarly, ideals in A as a Lie algebra are the same as submodules of A as a module over $A/Z(A)$.

Now let k be a field of characteristic 0, and suppose that A is a finite-dimensional Lie algebra over k. Suppose also that A is reductive as a Lie algebra, as in Section 11.3. Thus $Z(A)$ is the same as the solvable radical of A. In this case, $A/Z(A)$ is semisimple as a Lie algebra over k, as in Section 9.4.

Of course, $Z(A)$ is a submodule of A, as a module over $A/Z(A)$. Because $A/Z(A)$ is semisimple as a Lie algebra over k, there is a submodule B of A, as a module over $A/Z(A)$, such that A corresponds to the direct sum of $Z(A)$ and B, as in Section 13.7. This means that

$$Z(A) \cap B = \{0\}, \quad Z(A) + B = A, \tag{13.9.1}$$

and that B is an ideal in A, as before.

Observe that

$$[A, A] = [B, B] \subseteq B. \tag{13.9.2}$$

We also have that

$$[A/Z(A), A/Z(A)] = A/Z(A), \tag{13.9.3}$$

because $A/Z(A)$ is semisimple as a Lie algebra over k, as in Section 10.15. The canonical quotient mapping q from A onto $A/Z(A)$ maps $[A, A]$ onto the left side of (13.9.3). In this situation, the restriction of q to B is a one-to-one mapping from B onto $A/Z(A)$. It follows that

$$B = [A, A], \tag{13.9.4}$$

and that $[A, A]$ is semisimple as a Lie algebra over k. This shows that A corresponds to the direct sum of $Z(A)$ and $[A, A]$ as a Lie algebra over k, by definition of $Z(A)$. This corresponds to the second part of part (a) of Exercise 5 on p30 of [14], and to part (a) of the proposition on p102 of [14]. This also seems to correspond to a comment at the bottom of p50 in [25].

13.10 Semisimple ideals

Let k be a field of characteristic 0, and let $(B, [\cdot,\cdot]_B)$ be a Lie algebra over k with finite dimension as a vector space over k. Suppose that A is an ideal in B

that is semisimple as a Lie algebra over k. Under these conditions, there is a unique ideal B_0 in B such that B corresponds to the direct sum of A and B_0, as a Lie algebra over k. This is Corollary 1 on p47 of [25].

Of course, B may be considered as a module over itself, using the adjoint representation. We can restrict the action of B on itself to an action of A on B, so that B becomes a module over A, as a Lie algebra over k. Note that A may be considered as a submodule of B, as a module over A. As in Section 13.7, there is a submodule B_0 of B, as a module over A, such that B corresponds to the direct sum of A and B_0, as a module over A. In particular, B corresponds to the direct sum of A and B_0, as a vector space over k, so that

$$A \cap B_0 = \{0\} \quad \text{and} \quad A + B_0 = B. \tag{13.10.1}$$

Let us check that

$$[A, B_0] = \{0\}, \tag{13.10.2}$$

where the left side is defined as in Section 9.2, as usual. Clearly

$$[A, B_0] \subseteq [A, B] \subseteq A, \tag{13.10.3}$$

because A is an ideal in B. We also have that $[A, B_0] \subseteq B_0$, because B_0 is a submodule of B, as a module over A. Thus $[A, B_0] \subseteq A \cap B_0 = \{0\}$, as desired.

Suppose that $y \in B$ satisfies $[a, y]_B = 0$ for every $a \in A$. Because $A + B_0 = B$, there are $x \in A$ and $z \in B_0$ such that $y = x + z$. We already know that $[a, z]_B = 0$, by (13.10.2), and so we get that $[a, x]_B = 0$ for every $a \in A$. This implies that $x = 0$, because $x \in A$ and A is semisimple, so that the center of A is trivial. It follows that $y = z \in B_0$. This shows that B_0 is exactly the set of $y \in B$ such that $[a, y]_B = 0$ for every $a \in A$. Thus B_0 is uniquely determined by the properties of being a submodule of B, as a module over A, that is complementary to A.

Equivalently, B_0 is the centralizer of A in B, as in Section 7.6. It is easy to see that B_0 is an ideal in B, as a Lie algebra over k, because A is an ideal in B. More precisely, if $a \in A$, $w \in B$, and $y \in B_0$, then one can verify that

$$[a, [w, y]_B]_B = 0, \tag{13.10.4}$$

using the Jacobi identity and the fact that $[a, w]_B \in A$, because A is an ideal in B. We also have that B corresponds to the direct sum of A and B_0, as a Lie algebra over k, because of (13.10.2).

13.11 Another approach

Let us mention another approach to the statement in the previous section, using an argument like the one in the proof of the second theorem on p23 of [14]. Let k be a field, and let $(B, [\cdot, \cdot]_B)$ be a finite-dimensional Lie algebra over k. If $x \in B$, then

$$\mathrm{ad}_{B,x}(z) = [x, z]_B \tag{13.11.1}$$

defines a linear mapping from B into itself, as in Section 2.4. Put

$$b(x,y) = \operatorname{tr}_B(\operatorname{ad}_{B,x} \circ \operatorname{ad}_{B,y}) \tag{13.11.2}$$

for every $x, y \in B$, which is the Killing form on B, as in Section 7.9. Remember that

$$b([x,w]_B, y) = b(x, [w,y]_B) \tag{13.11.3}$$

for every $w, x, y \in B$, which is to say that (13.11.2) is associative as a bilinear form on B, or equivalently that (13.11.2) is invariant with respect to the adjoint representation on B.

Let A be an ideal in B, as a Lie algebra over k. If $x \in A$, then let $\operatorname{ad}_{A,x}$ be the restriction of (13.11.1) to $z \in A$, which defines a linear mapping from A into itself. Put

$$b_A(x,y) = \operatorname{tr}_A(\operatorname{ad}_{A,x} \circ \operatorname{ad}_{A,y}) \tag{13.11.4}$$

for every $x, y \in A$, which is the Killing form on A, as a Lie algebra over k. If $x, y \in A$, then

$$b_A(x,y) = b(x,y), \tag{13.11.5}$$

as in Section 7.10, because A is an ideal in B.

Put

$$A^\perp = \{x \in B : b(x,y) = 0 \text{ for every } y \in A\}. \tag{13.11.6}$$

It is easy to see that this is an ideal in B, using (13.11.3) and the hypothesis that A is an ideal in B, as in Section 10.14. Let us suppose from now on in this section that (13.11.4) is nondegenerate on A. Remember that this holds when A is semisimple as a Lie algebra and k has characteristic 0, as in Section 10.13. It follows that

$$A \cap A^\perp = \{0\} \tag{13.11.7}$$

in this situation. Note that $[A, A^\perp] \subseteq A \cap A^\perp$, because A and $A^\perp$ are ideals in A. Hence

$$[A, A^\perp] = \{0\}, \tag{13.11.8}$$

by (13.11.7).

If $x \in B$ and $y \in A$, then put

$$\lambda_x(y) = b(x,y), \tag{13.11.9}$$

which defines λ_x as a linear functional on A. Using the nondegeneracy of (13.11.4), we get that there is a $w \in A$ such that

$$\lambda_x(y) = b_A(w,y) \tag{13.11.10}$$

for every $y \in A$. This means that

$$b(x,y) = b_A(w,y) = b(w,y) \tag{13.11.11}$$

for every $y \in A$, so that $x - w \in A^\perp$. Thus

$$A + A^\perp = B. \tag{13.11.12}$$

This shows that B corresponds to the direct sum of A and $A^\perp$, as a Lie algebra over k.

One can check that $A^\perp$ is the same as the centralizer of A in B, as in the previous section. More precisely, $A^\perp$ is contained in the centralizer of A, by (13.11.8). The nondegeneracy of (13.11.4) on A implies that the center of A is trivial, and in fact that A is semisimple as a Lie algebra, as in Section 10.13. One can use this and (13.11.12) to get that $A^\perp$ is the centralizer of A, as before.

13.12 Inner derivations

Let k be a commutative ring with a multiplicative identity element, and let $(A, [\cdot, \cdot]_A)$ be a Lie algebra over k. If $x \in A$, then let $\operatorname{ad} x$ be the mapping from A into itself that sends $y \in A$ to $[x, y]_A$, as usual. Remember that the space $\operatorname{Der}(A)$ of derivations on A is a Lie algebra over k with respect to the commutator bracket associated to composition of mappings, as in Section 2.5. If $x \in A$, then $\operatorname{ad} x \in \operatorname{Der}(A)$, and $x \mapsto \operatorname{ad} x$ is a Lie algebra homomorphism from A into $\operatorname{Der}(A)$, as in Section 2.4. Let

$$\operatorname{ad} A = \{\operatorname{ad} x : x \in A\} \tag{13.12.1}$$

be the image of this mapping, whose elements are said to be *inner derivations* on A.

Let $x, y \in A$ and $\delta \in \operatorname{Der}(A)$ be given, and observe that

$$\begin{aligned} ([\delta, \operatorname{ad} x])(y) &= \delta((\operatorname{ad} x)(y)) - (\operatorname{ad} x)(\delta(y)) \\ &= \delta([x, y]_A) - [x, \delta(y)]_A = [\delta(x), y]_A = (\operatorname{ad} \delta(x))(y). \end{aligned} \tag{13.12.2}$$

This means that

$$[\delta, \operatorname{ad} x] = \operatorname{ad} \delta(x), \tag{13.12.3}$$

which implies that $\operatorname{ad} A$ is an ideal in $\operatorname{Der}(A)$. This corresponds to Exercise 2.1 on p9 of [14], and some remarks on p23 of [14]. This also comes up in the proof of Corollary 2 on p48 of [25].

Suppose from now on in this section that k is a field, and that A is a finite-dimensional semisimple Lie algebra over k. Remember that the kernel of the adjoint representation of A is the center of A, which is trivial, because A is semisimple. Thus the adjoint representation is a Lie algebra isomorphism from A onto $\operatorname{ad} A$, so that $\operatorname{ad} A$ is semisimple as a Lie algebra over k in particular. If k has characteristic 0, then it follows that $\operatorname{Der}(A)$ corresponds to the direct sum of $\operatorname{ad} A$ and the centralizer of $\operatorname{ad} A$ in $\operatorname{Der}(A)$, as in Section 13.10. If $x \in A$ and $\delta \in \operatorname{Der}(A)$ is in the centralizer of $\operatorname{ad} A$ in $\operatorname{Der}(A)$, then $\operatorname{ad} \delta(x) = 0$, by (13.12.3). This implies that $\delta(x) = 0$, because the kernel of the adjoint representation of A is trivial. This means that $\delta = 0$, so that every derivation on A is an element of $\operatorname{ad} A$. This corresponds to Corollary 2 on p48 of [25].

This also corresponds to the second theorem on p23 of [14]. The proof given there uses the argument in the previous section instead of the one in Section 13.10. This could be used when the Killing form on A is nondegenerate, without asking that k have characteristic 0.

Chapter 14

Nilpotence and diagonalizability

14.1 A duality argument

Let k be a commutative ring with a multiplicative identity element, and let $(A, [\cdot, \cdot]_A)$ be a Lie algebra over k. If $x \in A$, then put $\mathrm{ad}_x(y) = [x, y]_A$ for every $y \in A$, as usual. Let $\beta(\cdot, \cdot)$ be a bilinear form on A that is associative or invariant under the adjoint representation on A, so that

$$\beta(\mathrm{ad}_x(w), z) = -\beta(w, \mathrm{ad}_x(z)) \tag{14.1.1}$$

for every $w, x, z \in A$. In particular,

$$\beta(\mathrm{ad}_x(w), z) = 0 \tag{14.1.2}$$

when $[x, z]_A = 0$. This corresponds to part of part (a) of Exercise 2 on p54 of [25].

Suppose now that k is a field, that A has finite dimension as a vector space over k, and that $\beta(\cdot, \cdot)$ is also nondegenerate as a bilinear form on A. Let $x \in A$ be given, and note that the image

$$\{\mathrm{ad}_x(w) : w \in A\} \tag{14.1.3}$$

of ad_x is a linear subspace of A. If $z \in A$, then (14.1.2) holds for every $w \in A$ if and only if

$$\beta(w, \mathrm{ad}_x(z)) = 0 \tag{14.1.4}$$

for every $w \in A$, by (14.1.1). Because $\beta(\cdot, \cdot)$ is nondegenerate on A, (14.1.4) holds for every $w \in A$ if and only if $\mathrm{ad}_x(z) = 0$. Thus (14.1.2) holds for every $w \in A$ if and only if $\mathrm{ad}_x(z) = 0$.

Consider

$$\{y \in A : \beta(y, z) = 0 \text{ for every } z \in A \text{ such that } [x, z]_A = 0\}, \tag{14.1.5}$$

which is a linear subspace of A. Of course, (14.1.3) is contained in (14.1.5), because (14.1.2) holds for every $w \in A$ when $[x,z]_A = 0$, as in the preceding paragraph. In fact, (14.1.3) is equal to (14.1.5) in this situation, because $\beta(\cdot,\cdot)$ is nondegenerate on A. More precisely, this uses the fact that if $z \in A$ satisfies (14.1.2) for every $w \in A$, then $[x,z]_A = 0$, and hence $\beta(y,z) = 0$ for every y in (14.1.5). This corresponds to the second part of part (a) of Exercise 2 on p54 of [25].

Let us now take $\beta(\cdot,\cdot)$ to be the Killing form on A, so that

$$\beta(u,v) = \mathrm{tr}_A(\mathrm{ad}_u \circ \mathrm{ad}_v) \tag{14.1.6}$$

for every $u, v \in A$. Remember that this satisfies (14.1.1), as in Section 7.9. Suppose that $x, z \in A$ commute, in the sense that $[x,z]_A = 0$. This implies that ad_x and ad_z commute as linear mappings from A into itself, because the adjoint representation of A is a representation of A as a Lie algebra over k. If ad_x is also nilpotent as a linear mapping from A into itself, then it follows that $\mathrm{ad}_x \circ \mathrm{ad}_z$ is nilpotent as a linear mapping from A into itself, as in Section 9.7. In this case, we get that

$$\beta(x,z) = \mathrm{tr}_A(\mathrm{ad}_x \circ \mathrm{ad}_z) = 0, \tag{14.1.7}$$

by standard arguments. If the Killing form is nondegenerate on A, then the previous arguments imply that there is a $w \in A$ such that

$$\mathrm{ad}_x(w) = x. \tag{14.1.8}$$

This corresponds to part of part (b) of Exercise 2 on p54 of [25].

14.2 A criterion for nilpotence

Let k be a field of characteristic 0, and let $\mathcal{A}$ be an associative algebra over k, where multiplication of $a, b \in \mathcal{A}$ is expressed as $a\,b$. Also let δ be a derivation on $\mathcal{A}$, and suppose that $b \in \mathcal{A}$ is an eigenvector of δ with eigenvalue $\lambda \in k$, so that

$$\delta(b) = \lambda\, b. \tag{14.2.1}$$

In particular, this means that b commutes with $\delta(b)$. If j is an integer with $j \geq 2$, then

$$\delta(b^j) = j \cdot b^{j-1}\,\delta(b) = j \cdot \lambda\, b^j, \tag{14.2.2}$$

so that b^j is an eigenvector of δ with eigenvalue $j \cdot \lambda$. If $\lambda \neq 0$, then the eigenvalues $j \cdot \lambda$ with $j \in \mathbf{Z}_+$ are all distinct, because k has characteristic 0. If, for each $j \in \mathbf{Z}_+$, $b^j \neq 0$, then it follows that the b^j's are linearly independent in $\mathcal{A}$, as a vector space over k. If $\mathcal{A}$ has finite dimension as a vector space over k, then $b^j = 0$ for some $j \geq 1$.

Remember that

$$\delta_a(x) = [a,x] = a\,x - x\,a \tag{14.2.3}$$

defines a derivation on $\mathcal{A}$ for every $a \in \mathcal{A}$. Suppose that $b \in \mathcal{A}$ is an eigenvector of δ_a with eigenvalue $\lambda \in k$, which is to say that

$$\delta_a(b) = [a, b] = \lambda\, b. \tag{14.2.4}$$

If $\lambda \neq 0$ and $\mathcal{A}$ has finite dimension as a vector space over k, then b is nilpotent in $\mathcal{A}$, as in the preceding paragraph.

Now let $(A, [\cdot, \cdot]_A)$ be a Lie algebra over k, and suppose that $u, x \in A$ satisfy

$$[u, x]_A = x. \tag{14.2.5}$$

Let V be a vector space over k, and let ρ be a representation of A as a Lie algebra on V. Thus

$$\rho_{[u,x]_A} = [\rho_u, \rho_x] = \rho_u \circ \rho_x - \rho_x \circ \rho_u \tag{14.2.6}$$

on V. This means that

$$[\rho_u, \rho_x] = \rho_x, \tag{14.2.7}$$

by (14.2.5). Suppose that V has finite dimension, so that the algebra $\mathcal{L}(V)$ of linear mappings from V into itself has finite dimension as a vector space over k too. Under these conditions, we get that ρ_x is nilpotent as a linear mapping from V into itself. This corresponds to part of part (b) of Exercise 2 on p54 of [25].

Suppose that A has finite dimension as a vector space over k. Let x be an ad-nilpotent element of A, so that ad_x is nilpotent on A. If A is semisimple as a Lie algebra over k, then the Killing form on A is nondegenerate, as in Section 10.13. In this case, there is a $u \in A$ such that (14.2.5) holds, as in the previous section. This is another part of part (b) of Exercise 2 on p54 in [25].

14.3 ad-Diagonalizability

Let k be a field, let V be a finite-dimensional vector space over k, and let T be a linear mapping from V into itself. If k is algebraically closed and T is diagonalizable on V, then one may say that T is *semisimple* as a linear mapping on V, as on p17 of [14] and p40 of [25]. Otherwise, one may say that T is semisimple on V when T becomes diagonalizable after passing to an algebraic closure of k, as in Remark 1 after Theorem 5.1 on p50 of [25].

Let $(A, [\cdot, \cdot]_A)$ be a Lie algebra over k, with finite dimension as a vector space over k. If $x \in A$, then we put $\mathrm{ad}_x(y) = [x, y]_A$ for every $y \in A$, as usual. If ad_x is diagonalizable as a linear mapping from A into itself, then x is said to be ad-*diagonalizable* as an element of A. Similarly, x is said to be ad-*semisimple* as an element of A when ad_x is semisimple as a linear mapping from A into itself, as on p24 of [14], and Definition 5.5 on p52 of [25].

Suppose that k is an algebraically closed field of characteristic 0, and that A is semisimple as a Lie algebra over k. Let $x \in A$ be given, so that ad_x is a linear mapping from A into itself. Remember that ad_x can be expressed in a unique way as a sum of two commuting linear mappings from A into itself, where one of these linear mappings is diagonalizable and the other is nilpotent, as in Section 10.8. We have also seen that ad_x is a derivation on A, as a Lie algebra over k. The diagonalizable and nilpotent parts of ad_x are derivations on A as well, as in Section 10.9. Because k has characteristic 0 and A is semisimple, every derivation on A is an inner derivation, as in Section 13.12. This means that there are $x_1, x_2 \in A$ such that the diagonalizable and nilpotent parts of ad_x are given by ad_{x_1} and ad_{x_2}, respectively. Of course, x_1 and x_2 are uniquely determined by ad_{x_1} and ad_{x_2}, respectively, because the center of A is trivial, by semisimplicity. Similarly,

$$[x_1, x_2]_A = 0, \tag{14.3.1}$$

because ad_{x_1} and ad_{x_2} commute as linear mappings on A. By construction, x_1 is ad-diagonalizable on A, and x_2 is ad-nilpotent on A. Note that x_1 and x_2 are uniquely determined by these properties, because of the analogous uniqueness property for the diagonalizable and nilpotent parts of ad_x. This corresponds to remarks on p24 of [14], and Theorem 5.6 on p52 of [25]. In particular, this is called the *abstract Jordan decomposition* of x in A in [14].

Let V be a finite-dimensional vector space over k again, and suppose that A is a Lie subalgebra of $gl(V)$. Let $x \in A$ be given, so that x is a linear mapping from V into itself. As before, x can be expressed in a unique way as $y_1 + y_2$, where y_1 and y_2 are commuting linear mappings from V into itself, y_1 is diagonalizable on V, and y_2 is nilpotent on V. Of course, one would like to have $y_1, y_2 \in A$, as on p24 of [14]. It is easy to get this when $A = sl(V)$, as in [14]. Indeed, y_2 has trace 0 on V, because y_2 is nilpotent on V. This implies that $y_1 \in sl(V)$ in this case, because $x \in A$ by hypothesis. Some other situations will be discussed in the next section.

If $w, z \in gl(V)$, then put

$$\mathrm{ad}_{gl(V),w}(z) = [w, z] = w \circ z - z \circ w, \tag{14.3.2}$$

as usual. Let $y \in gl(V)$ be given, so that y can be expressed in a unique way as $y_1 + y_2$, where y_1 and y_2 are commuting linear mappings from V into itself, y_1 is diagonalizable on V, and y_2 is nilpotent on V, as before. It follows that

$$\mathrm{ad}_{gl(V),y} = \mathrm{ad}_{gl(V),y_1} + \mathrm{ad}_{gl(V),y_2}, \tag{14.3.3}$$

$\mathrm{ad}_{gl(V),y_1}$ commutes with $\mathrm{ad}_{gl(V),y_2}$ as linear mappings on $gl(V)$, $\mathrm{ad}_{gl(V),y_1}$ is diagonalizable on $gl(V)$, and $\mathrm{ad}_{gl(V),y_2}$ is nilpotent on $gl(V)$, as in Section 10.9. Let A be a Lie subalgebra of $gl(V)$. If $w \in A$, then $\mathrm{ad}_{gl(V),w}$ maps A into itself, and the restriction of $\mathrm{ad}_{gl(V),w}$ to A is the same as $\mathrm{ad}_{A,w}$. If $y_1 \in A$, then it follows that ad_{A,y_1} is diagonalizable as a linear mapping from A into itself. Similarly, if $y_2 \in A$, then ad_{A,y_2} is nilpotent as a linear mapping from A into itself. Of course, ad_{A,y_1} commutes with ad_{A,y_2} on A, because $\mathrm{ad}_{gl(V),y_1}$ commutes with $\mathrm{ad}_{gl(V),y_2}$ on $gl(V)$. Under these conditions, we also have that $y \in A$, and

$$\mathrm{ad}_{A,y} = \mathrm{ad}_{A,y_1} + \mathrm{ad}_{A,y_2}. \tag{14.3.4}$$

This corresponds to some more of the remarks on p24 of [14].

14.4 Semisimple subalgebras of $gl(V)$

Let k be an algebraically closed field of characteristic 0, and let V be a finite-dimensional vector space over k. Also let A be a Lie subalgebra of $gl(V)$, and suppose that A is semisimple as a Lie algebra over k. Let $x \in A$ be given, and remember that x can be expressed in a unique way as $y_1 + y_2$, where y_1 and y_2 are commuting linear mappings from V into itself, y_1 is diagonalizable on V, and y_2 is nilpotent on V. Under these conditions, $y_1, y_2 \in A$, as in the theorem on p29 of [14], and Corollary 5.4 on p52 of [25]. We shall follow the argument in [14] here, with some help from Section 13.10.

If $w \in gl(V)$, then let $\mathrm{ad}_{gl(V),w}$ be as in (14.3.2). Thus $\mathrm{ad}_{gl(V),x}$ maps A into itself, because $x \in A$. Remember that $\mathrm{ad}_{gl(V),y_1}$ and $\mathrm{ad}_{gl(V),y_2}$ are the corresponding diagonalizable and nilpotent parts of $\mathrm{ad}_{gl(V),x}$, as a linear mapping from $gl(V)$ into itself, as in Section 10.9. It follows that $\mathrm{ad}_{gl(V),y_1}$ and $\mathrm{ad}_{gl(V),y_2}$ map A into itself as well, as in Section 10.8. Let $N = N_{gl(V)}(A)$ be the normalizer of A in $gl(V)$, as in Section 9.8. The previous statement says that

(14.4.1) $$y_1, y_2 \in N.$$

If N were equal to A, then the proof would be finished, but this does not work, because constant multiples of the identity mapping on V are automatically in N. Thus we need some additional conditions on y_1, y_2.

Note that V may be considered as a module over A, as a Lie algebra over k. Let W be an A-submodule of V, which is to say a linear subspace of V such that every element of A maps W into itself. Let B_W be the collection of $z \in gl(V)$ such that $z(W) \subseteq W$, and the restriction of z to W has trace equal to 0, as a linear mapping from W into itself. Let us check that

(14.4.2) $$A \subseteq B_W.$$

If $z \in A$, then $z(W) \subseteq W$, by our hypothesis about W. Remember that $A = [A, A]$, because A is semisimple and k has characteristic 0, as in Section 10.15. One can use this to show that the trace of the restriction of z to W is 0, as desired. Note that B_W is a Lie subalgebra of $gl(V)$. In particular, we can take $W = V$, for which we get $B_V = sl(V)$.

Let us check that

(14.4.3) $$y_1, y_2 \in B_W$$

for every A-submodule W of V. Remember that x maps W into itself, because $x \in A$. This implies that y_1 and y_2 map W into itself, as in Section 10.8. The restriction of y_2 to W is nilpotent on W, because y_2 is nilpotent on V. Hence the trace of the restriction of y_2 to W is equal to 0. The trace of the restriction of x to W is equal to 0 too, as in the preceding paragraph. It follows that the trace of the restriction of y_1 to W is equal to 0 as well. This gives (14.4.3), as desired.

Let B be the intersection of N with all the subalgebras B_W, over all A-submodules W of V. Thus B is a Lie subalgebra of $gl(V)$, and

(14.4.4) $$A \subseteq B,$$

by (14.4.2). More precisely, A is an ideal in B, as a Lie algebra over k, because $B \subseteq N$, by construction. We also have that

$$y_1, y_2 \in B, \tag{14.4.5}$$

by (14.4.1) and (14.4.3). We would like to show that $A = B$.

Note that there is a unique ideal B_0 in B such that B corresponds to the direct sum of A and B_0, as in Section 13.10. In particular, $[A, B_0] = \{0\}$, as before.

Let W be an irreducible A-submodule of V. If $z \in B_0$, then z maps W into itself, and z commutes with every element of A. Because k is algebraically closed, Schur's lemma implies that z is equal to a constant multiple of the identity mapping on W, as in Section 6.14. However, we also have that the trace of the restriction of z to W is equal to 0, because $z \in B$. This implies that $z \equiv 0$ on W, because k has characteristic 0.

By Weyl's theorem, V can be expressed as the direct sum of irreducible A-submodules, as in Section 6.14. If $z \in B_0$, then it follows that $z \equiv 0$ on V, using the remarks in the preceding paragraph. This means that $B_0 = \{0\}$, so that $A = B$, as desired.

14.5 Tensors

Let k be a field, and let V be a vector space over k of positive finite dimension n. If p is a positive integer, then $T^p V$ is the pth tensor power of V, as in Section 7.15, which is to say the tensor product of p copies of V. This is a vector space over k of dimension n^p. More precisely, if $v_1, \ldots, v_n$ is a basis for V, then we can get a basis for $T^p V$ using elements of the form

$$v_{j_1} \otimes \cdots \otimes v_{j_p}, \tag{14.5.1}$$

where $j_1, \ldots, j_p \in \{1, \ldots, n\}$. If $p = 0$, then one can interpret $T^p V$ as being k, as a one-dimensional vector space over itself.

The dual space V' of V is a vector space over k of dimension n as well. If q is a nonnegative integer, then $T^q V'$ is defined as a vector space over k of dimension n^q, as before. Let $\lambda_1, \ldots, \lambda_q$ be q linear functionals on V for some $q \in \mathbf{Z}_+$, and consider

$$\prod_{j=1}^{q} \lambda_j(u_j) \tag{14.5.2}$$

as a k-valued function of $(u_1, \ldots, u_q)$ in the Cartesian product of q copies of V. This defines a multilinear mapping from the Cartesian product of q copies of V into k, which is to say a q-linear form on V. Of course, the space of q-linear forms on V is a vector space over k with respect to pointwise addition and scalar multiplication of functions. The mapping from $(\lambda_1, \ldots, \lambda_q)$ to (14.5.2) is multilinear over k as a mapping from the Cartesian product of q copies of V' into the space of q-linear forms on V. This leads to a linear mapping from $T^q V'$ into the space of q-linear forms on V, which is in fact a vector space isomorphism.

If p and q are nonnegative integers, then put

$$T^{p,q} V = T^p V \bigotimes T^q V', \tag{14.5.3}$$

which may also be denoted $V_{p,q}$, as on p40 of [25]. This reduces to $T^q V'$ when $p = 0$, and to $T^p V$ when $q = 0$. Note that there is a natural isomorphism from $T^{1,1} V = V \bigotimes V'$ onto the space $\mathcal{L}(V)$ of linear mappings from V into itself, as vector spaces over k, as in Section 13.4. Let $v_1, \ldots, v_n$ be a basis for V again, and let $\mu_1, \ldots, \mu_n$ be the corresponding dual basis for V', so that $\mu_j(v_l)$ is equal to 1 when $j = l$ and to 0 when $j \neq l$. We can get a basis for $T^{p,q} V$, as a vector space over k, using elements of the form

$$(v_{j_1} \otimes \cdots \otimes v_{j_p}) \otimes (\mu_{l_1} \otimes \cdots \otimes \mu_{l_q}), \tag{14.5.4}$$

where $j_1, \ldots, j_p, l_1, \ldots, l_q \in \{1, \ldots, n\}$.

Let A be a Lie algebra over k, and let ρ^V be a representation of A on V. If $a \in A$ and $\lambda \in V'$, then put

$$\rho_a^{V'}(\lambda) = -\lambda \circ \rho_a^V, \tag{14.5.5}$$

which is a linear functional on V. This defines $\rho^{V'}$ as a representation of A on V', as in Section 7.2, with $W = k$. Equivalently, if $a \in A$, then ρ_a^V is a linear mapping from V into itself, which leads to a dual linear mapping from V' into itself, as in Section 2.13. By construction, $\rho_a^{V'}$ is -1 times this dual linear mapping on V'.

Using ρ^V and $\rho^{V'}$, we can make $T^{p,q} V$ into a module over A, as in Section 7.12. More precisely, we have $p + q$ actions of A on $T^{p,q} V$, using the actions of A on the individual factors on V and V' in $T^{p,q} V$. These $p + q$ actions of A on $T^{p,q} V$ commute with each other, and $T^{p,q} V$ is considered as a module over A as a Lie algebra with respect to the sum of these $p + q$ actions, as before. If $p = 0$, then $T^{p,q} V = T^q V'$ can be identified with the space of q-linear forms on V, as mentioned earlier. In this case, the action of A corresponds to making the space of q-linear forms on V a module over A as a Lie algebra as in Section 7.5, using the trivial action of A on k, and combining the q actions of A corresponding to the q variables of a q-linear form on V.

14.6 Induced linear mappings

Let k be a field again, and let V be a finite-dimensional vector space over k of dimension $n \geq 1$. Also let p and q be nonnegative integers, at least one of which is positive. Of course, V may be considered as a module over $gl(V)$, as a Lie algebra over k. As in the previous section, $T^{p,q} V$ may be considered as a module over $gl(V)$ as well, by summing the actions on the various factors of V and V'. More precisely, let A be a linear mapping from V into itself, and let A'

be the corresponding dual linear mapping from the dual space V' into itself, as in Section 2.13. Let $w_1, \ldots, w_p \in V$ and $\lambda_1, \ldots, \lambda_q \in V'$ be given, so that

$$(w_1 \otimes \cdots \otimes w_p) \otimes (\lambda_1 \otimes \cdots \otimes \lambda_q) \tag{14.6.1}$$

is an element of $T^{p,q}V$. If $1 \le h \le p$, then the action of A on the hth factor of V in $T^{p,q}V$ sends (14.6.1) to

$$(w_1 \otimes \cdots \otimes w_{h-1} \otimes A(w_h) \otimes w_{h+1} \otimes \cdots \otimes w_p) \otimes (\lambda_1 \otimes \cdots \otimes \lambda_q). \tag{14.6.2}$$

Similarly, if $1 \le i \le q$, then A' acts on the ith factor of V' in $T^{p,q}V$, sending (14.6.1) to

$$(w_1 \otimes \cdots \otimes w_p) \otimes (\lambda_1 \otimes \cdots \otimes \lambda_{i-1} \otimes A'(\lambda_i) \otimes \lambda_{i+1} \otimes \cdots \otimes \lambda_q). \tag{14.6.3}$$

If we consider $T^{p,q}V$ as a module over $gl(V)$ as in the previous section, then A corresponds to a linear mapping $A_{p,q}$ from $T^{p,q}V$ into itself, as on p40 of [25]. By construction, $A_{p,q}$ sends (14.6.1) to the sum of (14.6.2) over $h = 1, \ldots, p$, minus the sum of (14.6.3) over $i = 1, \ldots, q$.

Suppose for the moment that A is diagonalizable on V, and let $v_1, \ldots, v_n$ be a basis of V consisting of eigenvectors of A. If $\mu_1, \ldots, \mu_n$ is the corresponding dual basis for V', then one can check that μ_j is an eigenvector for A' for each $j = 1, \ldots, n$. Under these conditions, the collection of elements of $T^{p,q}V$ of the form (14.5.4) is a basis for $T^{p,q}V$, as in the previous section. It is easy to see that each of these elements (14.5.4) is an eigenvector for $A_{p,q}$, so that $A_{p,q}$ is diagonalizable on $T^{p,q}V$. This corresponds to part of the proof of Lemma 6.3 on p41 of [25].

Suppose now that A is nilpotent on A, and observe that A' is nilpotent on V'. It is easy to see that each of the $p+q$ linear mappings on $T^{p,q}V$ corresponding to A as in (14.6.2) and (14.6.3) are nilpotent on $T^{p,q}V$. These $p+q$ linear mappings on $T^{p,q}V$ corresponding to A also commute with each other. It follows that $A_{p,q}$ is nilpotent on $T^{p,q}$ too, because $A_{p,q}$ is defined by adding and subtracting the $p+q$ linear mappings on $T^{p,q}V$, as appropriate. This corresponds to another part of the proof of Lemma 6.3 on p41 of [25].

As in the previous section, $T^{p,q}V$ is a module over $gl(V)$, as a Lie algebra over k, with respect to this action of $gl(V)$ on $T^{p,q}V$. Equivalently, the mapping from $A \in gl(V)$ to $A_{p,q} \in gl(T^{p,q}V)$ is a Lie algebra homomorphism. This means that $A \mapsto A_{p,q}$ is a linear mapping from $gl(V)$ into $gl(T^{p,q}V)$, and that

$$[A_{p,q}, B_{p,q}] = ([A, B])_{p,q} \tag{14.6.4}$$

for every $A, B \in gl(V)$. In particular, if A and B commute as linear mappings on V, then $A_{p,q}$ and $B_{p,q}$ commute as linear mappings on $T^{p,q}V$. This corresponds to part of the proof of Lemma 6.3 on p41 of [25] again.

Remember that there is a natural isomorphism from $T^{1,1}V = V \bigotimes V'$ onto the space $\mathcal{L}(V)$ of linear mappings from V into itself, as vector spaces over k, as in the previous section. One can check that $A_{1,1}$ corresponds to ad_A on $\mathcal{L}(V)$, as in Section 10.9.

14.7 Invariant tensors

Let k be a field, and let V be a finite-dimensional vector space over k again. Also let p and q be nonnegative integers, at least one of which is positive, and let t be an element of $T^{p,q}V$. Consider

$$\{A \in gl(V) : A_{p,q}(t) = 0\}, \tag{14.7.1}$$

where $A_{p,q}$ is as in the previous section. It is easy to see that (14.7.1) is a Lie subalgebra of $gl(V)$, because $A \mapsto A_{p,q}$ is a Lie algebra homomorphism from $gl(V)$ into $gl(T^{p,q}V)$.

Suppose from now on in this section that k is algebraically closed. Let A be a linear mapping from V into itself, and let A_1, A_2 be as in Section 10.8. Thus A_1 and A_2 are commuting linear mappings from V into itself, $A = A_1 + A_2$, A_1 is diagonalizable on V, and A_2 is nilpotent on V. Let $A_{p,q}$, $(A_1)_{p,q}$, and $(A_2)_{p,q}$ be the corresponding linear mappings from $T^{p,q}V$ into itself, as in the previous section. It follows that $(A_1)_{p,q}$ and $(A_2)_{p,q}$ commute on $T^{p,q}V$,

$$A_{p,q} = (A_1)_{p,q} + (A_2)_{p,q}, \tag{14.7.2}$$

$(A_1)_{p,q}$ is diagonalizable on $T^{p,q}V$, and $(A_2)_{p,q}$ is nilpotent on $T^{p,q}V$, as before. This means that $(A_1)_{p,q}$ and $(A_2)_{p,q}$ are the diagonalizable and nilpotent parts $(A_{p,q})_1$ and $(A_{p,q})_2$ of $A_{p,q}$, respectively, as linear mappings from $T^{p,q}V$ into itself, by uniqueness. This corresponds to Lemma 6.3 on p41 of [25].

In particular, $(A_1)_{p,q} = (A_{p,q})_1$ and $(A_2)_{p,q} = (A_{p,q})_2$ can be expressed as polynomials in $A_{p,q}$ with no constant term, as before. If $A_{p,q}(t) = 0$, then it follows that

$$(A_1)_{p,q}(t) = (A_2)_{p,q}(t) = 0. \tag{14.7.3}$$

Equivalently, if A is an element of (14.7.1), then A_1 and A_2 are elements of (14.7.1) as well. This argument is used in the proof of Corollary 5.4 on p52 of [25].

Let $\mathcal{A}$ be a Lie subalgebra of $gl(V)$, and suppose that $\mathcal{A}$ is semisimple as a Lie algebra over k. If k has characteristic 0, then Theorem 5.2 on p51 of [25] says that $\mathcal{A}$ can be characterized by its tensor invariants. This means that $\mathcal{A}$ can be expressed as the intersection of subalgebras of $gl(V)$ of the form (14.7.1). Corollary 5.4 on p52 of [25] says that under these conditions, $\mathcal{A}$ contains the semisimple and nilpotent parts of its elements. Remember that another approach to the latter was discussed in Section 14.4.

Now let $\mathcal{A}$ be any finite-dimensional semisimple Lie algebra over k. The abstract Jordan decomposition for elements of $\mathcal{A}$ is given in Theorem 5.6 on p52 of [25]. This is obtained from Corollary 5.4 in [25], applied to the image of $\mathcal{A}$ under the adjoint representation.

14.8 Diagonalizability and quotients

Let k be a field, let V be a vector space over k, and let W be a linear subspace of V. Consider the collection $\mathcal{L}_W(V)$ of all linear mappings T from V into itself such that

$$T(W) \subseteq W. \tag{14.8.1}$$

This is a subalgebra of the algebra $\mathcal{L}(V)$ of all linear mappings from V into itself. Let q be the canonical quotient mapping from V onto the quotient vector space V/W. If $T \in \mathcal{L}_W(V)$, then there is a unique linear mapping $T^{V/W}$ from V/W into itself such that

$$T^{V/W}(q(v)) = q(T(v)) \tag{14.8.2}$$

for every $v \in V$, as usual. It is easy to see that $T \mapsto T^{V/W}$ is an algebra homomorphism from $\mathcal{L}_W(V)$ into $\mathcal{L}(V/W)$, with respect to composition of mappings. More precisely, this homomorphism maps $\mathcal{L}_W(V)$ onto $\mathcal{L}(V/W)$. We shall normally be concerned with finite-dimensional vector spaces here, in which case the previous statement is more elementary.

In particular, if $T \in \mathcal{L}_W(V)$ is nilpotent as a linear mapping on V, then $T^{V/W}$ is nilpotent as a linear mapping on V/W. If $R, T \in \mathcal{L}_W(V)$ commute as linear mappings on V, then $R^{V/W}$, $T^{V/W}$ commute as linear mappings on V/W.

Let T be an element of $\mathcal{L}_W(V)$, and suppose that $v \in V$ is an eigenvector of T, with eigenvalue λ. Observe that

$$T^{V/W}(q(v)) = q(T(v)) = q(\lambda\, v) = \lambda\, q(v), \tag{14.8.3}$$

so that $q(v)$ is an eigenvector of $T^{V/W}$ with eigenvalue λ as well. If V is spanned by the eigenvectors of T, then it follows that V/W is spanned by the images under q of the eigenvectors of T, which are eigenvectors of $T^{V/W}$.

Let $(A, [\cdot,\cdot]_A)$ and $(B, [\cdot,\cdot]_B)$ be Lie algebras over k. Put

$$\mathrm{ad}_{A,x}(y) = [x, y]_A, \quad \mathrm{ad}_{B,w}(z) = [w, z]_B \tag{14.8.4}$$

for every $x, y \in A$ and $w, z \in B$, as usual. Suppose that ϕ is a Lie algebra homomorphism from A into B. This implies that

$$\phi(\mathrm{ad}_{A,x}(y)) = \phi([x, y]_A) = [\phi(x), \phi(y)]_B = \mathrm{ad}_{B,\phi(x)}(\phi(y)) \tag{14.8.5}$$

for every $x, y \in A$. Suppose for the moment that ϕ maps A onto B. If $x \in A$ and $\mathrm{ad}_{A,x}$ is nilpotent as a linear mapping from A into itself, then it follows that $\mathrm{ad}_{B,\phi(x)}$ is nilpotent as a linear mapping from B into itself. Equivalently, if $x \in A$ is ad-nilpotent in A, then $\phi(x)$ is ad-nilpotent in B.

If $x, y \in A$ and y is an eigenvector of $\mathrm{ad}_{A,x}$, then $\phi(y)$ is an eigenvector of $\mathrm{ad}_{B,\phi(x)}$, by (14.8.5). If A is spanned by the eigenvectors of $\mathrm{ad}_{A,x}$ and ϕ maps A onto B, then it follows that B is spanned by the eigenvectors of $\mathrm{ad}_{B,\phi(x)}$. These remarks correspond to part of the proof of the corollary on p30 of [14]. This also corresponds to Theorem 5.7 on p52 of [25], in the simpler case of surjective Lie algebra homomorphisms.

14.9 Diagonalizability and representations

Let k be an algebraically closed field of characteristic 0, and let V be a finite-dimensional vector space over k. Also let B be a Lie subalgebra of $gl(V)$, and suppose that B is semisimple as a Lie algebra over k. Let $x \in B$ be given, and remember that there are unique commuting linear mappings y_1 and y_2 on V such that $x = y_1 + y_2$, y_1 is diagonalizable on V, and y_2 is nilpotent on V, as in Section 10.8. In fact, $y_1, y_2 \in B$, because B is semisimple as a Lie algebra, as in Sections 14.4 and 14.7. Remember that y_1 is ad-diagonalizable on $gl(V)$, and y_2 is ad-nilpotent on $gl(V)$, as in Section 10.9. Using this, one can check that y_1 is ad-diagonalizable on B, and that y_2 is ad-nilpotent on B, because B is a Lie subalgebra of $gl(V)$. More precisely, if $y \in B$, then $\mathrm{ad}_{B,y}$ is the same as the restriction of $\mathrm{ad}_{gl(V),y}$ to B, because B is a Lie subalgebra of $gl(V)$. This means that y_1 and y_2 are the same as the ad-diagonalizable and ad-nilpotent parts of the abstract Jordan decomposition of x in B, by the uniqueness of the abstract Jordan decomposition, as in Section 14.3. This is the second part of the theorem on p29 of [14].

Let $(A, [\cdot,\cdot]_A)$ be a finite-dimensional semisimple Lie algebra over k, and let ϕ be a Lie algebra homomorphism from A into $gl(V)$. Put $B = \phi(A)$, which is a Lie subalgebra of $gl(V)$. Note that B is semisimple as a Lie algebra over k too, as in Section 10.14. Let $w \in A$ be given, and let $w = w_1 + w_2$ be the abstract Jordan decomposition of w in A, as in Section 14.3. Thus w_1 is ad-diagonalizable on A, w_2 is ad-nilpotent on A, and $[w_1, w_2]_A = 0$, as before. It follows that $\phi(w) = \phi(w_1) + \phi(w_2)$, where $\phi(w_1)$ is ad-diagonalizable on B and $\phi(w_2)$ is ad-nilpotent on B, as in the previous section. Note that $\phi(w_1)$ and $\phi(w_2)$ commute as linear mappings on V, because $[w_1, w_2]_A = 0$ and ϕ is a Lie algebra homomorphism. This means that $\phi(w_1)$ and $\phi(w_2)$ satisfy the requirements of the abstract Jordan decomposition of $\phi(w)$ in B. Put $x = \phi(w)$, and let $y_1, y_2 \in B$ be as in the preceding paragraph. It follows that

$$\phi(w_1) = y_1, \quad \phi(w_2) = y_2, \tag{14.9.1}$$

by uniqueness of the abstract Jordan decomposition of x in B. This corresponds to the corollary on p30 of [14], and to Theorem 7 on p7 of [24].

Let $(A_2, [\cdot,\cdot]_{A_2})$ be a finite-dimensional semisimple Lie algebra over k, and let A_1 be a Lie subalgebra of A_2 that is semisimple as a Lie algebra over k as well. If $x, y \in A_2$, then put $\mathrm{ad}_{A_2,x}(y) = [x, y]_{A_2}$, as usual. If $x \in A_1$, then $\mathrm{ad}_{A_1,x}$ is the same as the restriction of $\mathrm{ad}_{A_2,x}$ to A_1, because A_1 is a Lie subalgebra of A_2. Of course, A_2 is a finite-dimensional vector space over k in particular, so that $gl(A_2)$ is a Lie algebra over k with respect to the commutator bracket associated to composition of linear mappings. If $x \in A_1$, then put $\phi(x) = \mathrm{ad}_{A_2,x}$, which defines a Lie algebra homomorphism from A_1 into $gl(A_2)$. Let $w \in A_1$ be given, and let $w = w' + w''$ be the abstract Jordan decomposition of w in A_1. Thus

$$\mathrm{ad}_{A_2,w} = \mathrm{ad}_{A_2,w'} + \mathrm{ad}_{A_2,w''} \tag{14.9.2}$$

corresponds to the ordinary Jordan decomposition of $\mathrm{ad}_{A_2,w}$, as a linear mapping from A_2 into itself, as before. This means that $w = w' + w''$ also corresponds to the abstract Jordan decomposition of w in A_2, by uniqueness. This is the same as Exercise 9 on p31 of [14].

Let B_1, B_2 be finite-dimensional semisimple Lie algebras over k, and let ψ be a Lie algebra homomorphism from B_1 into B_2. Theorem 5.7 on p52 of [25] basically says that ψ maps abstract Jordan decompositions in B_1 to the corresponding abstract Jordan decompositions in B_2. Of course, this includes the case of subalgebras, as in the preceding paragraph. If ψ maps B_1 onto B_2, then this can be verified directly, as in the previous section. Otherwise, one can use this to reduce to the case of subalgebras.

14.10 Exponentiating nilpotents

Let T_1 and T_2 be commuting indeterminates, and remember that $\mathbf{Z}[T_1, T_2]$ is the space of formal polynomials in T_1 and T_2 with coefficients in $\mathbf{Z}$, as in Section 5.8. This is a commutative associative algebra over $\mathbf{Z}$ with respect to formal multiplication of polynomials, as before. If n is a nonnegative integer, then

$$(T_1 + T_2)^n = \sum_{j=0}^{n} \binom{n}{j} T_1^j \, T_2^{n-j}, \tag{14.10.1}$$

where $\binom{n}{j} = n!/j! \, (n-j)!$ is the usual binomial coefficient, as in the binomial theorem. Thus

$$(T_1 + T_2)^{n+1} = \sum_{j=0}^{n+1} \binom{n+1}{j} T_1^j \, T_2^{n+1-j} \tag{14.10.2}$$

is the same as

$$\begin{aligned} (T_1 + T_2)^n \, (T_1 + T_2) &= \sum_{j=0}^{n} \binom{n}{j} T_1^{j+1} \, T_2^{n-j} + \sum_{j=0}^{n} \binom{n}{j} T_1^j \, T_2^{n-j+1} \\ &= \sum_{j=1}^{n+1} \binom{n}{j-1} T_1^j \, T_2^{n+1-j} + \sum_{j=0}^{n} \binom{n}{j} T_1^j \, T_2^{n+1-j}. \end{aligned} \tag{14.10.3}$$

This implies the well-known identity

$$\binom{n+1}{j} = \binom{n}{j-1} + \binom{n}{j} \tag{14.10.4}$$

for $j = 1, \ldots, n$.

Let k be a field of characteristic 0. Alternatively, one can consider commutative rings k with multiplicative identity elements which are algebras over $\mathbf{Q}$. In this case, a module or algebra over k could also be considered as a vector space over $\mathbf{Q}$. Let $\mathcal{A}$ be an associative algebra over k with a multiplicative identity element e. Suppose that $x \in \mathcal{A}$ is nilpotent, so that $x^l = 0$ for some positive integer l. Under these conditions, the exponential of x is defined as an element of $\mathcal{A}$ by

$$\exp x = \sum_{j=0}^{\infty} (1/j!)\, x^j, \tag{14.10.5}$$

as usual. More precisely, $x^j = 0$ for all sufficiently large j, so that the infinite series reduces to a finite sum, and thus defines an element of $\mathcal{A}$. Of course, x^j is interpreted as being equal to e when $j = 0$.

Let y be another nilpotent element of $\mathcal{A}$, and suppose that x commutes with y. This implies that $x + y$ is nilpotent in $\mathcal{A}$, so that $\exp(x + y)$ can be defined as before. Observe that

$$\begin{aligned} \exp(x+y) &= \sum_{n=0}^{\infty} (1/n!)\,(x+y)^n = \sum_{n=0}^{\infty} (1/n!) \sum_{j=0}^{n} \binom{n}{j} x^j\, y^{n-j} \\ &= \sum_{n=0}^{\infty} \sum_{j=0}^{n} ((1/j!)\, x^j)\,((1/(n-j)!)\, y^{n-j}) = (\exp x)\,(\exp y). \end{aligned} \tag{14.10.6}$$

More precisely, the double sum is the same as the Cauchy product of the series defining $\exp x$ and $\exp y$, as in Section 4.2. The nilpotency conditions on x and y ensure that all of these sums reduce to finite sums. In particular, we can take $y = -x$, to get that

$$(\exp x)\, \exp(-x) = \exp(-x)\,(\exp x) = \exp 0 = e. \tag{14.10.7}$$

This means that $\exp x$ is invertible in $\mathcal{A}$, with

$$(\exp x)^{-1} = \exp(-x). \tag{14.10.8}$$

Let V be a module over k, and let T be a mapping from V into itself that is linear over k. Suppose that T is nilpotent on V, so that the lth power T^l of T with respect to composition is equal to 0 on V for some positive integer l. Thus the exponential $\exp T$ of T can be defined as a linear mapping from V into itself, using the algebra of linear mappings from V into itself with respect to composition of mappings in the previous remarks. Let W be a submodule of V, and suppose that T maps W into itself. It follows that $T^j(W) \subseteq W$ for every nonnegative integer j, so that

$$(\exp T)(W) \subseteq W. \tag{14.10.9}$$

More precisely, we have that

$$(\exp T)(W) = W \tag{14.10.10}$$

in this situation. This can be obtained from (14.10.9) and the analogous statement for $-T$. Alternatively, the restriction of $\exp T$ to W is the same as the exponential of the restriction of T to W, which is invertible on W.

Let k be a commutative ring with a multiplicative identity element, and let A be an algebra over k in the strict sense, where multiplication of $a, b \in A$ is expressed as $a\,b$. If δ is a derivation on A, then it is well known that

$$\delta^n(a\,b) = \sum_{j=0}^{n} \binom{n}{j} \cdot \delta^j(a)\,\delta^{n-j}(b) \tag{14.10.11}$$

for every nonnegative integer n and $a, b \in A$. More precisely, if this holds for some $n \geq 0$, then

$$\begin{aligned} \delta^{n+1}(a\,b) &= \delta(\delta^n(a\,b)) = \sum_{j=0}^{n} \binom{n}{j} (\delta^{j+1}(a)\,\delta^{n-j}(b) + \delta^j(a)\,\delta^{n-j+1}(b)) \\ &= \sum_{j=1}^{n+1} \binom{n}{j-1} \delta^j(a)\,\delta^{n+1-j}(b) + \sum_{j=0}^{n} \binom{n}{j} \delta^j(a)\,\delta^{n+1-j}(b). \end{aligned} \tag{14.10.12}$$

This implies the analogue of (14.10.11) for $n + 1$, by (14.10.4). It follows that (14.10.11) holds for all $n \geq 0$, by induction.

14.11 Nilpotent derivations

Let k be a commutative ring with a multiplicative identity element that is an algebra over $\mathbf{Q}$, or simply a field of characteristic 0, as in the previous section. Also let A be an algebra over k in the strict sense again, and let δ be a derivation on A that is nilpotent as a mapping from A into itself, so that $\delta^l = 0$ for some positive integer l. Thus $\exp \delta$ can be defined as a mapping from A into itself that is linear over k, as in the previous section. If $a, b \in A$, then

$$\begin{aligned} (\exp \delta)(a\,b) &= \sum_{n=0}^{\infty} (1/n!)\,\delta^n(a\,b) = \sum_{n=0}^{\infty} (1/n!) \sum_{j=0}^{n} \binom{n}{j} \delta^j(a)\,\delta^{n-j}(b) \\ &= \sum_{n=0}^{\infty} \sum_{j=0}^{n} ((1/j!)\,\delta^j(a))\,((1/(n-j)!)\,\delta^{n-j}(b)) \\ &= ((\exp \delta)(a))\,((\exp \delta)(b)). \end{aligned} \tag{14.11.1}$$

More precisely, the double sum is the same as the Cauchy product of the series defining $(\exp \delta)(a)$ and $(\exp \delta)(b)$, and the nilpotency condition on δ ensures that all of these sums reduce to finite sums. Note that $\exp \delta$ is invertible as a linear mapping from A into itself, as in the previous section. Thus (14.11.1) implies that $\exp \delta$ is an algebra automorphism on A, as on p9 of [14].

Let $(A, [\cdot, \cdot]_A)$ be a Lie algebra over k, and put $\mathrm{ad}_x(y) = [x, y]_A$ for every x, y in A, as usual. Remember that ad_x is a derivation on A, as in Section 2.5. If $x \in A$ is ad-nilpotent, then $\exp \mathrm{ad}_x$ defines a Lie algebra automorphism on A, as in the preceding paragraph. Let $\mathrm{Int}\, A$ be the subgroup of the group of all Lie algebra automorphisms of A generated by these automorphisms. The elements of $\operatorname{Int} A$ are called *inner automorphisms* of A, as on p9 of [14]. If ϕ is any Lie algebra automorphism on A, then it is easy to see that

$$\phi \circ \mathrm{ad}_x \circ \phi^{-1} = \mathrm{ad}_{\phi(x)} \tag{14.11.2}$$

for every $x \in A$. In particular, if $x \in A$ is ad-nilpotent, then $\phi(x)$ is ad-nilpotent as well. In this case, we get that

$$\phi \circ (\exp \mathrm{ad}_x) \circ \phi^{-1} = \exp \mathrm{ad}_{\phi(x)}, \tag{14.11.3}$$

by (14.11.2). This implies that $\operatorname{Int} A$ is a normal subgroup of the group of all Lie algebra automorphisms on A, as on p9 of [14].

Let B be a Lie subalgebra of A, and let x be an element of the normalizer of B in A, so that ad_x maps B into itself. If x is ad-nilpotent on A, then $\exp \mathrm{ad}_x$ can be defined as a linear mapping from A into itself as before. In fact, we have that

$$(\exp \mathrm{ad}_x)(B) = B, \tag{14.11.4}$$

as in (14.10.10). In particular, this holds when $x \in B$, in which case the restriction of ad_x to B is the same as $\mathrm{ad}_{B,x}$.

Now let A be an associative algebra over k with a multiplicative identity element e, where multiplication of $a, b \in A$ is expressed as $a\,b$ again. If $a \in A$, then let L_a and R_a be the usual operators of left and right multiplication by a on A, so that $L_a(x) = a\,x$ and $R_a(x) = x\,a$ for every $a \in A$. Note that

$$(L_a)^j = L_{a^j}, \quad (R_a)^j = R_{a^j} \tag{14.11.5}$$

for every nonnegative integer j. Suppose that a is nilpotent in A, which implies that L_a and R_a are nilpotent as linear mappings from A into itself. It is easy to see that

$$\exp L_a = L_{\exp a}, \quad \exp R_a = R_{\exp a} \tag{14.11.6}$$

under these conditions.

Remember that A may be considered as a Lie algebra over k with respect to the corresponding commutator bracket $[a, b] = a\,b - b\,a$. If $a \in A$, then

$$\mathrm{ad}_a = L_a - R_a = L_a + R_{-a}, \tag{14.11.7}$$

as a linear mapping from A into itself. Suppose that a is nilpotent in A again, and remember that L_a and R_{-a} commute as linear mappings from A into itself. This implies that ad_a is nilpotent on A, and that

$$\begin{aligned} \exp \mathrm{ad}_a &= \exp(L_a + R_{-a}) = (\exp L_a) \circ (\exp R_{-a}) \\ &= L_{\exp a} \circ R_{\exp(-a)} = L_{\exp a} \circ R_{(\exp a)^{-1}}. \end{aligned} \tag{14.11.8}$$

Equivalently,

$$(\exp \mathrm{ad}_a)(x) = (\exp a)\,x\,(\exp a)^{-1} \tag{14.11.9}$$

for every $x \in A$, as on p9 of [14].

14.12 Exponentials and homomorphisms

Let k be a commutative ring with a multiplicative identity element that is an algebra over $\mathbf{Q}$, or simply a field of characteristic 0, as before. Also let $\mathcal{A}$ and $\mathcal{B}$ be associative algebras over k with multiplicative identity elements $e_{\mathcal{A}}$ and $e_{\mathcal{B}}$, respectively. Suppose that ϕ is an algebra homomorphism from $\mathcal{A}$ into $\mathcal{B}$ such that $\phi(e_{\mathcal{A}}) = e_{\mathcal{B}}$. Let x be a nilpotent element of $\mathcal{A}$, which implies that $\phi(x)$ is nilpotent in $\mathcal{B}$. Under these conditions, it is easy to see that

$$\phi(\exp_{\mathcal{A}} x) = \exp_{\mathcal{B}} \phi(x), \tag{14.12.1}$$

where $\exp_{\mathcal{A}} x$ and $\exp_{\mathcal{B}} \phi(x)$ are the exponentials of x and $\phi(x)$ in $\mathcal{A}$ and $\mathcal{B}$, respectively.

Now let $(A, [\cdot,\cdot]_A)$ and $(B, [\cdot,\cdot]_B)$ be Lie algebras over k, and let ψ be a Lie algebra homomorphism from A into B.. As usual, we put $\mathrm{ad}_{A,x}(y) = [x, y]_A$ and $\mathrm{ad}_{B,w}(z) = [w, z]_B$ for every $x, y \in A$ and $w, z \in B$. If $x, y \in A$, then

$$\psi(\mathrm{ad}_{A,x}(y)) = \mathrm{ad}_{B,\psi(x)}(\psi(y)), \tag{14.12.2}$$

as in Section 14.8. It follows that

$$\psi((\mathrm{ad}_{A,x})^j(y)) = (\mathrm{ad}_{B,\psi(x)})^j(\psi(y)) \tag{14.12.3}$$

for every positive integer j. Suppose that x is ad-nilpotent in A, and that $\psi(x)$ is ad-nilpotent in B. Thus $\exp \mathrm{ad}_{A,x}$ and $\exp \mathrm{ad}_{B,\psi(x)}$ can be defined as linear mappings from A and B into themselves, as before. Using (14.12.3), we get that

$$\psi((\exp \mathrm{ad}_{A,x})(y)) = (\exp \mathrm{ad}_{B,\psi(x)})(\psi(y)) \tag{14.12.4}$$

for every $y \in A$.

If x is ad-nilpotent in A, and ψ maps A onto B, then $\psi(x)$ is ad-nilpotent in B, by (14.12.3), as in Section 14.8. Similarly, if $\psi(x)$ is ad-nilpotent in B, and ψ is injective, then x is ad-nilpotent in A.

Let V be a module over k, and let ρ be a representation of A on V. If R and T are mappings from V into itself that are linear over k, then put $\mathrm{ad}_R(T) = [R, T] = R \circ T - T \circ R$, as usual. Suppose that $x \in A$ has the property that ρ_x is nilpotent as a linear mapping from V into itself. Thus $\exp \rho_x$ is defined as an invertible linear mapping from V onto itself, as before. We also have that ad_{ρ_x} is nilpotent as a linear mapping on the space of linear mappings from V into itself, so that $\exp \mathrm{ad}_{\rho_x}$ is defined as an invertible linear mapping on the space of linear mappings from V into itself. In fact,

$$(\exp \mathrm{ad}_{\rho_x})(T) = (\exp \rho_x) \circ T \circ (\exp \rho_x)^{-1} \tag{14.12.5}$$

for every linear mapping T from V into itself, as in the previous section. In particular,

$$(\exp \mathrm{ad}_{\rho_x})(\rho_y) = (\exp \rho_x) \circ \rho_y \circ (\exp \rho_x)^{-1} \tag{14.12.6}$$

for every $y \in A$.

Suppose that x is ad-nilpotent in A, in addition to ρ_x being nilpotent on V. Thus $\exp \mathrm{ad}_{A,x}$ is defined as a linear mapping from A into itself, and

$$\rho_{(\exp \mathrm{ad}_{A,x})(y)} = (\exp \mathrm{ad}_{\rho_x})(\rho_y) \tag{14.12.7}$$

for every $y \in A$. This follows from (14.12.4), with B taken to be the space of linear mappings from V into itself, considered as a Lie algebra over k with respect to the commutator bracket associated to composition of linear mappings, and with ψ taken to be the Lie algebra homomorphism from A into B corresponding to ρ. This implies that

$$\rho_{(\exp \mathrm{ad}_{A,x})(y)} = (\exp \rho_x) \circ \rho_y \circ (\exp \rho_x)^{-1} \tag{14.12.8}$$

for every $y \in A$.

14.13 Representations and structure constants

Let k be a commutative ring with a multiplicative identity element, and let m and n be positive integers. The spaces k^m and k^n of m and n-tuples of elements of k are (free) modules over k with respect to coordinatewise addition and scalar multiplication, as usual. Let ρ be a bilinear action of k^m on k^n, which corresponds to a mapping from $k^m \times k^n$ into k^n that is bilinear over k. If $x = (x_1, \ldots, x_m) \in k^m$ and $v = (v_1, \ldots, v_n) \in k^n$, then $\rho_x(v) \in k^n$ can be expressed as

$$(\rho_x(v))_r = \sum_{j=1}^{m} \sum_{l=1}^{n} a_{j,l}^r \, x_j \, v_l, \tag{14.13.1}$$

where the left side is the rth coordinate of $\rho_x(v)$ for each $r = 1, \ldots, n$. The coefficients $a_{j,l}^r$ are elements of k for each $j = 1, \ldots, m$ and $l, r = 1, \ldots, n$, and do not depend on x or v. It is easy to see that these coefficients are uniquely determined by ρ. Conversely, any coefficients $a_{j,l}^r \in k$ determine a bilinear action of k^m on k^n in this way.

Let K be a commutative associative algebra over k, where multiplication of $y, z \in K$ is expressed as $y\,z$. The spaces K^m and K^n of m and n-tuples of elements of K may be considered as modules over k with respect to coordinatewise addition and scalar multiplication. If $x \in K^m$ and $v \in K^n$, then let $\rho_x^K(v)$ be the element of K^n whose rth coordinate is equal to

$$(\rho_x^K(v))_r = \sum_{j=1}^{m} \sum_{l=1}^{n} a_{j,l}^r \, x_j \, v_l \tag{14.13.2}$$

for each $r = 1, \ldots, n$. This uses both multiplication on K and scalar multiplication of elements of K by elements of k to define the terms of the sum on the right. This defines ρ^K as a bilinear action of K^m on K^n.

Suppose that k^m is a Lie algebra over k, with respect to a Lie bracket $[\cdot,\cdot]_{k^m}$. Using the structure constants for $[\cdot,\cdot]_{k^m}$, we get a Lie bracket $[\cdot,\cdot]_{K^m}$ on K^m, as in Section 9.14.

Suppose also that ρ is a representation of k^m, as a Lie algebra over k, on k^n. This means that

$$\rho_{[w,x]_{k^m}}(v) = \rho_w(\rho_x(v)) - \rho_x(\rho_w(v)) \tag{14.13.3}$$

for every $w, x \in k^m$ and $v \in k^n$. This can be characterized by suitable conditions on the coefficients $a^r_{j,l}$ associated to ρ and the structure constants for $[\cdot,\cdot]_{k^m}$. It follows that

$$\rho^K_{[w,x]_{K^m}}(v) = \rho^K_w(\rho^K_x(v)) - \rho^K_x(\rho^K_w(v)) \tag{14.13.4}$$

for every $w, x \in K^m$ and $v \in K^n$. Thus ρ^K is a representation of K^m, as a Lie algebra over k, on K^n under these conditions.

If T is a homomorphism from k^n into itself, as a module over k, then T corresponds to an $n \times n$ matrix with entries in k in the usual way. Using the same matrix, we get a homomorphism T_K from K^n into itself, as a module over k. This defines a homomorphism from $\mathrm{Hom}_k(k^n, k^n)$ into $\mathrm{Hom}_k(K^n, K^n)$, as associative algebras over k with respect to composition of mappings.

Suppose that K has a multiplicative identity element e, so that K^m and K^n may be considered as free modules over K with respect to coordinatewise addition and scalar multiplication. In this case, K^m may be considered as a Lie algebra over K with respect to $[\cdot,\cdot]_{K^m}$, as in Section 9.14. Similarly, ρ^K may be considered as a representation of K^m, as a Lie algebra over K, on K^n, as a module over K. If T is a homomorphism from k^n into itself as a module over k, then T_K is a homomorphism from K^n into itself as a module over K.

As before, $t \mapsto t\,e$ defines a ring homomorphism from k into K. This leads to homomorphisms from k^m and k^n into K^m and K^n, as modules over k. More precisely, this gives a homomorphism from k^m into K^m as Lie algebras over k. Similarly, if $x \in k^m$ and $v \in k^n$, then the image of $\rho_x(v)$ in K^n is the same as taking the images of x and v in K^m and K^n, respectively, and then using ρ^K. If T is a homomorphism from k^n into itself, as a module over k, and $v \in k^n$, then the image of $T(v)$ in K^n is the same as first taking the image of v in K^n, and then taking the image of that under T_K.

Suppose that $t \mapsto t\,e$ is injective as a mapping from k into K, so that the corresponding mappings from k^m and k^n into K^m and K^n, respectively, are injective as well. If T is a homomorphism from k^n into itself, as a module over k, and $T_K = 0$ on K^n, then $T = 0$ on k^n. Similarly, if T_K is nilpotent on K^n, then T is nilpotent on k^n.

Let $x \in k^m$ be given, and let x_K be its image in K^m. If $T = \rho_x$, then $T_K = \rho^K_{x_K}$. In particular, if $\rho^K_{x_K}$ is nilpotent as a mapping from K^n into itself, then ρ_x is nilpotent on k^n.

14.14 Lie's theorem and nilpotence

Let k be a field of characteristic 0, and let $(A, [\cdot,\cdot]_A)$ be a solvable Lie algebra over k with positive finite dimension m as a vector space over k. Also let V be a vector space over k of positive finite dimension n, and let ρ be a representation of A on V. Remember that $[A, A] \subseteq A$ is as defined in Section 9.2.

Suppose for the moment that k is algebraically closed. Under these conditions, there is a flag $\mathcal{F} = \{V_j\}_{j=0}^n$ in V such that

$$\rho_a(V_j) \subseteq V_j \tag{14.14.1}$$

for every $a \in A$ and $j = 0, 1, \ldots, n$, as in Section 9.13. If $a \in [A, A]$, then it follows that

$$\rho_a(V_j) \subseteq V_{j-1} \tag{14.14.2}$$

for every $j = 1, \ldots, n$, as in Section 9.11. In particular, this implies that

$$(\rho_a)^n = 0 \tag{14.14.3}$$

on V for every $a \in [A, A]$.

Otherwise, let K be an algebraically closed field that contains k as a subfield. We may as well suppose that $A = k^m$ as a vector space over k, and that $V = k^n$. As in Section 9.14, $[\cdot, \cdot]_A$ can be extended to a Lie bracket $[\cdot, \cdot]_{A_K}$ on $A_K = K^m$, so that A_K becomes a solvable Lie algebra over K. Similarly, we can use ρ to get a representation ρ^K of A_K, as a Lie algebra over K, on K^n, as a vector space over K, as in the previous section.

Of course, $[A_K, A_K]$ can be defined as a subset of A_K as in Section 9.2 too. If $a \in [A_K, A_K]$, then it follows that

$$(\rho_a^K)^n = 0 \tag{14.14.4}$$

on K^n, as before. In particular, this holds when $a \in [A, A]$. This implies that (14.14.3) holds on $V = k^n$ when $a \in [A, A]$.

Chapter 15

Complexifications and $sl_2(k)$ modules

15.1 Basic properties of $sl_2(k)$ modules

Let k be a commutative ring with a multiplicative identity element. Remember that $sl_2(k)$ is freely generated, as a module over k, by

$$x = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}, \quad y = \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix}, \quad \text{and} \quad h = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}, \tag{15.1.1}$$

as in Section 10.2. Thus every element of $sl_2(k)$ can be expressed in a unique way as a linear combination of x, y, and h, with coefficients in k. We also have that

$$[h, x] = 2 \cdot x, \quad [h, y] = -2 \cdot y, \quad \text{and} \quad [x, y] = h, \tag{15.1.2}$$

as before, using the commutator bracket associated to matrix multiplication.

Let V be a module over k, and let $\rho = \rho^V$ be a representation of $sl_2(k)$ on V, as a Lie algebra over k. Thus ρ_x, ρ_y, and ρ_h are homomorphisms from V into itself, as a module over k, such that

$$\begin{gathered}[\rho_h, \rho_x] = \rho_{[h,x]} = 2 \cdot \rho_x, \quad [\rho_h, \rho_y] = \rho_{[h,y]} = -2 \cdot \rho_y, \\ \text{and} \quad [\rho_x, \rho_y] = \rho_{[x,y]} = \rho_h.\end{gathered} \tag{15.1.3}$$

Equivalently, we may consider V as a module over $sl_2(k)$, as a Lie algebra over k, with

$$a \cdot v = \rho_a(v) \tag{15.1.4}$$

for every $a \in sl_2(k)$ and $v \in V$.

Let us now take k to be a field, so that V is a vector space over k. If $\lambda \in k$, then put

$$V_\lambda = \{v \in V : h \cdot v = \lambda\, v\}, \tag{15.1.5}$$

which is the linear subspace of V consisting of eigenvectors of ρ_h with eigenvalue λ. Thus $V_\lambda \neq \{0\}$ exactly when λ is an eigenvalue of ρ_h on V. In this case, λ may be called a *weight* of h on V, and V_λ may be called a *weight space*, as on p31 of [14]. An element of V_λ may be said to have *weight* λ, as on p17 of [24].

Suppose that $v \in V_\lambda$ for some $\lambda \in k$. Observe that

$$\begin{aligned} h \cdot (x \cdot v) &= ([h, x]) \cdot v + x \cdot (h \cdot v) \\ &= (2 \cdot x) \cdot v + x \cdot (\lambda\, v) = (\lambda + 2)\,(x \cdot v). \end{aligned} \tag{15.1.6}$$

More precisely, $\lambda + 2$ means $\lambda + 2 \cdot 1 = \lambda + 1 + 1$ as an element of k, where 1 is the multiplicative identity element in k. It follows that

$$x \cdot v \in V_{\lambda+2}. \tag{15.1.7}$$

Similarly,

$$\begin{aligned} h \cdot (y \cdot v) &= ([h, y]) \cdot v + y \cdot (h \cdot v) \\ &= (-2 \cdot y) \cdot v + y \cdot (\lambda\, v) = (\lambda - 2)\,(y \cdot v), \end{aligned} \tag{15.1.8}$$

where $\lambda - 2 = \lambda - 2 \cdot 1 = \lambda - 1 - 1$, as an element of k. This means that

$$y \cdot v \in V_{\lambda-2}. \tag{15.1.9}$$

Of course, if k has characteristic 0, then k may be considered as containing the rational numbers as a subfield.

Remember that nonzero eigenvectors of ρ_h with distinct eigenvalues are automatically linearly independent. If V has finite dimension as a vector space over k, then it follows that there are only finitely many weights λ of h on V.

15.2 Maximal or primitive vectors

Let us continue with the same notation and hypotheses as in the previous section. Suppose for the moment that k is an algebraically closed field of characteristic 0, and that V has positive finite dimension. This implies that ρ_h is diagonalizable on V, as in Section 14.9. This also uses the fact that h is ad-diagonalizable in $sl_2(k)$.

Under these conditions, there is a weight $\lambda \in k$ of h on V, because $V \neq \{0\}$. In fact, there is a weight λ of h on V such that $V_{\lambda+2} = \{0\}$, because there are only finitely many weights of h on V. In this case, if $v \in V_\lambda$, then

$$x \cdot v = 0, \tag{15.2.1}$$

by (15.1.7).

If v is a nonzero element of V_λ for some $\lambda \in k$ that satisfies (15.2.1), then v may be called a *maximal vector of weight* λ, as on p32 of [14]. In this situation, v may also be said to be *primitive of weight* λ, as in Definition 1 on p18 of [24]. Note that V does not need to have finite dimension for this definition.

If k is an algebraically closed field of characteristic 0 and V has positive finite dimension, then one can get a maximal vector of some weight $\lambda \in k$ by choosing λ so that $V_{\lambda+2} = \{0\}$, as before. Alternatively, if $v \in V$ is a nonzero eigenvector of ρ_h with eigenvalue $\lambda \in k$, then

$$\rho_h((\rho_x)^j(v)) = (\lambda + 2\,j)\,(\rho_x)^j(v) \tag{15.2.2}$$

for every nonnegative integer j, as before. We also have that $(\rho_x)^j(v) = 0$ for some positive integer j, because V has finite dimension. Let j_0 be the largest nonnegative integer such that $(\rho_x)^{j_0}(v) \neq 0$, so that $(\rho_x)^{j_0+1}(v) = 0$. This means that $(\rho_x)^{j_0}(v)$ is a maximal vector of weight $\lambda + 2\,j_0$, as in the alternate proof of Proposition 3 on p18 of [24].

Let B be the linear subspace of $sl_2(k)$ spanned by x and h. This is a Lie subalgebra of $sl_2(k)$, which is solvable as a Lie algebra over k. Let v be a nonzero element of V, so that

$$\{t\,v : t \in k\} \tag{15.2.3}$$

is a one-dimensional linear subspace of V. If v is primitive, then (15.2.3) is mapped into itself by ρ_h and ρ_x. Equivalently, this means that (15.2.3) is a submodule of V, as a module over B, as a Lie algebra over k.

Conversely, suppose that (15.2.3) is a submodule of V, as a module over B. This is the same as saying that v is an eigenvector of both ρ_h and ρ_x. It follows that

$$2 \cdot \rho_x(v) = ([\rho_h, \rho_x])(v) = 0. \tag{15.2.4}$$

If k does not have characteristic 2, then we get that $\rho_x(v) = 0$, so that v is primitive. This corresponds to Proposition 2 on p18 of [24].

Suppose that k is an algebraically closed field of characteristic 0 again, and that V has positive finite dimension. Because B is solvable, there is a $v \in V$ such that $v \neq 0$ and v is an eigenvector of ρ_b for every $b \in B$, as in Section 9.13. This implies that v is primitive, as in the preceding paragraph. This corresponds to the proof of Proposition 3 on p18 of [24], and to Exercise 1 on p34 of [14].

15.3 Related submodules

Let k be a field of characteristic 0, and let V be a vector space over k. Also let $\rho = \rho^V$ be a representation of $sl_2(k)$ on V, as a Lie algebra over k, so that V may be considered as a module over $sl_2(k)$. Suppose that v is a primitive element of V of weight $\lambda \in k$. Put

$$v_j = (1/j!)\,(\rho_y)^j(v) \tag{15.3.1}$$

for every positive integer j, as on p32 of [14], and Theorem 3 on p18 of [24]. More precisely, $(\rho_y)^j$ is the jth power of ρ_y with respect to composition, as a linear mapping from V into itself. We can define v_j as in (15.3.1) when $j = 0$ too, with the usual interpretations, so that $v_0 = v$. It is convenient to put $v_{-1} = 0$ as well.

Under these conditions, we have that

$$h \cdot v_j = (\lambda - 2\,j)\, v_j \tag{15.3.2}$$

for every $j \geq 0$, which is to say that $v_j \in V_{\lambda - 2\,j}$. This follows by using (15.1.9) repeatedly, or using induction. We also have that

$$y \cdot v_j = (j + 1) \cdot v_{j+1} \tag{15.3.3}$$

for every $j \geq -1$, by definition of v_j. Let us check that

$$x \cdot v_j = (\lambda - j + 1)\, v_{j-1} \tag{15.3.4}$$

for every $j \geq 0$. If $j = 0$, then this uses the hypothesis that $v_0 = v$ be primitive, so that $x \cdot v = 0$. Otherwise, if $j \geq 1$, then we can use (15.3.3) to get that

$$j\, x \cdot v_j = x \cdot (y \cdot v_{j-1}) = ([x, y]) \cdot v_{j-1} + y \cdot (x \cdot v_{j-1}). \tag{15.3.5}$$

Using induction, we may suppose that the analogue of (15.3.4) for $j - 1$ holds, so that

$$j\, x \cdot v_j = h \cdot v_{j-1} + (\lambda - (j - 1) + 1)\, y \cdot v_{j-2}. \tag{15.3.6}$$

It follows that

$$j\, x \cdot v_j = (\lambda - 2\,(j - 1))\, v_{j-1} + (\lambda - j + 2)\, ((j - 2) + 1)\, v_{j-1}, \tag{15.3.7}$$

by (15.3.2) and (15.3.3). This reduces to

$$\begin{aligned} j\, x \cdot v_j &= ((\lambda - 2\,j + 2) + (\lambda - j + 2)\, (j - 1))\, v_{j-1} \\ &= (\lambda + (\lambda - j)\, (j - 1))\, v_{j-1} = j\, (\lambda - j + 1)\, v_{j-1}. \end{aligned} \tag{15.3.8}$$

This implies (15.3.4), as desired. This corresponds to the lemma on p32 of [14], and Theorem 3 on p18 of [24].

Remember that $v_0 = v \neq 0$, because v is primitive, by hypothesis. As in Corollary 1 on p19 of [24], there are two cases to consider. In the first case,

$$\text{for each } j \geq 0, \text{ we have that } v_j \neq 0. \tag{15.3.9}$$

This means that the v_j's are linearly independent in V, because they are eigenvectors for ρ_h with distinct eigenvalues, by (15.3.2). In particular, this implies that V has infinite dimension as a vector space over k.

In the second case,

$$v_l = 0 \text{ for some } l \geq 1. \tag{15.3.10}$$

This implies that $v_j = 0$ for every $j \geq l$, by the definition of v_j. In this case, let m be the largest nonnegative integer such that $v_m \neq 0$. Thus $v_j \neq 0$ when $j \leq m$, and $v_j = 0$ when $j > m$. Observe that

$$x \cdot v_{m+1} = (\lambda - m)\, v_m, \tag{15.3.11}$$

by (15.3.4) with $j = m + 1$. It follows that

$$\lambda = m, \tag{15.3.12}$$

because $v_m \neq 0$ and $v_{m+1} = 0$. This is also related to some of the remarks on p32 of [14].

In this second case, let W be the linear span of $v_0, v_1, \ldots, v_m$ in V. It is easy to see that W is a submodule of V, as a module over $sl_2(k)$, by (15.3.2), (15.3.3), and (15.3.4). Let W_0 be a nontrivial linear subspace of W such that $\rho_h(W_0) \subseteq W_0$. Because ρ_h is diagonalizable on W, we get that the restriction of ρ_h to W_0 is diagonalizable as well. In particular, W_0 contains a nonzero eigenvector of ρ_h. In this situation, this means that $v_{j_0} \in W_0$ for some j_0, $0 \le j_0 \le m$, because the corresponding eigenvalues for ρ_h on W are distinct. If W_0 is a submodule of W, as a module over $sl_2(k)$, then it follows that $v_j \in W_0$ for every $j = 0, 1, \ldots, m$, by (15.3.3) and (15.3.4). This implies that $W_0 = W$, so that W is irreducible as a module over $sl_2(k)$. This corresponds to Corollary 2 on p19 of [24], as well as some of the remarks on p32-3 and part of Exercise 3 on p34 of [14].

15.4 Constructing modules $W(m)$

Let k be a commutative ring with a multiplicative identity element, and let m be a nonnegative integer. Also let $W(m)$ be a module over k freely generated by $m+1$ nonzero distinct elements $v_0, v_1, \ldots, v_m$. This corresponds to $V(m)$ on p33 of [14], and to W_m on p19 of [24]. More precisely, one can take $W(m)$ to be the space k^{m+1} of $(m+1)$-tuples of elements of k, as a module over k with coordinatewise addition and scalar multiplication, and $v_0, v_1, \ldots, v_m$ to be the standard basis vectors in k^{m+1}. It will be convenient to put $v_{-1} = v_{m+1} = 0$, as elements of $W(m)$.

Put

$$H(v_j) = (m - 2\,j) \cdot v_j, \tag{15.4.1}$$

$$Y(v_j) = (j + 1) \cdot v_{j+1}, \tag{15.4.2}$$

$$X(v_j) = (m - j + 1) \cdot v_{j-1} \tag{15.4.3}$$

for $j = 0, 1, \ldots, m$. More precisely, there are unique module homomorphisms H, Y, and X from $W(m)$ into itself that satisfy these conditions. Note that (15.4.1) holds trivially when $j = -1$ or $m + 1$. Similarly, (15.4.2) holds trivially when $j = -1$, and (15.4.3) holds trivially when $j = m + 1$.

Observe that

$$\begin{aligned} H(X(v_j)) - X(H(v_j)) &= (m - j + 1) \cdot H(v_{j-1}) - (m - 2\,j) \cdot X(v_j) \\ &= (m - j + 1)\,(m - 2\,(j - 1)) \cdot v_{j-1} \\ &\quad - (m - 2\,j) \cdot X(v_j) \\ &= ((m - 2\,(j - 1)) - (m - 2\,j)) \cdot X(v_j) = 2 \cdot X(v_j) \end{aligned} \tag{15.4.4}$$

for each $j = 0, 1, \ldots, m$. Similarly,

$$\begin{aligned} H(Y(v_j)) - Y(H(v_j)) &= (j+1) \cdot H(v_{j+1}) - (m - 2\,j) \cdot Y(v_j) \\ &= (j+1)\,(m - 2\,(j+1)) \cdot v_{j+1} - (m - 2\,j) \cdot Y(v_j) \\ &= ((m - 2\,(j+1)) - (m - 2\,j)) \cdot Y(v_j) = -2 \cdot Y(v_j) \end{aligned} \tag{15.4.5}$$

for every $j = 0, 1, \cdots, m$. We also have that

$$\begin{aligned} X(Y(v_j)) - Y(X(v_j)) &= (j+1) \cdot X(v_{j+1}) - (m - j + 1) \cdot Y(v_{j-1}) \\ &= (j+1)\,(m - (j+1) + 1) \cdot v_j \\ &\quad -(m - j + 1)\,((j-1) + 1) \cdot v_j \\ &= ((j+1)\,(m - j) - (m - j + 1)\,j) \cdot v_j \\ &= ((m - j) - j) \cdot v_j = H(v_j) \end{aligned} \tag{15.4.6}$$

for each $j = 0, 1, \ldots, n$. This shows that

$$[H, X] = 2 \cdot X, \quad [H, Y] = -2 \cdot Y, \quad \text{and} \quad [X, Y] = H, \tag{15.4.7}$$

using the commutator bracket associated to composition of module homomorphisms from $W(m)$ into itself.

Let x, y, and h be the usual elements of $sl_2(k)$, as in (15.1.1). Thus every element of $sl_2(k)$ can be expressed in a unique way as a linear combination of x, y, and h with coefficients in k, as in Section 10.2. The Lie brackets of x, y, and h in $sl_2(k)$ satisfy (15.1.2), as before. Put

$$\rho_x = X, \quad \rho_y = Y, \quad \text{and} \quad \rho_h = H. \tag{15.4.8}$$

If $a \in sl_2(k)$, then we can define ρ_a as a module homomorphism from $W(m)$ into itself that satisfies (15.4.8) and is linear over k in a. This defines a representation $\rho = \rho^{W(m)}$ of $sl_2(k)$, as a Lie algebra over k, on $W(m)$, because of (15.4.7). This corresponds to the statement before Theorem 2 on p20 of [24], as well as remarks on p33 and part of Exercise 3 on p34 of [14].

If $m = 0$, then ρ corresponds to the trivial representation of $sl_2(k)$ on k. If $m = 1$, then ρ corresponds to the standard representation of $sl_2(k)$ on k^2. If $m = 2$, then one can check that ρ is isomorphic to the adjoint representation on $sl_2(k)$. More precisely, if one takes $v_0 = x$, $v_1 = -h$, and $v_2 = y$, then X, Y, and H correspond to ad_x, ad_y, and ad_h on $sl_2(k)$, respectively. This corresponds to the examples mentioned on p20 of [24], and some remarks on p33 of [14].

15.5 More on $W(m)$

Let k be a field of characteristic 0, and let m be a nonnegative integer. Also let $W(m)$ be as in the previous section, so that $W(m)$ is a vector space over k of dimension $m + 1$, and $\rho = \rho^{W(m)}$ is a representation of $sl_2(k)$ on $W(m)$. In this situation, v_0 is a primitive element of $V = W(m)$ with weight $\lambda = m$, by construction. Of course, (15.3.2), (15.3.3), and (15.3.4) correspond to (15.4.1), (15.4.2), and (15.4.3) here, respectively. Thus $v_1, \ldots, v_m$ in the previous section correspond to the analogous vectors in Section 15.3, and $v_j = 0$ when $j > m$ in the notation of Section 15.3. This means that we are in the second case (15.3.10), and $W(m)$ is the same as W in Section 15.3. In particular, $W(m)$ is irreducible as a module over $sl_2(k)$, as before. This corresponds to part (a) of Theorem 2 on p20 of [24], as well as remarks on p33 and part of Exercise 3 on p34 of [14].

Let V be a vector space over k, and let ρ^V be a representation of $sl_2(k)$ on V. Suppose that $v \in V$ is primitive of weight $\lambda \in k$, as in Section 15.3, and that we are in the second case (15.3.10), which holds automatically when V has finite dimension. If $W \subseteq V$ and $m \geq 0$ are as in Section 15.3, then W is isomorphic to $W(m)$ in the previous section, as modules over $sl_2(k)$. If V is irreducible as a module over $sl_2(k)$, then $V = W$, so that V is isomorphic to $W(m)$ as a module over $sl_2(k)$.

Suppose now that k is algebraically closed, and that V has positive finite dimension. Under these conditions, there is a $v \in V$ that is primitive of some weight $\lambda \in k$, as in Section 15.1. In this situation, we are automatically in the second case (15.3.10), as in the preceding paragraph. This corresponds to part (b) of Theorem 2 on p20 of [24], and the theorem on p33 of [14].

Let k be a field, and let $W(m)$ be as in the previous section for each nonnegative integer m again. Note that $W(0)$ is automatically irreducible as a module over $sl_2(k)$. Similarly, $W(1)$ is irreducible as a module over $sl_2(k)$. Suppose from now on in this section that k has positive characteristic, and that $m \geq 2$.

Suppose for the moment that m is strictly less than the characteristic of k, which is thus greater than 2. Under these conditions, $W(m)$ is irreducible as a module over $sl_2(k)$, as in Exercise 5 on p34 of [14]. To see this, let W_0 be a nontrivial linear subspace of $W(m)$ such that $H(W_0) \subseteq W_0$. The restriction of H to W_0 is diagonalizable on W_0, because H is diagonalizable on $W(m)$. This implies that W_0 contains a nonzero eigenvector of H. One can check that the eigenvalues of H on $W(m)$ are distinct as elements of k in this situation. It follows that $v_{j_0} \in W_0$ for some j_0, $0 \leq j_0 \leq m$.

Suppose that W_0 is a submodule of $W(m)$, as a module over $sl_2(k)$. One can verify that $v_j \in W_0$ for every $j = 0, 1, \ldots, m$, using (15.4.2) and (15.4.3). More precisely, this uses the fact that the relevant coefficients on the right sides of (15.4.2) and (15.4.3) correspond to nonzero elements of k. This implies that $W_0 = W(m)$, as desired.

If k has characteristic equal to m, then $W(m)$ is reducible as a module over $sl_2(k)$, as in Exercise 5 on p34 of [14]. To see this, consider the linear span W_1 of $v_1, \ldots, v_{m-1}$ in $W(m)$. Clearly $H(W_1) \subseteq W_1$, because the v_j's are eigenvectors for H. It is easy to see that $Y(W_1) \subseteq W_1$, because $Y(v_{m-1}) = 0$ when the characteristic of k is equal to m, by (15.4.2). Similarly, one can check that $X(W_1) \subseteq W_1$, because $X(v_1) = 0$ when the characteristic of k is m, by (15.4.3). This implies that W_1 is a submodule of $W(m)$, as a module over $sl_2(k)$. Of course, $W_1 \neq \{0\}, W(m)$.

15.6 Another construction

Let k be a commutative ring with a multiplicative identity element, and let T_1, T_2 be commuting indeterminates. Remember that $k[T_1, T_2]$ is the space of formal polynomials in T_1, T_2 with coefficients in k, as in Section 5.8. This is a commutative associative algebra over k with respect to the usual formal multiplication of polynomials, as before. If d is a nonnegative integer, then the space $k_d[T_1, T_2]$ of formal polynomials in T_1, T_2 with coefficients in k that are homogeneous of degree d is a submodule of $k[T_1, T_2]$, as a module over k, as in Section 5.13. More precisely, $k[T_1, T_2]$ corresponds to the direct sum of the submodules $k_d[T_1, T_2]$ over $d \geq 0$, as a module over k, as before.

We would like to make $k[T_1, T_2]$ into a module over $sl_2(k)$, as a Lie algebra over k, as in Exercise 4 on p34 of [14], and the remark on p20 of [24]. Thus, if $a \in sl_2(k)$ and $f(T) \in k[T_1, T_2]$, then we need to define $a \cdot f(T)$ as an element of $k[T_1, T_2]$. More precisely, if $f(T) \in k_d[T_1, T_2]$ for some $d \geq 0$, then $a \cdot f(T)$ will be an element of $k_d[T_1, T_2]$. This means that $k_d[T_1, T_2]$ will be a submodule of $k[T_1, T_2]$, as a module over $sl_2(k)$, for each $d \geq 0$. Indeed, $k[T_1, T_2]$ will correspond to the direct sum of $k_d[T_1, T_2]$ over $d \geq 0$, as a module over $sl_2(k)$.

Of course, $k_0[T_1, T_2]$ corresponds to constant formal polynomials with coefficients in k, and is isomorphic to k in an obvious way. If $a \in sl_2(k)$ and $f(T) \in k_0[T_1, T_2]$, then we put $a \cdot f(T) = 0$.

An element of $k_1[T_1, T_2]$ can be expressed in a unique way as

$$f(T) = f_1\, T_1 + f_2\, T_2, \tag{15.6.1}$$

where $f_1, f_2 \in k$. In the notation of Section 5.8, f_1 and f_2 correspond to f_α with $\alpha = (1, 0)$ and $(0, 1)$, respectively. If $a \in sl_2(k)$, then we can define $a \cdot f(T)$ as an element of $k_1[T_1, T_2]$ using the standard action of $sl_2(k)$ on (f_1, f_2) as an element k^2. In particular, if $x, y, h \in sl_2(k)$ are as in (15.1.1), as usual, then

$$x \cdot f(T) = f_2\, T_1, \quad y \cdot f(T) = f_1\, T_2, \quad \text{and} \quad h \cdot f(T) = f_1\, T_1 - f_2\, T_2. \tag{15.6.2}$$

This makes $k_1[T_1, T_2]$ into a module over $sl_2(k)$, as a Lie algebra over k.

If $a \in sl_2(k)$, then we would like to define the action of a on $k[T_1, T_2]$ so that it is a derivation, as in Exercise 4 on p34 of [14]. Thus we would like to have that

$$a \cdot (f(T)\, g(T)) = (a \cdot f(T))\, g(T) + f(T)\, (a \cdot g(T)) \tag{15.6.3}$$

for every $f(T), f(T) \in k[T_1, T_2]$. If $\alpha = (\alpha_1, \alpha_2)$ is an ordered pair of nonnegative integers, then we should have that

$$a \cdot (T_1^{\alpha_1}\, T_2^{\alpha_2}) = \alpha_1 \cdot (a \cdot T_1)\, T_1^{\alpha_1 - 1}\, T_2^{\alpha_2} + \alpha_2 \cdot (a \cdot T_2)\, T_1^{\alpha_1}\, T_2^{\alpha_2 - 1}. \tag{15.6.4}$$

More precisely, if α_1 or α_2 is 0, then the corresponding term on the right should be interpreted as being equal to 0. One can use this to define the left side of the equation, using the definition of $a \cdot T_1$ and $a \cdot T_2$ from the preceding paragraph. This can be used to define $a \cdot f(T)$ for every $f(T) \in k[T_1, T_2]$, by linearity. Using this definition, one can check that (15.6.3) holds for every $f(T), g(T) \in k[T_1, T_2]$.

Let ρ_a be the action of $a \in sl_2(k)$ on $k[T_1, T_2]$ defined in the previous paragraph. Thus ρ_a is a derivation on $k[T_1, T_2]$ for every $a \in sl_2(k)$, and it is easy to see that ρ_a is linear over k in a. We also have that ρ_a maps $k_d[T_1, T_2]$ into itself for every $a \in sl_2(k)$ and $d \geq 0$, by construction. In order to show that this defines a representation of $sl_2(k)$, as a Lie algebra over k, on $k[T_1, T_2]$, we should verify that

$$[\rho_a, \rho_b] = \rho_{[a,b]} \tag{15.6.5}$$

for every $a, b \in sl_2(k)$. Note that the left side is a derivation on $k[T_1, T_2]$ as well, as in Section 2.5. We already have that ρ defines a representation of $sl_2(k)$ on $k_0[T_1, T_2]$ and $k_1[T_1, T_2]$, so that (15.6.5) holds on these subspaces of $k[T_1, T_2]$. One can use this to check that (15.6.5) holds on all of $k[T_1, T_2]$, because both sides of (15.6.5) are derivations on $k[T_1, T_2]$.

Let $\alpha = (\alpha_1, \alpha_2)$ be an ordered pair of nonnegative integers again. Observe that

$$x \cdot (T_1^{\alpha_1} T_2^{\alpha_2}) = \alpha_2 \cdot T_1^{\alpha_1+1} T_2^{\alpha_2-1}, \tag{15.6.6}$$

$$y \cdot (T_1^{\alpha_1} T_2^{\alpha_2}) = \alpha_1 \cdot T_1^{\alpha_1-1} T_2^{\alpha_2+1}, \tag{15.6.7}$$

$$h \cdot (T_1^{\alpha_1} T_2^{\alpha_2}) = (\alpha_1 - \alpha_2) \cdot T_1^{\alpha_1} T_2^{\alpha_2}. \tag{15.6.8}$$

If $a \in sl_2(k)$, then ρ_a corresponds to the formal differential operator

$$(a \cdot T_1)\, \partial_1 + (a \cdot T_2)\, \partial_2 = (a \cdot T_1)\, \frac{\partial}{\partial T_1} + (a \cdot T_2)\, \frac{\partial}{\partial T_2} \tag{15.6.9}$$

on $k[T_1, T_2]$, in the notation of Section 5.11. More precisely, this is a first-order differential operator, as in Section 5.12, which is homogeneous of degree 0, as in Section 5.14.

15.7 Some exponentials

Let k be a field of characteristic 0, or a commutative ring with a multiplicative identity element that is an algebra over $\mathbf{Q}$, for simplicity. As in (15.1.1), we put $x = \left(\begin{smallmatrix} 0 & 1 \\ 0 & 0 \end{smallmatrix}\right)$ and $y = \left(\begin{smallmatrix} 0 & 0 \\ 1 & 0 \end{smallmatrix}\right)$. Note that $x^2 = y^2 = 0$, so that x and y are nilpotent as elements of the algebra $M_2(k)$ of 2×2 matrices with entries in k. Thus the exponentials of x and y are defined in $M_2(k)$ as in Section 14.10, with

$$\exp x = I + x = \begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix}, \quad \exp y = I + y = \begin{pmatrix} 1 & 0 \\ 1 & 1 \end{pmatrix}, \tag{15.7.1}$$

where $I = I_2 = \left(\begin{smallmatrix} 1 & 0 \\ 0 & 1 \end{smallmatrix}\right)$ is the identity matrix in $M_2(k)$. Similarly,

$$\exp(-y) = I - y = \begin{pmatrix} 1 & 0 \\ -1 & 1 \end{pmatrix}. \tag{15.7.2}$$

Observe that

$$(\exp x)\,(\exp -y) = \begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -1 & 1 \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ -1 & 1 \end{pmatrix}, \tag{15.7.3}$$

and hence

$$(15.7.4) \qquad (\exp x)\,(\exp -y)\,(\exp x) = \begin{pmatrix} 0 & 1 \\ -1 & 1 \end{pmatrix} \begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}.$$

Remember that $[x, y] = h = \left(\begin{smallmatrix} 1 & 0 \\ 0 & -1 \end{smallmatrix}\right)$, $[h, x] = 2 \cdot x$, and $[h, y] = -2 \cdot y$.

Put $\mathrm{ad}_x(z) = [x, z]$ and $\mathrm{ad}_y(z) = [y, z]$ for every $z \in sl_2(k)$, as usual. Thus $\mathrm{ad}_x(x) = \mathrm{ad}_y(y) = 0$,

$$(15.7.5) \quad \mathrm{ad}_x(y) = -\mathrm{ad}_y(x) = h, \quad \mathrm{ad}_x(h) = -2 \cdot x, \quad \mathrm{ad}_y(h) = 2 \cdot y.$$

This implies that

$$(15.7.6) \qquad (\mathrm{ad}_x)^2(h) = (\mathrm{ad}_y)^2(h) = 0.$$

Similarly,

$$(15.7.7) \quad (\mathrm{ad}_x)^2(y) = \mathrm{ad}_x(h) = -2 \cdot x, \quad (\mathrm{ad}_y)^2(x) = \mathrm{ad}_y(-h) = -2 \cdot y.$$

It follows that $(\mathrm{ad}_x)^3 = (\mathrm{ad}_y)^3 = 0$ as mappings from $sl_2(k)$ into itself, so that x and y are ad-nilpotent in $sl_2(k)$.

This means that the exponentials of ad_x and ad_y are defined as linear mappings from $sl_2(k)$ into itself, as in Section 14.10. In this situation, we have that

$$(15.7.8) \qquad \exp \mathrm{ad}_x = I + \mathrm{ad}_x + (1/2)\,(\mathrm{ad}_x)^2,$$

$$(15.7.9) \qquad \exp \mathrm{ad}_y = I + \mathrm{ad}_y + (1/2)\,(\mathrm{ad}_y)^2,$$

where I is the identity mapping on $sl_2(k)$. Similarly,

$$(15.7.10) \qquad \exp(-\mathrm{ad}_y) = I - \mathrm{ad}_y + (1/2)\,(\mathrm{ad}_y)^2.$$

Observe that

$$(15.7.11) \qquad (\exp \mathrm{ad}_x)(x) = x, \quad (\exp \mathrm{ad}_x)(h) = h - 2 \cdot x, \quad \text{and} \quad (\exp \mathrm{ad}_x)(y) = y + h - x.$$

We also have that

$$(15.7.12) \qquad (\exp -\mathrm{ad}_y)(y) = y, \quad (\exp -\mathrm{ad}_y)(h) = h - 2 \cdot y, \quad \text{and} \quad (\exp -\mathrm{ad}_y)(x) = x + h - y.$$

Put

$$(15.7.13) \qquad \sigma = (\exp \mathrm{ad}_x) \circ (\exp -\mathrm{ad}_y) \circ (\exp \mathrm{ad}_x),$$

which defines a linear mapping from $sl_2(k)$ into itself. More precisely, this is an inner automorphism of $sl_2(k)$, as in Section 14.11. Observe that

$$(15.7.14) \quad \sigma(x) = (\exp \mathrm{ad}_x)(x + h - y) = x + h - 2 \cdot x - y - h + x = -y.$$

Similarly,

$$\begin{aligned} \sigma(y) &= (\exp \mathrm{ad}_x)((\exp -\mathrm{ad}_y)(y + h - x)) \\ &= (\exp \mathrm{ad}_x)(y + h - 2 \cdot y - x - h + y) = (\exp \mathrm{ad}_x)(-x) = -x. \end{aligned} \tag{15.7.15}$$

We also have that

$$\begin{aligned} \sigma(h) &= (\exp \mathrm{ad}_x)((\exp -\mathrm{ad}_y)(h - 2 \cdot x)) \\ &= (\exp \mathrm{ad}_x)(h - 2 \cdot y - 2 \cdot x - 2 \cdot h + 2 \cdot y) \\ &= (\exp \mathrm{ad}_x)(-h - 2 \cdot x) = -h + 2 \cdot x - 2 \cdot x = -h. \end{aligned} \tag{15.7.16}$$

It follows from (15.7.14), (15.7.15), and (15.7.16) that

$$\sigma(z) = -z^t \tag{15.7.17}$$

for every $z \in sl_2(k)$, where z^t is the transpose of z. This is the same as conjugating $z \in sl_2(k)$ by (15.7.4), as in Section 14.11. This corresponds to some remarks on p9 and Exercise 10 on p10 of [14].

15.8 Exponentials and $W(m)$

Let k be a commutative ring with a multiplicative identity element that is an algebra over $\mathbf{Q}$, or simply a field of characteristic 0, and let m be a nonnegative integer. Remember that $W(m)$ is defined as a module over k as in Section 15.4, with corresponding linear mappings X, Y, and H. Note that X and Y are nilpotent as linear mappings on $W(m)$, so that their exponentials are defined as invertible linear mappings on $W(m)$, as in Section 14.10. Put

$$\theta = (\exp X) \circ (\exp -Y) \circ (\exp X), \tag{15.8.1}$$

which is an invertible linear mapping from $W(m)$ into itself.

Let ρ be the representation of $sl_2(k)$ on $W(m)$ corresponding to X, Y, and H as before. Thus $\rho_x = X$, $\rho_y = Y$, and $\rho_h = H$, where x, y, and h are the usual elements of $sl_2(k)$. Remember that $\exp \mathrm{ad}_x$ and $\exp \mathrm{ad}_y$ are defined as invertible linear mappings on $sl_2(k)$, because x and y are ad-nilpotent in $sl_2(k)$. If $z \in sl_2(k)$, then

$$\rho_{(\exp \mathrm{ad}_x)(z)} = (\exp \rho_x) \circ \rho_z \circ (\exp \rho_x)^{-1}, \tag{15.8.2}$$

as in Section 14.12. Similarly,

$$\rho_{(\exp -\mathrm{ad}_y)(z)} = (\exp -\rho_y) \circ \rho_z \circ (\exp -\rho_y)^{-1} \tag{15.8.3}$$

for every $z \in sl_2(k)$.

If σ is as in (15.7.13), then we get that

$$\rho_{\sigma(z)} = \theta \circ \rho_z \circ \theta^{-1} \tag{15.8.4}$$

for every $z \in sl_2(k)$. In particular,

$$-Y = \rho_{\sigma(x)} = \theta \circ \rho_x \circ \theta^{-1} = \theta \circ X \circ \theta^{-1}, \tag{15.8.5}$$

using (15.7.14) in the first step. Similarly,

$$-X = \rho_{\sigma(y)} = \theta \circ \rho_y \circ \theta^{-1} = \theta \circ Y \circ \theta^{-1}, \tag{15.8.6}$$

using (15.7.15) in the first step. We also have that

$$-H = \rho_{\sigma(h)} = \theta \circ \rho_h \circ \theta^{-1} = \theta \circ H \circ \theta^{-1}, \tag{15.8.7}$$

using (15.7.16) in the first step. This corresponds to remarks on p33-4 of [14], and Remark 1 on p21 of [24].

15.9 Additional properties of $sl_2(k)$ modules

Let K be a field, and let k be a subfield of K. Also let n be a positive integer, so that $V = k^n$ is an n-dimensional vector space over k, and $V_K = K^n$ is an n-dimensional vector space over K. If T is a linear mapping from V into itself, as a vector space over k, then there is a unique extension T_K of T to a linear mapping from V_K into itself, as a vector space over K. If T is invertible on V, then T_K is invertible on V_K, with inverse equal to the extension of T^{-1} on V to V_K as before. If $\lambda \in k$ is an eigenvalue of T on V, then λ is an eigenvalue of T_K on V_K. However, if $\lambda \in k$ is not an eigenvalue of T on V, then λ is not an eigenvalue of T_K on V_K. More precisely, $T - \lambda\, I_V$ is invertible on V in this case, where I_V is the identity mapping on V. This implies that $T_K - \lambda\, I_{V_K}$ is invertible on V_K, where I_{V_K} is the identity mapping on V_K. Thus the eigenvalues of T on V are the same as the eigenvalues of T_K on V_K that are elements of k.

Let ρ^V be a representation of $sl_2(k)$, as a Lie algebra over k, on $V = k^n$. This leads to a representation ρ^{V_K} of $sl_2(K)$, as a Lie algebra over K, on $V_K = K^n$, in a natural way. More precisely, if $z \in sl_2(k)$, then $\rho^{V_K}_z$ is the K-linear mapping on K^n that corresponds to ρ^V_z as a k-linear mapping on k^n as in the preceding paragraph. In particular, this can be applied to the usual elements x, y, and h of $sl_2(k)$, as in (15.1.1). If $z \in sl_2(K)$, then z can be expressed as a linear combination of x, y, and h with coefficients in K, and one can take $\rho^{V_K}_z$ to be the corresponding linear combination of $\rho^{V_K}_x$, $\rho^{V_K}_y$, and $\rho^{V_K}_h$.

Suppose now that k has characteristic 0, and that K is algebraically closed. Of course, we may consider $\mathbf{Q}$ as a subfield of k, and thus as a subfield of K. Remember that V_K can be expressed as the direct sum of finitely many irreducible $sl_2(K)$ modules, by Weyl's theorem. Each of these irreducible $sl_2(K)$ modules is isomorphic to the analogue of $W(m)$ in Section 15.4 for K, and for some nonnegative integer m, as in Section 15.5. It follows that $\rho^{V_K}_h$ is diagonalizable on V_K, with eigenvalues in $\mathbf{Z}$.

In particular, $\rho^{V_K}_h$ has an eigenvalue λ in $\mathbf{Z}$, which implies that λ is an eigenvalue for ρ^V_h on V, as before. One can use this to show that there is a maximal or primitive vector in V of some weight, as in Section 15.2. If V is irreducible as an $sl_2(k)$ module, then it follows that V is isomorphic as an $sl_2(k)$ module to $W(m)$ for some nonnegative integer m, as in Section 15.5. Otherwise, one can use Weyl's theorem to reduce to this case. This corresponds to Exercise 2 on p62 of [25], with $n = 2$.

15.10 Complexifying real vector spaces

Let V_1 be a vector space over the real numbers. The *complexification* of V_1 may be defined as a vector space V_2 over the complex numbers as follows. We start by taking V_2 to be the direct sum $V_1 \oplus V_1$ of V_1 with itself, as a vector space over the real numbers. Equivalently, V_2 is the Cartesian product $V_1 \times V_1$ of V_1 with itself, where addition and scalar multiplication by real numbers is defined coordinatewise. If $(v, w) \in V_1 \times V_1$, then $i\,(v, w)$ is defined as an element of $V_1 \times V_1$ by

$$i\,(v, w) = (-w, v). \tag{15.10.1}$$

It is easy to see that this makes V_2 into a vector space over the complex numbers. We shall normally identify $v \in V_1$ with $(v, 0) \in V_1 \times V_1 = V_2$, so that V_1 may be considered as a subset of V_2. Note that any basis for V_1 as a vector space over the real numbers may be considered as a basis for V_2 as a vector space over the complex numbers.

Let V be a vector space over the complex numbers, so that V may be considered as a vector space over the real numbers too. Suppose that V_0 is a *real-linear subspace* of V, which is to say that V_0 is a linear subspace of V as a vector space over the real numbers. In this case,

$$i\,V_0 = \{i\,v : v \in V_0\} \tag{15.10.2}$$

is a real-linear subspace of V as well. Note that $V_0 + i\,V_0$ is a *complex-linear subspace* of V, which is to say a linear subspace of V as a vector space over the complex numbers. Let us say that V_0 is *totally real* in V if

$$V_0 \cap (i\,V_0) = \{0\}. \tag{15.10.3}$$

This means that $V_0 + i\,V_0$ is isomorphic to the direct sum of of V_0 and $i\,V_0$, as a vector space over the real numbers. Under these conditions, there is a natural isomorphism from the complexification of V_0 onto $V_0 + i\,V_0$, as vector spaces over the complex numbers, which is the identity mapping on V_0.

Let V_1 be a vector space over the real numbers again, and let W be a vector space over the complex numbers. Thus W may be considered as a vector space over the real numbers, and a linear mapping from V_1 into W, as a vector space over $\mathbf{R}$, may be called a *real-linear mapping*. One can verify that a real-linear mapping from V_1 into W has a unique extension to a complex-linear mapping from the complexification V_2 of V_1 into W.

Let W_1 be a vector space over the real numbers, and let W_2 be the complexification of W_1. If ϕ_1 is a linear mapping from V_1 into W_1, as vector spaces over the real numbers, then ϕ_1 may be considered as a real-linear mapping from V_1

into W_2, because W_1 is identified with a real-linear subspace of W_2. Thus ϕ_2 has a unique extension to a complex-linear mapping ϕ_2 from V_2 into W_2, as in the preceding paragraph. If ϕ_1 is injective as a mapping from V_1 into W_1, then one can check that ϕ_2 is injective as a mapping from V_2 into W_2. Similarly, if ϕ_1 maps V_1 onto W_1, then ϕ_2 maps V_2 onto W_2.

Let W be a vector space over the complex numbers again, let ϕ_1 be a real-linear mapping from V_1 into W, and let ϕ_2 be the extension of ϕ_1 to a complex-linear mapping from V_2 into W. If ϕ_1 is injective as a mapping from V_1 into W, and if $\phi_1(V_1)$ is totally real as a real-linear subspace of W, then one can verify that ϕ_2 is injective as a mapping from V_2 into W.

Let W_1 be a vector space over the real numbers again, and let Z_1 be another vector space over the real numbers. Also let ϕ_1 be a linear mapping from V_1 into W_1, and let ψ_1 be a linear mapping from W_1 into Z_1, as vector spaces over $\mathbf{R}$. As before, ϕ_1 and ψ_1 have unique complex-linear extensions ϕ_2 from V_2 into W_2 and ψ_2 from W_2 into the complexification Z_2 of Z_1, respectively. Of course, $\psi_1 \circ \phi_1$ is a linear mapping from V_1 into Z_1, as vector spaces over $\mathbf{R}$. Note that $\psi_2 \circ \phi_2$ is the unique extension of $\psi_1 \circ \phi_1$ to a complex-linear mapping from V_2 into Z_2.

Let Z be a vector space over the complex numbers again. A mapping from $V_1 \times W_1$ into Z that is bilinear over $\mathbf{R}$, where Z is considered as a vector space over the real numbers, may be called a *real-bilinear mapping.* One can check that such a mapping has a unique extension to a mapping from $V_2 \times W_2$ into Z that is bilinear over $\mathbf{C}$. If Z_1 is a vector space over the real numbers, then a mapping from $V_1 \times W_1$ into Z_1 that is bilinear over $\mathbf{R}$ may be considered as a real-bilinear mapping from $V_1 \times W_1$ into the complexification Z_2 of Z_1. This can be extended to a mapping from $V_2 \times W_2$ into Z_2 that is bilinear over $\mathbf{C}$, as before.

15.11 Spaces of linear mappings

Let V_1 be a vector space over the real numbers, and let V_2 be its complexification, as in the previous section. If W is a vector space over the complex numbers, then we let $\mathcal{L}_{\mathbf{R}}(V_1, W)$ be the space of real-linear mappings from V_1 into W, and $\mathcal{L}_{\mathbf{C}}(V_2, W)$ be the space of complex-linear mappings from V_2 into W. If ϕ_1 is a real-linear mapping from V_1 into W, then there is a unique extension ϕ_2 of ϕ_1 to a complex-linear mapping from V_2 into W, as before. Conversely, if ϕ_2 is any complex-linear mapping from V_2 into W, then the restriction of ϕ_2 to V_1, considered as a real-linear subspace of V_2, is a real-linear mapping from V_1 into W. This defines a one-to-one correspondence between $\mathcal{L}_{\mathbf{R}}(V_1, W)$ and $\mathcal{L}_{\mathbf{C}}(V_2, W)$.

Note that $\mathcal{L}_{\mathbf{R}}(V_1, W)$ may be considered as a vector space over the complex numbers, with respect to pointwise addition and scalar multiplication by complex numbers of mappings into W. It is easy to see that this corresponds to pointwise addition and scalar multiplication by complex numbers on $\mathcal{L}_{\mathbf{C}}(V_2, W)$. Thus the one-to-one correspondence between $\mathcal{L}_{\mathbf{R}}(V_1, W)$ and $\mathcal{L}_{\mathbf{C}}(V_2, W)$ mentioned in the preceding paragraph is an isomorphism between complex vector spaces.

Let W_1 be another vector over the real numbers, and let W_2 be its complexification, as before. The space $\mathcal{L}(V_1, W_1)$ of linear mappings from V_1 into W_1 may be considered as a real-linear subspace of the space $\mathcal{L}_{\mathbf{R}}(V_1, W_2)$ of real-linear mappings from V_1 into W_2, because W_1 is identified with a real-linear subspace of W_2. Similarly, $i\,W_1$ may be considered as a real-linear subspace of W_2, so that the space $\mathcal{L}(V_1, i\,W_1)$ of linear mappings from V_1 into $i\,W_1$, as vector spaces over $\mathbf{R}$, may be considered as a real-linear subspace of $\mathcal{L}_{\mathbf{R}}(V_1, W_2)$. Observe that

$$\mathcal{L}(V_1, i\,W_1) = i\,\mathcal{L}(V_1, W_1), \tag{15.11.1}$$

as real-linear subspaces of $\mathcal{L}_{\mathbf{R}}(V_1, W_2)$. It is easy to see that

$$\mathcal{L}(V_1, W_1) \cap (i\,\mathcal{L}(V_1, W_1)) = \{0\}, \tag{15.11.2}$$

because $W_1 \cap (i\,W_1) = \{0\}$ in W_2. We also have that

$$\mathcal{L}(V_1, W_1) + \mathcal{L}(V_1, i\,W_1) = \mathcal{L}_{\mathbf{R}}(V_1, W_2). \tag{15.11.3}$$

More precisely, $\mathcal{L}_{\mathbf{R}}(V_1, W_2)$ corresponds to the direct sum of $\mathcal{L}(V_1, W_1)$ and $\mathcal{L}(V_1, i\,W_1)$ as a vector space over $\mathbf{R}$, because W_2 corresponds to the direct sum of W_1 and $i\,W_1$ as a vector space over $\mathbf{R}$. Equivalently, this means that

$$\mathcal{L}(V_1, W_1) + i\,\mathcal{L}(V_1, W_1) = \mathcal{L}_{\mathbf{R}}(V_1, W_2). \tag{15.11.4}$$

Thus the complexification of $\mathcal{L}(V_1, W_2)$ can be identified with $\mathcal{L}_{\mathbf{R}}(V_1, W_2)$, as a vector space over the complex numbers, as in the previous section.

Remember that there is a natural isomorphism between $\mathcal{L}_{\mathbf{R}}(V_1, W_2)$ and $\mathcal{L}_{\mathbf{C}}(V_2, W_2)$, as before. This leads to a natural embedding of $\mathcal{L}(V_1, W_2)$ into $\mathcal{L}_{\mathbf{C}}(V_2, W_2)$. More precisely, this embedding takes a linear mapping ϕ_1 from V_1 into W_1, and associates to it the unique extension ϕ_2 of ϕ_1 to a complex-linear mapping from V_2 into W_2, where V_1, W_1 are identified with real-linear subspaces of V_2, W_2, as usual. The image of $\mathcal{L}(V_1, W_1)$ in $\mathcal{L}_{\mathbf{C}}(V_2, W_2)$ consists of the complex-linear mappings ϕ_2 from V_2 into W_2 such that

$$\phi_2(V_1) \subseteq W_1. \tag{15.11.5}$$

Using this embedding, we get an isomorphism between the complexification of $\mathcal{L}(V_1, W_1)$ and $\mathcal{L}_{\mathbf{C}}(V_2, W_2)$.

Let n be a positive integer, so that $\mathbf{R}^n$ is a vector space over the real numbers, whose complexification can be identified with $\mathbf{C}^n$. Remember that the space $\mathcal{L}(\mathbf{R}^n)$ of linear mappings from $\mathbf{R}^n$ into itself is isomorphic to the space $M_n(\mathbf{R})$ of $n \times n$ matrices with entries in $\mathbf{R}$ in the usual way. Similarly, the space $\mathcal{L}_{\mathbf{C}}(\mathbf{C}^n)$ of complex-linear mappings from $\mathbf{C}^n$ into itself is isomorphic to the space $M_n(\mathbf{C})$ of $n \times n$ matrices with entries in $\mathbf{C}$ in essentially the same way. Of course, $M_n(\mathbf{R})$ may be considered as a real-linear subspace of $M_n(\mathbf{C})$, and $M_n(\mathbf{C})$ can be identified with the complexification of $M_n(\mathbf{R})$. This corresponds to identifying a linear mapping from $\mathbf{R}^n$ into itself with a complex-linear mapping from $\mathbf{C}^n$ into itself that takes $\mathbf{R}^n$ into itself, as in the preceding paragraph.

15.12 Complexifying algebras over R

Let A_1 be an algebra over the real numbers in the strict sense, and let A_2 be the complexification of A_1 as a vector space over $\mathbf{R}$, as in Section 15.10. The algebra structure on A_1 corresponds to a mapping from $A_1 \times A_1$ into A_1 that is bilinear over $\mathbf{R}$, which has a unique extension to a mapping from $A_2 \times A_2$ into A_2 that is bilinear over $\mathbf{C}$, as before. This makes A_2 into an algebra over $\mathbf{C}$ in the strict sense. If A_1 is commutative, associative, or a Lie algebra, then one can check that A_2 has the analogous property, as an algebra over $\mathbf{C}$. Similarly, if A_1 has a multiplicative identity element e, then e is the multiplicative identity element in A_2 as well.

Let B be an algebra over the complex numbers in the strict sense, which may be considered as an algebra over the real numbers in the strict sense too. If ϕ_1 is a real-linear mapping from A_1 into B, then there is a unique extension of ϕ_1 to a complex-linear mapping ϕ_2 from A_2 into B, as in Section 15.10. If ϕ_1 is an algebra homomorphism from A_1 into B, then it is easy to see that ϕ_2 is an algebra homomorphism from A_2 into B. Similarly, if ϕ_1 is an opposite algebra homomorphism from A_1 into B, then ϕ_2 is an opposite algebra homomorphism from A_2 into B.

If B_1 is an algebra over the real numbers in the strict sense, then its complexification B_2 is an algebra over the complex numbers in the strict sense, as before. If ϕ_1 is a linear mapping from A_1 into B_1, as vector spaces over the real numbers, then ϕ_1 may be considered as a real-linear mapping from A_1 into B_2. Thus there is a unique extension of ϕ_1 to a complex-linear mapping ϕ_2 from A_2 into B_2, as before. If ϕ_1 is an algebra homomorphism or an opposite algebra homomorphism from A_1 into B_1, then ϕ_2 has the analogous property as a mapping from A_2 into B_2.

Let A be an algebra over the complex numbers in the strict sense, which may also be considered as an algebra over the real numbers in the strict sense. Suppose that A_0 is a real-linear subspace of A that is totally real in A. This implies that there is a natural isomorphism between the complexification of A_0, as a vector space over $\mathbf{R}$, and $A_0 + i\,A_0$, as in Section 15.10. If A_0 is a subalgebra of A too, as an algebra over $\mathbf{R}$ in the strict sense, then it is easy to see that $A_0 + i\,A_0$ is a subalgebra of A, as an algebra over $\mathbf{C}$ in the strict sense. In this case, $A_0 + i\,A_0$ is isomorphic to the complexification of A_0, as an algebra over $\mathbf{R}$ in the strict sense.

Let V_1 be a vector space over the real numbers, with complexification V_2, as in Section 15.10. Remember that the space $\mathcal{L}(V_1)$ of linear mappings from V_1 into itself is an associative algebra over $\mathbf{R}$ with respect to composition of mappings. Similarly, the space $\mathcal{L}_{\mathbf{C}}(V_2)$ of complex-linear mappings from V_2 into itself is an associative algebra over $\mathbf{C}$ with respect to composition of mappings. We have also seen that $\mathcal{L}_{\mathbf{C}}(V_2)$ can be identified with the complexification of $\mathcal{L}(V_1)$, as a vector space over $\mathbf{R}$, as in the previous section. More precisely, this uses the correspondence between linear mappings from V_1 into itself and complex-linear mappings from V_2 into itself that map V_1 into itself, where V_1 is considered as a real-linear subspace of V_2, as usual. This correspondence sends compositions of linear mappings on V_1 to the analogous compositions of complex-linear mappings on V_2, as in Section 15.10. Thus $\mathcal{L}(V_1)$ corresponds to a subalgebra of $\mathcal{L}_{\mathbf{C}}(V_2)$, as an algebra over $\mathbf{R}$. It follows that $\mathcal{L}_{\mathbf{C}}(V_2)$ can be identified with the complexification of $\mathcal{L}(V_1)$ as an algebra over $\mathbf{R}$ in the same way, as in the preceding paragraph.

Similarly, $gl(V_1)$ is a Lie algebra over the real numbers, and the space $gl(V_2) = gl_{\mathbf{C}}(V_2)$ of complex-linear mappings from V_2 into itself is a Lie algebra over $\mathbf{C}$, with respect to the usual commutator brackets. As before, $gl_{\mathbf{C}}(V_2)$ can be identified with the complexification of $gl(V_1)$, as a vector space over $\mathbf{R}$, and in fact as a Lie algebra over $\mathbf{R}$.

Suppose that V_1 has finite dimension as a vector space over $\mathbf{R}$, so that V_2 has the same dimension as a vector space over $\mathbf{C}$. Let ϕ_1 be a linear mapping from V_1 into itself, and let ϕ_2 be the extension of ϕ_1 to a complex-linear mapping from V_2 into itself. It is easy to see that

$$\mathrm{tr}_{V_1}\phi_1 = \mathrm{tr}_{V_2}\phi_2, \tag{15.12.1}$$

where the left side is the trace of ϕ_1 on V_1, and the right side is the trace of ϕ_2 on V_2. This uses the fact that a basis for V_1 as a vector space over $\mathbf{R}$ may be considered as a basis for V_2 as a vector space over $\mathbf{C}$. It follows that the space $sl(V_2) = sl_{\mathbf{C}}(V_2)$ of complex-linear mappings from V_2 into itself with trace 0 corresponds to the complexification of $sl(V_1)$ as a vector space over $\mathbf{R}$, and hence as a Lie algebra over $\mathbf{R}$.

Let n be a positive integer, and remember that the spaces $M_n(\mathbf{R})$, $M_n(\mathbf{C})$ of $n \times n$ matrices with entries in $\mathbf{R}$, $\mathbf{C}$, respectively, are associative algebras over $\mathbf{R}$, $\mathbf{C}$ with respect to matrix multiplication. As before, $M_n(\mathbf{C})$ can be identified with the complexification of $M_n(\mathbf{R})$ as a vector space over $\mathbf{R}$, and more precisely as an algebra over $\mathbf{R}$. Similarly, $gl_n(\mathbf{C})$ can be identified with the complexification of $gl_n(\mathbf{R})$ as a Lie algebra over $\mathbf{R}$. We can also identify $sl_n(\mathbf{C})$ with the complexification of $sl_n(\mathbf{R})$ as a Lie algebra over $\mathbf{R}$.

15.13 Conjugate-linear involutions

Let A be a vector space over the complex numbers, and let

$$a \mapsto a^* \tag{15.13.1}$$

be a conjugate-linear mapping from A into itself. Put

$$A_{sa} = \{a \in A : a^* = a\} \tag{15.13.2}$$

and

$$A_{asa} = \{a \in A : a^* = -a\}, \tag{15.13.3}$$

which are the collections of vectors in A that are *self-adjoint* and *anti-self-adjoint* with respect to (15.13.1), respectively. Clearly A_{sa} and A_{asa} are real-linear subspaces of A, with

$$A_{asa} = i\, A_{sa}. \tag{15.13.4}$$

We also have that

(15.13.5) $$A_{sa} \cap A_{asa} = \{0\},$$

so that A_{sa} and A_{asa} are totally real in A. Thus $A_{sa}+A_{asa}$ can be identified with the complexifications of A_{sa} and A_{asa}, as vector spaces over the real numbers, as in Section 15.10.

Suppose that

(15.13.6) $$(a^*)^* = a$$

for every $a \in A$, so that $a \mapsto a^*$ is a conjugate-linear *involution* on A. If $a \in A$, then

(15.13.7) $$a_{sa} = (a + a^*)/2 \in A_{sa}, \quad a_{asa} = (a - a^*)/2 \in A_{asa},$$

and $a = a_{sa} + a_{asa}$. This means that $A = A_{sa} + A_{asa}$, so that A can be identified with the complexifications of A_{sa} and A_{asa}, as vector spaces over the real numbers.

Suppose now that A is an associative algebra over the complex numbers, and that (15.13.1) is a conjugate-linear algebra involution on A. Let $A_{Lie,\mathbf{C}}$ be A considered as a Lie algebra over the complex numbers with respect to the corresponding commutator bracket, and let $A_{Lie,\mathbf{R}}$ be $A_{Lie,\mathbf{C}}$ considered as a Lie algebra over the real numbers. In this situation, A_{asa} is a Lie subalgebra of $A_{Lie,\mathbf{R}}$, and $A_{Lie,\mathbf{C}}$ can be identified with the complexification of A_{asa}, as a Lie algebra over the real numbers.

Let V be a finite-dimensional vector space over the complex numbers, and let $\beta(\cdot,\cdot)$ be a nondegenerate Hermitian form on V. If T is a linear mapping from V into itself, then there is a unique adjoint linear mapping $T^{*,\beta}$ from V into itself such that

(15.13.8) $$\beta(T(v), w) = \beta(v, T^{*,\beta}(w))$$

for every $v, w \in V$. Under these conditions,

(15.13.9) $$T \mapsto T^{*,\beta}$$

defines a conjugate-linear algebra involution on the algebra $\mathcal{L}(V)$ of all linear mappings from V into itself. Remember that $gl(V)$ is the same as $\mathcal{L}(V)$, considered as a Lie algebra over the complex numbers with respect to the corresponding commutator bracket. Let $u_\beta(V)$ be the collection of linear mappings T from V into itself that are anti-self-adjoint with respect to β. Thus $u_\beta(V)$ is a real-linear subspace of $gl(V)$, and a Lie subalgebra of $gl(V)$, considered as a Lie algebra over the real numbers. As in the preceding paragraph, $gl(V)$ can be identified with the complexification of $u_\beta(V)$, as a Lie algebra over the real numbers.

If $T \in \mathcal{L}(V)$, then

(15.13.10) $$\mathrm{tr}_V T^{*,\beta} = \overline{\mathrm{tr}_V T},$$

where $\mathrm{tr}_V T$ denotes the trace of T on V. This can be seen by choosing a basis for V to reduce to the case where $V = \mathbf{C}^n$ for some positive integer n, and expressing $\beta(\cdot,\cdot)$ and $T^{*,\beta}$ in terms of matrices, as in Section 3.13. In particular, this implies that $sl(V)$ is invariant under (15.13.9). Note that $\mathrm{tr}_V T$ is real when

T is self-adjoint with respect to β, and imaginary when T is anti-self-adjoint with respect to β, by (15.13.10). Put

$$su_\beta(V) = sl(V) \cap u_\beta(V), \tag{15.13.11}$$

which is a real-linear subspace of $sl(V)$, and in fact a Lie subalgebra of $sl(V)$, considered as a Lie algebra over the complex numbers. If $T \in sl(V)$, then $T^{*,\beta} \in sl(V)$, and hence the self-adjoint and anti-self-adjoint parts of T with respect to β are contained in $sl(V)$ too. Thus $sl(V)$ can be identified with the complexification of $su_\beta(V)$, as a Lie algebra over the real numbers.

Chapter 16

Module homomorphisms

16.1 Bilinear actions and homomorphisms

Let k be a commutative ring with a multiplicative identity element, and let V, W be modules over k. Remember that $\mathrm{Hom}(V, W) = \mathrm{Hom}_k(V, W)$ is the space of homomorphisms from V into W, as modules over k. This is a module over k too, with respect to pointwise addition and scalar multiplication of mappings. Let A be another module over k, and let ρ^V, ρ^W be bilinear actions of A on V and W, as in Section 6.1. Also let ϕ be a homomorphism from V into W, as modules over k. Remember that ϕ is said to *intertwine* ρ^V, ρ^W when

$$\phi \circ \rho_a^V = \rho_a^W \circ \phi \tag{16.1.1}$$

for every $a \in A$, as in Section 6.2. In this case, we may say that ϕ is a homomorphism from V into W, with respect to the bilinear actions ρ^V, ρ^W. Let

$$\mathrm{Hom}^A(V, W) = \mathrm{Hom}_k^A(V, W) \tag{16.1.2}$$

be the space of these homomorphisms from V into W with respect to ρ^V, ρ^W. It is easy to see that this is a submodule of $\mathrm{Hom}_k(V, W)$, as a module over k.

Let Z be another module over k. If ϕ is a homomorphism from V into W, and ψ is a homomorphism from W into Z, as modules over k, then $\psi \circ \phi$ is a homomorphism from V into Z, as modules over k. Suppose that ρ^Z is a bilinear action of A on Z. If ϕ is a homomorphism from V into W with respect to ρ^V, ρ^W, and if ψ is a homomorphism from W into Z with respect to ρ^W, ρ^Z, then $\psi \circ \phi$ is a homomorphism from V into Z with respect to ρ^V, ρ^Z. Indeed, if $a \in A$, then

$$(\psi \circ \phi) \circ \rho_a^V = \psi \circ (\rho_a^W \circ \phi) = \rho_a^Z \circ (\psi \circ \phi). \tag{16.1.3}$$

Let us now take $V = W$, and remember that $\mathrm{Hom}_k(V, V)$ is an associative algebra over k, with respect to composition of mappings. More precisely, let us use the same bilinear action ρ^V of A on V on both the domain and range of these homomorphisms. Observe that $\mathrm{Hom}_k^A(V, V)$ is a subalgebra of $\mathrm{Hom}_k(V, V)$, as in the preceding paragraph. Of course, the identity mapping $I = I_V$ on V is a homomorphism from V into itself, with respect to ρ^V. Similarly, if $t \in k$, then $t\, I_V$ is an element of $\mathrm{Hom}_k^A(V, V)$.

Suppose for the moment that k is a field, so that V is a vector space over k, and the algebra of linear mappings from V into itself may be denoted $\mathcal{L}(V)$. Remember that $\mathcal{L}^\rho(V)$ may be used to denote the subalgebra of $\mathcal{L}(V)$ consisting of linear mappings from V into itself that are homomorphisms from V into itself with respect to ρ, as in Section 6.14. If V is irreducible with respect to ρ, then Schur's lemma says that every nonzero element of $\mathcal{L}^\rho(V)$ is invertible in $\mathcal{L}^\rho(V)$. If k is also algebraically closed, and V has finite dimension as a vector space over k, then $\mathcal{L}_\rho(V)$ consists exactly of the multiples of I_V by elements of k. This is related to Exercises 4 and 5 on p54-5 of [25], for irreducible modules over a Lie algebra over k.

Now let $(A, [\cdot, \cdot]_A)$ be a Lie algebra over k, and let us consider A as a module over itself, with respect to the adjoint representation. If $x, y \in A$, then put $\mathrm{ad}_x(y) = [x, y]_A$, as usual. Let ϕ be a homomorphism from A into itself, as a module over k. Thus ϕ is a homomorphism from A into itself, as a module over itself with respect to the adjoint representation, if and only if

$$\phi(\mathrm{ad}_x(y)) = \mathrm{ad}_x(\phi(y)) \tag{16.1.4}$$

for every $x, y \in A$. This is the same as saying that

$$\phi([x, y]_A) = [x, \phi(y)]_A \tag{16.1.5}$$

for every $x, y \in A$. If k is a field, then we may use $\mathcal{L}^{\mathrm{ad}}(A)$ to denote the algebra of linear mappings from A into itself, as a vector space over k, that are homomorphisms from A into itself, as a module over itself with respect to the adjoint representation.

16.2 Homomorphisms and semisimplicity

Let k be a field, and let $(A, [\cdot, \cdot]_A)$ be a Lie algebra over k. Also let $A_1, \ldots, A_n$ be ideals in A, and suppose that A corresponds to the direct sum of the A_j's. This means that every $z \in A$ can be expressed in a unique way as

$$z = \sum_{j=1}^{n} \pi_j(z), \tag{16.2.1}$$

where $\pi_j(z) \in A_j$ for each $j = 1, \ldots, n$. In particular, this implies that $A_j \cap A_l = \{0\}$ when $j \neq l$, so that $[A_j, A_l] = \{0\}$ when $j \neq l$, as in Section 10.15. It follows that π_j is a Lie algebra homomorphism from A into A_j for each $j = 1, \ldots, n$. The restriction of π_j to A_j is the same as the identity mapping on A_j for each $j = 1, \ldots, n$, so that π_j maps A onto A_j. Observe that

$$\pi_j([x, y]_A) = [x, \pi_j(y)]_A \tag{16.2.2}$$

for every $x, y \in A$ and $j = 1, \ldots, n$. Thus π_j may be considered as a homomorphism from A into itself, as a module over itself with respect to the adjoint representation, for each $j = 1, \ldots, n$.

Let ϕ be a linear mapping from A into itself, and suppose that ϕ is a homomorphism from A into itself, as a module over itself with respect to the adjoint representation. Let $x \in A_j$ and $y \in A_l$ be given, for some $j, l \in \{1, \ldots, n\}$ such that $j \neq l$. This implies that $[x, y]_A = 0$, so that

$$[x, \phi(y)]_A = \phi([x, y]_A) = 0, \tag{16.2.3}$$

using (16.1.5) in the first step. It follows that

$$[x, \pi_j(\phi(y))]_A = 0, \tag{16.2.4}$$

because $[x, \pi_r(\phi(y))]_A = 0$ automatically when $r \neq j$. Equivalently, this means that $\pi_j(\phi(y))$ is an element of the center $Z(A_j)$ of A_j, as a Lie algebra over k. If $Z(A_j) = \{0\}$, then we get that

$$\pi_j(\phi(y)) = 0. \tag{16.2.5}$$

If $Z(A_j) = \{0\}$ for every $j = 1, \ldots, n$, then

$$\phi(A_l) \subseteq A_l \tag{16.2.6}$$

for every $l = 1, \ldots, n$. In this situation, one can check that the restriction of ϕ to A_l is a homomorphism from A_l into itself, as a module over itself with respect to the adjoint representation.

Suppose now that ϕ_l is a homomorphism from A_l into itself, as a module over itself with respect to the adjoint representation, for each $l = 1, \ldots, n$. Under these conditions, one can verify that

$$\phi = \sum_{l=1}^{n} \phi_l \circ \pi_l \tag{16.2.7}$$

defines a homomorphism from A into itself, as a module over itself with respect to the adjoint representations. If $Z(A_j) = \{0\}$ for each $j = 1, \ldots, n$, then we get that $\mathcal{L}^{\mathrm{ad}}(A)$ corresponds to the direct sum of $\mathcal{L}^{\mathrm{ad}}(A_l)$, $1 \leq l \leq n$. This is related to parts (a) and (b) of Exercise 5 on p55 of [25].

Suppose from now on in this section that A_j is simple as a Lie algebra over k for each $j = 1, \ldots, n$. In particular, this means that $Z(A_j) = \{0\}$ for every $j = 1, \ldots, n$. We also get that A_j is irreducible as a module over itself with respect to the adjoint representation for every $j = 1, \ldots, n$. Suppose that k is algebraically closed, and that A_j has positive finite dimension as a vector space over k for each $j = 1, \ldots, n$. Schur's lemma implies that $\mathcal{L}^{\mathrm{ad}}(A_j)$ consists of multiples of the identity mapping on A_j by elements of k for each $j = 1, \ldots, n$, as in the previous section. It follows that $\mathcal{L}^{ad}(A)$ is isomorphic to the direct sum of n copies of k, as an associative algebra over k, as in the preceding paragraph. This corresponds to part (a) of Exercise 5 on p55 of [25].

16.3 Linear mappings and dimensions

Let k be a field, and let n, r be positive integers. Thus the spaces k^n, k^r of n, r-tuples of elements of k may be considered as vector spaces over k with respect to coordinatewise addition and scalar multiplication, respectively. Let T be a linear mapping from k^n into k^r, and let $\lambda_l(v)$ be the lth component of $T(v) \in k^r$ for each $l = 1, \ldots, r$ and $v \in k^n$. Equivalently, λ_l is a linear functional on k^n for each $l = 1, \ldots, r$, and any collection of r linear functionals $\lambda_1, \ldots, \lambda_r$ on k^n determine a linear mapping T from k^n into k^r in this way. Let us suppose that $T \neq 0$, to avoid trivialities, so that $\lambda_l \neq 0$ for some l. Let r_0 be the maximal number of λ_l's that are linearly independent as linear functionals on k^n. We can rearrange the λ_l's, if necessary, to get that $\lambda_1, \ldots, \lambda_{r_0}$ are linearly independent as linear functionals on k^n, and that λ_l can be expressed as a linear combination of $\lambda_1, \ldots, \lambda_{r_0}$ when $l > r_0$.

Similarly, let T_0 the linear mapping from k^n into k^{r_0} that corresponds to $\lambda_1, \ldots, \lambda_{r_0}$. By construction, the kernel of T_0 is the same as the kernel of T. It is well known that

$$T_0(k^n) = k^{r_0} \tag{16.3.1}$$

under these conditions, and in particular that $r_0 \leq n$. The dimension of the kernel of T_0 is $n - r_0$, as a vector space over k.

Let k_1 be a field that contains k as a subfield. Thus k_1^n, k_1^r, and $k_1^{r_0}$ may be considered as vector spaces over k_1, which contain k^n, k^r, and k^{r_0} as subsets, respectively. Let T_{k_1} be the natural extension of T to a mapping from k_1^n into k_1^r that is linear over k_1, and let λ_{l,k_1} be the natural extension of λ_l to a linear functional on k_1^n for each $l = 1, \ldots, r$. Thus λ_{l,k_1} corresponds to the lth coordinate of T_{k_1} for each $l = 1, \ldots, r$, as before. If $l > r_0$, then λ_{l,k_1} can be expressed as a linear combination of $\lambda_{1,k_1}, \ldots, \lambda_{r_0,k_1}$ with coefficients in k, because of the analogous property of λ_l.

Let T_{0,k_1} be the natural extension of T_0 to a mapping from k_1^n into $k_1^{r_0}$ that is linear over k_1. This corresponds to $\lambda_{1,k_1}, \ldots, \lambda_{r_0,k_1}$ in the usual way. The kernel of T_{0,k_1} in k_1^n is the same as the kernel of T_{k_1}, because of the property of λ_{l,k_1} when $l > r_0$ mentioned in the preceding paragraph. It is easy to see that

$$T_{0,k_1}(k_1^n) = k_1^{r_0}, \tag{16.3.2}$$

using (16.3.1). This implies that $\lambda_{1,k_1}, \ldots, \lambda_{r_0,k_1}$ are linearly independent as linear functionals on k_1^n, and that the dimension of the kernel of T_{0,k_1} in k_1^n is $n - r_0$, as a vector space over k_1.

16.4 Homomorphisms and dimensions

Let k be a field, and let $(A, [\cdot, \cdot])$ be a Lie algebra over k, with positive finite dimension n as a vector space over k. We may as well take $A = k^n$, by choosing a basis for A as a vector space over k. As in Section 9.14, the Lie bracket on A

can be given by

$$([x, y])_r = \sum_{j=1}^{n} \sum_{l=1}^{n} c_{j,l}^r \, x_j \, y_l \tag{16.4.1}$$

for every $x, y \in k^n$, where the left side is the rth coordinate of $[x, y]$ as an element of k^n, and the structure constants $c_{j,l}^r$ are elements of k for each $j, l, r = 1, \ldots, n$. More precisely, the structure constants satisfy (9.14.5), (9.14.7), and (9.14.8), as before.

Let $u_1, \ldots, u_n$ be the standard basis vectors in k^n, so that the jth coordinate of u_l is equal to 1 when $j = l$, and to 0 when $j \neq l$. Also let ϕ be a linear mapping from k^n into itself, as a vector space over k. It is easy to see that ϕ is a homomorphism from A into itself, as a module over itself with respect to the adjoint representation, if and only if

$$\phi([u_j, u_l]) = [u_j, \phi(u_l)] \tag{16.4.2}$$

for every $j, l = 1, \ldots, n$. Of course, the space $\mathcal{L}(A)$ of linear mappings from A into itself, as a vector space over k, corresponds to the space $M_n(k)$ of $n \times n$ matrices with entries in k in the usual way. The space $\mathcal{L}^{\mathrm{ad}}(A)$ of homomorphisms from A into itself, as a module over itself with respect to the adjoint representation, corresponds to a linear subspace of $M_n(k)$ that can be described in terms of linear equations for the matrix entries, using (16.4.2).

Let k_1 be a field that contains k as a subfield, so that $k^n \subseteq k_1^n$. Let us take A_{k_1} to be k_1^n, as a vector space over k_1 with respect to coordinatewise addition and scalar multiplication. If $x, y \in A_{k_1}$, then $[x, y]$ can be defined as an element of A_{k_1} as in (16.4.1), where the right side is now an element of k_1 for each $r = 1, \ldots, n$. This makes A_{k_1} a Lie algebra over k_1, as before.

Of course, $u_1, \ldots, u_n$ may be considered as the standard basis vectors in k_1^n as well. Let ϕ be a linear mapping from k_1^n into itself, as a vector space over k_1. As before, ϕ is a homomorphism from A_{k_1} into itself, as a module over itself with respect to the adjoint representation, if and only if (16.4.2) holds for every $j, l = 1, \ldots, n$. As usual, the space $\mathcal{L}(A_{k_1})$ of linear mappings from A_{k_1} into itself, as a vector space over K, corresponds to the space $M_n(k_1)$ of $n \times n$ matrices with netries in k_1. The space $\mathcal{L}^{\mathrm{ad}}(A_{k_1})$ of homomorphisms from A_{k_1} into itself, as a module over itself with respect to the adjoint representation, corresponds to a linear subspace of $M_n(k_1)$ that can be described in terms of essentially the same linear equations for the matrix entries as for k, using (16.4.2) again.

This brings us to the same type of situation as discussed in the previous section. It follows that the dimension of $\mathcal{L}^{\mathrm{ad}}(A_{k_1})$, as a vector space over k_1, is the same as the dimension of $\mathcal{L}^{\mathrm{ad}}(A)$, as a vector space over k. This is related to part of part (b) of Exercise 5 on p55 of [25].

16.5 Semisimplicity and dimensions

Let k be a field of characteristic 0, and let $(A, [\cdot, \cdot])$ be a Lie algebra over k of positive finite dimension n. As in the previous section, we may as well take

$A = k^n$, with Lie bracket as in (16.4.1). Let k_1 be an algebraically closed field that contains k as a subfield. As before, $A_{k_1} = k_1^n$ is a Lie algebra over k_1, with Lie bracket as in (16.4.1). In this section, we suppose that A is semisimple as a Lie algebra over k, which is equivalent to asking that A_{k_1} be semisimple as a Lie algebra over k_1, as in Section 11.5.

As in Section 10.15, A_{k_1} is isomorphic to the direct sum of h simple Lie algebras over k_1, for some positive integer h. Remember that the space $\mathcal{L}^{ad}(A_{k_1})$ of module homomorphisms from A_{k_1} into itself, as a module over itself with respect to the adjoint representation, is an associative algebra over k_1 with respect to composition of mappings. In this situation, $\mathcal{L}^{\mathrm{ad}}(A_{k_1})$ is isomorphic to the direct sum of h copies of k_1, as in Section 16.2. In particular, the dimension of $\mathcal{L}^{\mathrm{ad}}(A_{k_1})$ is h, as a vector space over k_1. We also get that $\mathcal{L}^{\mathrm{ad}}(A_{k_1})$ is commutative as an algebra over k_1.

Similarly, the space $\mathcal{L}^{ad}(A)$ of module homomorphisms from A into itself, as a module over itself with respect to the adjoint representation, is an associative algebra over k with respect to composition of mappings. As in the previous section, the dimension of $\mathcal{L}^{\mathrm{ad}}(A)$, as a vector space over k, is the same as the dimension of $\mathcal{L}^{\mathrm{ad}}(A_{k_1})$ as a vector space over k_1, which is equal to h. This corresponds to the first part of part (b) of Exercise 5 on p55 of [25].

If ϕ is a linear mapping from A into itself, as a vector space over k, then ϕ has a natural extension to a linear mapping from A_{k_1} into itself, as a vector space over k_1. If ϕ is a homomorphism from A into itself, as a module over itself with respect to the adjoint representation, then the extension of ϕ to A_{k_1} is a homomorphism from A_{k_1} into itself, as a module over itself with respect to the adjoint representation. This follows from the characterization of module homomorphisms as linear mappings that satisfy (16.4.2) in both cases. Using this, we get that $\mathcal{L}^{\mathrm{ad}}(A)$ is commutative as an algebra over k with respect to composition of mappings, because $\mathcal{L}^{\mathrm{ad}}(A_{k_1})$ is commutative, as before. This is related to the second part of part (b) of Exercise 5 on p55 of [25].

Suppose that A is simple as a Lie algebra over k, which implies that A is irreducible as a module over itself, with respect to the adjoint representation. In this case, nonzero elements of $\mathcal{L}^{\mathrm{ad}}(A)$ are invertible in $\mathcal{L}^{\mathrm{ad}}(A)$, by Schur's lemma, as in Section 16.1. This means that $\mathcal{L}^{ad}(A)$ is a field, because $\mathcal{L}^{\mathrm{ad}}(A)$ is commutative, as in the preceding paragraph. This corresponds to the second part of part (b) of Exercise 5 on p55 of [25], with $m = 1$. Otherwise, A is isomorphic to the direct sum of simple Lie algebras $A_1, \ldots, A_m$ over k for some positive integer m, as in Section 10.15. This implies that $\mathcal{L}^{\mathrm{ad}}(A)$ is isomorphic to the direct sum of $\mathcal{L}^{\mathrm{ad}}(A_1), \ldots, \mathcal{L}^{\mathrm{ad}}(A_m)$ as an associative algebra over k, as in Section 16.2. It follows that $\mathcal{L}^{\mathrm{ad}}(A)$ is isomorphic to the direct sum of m fields, as in the second part of part (b) of Exercise 5 on p55 of [25].

16.6 Absolutely simple Lie algebras

Let k be a field, and let $(A, [\cdot, \cdot])$ be a Lie algebra over k of positive finite dimension n, as a vector space over k. As before, we may as well take A to be

k^n, with Lie bracket as in (16.4.1). Let k_1 be an algebraically closed field that contains k as a subfield, and take $A_{k_1} = k_1^n$ as a Lie algebra over k_1, with Lie bracket defined as in (16.4.1). If A_{k_1} is simple as a Lie algebra over k_1, then A is said to be *absolutely simple* as a Lie algebra over k, as in part (c) of Exercise 5 on p55 of [25]. This implies that A is simple as a Lie algebra over k, as in Section 11.4.

Suppose that A is absolutely simple, so that A_{k_1} is simple as a Lie algebra over k_1. This implies that A_{k_1} is irreducible as a module over itself with respect to the adjoint representation. Remember that $\mathcal{L}^{\mathrm{ad}}(A_{k_1})$ is the algebra of homomorphisms from A_{k_1} into itself, as a module over itself with respect to the adjoint representation. Under these conditions, $\mathcal{L}^{\mathrm{ad}}(A_{k_1})$ consists exactly of multiples of the identity mapping on A_{k_1} by elements of k_1, by Schur's lemma, as in Section 16.1. Equivalently, this means that the dimension of $\mathcal{L}^{\mathrm{ad}}(A_{k_1})$, as a vector space over k_1, is equal to one. It follows that the space $\mathcal{L}^{\mathrm{ad}}(A)$ of homomorphisms from A into itself, as a module over itself with respect to the adjoint representation, is equal to one as a vector space over k, as in Section 16.4. Of course, $\mathcal{L}^{\mathrm{ad}}(A)$ automatically contains all multiples of the identity mapping on A by elements of k. This means that $\mathcal{L}^{\mathrm{ad}}(A)$ consists exactly of multiples of the identity mapping on A by elements of k in this situation. This corresponds to part of the first part of part (c) of Exercise 5 on p55 of [25].

Conversely, suppose that $\mathcal{L}^{\mathrm{ad}}(A)$ consists exactly of multiples of the identity mapping on A by elements of k. This is the same as saying that $\mathcal{L}^{\mathrm{ad}}(A)$ has dimension one as a vector space over k, as before. It follows that $\mathcal{L}^{\mathrm{ad}}(A_{k_1})$ has dimension one as a vector space over k_1, as in Section 16.4. Suppose that k has characteristic 0, so that k_1 has characteristic 0 too. If A_{k_1} is semisimple as a Lie algebra over k_1, then A_{k_1} is isomorphic to the direct sum of h simple Lie algebras over k_1 for some positive integer h, as in Section 10.15. This implies that the dimension of $\mathcal{L}^{\mathrm{ad}}(A_{k_1})$ is equal to h as a vector space over k_1, as in the previous section. Under these conditions, we get that $h = 1$, so that A_{k_1} is simple as a Lie algebra over k_1. This corresponds to the other part of the first part of part (c) of Exercise 5 on p55 of [25].

Suppose now that A is simple as a Lie algebra over k, and that k has characteristic 0. In particular, this means that A is semisimple as a Lie algebra over k. Put $K = \mathcal{L}^{\mathrm{ad}}(A)$, which is a field in this situation, as in the previous section. By construction, the elements of K are linear mappings from A into itself, as a vector space over k. We may consider A as a vector space over K, where scalar multiplication by an element of K is defined by the corresponding linear mapping on A. It is easy to see that the Lie bracket on A is bilinear over K, as a mapping from $A \times A$ into A, because the elements of K are homomorphisms from A into itself, as a module over itself as a Lie algebra over k, with respect to the adjoint representation. Thus A may be considered as a Lie algebra over K, with respect to the Lie bracket already defined on A as a Lie algebra over k.

Let us use A_K to refer to A as a Lie algebra over K in this way. As before, $\mathcal{L}^{\mathrm{ad}}(A_K)$ denotes the space of linear mappings from A_K into itself, as a vector space over K, that are homomorphisms from A_K into itself as a module over itself, as a Lie algebra over K, and with respect to the adjoint representation.

Of course, $\mathcal{L}^{\mathrm{ad}}(A_K)$ contains the multiples of the identity mapping on A by elements of K, which correspond to linear mappings from A into itself as a vector space over k. Conversely, if ϕ is any element of $\mathcal{L}^{\mathrm{ad}}(A_K)$, then ϕ is linear as a mapping from A into itself, as a vector space over k. This follows from the fact that K contains the multiples of the identity mapping on A by elements of k, by construction. We also have that ϕ is a homomorphism from A into itself, as a module over itself as a Lie algebra over k, and with respect to the adjoint representation, because of the analogous property of ϕ as a mapping on A_K. This means that ϕ is an element of $\mathcal{L}^{\mathrm{ad}}(A) = K$. Thus $\mathcal{L}^{\mathrm{ad}}(A_K)$ consists exactly of multiples of the identity mapping on A by elements of K. This implies that A_K is absolutely simple as a Lie algebra over K, as before. This is the second part of part (c) of Exercise 5 on p55 of [25].

16.7 Algebras over subrings

Let k be a commutative ring with a multiplicative identity element, and let k_0 be a subring of k that contains the multiplicative identity element. If A is a module over k, then A may be considered as a module over k_0 as well. Let A_0 be A considered as a module over k_0. If B is a submodule of A, as a module over k, then B may be considered as a submodule of A_0 too.

Similarly, if A is an algebra over k in the strict sense, then A may be considered as an algebra over k_0 in the strict sense. Let A_0 be A considered as an algebra over k_0 in the strict sense. If B is a subalgebra of A, as an algebra over k in the strict sense, then B may be considered as a subalgebra of A_0, as an algebra over k_0 in the strict sense. If B is a one or two-sided ideal in A, as an algebra over k in the strict sense, then B has the analogous property in A_0 as well.

Now let $(A, [\cdot, \cdot])$ be a Lie algebra over k. As before, let A_0 be A, considered as a Lie algebra over k_0. It is easy to see that A is commutative, solvable, or nilpotent as a Lie algebra over k if and only if A_0 has the same property as a Lie algebra over k_0.

Let B be an ideal in A, as a Lie algebra over k. Thus B may be considered as an ideal in A_0, as a Lie algebra over k_0. Let B_0 be B, considered as an ideal in A_0, and as a Lie algebra over k_0 in particular. If B is solvable, as a Lie algebra over k, then B_0 is solvable, as a Lie algebra over k_0, as in the preceding paragraph. If A_0 is semisimple as a Lie algebra over k_0, then it follows that A is semisimple as a Lie algebra over k.

Of course, k may be considered as a module over k_0. Let us suppose from now on in this section that k is free as a module over k_0, of rank n_0 for some positive integer n_0. This means that k is isomorphic to $k_0^{n_0}$ as a module over k_0, where $k_0^{n_0}$ is the space of n_0-tuples of elements of k_0, considered as a module over k_0 with respect to pointwise addition and scalar multiplication.

If $x \in k$, then $M_x(y) = x\,y$ defines a homomorphism from k into itself, as a module over k_0. Let $\mathrm{tr}_{k/k_0}\, x$ be the trace of M_x, as a homomorphism from k into itself, as a free module over k_0 of rank n_0. This defines a homomorphism from k into k_0, as modules over k_0. This uses the fact that $x \mapsto M_x$ is linear over k_0, as a mapping from k into the space homomorphisms from k into itself, as a module over k_0. If $x \in k_0$, then

$$\mathrm{tr}_{k/k_0} x = n_0 \cdot x. \tag{16.7.1}$$

Let n be a positive integer, so that $V = k^n$ is a free module over k with respect to coordinatewise additional and scalar multiplication. We may also consider V as a free module over k_0 of rank $n_0\, n$, because k is a free module over k_0 of rank n_0. If T is a homomorphism from V into itself as a module over k, then T may be considered as a homomorphism from V into itself as a module over k_0 as well. Let $\mathrm{tr}_{V,k}\, T \in k$ be the trace of T as a homomorphism from V into itself as a free module over k of rank n, and let $\mathrm{tr}_{V,k_0}\, T \in k_0$ be the trace of T as a homomorphism from V into itself as a free module over k_0 of rank $n_0\, n$. One can check that

$$\mathrm{tr}_{V,k_0} T = \mathrm{tr}_{k/k_0}(\mathrm{tr}_{V,k} T). \tag{16.7.2}$$

16.8 Lie algebras over subfields

Let k be a field, and let k_0 be a subfield of k. Also let $(A, [\cdot,\cdot])$ be a Lie algebra over k, and let A_0 be A considered as a Lie algebra over k_0. Suppose that k has finite dimension n_0 as a vector space over k_0, and that A has positive finite dimension n as a vector space over k. Thus A_0 has dimension $n_0\, n$ as a vector space over k_0. If $x \in A$, then put $\mathrm{ad}_x(z) = [x, z]$ for every $z \in A$, as usual. This defines ad_x as a linear mapping from A into itself, as a vector space over k. Of course, ad_x may be considered as a linear mapping from A_0 into itself as well, as a vector space over k_0.

The Killing form for A, as a Lie algebra over k, is defined by

$$b(x, y) = \mathrm{tr}_A(\mathrm{ad}_x \circ \mathrm{ad}_y) \in k \tag{16.8.1}$$

for every $x, y \in A$, using the trace of $\mathrm{ad}_x \circ \mathrm{ad}_y$ on A as a vector space over k. Similarly, the Killing form for A_0 is defined by

$$b_0(x, y) = \mathrm{tr}_{A_0}(\mathrm{ad}_x \circ \mathrm{ad}_y) \in k_0 \tag{16.8.2}$$

for every $x, y \in A_0$, using the trace of $\mathrm{ad}_x \circ \mathrm{ad}_y$ on A_0 as a vector space over k. Let tr_{k/k_0} be the trace mapping from k into k_0 mentioned in the previous section. If $x, y \in A$, then

$$b_0(x, y) = \mathrm{tr}_{k/k_0} b(x, y), \tag{16.8.3}$$

as in (16.7.2).

Suppose that $b(\cdot,\cdot)$ is nondegenerate on A. Let $x \in A$ with $x \neq 0$ be given, so that there is a $y \in A$ such that $b(x, y) \neq 0$. Put $y_1 = (1/b(x, y))\, y$, so that

$$b(x, y_1) = 1. \tag{16.8.4}$$

This implies that

$$b_0(x, y_1) = \mathrm{tr}_{k/k_0} 1 = n_0 \cdot 1, \tag{16.8.5}$$

using (16.8.3) in the first step, and (16.7.1) in the second step.

Suppose from now on in this section that k_0 has characteristic 0, which is the same as saying that k has characteristic 0. In this case, (16.8.5) implies that $b_0(x, y_1) \neq 0$ in k_0. This means that $b_0(\cdot, \cdot)$ is nondegenerate on A_0 in this situation.

Suppose that A is semisimple as a Lie algebra over k, so that $b(\cdot, \cdot)$ is nondegenerate on A, as in Section 10.13. This implies that $b_0(\cdot, \cdot)$ is nondegenerate on A_0, as in the preceding paragraphs. It follows that A_0 is semisimple as a Lie algebra over k_0, as in Section 10.13 again.

As in Section 10.15, there are finitely many ideals $A_{0,1}, \ldots, A_{0,r}$ in A_0, as a Lie algebra over k_0, such that $A_{0,j}$ is simple as a Lie algebra over k_0 for each $j = 1, \ldots, r$, and A_0 corresponds to the direct sum of $A_{0,1}, \ldots, A_{0,r}$ as a Lie algebra over k_0. If $t \in k$, then

$$\phi_t(x) = t\, x \tag{16.8.6}$$

defines a linear mapping from A_0 into itself as a vector space over k_0, and in fact a homomorphism from A_0 into itself as a module over itself, with respect to the adjoint representation. It follows that

$$\phi_t(A_{0,j}) \subseteq A_{0,j} \tag{16.8.7}$$

for each $j = 1, \ldots, r$, as in Section 16.2. This means that $A_{0,j}$ is a linear subspace of A, as a vector space over k, for each $j = 1, \ldots, r$. Thus $A_{0,j}$ is an ideal in A, as a Lie algebra over k, for each $j = 1, \ldots, r$.

In particular, $A_{0,j}$ is a Lie subalgebra of A, as a Lie algebra over k, for each $j = 1, \ldots, r$. It is easy to see that $A_{0,j}$ is simple as a Lie algebra over k for each $j = 1, \ldots, r$, because $A_{0,j}$ is simple as a Lie algebra over k_0.

If A is simple as a Lie algebra over k, then A is semisimple. In this case, we get that $r = 1$ in the previous argument, so that $A_0 = A_{0,1}$ is simple as a Lie algebra over k_0. This corresponds to part (d) of Exercise 5 on p55 of [25].

Part III

Toral subalgebras and roots

Chapter 17

Subalgebras and diagonalizability

17.1 Toral subalgebras

Let k be a field, and let $(A, [\cdot,\cdot]_A)$ be a finite-dimensional Lie algebra over k. Suppose that y, z are ad-diagonalizable elements of A such that

$$[y, z]_A = 0. \tag{17.1.1}$$

This implies that ad_y and ad_z commute as linear mappings from A into itself, as in Section 2.4. It follows that $\mathrm{ad}_y + \mathrm{ad}_z$ is diagonalizable as a linear mapping from A into itself, as in Section 10.6. This means that $y+z$ is ad-diagonalizable, as an element of A.

If every element of A is ad-nilpotent, then A is nilpotent as a Lie algebra over k, as in Section 9.10. Suppose that k is an algebraically closed field of characteristic 0, and that A is semisimple as a Lie algebra over k. If $A \neq \{0\}$, then A is not nilpotent, and hence there is an $x \in A$ that is not ad-nilpotent. Using the abstract Jordan decomposition, as in Section 14.3, we get that there are $x_1, x_2 \in A$ such that $x = x_1 + x_2$, x_1 is ad-diagonalizable, and x_2 is ad-nilpotent. In particular, $x_1 \neq 0$, because x is not ad-nilpotent.

A Lie subalgebra B of A is said to be *toral* if every element of B is ad-diagonalizable, as an element of A, at least when k is algebraically closed, as on p35 of [14]. Under the conditions mentioned in the preceding paragraph, there are nonzero toral subalgebras of A, as on p35 of [14]. More precisely, one can take the linear span of a nonzero ad-diagonalizable element of A.

Let k be any field again, and let A be a finite-dimensional Lie algebra over k. If B is a Lie subalgebra of A, and if every element of B is ad-diagonalizable as an element of A, then B is commutative as a Lie algebra over k, as in the lemma on p35 of [14]. To see this, let $x \in B$ be given, and note that ad_x maps B into itself, because B is a Lie subalgebra of A. The restriction of ad_x to B is the same as $\mathrm{ad}_{B,x}$. We would like to show that $\mathrm{ad}_{B,x} = 0$.

Of course, ad_x is diagonalizable as a linear mapping from A into itself, by hypothesis. This implies that $\mathrm{ad}_{B,x}$ is diagonalizable as a linear mapping from B into itself, as in Section 10.6. Let $\lambda \in k$ be an eigenvalue of $\mathrm{ad}_{B,x}$, so that there is a $y \in B$ such that $y \neq 0$ and

$$\mathrm{ad}_{B,x}(y) = [x, y]_A = \lambda\, y. \tag{17.1.2}$$

We would like to show that $\lambda = 0$.

Equivalently,

$$\mathrm{ad}_{B,y}(x) = -\lambda\, y, \tag{17.1.3}$$

by (17.1.2). Remember that y is ad-diagonalizable as an element of A, by hypothesis. This implies that $\mathrm{ad}_{B,y}$ is diagonalizable as a linear mapping from B into itself, as before. Thus x can be expressed as a sum of eigenvectors of $\mathrm{ad}_{B,y}$. It follows that $\mathrm{ad}_{B,y}(x)$ is a sum of eigenvectors of $\mathrm{ad}_{B,y}$ corresponding to nonzero eigenvalues of $\mathrm{ad}_{B,y}$, if there are any.

If $\mathrm{ad}_{B,y}(x) \neq 0$, then the previous statement implies that $\mathrm{ad}_{B,y}(\mathrm{ad}_{B,y}(x)) \neq 0$. However,

$$\mathrm{ad}_{B,y}(\mathrm{ad}_{B,y}(x)) = -\lambda\, \mathrm{ad}_{B,y}(y) = -\lambda\, [y, y]_A = 0, \tag{17.1.4}$$

using (17.1.3) in the first step. Thus $\mathrm{ad}_{B,y}(x) = 0$, so that $\lambda = 0$, by (17.1.3). This means that $\mathrm{ad}_{B,x} = 0$, because $\mathrm{ad}_{B,x}$ is diagonalizable on B, and 0 is its only eigenvalue. This shows that B is commutative as a Lie algebra, as desired.

Note that we only used the diagonalizability of $\mathrm{ad}_{B,z}$ on B for each $z \in B$, rather than the diagonalizability of ad_z on A. This also corresponds to simply taking $A = B$.

17.2 Simultaneous diagonalizability

Let k be a field, and let $(A, [\cdot, \cdot]_A)$ be a finite-dimensional Lie algebra over k. Also let B be a Lie subalgebra of A, and suppose that every element of B is ad-diagonalizable as an element of A. Thus B is commutative as a Lie algebra over k, as in the previous section. Let B' be the dual of B, as a vector space over k. Remember that B' has the same dimension as B.

Suppose that $x \in A$ is an eigenvector for ad_w for each $w \in B$, so that

$$\mathrm{ad}_w(x) = [w, x]_A = \alpha(w)\, x \tag{17.2.1}$$

for some $\alpha(w) \in k$. If $x \neq 0$, then $\alpha(w)$ is linear in w, and hence defines an element of B'.

If $\alpha \in B'$, then put

$$A_\alpha = \{x \in A : \text{ for each } w \in B,\ \mathrm{ad}_w(x) = [w, x]_A = \alpha(w)\, x\}. \tag{17.2.2}$$

This is a linear subspace of A, as a vector space over k. An element of A_α is said to have *weight* α, as on p43 of [24].

In particular, if we take $\alpha = 0$, then we get

$$A_0 = \{x \in A : \text{ for each } w \in B,\ \mathrm{ad}_w(x) = [w, x]_A = 0\}. \tag{17.2.3}$$

This is the same as the centralizer $C_A(B)$ of B in A, as in Section 7.6. Note that

$$B \subseteq A_0 = C_A(B), \tag{17.2.4}$$

because B is commutative as a Lie algebra, as before.

Let us suppose that $B \neq \{0\}$, to avoid trivialities. This implies that $A_0 \neq \{0\}$, by (17.2.4). Put

$$\Phi_B = \{\alpha \in B' : \alpha \neq 0 \text{ and } A_\alpha \neq \{0\}\}. \tag{17.2.5}$$

Thus $\Phi_B \cup \{0\}$ is the same as the set of $\alpha \in B'$ such that $A_\alpha \neq \{0\}$.

If $u, v \in B$, then $[u, v]_A = 0$, as before. This implies that ad_u and ad_v commute as linear mappings from A into itself, as in Section 2.4. By hypothesis, ad_u is diagonalizable as a linear mapping from A into itself for each $u \in B$. It follows that the linear mappings ad_u, $u \in B$, are simultaneously diagonalizable on A, by standard arguments.

This means that A corresponds to the direct sum of the subspaces A_α with $\alpha \in \Phi_B \cup \{0\}$, as a vector space over k. In particular, the number of elements of Φ_B is strictly less than the dimension of A. This corresponds to some of the remarks on p35 of [14], and to Theorem 1 on p43 of [24].

Let $\alpha, \beta \in B'$ be given, and suppose that $x \in A_\alpha$, $y \in A_\beta$. If $w \in B$, then

$$\begin{aligned} [w, [x, y]_A]_A &= [[w, x]_A, y]_A + [x, [w, y]_A]_A \\ &= \alpha(w)\,[x, y]_A + \beta(w)\,[x, y]_A. \end{aligned} \tag{17.2.6}$$

This uses the Jacobi identity in the first step, or, equivalently, the fact that ad_w is a derivation on A. Thus

$$[x, y]_A \in A_{\alpha+\beta} \tag{17.2.7}$$

under these conditions. This corresponds to the first part of the proposition near the top of p36 in [14], and to the statement 2.1 on p45 of [24].

If $\alpha \in B'$ and $x \in A_\alpha$, then

$$\mathrm{ad}_x(A_\gamma) \subseteq A_{\alpha+\gamma} \tag{17.2.8}$$

for every $\gamma \in B'$, by (17.2.7). This implies that

$$(\mathrm{ad}_x)^n(A_\gamma) \subseteq A_{n\cdot\alpha+\gamma} \tag{17.2.9}$$

for every positive integer n, where $(\mathrm{ad}_x)^n$ is the nth power of ad_x on A, with respect to composition of mappings. If $\alpha \neq 0$ and k has characteristic 0, then one can use this to get that x is ad-nilpotent as an element of A, as in the second part of the proposition at the top of p36 in [14]. This could also be obtained as in Section 14.2.

Similarly, if $x \in A_\alpha$ and $y \in A_\beta$ for some $\alpha, \beta \in B'$, then

$$(\mathrm{ad}_x \circ \mathrm{ad}_y)(A_\gamma) = \mathrm{ad}_x(\mathrm{ad}_y(A_\gamma)) \subseteq A_{\alpha+\beta+\gamma} \tag{17.2.10}$$

for every $\gamma \in B'$, by (17.2.8).

17.3 Related bilinear forms

Let us continue with the same notation and hypotheses as in the previous section. Let $b(\cdot, \cdot)$ be a bilinear form on A that is associative, or equivalently invariant with respect to the adjoint representation on A. Thus

$$b([w, x]_A, y) = -b(x, [w, y]_A) \tag{17.3.1}$$

for every $w, x, y \in A$, as in Sections 6.10 and 7.7. In particular, the Killing form

$$b_A(x, y) = \mathrm{tr}_A(\mathrm{ad}_x \circ \mathrm{ad}_y) \tag{17.3.2}$$

on A has this property, as in Section 7.9.

Let $\alpha, \beta \in B'$, $x \in A_\alpha$, $y \in A_\beta$, and $w \in B$ be given. Using (17.3.1), we get that

$$\alpha(w)\, b(x, y) = -\beta(w)\, b(x, y). \tag{17.3.3}$$

If $\alpha + \beta \neq 0$, then there is a $w \in B$ such that $\alpha(w) \neq -\beta(w)$, and hence

$$b(x, y) = 0. \tag{17.3.4}$$

This corresponds to the third part of the proposition on the top of p36 in [14], and the first part of Theorem 3 (i) on p44 of [24]. Alternatively, if $b(\cdot, \cdot)$ is the Killing form (17.3.2) on A, then (17.3.4) follows from (17.2.10).

Let $\alpha \in B'$ and $w \in B$ be given again. If $x \in A_\alpha$ and $y \in A$, then

$$b(w, [x, y]_A) = b([w, x]_A, y) = \alpha(w)\, b(x, y). \tag{17.3.5}$$

Similarly, if $x \in A$ and $y \in A_{-\alpha}$, then

$$b([x, y]_A, w) = b(x, [y, w]_A) = \alpha(w)\, b(x, y). \tag{17.3.6}$$

This corresponds to Theorem 3 (ii) on p44 of [24], and is related to part (c) of the proposition on p37 of [14]. Note that

$$[x, y]_A \in A_0 \tag{17.3.7}$$

when $x \in A_\alpha$ and $y \in A_{-\alpha}$, as in (17.2.7).

Suppose now that $b(\cdot, \cdot)$ is also nondegenerate on A. In this case, the restriction of $b(\cdot, \cdot)$ to A_0 is nondegenerate on A_0, because of (17.3.4). This corresponds to the corollary on p36 of [14], and to the third part of Theorem 3 (i) on p44 of [24].

Let $\alpha \in B'$ with $\alpha \neq 0$ be given. If $x \in A_\alpha$ and $x \neq 0$, then there is a $y \in A$ such that

$$b(x, y) \neq 0, \tag{17.3.8}$$

because $b(\cdot, \cdot)$ is nondegenerate on A. More precisely, we can take $y \in A_{-\alpha}$, because of (17.3.4). In particular, this shows that $A_{-\alpha} \neq \{0\}$ when $A_\alpha \neq \{0\}$. Equivalently, if $\alpha \in \Phi_B$, then $-\alpha \in \Phi_B$. This corresponds to part (b) of the proposition on p37 of [14], and part of Theorem 2 (a) on p43 of [24]. Similarly, the restriction of $b(\cdot, \cdot)$ to

$$A_\alpha + A_{-\alpha} \tag{17.3.9}$$

is nondegenerate. This corresponds to the second part of Theorem 3 (i) on p44 of [24].

17.4 Maximal toral subalgebras

Let k be a field, and let V be a finite-dimensional vector space over k. Also let R and T be commuting linear mappings from V into itself. If T is nilpotent on V, then $R \circ T$ is nilpotent on V as well. In particular, this implies that

$$\mathrm{tr}_V(R \circ T) = 0. \tag{17.4.1}$$

This is the lemma on p36 of [14].

Let k be an algebraically closed field of characteristic 0, and let $(A, [\cdot, \cdot]_A)$ be a finite-dimensional semisimple Lie algebra over k. Suppose that B is a toral subalgebra of A, as in Section 17.1, and that B is maximal with respect to inclusion. Under these conditions,

$$C_A(B) = B, \tag{17.4.2}$$

where $C_A(B)$ is the centralizer of B in A, as in Section 7.6. This is the second proposition on p36 of [14].

Remember that $C_A(B)$ is a Lie subalgebra of A, as in Section 7.6. In this situation, $B \subseteq C_A(B)$, because B is commutative as a Lie algebra, as in (17.2.4). Thus we would like to show that

$$C_A(B) \subseteq B. \tag{17.4.3}$$

Let $x \in C_A(B)$ be given, and let

$$x = x_1 + x_2 \tag{17.4.4}$$

be the abstract Jordan decomposition of x in A, as in Section 14.3. Thus $x_1, x_2 \in A$,

$$\mathrm{ad}_x = \mathrm{ad}_{x_1} + \mathrm{ad}_{x_2}, \tag{17.4.5}$$

and ad_{x_1}, ad_{x_2} are the diagonalizable and nilpotent parts of ad_x, as a linear mapping from A into itself, as in Section 10.8. The condition that $x \in C_A(B)$ means exactly that ad_x maps B into $\{0\}$. This implies that ad_{x_1} and ad_{x_2} map B into $\{0\}$ as well, as in Section 10.8. It follows that

$$x_1, x_2 \in C_A(B), \tag{17.4.6}$$

as in Step (1) of the proof on p36 of [14].

If $x \in C_A(B)$, then the linear span

$$B(x) = \{w + t\,x : w \in B,\ t \in k\} \tag{17.4.7}$$

of B and x in A is a Lie subalgebra of A that is commutative as a Lie algebra. More precisely, this uses the fact that B is commutative as a Lie algebra, and that $[w, x]_A = 0$ for every $w \in B$. If x is ad-diagonalizable as an element of A too, then $B(x)$ is a toral subalgebra of A, by the remark at the beginning of

Section 17.1. This implies that $B(x) = B$, because B is supposed to be maximal in A, so that

$$x \in B. \tag{17.4.8}$$

This is Step (2) of the proof on p36 of [14].

Let $b_A(\cdot, \cdot)$ be the Killing form on A, as in (17.3.2). Remember that $b_A(\cdot, \cdot)$ is nondegenerate on A, because A is semisimple and k has characteristic 0, as in Section 10.13. This implies that the restriction of $b_A(\cdot, \cdot)$ to $A_0 = C_A(B)$ is nondegenerate, as in the previous section. Step (3) of the proof on p36 of [14] states that the restriction of $b_A(\cdot, \cdot)$ to B is nondegenerate.

To see this, let $x \in B$ be given, and suppose that

$$b_A(x, y) = 0 \tag{17.4.9}$$

for every $y \in B$. We would like to show that $x = 0$. If (17.4.9) holds for every $y \in C_A(B)$, then $x = 0$, because $b_A(\cdot, \cdot)$ is nondegenerate on $C_A(B)$, as in the preceding paragraph.

Let $z \in C_A(B)$ be given, and so that $[x, z]_A = 0$, because $x \in B$. This implies that ad_x and ad_z commute as linear mappings from A into itself, as in Section 2.4. If ad_z is nilpotent on A, then it follows that

$$b_A(x, z) = \mathrm{tr}_A(\mathrm{ad}_x \circ \mathrm{ad}_z) = 0, \tag{17.4.10}$$

as in (17.4.1).

Let $y \in C_A(B)$ be given, and let $y = y_1 + y_2$ be the abstract Jordan decomposition of y. Thus $y_1, y_2 \in C_A(B)$, as before. We also have that $y_1 \in B$, because y_1 is ad-diagonalizable as an element of A. It follows that $b_A(x, y_1) = 0$, by hypothesis. Observe that $b_A(x, y_2) = 0$, because y_2 is ad-nilpotent as an element of A, as in (17.4.10). Combining thise two staements, we get that (17.4.9) holds. This implies that $x = 0$, because y is an arbitrary element of $C_A(B)$, as desired.

Step (4) of the proof on p36 of [14] states that $C_A(B)$ is nilpotent as a Lie algebra over k. Let $x \in C_A(B)$ be given. We would like to show that x is ad-nilpotent as an element of $C_A(B)$, which is to say that $\mathrm{ad}_{C_A(B),x}$ is nilpotent as a linear mapping from $C_A(B)$ into itself. Let (17.4.4) be the abstract Jordan decomposition of x in A again. Thus $x_1 \in B$, by the first two steps, which implies that $\mathrm{ad}_{C_A(B),x_1} = 0$. We also have that $\mathrm{ad}_{C_A(B),x_2}$ is nilpotent on $C_A(B)$, because ad_{x_2} is nilpotent on A by construction, and $\mathrm{ad}_{C_A(B),x_2}$ is the same as the restriction of ad_{x_2} to $C_A(B)$. This implies that

$$\mathrm{ad}_{C_A(B),x} = \mathrm{ad}_{C_A(B),x_2} \tag{17.4.11}$$

is nilpotent on $C_A(B)$. It follows that $C_A(B)$ is nilpotent as a Lie algebra over k, as in Section 9.10.

Step (5) of the continuation of the proof on p37 of [14] states that

$$B \cap ([C_A(B), C_A(B)]) = \{0\}. \tag{17.4.12}$$

To see this, observe that

$$b_A([x_1, x_2]_A, y) = b_A(x_1, [x_2, y]_A) = 0 \tag{17.4.13}$$

for every $x_1, x_2 \in C_A(B)$ and $y \in B$. This uses the associativity of $b_A(\cdot, \cdot)$ on A in the first step, and the fact that $[x_2, y]_A = 0$ in the second step. It follows that $b_A(x, y) = 0$ for every $x \in [C_A(B), C_A(B)]$ and $y \in B$. If $x \in B$ as well, then we get that $x = 0$, because $b_A(\cdot, \cdot)$ is nondegenerate on B.

Step (6) of the proof on p37 of [14] states that $C_A(B)$ is commutative as a Lie algebra over k. Suppose for the sake of a contradiction that

$$[C_A(B), C_A(B)] \neq \{0\}. \tag{17.4.14}$$

This implies that

$$([C_A(B), C_A(B)]) \cap Z(C_A(B)) \neq \{0\}, \tag{17.4.15}$$

because $[C_A(B), C_A(B)]$ is an ideal in $C_A(B)$, and $C_A(B)$ is nilpotent as a Lie algebra, as in Section 9.10. Let z be an element of the left side of (17.4.15) with $z \neq 0$. Note that $z \notin B$, by the previous step.

It follows that z is not ad-diagonalizable as an element of A, as before. Let $z = z_1 + z_2$ be the abstract Jordan decomposition of z in A. Thus z_2 is ad-nilpotent as an element of A, $z_2 \in C_A(B)$, as before, and $z_2 \neq 0$, because z is not ad-diagonalizable. Because $z \in Z(C_A(B))$, ad_z commutes with ad_x for every $x \in C_A(B)$, as in Section 2.4. This implies that ad_{z_2} commutes with ad_x for every $x \in C_A(B)$, as in Section 10.8. Hence

$$b_A(x, z_2) = \mathrm{tr}_A(\mathrm{ad}_x \circ \mathrm{ad}_{z_2}) = 0 \tag{17.4.16}$$

for every $x \in C_A(B)$, as in (17.4.1), because ad_{z_2} is nilpotent on A. This means that $z_2 = 0$, because $b_A(\cdot, \cdot)$ is nondegenerate on $C_A(B)$.

Step (7) of the proof on p37 of [14] states that (17.4.2) holds. Otherwise, there is an element x of $C_A(B)$ not in B, and we can take x to be ad-nilpotent as an element of A. If $y \in C_A(B)$, then $[x, y]_A = 0$, by the previous step, so that ad_x commutes with ad_y on A, as in Section 2.4. It follows that

$$b_A(x, y) = \mathrm{tr}_A(\mathrm{ad}_x \circ \mathrm{ad}_y) = 0, \tag{17.4.17}$$

as in (17.4.1), because ad_x is nilpotent on A. This implies that $x = 0$, because $b_A(\cdot, \cdot)$ is nondegenerate on $C_A(B)$.

If $k = \mathbf{C}$, then Lie subalgebras B of A with the same types of properties are given in Theorem 3 on p15 of [24].

17.5 Self-centralizability and diagonalizability

Let k be a commutative ring with a multiplicative identity element, and let $(A, [\cdot, \cdot]_A)$ be a Lie algebra over k. Also let B be a Lie subalgebra of A that is commutative as a Lie algebra. This implies that

$$B \subseteq C_A(B), \tag{17.5.1}$$

where $C_A(B)$ is the centralizer of B in A, as in Section 7.6. If B_1 is another Lie subalgebra of A that is commutative as a Lie algebra, and if $B \subseteq B_1$, then

$$B_1 \subseteq C_A(B_1) \subseteq C_A(B). \tag{17.5.2}$$

If

$$C_A(B) = B, \tag{17.5.3}$$

then it follows that $B_1 \subseteq B$. This means that B is maximal as a commutative Lie subalgebra of A under these conditions. This corresponds to Corollary 1 on p15 of [24].

Conversely, let $x \in C_A(B)$ be given, and let $B(x)$ be the linear span of B and x in A, as in (17.4.7). This is a commutative Lie subalgebra of A that contains B, as in the previous section. If B is maximal as a commutative Lie subalgebra of A, then $x \in B$, and hence (17.5.3) holds.

Suppose now that k is a field, and that A is a finite-dimensional Lie algebra over k. Let B be a Lie subalgebra of A such that every element of B is ad-diagonalizable as an element of A. This implies that B is commutative as a Lie algebra, as in Section 17.1, so that (17.5.1) holds. If α is an element of the dual B' of B, then we let A_α be the set of $x \in A$ such that

$$\mathrm{ad}_w(x) = [w, x]_A = \alpha(w)\, x \tag{17.5.4}$$

for every $w \in B$, as in Section 17.2. Let Φ_B be the set of $\alpha \in B'$ such that $\alpha \neq 0$ and $A_\alpha \neq \{0\}$, as before.

Suppose that $w \in B$ satisfies $\alpha(w) = 0$ for every $\alpha \in \Phi_B$. This implies that $[w, x]_A = 0$ for every $x \in A_\alpha$ when $\alpha \in \Phi_B$, which holds automatically when $\alpha = 0$. It follows that $[w, x]_A = 0$ for every $x \in A$, because A is spanned by the A_α's with $\alpha \in \Phi_B \cup \{0\}$. This means that w is an element of the center $Z(A)$ of A as a Lie algebra. Of course, if $Z(A) = \{0\}$, then $w = 0$. In this case, we get that the linear span of Φ_B in B' is equal to B'. This corresponds to part (a) of the proposition on p37 of [14], and to the statement 2.2 on p45 of [24].

Let $b(\cdot, \cdot)$ be a bilinear form on A that is associative, or equivalently invariant under the adjoint representation on A, as in Section 17.3. Suppose that $b(\cdot, \cdot)$ is nondegenerate on A, so that the restriction of $b(\cdot, \cdot)$ to $A_0 = C_A(B)$ is nondegenerate, as before. Let us suppose from now on in this section that (17.5.3) holds, which means that the restriction of $b(\cdot, \cdot)$ to B is nondegenerate. If $\alpha \in B'$, then it follows that there is a unique $t_{b,\alpha} \in B$ such that

$$\alpha(w) = b(w, t_{b,\alpha}) \tag{17.5.5}$$

for every $w \in B$.

Let $\alpha \in B'$, $x \in A_\alpha$, and $y \in A_{-\alpha}$ be given, so that

$$[x, y]_A \in A_0 = C_A(B) = B. \tag{17.5.6}$$

Remember that

$$b(w, [x, y]_A) = \alpha(w)\, b(x, y) \tag{17.5.7}$$

for every $w \in B$, as in Section 17.3. It follows that

$$[x, y]_A = b(x, y)\, t_{b,\alpha}, \tag{17.5.8}$$

because of (17.5.5) and the nondegeneracy of $b(\cdot, \cdot)$ on B. This corresponds to part (c) of the proposition on p37 of [14], and to Theorem 3 (iii) on p44 of [24].

Put

$$B_\alpha = [A_\alpha, A_{-\alpha}] \tag{17.5.9}$$

for each $\alpha \in B'$, using the notation in Section 9.2 on the right side. If $\alpha \in \Phi_B$, then there is an $x \in A_\alpha$ with $x \neq 0$, and hence a $y \in A_{-\alpha}$ such that $b(x, y) \neq 0$, as in Section 17.3. This implies that B_α is the same as the one-dimensional linear subspace of B spanned by $t_{b,\alpha}$, because of (17.5.8). This corresponds to part (d) of the proposition on p37 in [24], and to the part of Theorem 2 (b) on p43 of [24] shown in statement 2.3 on p45 of [24].

17.6 Characteristic 0, $Z(A) = \{0\}$

Let us continue with the same notation and hypotheses as in the previous section. Let us also suppose in this section that k has characteristic 0, and that $Z(A) = \{0\}$ again. Let $\alpha \in \Phi_B$ be given, and let us show that

$$\alpha(t_{b,\alpha}) = b(t_{b,\alpha}, t_{b,\alpha}) \neq 0. \tag{17.6.1}$$

This corresponds to part (e) of the proposition on p37 of [14], and to the proof of statement 2.4 on p45 of [24].

Suppose for the sake of a contradiction that $\alpha(t_{b,\alpha}) = 0$. This implies that

$$[t_{b,\alpha}, x]_A = \alpha(t_{b,\alpha})\, x = 0 \tag{17.6.2}$$

for every $x \in A_\alpha$, and that

$$[t_{b,\alpha}, y]_A = -\alpha(t_{b,\alpha})\, y = 0 \tag{17.6.3}$$

for every $y \in A_{-\alpha}$. As before, there are $x \in A_\alpha$ and $y \in A_{-\alpha}$ such that $b(x, y) \neq 0$, and we can choose them so that $b(x, y) = 1$. Thus

$$[x, y]_A = t_{b,\alpha}, \tag{17.6.4}$$

by (17.5.8).

Let C be the linear span of x, y, and $t_{b,\alpha}$ in A. This is a Lie subalgebra of A, which is nilpotent and hence solvable as a Lie algebra over k, by (17.6.2), (17.6.3), and (17.6.4). The restriction of the adjoint representation on A to C defines a representation of C, as a Lie algebra over k, on A, as a vector space over k. Because $t_{b,\alpha} \in [C, C]$, by (17.6.4), we get that $\mathrm{ad}_{t_{b,\alpha}}$ is nilpotent as a linear mapping from A into itself, as in Section 14.14. However, $\mathrm{ad}_{t_{b,\alpha}}$ is diagonalizable as a linear mapping from A into itself, because $t_{b,\alpha} \in B$. It follows that $\mathrm{ad}_{t_{b,\alpha}} = 0$, so that $t_{b,\alpha} \in Z(A)$. This means that $t_{b,\alpha} = 0$, because

$Z(A) = \{0\}$, by hypothesis. This contradicts the fact that $\alpha \neq 0$, by definition of Φ_B.

Let $\alpha \in \Phi_B$ be given again, and put

$$h_\alpha = 2\, b(t_{b,\alpha}, t_{b,\alpha})^{-1}\, t_{b,\alpha} = 2\, \alpha(t_{b,\alpha})^{-1}\, t_{b,\alpha}. \tag{17.6.5}$$

Thus

$$\alpha(h_\alpha) = 2\, \alpha(t_{b,\alpha})^{-1}\, \alpha(t_{b,\alpha}) = 2. \tag{17.6.6}$$

Note that h_α is uniquely determined as an element of (17.5.9) by (17.6.6), as in Theorem 2 (b) on p43-4 of [24].

Let x_α be a nonzero element of A_α. As before, there is a $y \in A_{-\alpha}$ such that $b(x_\alpha, y) \neq 0$. More precisely, we can choose $y_\alpha \in A_{-\alpha}$ such that

$$b(x_\alpha, y_\alpha) = 2\, b(t_{b,\alpha}, t_{b,\alpha})^{-1}. \tag{17.6.7}$$

This implies that

$$[x_\alpha, y_\alpha]_A = h_\alpha, \tag{17.6.8}$$

by (17.5.8).

Observe that

$$[h_\alpha, x_\alpha]_A = \alpha(h_\alpha)\, x_\alpha = 2\, x_\alpha, \tag{17.6.9}$$

using the facts that $h_\alpha \in B$ and $x_\alpha \in A_\alpha$ in the first step. Similarly,

$$[h_\alpha, y_\alpha]_A = -\alpha(h_\alpha)\, y_\alpha = -2\, y_\alpha, \tag{17.6.10}$$

because $y_\alpha \in A_{-\alpha}$. This shows that the linear span of x_α, y_α, and h_α in A is a Lie subalgebra of A, which is isomorphic to $sl_2(k)$ as a Lie algebra over k. More precisely, x_α, y_α, and h_α correspond to the usual basis elements $\begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}$, $\begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix}$, and $\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$ of $sl_2(k)$ under this isomorphism, as in Section 10.2. This corresponds to part (f) of the proposition on p37 of [14], and to part of Theorem 2 (c) on p44 of [24], as in statement 2.5 on p45 of [24].

It is easy to see that

$$t_{b,-\alpha} = -t_{b,\alpha}, \tag{17.6.11}$$

by the definition (17.5.5) of $t_{b,\alpha}$. Remember that $-\alpha \in \Phi_B$, because $\alpha \in \Phi_B$, as in Section 17.3. Using (17.6.11), we get that

$$h_{-\alpha} = -h_\alpha, \tag{17.6.12}$$

as in part (g) of the proposition on p37 of [14].

17.7 The dimension of A_α

Let us continue with the situation considered in the previous two sections. Thus k is a field of characteristic 0, and $(A, [\cdot,\cdot]_A)$ is a finite-dimensional Lie algebra over k. Let B be a Lie subalgebra of A such that every element of B is ad-diagonalizable as an element of A, so that B is commutative as a Lie algebra, as in Section 17.1. If α is an element of the dual B' of B, then A_α is the set of $x \in A$ such that

$$\mathrm{ad}_w(x) = [w, x]_A = \alpha(w)\, x \tag{17.7.1}$$

for every $w \in B$, as before. In particular, A_0 is the same as the centralizer $C_A(B)$ of B in A. We suppose here that this is equal to B, so that

$$A_0 = C_A(B) = B, \tag{17.7.2}$$

and that $Z(A) = \{0\}$. Remember that Φ_B is the set of $\alpha \in B'$ such that $\alpha \neq 0$ and $A_\alpha \neq 0$.

Suppose that $b(\cdot, \cdot)$ is a nondegenerate bilinear form on A that is associative, or equivalently invariant under the adjoint representation on A. It follows that $b(\cdot, \cdot)$ is nondegenerate on (17.7.2), as before. If $\alpha \in B'$, then we take $t_{b,\alpha}$ to be the unique element of B such that

$$\alpha(w) = b(w, t_{b,\alpha}) \tag{17.7.3}$$

for every $w \in B$, as in Section 17.5.

Let $\alpha \in \Phi_B$ be given, so that $-\alpha \in \Phi_B$ too, and the restriction of $b(\cdot, \cdot)$ to $A_\alpha + A_{-\alpha}$ is nondegenerate, as in Section 17.3. Remember that the restriction of $b(\cdot, \cdot)$ to each of A_α and $A_{-\alpha}$ is equal to 0. One can use this and the nondegeneracy of $b(\cdot, \cdot)$ on $A_\alpha + A_{-\alpha}$ to get that the dimensions of A_α and $A_{-\alpha}$ are the same, as vector spaces over k.

Let h_α be as in (17.6.5), let x_α be a nonzero element of A_α, and let $y_\alpha \in A_{-\alpha}$ be as in (17.6.7). Suppose for the sake of a contradiction that the dimension of A_α is strictly larger than 1, which means that the dimension of $A_{-\alpha}$ is strictly larger than 1 too. This implies that there is a $y \in A_{-\alpha}$ such that $y \neq 0$ and

$$b(x_\alpha, y) = 0. \tag{17.7.4}$$

It follows that

$$[x_\alpha, y]_A = 0, \tag{17.7.5}$$

by (17.5.8). Note that

$$[h_\alpha, y]_A = -\alpha(h_\alpha)\, y = -2\, y, \tag{17.7.6}$$

because $h_\alpha \in B$, $y \in A_\alpha$, and $\alpha(h_\alpha) = 2$.

Remember that the linear span of x_α, y_α,, and h_α in A is a Lie subalgebra of A that is isomorphic to $sl_2(k)$ as a Lie algebra over k. Thus A may be considered as a module over $sl_2(k)$, using the restriction of the adjoint representation on A to this Lie subalgebra of A, acting on A as a vector space over k. With respect to this representation, y is a maximal or primitive vector of weight -2, as in Section 15.2. This contradicts the fact that the weight of y should be nonnegative, as in Section 15.3. This shows that A_α has dimension one as a vector space over k, as in Theorem 2 (b) on p43 of [24], and statement 2.6 on p45 of [24].

Of course, this means that the dimension of $A_{-\alpha}$ is one as well. Remember that $B_\alpha = [A_\alpha, A_{-\alpha}]$ is the same as the one-dimensional linear subspace of B spanned by h_α, as in the previous two sections. It follows that

$$A_\alpha + A_{-\alpha} + B_\alpha \tag{17.7.7}$$

is the same as the linear span in A of x_α, y_α, and h_α, which is a Lie subalgebra of A isomorphic to $sl_2(k)$, as before. This corresponds to part of Theorem 2 (c) on p44 of [24], and to statement 2.7 on p46 of [24]. Because $A_{-\alpha}$ has dimension one, $y_\alpha \in A_{-\alpha}$ is uniquely determined by $x_\alpha \in A_\alpha$ and (17.6.7), as in Theorem 2 (c) on p44 of [24] and statement 2.8 on p46 of [24].

Now let us consider the argument given on the bottom of p38 of [14], which can also be used to get some of the same properties as before. Let C be the linear span in A of B and the linear subspaces of the form $A_{c\,\alpha}$, where $c \in k$ and

$$c\,\alpha \in \Phi_B, \tag{17.7.8}$$

which implies that $c \neq 0$. This is a Lie subalgebra of A, because of (17.2.7). In particular, C is a submodule of A, as a module over the Lie subalgebra spanned by x_α, y_α, and h_α, because $x_\alpha, y_\alpha, h_\alpha \in C$. Thus C may be considered as a module over $sl_2(k)$.

Of course, $[h_\alpha, w]_A = 0$ for every $w \in B$, because B is commutative as a Lie algebra over k. If $z \in A_{c\,\alpha}$ for some $c \in k$, then

$$[h_\alpha, z]_A = c\,\alpha(h_\alpha)\,z = 2\,c\,z, \tag{17.7.9}$$

because $\alpha(h_\alpha) = 2$. This means that the weights of h_α on C consist of 0 and $2\,c$ for each $c \in k$ satisfying (17.7.8), as in Section 15.1. In particular, the action of h_α on C is diagonalizable in this situation.

Remember that C corresponds to the direct sum of finitely many irreducible submodules, as a module over $sl_2(k)$, by Weyl's theorem, as in Section 13.2. Any submodule of C, as a module over $sl_2(k)$, is mapped into itself by the action of h_α, and hence the action of h_α on this submodule is diagonalizable, as in Section 10.6. This implies that any nonzero submodule of C has a maximal or primitive vector, as in Section 15.2. It follows that any nonzero irreducible submodule of C is as in Section 15.3.

The weights of h_α on any nonzero irreducible submodule of C correspond to integers, under the usual embedding of $\mathbf{Q}$ into k, as in Section 15.3. This means that the weights of h_α on C correspond to integers. If $c \in k$ satisfies (17.7.8), then we get that $2\,c$ corresponds to an integer.

If $w \in B$ satisfies $\alpha(w) = 0$, then $[w, x_\alpha]_A = \alpha(w)\,x_\alpha = 0$ and $[w, y_\alpha]_A = -\alpha(w)\,y_\alpha = 0$. Of course, $[w, h_\alpha]_A = 0$, because B is commutative as a Lie algebra. Thus the linear span of x_α, y_α, and h_α acts trivially on the kernel of α in B.

Note that the linear span of x_α, y_α, and h_α is a submodule of C. More precisely, this is an irreducible submodule of C, because $sl_2(k)$ is simple as a Lie algebra over k, as in Section 11.1.

Of course, B is spanned by h_α and the kernel of α in B, so that the linear span in A of the kernel of α in B, x_α, y_α, and h_α is the same as the linear span of B, x_α, and y_α. This is a submodule of C, and the proof of Weyl's theorem shows that C corresponds to the direct sum of this submodule and finitely many irreducible submodules of C, if necessary.

The elements of C of weight 0 with respect to h_α are in B. Thus nonzero elements of irreducible submodules of C complementary to the linear span of B, x_α, and y_α cannot have weight 0 with respect to h_α. This implies that the weights of h_α on these complementary irreducible submodules of C correspond to odd integers, as in Section 15.3. It follows that the only even integers which can correspond to weights of h_α on C are 0 and ± 2, which are the weights of h_α on B, x_α, and y_α.

In particular, 4 does not correspond to a weight of h_α on C, which implies that

$$2\,\alpha \notin \Phi_B. \tag{17.7.10}$$

If $\alpha/2$ were in Φ_B, then we could apply the same argument to it, to get that $\alpha \notin \Phi_B$. Thus

$$\alpha/2 \notin \Phi_B. \tag{17.7.11}$$

This shows that 1 is not a weight of h_α on C.

Suppose for the sake of a contradiction that C_1 is a nonzero irreducible submodule of C complementary to the linear span of B, x_α, and y_α. Thus C_1 does not contain any nonzero elements with weight 0 or 1 with respect to h_α, as in the previous two paragraphs. This is a contradiction, as in Section 15.3. This means that C is the same as the linear span of B, x_α, and y_α.

It follows in particular that A_α and $A_{-\alpha}$ are spanned by x_α and y_α, respectively, so that the dimensions of A_α and $A_{-\alpha}$ are both equal to one, as vector spaces over k. We also get that $\pm\alpha$ are the only multiples of α by elements of k in Φ_B. This corresponds to parts (a) and (b) of the proposition on p39 of [14]. The second statement corresponds to the second part of Theorem 2 (a) on p43 of [24] as well.

17.8 Other elements of Φ_B

Let us continue with the same notation and hypotheses as in the previous section. Let $\alpha, \beta \in \Phi_B$ be given, and remember that $h_\alpha \in B$ is as in (17.6.5). Let x_α be a nonzero element of A_α again, and let $y_\alpha \in A_{-\alpha}$ be as in (17.6.7), so that the linear span of x_α, y_α, and h_α in A is a Lie subalgebra of A that is isomorphic to $sl_2(k)$, as a Lie algebra over k. Thus A may be considered as a module over the linear span of x_α, y_α, and h_α, or over $sl_2(k)$. Weyl's theorem implies that A corresponds to the direct sum of finitely many irreducible submodules. Any submodule of A is mapped into itself by ad_{h_α}, and ad_{h_α} is diagonalizable on the submodule. This implies that any nonzero submodule of A has a maximal or primitive vector, as in Section 15.2, and hence a nonzero irreducible submodule is as in Section 15.3. In particular, the eigenvalues of ad_{h_α} on A correspond to integers, with respect to the usual embedding of $\mathbf{Q}$ in k.

Let y be a nonzero element of A_β, so that

$$\mathrm{ad}_{h_\alpha}(y) = [h_\alpha, y]_A = \beta(h_\alpha)\, y. \tag{17.8.1}$$

Thus $\beta(h_\alpha)$ corresponds to an integer, with respect to the standard embedding of $\mathbf{Q}$ in k, as in the preceding paragraph. This is part of statement 2.9 on p46 of [24].

Let n be the integer corresponding to $\beta(h_\alpha)$, and put

$$\begin{aligned} z &= (\mathrm{ad}_{y_\alpha})^n(y) \quad \text{when } n \ge 0 \\ &= (\mathrm{ad}_{x_\alpha})^{-n}(y) \quad \text{when } n \le 0. \end{aligned} \tag{17.8.2}$$

One can check that $z \neq 0$, because A corresponds to the direct sum of finitely many irreducible submodules, each of which is as in Section 15.3. We also have that

$$z \in A_{\beta - \beta(h_\alpha)\,\alpha}, \tag{17.8.3}$$

because $y \in A_\beta$, $x_\alpha \in A_\alpha$, and $y_\alpha \in A_{-\alpha}$, and using (17.2.7). In particular,

$$A_{\beta - \beta(h_\alpha)\,\alpha} \neq \{0\}, \tag{17.8.4}$$

because $z \neq 0$.

Let us check that

$$\beta - \beta(h_\alpha)\,\alpha \neq 0. \tag{17.8.5}$$

Otherwise, if $\beta - \beta(h_\alpha)\,\alpha = 0$, then

$$0 = \beta(h_\alpha) - \beta(h_\alpha)\,\alpha(h_\alpha) = \beta(h_\alpha) - 2\,\beta(h_\alpha) = -\beta(h_\alpha), \tag{17.8.6}$$

because $\alpha(h_\alpha) = 2$. In this case, we get that $\beta = 0$, contradicting the hypothesis that $\beta \in \Phi_B$. Thus (17.8.5) holds, and hence

$$\beta - \beta(h_\alpha)\,\alpha \in \Phi_B, \tag{17.8.7}$$

by (17.8.4). This corresponds to statement 2.9 on p46 of [24].

If $\beta = \alpha$, then

$$\beta - \beta(h_\alpha)\,\alpha = \alpha - \alpha(h_\alpha)\,\alpha = \alpha - 2\,\alpha = -\alpha, \tag{17.8.8}$$

because $\alpha(h_\alpha) = 2$, as before. Similarly, if $\beta = -\alpha$, then

$$\beta - \beta(h_\alpha)\,\alpha = -\alpha - (-\alpha(h_\alpha))\,\alpha = -\alpha + 2\,\alpha = \alpha. \tag{17.8.9}$$

This is part of statement 2.10 on p46 of [24].

Here is another proof of the fact that $c \in k$ satisfies $c\,\alpha \in \Phi_B$ only when $c = \pm 1$, as in statement 2.11 on p4 of [24]. If $\beta = c\,\alpha \in \Phi_B$, then $\beta(h_\alpha) = c\,\alpha(h_\alpha) = 2\,c$ corresponds to an integer, as before. Similarly, we can interchange the roles of α and β, to get that $2/c$ corresponds to an integer. Thus the only possibilities for c are ± 1, $\pm 1/2$, and ± 2.

It suffices to show that $2\,\alpha \not\in \Phi_B$, which is to say that $c \neq 2$. This will imply that $\alpha/2 \not\in \Phi_B$, since otherwise we would have that $\alpha \not\in \Phi_B$. Similarly, this will show that $c \neq -1/2, -2$, because $-\alpha \in \Phi_B$, as in Section 17.3.

Suppose for the sake of a contradiction that $2\,\alpha \in \Phi_B$, and let y be a nonzero element of $A_{2\,\alpha}$. Thus

$$[h_\alpha, y]_A = 2\,\alpha(h_\alpha)\,y = 4\,y. \tag{17.8.10}$$

Note that $\mathrm{ad}_{x_\alpha}(y) \in A_{3\,\alpha}$, by (17.2.7), and because $x_\alpha \in A_\alpha$. However, $A_{3\,\alpha} = \{0\}$, because $3\,\alpha \not\in \Phi_B$, as before. This means that

$$\mathrm{ad}_{x_\alpha}(y) = 0. \tag{17.8.11}$$

Observe that

$$\mathrm{ad}_{h_\alpha}(y) = \mathrm{ad}_{x_\alpha}(\mathrm{ad}_{y_\alpha}(y)) - \mathrm{ad}_{y_\alpha}(\mathrm{ad}_{x_\alpha}(y)) = \mathrm{ad}_{x_\alpha}(\mathrm{ad}_{y_\alpha}(y)), \tag{17.8.12}$$

using (17.6.8) in the first step, and (17.8.11) in the second step. Using (17.2.7) again, we get that $\mathrm{ad}_{y_\alpha}(y) \in A_\alpha$, because $y_\alpha \in A_{-\alpha}$ and $y \in A_{2\,\alpha}$. This means that $\mathrm{ad}_{y_\alpha}(y)$ is a multiple of x_α, because A_α has dimension one as a vector space over k, as in the previous section. It follows that

$$\mathrm{ad}_{x_\alpha}(\mathrm{ad}_{y_\alpha}(y)) = 0, \tag{17.8.13}$$

because $\mathrm{ad}_{x_\alpha}(x_\alpha) = 0$. This contradicts (17.8.10), because of (17.8.12) and the fact that $y \neq 0$.

17.9 Adding elements of Φ_B

Let us continue with the same notation and hypotheses as in the previous two sections. Let $\alpha, \beta \in \Phi_B$ be given again, and suppose that

$$\beta \neq \pm\alpha. \tag{17.9.1}$$

Thus, for each $j \in \mathbf{Z}$,

$$\beta + j\,\alpha \neq 0, \tag{17.9.2}$$

as in the previous sections. Let E be the linear span in A of the subspaces

$$A_{\beta + j\,\alpha}, \tag{17.9.3}$$

where $j \in \mathbf{Z}$. More precisely, we may restrict our attention to $j \in \mathbf{Z}$ such that

$$\beta + j\,\alpha \in \Phi_B, \tag{17.9.4}$$

since otherwise (17.9.3) is equal to $\{0\}$.

Remember that $h_\alpha \in B$ is as in (17.6.5), and let x_α be a nonzero element of A_α again. Also let $y_\alpha \in A_{-\alpha}$ be as in (17.6.7), so that the linear span of x_α, y_α, and h_α in A is a Lie subalgebra of A that is isomorphic to $sl_2(k)$, as a Lie algebra over k. As before, A may be considered as a module over the linear span of x_α, y_α, and h_α, or over $sl_2(k)$. In fact, E is a submodule of A, because of (17.2.7). The weights of h_α on E are given by

$$\beta(h_\alpha) + j\,\alpha(h_\alpha) \tag{17.9.5}$$

for $j \in \mathbf{Z}$ such that (17.9.4) holds, as in Section 15.1. Of course, (17.9.5) is the same as

$$\beta(h_\alpha) + 2\,j, \tag{17.9.6}$$

because $\alpha(h_\alpha) = 2$. Note that $j = 0$ satisfies (17.9.4) automatically.

Weyl's theorem implies that E corresponds to the direct sum of finitely many irreducible submodules, as in Section 13.2. Any submodule of E is mapped into itself by the action of h_α, and the action of h_α on this submodule is diagonalizable, as in Section 10.6. Hence any nonzero submodule of E has a maximal or primitive vector, as in Section 15.2. This implies that any nonzero irreducible submodule of E is as in Section 15.3.

Remember that (17.9.3) has dimension one as a vector space over k when (17.9.4) holds, as in Section 17.7. One can use this to check that E is irreducible as a module over $sl_2(k)$. More precisely, note that at most one of 0 and 1 can be of the form (17.9.6), as mentioned near the top of p39 of [14].

Thus there is a nonnegative integer m such that E is as in Section 15.3, as a module over $sl_2(k)$. In particular, the dimension of E is $m + 1$, as a vector space over k.

Let q and r be the largest integers such that (17.9.4) holds with $j = q$ and $j = -r$, respectively. Note that $q, r \geq 0$, because (17.9.4) holds when $j = 0$. The maximal and minimal weights of h_α on E are

$$m = \beta(h_\alpha) + 2\,q \tag{17.9.7}$$

and

$$-m = \beta(h_\alpha) - 2\,r, \tag{17.9.8}$$

as in Section 15.3. In particular,

$$\beta(h_\alpha) = r - q. \tag{17.9.9}$$

Suppose that $j \in \mathbf{Z}$ satisfies

$$-r \leq j \leq q, \tag{17.9.10}$$

so that

$$\beta(h_\alpha) - 2\,r \leq \beta(h_\alpha) + 2\,j \leq \beta(h_\alpha) + 2\,q. \tag{17.9.11}$$

Under these conditions, $\beta(h_\alpha) + 2\,j$ is a weight of h_α on E, as in Section 15.3. This means that (17.9.4) holds, as in part (e) of the proposition on p39 of [14].

Similarly, if $j \in \mathbf{Z}$ satisfies

$$-r \le j \le q - 1, \tag{17.9.12}$$

then the restriction of ad_{x_α} to $A_{\beta + j\,\alpha}$ is a one-to-one mapping onto

$$A_{\beta+(j+1)\,\alpha}. \tag{17.9.13}$$

This follows from Section 15.3 again. These properties of E, q, and r correspond to statement 2.12 on p46 of [24].

The same type of arguments are discussed starting at the bottom of p38 and continuing on p39 of [14], as before. In particular, these arguments can also be used to get that $\beta(h_\alpha)$ corresponds to an integer for which (17.8.7) holds, as in part (c) of the proposition on p39 of [14].

Suppose now that $\alpha + \beta \in \Phi_B$. This means that (17.9.4) holds with $j = 1$, and in particular that $q \ge 1$. Thus $j = 0$ satisfies (17.9.12), so that ad_{x_α} maps A_β onto $A_{\beta+\alpha}$, as before. This implies that

$$[A_\alpha, A_\beta] = A_{\alpha+\beta}, \tag{17.9.14}$$

as in Theorem 2 (d) on p44 of [24], and statement 2.13 on p47 of [24]. This corresponds to part (d) of the proposition on p39 of [14] as well.

17.10 The dual of B

Let k be a field of characteristic 0 again, and let $(A, [\cdot,\cdot]_A)$ be a finite-dimensional Lie algebra over k. Also let B be a Lie subalgebra of A such that every element of B is ad-diagonalizable as an element of A, so that B is commutative as a Lie algebra, as in Section 17.1. If α is an element of the dual B' of B, then put

$$A_\alpha = \{x \in A : \text{ for every } w \in B,\ \mathrm{ad}_w(x) = [w, x]_A = \alpha(w)\, x\}, \tag{17.10.1}$$

as before. Thus A_0 is the same as the centralizer $C_A(B)$ of B in A, and we suppose again that this is equal to B, so that

$$A_0 = C_A(B) = B. \tag{17.10.2}$$

We suppose that the center $Z(A)$ of A as a Lie algebra is equal to $\{0\}$ again too.

Suppose that $b(\cdot,\cdot)$ is a nondegenerate bilinear form on A that is associative, or equivalently invariant under the adjoint representation on A, as before. This implies that that the restriction of $b(\cdot,\cdot)$ to (17.10.2) is nondegenerate, as in Section 17.3. If $\alpha \in B'$, then there is a unique $t_{b,\alpha} \in B$ such that

$$\alpha(w) = b(w, t_{b,\alpha}) \tag{17.10.3}$$

for every $w \in B$, as in Section 17.5. Note that $\alpha \mapsto t_{b,\alpha}$ is a one-to-one linear mapping from B' onto B.

If $\alpha, \beta \in B'$, then put

$$b'(\alpha, \beta) = b(t_{b,\alpha}, t_{b,\beta}). \tag{17.10.4}$$

This defines a bilinear form on B'. Equivalently,

$$b'(\alpha, \beta) = \beta(t_{b,\alpha}) \tag{17.10.5}$$

for every $\alpha, \beta \in B'$. Observe that (17.10.4) is nondegenerate on B'.

Let Φ_B be the set of $\alpha \in B'$ such that $\alpha \neq 0$ and $A_\alpha \neq \{0\}$, as before. If $\alpha \in \Phi_B$, then

$$b'(\alpha, \alpha) = b(t_{b,\alpha}, t_{b,\alpha}) \neq 0, \tag{17.10.6}$$

as in Section 17.6. In this case, we put

$$h_\alpha = 2\, b(t_{b,\alpha}, t_{b,\alpha})^{-1}\, t_{b,\alpha} = 2\, b'(\alpha, \alpha)^{-1}\, t_{b,\alpha}, \tag{17.10.7}$$

as before, so that $\alpha(h_\alpha) = 2$. If $\beta \in B'$, then

$$2\, b'(\alpha, \beta)\, b'(\alpha, \alpha)^{-1} = 2\, \beta(t_{b,\alpha})\, b'(\alpha, \alpha)^{-1} = \beta(h_\alpha). \tag{17.10.8}$$

If $\beta \in \Phi_B$, then (17.10.8) corresponds to an integer, with respect to the standard embedding of $\mathbf{Q}$ into k, as in Section 17.8.

Remember that the linear span of Φ_B in B' is equal to B', as in Section 17.5. Let $\alpha_1, \ldots, \alpha_n$ be a basis for B' consisting of elements of Φ_B. Let $\beta \in \Phi_B$ be given, so that β can be expressed in a unique way as

$$\beta = \sum_{j=1}^{n} c_j\, \alpha_j, \tag{17.10.9}$$

where $c_j \in k$ for each $j = 1, \ldots, n$. We would like to show that c_j corresponds to an element of $\mathbf{Q}$ for every $j = 1, \ldots, n$, with respect to the standard embedding of $\mathbf{Q}$ into k, as discussed near the bottom of p39 of [14].

Of course,

$$b'(\alpha_l, \beta) = \sum_{j=1}^{n} c_j\, b'(\alpha_l, \alpha_j) \tag{17.10.10}$$

for each $l = 1, \ldots, n$. This implies that

$$2\, b'(\alpha_l, \beta)\, b'(\alpha_l, \alpha_l)^{-1} = \sum_{j=1}^{n} 2\, b'(\alpha_l, \alpha_j)\, b'(\alpha_l, \alpha_l)^{-1}\, c_j \tag{17.10.11}$$

for every $l = 1, \ldots, n$. The left side corresponds to an integer for every $l = 1, \ldots, n$, because $\beta \in \Phi_B$, as before. Similarly,

$$2\, b'(\alpha_l, \alpha_j)\, b'(\alpha_l, \alpha_l)^{-1} \tag{17.10.12}$$

corresponds to an integer for every $j, l = 1, \ldots, n$.

Note that $(b'(\alpha_l, \alpha_j))$ is invertible as an $n \times n$ matrix with entries in k, because $b'(\cdot, \cdot)$ is nondegenerate as a bilinear form on B'. This implies that the $n \times n$ matrix with entries (17.10.12) is invertible as well. Equivalently, the determinant of this matrix is not 0. As in the preceding paragraph, this corresponds to an $n \times n$ matrix of integers, whose determinant is not 0.

Thus the entries of the inverse of the matrix in (17.10.12) correspond to rational numbers. This permits us to solve (17.10.11), to get that c_j corresponds to an element of $\mathbf{Q}$ for each $j = 1, \ldots, n$, as desired.

17.11 Using the Killing form

Let us continue with the same notation and hypotheses as in the previous section, with some additional conditions, as follows. Suppose that A is semisimple, and let

$$b_A(x, y) = \mathrm{tr}_A(\mathrm{ad}_x \circ \mathrm{ad}_y) \tag{17.11.1}$$

be the Killing form on A. Thus b_A is associative on A, or equivalently invariant under the adjoint representation on A, and b_A is nondegenerate on A, as in Sections 7.9 and 10.13. In particular, we can take $b = b_A$ in the previous section.

Remember that the restriction of b_A to (17.10.2) is nondegenerate, as before. If $\alpha \in B'$, then there is a unique $t_\alpha = t_{b_A, \alpha} \in B$ such that

$$\alpha(w) = b_A(w, t_\alpha) \tag{17.11.2}$$

for every $w \in B$, as in (17.10.3). Put

$$b'_A(\alpha, \beta) = b_A(t_\alpha, t_\beta) \tag{17.11.3}$$

for every $\alpha, \beta \in B'$, as in (17.10.4). Equivalently,

$$b'_A(\alpha, \beta) = \beta(t_\alpha) \tag{17.11.4}$$

for every $\alpha, \beta \in B'$, as in (17.10.5).

If $x, y \in B$, then

$$b_A(x, y) = \sum_{\alpha \in \Phi_B} \alpha(x)\, \alpha(y). \tag{17.11.5}$$

To see this, remember that A corresponds to the direct sum of the subspaces A_α, $\alpha \in \Phi_B \cup \{0\}$, as a vector space over k, as in Section 17.2. These subspaces are mapped into themselves by ad_x and ad_y, so that the trace of $\mathrm{ad}_x \circ \mathrm{ad}_y$ over A is the same as the sum of the traces over A_α, $\alpha \in \Phi_B \cup \{0\}$. The trace over A_0 is equal to 0, because $\mathrm{ad}_x = \mathrm{ad}_y = 0$ on A_0, and so it suffices to consider the sum over $\alpha \in \Phi_B$. By construction, ad_x and ad_y correspond to multiplication by $\alpha(x)$ and $\alpha(y)$ on A_α. If $\alpha \in \Phi_B$, then the dimension of A_α is equal to one, as in Section 17.7. This implies (17.11.5).

If $\lambda, \mu \in B'$, then we get that

$$b'_A(\lambda, \mu) = b_A(t_\lambda, t_\mu) = \sum_{\alpha \in \Phi_B} \alpha(t_\lambda)\, \alpha(t_\mu). \tag{17.11.6}$$

It follows that

$$b'_A(\lambda, \mu) = \sum_{\alpha \in \Phi_B} b'_A(\lambda, \alpha)\, b'_A(\mu, \alpha), \tag{17.11.7}$$

by (17.11.4). In particular,

$$b'_A(\lambda, \lambda) = \sum_{\alpha \in \Phi_B} b'_A(\lambda, \alpha)^2. \tag{17.11.8}$$

Suppose that $\beta \in \Phi$, so that $b'_A(\beta, \beta) \neq 0$, as in (17.10.6). Using (17.11.8) with $\lambda = \beta$ and multipliying both sides by $1/b'_A(\beta, \beta)^2$, we get that

$$1/b'_A(\beta, \beta) = \sum_{\alpha \in \Phi_B} b'_A(\beta, \alpha)^2 / b'_A(\beta, \beta)^2. \tag{17.11.9}$$

If $\alpha \in \Phi_B$, then

$$2\, b'_A(\beta, \alpha)/b'_A(\beta, \beta) \tag{17.11.10}$$

corresponds to an integer under the standard embedding of $\mathbf{Q}$ into k, as mentioned in the previous section. This implies that the right side of (17.11.9) corresponds to a rational number. Thus $b'_A(\beta, \beta)$ corresponds to a rational number. It follows that

$$b'_A(\beta, \alpha) \tag{17.11.11}$$

corresponds to a rational number as well when $\alpha \in \Phi_B$, because (17.11.10) corresponds to an integer. This corresponds to some of the remarks near the top of p40 of [14].

17.12 Vector spaces over Q

Let us return for the moment to the situation considered in Section 17.10. We may consider the dual B' of B as a vector space over the rational numbers, using the standard embedding of $\mathbf{Q}$ into k. Let $E_{\mathbf{Q}}$ be the linear subspace of B', as a vector space over $\mathbf{Q}$, spanned by Φ_B. Equivalently, $E_{\mathbf{Q}}$ consists of linear combinations of elements of Φ_B whose coefficients in k correspond to rational numbers. If $\alpha_1, \ldots, \alpha_n$ are elements of Φ_B that form a basis for B' as a vector space over k, then $\alpha_1, \ldots, \alpha_n$ forms a basis for $E_{\mathbf{Q}}$ as a vector space over $\mathbf{Q}$, as in Section 17.10. Of course, linear independence over k automatically implies linear independence over $\mathbf{Q}$. In particular, the dimension of $E_{\mathbf{Q}}$ as a vector space over $\mathbf{Q}$ is the same as the dimension of B' as a vector space over k, which is equal to the dimension of B as a vector space over k.

Suppose now that we are in the more particular situation considered in the previous section. If $\alpha, \beta \in \Phi_B$, then $b'_A(\alpha, \beta)$ corresponds to a rational number with respect to the standard embedding of $\mathbf{Q}$ into k, as before. It follows that $b'_A(\alpha, \beta)$ corresponds to a rational number when $\alpha, \beta \in E_{\mathbf{Q}}$. Let $(\alpha, \beta)_{E_{\mathbf{Q}}}$ be the rational number that corresponds to $b'_A(\alpha, \beta)$ when $\alpha, \beta \in E_{\mathbf{Q}}$. This defines a bilinear form on $E_{\mathbf{Q}}$, as a vector space over $\mathbf{Q}$. If $\lambda, \mu \in E_{\mathbf{Q}}$, then

$$(\lambda, \mu)_{E_{\mathbf{Q}}} = \sum_{\alpha \in \Phi_B} (\lambda, \alpha)_{E_{\mathbf{Q}}} (\mu, \alpha)_{E_{\mathbf{Q}}}, \tag{17.12.1}$$

as in (17.11.7).

It follows that

$$(\lambda, \lambda)_{E_{\mathbf{Q}}} = \sum_{\alpha \in \Phi_B} (\lambda, \alpha)^2_{E_{\mathbf{Q}}} \tag{17.12.2}$$

for every $\lambda \in E_{\mathbf{Q}}$. This implies that

$$(\lambda, \lambda)_{E_{\mathbf{Q}}} \geq 0 \tag{17.12.3}$$

for every $\lambda \in E_{\mathbf{Q}}$. More precisely, $(\lambda, \lambda)_{E_{\mathbf{Q}}} = 0$ if and only if

$$(\lambda, \alpha)_{E_{\mathbf{Q}}} = 0 \quad \text{for every } \alpha \in \Phi_B. \tag{17.12.4}$$

Let us check that this can only happen when $\lambda = 0$.

Of course, (17.12.4) is the same as saying that

$$b'_A(\lambda, \alpha) = 0 \tag{17.12.5}$$

for every $\alpha \in \Phi_B$. This implies that (17.12.5) holds for every $\alpha \in B'$, because the linear span of Φ_B in B', as a vector space over k, is equal to B'. It follows that $\lambda = 0$, because b'_A is nondegenerate on B'. This corresponds to some more of the remarks near the top of p40 in [14].

17.13 Vector spaces over R

Let us return again for the moment to the situation considered in Section 17.10, and the beginning of the previous section. Thus $E_{\mathbf{Q}}$ is the linear subspace of B', as a vector space over $\mathbf{Q}$, spanned by Φ_B. Let n be the dimension of B and B' as vector spaces over k, which is the same as the dimension of $E_{\mathbf{Q}}$ as a vector space over $\mathbf{Q}$. Using any basis for $E_{\mathbf{Q}}$, we get that $E_{\mathbf{Q}}$ is isomorphic to $\mathbf{Q}^n$, as a vector space over $\mathbf{Q}$. We can get a vector space $E_{\mathbf{R}}$ over the real numbers with the same basis, using formal linear combinations with coefficients in $\mathbf{R}$. This amounts to taking $\mathbf{R}^n$ as a vector space over $\mathbf{R}$ that contains $\mathbf{Q}^n$. This does not depend on the choice of basis for $E_{\mathbf{Q}}$, up to suitable equivalence. In particular, $E_{\mathbf{Q}}$ corresponds to a subset of $E_{\mathbf{R}}$.

Suppose now, for the rest of the section, that we are in the more particular situation considered in Section 17.11 again, and as in the previous section. Thus $(\alpha, \beta)_{E_{\mathbf{Q}}}$ is defined as a bilinear form on $E_{\mathbf{Q}}$, as a vector space over $\mathbf{Q}$, as before.

This has a natural extension to a bilinear form $(\alpha, \beta)_{E_{\mathbf{R}}}$ on $E_{\mathbf{R}}$, as a vector space over $\mathbf{R}$. If $\lambda, \mu \in E_{\mathbf{R}}$, then

$$(\lambda, \mu)_{E_{\mathbf{R}}} = \sum_{\alpha \in \Phi_B} (\lambda, \alpha)_{E_{\mathbf{R}}} \, (\mu, \alpha)_{E_{\mathbf{R}}}, \tag{17.13.1}$$

as in (17.12.1). This implies that

$$(\lambda, \lambda)_{E_{\mathbf{R}}} = \sum_{\alpha \in \Phi_B} (\lambda, \alpha)_{E_{\mathbf{R}}}^2 \geq 0 \tag{17.13.2}$$

for every $\lambda \in E_{\mathbf{R}}$.

Let us verify that $\lambda \in E_{\mathbf{R}}$ satisfies $(\lambda, \lambda)_{E_{\mathbf{R}}} = 0$ only when $\lambda = 0$, so that $(\cdot, \cdot)_{E_{\mathbf{R}}}$ defines an inner product on $E_{\mathbf{R}}$. One way to do this is to use an orthogonal basis for $E_{\mathbf{Q}}$ with respect to $(\cdot, \cdot)_{E_{\mathbf{Q}}}$, which is an orthogonal basis for $E_{\mathbf{R}}$ with respect to $(\cdot, \cdot)_{E_{\mathbf{R}}}$ as well. If $\lambda \in E_{\mathbf{R}}$ and $\lambda \neq 0$, then one can get that $(\lambda, \lambda)_{E_{\mathbf{R}}} > 0$ from the analogous condition for the basis vectors in $E_{\mathbf{Q}}$.

Alternatively, let $\alpha_1, \ldots, \alpha_n$ be elements of Φ_B that form a basis for B' as a vector space over k, so that $\alpha_1, \ldots, \alpha_n$ forms a basis for $E_{\mathbf{Q}}$ as a vector space over $\mathbf{Q}$ too, as before. If $\mu \in E_{\mathbf{Q}}$ satisfies

$$(\mu, \alpha_j)_{E_{\mathbf{Q}}} = 0 \tag{17.13.3}$$

for each $j = 1, \ldots, n$, then

$$b'_A(\mu, \alpha_j) = 0 \tag{17.13.4}$$

for every $j = 1, \ldots, n$. This implies that

$$b'_A(\mu, \alpha) = 0 \tag{17.13.5}$$

for every $\alpha \in B'$, and hence that $\mu = 0$, because b'_A is nondegenerate on B'. Of course,

$$\mu \mapsto (\mu, \alpha_j)_{E_{\mathbf{Q}}} \tag{17.13.6}$$

defines a linear functional on $E_{\mathbf{Q}}$ for each $j = 1, \ldots, n$. Using these linear functionals, we get a mapping from $E_{\mathbf{Q}}$ into $\mathbf{Q}^n$ that is linear over $\mathbf{Q}$. The kernel of this linear mapping is trivial, by the previous remarks. It follows that this linear mapping sends $E_{\mathbf{Q}}$ onto $\mathbf{Q}^n$, because $E_{\mathbf{Q}}$ has dimension n as a vector space over $\mathbf{Q}$.

Similarly,

$$\mu \mapsto (\mu, \alpha_j)_{E_{\mathbf{R}}} \tag{17.13.7}$$

is a linear functional on $E_{\mathbf{R}}$ for each $j = 1, \ldots, n$. Using these linear functionals, we get a mapping from $E_{\mathbf{R}}$ into $\mathbf{R}^n$ that is linear over $\mathbf{R}$. The image of this linear mapping contains $\mathbf{Q}^n$, as in the preceding paragraph. This implies that this linear mapping sends $E_{\mathbf{R}}$ onto $\mathbf{R}^n$, because the image is a linear subspace of $\mathbf{R}^n$, as a vector space over $\mathbf{R}$. It follows that this linear mapping is injective, because $E_{\mathbf{R}}$ has dimension n, as a vector space over $\mathbf{R}$. Thus, if $\lambda \in E_{\mathbf{R}}$ satisfies

$$(\lambda, \alpha_j)_{E_{\mathbf{R}}} = 0 \tag{17.13.8}$$

for every $j = 1, \ldots, n$, then $\lambda = 0$. If $(\lambda, \lambda)_{E_{\mathbf{R}}} = 0$, then (17.13.8) holds for each $j = 1, \ldots, n$, by (17.13.2), so that $\lambda = 0$. This corresponds to some of the remarks near the top of p40 of [14] again.

17.14 Normalizers and centralizers

Let k be a commutative ring with a multiplicative identity element, and let $(A, [\cdot, \cdot]_A)$ be a Lie algebra over k. Also let B be a Lie subalgebra of A. Remember that the centralizer $C_A(B)$ of B in A consists of the $x \in A$ such that $[x, w]_A = 0$ for every $w \in B$, as in Section 7.6. The normalizer $N_A(B)$ of B in A is the set of $x \in A$ such that $[x, w]_A \in B$ for every $w \in B$, as in Section 9.8. Thus

$$B \subseteq N_A(B), \tag{17.14.1}$$

because B is a Lie subalgebra of A. Note that

$$C_A(B) \subseteq N_A(B). \tag{17.14.2}$$

Both $C_A(B)$ and $N_A(B)$ are Lie subalgebras of A, as before. Of course, if B is commutative as a Lie algebra over k, then $B \subseteq C_A(B)$.

Suppose from now on in this section that k is a field, and that A is a finite-dimensional Lie algebra over k. Let B be a Lie subalgebra of A such that every element of B is ad-diagonalizable as an element of A. Thus B is commutative as a Lie algebra over k, as in Section 17.1. Let B' be the dual of B, as a vector space over k, and for each $\alpha \in B'$, let A_α be the set of $x \in A$ such that $\mathrm{ad}_w(x) = [w, x]_A = \alpha(w)\, x$ for every $w \in B$, as usual. If $\alpha = 0$, then this is the same as $C_A(B)$, as before.

In particular, $B \subseteq C_A(B) = A_0$. Let us suppose that $B \neq \{0\}$, to avoid trivialities, so that $A_0 \neq \{0\}$. Let Φ_B be the set of $\alpha \in B'$ such that $\alpha \neq 0$ and $A_\alpha \neq \{0\}$ again. Remember that A corresponds to the direct sum of A_α, $\alpha \in \Phi_B \cup \{0\}$, as a vector space over k, as in Section 17.2.

Let us check that

$$A_0 = N_A(B) \tag{17.14.3}$$

under these conditions. Of course, $A_0 \subseteq N_A(B)$, as in (17.14.2). Let $x \in A$ be given, so that x can be expressed in a unique way as

$$x = \sum_{\alpha \in \Phi_B \cup \{0\}} x_\alpha, \tag{17.14.4}$$

where $x_\alpha \in A_\alpha$ for each $\alpha \in \Phi_B \cup \{0\}$. If $w \in B$, then

$$[w, x]_A = \sum_{\alpha \in \Phi_B \cup \{0\}} [w, x_\alpha]_A = \sum_{\alpha \in \Phi_B} \alpha(w)\, x_\alpha. \tag{17.14.5}$$

This is in B, or even A_0, only when it is equal to 0. If this happens for every $w \in B$, then it follows that $x \in A_0 = C_A(B)$. Equivalently, this means that $x_\alpha = 0$ for every $\alpha \in \Phi_B$. This shows that $N_A(B) \subseteq A_0$, so that (17.14.3) holds.

If $C_A(B) = B$, then we get that $N_A(B) = B$. This corresponds to Exercise 5 on p40 of [14].

17.15 Semisimplicity and diagonalizability

Let k be a field, and let $(A, [\cdot,\cdot]_A)$ be a Lie algebra over k with positive finite dimension, as a vector space over k. Also let B be a Lie subalgebra of A such that every element of B is ad-diagonalizable as an element of A. Thus B is commutative as a Lie algebra over k, as in Section 17.1. Let B' be the dual of B, as a vector space over k, and for each $\alpha \in B'$, let A_α be the set of $x \in A$ such that $\mathrm{ad}_w(x) = [w, x]_A = \alpha(w)\, x$ for every $w \in B$, as before. Remember that A_0 is the same as the centralizer $C_A(B)$ of B in A, which contains B, because B is commutative as a Lie algebra.

Suppose that

$$B = C_A(B) = A_0. \tag{17.15.1}$$

This implies that $B \neq \{0\}$, because $A \neq \{0\}$, by hypothesis. Let Φ_B be the set of $\alpha \in B'$ such that $\alpha \neq 0$ and $A_\alpha \neq \{0\}$ again, so that A corresponds to the direct sum of A_α, $\alpha \in \Phi_B \cup \{0\}$, as a vector space over k, as in Section 17.2. Note that the center $Z(A)$ of A as a Lie algebra is contained in A_0. Let us suppose also that

$$Z(A) = \{0\}. \tag{17.15.2}$$

Suppose in addition that for each $\alpha \in \Phi_B$ and $x_\alpha \in A_\alpha$ with $x_\alpha \neq 0$ there is a $y_\alpha \in A_{-\alpha}$ with the following property. Put

$$z_\alpha = [x_\alpha, y_\alpha]_A, \tag{17.15.3}$$

so that $z_\alpha \in A_0$, as in Section 17.2. This means that $z_\alpha \in B$, by (17.15.1), and we ask that

$$\alpha(z_\alpha) \neq 0. \tag{17.15.4}$$

We have seen that this holds under some additional conditions, as in Section 17.6.

We would like to show that A is semisimple as a Lie algebra over k in this situation. This corresponds to Step (13) on p100 of [14], and to (k) on p55 of [24]. Let C be an ideal in A such that C is commutative as a Lie algebra. It suffices to show that $C = \{0\}$, as in Section 9.4.

If $w \in B$, then ad_w maps C into itself, because C is an ideal in A. The restriction of ad_w to C is diagonalizable, as in Section 10.6, because ad_w is diagonalizable on A, by hypothesis. Remember that the mappings ad_w, with $w \in B$, commute on A, because B is commutative as a Lie algebra, as in Section 17.2. This implies that the linear mappings ad_w, $w \in B$, are simultaneously diagonalizable on C, as before. If $C \neq \{0\}$, then it follows that C is spanned by its intersections with the subspaces A_α, with $\alpha \in \Phi_B \cup \{0\}$.

Suppose for the sake of a contradiction that there is an $\alpha \in \Phi_B$ such that $A_\alpha \cap C \neq \{0\}$. Let x_α be a nonzero element of $A_\alpha \cap C$, and let $y_\alpha \in A_{-\alpha}$ and $z_\alpha \in B$ be as before. Observe that $z_\alpha \in C$, because of (17.15.3) and the hypothesis that C be an ideal in A. Remember that

$$[z_\alpha, y_\alpha]_A = -\alpha(z_\alpha)\, y_\alpha, \tag{17.15.5}$$

because $y_\alpha \in A_{-\alpha}$ and $z_\alpha \in B$. This implies that $y_\alpha \in C$ too, because of (17.15.4). It follows that $z_\alpha = 0$, by (17.15.3) and the commutativity of C as a Lie algebra. This contradicts (17.15.4), as desired.

This shows that $A_\alpha \cap C = \{0\}$ for every $\alpha \in \Phi_B$, so that

$$C \subseteq A_0 = B. \tag{17.15.6}$$

Let $\alpha \in \Phi_B$ and $x_\alpha \in A_\alpha$ be given, so that

$$[w, x_\alpha]_A = \alpha(w)\, x_\alpha \tag{17.15.7}$$

for every $w \in B$. If $w \in C$, then $[w, x_\alpha]_A \in C$, because C is an ideal in A. Combining this with (17.15.7), we get that

$$[w, x_\alpha]_A = 0, \tag{17.15.8}$$

because $A_0 \cap A_\alpha = \{0\}$ when $\alpha \neq 0$. If $x_0 \in A_0$, then $[w, x_0]_A = 0$ for every $w \in B$, and hence every $w \in C$, by (17.15.6). This implies that C is contained in the center of A, because A is spanned by A_α, $\alpha \in \Phi_B \cup \{0\}$. It follows that $C = \{0\}$, by (17.15.2), as desired.

Chapter 18

Cartan subalgebras

18.1 Subspaces related to ad_x

Let k be a field, and let $(A, [\cdot,\cdot]_A)$ be a Lie algebra over k. Also let $x \in A$ be given, so that $\mathrm{ad}_x(w) = [x, w]_A$ defines a linear mapping from A into itself, as usual. If $\alpha \in k$, then put

$$A_{x,\alpha} = \{y \in A : (\mathrm{ad}_x - \alpha\, I)^l(y) = 0 \text{ for some } l \in \mathbf{Z}_+\}, \tag{18.1.1}$$

where I is the identity mapping on A. This is a linear subspace of A, as in Section 10.7. Note that $A_{x,\alpha} \neq \{0\}$ if and only if α is an eigenvalue of ad_x on A, as before.

Let $y, z \in A$ and $\alpha, \beta \in k$ be given. Remember that ad_x is a derivation on A, as in Section 2.5. It follows that

$$\begin{aligned}(\mathrm{ad}_x - (\alpha+\beta)\, I)([y,z]_A) &= [\mathrm{ad}_x(y), z]_A + [y, \mathrm{ad}_x(z)]_A - \alpha\,[y,z]_A - \beta\,[y,z]_A \\ &= [(\mathrm{ad}_x - \alpha\, I)(y), z]_A + [y, (\mathrm{ad}_x - \beta\, I)(z)]_A,\end{aligned} \tag{18.1.2}$$

as in Section 10.9. If $y \in A_{x,\alpha}$ and $z \in A_{x,\beta}$, then one can use this repeatedly to get that

$$(\mathrm{ad}_x - (\alpha+\beta)\, I)^j([y,z]_A) = 0 \tag{18.1.3}$$

when j is sufficiently large. This means that

$$[y,z]_A \in A_{x,\alpha+\beta}, \tag{18.1.4}$$

as in Section 10.9. In particular, $A_{x,0}$ is a Lie subalgebra of A. This corresponds to the first two assertions in the lemma at the bottom of p78 of [14], and to parts (b) and (c) of Proposition 2 on p11 of [24].

Let $\alpha_1 \ldots, \alpha_n \in k$ be finitely many distinct eigenvalues of ad_x, and suppose that $y_j \in A_{x,\alpha_j}$ for each $j = 1, \ldots, n$. If $\sum_{j=1}^n y_j = 0$, then $y_j = 0$ for each $j = 1, \ldots, n$, as in Section 10.7.

Suppose from now on in this section that k is algebraically closed, and that A has positive finite dimension as a vector space over k. In this case, A corresponds to the direct sum of the subspaces $A_{x,\alpha}$ with $\alpha \in k$ an eigenvalue of ad_x, as a vector space over k. This is part (a) of Proposition 2 on p11 of [24], when $k = \mathbf{C}$, and is mentioned on p78 of [14].

Suppose that k has characteristic 0. If $y \in A_{x,\alpha}$ for some $\alpha \in k$ with $\alpha \neq 0$, then one can check that y is ad-nilpotent as an element of A, using (18.1.4) and the fact that there are only finitely many eigenvalues of ad_x on A. This is the third assertion of the lemma on p78 of [14].

18.2 Some remarks about characteristic polynomials

Let k be a field, and let V be a vector space over k of positive finite dimension. Also let a be a linear mapping from V into itself, and let T be an indeterminate. As usual, the characteristic polynomial of a is defined as a formal polynomial in T with coefficients in k by

$$p_a(T) = \det(a - T\,I), \tag{18.2.1}$$

where I is the identity mapping on V. More precisely, one can choose a basis for V, so that a corresponds to a matrix with entries in k, and $a - T\,I$ corresponds to a matrix with entries in the algebra $k[T]$ of formal polynomials in T with coefficients in k. The determinant of this matrix is an element of $k[T]$, which does not depend on the choice of basis for V.

Let V_0 be a proper nontrivial linear subspace of V, and suppose that

$$a(V_0) \subseteq V_0. \tag{18.2.2}$$

Let V_1 be the quotient space V/V_0, so that a induces a linear mapping a_1 from V_1 into itself. If a_0 is the restriction of a to V_0, then

$$p_a(T) = p_{a_0}(T)\,p_{a_1}(T), \tag{18.2.3}$$

where $p_{a_0}(T)$, $p_{a_1}(T)$ are the characteristic polynomials of a_0, a_1 as linear mappings on V_0, V_1, respectively. This can be seen using a basis for V that contains a basis for V_0. The basis vectors not in V_0 can be mapped into V_1 by the canonical quotient mapping, to get a basis for V_1.

Remember that

$$V_0 = \{v \in V : a^l(v) = 0 \text{ for some } l \in \mathbf{Z}_+\} \tag{18.2.4}$$

is a linear subspace of V, as in Section 10.7. Clearly V_0 satisfies (18.2.2). If $v \in V$ and $a(v) \in V_0$, then it is easy to see that $v \in V_0$ too. This implies that the kernel of the induced mapping a_1 on $V_1 = V/V_0$ is trivial. Note that $V_0 \neq \{0\}$ exactly when 0 is an eigenvalue of a on V, as in Section 10.7.

Let n_0 be the dimension of V_0, as a vector space over k. If $n_0 \geq 1$, then it is well known that

$$p_{a_0}(T) = (-1)^{n_0}\,T^{n_0}. \tag{18.2.5}$$

Suppose for the moment that $V_0 \neq V$, so that $V_1 \neq \{0\}$. Of course, the constant term in $p_{a_1}(T)$ is the same as the determinant of a_1 on V. This is a nonzero element of k, because a_1 is invertible on V_1, as in the preceding paragraph.

If $V_0 = V$, then $p_a(T) = p_{a_0}(T)$ is as in (18.2.5). If $V_0 = \{0\}$, then 0 is not an eigenvalue of a on V, and the constant term in $p_a(T)$ is nonzero.

18.3 Characteristic polynomials and ad_x

Let k be a field, and let $(A, [\cdot,\cdot]_A)$ be a Lie algebra over k, with positive finite dimension n as a vector space over k. Also let T be an indeterminate, so that the characteristic polynomial of a linear mapping from A into itself is defined as a formal polynomial in T with coefficients in k, as in the previous section. If $x \in A$, then let

$$Q_x(T) = \det(\mathrm{ad}_x - T\,I) \tag{18.3.1}$$

be the characteristic polynomial of ad_x, as a linear mapping from A into itself. This is the same as $(-1)^n$ times the polynomial $P_x(T)$ defined on p10 of [24].

Using a basis for A, we can identify A with the space k^n of n-tuples of elements of k, as a vector space over k. Of course, ad_x depends linearly on x, and can be expressed in terms of the coordinates of x and the corresponding structure constants for the Lie bracket on A. Similarly, (18.3.1) can be expressed as

$$Q_x(T) = \sum_{j=0}^{n} q_j(x)\,T^j, \tag{18.3.2}$$

where $q_j(x)$ corresponds to a homogeneous polynomial of degree $n - j$ in the coordinates of x for each $j = 0, 1, \ldots, n$, as on p11 of [24]. More precisely, the coefficients for q_j can be given in terms of the structure constants for the Lie bracket on A. By construction, $q_n(x)$ corresponds to the constant polynomial $(-1)^n$.

Suppose for the moment that A is nilpotent as a Lie algebra over k. In this case, we can choose a basis for A such that ad_x is always corresponds to a strictly upper-triangular matrix. This implies that the coefficients of $q_j(x)$ are all equal to 0 when $j < n$.

Let $x \in A$ be given, and let $A_{x,0}$ be as in (18.1.1). This is the same as (18.2.4), with $V = A$ and $a = \mathrm{ad}_x$. Let $n_0(x)$ be the dimension of $A_{x,0}$. Note that $x \in A_{x,0}$, and that $A_{x,0} = A$ when $x = 0$, so that $n_0(x) \geq 1$. We also have that

$$q_j(x) = 0 \quad \text{when } j < n_0(x), \tag{18.3.3}$$

and

$$q_{n_0(x)}(x) \neq 0, \tag{18.3.4}$$

as in the previous section.

Of course, $n_0(x) = n$ exactly when ad_x is nilpotent on A. If this happens for every $x \in A$, then A is nilpotent as a Lie algebra, as in Section 9.10. These remarks correspond to some of those on p11 in [24].

18.4 Engel subalgebras

Let k be a field, and let $(A, [\cdot,\cdot]_A)$ be a Lie algebra over k. If $x \in A$, then

$$A_{x,0} = \{y \in A : (\mathrm{ad}_x)^l(y) = 0 \text{ for some } l \in \mathbf{Z}_+\} \tag{18.4.1}$$

is a Lie subalgebra of A, as in Section 18.1. A Lie subalgebra of A of this form is called an *Engel subalgebra*, following Barnes, as on p79 of [14].

Let us suppose from now on in this section that A has positive finite dimension n as a vector space over k, and that the number of elements of k is strictly larger than n, as in Exercise 5 on p81 of [14]. Let C be a Lie subalgebra of A, and let z be an element of C such that $A_{z,0}$ is minimal with respect to inclusion among the $A_{x,0}$'s with $x \in C$. Of course, it suffices to choose $z \in C$ so that the dimension of $A_{z,0}$, as a vector space over k, is minimal. If

$$C \subseteq A_{z,0}, \tag{18.4.2}$$

then

$$A_{z,0} \subseteq A_{x,0} \tag{18.4.3}$$

for every $x \in C$. This is Lemma A on p79 of [14].

We may as well suppose that $A_{z,0} \neq \{0\}$, since otherwise (18.4.3) is trivial. We may as well suppose too that $A_{z,0} \neq A$, because (18.4.3) would follow from the minimality of $A_{z,0}$ otherwise. Let r be the dimension of $A_{z,0}$ as a vector space over k, so that $1 \le r < n$.

Let $x \in C$ and $c \in k$ be given, and observe that

$$z + c\,x \in C. \tag{18.4.4}$$

Thus $z + c\,x \in A_{z,0}$, by (18.4.2). This implies that $\mathrm{ad}_{z+c\,x}$ maps $A_{z,0}$ into itself, because $A_{z,0}$ is a Lie subalgebra of A. The quotient $A/A_{z,0}$ is defined as a vector space over k, and $\mathrm{ad}_{z+c\,x}$ induces a mapping from $A/A_{z,0}$ into itself in the usual way.

Note that $A_{z,0}$ corresponds to (18.2.4) with $V = A$ and $a = \mathrm{ad}_z$. Thus the mapping from $A/A_{z,0}$ into itself induced by ad_z is injective, as before.

Let T be an indeterminate, and let $h(T, c)$ be the characteristic polynomial of $\mathrm{ad}_{z+c\,x}$ on A. As in Section 18.2, this can be expressed as

$$h(T, c) = f(T, c)\,g(T, c), \tag{18.4.5}$$

where $f(T, c)$ is the characteristic polynomial of the restriction of $\mathrm{ad}_{z+c\,x}$ to $A_{z,0}$, and $g(T, c)$ is the characteristic polynomial of the linear mapping from $A/A_{z,0}$ into itself induced by $\mathrm{ad}_{z+c\,x}$. These polynomials can be expressed as

$$f(T, c) = (-1)^r\,T^r + f_1(c)\,T^{r-1} + \cdots + f_r(c) \tag{18.4.6}$$

and

$$g(T, c) = (-1)^{n-r}\,T^{n-r} + g_1(c)\,T^{n-r-1} + \cdots + g_{n-r}(c), \tag{18.4.7}$$

as on p79 of [14]. More precisely, $f_j(c)$ and $g_j(c)$ can be given by polynomials with coefficients in k, of degree less than or equal to j.

Observe that $g_{n-r}(0) \neq 0$, because the mapping induced on $A/A_{z,0}$ by ad_z is invertible. In particular, $g_{n-r} \not\equiv 0$ on k, so that g_{n-r} has at most $n-r$ zeros in k. Remember that k has at least $n+1$ elements, by hypothesis. It follows that there are $r+1$ distinct elements $c_1, \ldots, c_{r+1}$ of k such that

$$g_{n-r}(c_l) \neq 0 \tag{18.4.8}$$

for each $l = 1, \ldots, r+1$.

By construction, $g_{n-r}(c)$ is the determinant of the linear mapping from $A/A_{z,0}$ into itself induced by $\mathrm{ad}_{z+c\,x}$. Suppose for the moment that $c \in k$ has the property that $g_{n-r}(c) \neq 0$, so that the mapping from $A/A_{z,0}$ into itself induced by $\mathrm{ad}_{z+c\,x}$ is injective. Of course, this implies that all positive powers of this mapping are injective. Remember that the positive powers of the mapping from $A/A_{z,0}$ induced by $\mathrm{ad}_{z+c\,x}$ correspond to the mappings from $A/A_{z,0}$ into itself induced by the positive powers of $\mathrm{ad}_{z+c\,x}$. It follows that the kernels of the positive powers of $\mathrm{ad}_{z+c\,x}$ on A are contained $A_{z,0}$. This implies that

$$A_{z+c\,x,0} \subseteq A_{z,0}. \tag{18.4.9}$$

Under these conditions, we get that

$$A_{z+c\,x,0} = A_{z,0}, \tag{18.4.10}$$

because of the minimality condiiton on $A_{z,0}$.

As before, $A_{z+c\,x,0}$ corresponds to (18.2.4) with $V = A$ and $a = \mathrm{ad}_{z+c\,x}$. If (18.4.10) holds, then the characteristic polynomial $f(T,c)$ of the restriction of $\mathrm{ad}_{z+c\,x}$ to (18.4.10) is equal to $(-1)^r\,T^r$. This means that

$$f_j(c) = 0 \tag{18.4.11}$$

for each $j = 1, \ldots, r$. In particular, this holds for $r+1$ distinct elements of k, as in (18.4.8). This implies that

$$f_j \equiv 0 \tag{18.4.12}$$

on k for each $j = 1, \ldots, r$, because f_j is given by a polynomial of degree less than or equal to j.

Equivalently,

$$f(T,c) = (-1)^r\,T^r \tag{18.4.13}$$

for every $c \in k$. Let $c \in k$ be given again, and consider

$$A_{z+c\,x,0} \cap A_{z,0}, \tag{18.4.14}$$

which is a linear subspace of $A_{z,0}$. If $V = A_{z,0}$ and $a = \mathrm{ad}_{z+c\,x}$, then (18.4.14) corresponds to (18.2.4). Using (18.4.13), we get that (18.4.14) is the same as $A_{z,0}$, as in Section 18.2. This means that

$$A_{z,0} \subseteq A_{z+c\,x,0} \tag{18.4.15}$$

for every $c \in k$.

Remember that this holds for every $x \in C$. Thus we can replace x with $x - z$ and take $c = 1$ to get (18.4.3), as desired.

18.5 Self-normalizing subalgebras

Let k be a field again, and let $(A, [\cdot, \cdot])$ be a Lie algebra over k. Also let C be a Lie subalgebra of A, and remember that the normalizer $N_A(C)$ of C in A is the set of $w \in A$ such that $[w, z]_A \in C$ for every $z \in C$. This is the largest Lie subalgebra of A that contains C as an ideal, as in Section 9.8. If $N_A(C) = C$, then C is said to be self-normalizing in A, as before.

Let $x \in A$ be given, and let $A_{x,0}$ be the set of $y \in A$ such that $(\mathrm{ad}_x)^l(y) = 0$ for some positive integer l, as before. This is a Lie subalgebra of A, as in Section 18.1. Equivalently, if $V = A$ and $a = \mathrm{ad}_x$, then $A_{x,0}$ is the same as (18.2.4). Remember that the mapping from $A/A_{x,0}$ into itself induced by ad_x is injective, as in Section 18.2.

Let w be an element of the normalizer $N_A(A_{x,0})$ of $A_{x,0}$ in A. Note that $x \in A_{x,0}$, so that

(18.5.1) $$[w, x]_A \in A_{x,0}.$$

This means that $(\mathrm{ad}_x)^l([w, x]_A) = 0$ for some positive integer l, and hence $(\mathrm{ad}_x)^{l+1}(w) = 0$. It follows that $w \in A_{x,0}$, so that

(18.5.2) $$N_A(A_{x,0}) = A_{x,0}.$$

This corresponds to the last part of the proof of Theorem 1 on p12 of [24].

Suppose from now on in this section that the dimension of A is finite, as a vector space over k. Thus the dimension of the quotient space $A/A_{x,0}$ is finite too. It follows that the mapping on $A/A_{x,0}$ induced by ad_x is invertible, because it is injective, as before.

Suppose that C is a Lie subalgebra of A with

(18.5.3) $$A_{x,0} \subseteq C.$$

In particular, $x \in C$, because $x \in A_{x,0}$. Thus ad_x maps C into itself, so that the mapping on $A/A_{x,0}$ induced by ad_x maps $C/A_{x,0}$ into itself. More precisely, the mapping induced on $A/A_{x,0}$ maps $C/A_{x,0}$ onto itself, because this mapping is injective, and the dimension of $C/A_{x,0}$ is finite.

The normalizer $N_A(C)$ of C in A is mapped into C by ad_x, because $x \in C$. This implies that the mapping induced on $A/A_{x,0}$ by ad_x maps $N_A(C)/A_{x,0}$ into $C/A_{x,0}$. It follows that

(18.5.4) $$N_A(C)/A_{x,0} = C/A_{x,0},$$

because the mapping induced on $A/A_{x,0}$ by ad_x is injective and maps $C/A_{x,0}$ onto itself.

This means that

$$N_A(C) = C, \tag{18.5.5}$$

because of (18.5.3) and the fact that $C \subseteq N_A(C)$. This corresponds to Lemma B on p79 of [14].

18.6 Orthogonality conditions

Let k be a field, and let $(A, [\cdot,\cdot]_A)$ be a Lie algebra over k. Also let $b(\cdot,\cdot)$ be a bilinear form on A that is associative, or equivalently invariant under the adjoint representation. This means that

$$b([w, y]_A, z) = -b(y, [w, z]_A) \tag{18.6.1}$$

for every $w, y, z \in A$, as in Sections 6.10 and 7.7. Let $x \in A$ be given, so that

$$b(\mathrm{ad}_x(y), z) + b(y, \mathrm{ad}_x(z)) = 0 \tag{18.6.2}$$

for every $y, z \in A$. If $\alpha, \beta \in k$, then we get that

$$b((\mathrm{ad}_x - \alpha\, I)(y), z) + b(y, (\mathrm{ad}_x - \beta\, I)(z)) = -(\alpha + \beta)\, b(y, z) \tag{18.6.3}$$

for every $y, z \in A$.

Let l be a positive integer, and consider

$$(-1)^l\, (\alpha + \beta)^l\, b(y, z). \tag{18.6.4}$$

If l_1 and l_2 are nonnegative integers, then consider

$$b((\mathrm{ad}_x - \alpha\, I)^{l_1}(y), (\mathrm{ad}_x - \beta\, I)^{l_2}(z)). \tag{18.6.5}$$

If l_1 or l_2 is equal to 0, then $(\mathrm{ad}_x - \alpha\, I)^{l_1}$ or $(\mathrm{ad}_x - \beta\, I)^{l_2}$ is interpreted as being the identity operator on A, as appropriate. We can express (18.6.4) as a sum of terms of the form (18.6.5), using (18.6.3) repeatedly. More precisely, we have that

$$l_1 + l_2 = l \tag{18.6.6}$$

in each of the terms of the form (18.6.5).

Remember that $A_{x,\alpha}$ consists of the $y \in A$ such that $(\mathrm{ad}_x - \alpha\, I)^j(y) = 0$ for all sufficiently large positive integers j, as in Section 18.1, and similarly for β. If $y \in A_{x,\alpha}$ and $z \in A_{x,\beta}$, then (18.6.5) is equal to 0 when l_1 or l_2 is sufficiently large. This implies that

$$(\alpha + \beta)^l\, b(y, z) = 0 \tag{18.6.7}$$

when l is sufficiently large. It follows that

$$b(y, z) = 0 \tag{18.6.8}$$

when $\alpha + \beta \neq 0$. This corresponds to a remark in the proof of part (d) of Theorem 3 on p15 of [24].

Remember that $A_{x,\alpha} \neq \{0\}$ exactly when $\alpha \in k$ is an eigenvalue of ad_x on A. Suppose now that k is algebraically closed, and that A has positive finite dimension as a vector space over k. In this case, A corresponds to the direct sum of the nonzero subspaces $A_{x,\alpha}$, as a vector space over k.

Suppose that $b(\cdot,\cdot)$ is also nondegenerate on A. Under these conditions, it is easy to see that the restriction of $b(\cdot,\cdot)$ to $A_{x,0}$ is nondegenerate, using (18.6.8). This corresponds to part (d) of Theorem 3 on p15 of [24].

18.7 Nilpotence and normalizing elements

Let k be a field, and let $(A, [\cdot,\cdot]_A)$ be a finite-dimensional Lie algebra over k. Also let C_1, C_2 be Lie subalgebras of A, with

$$C_1 \subseteq C_2. \tag{18.7.1}$$

Thus the quotient C_2/C_1 is defined as a vector space over k, and we let q be the canonical quotient mapping from C_2 onto C_2/C_1.

If $x \in C_1$, then ad_x maps C_1 and C_2 into themselves. This leads to a linear mapping $\mathrm{ad}_x^{C_2/C_1}$ from C_2/C_1 into itself, with

$$\mathrm{ad}_x^{C_2/C_1} \circ q = q \circ \mathrm{ad}_x. \tag{18.7.2}$$

It is easy to see that $x \mapsto \mathrm{ad}_x^{C_2/C_1}$ defines a representation of C_1, as a Lie algebra over k, on C_2/C_1. In particular,

$$\{\mathrm{ad}_x^{C_2/C_1} : x \in C_1\} \tag{18.7.3}$$

is a Lie subalgebra of the Lie algebra $gl(C_2/C_1)$ of linear mappings from C_2/C_1 into itself, with respect to the usual commutator bracket.

Observe that

$$(\mathrm{ad}_x^{C_2/C_1})^l = 0 \tag{18.7.4}$$

for some positive integer l if and only if

$$q \circ (\mathrm{ad}_x)^l = 0. \tag{18.7.5}$$

Equivalently, this means that

$$(\mathrm{ad}_x)^l(C_2) \subseteq C_1. \tag{18.7.6}$$

In this case, if ad_x is nilpotent on C_1, then it follows that ad_x is nilpotent on C_2. Of course, if ad_x is nilpotent on C_2, then $\mathrm{ad}_x^{C_2/C_1}$ is nilpotent on C_2/C_1.

Suppose that $C_1 \neq C_2$, so that $C_2/C_1 \neq \{0\}$, and that $\mathrm{ad}_x^{C_2/C_1}$ is nilpotent on C_2/C_1 for each $x \in C_1$. Under these conditions, there is a nonzero element of C_2/C_1 that is mapped to 0 by $\mathrm{ad}_x^{C_2/C_1}$ for every $x \in C_1$, as in Section 9.9. This means that there is a $y \in C_2$ such that $y \notin C_1$ and

$$\mathrm{ad}_x^{C_2/C_1}(q(y)) = 0 \tag{18.7.7}$$

for every $x \in X_1$, and hence

$$q(\mathrm{ad}_x(y)) = 0 \tag{18.7.8}$$

for every $x \in C_1$. This is the same as saying that

$$\mathrm{ad}_x(y) = [x, y]_A \in C_1 \tag{18.7.9}$$

for every $x \in C_1$. Equivalently, this means that y is an element of the normalizer $N_A(C_1)$ of C_1 in A, as in Section 9.8.

If C_2 is nilpotent as a Lie algebra over k, then ad_x is nilpotent on C_2 for every $x \in C_2$. In particular, this implies that $\mathrm{ad}_x^{C_2/C_1}$ is nilpotent on C_2/C_1 for every $x \in C_1$, as before. If C_1 is a proper Lie subalgebra of C_2, then it follows that C_1 is a proper subset of its normalizer $N_{C_2}(C_1)$ in C_2, as in the preceding paragraph. This corresponds to Exercise 7 on p14 of [14].

18.8 Minimal Engel subalgebras

Let k be a field, and let $(A, [\cdot, \cdot]_A)$ be a Lie algebra over k. A Lie subalgebra C of A is said to be a *Cartan subalgebra* if C is nilpotent as a Lie algebra over k, and C is self-normalizing in A, as on p80 of [14], and Definition 1 on p10 of [24]. Remember that the normalizer $N_A(C)$ of C in A is the largest Lie subalgebra of A that contains C as an ideal, and that C is self-normalizing in A when $N_A(C) = C$, as in Section 9.8.

Let us suppose from now on in this section that A has finite dimension as a vector space over k, and that the number of elements of k is strictly larger than the dimension of A as a vector space over k. If $x \in A$, then $A_{x,0}$ is the set of $y \in A$ such that $(\mathrm{ad}_x)^l(y) = 0$ for some positive integer l, as in Section 18.1. This is a Lie subalgebra of A, which is known as an Engel subalgebra of A, as before. Remember that Engel subalgebras of A are self-normalizing in A, as in Section 18.5.

Suppose that $z \in A$ has the property that $A_{z,0}$ is minimal with respect to inclusion among Engel subalgebras of A. In particular, one could take $A_{z,0}$ to be an Engel subalgebra of minimal dimension, as a vector space over k. Under these conditions, $A_{z,0}$ is a Cartan subalgebra of A, as in the theorem on p80 of [14]. This is related to Theorem 1 on p12 of [24] when $k = \mathbf{C}$.

It suffices to show that $A_{z,0}$ is nilpotent as a Lie algebra over k, because $A_{z,0}$ is self-normalizing in A, as before. Note that $C = A_{z,0}$ satisfies the conditions in Section 18.4, because $A_{z,0}$ is minimal, by hypothesis. If $x \in A_{z,0}$, then we get that

$$A_{z,0} \subseteq A_{x,0}, \tag{18.8.1}$$

as before. Thus, for each $y \in A_{z,0}$, we have that $(\mathrm{ad}_x)^l(y) = 0$ for some positive integer l. This implies that the restriction of ad_x to $A_{z,0}$ is nilpotent as a linear mapping from $A_{z,0}$ into itself. Equivalently, this means that x is ad-nilpotent as an element of $A_{z,0}$, considered as a Lie algebra over k. It follows that $A_{z,0}$ is nilpotent as a Lie algebra over k, as in Section 9.10.

Let C be a Lie subalgebra of A. If $x \in C$, then $\mathrm{ad}_{C,x}$ is the same as the restriction of ad_x to C. Suppose that C is nilpotent as a Lie algebra over k, so that $\mathrm{ad}_{C,x}$ is nilpotent on C for every $x \in C$. This implies that

(18.8.2) $$C \subseteq A_{x,0}$$

for every $x \in C$. In particular, if C is an Engel subalgebra of A, then it follows that C is minimal among Engel subalgebras of A.

If C is a Cartan subalgebra of A, then the other part of the theorem on p80 of [14] states that C is a minimal Engel subalgebra of A. This corresponds to Corollary 2 on p13 of [24] when $k = \mathbf{C}$. Of course, (18.8.2) holds for every $x \in C$ in this case, because C is nilpotent. Suppose for the sake of a contradiction that for each $x \in C$, $C \neq A_{x,0}$. Let z be an element of C be such that $A_{z,0}$ is minimal with respect to inclusion. As usual, one can take $z \in C$ such that $A_{z,0}$ has minimal dimension, as a vector space over k. Note that

(18.8.3) $$C \subseteq A_{z,0},$$

by (18.8.2). Under these conditions, we get that (18.8.1) holds for every $x \in C$, as in Section 18.4 again.

Let $x \in C$ be given. Of course, ad_x maps C into itself, because C is a Lie subalgebra of A. Observe that $x \in A_{z,0}$, by (18.8.3). Thus ad_x maps $A_{z,0}$ into itself, because $A_{z,0}$ is a Lie subalgebra of A too. The restriction of ad_x to $A_{z,0}$ is nilpotent, because of (18.8.1).

Consider the quotient $A_{z,0}/C$, as a finite-dimensional vector space over k. If $x \in C$, then ad_x induces a linear mapping from $A_{z,0}/C$ into itself, by the remarks in the preceding paragraph. This defines a representation of C, as a Lie algebra over k, on $A_{z,0}/C$. The mapping induced on $A_{z,0}/C$ by ad_x is nilpotent for each $x \in C$, because ad_x is nilpotent on $A_{z,0}$.

By hypothesis, $C \neq A_{z,0}$, so that $A_{z,0}/C \neq \{0\}$. It follows that there is a nonzero element of $A_{z,0}/C$ that is mapped to 0 by the mapping induced by ad_x for every $x \in C$, as in Section 9.9. Equivalently, this means that there is a $y \in A_{z,0}$ such that $y \notin C$ and

(18.8.4) $$\mathrm{ad}_x(y) = [x, y]_A \in C$$

for every $x \in C$. This means that $y \in N_A(C)$, which is a contradiction, because C is supposed to be self-normalizing in A. This is another instance of the argument in the previous section.

18.9 Nilpotent vectors and sums

Let k be a field, and let V be a vector space over k. If T is a linear mapping from V into itself, then let $\mathcal{E}_0(T)$ be the set of $v \in V$ such that $T^l(v) = 0$ for some positive integer l, as in Section 10.7. Remember that this is a linear subspace of

V, as before. Let R be another linear mapping from V into itself, and suppose that R commutes with T. Under these conditions, one can check that

$$\mathcal{E}_0(R) \cap \mathcal{E}_0(T) \subseteq \mathcal{E}_0(R+T). \tag{18.9.1}$$

More precisely, if $v \in V$ and $l \in \mathbf{Z}_+$, then

$$(R+T)^l(v) \tag{18.9.2}$$

can be expressed as a sum of terms of the form

$$R^{l_1}(T^{l_2}(v)) = T^{l_2}(R^{l_1}(v)), \tag{18.9.3}$$

where l_1, l_2 are nonnegative integers such that $l_1 + l_2 = l$. If v is an element of the left side of (18.9.1), then (18.9.3) is equal to 0 when l_1 or l_2 is sufficiently large. This implies that (18.9.2) is equal to 0 when l is sufficiently large, as desired.

Suppose for the moment that

$$\mathcal{E}_0(R) = V, \tag{18.9.4}$$

so that

$$\mathcal{E}_0(T) \subseteq \mathcal{E}_0(R+T), \tag{18.9.5}$$

by (18.9.1). Similarly,

$$\mathcal{E}_0(R+T) \subseteq \mathcal{E}_0(T), \tag{18.9.6}$$

by considering T as $(R+T) + (-R)$. Thus

$$\mathcal{E}_0(T) = \mathcal{E}_0(T+R) \tag{18.9.7}$$

under these conditions. If T is diagonalizable on V, then one can check that $\mathcal{E}_0(T)$ is the same as the kernel of T.

Let $(A, [\cdot,\cdot]_A)$ be a Lie algebra over k. If $x \in A$, then

$$A_{x,0} = \mathcal{E}_0(\mathrm{ad}_x) \tag{18.9.8}$$

in the notation of Section 18.1, with $V = A$ as a vector space over k on the right side. Suppose that $y \in A$ satisfies $[x,y]_A = 0$, so that ad_x and ad_y commute on A, as in Section 2.4. This implies that

$$A_{x,0} \cap A_{y,0} \subseteq A_{x+y,0}, \tag{18.9.9}$$

as in (18.9.1). If $A_{y,0} = A$, then we get that

$$A_{x,0} = A_{x+y,0}, \tag{18.9.10}$$

as in (18.9.7). If ad_x is diagonalizable on A, then $A_{x,0}$ is the same as the kernel of ad_x on A, as before. This means that

$$A_{x,0} = C_A(x) = C_A(\{x\}) \tag{18.9.11}$$

is the centralizer of x in A, as in Section 7.6.

Suppose that k is an algebraically closed field of characteristic 0, and that A is a finite-dimensional semisimple Lie algebra over k. Let $x \in A$ be given, and let $x = x_1 + x_2$ be the abstract Jordan decomposition of x in A, as in Section 14.3. Thus $x_1 \in A$ is ad-diagonalizable, $x_2 \in A$ is ad-nilpotent, and $[x_1, x_2]_A = 0$. It follows that

$$A_{x,0} = A_{x_1,0} = C_A(x_1), \tag{18.9.12}$$

as in (18.9.10) and (18.9.11). This corresponds to some of the arguments in the proof of the corollary on p80 in [14].

18.10 Cartan subalgebras and semisimplicity

Let k be an algebraically closed field of characteristic 0, and let $(A, [\cdot,\cdot]_A)$ be a finite-dimensional semisimple Lie algebra over k. If B is a maximal toral subalgebra of A, then B is commutative as a Lie algebra, and the centralizer $C_A(B)$ of B in A is equal to B, as in Sections 17.1 and 17.4. The normalizer $N_A(B)$ of B in A is equal to B too, as in Section 17.14. It follows that B is a Cartan subalgebra of A, as mentioned at the top of p80 of [14].

Conversely, let C be any Cartan subalgebra of A. In particular, C is an Engel subalgebra of A, as in Section 18.8. Thus there is an $x \in A$ such that

$$C = A_{x,0}, \tag{18.10.1}$$

and one can take x to be ad-diagonalizable, as in the previous section. This means that the linear span of x in A is a toral subalgebra of A. Let B be a maximal toral subalgebra of A that contains x, which can be obtained by taking B to have maximal dimension. Observe that

$$B \subseteq C_A(x) = C, \tag{18.10.2}$$

because B is commutative as a Lie algebra, as in Section 17.1. However, B is a Cartan subalgebra of A, as in the preceding paragraph, and hence an Engel subagebra of A, as in Section 18.8. It follows that

$$B = C, \tag{18.10.3}$$

because C is a minimal Engel subalgebra of A, as in Section 18.8. This is the corollary on p80 of [14].

Alternatively, suppose for the moment that k is any field of characteristic 0, and that A is a finite-dimensional semisimple Lie algebra over k. Suppose also that (18.10.1) is a Cartan subalgebra of A for some $x \in A$. Remember that the Killing form on A is nondegenerate, as in Section 10.13. This implies that the restriction of the Killing form on A to C is nondegenerate, as in Section 18.6, and part (d) of Theorem 3 on p15 of [24].

Remember that the collection of linear mappings on A of the form ad_w, $w \in A$, is a Lie subalgebra of the Lie algebra $gl(A)$ of all linear mappings from A into itself, with respect to the usual commutator bracket. This is the same as the image of A under the adjoint representation. Similarly,

$$\{\mathrm{ad}_w : w \in C\} \tag{18.10.4}$$

is a Lie subalgebra of the Lie algebra just mentioned, because C is a Lie subalgebra of A. More precisely, (18.10.4) is nilpotent as a Lie algebra, because C is nilpotent, by hypothesis. In particular, (18.10.4) is solvable as a Lie algebra over k.

If $w, y, z \in C$, then it follows that

$$\mathrm{tr}_A(\mathrm{ad}_w \circ \mathrm{ad}_{[y,z]_A}) = 0, \tag{18.10.5}$$

as in Section 10.5. This uses the fact that $\mathrm{ad}_{[y,z]_A} = [\mathrm{ad}_y, \mathrm{ad}_z]$, as in Section 2.4. This implies that

$$[y, z]_A = 0 \tag{18.10.6}$$

for every $y, z \in C$, because the restriction of the Killing form on A to C is nondegenerate, as before. This shows that C is commutative as a Lie algebra over k, as in part (a) of Theorem 3 on p15 of [24].

It follows that C is contained in its centralizer in A. The centralizer of C in A is automatically contained in the normalizer $N_A(C)$ of C in A, as in Section 17.14. In this situation, $N_A(C) = C$, so that C is equal to its centralizer in A. This is part (b) of Theorem 3 on p80 of [24]. This implies that C is maximal among commutative Lie subalgebras of A, as in Corollary 1 on p15 of [24].

Suppose now that k is also algebraically closed again. Let $w \in C$ be given, and let

$$w = w_1 + w_2 \tag{18.10.7}$$

be the abstract Jordan decomposition of w in A, as in Section 14.3. This means that $w_1 \in A$ is ad-diagonalizable, $w_2 \in A$ is ad-nilpotent, and $[w_1, w_2]_A = 0$. Let $y \in C$ be given, so that $[w, y]_A = 0$, and hence ad_w commutes with ad_y on A, as in Section 2.4. This implies that ad_y commutes with ad_{w_1} and ad_{w_2}, as in Section 10.8. It follows that

$$[w_1, y]_A = [w_2, y]_A = 0. \tag{18.10.8}$$

More precisely, this uses the fact that the kernel of the adjoint representation of A is the center of A as a Lie algebra, which is trivial in this case, because A is semisimple by hypothesis.

Thus ad_{w_2} commutes with ad_y on A, as in Section 2.4. This implies that $\mathrm{ad}_{w_2} \circ \mathrm{ad}_y$ is nilpotent on A, because ad_{w_2} is nilpotent on A. It follows that

$$\mathrm{tr}_A(\mathrm{ad}_{w_2} \circ \mathrm{ad}_y) = 0. \tag{18.10.9}$$

This shows that $w_2 = 0$, because the restriction of the Killing form on A to C is nondegenerate, as before. This means that $w = w_1$ is ad-diagonalizable as an element of A, as in part (c) of Theorem 3 on p15 of [24].

The hypothesis that (18.10.1) be a Cartan subalgebra of A really means that C is nilpotent as a Lie algebra over k, because Engel subalgebras of A are self-normalizing, as in Section 18.5. In the previous arguments, it is enough to ask that C be solvable as a Lie algebra over k, so that (18.10.4) is solvable as a Lie algebra. The same conclusion is mentioned in Exercise 2 on p81 of [14].

18.11 Subalgebras and homomorphisms

Let k be a field, and let $([\cdot,\cdot]_A)$ be a Lie algebra over k. If C is a Cartan subalgebra of A, then C is maximal among nilpotent Lie subalgebras of A. This is the first part of Exercise 4 on p81 in [14], and it follows from the statement mentioned at the end of Section 18.7.

If C_1, C_2 are Cartan subalgebras of A with

$$C_1 \subseteq C_2, \tag{18.11.1}$$

then

$$C_1 = C_2, \tag{18.11.2}$$

because C_1 is maximal among nilpotent Lie subalgebras of A, as in the preceding paragraph. Alternatively, if C_1, C_2 are Engel subalgebras of A, and C_2 is minimal among Engel subalgebras of A, then (18.11.1) implies (18.11.2).

Let $\widetilde{A}$ and C be Lie subalgebras of A, with

$$C \subseteq \widetilde{A}. \tag{18.11.3}$$

It is easy to see that

$$N_{\widetilde{A}}(C) = N_A(C) \cap \widetilde{A}, \tag{18.11.4}$$

where $N_A(C)$, $N_{\widetilde{A}}(C)$ are the normalizers of C in A and $\widetilde{A}$, respectively. In particular, if C is self-normalizing in A, then C is self-normalizing in $\widetilde{A}$. If C is a Cartan subalgebra of A, then it follows that C is a Cartan subalgebra of $\widetilde{A}$.

Let $(A', [\cdot,\cdot]_{A'})$ be another Lie algebra over k, and let ϕ be a Lie algebra homomorphism from A onto A'. If $x \in A$ and $x' \in A'$, then we put

$$\mathrm{ad}_{A,x}(y) = [x,y]_A, \quad \mathrm{ad}_{A',x'}(y') = [x',y']_{A'} \tag{18.11.5}$$

for every $y \in A$, $y' \in A'$, as usual. Thus

$$\phi(\mathrm{ad}_{A,x}(y)) = \phi([x,y]_A) = [\phi(x),\phi(y)]_{A'} = \mathrm{ad}_{A',\phi(x)}(\phi(y)) \tag{18.11.6}$$

for every $x, y \in A$.

Let C' be a Lie subalgebra of A'. If $x \in A$, then it is easy to see that

$$\mathrm{ad}_{A',\phi(x)}(C') \subseteq C' \tag{18.11.7}$$

if and only if

$$\mathrm{ad}_{A,x}(\phi^{-1}(C')) \subseteq \phi^{-1}(C'), \tag{18.11.8}$$

using (18.11.6). This means that $\phi(x)$ is an element of the normalizer $N_{A'}(C')$ of C' in A' if and only if x is an element of the normalizer $N_A(\phi^{-1}(C'))$ of $\phi^{-1}(C')$ in A. It follows that C' is self-normalizing in A' if and only if $\phi^{-1}(C')$ is self-normalizing in A.

Suppose from now on in this section that A has finite dimension as a vector space over k, so that the dimension of A' is finite as well. If $\phi^{-1}(C')$ contains an Engel subalgebra of A, then $\phi^{-1}(C')$ is self-normalizing in A, as in Section 18.5.

Let C be a Lie subalgebra of A again, so that $\phi(C)$ is a Lie subalgebra of A'. Note that $\phi^{-1}(\phi(C))$ is a Lie subalgebra of A, which is spanned by C and the kernel of ϕ. If C contains an Engel subalgebra of A, then $\phi^{-1}(\phi(C))$ contains the same Engel subalgebra of A.

Suppose for the rest of the section that the number of elements of k is strictly larger than the dimension of A as a vector space over k. If C is a Cartan subalgebra of A, then C is an Engel subalgebra of A, as in Section 18.8. It follows that $\phi(C)$ is self-normalizing in A', as in the previous paragraphs. We also have that C is nilpotent as a Lie algebra over k, so that $\phi(C)$ is nilpotent too, as in Section 9.5. This shows that $\phi(C)$ is a Cartan subalgebra of A', as in Lemma A on p81 of [14].

Suppose now that C' is a Cartan subalgebra of A', and that C is a Cartan subalgebra of $\phi^{-1}(C')$, as a Lie algebra over k. We would like to show that C is a Cartan subalgebra of A too, as in Lemma B on p81 of [14]. Observe that $\phi(C)$ is a Cartan subalgebra of $\phi(\phi^{-1}(C')) = C'$, as in the preceding paragraph. We also have that C' is a Cartan subalgebra of itself, because C' is nilpotent as a Lie algebra. This implies that

$$\phi(C) = C', \tag{18.11.9}$$

as in (18.11.2).

Suppose that x is an element of the normalizer $N_A(C)$ of C in A, and let us check that $x \in C$. It is easy to see that $\phi(x)$ is in the normalizer $N_{A'}(\phi(C))$ of $\phi(C)$ in A'. This implies that $\phi(x) \in \phi(C)$, because of (18.11.9) and the hypothesis that C' be a Cartan subalgebra of A'. Thus

$$x \in \phi^{-1}(\phi(C)) = \phi^{-1}(C'). \tag{18.11.10}$$

It follows that $x \in C$, as desired, because C is a Cartan subalgebra of $\phi^{-1}(C')$, by hypothesis.

18.12 Unions of hyperplanes

Let k be a field, and let V be a nonzero vector space over k. By a hyperplane in V we mean a linear subspace W of codimension 1 in V, so that V is spanned by W and a single vector in V that is not in W. Equivalently, this means that W is the kernel of a nonzero linear functional on V. If $W_1, \ldots, W_r$ are finitely many hyperplanes in V, and if r is less than or equal to the number of elements of k, then we would like to check that $\bigcup_{j=1}^r W_j$ is a proper subset of V. Note that $\bigcap_{j=1}^r W_j$ is a linear subspace of V with codimension less than or equal to r. Thus the quotient space $V/\bigcap_{j=1}^r W_j$ is a vector space over k of dimension less than or equal to r. We may as well suppose that the dimension of V is finite, since otherwise we could replace V with this quotient.

Of course, $k^2 = k \times k$ is a two-dimensional vector space over k, with respect to coordinatewise addition and scalar multiplication. The lines in k^2 are characterized by their slope in k, except for the second coordinate axis. The number of distinct lines in k^2 is the number of elements of k plus 1, which is to say that there are infinitely many distinct lines in k^2 when k has infinitely many elements. These lines are pairwise disjoint away from 0. It follows that k^2 cannot be expressed as the union of finitely many lines, where the number of lines is less than or equal to the number of elements of k.

If V has dimension one, then $\{0\}$ is the only hyperplane in V, and the statement under consideration is trivial. If V has dimension at least two, then one can find at least as many distinct hyperplanes in V as lines in k^2. In particular, there is a hyperplane Z in V that is different from W_j for each $j = 1, \ldots, r$. Thus $Z \cap W_j$ is a hyperplane in Z for each $j = 1, \ldots, r$. Note that the dimension of Z is one less than the dimension of V, which is strictly less than the dimension of V, because the dimension of V is finite. This permits us to use induction to get that the union of $Z \cap W_j$, $1 \le j \le r$, is a proper subset of Z. This implies that the union of W_j, $1 \le j \le r$, is a proper subset of V, as desired.

If a is a nonzero element of V, then

$$V'_a = \{\lambda \in V' : \lambda(a) = 0\} \tag{18.12.1}$$

is a hyperplane in the dual space V' of linear functionals on V. If A is a nonempty finite set of nonzero elements of V, and if the number of elements of A is less than or equal to the number of elements in k, then it follows that the union of V'_a, $a \in A$, is a proper subset of V'. This means that there is a linear functional λ on V such that

$$\lambda(a) \neq 0 \tag{18.12.2}$$

for every $a \in A$.

18.13 Centralizers and diagonalizability

Let k be a field, and let $(A, [\cdot,\cdot]_A)$ be a finite-dimensional Lie algebra over k. Also let B be a nonzero Lie subalgebra of A such that every element of B is ad-diagonalizable as an element of A. This implies that B is commutative as a Lie algebra over k, as in Section 17.1. Let B' be the dual of B, as a vector space over k, as usual. If $\alpha \in B'$, then we let A_α be the set of $x \in A$ such that $\mathrm{ad}_w(x) = [w, x]_A = \alpha(w)\, x$ for every $w \in B$, as before.

Thus A_0 is the same as the centralizer $C_A(B)$ of B in A. Of course, B is contained in $C_A(B)$, because B is commutative as a Lie algebra. Let Φ_B be the set of $\alpha \in B'$ such that $\alpha \neq 0$ and $A_\alpha \neq \{0\}$, as in Section 17.2. Remember that A corresponds to the direct sum of A_α, $\alpha \in \Phi_B \cup \{0\}$, as before.

Let $w \in B$ be given, and let $C_A(w) = C_A(\{w\})$ be the centralizer of w in A, which is the set of $x \in A$ such that $[w, x]_A = 0$. This corresponds to the direct sum of A_α, where $\alpha \in \Phi_B \cup \{0\}$ satisfies

$$\alpha(w) = 0. \tag{18.13.1}$$

Of course, this holds automatically when $\alpha = 0$. If

$$\alpha(w) \neq 0 \tag{18.13.2}$$

for every $\alpha \in \Phi_B$, then we get that

$$C_A(w) = A_0 = C_A(B). \tag{18.13.3}$$

This is related to the second part of Exercise 7 on p41 of [14].

Chapter 19

Root systems

19.1 Symmetries and reflections

Let V be a finite-dimensional vector space over the real numbers, and let α be a nonzero element of V. A one-to-one linear mapping σ from V onto itself is said to be a *symmetry with vector* α if it satisfies the following two conditions. First,

(19.1.1) $$\sigma(\alpha) = -\alpha.$$

Second, the linear subspace

(19.1.2) $$H = \{v \in V : \sigma(v) = v\}$$

of V is a hyperplane, which is to say that it has codimension one in V. Let

(19.1.3) $$L_\alpha = \{t\,\alpha : t \in \mathbf{R}\}$$

be the line in V passing through α. Note that

(19.1.4) $$L_\alpha + H = V, \quad L_\alpha \cap H = \{0\},$$

so that L_α and H are complementary linear subspaces of V. It is easy to see that σ is uniquely determined by L_α and H. One can also get a symmetry on V from any line and complementary hyperplane in V, where the symmetry is the same as multiplication by -1 on the line, and the identity mapping on the hyperplane.

Let V' be the dual space of linear functionals on V, as a vector space over $\mathbf{R}$, as usual. In this situation, there is a unique $\lambda_\alpha \in V'$ such that

(19.1.5) $$\lambda_\alpha(\alpha) = 2$$

and

(19.1.6) $$\lambda_\alpha(v) = 0 \quad \text{for every } v \in H.$$

Observe that

$$\sigma(v) = v - \lambda_\alpha(v)\,\alpha \tag{19.1.7}$$

for every $v \in V$. Conversely, if $\alpha \in V$ and $\lambda_\alpha \in V'$ satisfy (19.1.5), then (19.1.7) defines a symmetry on V with vector α, for which the kernel of λ_α is the fixed-point set. These remarks correspond to the discussion on p24 of [24].

Suppose now that (v, w) is an inner product on V. Let σ be a symmetry on V with vector α and fixed hyperplane H as in (19.1.2) again. Suppose that α is orthogonal to H, so that

$$(v, \alpha) = 0 \tag{19.1.8}$$

for every $v \in H$. Let us say that σ is a *reflection* on V with respect to $(\cdot, \cdot)$ in this case, as on p42 of [14]. One can check that σ is an orthogonal transformation on V with respect to $(\cdot, \cdot)$ under these conditions, which is to say that

$$(\sigma(v), \sigma(w)) = (v, w) \tag{19.1.9}$$

for every $v, w \in V$.

Conversely, suppose that σ is a symmetry on V with vector α, and that σ is an orthogonal transformation on V with respect to $(\cdot, \cdot)$. If v is an element of the hyperplane H in (19.1.2), then

$$(v, \alpha) = (\sigma(v), \sigma(\alpha)) = -(v, \alpha). \tag{19.1.10}$$

This implies (19.1.8), so that σ is a reflection on V. This is related to some of the remarks on p28 of [24].

Let $\alpha \in V$, $\alpha \neq 0$, be given, and let

$$H_\alpha = \{v \in V : (v, \alpha) = 0\} \tag{19.1.11}$$

be the hyperplane in V orthogonal to α. Put

$$\mu_\alpha(v) = 2\,(v, \alpha)\,(\alpha, \alpha)^{-1} \tag{19.1.12}$$

for every $v \in V$, which defines a linear functional on V. By construction,

$$\mu_\alpha(\alpha) = 2, \tag{19.1.13}$$

and (19.1.11) is the kernel of μ_α. The reflection associated to α on V is given by

$$\sigma(v) = v - \mu_\alpha(v)\,\alpha = v - 2\,(v, \alpha)\,(\alpha, \alpha)^{-1}\,\alpha \tag{19.1.14}$$

for every $v \in V$, as in (19.1.7). This corresponds to some of the remarks on p42 of [14], and p28 of [24].

19.2 Invariant inner products

Let V be a vector space over the real numbers of positive finite dimension, and let G be a finite subgroup of the general linear group $GL(V)$ of invertible linear mappings on V. Under these conditions, it is well known that there is an inner product (v, w) on V that is invariant under G, so that the elements of G are orthogonal transformations on V with respect to (v, w). More precisely, if $(v, w)_0$ is any inner product on V, then one can verify that

$$(v, w) = \sum_{g \in G} (g(v), g(w))_0 \tag{19.2.1}$$

is an inner product on V that is invariant under the elements of G.

Let A be a nonempty subset of V, and let G_A be the collection of one-to-one linear mappings T from V onto itself such that

$$T(A) = A. \tag{19.2.2}$$

Of course, G_A is a subgroup of $GL(V)$. The mapping from $T \in G_A$ to the restriction of T to A defines a group homomorphism from G_A into the group of one-to-one mappings from A onto itself. Suppose that the linear span of A in V is equal to V. If $T \in G_A$ is equal to the identity mapping on A, then it follows that T is the identity mapping on V. If A has only finitely many elements, then G_A has only finitely many elements too. This implies that there is an inner product on V that is invariant under G_A, as in the preceding paragraph.

Let α be a nonzero element of V, and let A be a finite subset of V whose linear span in V is equal to V again. Under these conditions, there is at most one symmetry σ on V with vector α that maps A onto itself, as in the lemma on the top of p25 in [24]. To see this, let (v, w) be an inner product on V that is invariant under G_A, as in the preceding paragraph. Thus σ is an orthogonal transformation on V with respect to (v, w), because $\sigma \in G_A$, by hypothesis. It follows that σ is the reflection on V associated to α with respect to (v, w), as in the previous section.

Another version of this lemma is stated on p42 of [14], in terms of reflections. In this version, V is equipped with an inner product $(v, w)_V$, and A is a finite subset of V whose linear span in V is equal to V again. Let σ be a symmetry on V with vector $\alpha \in A$, which is not necessarily a reflection on V with respect to $(v, w)_V$. Suppose that $\sigma(A) = A$, and that the reflection σ_α on V associated to α with respect to $(v, w)_V$ maps A onto itself. Under these conditions, $\sigma = \sigma_\alpha$.

This follows from the previous version, because σ_α is a symmetry on V with vector α. Note however that $(v, w)_V$ is not necessarily invariant under G_A. Of course, any symmetry on V with vector α is the reflection associated to α with respect to some inner product on V.

19.3 Defining root systems

Let V be a vector space over the real numbers of positive finite dimension. A subset A of V is said to be a *root system* in V if it satisfies the following three conditions, as in Definition 1 on p25 of [24]. First, A has only finitely many elements, the linear span of A in V is equal to V, and $0 \notin A$. Second, for each $\alpha \in A$, there is a symmetry σ_α on V with vector α such that

$$\sigma_\alpha(A) = A. \tag{19.3.1}$$

Note that σ_α is uniquely determined by these properties, as in the previous section. Third, for every $\alpha, \beta \in A$,

$$\sigma_\alpha(\beta) - \beta \text{ is an integer multiple of } \alpha. \tag{19.3.2}$$

The dimension of V may be called the *rank* of A, and the elements of A may be called *roots* of V with respect to A.

If $\alpha \in A$, then there is a unique linear functional λ_α on V such that $\lambda_\alpha(\alpha) = 2$ and $\lambda_\alpha = 0$ on the hyperplane in V consisting of vectors fixed by σ_α, as in Section 19.1. Remember that

$$\sigma_\alpha(v) = v - \lambda_\alpha(v)\,\alpha \tag{19.3.3}$$

for every $v \in V$, as in (19.1.7). Using this, the third condition in the preceding paragraph can be reformulated as saying that for every $\alpha, \beta \in A$,

$$\lambda_\alpha(\beta) \in \mathbf{Z}. \tag{19.3.4}$$

If $\alpha \in A$, then we also have that

$$-\alpha \in A, \tag{19.3.5}$$

by (19.3.1) and the fact that $s_\alpha(\alpha) = -\alpha$.

A root system A in V is said to be *reduced* if for every $\alpha \in A$, the only elements of A that are proportional to α are α and $-\alpha$, as in Definition 2 on p25 of [24]. Otherwise, suppose that $\alpha \in A$ and $t\,\alpha \in A$ for some $t \in \mathbf{R}$ with $t \neq \pm 1$. Of course, $t \neq 0$, because $0 \notin A$, and we may as well suppose that $|t| < 1$, since otherwise we could interchange the roles of α and $t\,\alpha$. Using (19.3.4), we get that $2\,t \in \mathbf{Z}$, because $\lambda_\alpha(\alpha) = 2$. This means that $t = \pm 1/2$.

In the definition of a root system on p42 of [14], one supposes that V is already equipped with an inner product (v, w), and that the symmetries σ_α are reflections with respect to this inner product. This means that

$$\lambda_\alpha(v) = 2\,(v, \alpha)\,(\alpha, \alpha)^{-1} \tag{19.3.6}$$

for every $\alpha \in A$ and $v \in V$, as in Section 19.1. In this situation, (19.3.4) is the same as saying that

$$2\,(\beta, \alpha)\,(\alpha, \alpha)^{-1} \in \mathbf{Z} \tag{19.3.7}$$

for every $\alpha, \beta \in A$. The condition that the root system be reduced is also included in the definition, as discussed further on p43 of [14]. If A is a root system in V as before, then one can find a compatible inner product on V, as in the next section.

Of course, we have seen properties like these in connection with Lie algebras, in Chapter 17. This corresponds to the remarks following the theorem on p40 of [14], and part (a) of Theorem 2 on p43 of [24]. This will be discussed further in Section 22.1. Some classical examples of root systems will be discussed starting in Section 20.10.

19.4 The Weyl group

Let V be a vector space over the real numbers of positive finite dimension, and let A be a root system in V. The *Weyl group* of A is defined to be the subgroup W of $GL(V)$ generated by the symmetries σ_α, $\alpha \in A$, as in Definition 3 on p27 of [24]. Let G_A be the subgroup of $GL(V)$ consisting of invertible linear mappings T on V that map A onto itself, as in Section 19.2. Thus

$$W \subseteq G_A, \tag{19.4.1}$$

because $\sigma_\alpha \in G_A$ for every $\alpha \in A$, by definition of a root system. Remember that G_A has only finitely many elements in this situation, because A is a finite subset of V that spans V.

More precisely, W is a normal subgroup of G_A, as mentioned on p27 of [24]. To see this, let $\alpha \in A$ and $T \in G_A$ be given. It is easy to see that $T \circ \sigma_\alpha \circ T^{-1}$ is a symmetry on V with vector $T(\alpha)$. We also have that

$$(T \circ \sigma_\alpha \circ T^{-1})(A) = A, \tag{19.4.2}$$

because σ_α and T both map A onto itself. This implies that

$$T \circ \sigma_\alpha \circ T^{-1} = \sigma_{T(\alpha)}, \tag{19.4.3}$$

because $T(\alpha) \in A$, as in the previous section. It follows that W is invariant under conjugation by T, as desired. Note that (19.4.3) corresponds to the first part of the lemma on p43 of [14], just after the definition of the Weyl group.

Let $\alpha \in A$ be given again, and let $\lambda_\alpha \in V'$ be as in the previous section, so that σ_α can be expressed as in (19.3.3). If $T \in GL(V)$, then it follows that

$$(T \circ \sigma_\alpha \circ T^{-1})(v) = v - \lambda_\alpha(T^{-1}(v))\, T(\alpha) \tag{19.4.4}$$

for every $v \in V$. Suppose that $T \in G_A$, and let $\lambda_{T(\alpha)}$ be the linear functional on V corresponding to $T(\alpha) \in A$ in the same way. Thus

$$\sigma_{T(\alpha)}(v) = v - \lambda_{T(\alpha)}(v)\, T(\alpha) \tag{19.4.5}$$

for every $v \in V$, as before. This means that

$$\lambda_{T(\alpha)}(v) = \lambda_\alpha(T^{-1}(v)) \tag{19.4.6}$$

for every $v \in V$, because of (19.4.3).

Because the Weyl group W has only finitely many elements, one can find an inner product on V that is invariant under W as in Section 19.2. This corresponds to Proposition 1 on p27 of [24]. The choice of such an inner product is sometimes included in the definition of a root system, as in [14], and mentioned on p28 of [25].

Let (v, w) be an inner product on V that is invariant under W. If $\alpha \in A$, then $\lambda_\alpha \in V'$ can be expressed in terms of $(\cdot, \cdot)$ as in (19.3.6). Similarly, if $T \in G_A$, then $T(\alpha) \in A$, and

$$\lambda_{T(\alpha)}(v) = 2\,(v, T(\alpha))\,(T(\alpha), T(\alpha))^{-1} \tag{19.4.7}$$

for every $v \in V$. Combining this with (19.4.6), we get that

$$(v, T(\alpha))\, (T(\alpha), T(\alpha))^{-1} = (T^{-1}(v), \alpha)\, (\alpha, \alpha)^{-1} \tag{19.4.8}$$

for every $v \in V$. Equivalently, this means that

$$(T(u), T(\alpha))\, (T(\alpha), T(\alpha))^{-1} = (u, \alpha)\, (\alpha, \alpha)^{-1} \tag{19.4.9}$$

for every $u \in V$. This corresponds to the second part of the lemma on p43 of [14]. Note that this holds automatically when $(\cdot, \cdot)$ is invariant under G_A.

19.5 Isomorphic root systems

Let V and $\widetilde{V}$ be vector spaces over the real numbers with the same positive finite dimension, and let A and $\widetilde{A}$ be root systems in V and $\widetilde{V}$, respectively. Let us say that a one-to-one linear mapping T from V onto $\widetilde{V}$ is an *isomorphism* between these root systems if

$$T(A) = \widetilde{A}. \tag{19.5.1}$$

In particular, an invertible linear mapping on V is an automorphism of the root system A if it maps A onto itself, as on p27 of [24].

Let $T : V \to \widetilde{V}$ be an isomorphism between the root systems A and $\widetilde{A}$, and let $\alpha \in A$ be given. If σ_α is the corresponding symmetry on V with vector α, then it is easy to see that $T \circ \sigma_\alpha \circ T^{-1}$ is a symmetry on $\widetilde{V}$ with vector $T(\alpha)$. Observe that

$$(T \circ \sigma_\alpha \circ T^{-1})(\widetilde{A}) = \widetilde{A}, \tag{19.5.2}$$

because of (19.5.1) and the fact that $\sigma_\alpha(A) = A$. It follows that

$$T \circ \sigma_\alpha \circ T^{-1} = \widetilde{\sigma}_{T(\alpha)}, \tag{19.5.3}$$

where the right side is the symmetry on $\widetilde{V}$ corresponding to $T(\alpha) \in \widetilde{A}$ as in Section 19.3.

Of course, if τ is a one-to-one linear mapping from V onto itself, then

$$T \circ \tau \circ T^{-1} \tag{19.5.4}$$

is a one-to-one linear mapping from $\widetilde{V}$ onto itself. More precisely,

$$\tau \mapsto T \circ \tau \circ T^{-1} \tag{19.5.5}$$

defines a group isomorphism from $GL(V)$ onto $GL(\widetilde{V})$. This isomorphism sends the Weyl group W of A onto the Weyl group $\widetilde{W}$ of $\widetilde{A}$, because of (19.5.3).

Let λ_α be the linear functional on V corresponding to σ_α as before, so that σ_α can be expressed as in (19.3.3). Thus

$$(T \circ \sigma_\alpha \circ T^{-1})(\widetilde{v}) = \widetilde{v} - \lambda_\alpha(T^{-1}(\widetilde{v}))\, T(\alpha) \tag{19.5.6}$$

for every $\widetilde{v} \in \widetilde{V}$. Let $\widetilde{\lambda}_{T(\alpha)}$ be the linear functional on $\widetilde{V}$ that corresponds to $T(\alpha) \in \widetilde{A}$ in the same way, so that

$$\widetilde{\sigma}_{T(\alpha)}(\widetilde{v}) = \widetilde{v} - \widetilde{\lambda}_{T(\alpha)}(\widetilde{v})\, T(\alpha) \tag{19.5.7}$$

for every $\widetilde{v} \in \widetilde{V}$. It follows that

$$\widetilde{\lambda}_{T(\alpha)}(\widetilde{v}) = \lambda_\alpha(T^{-1}(\widetilde{v})) \tag{19.5.8}$$

for every $\widetilde{v} \in \widetilde{V}$, by (19.5.3). Equivalently,

$$\widetilde{\lambda}_{T(\alpha)}(T(v)) = \lambda_\alpha(v) \tag{19.5.9}$$

for every $v \in V$.

Suppose that $(\cdot,\cdot)_V$ and $(\cdot,\cdot)_{\widetilde{V}}$ are inner products on V and $\widetilde{V}$ that are compatible with the root systems A and $\widetilde{A}$, respectively, in the sense that σ_α and $\widetilde{\sigma}_{\widetilde{\alpha}}$ are reflections on V and $\widetilde{V}$ with respect to $(\cdot,\cdot)_V$ and $(\cdot,\cdot)_{\widetilde{V}}$ for every $\alpha \in A$ and $\widetilde{\alpha} \in \widetilde{A}$, respectively. Thus

$$\lambda_\alpha(v) = 2\,(v,\alpha)_V\,(\alpha,\alpha)_V^{-1} \tag{19.5.10}$$

for every $\alpha \in A$ and $v \in V$, as in (19.3.6), and similarly

$$\widetilde{\lambda}_{\widetilde{\alpha}}(\widetilde{v}) = 2\,(\widetilde{v},\widetilde{\alpha})_{\widetilde{V}}\,(\widetilde{\alpha},\widetilde{\alpha})_{\widetilde{V}}^{-1} \tag{19.5.11}$$

for every $\widetilde{\alpha} \in \widetilde{A}$ and $\widetilde{v} \in \widetilde{V}$. In this case, (19.5.9) is the same as saying that

$$(T(v),T(\alpha))_{\widetilde{V}}\,(T(\alpha),T(\alpha))_{\widetilde{V}}^{-1} = (v,\alpha)_V\,(\alpha,\alpha)_V^{-1} \tag{19.5.12}$$

for every $\alpha \in A$ and $v \in V$. This is related to some of the remarks on p43 of [14]. In particular, (19.5.12) holds automatically when

$$(T(u),T(v))_{\widetilde{V}} = (u,v)_V \tag{19.5.13}$$

for every $u, v \in V$.

19.6 Duality and symmetries

Let V be a vector space over the real numbers of positive finite dimension, and let V' be the dual space of all linear functionals on V. Remember that V' has the same dimension as V. If $v \in V$ and $\mu \in V'$, then put

$$L_v(\mu) = \mu(v). \tag{19.6.1}$$

This defines L_v as a linear functional on V', so that L_v is an element of the dual space $V'' = (V')'$ of V'. More precisely, $v \mapsto L_v$ is a one-to-one linear mapping from V onto V''.

If T is a linear mapping from V into itself and $\mu \in V'$, then

$$T'(\mu) = \mu \circ T \tag{19.6.2}$$

defines a linear functional on V too. Equivalently,

$$(T'(\mu))(v) = \mu(T(v)) \tag{19.6.3}$$

for every $v \in V$. This defines T' as a linear mapping from V' into itself, which is the dual linear mapping associated to T. If T_1, T_2 are linear mappings from V into itself, then

$$(T_1 \circ T_2)' = T_2' \circ T_1', \tag{19.6.4}$$

as linear mappings from V' into itself. Note that

$$(I_V)' = I_{V'}, \tag{19.6.5}$$

where I_V and $I_{V'}$ are the identity mappings on V and V', respectively.

If T is a linear mapping from V into itself again, then T' is a linear mapping from V' into itself, which leads to a dual mapping $T'' = (T')'$ from V'' into itself. Thus, if $L \in V''$, then

$$T''(L) = L \circ T', \tag{19.6.6}$$

as a linear functional on V'. This means that

$$(T''(L))(\mu) = L(T'(\mu)) = L(\mu \circ T) \tag{19.6.7}$$

for every $\mu \in V'$. If $v \in V$ and $L_v \in V''$ is as in (19.6.1), then it follows that

$$(T''(L_v))(\mu) = L_v(\mu \circ T) = \mu(T(v)) = L_{T(v)}(\mu) \tag{19.6.8}$$

for every $\lambda \in V'$. This means that

$$T''(L_v) = L_{T(v)} \tag{19.6.9}$$

for every $v \in V$.

Let $z \in V$ and $\tau \in V'$ be given, so that

$$T_{z,\tau}(v) = \tau(v)\, z \tag{19.6.10}$$

defines a linear mapping from V into itself. If $\mu \in V'$, then

$$(T'_{z,\tau}(\mu))(v) = \mu(T_{z,\tau}(v)) = \tau(v)\, \mu(z) = \tau(v)\, L_z(\mu) \tag{19.6.11}$$

for every $v \in V$. Equivalently, this means that

$$T'_{z,\tau}(\mu) = L_z(\mu)\, \tau \tag{19.6.12}$$

for every $\mu \in V'$.

Let σ be a symmetry on V with vector $\alpha \in V$. Thus there is a linear functional λ_α on V such that $\lambda_\alpha(\alpha) = 2$ and $\sigma(v) = v - \lambda_\alpha(v)\,\alpha$ for every $v \in V$, as in Section 19.1. This is the same as saying that

$$\sigma = I_V - T_{\alpha,\lambda_\alpha}, \tag{19.6.13}$$

where $T_{\alpha,\lambda_\alpha}$ is as in (19.6.10). The corresponding dual linear mapping is given by

$$\sigma'(\mu) = \mu - L_\alpha(\mu)\,\lambda_\alpha \tag{19.6.14}$$

for every $\mu \in V'$, by (19.6.5) and (19.6.12). Note that

$$L_\alpha(\lambda_\alpha) = \lambda_\alpha(\alpha) = 2. \tag{19.6.15}$$

It follows that σ' is a symmetry on V' with vector λ_α, as in Section 19.1. Alternatively, one can check more directly that

$$\sigma'(\lambda_\alpha) = \lambda_\alpha \circ \sigma = -\lambda_\alpha, \tag{19.6.16}$$

because $\sigma(\alpha) = -\alpha$ and the kernel of λ_α is the fixed-point set of σ. If $\mu \in V'$ satisfies $\mu(\alpha) = 0$, then one can verify that

$$\sigma'(\mu) = \mu \circ \sigma = \mu, \tag{19.6.17}$$

because σ is equal to the identity on a hyperplane in V complementary to the line passing through α.

19.7 Adjoints and reflections

Let V be a vector space over the real numbers of positive finite dimension again, and suppose that (v, w) is an inner product on V. If T is a linear mapping from V into itself, then there is a unique adjoint linear mapping T^* from V into itself such that

$$(T(v), w) = (v, T^*(w)) \tag{19.7.1}$$

for every $v, w \in V$, as before. Remember that

$$(T_1 \circ T_2)^* = T_2^* \circ T_1^* \tag{19.7.2}$$

for all linear mappings T_1 and T_2 from V into itself, and that $I_V^* = I_V$. If T is any linear mapping from V into itself, then $(T^*)^* = T$. We also have that T is an orthogonal transformation on V with respect to $(\cdot, \cdot)$, in the sense that

$$(T(v), T(w)) = (v, w) \tag{19.7.3}$$

for every $v, w \in V$, if and only if T is invertible on V, with $T^{-1} = T^*$.

If $u \in V$, then

$$\mu_u(v) = (v, u) \tag{19.7.4}$$

defines a linear functional on V, and $u \mapsto \mu_u$ is a one-to-one linear mapping from V onto V'. If T is a linear mapping from V into itself, then it is easy to see that

$$T'(\mu_u) = \mu_{T^*(u)} \tag{19.7.5}$$

for every $u \in V$. Let $u, z \in V$ be given, and put

$$T_{z,u}(v) = (v, u)\, z \tag{19.7.6}$$

for every $v \in V$. This defines a linear mapping from V into itself, which corresponds to (19.6.10), with $\tau = \mu_u$. Observe that

$$(T_{z,u}(v), w) = (v, u)\,(z, w) = (v, T_{u,z}(w)) \tag{19.7.7}$$

for every $v, w \in V$, so that

$$(T_{z,u})^* = T_{u,z}. \tag{19.7.8}$$

Let $\alpha \in V$ with $\alpha \neq 0$ be given, and put

$$\widehat{\alpha} = 2\,\alpha\,(\alpha, \alpha)^{-1}. \tag{19.7.9}$$

Thus

$$\mu_{\widehat{\alpha}}(v) = (v, \widehat{\alpha}) = 2\,(v, \alpha)\,(\alpha, \alpha)^{-1} \tag{19.7.10}$$

for every $v \in V$, in the notation of (19.7.4). Note that

$$\mu_{\widehat{\alpha}}(\alpha) = 2, \tag{19.7.11}$$

and that

$$\sigma_\alpha(v) = v - \mu_{\widehat{\alpha}}(v)\,\alpha = v - 2\,(v, \alpha)\,(\alpha, \alpha)^{-1}\,\alpha \tag{19.7.12}$$

is the reflection on V associated to α with respect to $(\cdot, \cdot)$, as in Section 19.1. It is easy to see that

$$\sigma_\alpha^* = \sigma_\alpha, \tag{19.7.13}$$

using (19.7.8). This also corresponds to the fact that σ_α is an orthogonal transformation on V, and its own inverse.

Observe that σ_α may be considered as the reflection on V associated to $\widehat{\alpha}$ with respect to $(\cdot, \cdot)$ as well, so that

$$\sigma_{\widehat{\alpha}} = \sigma_\alpha. \tag{19.7.14}$$

Indeed, σ_α only depends on the line in V passing through α. Put

$$\widehat{(\widehat{\alpha})} = 2\,\widehat{\alpha}\,(\widehat{\alpha}, \widehat{\alpha})^{-1}, \tag{19.7.15}$$

as in (19.7.9). Clearly

$$(\widehat{\alpha}, \widehat{\alpha}) = 4\,(\alpha, \alpha)\,(\alpha, \alpha)^{-2} = 4\,(\alpha, \alpha)^{-1}, \tag{19.7.16}$$

so that

$$\widehat{(\widehat{\alpha})} = 4\,\alpha\,(\alpha, \alpha)^{-1}\,(4\,(\alpha, \alpha)^{-1})^{-1} = \alpha. \tag{19.7.17}$$

Using (19.7.12), we have that

$$\sigma_\alpha(v) = v - \mu_\alpha(v)\,\widehat{\alpha} = v - \mu_{\widehat{(\widehat{\alpha})}}(v)\,\widehat{\alpha} \tag{19.7.18}$$

for every $v \in V$, which is another way to look at (19.7.14).

Let $\beta \in V$ with $\beta \neq 0$ be given, and put $\widehat{\beta} = 2\,\beta\,(\beta,\beta)^{-1}$, as in (19.7.9). If T is an orthogonal transformation on V with respect to $(\cdot,\cdot)$, then

$$T(\widehat{\beta}) = 2\,T(\beta)\,(\beta,\beta)^{-1} = 2\,T(\beta)\,(T(\beta),T(\beta))^{-1} = \widehat{T(\beta)}, \tag{19.7.19}$$

where $\widehat{T(\beta)}$ is defined as in (19.7.9) too.

19.8 Inverse roots

Let V be a vector space over the real numbers of positive finite dimension, and let A be a root system in V. If $\alpha \in A$, then there is a unique symmetry σ_α on V with vector α that maps A onto itself, as in Section 19.3. Let λ_α be the linear functional on V such that $\lambda_\alpha(\alpha) = 2$ and $\lambda_\alpha = 0$ on the hyperplane of vectors in V fixed by σ_α, so that

$$\sigma_\alpha(v) = v - \lambda_\alpha(v)\,\alpha \tag{19.8.1}$$

for every $v \in V$, as before. As on p25 of [24], λ_α may be called the *inverse root* associated to α in the dual space V' of V. Let

$$A' = \{\lambda_\alpha : \alpha \in A\} \tag{19.8.2}$$

be the set of these inverse roots, which is a finite subset of V' that does not contain 0.

Let (v,w) be an inner product on V that is invariant under the Weyl group W of A, as in Section 19.4. Thus σ_α is the reflection on V associated to α with respect to (v,w), as in Section 19.1. In this situation,

$$\lambda_\alpha(v) = \mu_{\widehat{\alpha}}(v) = (v,\widehat{\alpha}) = 2\,(v,\alpha)\,(\alpha,\alpha)^{-1} \tag{19.8.3}$$

for every $v \in V$, using the notation in (19.7.4) and (19.7.9). Put

$$\widehat{A} = \{\widehat{\alpha} : \alpha \in A\} = \{2\,\alpha\,(\alpha,\alpha)^{-1} : \alpha \in A\}, \tag{19.8.4}$$

which is a finite subset of V that does not contain 0. It is easy to see that the linear span of (19.8.4) in V is equal to V, because of the corresponding property of A. Note that (19.8.4) corresponds to (19.8.2) under the isomorphism $u \mapsto \mu_u$ from V onto V' associated to the inner product. It follows that the linear span of A' in V' is equal to V'.

If $\beta \in V$, $\beta \neq 0$, and $\widehat{\beta}$ is as in (19.7.9), then

$$\sigma_\alpha(\widehat{\beta}) = (\widehat{\sigma_\alpha(\beta)}), \tag{19.8.5}$$

where $(\widehat{\sigma_\alpha(\beta)})$ is defined as in (19.7.9) too. This follows from (19.7.19), because σ_α is an orthogonal transformation on V with respect to $(\cdot, \cdot)$. This implies that

$$\sigma_\alpha(\widehat{A}) = \widehat{A}, \tag{19.8.6}$$

because $\sigma_\alpha(A) = A$. This is the same as saying that

$$\sigma_{\widehat{\alpha}}(\widehat{A}) = \widehat{A}, \tag{19.8.7}$$

because $\sigma_{\widehat{\alpha}} = \sigma_\alpha$, as in (19.7.14). Using (19.8.6), we get that

$$\sigma'_\alpha(A') = A', \tag{19.8.8}$$

where σ'_α is the dual linear mapping on V' associated to σ_α. This also uses the correspondence between (19.8.2) and (19.8.4) mentioned earlier, the correspondence between adjoints and dual linear mappings in (19.7.5), and the self-adjointness of σ_α, as in (19.7.13). Remember that σ'_α is a symmetry on V' with vector λ_α, as in Section 19.6.

If $\mu \in V'$, then

$$\sigma'_\alpha(\mu) = \mu - L_\alpha(\mu)\,\lambda_\alpha = \mu - \mu(\alpha)\,\lambda_\alpha, \tag{19.8.9}$$

as in (19.6.1) and (19.6.14). Let $\beta \in A$ be given, and let λ_β be the corresponding element of (19.8.2). We would like to check that

$$\sigma'_\alpha(\lambda_\beta) - \lambda_\beta \text{ is an integer multiple of } \lambda_\alpha. \tag{19.8.10}$$

This is the same as saying that

$$\lambda_\beta(\alpha) \in \mathbf{Z}, \tag{19.8.11}$$

by (19.8.9). This condition holds because A is a root system in V, as in Section 19.3. This shows that A' is a root system in V', as in Proposition 2 on p28 of [24]. This is called the *inverse system* or *dual system* of A in V'.

Alternatively, let us check that

$$\sigma_{\widehat{\alpha}}(\widehat{\beta}) - \widehat{\beta} \text{ is an integer multiple of } \widehat{\alpha}. \tag{19.8.12}$$

This means that

$$(\alpha, \widehat{\beta}) \in \mathbf{Z}, \tag{19.8.13}$$

by (19.7.14) and (19.7.18). This condition holds because A is a root system in V, as before. This shows that $\widehat{A}$ is a root system in V, which may be called the *inverse system* or *dual system* of A in V with respect to $(\cdot, \cdot)$. This corresponds to the formulation on p43 of [14].

If T is an invertible linear mapping on V, then the dual linear mapping T' is invertible on V', with

$$(T')^{-1} = (T^{-1})'. \tag{19.8.14}$$

It is well known and easy to see that the mapping from T to (19.8.14) defines a group isomorphism from $GL(V)$ onto $CL(V')$. This isomorphism takes the Weyl group of A onto the Weyl group of A'.

Similarly, if T is an invertible linear mapping on V, then the adjoint T^* of T with respect to $(\cdot,\cdot)$ is invertible on V as well, with

$$(T^*)^{-1} = (T^{-1})^*. \tag{19.8.15}$$

The mapping from T to (19.8.15) defines a group automorphism on $GL(V)$. The Weyl group of $\widehat{A}$ is the same as the Weyl group of A, because it is generated by the same reflections on V.

19.9 Angles between roots

Let V be a vector space over the real numbers of positive finite dimension, and let A be a root system in V. If $\alpha \in A$, then let σ_α be the unique symmetry on V with vector α that maps A onto itself, as in Section 19.3. Also let λ_α be the linear functional on V such that $\lambda_\alpha(\alpha) = 2$ and $\lambda_\alpha = 0$ on the hyperplane of vectors in V fixed by σ_α, as before. If $\beta \in A$ too, then put

$$n(\beta,\alpha) = \lambda_\alpha(\beta), \tag{19.9.1}$$

as on p29 of [24]. Remember that $n(\beta,\alpha) \in \mathbf{Z}$, as in Section 19.3.

Let (v,w) be an inner product on V that is invariant under the Weyl group of A, as in Section 19.4. If $v \in V$, then put

$$\|v\| = (v,v)^{1/2}, \tag{19.9.2}$$

which is the norm on V associated to $(\cdot,\cdot)$. Note that

$$n(\beta,\alpha) = 2\,(\beta,\alpha)\,(\alpha,\alpha)^{-1} \tag{19.9.3}$$

for every $\alpha,\beta \in A$, as in Section 19.3. Of course,

$$(\beta,\alpha) = \|\alpha\|\,\|\beta\|\,\cos\theta, \tag{19.9.4}$$

where $\theta \in [0,\pi]$ is the angle between α and β with respect to $(\cdot,\cdot)$. Thus

$$n(\beta,\alpha) = 2\,\|\alpha\|^{-1}\,\|\beta\|\,\cos\theta. \tag{19.9.5}$$

It follows that

$$n(\beta,\alpha)\,n(\alpha,\beta) = 4\,\cos^2\theta \tag{19.9.6}$$

for every $\alpha,\beta \in A$. The left side is an integer, and the right side is a nonnegative real number less than or equal to 4. This means that $4\cos^2\theta$ can only take the values $0,1,2,3,4$. Of course,

$$4\,\cos^2\theta = 4 \tag{19.9.7}$$

exactly when $\theta = 0$ or π, which means that α and β are proportional in V. Let us suppose now that α and β are not proportional in V, so that $0 < \theta < \pi$.

Similarly,

$$4 \cos^2 \theta = 0 \tag{19.9.8}$$

exactly when $\theta = \pi/2$, in which case

$$n(\beta, \alpha) = n(\alpha, \beta) = 0. \tag{19.9.9}$$

Otherwise, if $\theta \neq \pi/2$, then $\cos\theta \neq 0$, $(\alpha, \beta) \neq 0$, and

$$n(\alpha, \beta)/n(\beta, \alpha) = \|\alpha\|^2/\|\beta\|^2. \tag{19.9.10}$$

Remember that $\cos^2\theta + \sin^2\theta = 1$. Note that

$$4 \cos^2 \theta = 2 \tag{19.9.11}$$

if and only if $\theta = \pi/4$ or $3\,\pi/4$. If $\theta = \pi/4$, then we either have that

$$n(\alpha, \beta) = 1, \quad n(\beta, \alpha) = 2, \quad \text{and} \quad \|\beta\| = \sqrt{2}\,\|\alpha\|, \tag{19.9.12}$$

or the analogous conditions with α and β interchanged. If $\theta = 3\,\pi/4$, then we either have that

$$n(\alpha, \beta) = -1, \quad n(\beta, \alpha) = -2, \quad \text{and} \quad \|\beta\| = \sqrt{2}\,\|\alpha\|, \tag{19.9.13}$$

or the analogous conditions with α and β interchanged.

We also have that

$$4 \cos^2 \theta = 1 \tag{19.9.14}$$

if and only of $\theta = \pi/3$ or $2\,\pi/3$. More precisely,

$$n(\alpha, \beta) = n(\beta, \alpha) = 1 \tag{19.9.15}$$

when $\theta = \pi/3$, and

$$n(\alpha, \beta) = n(\beta, \alpha) = -1 \tag{19.9.16}$$

when $\theta = 2\,\pi/3$. In both cases,

$$\|\alpha\| = \|\beta\|. \tag{19.9.17}$$

Similarly,

$$4 \cos^2 \theta = 3 \tag{19.9.18}$$

if and only if $\theta = \pi/6$ or $5\,\pi/6$. If $\theta = \pi/6$, then we either have that

$$n(\alpha, \beta) = 1, \quad n(\beta, \alpha) = 3, \quad \text{and} \quad \|\beta\| = \sqrt{3}\,\|\alpha\|, \tag{19.9.19}$$

or the analogous conditions with α and β interchanged. If $\theta = 5\,\pi/6$, then we either have that

$$n(\alpha, \beta) = -1, \quad n(\beta, \alpha) = -3, \quad \text{and} \quad \|\beta\| = \sqrt{3}\,\|\alpha\|, \tag{19.9.20}$$

or the analogous conditions with α and β interchanged. This corresponds to remarks on p44 of [14], and p29 of [24].

If α and β are not proportional in V and

$$n(\alpha, \beta) > 0, \tag{19.9.21}$$

then

$$\alpha - \beta \in A, \tag{19.9.22}$$

as in Proposition 3 on p29 of [24]. Note that (19.9.21) is the same as saying that $\theta < \pi/2$, which is symmetric in α and β. In this situation, we have that $n(\alpha, \beta) = 1$ or $n(\beta, \alpha) = 1$, as before. Suppose that $n(\beta, \alpha) = 1$, so that $\lambda_\alpha(\beta) = 1$, as in (19.9.1). In this case,

$$\alpha - \beta = -(\beta - \lambda_\alpha(\beta)\,\alpha) = -\sigma_\alpha(\beta), \tag{19.9.23}$$

by the usual expression for σ_α in terms of λ_α. This implies (19.9.22), because $\sigma_\alpha(\beta) \in A$, and A is symmetric about 0 in V. If $n(\alpha, \beta) = 1$, then $\alpha - \beta = \sigma_\beta(\alpha) \in A$.

Of course, (19.9.21) is equivalent to

$$(\alpha, \beta) > 0, \tag{19.9.24}$$

by (19.9.3). The lemma on p45 of [14] is stated in terms of (19.9.24), where it is also mentioned that

$$\alpha + \beta \in A \tag{19.9.25}$$

when α and β are not proportional and

$$(\alpha, \beta) < 0. \tag{19.9.26}$$

This follows from the previous statement, applied to β in place of $-\beta$.

19.10 A criterion for linear independence

Let V be a vector space over the real numbers, and let (v, w) be an inner product on V. Also let τ be a linear functional on V, and let B be a nonempty subset of V. Suppose that

$$\tau(\beta) > 0 \tag{19.10.1}$$

for every $\beta \in B$, and that

$$(\beta, \gamma) \le 0 \tag{19.10.2}$$

for every $\beta, \gamma \in B$ with $\beta \neq \gamma$. Under these conditions, the elements of B are linearly independent in V. This corresponds to Lemma 4 on p31 of [24], and Step (3) on p48 of [14].

To see this, observe that a linear relation between elements of B can be expressed as

$$\sum_{\beta \in B_1} b_\beta\,\beta = \sum_{\gamma \in B_2} c_\gamma\,\gamma, \tag{19.10.3}$$

where B_1 and B_2 are nonempty disjoint finite subsets of B, and the coefficients b_β and c_γ are nonnegative real numbers. Let $v \in V$ be the vector determined by (19.10.3), so that

$$(v, v) = \sum_{\beta \in B_1} \sum_{\gamma \in B_2} b_\beta \, c_\gamma (\beta, \gamma). \tag{19.10.4}$$

It follows that $(v, v) \le 0$, by (19.10.2). Of course, this means that $v = 0$.

Using this, we get that

$$0 = \tau(v) = \sum_{\beta \in B_1} b_\beta \, \tau(\beta). \tag{19.10.5}$$

This implies that $b_\beta = 0$ for every $\beta \in B_1$, because of (19.10.1). Similarly, $c_\gamma = 0$ for every $\gamma \in B_2$, as desired.

19.11 Bases for root systems

Let V be a vector space over the real numbers of positive finite dimension, and let A be a root system in V. A subset B of A is said to be a *base* for A if it satisfies the following two conditions. The first condition is that B is a basis for V as a vector space over $\mathbf{R}$. The second condition is that every $\alpha \in A$ can be expressed as

$$\alpha = \sum_{\beta \in B} m_\beta \, \beta, \tag{19.11.1}$$

where $m_\beta \in \mathbf{Z}$ for every $\beta \in B$, and either $m_\beta \ge 0$ for every $\beta \in B$, or $m_\beta \le 0$ for every $\beta \in B$. This is Definition 4 on p30 of [24], which corresponds to the definition of a base on p47 of [14]. A base for a root system may also be called a *simple root system* or a *fundamental root system*, as mentioned on p30 of [24]. Similarly, the elements of the base may be called *simple roots*.

Of course, the second condition in the preceding paragraph implies in particular that A is contained in the linear span of B in V. Remember that the linear span of A in V is equal to V, by definition of a root system. Thus the second condition implies that the linear span of B in V is equal to V too.

Theorem 1 on p30 of [24] states that bases exist, which corresponds to the theorem at the top of p48 of [14]. More precisely, if τ is a linear functional on V, then put

$$A_\tau^+ = \{\alpha \in A : \tau(\alpha) > 0\}. \tag{19.11.2}$$

Let us choose $\tau \in V'$ so that for every $\alpha \in A$,

$$\tau(\alpha) \ne 0. \tag{19.11.3}$$

One can find such a $\tau \in V'$ as in Section 18.12. This implies that

$$A = A_\tau^+ \cup (-A_\tau^+). \tag{19.11.4}$$

Let us say that $\alpha \in A_\tau^+$ is decomposable if it can be expressed as the sum of two elements of A_τ^+, and indecomposable otherwise. The first part of Proposition 4 on p30 of [24] states that

$$B_\tau = \{\alpha \in A_\tau^+ : \alpha \text{ is indecomposable}\} \tag{19.11.5}$$

is a base for A. This corresponds to the first part of the second theorem on p48 of [14].

The first step in the proof is Lemma 2 on p30 of [24], which corresponds to Step (1) on p48 of [14]. This states that every element of A_τ^+ can be expressed as a linear combination of elements of B_τ, with coefficients that are nonnegative integers. Otherwise, there would be an $\alpha \in A_\tau^+$ that does not have this property, and for which $\tau(\alpha)$ is as small as possible. In particular, $\alpha \notin B_\tau$, so that α is decomposable. Thus there are $\alpha_1, \alpha_2 \in A_\tau^+$ whose sum is equal to α. This implies that

$$\tau(\alpha) = \tau(\alpha_1) + \tau(\alpha_2), \tag{19.11.6}$$

and hence

$$\tau(\alpha_1), \tau(\alpha_2) < \tau(\alpha), \tag{19.11.7}$$

because $\tau(\alpha_1), \tau(\alpha_2) > 0$. It follows that α_1 and α_2 can be expressed as linear combinations of elements of B_τ with coefficients that are nonnegative integers, by the minimality of $\tau(\alpha)$. This means that α has the same property, which is a contradiction.

Let (v, w) be an inner product on V that is invariant under the Weyl group of A, as in Section 19.4. If β_1 and β_2 are distinct elements of B_τ, then

$$(\beta_1, \beta_2) \leq 0. \tag{19.11.8}$$

This corresponds to Lemma 3 on p30 of [24], and Step (2) on p48 of [14]. Suppose for the sake of a contradiction that

$$(\beta_1, \beta_2) > 0. \tag{19.11.9}$$

If β_1 and β_2 are proportional in V, then the proportionality constant is positive, by (19.11.9). This implies that one of β_1 and β_2 is equal to 2 times the other, as in Section 19.3, because $\beta_1 \neq \beta_2$, by hypothesis. However, this would contradict the fact that the elements of B_τ are indecomposable. Otherwise, if β_1 and β_2 are not proportional in V, then $\gamma = \beta_1 - \beta_2 \in A$, as in Section 19.9. If $\gamma \in A_\tau^+$, then $\beta_1 = \beta_2 + \gamma$ is decomposable, contradicting the hypothesis that $\beta_1 \in B_\tau$. Similarly, if $-\gamma \in A_\tau^+$, then $\beta_2 = \beta_1 + (-\gamma)$ is decomposable, contradicting the hypothesis that $\beta_2 \in B_\tau$.

Using (19.11.8) and the fact that $B_\tau \subseteq A_\tau^+$, by construction, we get that the elements of B_τ are linearly independent in V, as in the previous section. Remember that the elements of A_τ^+ can be expressed as linear combinations of elements of B_τ, with coefficients that are nonnegative integers. Thus the elements of $-A_\tau^+$ can be expressed as linear combinations of elements of B_τ with coefficients that are integers less than or equal to 0. This shows that B_τ

satisfies the second condition in the definition of a base for A. In particular, the linear span of B_τ in V is equal to V, as before. It follows that B_τ is a basis for V as a vector space over $\mathbf{R}$. This implies that B_τ is a base for A, as on p31 of [24], and Step (4) on p48 of [14].

Conversely, suppose that B is any base for A. Let τ be a linear functional on V such that

$$\tau(\beta) > 0 \tag{19.11.10}$$

for every $\beta \in B$. It is easy to find such a $\tau \in V'$, because B is a basis for V. Let A^+ be the set of $\alpha \in A$ that can be expressed as a linear combination of elements of B with coefficients that are nonnegative integers. Observe that

$$A^+ \subseteq A^+_\tau, \tag{19.11.11}$$

where A^+_τ is as in (19.11.2). This implies that

$$-A^+ \subseteq -A^+_\tau. \tag{19.11.12}$$

It follows that

$$A^+ = A^+_\tau, \tag{19.11.13}$$

because $A = A^+ \cup (-A^+)$, by hypothesis. We also get that (19.11.3) holds, so that the remarks in the previous paragraphs hold for τ. Using (19.11.13), we obtain that the elements of B are indecomposable in A^+_τ, so that $B \subseteq B_\tau$. This implies that

$$B = B_\tau, \tag{19.11.14}$$

because B and B_τ have the same number of elements, which is the dimension of V. This corresponds to the second part of Proposition 4 on p30 of [24], and the second part of the second theorem on p48 of [14].

If β_1 and β_2 are distinct elements of B, then it is easy to see that their difference is not a root, using the second condition in the definition of a base for A. We also have that β_1 and β_2 are not proportional in V, because B is a basis for V. This implies that (19.11.8) holds, as in Section 19.9. This corresponds to the lemma on p47 of [14]. This could also be obtained from (19.11.14) and the previous proof, but this argument is more direct.

19.12 Positive roots

Let V be a vector space over the real numbers of positive finite dimension again, and let A be a root system in V. Also let B be a base for A, and let A^+ be the set of $\alpha \in A$ such that α can be expressed as a linear combination of elements of B with coefficients that are nonnegative integers, as in the previous section. The elements of A^+ are called *positive roots* with respect to B, as on p31 of [24], and p47 of [14].

Let τ be the linear functional on V such that

$$\tau(\beta) = 1 \tag{19.12.1}$$

for every $\beta \in B$. If $\gamma \in A^+$, then

$$\tau(\gamma) \in \mathbf{Z}_+. \tag{19.12.2}$$

Let (v, w) be an inner product on V that is invariant under the Weyl group of A, as in Section 19.4. If $\gamma \in A^+$, then we would like to check that there is a $\beta \in B$ such that

$$(\beta, \gamma) > 0. \tag{19.12.3}$$

Suppose for the sake of a contradiction that $(\beta, \gamma) \le 0$ for every $\beta \in B$. Remember that $(\beta_1, \beta_2) \le 0$ for all $\beta_1, \beta_2 \in B$ with $\beta_1 \ne \beta_2$, as in the previous section. Under these conditions, we get that $B \cup \{\gamma\}$ is linearly independent in V, as in Section 19.10, which is a contradiction.

Let $\gamma \in A^+$ be given, and put $r = \tau(\gamma) \in \mathbf{Z}_+$. Proposition 5 on p32 of [24] states that γ can be expressed as

$$\gamma = \sum_{j=1}^{r} \alpha_j, \tag{19.12.4}$$

where $\alpha_j \in B$ for each $j = 1, \ldots, r$, and

$$\sum_{j=1}^{l} \alpha_j \in A \tag{19.12.5}$$

for every $l = 1, \ldots, r$. This corresponds to the corollary to Lemma A on p50 of [14]. If $r = 1$, then $\gamma \in B$, and this is trivial. Otherwise, we can use induction on r, as follows.

As before, there is a $\beta \in B$ such that (19.12.3) holds. If β and γ are proportional in V, then one can check that either $\gamma = \beta$ or $\gamma = 2\,\beta$, using remarks in Section 19.3. The statement in the preceding paragraph obviously holds in both cases, and so we suppose now that β and γ are not proportional in V. This implies that

$$\gamma - \beta \in A, \tag{19.12.6}$$

as in Section 19.9.

If $\gamma - \beta \in -A^+$, so that $\beta - \gamma \in A^+$, then $\beta = \gamma + (\beta - \gamma)$ would be the sum of two elements of A^+. This is not possible, because $\beta \in B$. Otherwise, $\gamma - \beta \in A^+$, and of course

$$\tau(\gamma - \beta) = \tau(\gamma) - \tau(\beta) = r - 1. \tag{19.12.7}$$

This means that the induction hypothesis can be applied to $\gamma - \beta$. Thus the desired statement for γ can be obtained from the analogous statement for $\gamma - \beta$, with $\alpha_r = \beta$.

Suppose now that A is reduced, as in Section 19.3. Let $\alpha \in B$ be given, and let σ_α be the symmetry on V with vector α that maps A onto itself. Under these conditions,

$$\sigma_\alpha(A^+ \setminus \{\alpha\}) = A^+ \setminus \{\alpha\}, \tag{19.12.8}$$

as in Proposition 6 on p32 of [24], and Lemma B on p50 of [14]. To see this, it suffices to verify that

$$\sigma_\alpha(A^+ \setminus \{\alpha\}) \subseteq A^+ \setminus \{\alpha\}, \tag{19.12.9}$$

because σ_α is its own inverse on V.

Let $\gamma \in A^+ \setminus \{\alpha\}$ be given. Thus γ can be expressed as

$$\gamma = \sum_{\beta \in B} m_\beta \, \beta, \tag{19.12.10}$$

where m_β is a nonnegative integer for each $\beta \in B$, because $\gamma \in A^+$. Observe that γ is not proportional to α in this situation, because $\gamma \neq \alpha$ by hypothesis, and A is reduced. This means that there is a $\beta \in B$ such that $\beta \neq \alpha$ and $m_\beta \neq 0$.

Remember that $\sigma_\alpha(\gamma)$ is equal to γ minus a multiple of α. If we express $\sigma_\alpha(\gamma)$ as a linear combination of the basis vectors in B, we get that the coefficient of β in the expression for $\sigma_\alpha(\gamma)$ is equal to m_β too. This implies that $\sigma_\alpha(\gamma) \in A^+$, because $\sigma_\alpha(\gamma) \in A$, $m_\beta > 0$, and B is a base for A. We also have that $\sigma_\alpha(\gamma) \neq \alpha$, because $m_\beta \neq 0$, as desired.

Put

$$\rho = \frac{1}{2} \sum_{\gamma \in A^+} \gamma, \tag{19.12.11}$$

which is an element of V. Let us check that

$$\sigma_\alpha(\rho) = \rho - \alpha, \tag{19.12.12}$$

as in the corollary on p32 of [24], and the corollary to Lemma B on p50 of [14]. Put

$$\rho_\alpha = \frac{1}{2} \sum_{\gamma \in A^+ \setminus \{\alpha\}} \gamma, \tag{19.12.13}$$

which is interpreted as being 0 when $A^+ = \{\alpha\}$. Using (19.12.8), we get that $\sigma_\alpha(\rho_\alpha) = \rho_\alpha$. Note that $\rho = \rho_\alpha + \alpha/2$, by construction. We also have that $\sigma_\alpha(\alpha) = -\alpha$. Thus

$$\sigma_\alpha(\rho) = \sigma_\alpha(\rho_\alpha) + \sigma_\alpha(\alpha)/2 = \rho_\alpha - \alpha/2 = \rho - \alpha, \tag{19.12.14}$$

as desired.

19.13 Bases and duality

Let V be a vector space over the real numbers of positive finite dimension, and let A be a root system in V. If $\alpha \in A$, then we let σ_α be the symmetry on V with vector α that maps A onto itself, as usual. Let $\lambda_\alpha \in V'$ be the corresponding linear functional on V, so that $\lambda_\alpha(\alpha) = 2$ and $\lambda_\alpha = 0$ on the hyperplane of vectors in V fixed by σ_α. Remember that

$$A' = \{\lambda_\alpha : \alpha \in A\} \tag{19.13.1}$$

is a root system in the dual space V', as in Section 19.8.

If $\alpha \in A$ and $2\,\alpha \in A$, then

$$\sigma_{2\,\alpha} = \sigma_\alpha, \tag{19.13.2}$$

because σ_α may also be considered as a symmetry on V with vector $2\,\alpha$. In particular, this means that λ_α and $\lambda_{2\,\alpha}$ have the same kernel in V. One can check that

$$\lambda_{2\,\alpha} = \lambda_\alpha/2, \tag{19.13.3}$$

using the condition that $\lambda_{2\,\alpha}(2\,\alpha) = 2$.

Let B be a base for A, and put

$$B_1 = \{\beta \in B : 2\,\beta \notin A\}, \tag{19.13.4}$$

$$B_2 = \{\beta \in B : 2\,\beta \in A\}. \tag{19.13.5}$$

Of course, $B_2 = \emptyset$ when A is reduced. We would like to show that

$$\{\lambda_\beta : \beta \in B_1\} \cup \{\lambda_\beta/2 : \beta \in B_2\} \tag{19.13.6}$$

is a base for A'. This corresponds to Proposition 7 on p32 and the remark on p33 of [24]. Note that (19.13.6) is contained in A', by (19.13.3).

Let (v, w) be an inner product on V that is invariant under the Weyl group of A, as in Section 19.4. Using $(\cdot, \cdot)$, we get an isomorphism between V and V' in the usual way, as in Section 19.7. If $\alpha \in V$ and $\alpha \neq 0$, then put

$$\widehat{\alpha} = 2\,\alpha\,(\alpha, \alpha)^{-1}, \tag{19.13.7}$$

as before. Clearly

$$\widehat{(2\,\alpha)} = \widehat{\alpha}/2 \tag{19.13.8}$$

in this case.

If $\alpha \in A$, then we have seen that $\widehat{\alpha}$ corresponds to λ_α under the isomorphism between V and V' associated to $(\cdot, \cdot)$. Thus

$$\widehat{A} = \{\widehat{\alpha} : \alpha \in A\} \tag{19.13.9}$$

corresponds to A' under this isomorphism, as before. We also have that $\widehat{A}$ is a root system in V, as in Section 19.8.

We would like to show that

$$\{\widehat{\beta} : \beta \in B_1\} \cup \{\widehat{\beta}/2 : \beta \in B_2\} \tag{19.13.10}$$

is a base for $\widehat{A}$, as in [24]. This corresponds to Exercise 1 on p54 of [14], in the reduced case. Observe that (19.13.10) is contained in $\widehat{A}$, because of (19.13.8). It will follow that (19.13.6) is a base for A', because of the isomorphism between V and V' associated to $(\cdot, \cdot)$. It is easy to see that (19.13.10) is a basis for V, because B is a basis for V.

Let A^+ be the set of $\alpha \in A$ that can be expressed as a linear combination of elements of B with coefficients that are nonnegative integers, as before. Also let τ be a linear functional on V such that $\tau(\beta) > 0$ for every $\beta \in B$. If $\alpha \in A^+$, then $\tau(\alpha) > 0$, and hence

$$\tau(\widehat{\alpha}) > 0. \tag{19.13.11}$$

Similarly, if $\alpha \in -A^+$, then $\tau(\alpha) < 0$, so that

$$\tau(\widehat{\alpha}) < 0. \tag{19.13.12}$$

In particular, τ is nonzero at every element of $\widehat{A}$.

Let $(\widehat{A})^+_\tau$ be the set of elements of $\widehat{A}$ on which τ is positive, as in Section 19.11. Equivalently,

$$(\widehat{A})^+_\tau = \{\widehat{\alpha} : \alpha \in A^+\}, \tag{19.13.13}$$

as in the preceding paragraph. Let us say that an element of $(\widehat{A})^+_\tau$ is decomposable if it can be expressed as the sum of two elements of $(\widehat{A})^+_\tau$, and indecomposable otherwise, as in Section 19.11. The set of indecomposable elements of $(\widehat{A})^+_\tau$ is a base for $\widehat{A}$, as before. Note that (19.13.10) is contained in $(\widehat{A})^+_\tau$.

It suffices to show that (19.13.10) is the same as the set of indecomposable elements of $(\widehat{A})^+_\tau$. If an element of (19.13.10) is decomposable as an element of $(\widehat{A})^+_\tau$, then it could be expressed as the sum of two proportional elements of $(\widehat{A})^+_\tau$. One can check that this is not possible, because of the way that B_1 and B_2 are defined. Thus (19.13.10) is contained in the set of indecomposable elements of $(\widehat{A})^+_\tau$. It follows that these two sets are the same, because they have the same number of elements, which is the dimension of V.

The argument in [24] considers the associated convex cones in V. More precisely, let C be the set of vectors in V that can be expressed as linear combinations of elements of B with coefficients that are nonnegative real numbers. This is the same as the closed convex cone in V generated by A^+. This is also the same as the closed convex cone in V generated by $(\widehat{A})^+_\tau$, by (19.13.13). The extremal rays in C correspond exactly to half-lines through elements of B. Similarly, the extremal rays in C correspond to half-lines through the indecomposable elements of $(\widehat{A})^+_\tau$. This means that these collections of half-lines in V are the same. It follows that the indecomposable elements of $(\widehat{A})^+_\tau$ are all proportional to elements of B. One can use this to check that the set of indecomposable elements of $(\widehat{A})^+_\tau$ is the same as (19.13.10), as desired.

19.14 Bases and the Weyl group

Let V be a vector space over the real numbers of positive finite dimension, and let A be a reduced root system in V. Also let σ_α be the symmetry on V with vector $\alpha \in A$ that maps A onto itself, as usual. Thus the Weyl group W of A is the subgroup of $GL(V)$ generated by σ_α, $\alpha \in A$. Let B be a base for A, and let W_B be the subgroup of W generated by σ_β, $\beta \in B$. It is well known that

$$W_B = W, \tag{19.14.1}$$

as in Theorem 2 on p33 of [24], and the theorem on p51 of [14].

To show this, we first consider some other properties of W_B, as in [14, 24]. Let τ be a linear functional on V. If $\sigma \in W$, then let σ' be the corresponding dual linear mapping on the dual space V' of V, so that

$$\sigma'(\tau) = \tau \circ \sigma. \tag{19.14.2}$$

We would like to find a $\sigma \in W_B$ such that

$$(\sigma'(\tau))(\beta) = \tau(\sigma(\beta)) \geq 0 \tag{19.14.3}$$

for every $\beta \in B$. This corresponds to part (a) of Theorem 2 on p33 of [24], as mentioned in its proof. Part (a) of the theorem on p51 of [14] is very similar, but formulated a bit differently. See also Exercise 14 on p55 of [14].

Let A^+ be the set of $\alpha \in A$ that can be expressed as a linear combination of elements of B with coefficients that are nonnegative integers, as usual. Also let ρ be the element of V that is one-half the sum of the elements of A^+. We can choose $\sigma \in W_B$ such that

$$(\sigma'(\tau))(\rho) = \tau(\sigma(\rho)) \tag{19.14.4}$$

is maximal in $\mathbf{R}$. If $\beta \in B$, then $\sigma \circ \sigma_\beta \in W_B$, so that

$$(\sigma'(\tau))(\rho) \geq ((\sigma \circ \sigma_\beta)'(\tau))(\rho). \tag{19.14.5}$$

Of course,

$$((\sigma \circ \sigma_\beta)'(\tau))(\rho) = \tau(\sigma(\sigma_\beta(\rho))). \tag{19.14.6}$$

Under these conditions, we have that

$$\sigma_\beta(\rho) = \rho - \beta, \tag{19.14.7}$$

as in (19.12.12). Thus

$$((\sigma \circ \sigma_\beta)'(\tau))(\rho) = \tau(\sigma(\rho - \beta)) = (\sigma'(\tau))(\rho - \beta). \tag{19.14.8}$$

It follows that

$$(\sigma'(\tau))(\rho) \geq (\sigma'(\tau))(\rho - \beta), \tag{19.14.9}$$

by (19.14.5). This implies (19.14.3), as desired.

If $\widetilde{B}$ is another base for A, then there is a $\sigma \in W_B$ such that

$$\sigma(B) = \widetilde{B} \tag{19.14.10}$$

This corresponds to part (b) of Theorem 2 on p33 of [24], and part (b) of the theorem on p51 of [14], as mentioned in their proofs again. To see this, let $\widetilde{\tau}$ be a linear functional on V such that

$$\widetilde{\tau}(\widetilde{\beta}) > 0 \tag{19.14.11}$$

for every $\widetilde{\beta} \in \widetilde{B}$, which is possible because $\widetilde{B}$ is a basis for V. As in the previous paragraphs, there is a $\sigma \in W_B$ such that

(19.14.12) $$(\sigma'(\widetilde{\tau}))(\beta) \geq 0$$

for every $\beta \in B$. Put

(19.14.13) $$\tau = \sigma'(\widetilde{\tau}) = \widetilde{\tau} \circ \sigma \in V',$$

so that

(19.14.14) $$\tau(\beta) \geq 0$$

for every $\beta \in B$.

If $\alpha \in A$ can be expressed as a linear combination of elements of $\widetilde{B}$ with coefficients that are nonnegative integers, then $\widetilde{\tau}(\alpha) > 0$, as usual. Otherwise, $\widetilde{\alpha} < 0$, so that $\widetilde{\tau}(\alpha) \neq 0$ for every $\alpha \in A$. This implies that

(19.14.15) $$\tau(\alpha) = \widetilde{\tau}(\sigma(\alpha)) \neq 0$$

for every $\alpha \in A$, because $\sigma(A) = A$. It follows that $\tau(\beta) > 0$ for every $\beta \in B$, because of (19.14.14).

Let A^+_τ and $A^+_{\widetilde{\tau}}$ be the collections of $\alpha \in A$ such that

(19.14.16) $$\widetilde{\tau}(\sigma(\alpha)) = \tau(\alpha) > 0$$

and $\widetilde{\tau}(\alpha) > 0$, respectively. It is easy to see that

(19.14.17) $$\sigma(A^+_\tau) = A^+_{\widetilde{\tau}},$$

because $\sigma(A) = A$. The elements of B and $\widetilde{B}$ may be characterized as the indecomposable elements of A^+_τ and $A^+_{\widetilde{\tau}}$, respectively, as in Section 19.11. Thus (19.14.10) follows from (19.14.17), as desired.

If $\gamma \in A$, then there is a $\sigma \in W_B$ such that

(19.14.18) $$\sigma(\gamma) \in B.$$

This corresponds to part (c) of Theorem 2 on p33 of [24], and part (c) of the theorem on p51 of [14], as mentioned in their proofs. In this argument, it will be convenient to let

(19.14.19) $$V'_a = \{\lambda \in V' : \lambda(a) = 0\}$$

be the hyperplane in V' dual to a nonzero element a of V. If b is another nonzero element of V, then $V'_a = V'_b$ exactly when a and b are proportional in V. In particular, if $\alpha \in A$ and $\alpha \neq \pm\gamma$, then

(19.14.20) $$V'_\alpha \neq V'_\gamma,$$

because A is reduced, by hypothesis.

Thus, if $\alpha \in A$ and $\alpha \neq \pm\gamma$, then

(19.14.21) $$V'_\alpha \cap V'_\gamma$$

is a hyperplane in V'_γ. The union of (19.14.21) over $\alpha \in A$ with $\alpha \neq \pm\gamma$ is not all of V'_γ, as in Section 18.12. This implies that there is a $\tau_0 \in V'$ such that $\tau_0(\gamma) = 0$ and $\tau_0(\alpha) \neq 0$ for every $\alpha \in A$ with $\alpha \neq \pm\gamma$. Of course, there is also a linear functional on V that is positive on γ. By adding a sufficiently small multiple of such a linear functional on V to τ_0, we can get $\tau \in V'$ such that

$$\tau(\gamma) > 0 \tag{19.14.22}$$

and

$$|\tau(\alpha)| > \tau(\gamma) \tag{19.14.23}$$

for every $\alpha \in A$ with $\alpha \neq \pm\gamma$.

In particular, $\tau(\alpha) \neq 0$ for every $\alpha \in A$. Thus we can get a base B_τ for A using τ as in Section 19.11. One can check that

$$\gamma \in B_\tau \tag{19.14.24}$$

in this situation, which is to say that γ is indecomposable as an element of the set A_τ^+ of $\alpha \in A$ with $\tau(\alpha) > 0$. As in (19.14.10), there is an element of W_B that maps B onto B_τ. Using this, we can get (19.14.18) from (19.14.24), as desired.

Let us now use (19.14.18) to obtain (19.14.1), as in [14, 24]. If $\gamma \in A$, then we would like to show that

$$\sigma_\gamma \in W_B. \tag{19.14.25}$$

Let σ be an element of W_B such that $\sigma(\gamma) \in B$, which implies that $\sigma_{\sigma(\gamma)} \in W_B$. It is easy to see that

$$\sigma \circ \sigma_\gamma \circ \sigma^{-1} \tag{19.14.26}$$

is a symmetry on V with vector $\sigma(\gamma)$, because σ_γ is a symmetry on V with vector γ. We also have that (19.14.26) maps A onto itself, because $\sigma(A) = \sigma_\gamma(A) = A$. This implies that (19.14.26) is equal to $\sigma_{\sigma(\gamma)}$. Equivalently, this means that

$$\sigma_\gamma = \sigma^{-1} \circ \sigma_{\sigma(\gamma)} \circ \sigma. \tag{19.14.27}$$

It follows that (19.14.25) holds, as desired, because $\sigma, \sigma_{\sigma(\gamma)} \in W_B$.

19.15 Weyl chambers

Let V be a vector space over the real numbers of positive finite dimension n, and let A be a root system in V. Let us say that a linear functional τ on V is *regular* with respect to A if for every $\alpha \in A$, $\tau(\alpha) \neq 0$. This corresponds to terminology on p48 of [14], although in [14] an inner product on V is used, so that the dual space V' of V can be identified with V. The set of linear functionals on V that are regular with respect to A is the same as

$$V' \setminus \Big(\bigcup_{\alpha \in A} V'_\alpha \Big), \tag{19.15.1}$$

where V'_α is the hyperplane in V' dual to $\alpha \in A$, as in (19.14.19). Of course, V' is isomorphic to $\mathbf{R}^n$, as a vector space over $\mathbf{R}$. This leads to a natural topology on V', corresponding to the standard topology on $\mathbf{R}^n$. This topology does not depend on the particular isomorphism with $\mathbf{R}^n$, because linear mappings on $\mathbf{R}^n$ are continuous with respect to the standard topology. Note that (19.15.1) is an open set with respect to this topology. Remember that (19.15.1) is nonempty, as in Section 18.12.

Let B be a base for A, and let $A^{B,+}$ be the set of $\alpha \in A$ that can be expressed as a linear combination of elements of B with coefficients that are nonnegative integers. Thus

$$A = A^{B,+} \cup (-A^{B,+}), \tag{19.15.2}$$

by the definition of a base. If $\tau \in V'$ satisfies

$$\tau(\beta) > 0 \quad \text{for every } \beta \in B, \tag{19.15.3}$$

then

$$\tau(\alpha) > 0 \quad \text{for every } \alpha \in A^{B,+}, \tag{19.15.4}$$

as before. The converse holds trivially, because $B \subseteq A^{B,+}$. Observe that τ is regular with respect to A when (19.15.4) holds, because of (19.15.2). The set of $\tau \in V'$ that satisfy (19.15.3) is called the *Weyl chamber* associated to B, as in Remark 2 on p34 of [24]. This corresponds to the fundamental Weyl chamber relative to B defined on p49 of [14], using an inner product on V, as before.

Let τ be a linear functional on V that is regular with respect to A, and let A_τ^+ be the set of $\alpha \in A$ such that $\tau(\alpha) > 0$, as in Section 19.11. If τ satisfies (19.15.3) and hence (19.15.4), then $A^{B,+} \subseteq A_\tau^+$, which implies that

$$A^{B,+} = A_\tau^+, \tag{19.15.5}$$

because of (19.15.2), as in Section 19.11. Conversely, (19.15.5) implies (19.15.4), and thus (19.15.3). Let B_τ be the set of indecomposable elements of A_τ^+, which is a base for A, as in Section 19.11. If τ satisfies (19.15.3), then $B = B_\tau$, as before. Conversely, if $B = B_\tau$, then $B \subseteq A_\tau^+$, which means that (19.15.3) holds. This shows that the Weyl chamber associated to B consists exactly of the linear functionals τ on V that are regular with respect to A and satisfy $B = B_\tau$. In particular, if τ is any linear functional on V that is regular with respect to A, then τ is an element of the Weyl chamber associated to B_τ.

It is easy to see that the Weyl chamber associated to B is an open convex cone in V, so that it is connected in particular. If $\widetilde{B}$ is another base for A, $\widetilde{B} \neq B$, then the Weyl chambers associated to B and $\widetilde{B}$ are disjoint, by the remarks in the preceding paragraph. The union of the Weyl chambers associated to bases for A is equal to the set of linear functionals on V that are regular with respect to A, as before. It follows that the Weyl chambers associated to bases for A are the same as the connected components of (19.15.1).

If $\widetilde{B}$ is another base for A and

$$\widetilde{B} \subseteq A^{B,+}, \tag{19.15.6}$$

then

$$\widetilde{B} = B. \tag{19.15.7}$$

Indeed, if $\tau \in V'$ satisfies (19.15.3) and hence (19.15.4), then $\tau(\widetilde{\beta}) > 0$ for every $\widetilde{\beta} \in \widetilde{B}$. This implies that $\widetilde{B} = B_\tau$, as before, so that (19.15.7) holds, because $B = B_\tau$ too.

Chapter 20

Root systems, 2

20.1 Products in the Weyl group

Let V be a vector space over the real numbers of positive finite dimension, and let A be a reduced root system in V. If $\alpha \in A$, then we let σ_α be the symmetry on V with vector α that maps A onto itself, as before. Let B be a base for A, and remember that the Weyl group W of A is generated by σ_β, $\beta \in B$, as in Section 19.14.

Let $r \geq 2$ be an integer, and let $\gamma_1, \ldots, \gamma_r$ be r elements of B, possibly with repetitions. Put $\sigma_j = \sigma_{\gamma_j}$ for each $j = 1, \ldots, r$, and consider

$$(\sigma_1 \circ \cdots \circ \sigma_{r-1})(\gamma_r), \tag{20.1.1}$$

which is an element of A. Thus (20.1.1) can be expressed as a linear combination of elements of B with integer coefficients, and where the coefficients are either all greater than or equal to 0, or all less than or equal to 0. If the coefficients are all less than or equal to 0, then there is a positive integer $n < r$ such that

$$\sigma_1 \circ \cdots \circ \sigma_r = \sigma_1 \circ \cdots \sigma_{n-1} \circ \sigma_{n+1} \circ \cdots \circ \sigma_{r-1}. \tag{20.1.2}$$

This corresponds to Lemma C on p50 of [14]. More precisely, in the first part of the right side of (20.1.2), $\sigma_1 \circ \cdots \circ \sigma_{n-1}$ is interpreted as being the identity mapping on V when $n = 1$. Similarly, if $n = r - 1$, then $\sigma_{n+1} \circ \cdots \circ \sigma_{r-1}$ is interpreted as being the identity mapping on V in the second part of the right side of (20.1.2).

To see this, put

$$\delta_j = (\sigma_{j+1} \circ \cdots \circ \sigma_{r-1})(\gamma_r) \tag{20.1.3}$$

for $j = 0, \ldots, r-2$, and $\delta_{r-1} = \gamma_r$. Note that δ_0 is the same as (20.1.1), whose coefficients with respect to B are all less than or equal to 0, by hypothesis. Of course, the coefficients of $\delta_{r-1} = \gamma_r$ with respect to B are all greater than or equal to 0, because $\gamma_r \in B$. Let n be the smallest positive integer less than or equal to 0 such that the coefficients of δ_n with respect to B are all greater than or equal to 0, so that the coefficients of

$$\delta_{n-1} = \sigma_n(\delta_n) \tag{20.1.4}$$

with respect to B are all less than or equal to 0. This implies that

$$\gamma_n = \delta_n, \tag{20.1.5}$$

by (19.12.8).

If $\alpha \in A$ and T is an invertible linear mapping on V that maps A onto itself, then $T \circ \sigma_\alpha \circ T^{-1} = \sigma_{T(\alpha)}$, as in Section 19.4. Let us take $\alpha = \gamma_r$ and $T = \sigma_{n+1} \circ \cdots \circ \sigma_{r-1}$, so that $T(\alpha) = \delta_n$. Combining this with (20.1.5), we obtain that

$$\sigma_n = (\sigma_{n+1} \circ \cdots \circ \sigma_{r-1}) \circ \sigma_r \circ (\sigma_{r-1} \circ \cdots \circ \sigma_{n+1}). \tag{20.1.6}$$

It is easy to get (20.1.2) from (20.1.6).

Put

$$\sigma = \sigma_1 \circ \cdots \circ \sigma_r, \tag{20.1.7}$$

and suppose now that r is the smallest positive integer such that σ can be expressed as the composition of r symmetries associated to elements of B. The previous statement implies that the coefficients of (20.1.1) with respect to B are all greater than or equal to 0. Remember that $\sigma_r(\gamma_r) = -\gamma_r$, so that

$$\sigma(\gamma_r) = -(\sigma_1 \circ \cdots \circ \sigma_{r-1})(\gamma_r). \tag{20.1.8}$$

It follows that the coefficients of $\sigma(\gamma_r)$ with respect to B are all less than or equal to 0, as in the corollary to Lemma C on p50 of [14]. Note that this holds automatically when $r = 1$.

If σ is any element of the Weyl group W of A, then σ can be expressed as the composition of finitely many symmetries associated to elements of B, as before. In particular, if σ is not the identity mapping on V, then one needs at least one of these symmetries. This means that σ can be expressed as in (20.1.7) for some positive integer r, and we may as well take r to be as small as possible. Under these conditions, σ cannot map B onto itself, as in the preceding paragraph.

Equivalently, if $\sigma \in W$ satisfies

$$\sigma(B) = B, \tag{20.1.9}$$

then σ is the identity mapping on V. This corresponds to part (e) of the theorem on p51 of [14]. This also corresponds to Proposition 4 on p62 of [24].

20.2 The Cartan matrix

Let V be a vector space over the real numbers of positive finite dimension, and let A be a root system in V. If $\alpha \in A$, then let σ_α be the symmetry on V

with vector α that maps A onto itself, and let λ_α be the corresponding linear functional on V. Thus $\lambda_\alpha(\alpha) = 2$, and $\lambda_\alpha = 0$ on the hyperplane of vectors in V that are fixed by σ_α. If $\beta \in A$ too, then we put

$$n(\alpha, \beta) = \lambda_\beta(\alpha), \tag{20.2.1}$$

as in Section 19.9. Of course, this is an integer, by the definition of a root system.

Let $(\cdot, \cdot)$ be an inner product on V that is invariant under the Weyl group W of A. This means that σ_α is the reflection on V with respect to $(\cdot, \cdot)$ associated to $\alpha \in A$, so that $\lambda_\alpha(v) = 2\,(v, \alpha)\,(\alpha, \alpha)^{-1}$ for every $v \in V$. In particular,

$$n(\alpha, \beta) = 2\,(\alpha, \beta)\,(\beta, \beta)^{-1} \tag{20.2.2}$$

for every $\alpha, \beta \in A$.

Let B be a base for A. The *Cartan matrix* of A with respect to B is $n(\alpha, \beta)$ as a function of $\alpha, \beta \in B$, as in Definition 5 on p34 of [24], and p55 of [14]. Note that $n(\alpha, \alpha) = \lambda_\alpha(\alpha) = 2$ for every $\alpha \in A$, and in particular for $\alpha \in B$. If $\alpha, \beta \in B$ and $\alpha \neq \beta$, then $n(\alpha, \beta) \leq 0$, by (19.11.8) and (20.2.2). Of course, α and β are not proportional in this situation. It follows that

$$n(\alpha, \beta) \in \{0, -1, -2, -3\} \tag{20.2.3}$$

when $\alpha \neq \beta$, as in Section 19.9, and mentioned on p34 of [24]. If A is reduced, then A is determined up to isomorphism by the Cartan matrix, as in Proposition 8 on p34 of [24].

More precisely, let $\widetilde{V}$ be another vector space over the real numbers of positive finite dimension, and let $\widetilde{A}$ be a reduced root system in $\widetilde{V}$. If $\widetilde{\alpha} \in \widetilde{A}$, then let $\widetilde{\sigma}_{\widetilde{\alpha}}$ on $\widetilde{V}$ with vector $\widetilde{\alpha}$ that maps $\widetilde{A}$ onto itself, as usual. Also let $\widetilde{\lambda}_{\widetilde{\alpha}}$ be the corresponding linear functional on $\widetilde{V}$, so that $\widetilde{\lambda}_{\widetilde{\alpha}}(\widetilde{\alpha}) = 2$ and $\widetilde{\lambda}_{\widetilde{\alpha}} = 0$ on the hyperplane of vectors in $\widetilde{V}$ that are fixed by $\widetilde{\sigma}_{\widetilde{\alpha}}$. If $\widetilde{\beta} \in \widetilde{A}$ too, then we put

$$\widetilde{n}(\widetilde{\alpha}, \widetilde{\beta}) = \widetilde{\lambda}_{\widetilde{\beta}}(\widetilde{\alpha}), \tag{20.2.4}$$

as before. Let $\widetilde{B}$ be a base for $\widetilde{A}$, so that the restriction of (20.2.4) to $\widetilde{\alpha}, \widetilde{\beta} \in \widetilde{B}$ is the Cartan matrix of $\widetilde{A}$ with respect to $\widetilde{B}$.

Suppose that ϕ is a one-to-one mapping from B onto $\widetilde{B}$ such that

$$\widetilde{n}(\phi(\alpha), \phi(\beta)) = n(\alpha, \beta) \tag{20.2.5}$$

for every $\alpha, \beta \in B$. If A is reduced, then ϕ extends to a unique one-to-one linear mapping f from V onto $\widetilde{V}$ such that

$$f(A) = \widetilde{A}. \tag{20.2.6}$$

This is Proposition 8' on p35 of [24], which corresponds to the proposition on p55 of [14]. Remember that B and $\widetilde{B}$ are bases for V and $\widetilde{V}$, respectively, as vector spaces over $\mathbf{R}$, by the definition of a base for a root system. Thus ϕ automatically extends to a unique one-to-one linear mapping f from V onto $\widetilde{V}$, and in particular V and $\widetilde{V}$ have the same dimension as vector spaces over $\mathbf{R}$.

If $\alpha, \beta \in B$, then

$$(\widetilde{\sigma}_{\phi(\alpha)} \circ f)(\beta) = \widetilde{\sigma}_{\phi(\alpha)}(\phi(\beta)) = \phi(\beta) - \widetilde{n}(\phi(\beta), \phi(\alpha))\, \phi(\alpha) \tag{20.2.7}$$

and

$$(f \circ \sigma_\alpha)(\beta) = f(\beta - n(\beta, \alpha)\, \alpha) = \phi(\beta) - n(\beta, \alpha)\, \phi(\alpha). \tag{20.2.8}$$

Using our hypothesis (20.2.5), we get that the right sides of (20.2.7) and (20.2.8) are the same. This implies that

$$\widetilde{\sigma}_{\phi(\alpha)} \circ f = f \circ \sigma_\alpha \tag{20.2.9}$$

on V for every $\alpha \in B$, because V is spanned by $\beta \in B$. Equivalently,

$$\widetilde{\sigma}_{\phi(\alpha)} = f \circ \sigma_\alpha \circ f^{-1} \tag{20.2.10}$$

on $\widetilde{V}$ for every $\alpha \in B$.

As usual, $GL(V)$ and $GL(\widetilde{V})$ denote the general linear groups of invertible linear mappings on V and $\widetilde{V}$, respectively. Of course,

$$\sigma \mapsto f \circ \sigma \circ f^{-1} \tag{20.2.11}$$

is a group isomorphism from $GL(V)$ onto $GL(\widetilde{V})$. Remember that the Weyl groups W and $\widetilde{W}$ of A and $\widetilde{A}$ are generated by the symmetries associated to elements of B and $\widetilde{B}$, respectively, as in Section 19.14. Using this and (20.2.10), we get that (20.2.11) maps W onto $\widetilde{W}$.

Remember that A is the same as the set of images of elements of B under elements of W, and similarly for $\widetilde{A}$, as in Section 19.14. Using this and the remarks in the preceding paragraph, it is easy to see that (20.2.6) holds, as desired.

Of course, a one-to-one linear mapping f from V onto $\widetilde{V}$ that satisfies (20.2.6) is the same as an isomorphism between the root systems A and $\widetilde{A}$, as in Section 19.5. In this case, we have that

$$\widetilde{n}(f(\alpha), f(\beta)) = n(\alpha, \beta) \tag{20.2.12}$$

for every $\alpha, \beta \in A$, by (19.5.9).

Let $\mathrm{Aut}(A)$ be the group of automorphisms of A, which is the subgroup of $GL(V)$ consisting of invertible linear mappings on V that send A onto itself. Remember that the Weyl group W of A is a normal subgroup of $\mathrm{Aut}(A)$, as in Section 19.4. If $T \in \mathrm{Aut}(A)$, then

$$n(T(\alpha), T(\beta)) = n(\alpha, \beta) \tag{20.2.13}$$

for every $\alpha, \beta \in A$, as in (20.2.12). Of course,

$$\{T \in \mathrm{Aut}(A) : T(B) = B\} \tag{20.2.14}$$

is a subgroup of $\mathrm{Aut}(A)$ as well. The elements of this subgroup are uniquely determined by their restrictions to B, because B is a basis for V as a vector space over $\mathbf{R}$. If A is reduced, then the restrictions of elements of (20.2.14) to B are characterized by the condition that (20.2.13) hold for every $\alpha, \beta \in B$, as before. In this case, the intersection of W and (20.2.14) is the trivial subgroup of $\mathrm{Aut}(A)$, as in the previous section.

If T is any element of $\mathrm{Aut}(A)$, then it is easy to see that $T(B)$ is a base for A too. If A is reduced, then there is a $\sigma \in W$ such that

$$\sigma(T(B)) = B, \tag{20.2.15}$$

as in Section 19.14. Equivalently, this means that $\sigma \circ T$ is an element of (20.2.14). This corresponds to Proposition 9 on p35 of [24], and some remarks beginning on p65 of [14].

20.3 Coxeter graphs

As on p35 of [24], a *Coxeter graph* is a finite graph, where each pair of distinct vertices may be joined by 0, 1, 2, or 3 edges.

Let V be a vector space over the real numbers of positive finite dimension, let A be a root system in V, and let B be a base for A. If $\alpha, \beta \in A$, then $\lambda_\alpha \in V'$ and $n(\alpha, \beta) \in \mathbf{Z}$ are defined in the usual way, as in the previous section. If $\alpha, \beta \in B$ and $\alpha \neq \beta$, then α and β are not proportional, and

$$n(\alpha, \beta)\, n(\beta, \alpha) \tag{20.3.1}$$

can only be equal to 0, 1, 2, or 3, as in Section 19.9. Of course, (20.3.1) is symmetric in α and β.

The *Coxeter graph of A with respect to B* is defined as follows, as on p35 of [24], and p56 of [14]. We take B to be the set of vertices of the Coxeter graph. If α and β are distinct elements of B, then the number of edges between α and β is equal to (20.3.1).

If $\widetilde{B}$ is another base for A, then there is an element σ of the Weyl group of A that maps B onto $\widetilde{B}$, as in Section 19.14. This leads to an isomorphism between the Coxeter graphs of A with respect to B and $\widetilde{B}$.

Let $(\cdot, \cdot)$ be an inner product on V that is invariant under the Weyl group of A. Using (20.2.2), we get that

$$n(\alpha, \beta)\, n(\beta, \alpha) = 4\, (\alpha, \beta)^2\, \|\alpha\|^{-2}\, \|\beta\|^{-2} \tag{20.3.2}$$

for every $\alpha, \beta \in A$, where $\|\cdot\|$ is the norm on V associated to $(\cdot, \cdot)$. Equivalently, this is the same as 4 times the square of the cosine of the angle between α and β, as in Section 19.9. In particular, (20.3.2) is equal to 0 exactly when $(\alpha, \beta) = 0$.

The Coxeter graph of A with respect to B is determined by the Cartan matrix of A with respect to B in an obvious way. Remember that the diagonal entries of the Cartan matrix are equal to 2, and that the other entries are less than or equal to 0. It is easy to see that the Cartan metrix of A with respect to B is determined by the Coxeter graph of A with respect to B together with the ratios of the norms of the elements of B.

More precisely, let α and β be distinct elements of B. If (20.3.2) is equal to 0, then $(\alpha, \beta) = 0$, and hence $n(\alpha, \beta) = 0$. Otherwise, if (20.3.2) is not zero, and if one knows if $\|\alpha\|$ and $\|\beta\|$ are the same, or which is larger, then $n(\alpha, \beta)$ can be determined from (20.3.2) as in Section 19.9. This is discussed beginning on p56 of [14], and on p38 of [24].

20.4 Reducibility

Let V be a vector space over the real numbers of positive finite dimension again, let A be a root system in V, and let $(\cdot, \cdot)$ be an inner product on V that is invariant under the Weyl group of A. Suppose for the moment that V is the direct sum of two nontrivial linear subspaces V_1 and V_2, as a vector space over $\mathbf{R}$, and that

$$A \subseteq V_1 \cup V_2. \tag{20.4.1}$$

Put $A_j = A \cap V_j$ for $j = 1, 2$. If $\alpha \in V_1$ and $\beta \in V_2$, then $\alpha - \beta$ is not an element of $V_1 \cup V_2$, and thus is not in A. This implies that $(\alpha, \beta) \leq 0$, as in Section 19.9. The same argument could be applied to α and $-\beta$, to get that $(\alpha, \beta) \geq 0$, and hence

$$(\alpha, \beta) = 0. \tag{20.4.2}$$

It is easy to see that the linear span of A_j is equal to V_j for each $j = 1, 2$, because the linear span of A is V. It follows that the elements of V_1 and V_2 are orthogonal to each other with respect to $(\cdot, \cdot)$, as in part (a) of Proposition 10 on p36 of [24].

If $\alpha \in A$, then the symmetry σ_α on V with vector α that maps A onto itself is the reflection associated to α with respect to $(\cdot, \cdot)$. If $\alpha \in A_1$, then σ_α fixes every element of the hyperplane orthogonal to α, which contains V_2. In particular, $\sigma_\alpha(V_2) = V_2$, which implies that $\sigma_\alpha(V_1) = V_1$. One also can check the latter more directly. It follows that A_1 is a root system in V_1, and similarly A_2 is a root system in V_2. This is part (b) of Proposition 10 on p36 of [24]. Under these conditions, A is considered to be the *sum* of A_1 and A_2, as on p36 of [24]. If A cannot be expressed as the sum of two root systems in this way, then A is said to be *irreducible*, as on p36 of [24], and p52 of [14].

Irreducibility of A is equivalent to the connectedness of the Coxeter graph of A, as in Proposition 12 on p36 of [24], and mentioned on p57 of [14]. More precisely, the connectedness of the Coxeter graph of A with respect to a base B for A does not depend on the choice of B, because other choices lead to isomorphic graphs, as before.

Suppose that A corresponds to the sum of subsystems A_1 and A_2, as before. If B_1 and B_2 are bases for A_1 and A_2, then it is easy to see that $B_1 \cup B_2$ is a base for A. If $\alpha \in B_1$ and $\beta \in B_2$, then $(\alpha, \beta) = 0$, so that α and β are not connected by any edges in the Coxeter graph of A with respect to $B_1 \cup B_2$. This means that the Coxeter graph of A with respect to $B_1 \cup B_2$ is not connected, as desired. This is one half of the proof of Proposition 12 on p36 of [24].

Alternatively, let B be any base for A, and put $B_j = A_j \cap B$ for $j = 1, 2$. Every element of B_1 is orthogonal to every element of B_2, so that there are no edges between B_1 and B_2 in the Coxeter graph of A with respect to B. To get that the Coxeter graph is not connected, one has to check that $B_1, B_2 \neq \emptyset$. Equivalently, one can verify that B cannot be contained in A_1 or A_2, as on p52 of [14].

Conversely, suppose that the Coxeter graph of A with respect to a base B is not connected. This implies that B can be expressed as the union of disjoint nonempty subsets B_1 and B_2, with no edges in the Coxeter graph between elements of B_1 and B_2. Equivalently, every element of B_1 is orthogonal to every element of B_2 with respect to $(\cdot, \cdot)$. Let V_1 and V_2 be the linear subspaces of V spanned by B_1 and B_2, respectively, so that every element of V_1 is orthogonal to every element of V_2. Note that V corresponds to the direct sum of V_1 and V_2, because V is spanned by B.

If $\beta \in B_1$, then σ_β fixes every element of the hyperplane orthogonal to β, which contains V_2. Thus $\sigma_\beta(V_2) = V_2$, which implies that $\sigma_\beta(V_1) = V_1$. Alternatively, one can check directly that $\sigma_\beta(V_1) = V_1$, which implies that $\sigma_\beta(V_2) = V_2$. Similarly, if $\beta \in B_2$, then σ_β maps V_1 and V_2 onto themselves. Remember that every element α of A can be obtained from elements of B by compositions of the reflections σ_β, $\beta \in B$, as in Section 19.14. It follows that α is contained in V_1 or V_2. This implies that A is reducible, as on p37 of [24], and p52 of [14].

20.5 Root strings

Let V be a vector space over the real numbers of positive finite dimension, let A be a root system in V, and let $(\cdot, \cdot)$ be an inner product on V that is invariant under the Weyl group of A. Suppose that α and β are nonproportional elements of A. Consider the elements of A of the form

(20.5.1) $$\beta + j\,\alpha,$$

where j is an integer. The collection of these elements of A is called the *α-string through β* in A, as on p45 of [14]. Let r and q be the largest integers such that

(20.5.2) $$\beta - r\,\alpha,\ \beta + q\,\alpha \in A,$$

respectively. Thus $r, q \geq 0$, because $\beta \in A$, by hypothesis. We would like to show that if $j \in \mathbf{Z}$ satisfies $-r < j < q$, then (20.5.1) is an element of A too.

Otherwise, there are integers j_1, j_2 such that $-r \leq j_1 < j_2 \leq q$ such that

(20.5.3) $$\beta + j_1\,\alpha,\ \beta + j_2\,\alpha \in A$$

and

(20.5.4) $$\beta + (j_1 + 1)\,\alpha,\ \beta + (j_2 - 1)\,\alpha \notin A.$$

Observe that neither $\beta + j_1\,\alpha$ nor $\beta + j_2\,\alpha$ is proportional to α, because β is not proportional to α, by hypothesis. It follows that

$$(\alpha, \beta + j_1\,\alpha) \ge 0, \quad (\alpha, \beta + j_2\,\alpha) \le 0, \tag{20.5.5}$$

as in Section 19.9. However,

$$(j_2 - j_1)\,(\alpha, \alpha) > 0, \tag{20.5.6}$$

because $j_1 < j_2$ and $\alpha \ne 0$. This is a contradiction, as on p45 of [14].

The fact that (20.5.1) is an element of A when $j \in \mathbf{Z}$ satisfies $-r < j < q$ also came up in the Lie algebra setting in Section 17.9, as in part (e) of the proposition on p39 of [14].

Let σ_α be the symmetry on V with vector α that maps A onto itself, which is the reflection on V associated to α with respect to $(\cdot, \cdot)$. Remember that $\sigma_\alpha(\beta) - \beta$ is an integer multiple of α, by the definition of a root system. If $j \in \mathbf{Z}$, then

$$\sigma_\alpha(\beta + j\,\alpha) = \sigma_\alpha(\beta) - j\,\alpha \tag{20.5.7}$$

is the sum of β and an integer multiple of α as well. Thus σ_α maps the α-string through β onto itself, because $\sigma_\alpha(A) = A$. Using this, it is easy to see that

$$\sigma_\alpha(\beta + q\,\alpha) = \beta - r\,\alpha. \tag{20.5.8}$$

Equivalently, $\sigma_\alpha(\beta) - q\,\alpha = \beta - r\,\alpha$, so that

$$\sigma_\alpha(\beta) - \beta = (q - r)\,\alpha. \tag{20.5.9}$$

This means that

$$2\,(\beta, \alpha)\,(\alpha, \alpha)^{-1} = r - q, \tag{20.5.10}$$

by the usual expression for σ_α in terms of α and $(\cdot, \cdot)$. It follows that

$$|r - q| \le 3, \tag{20.5.11}$$

because α and β are not proportional, as in Section 19.9.

Put $\beta_0 = \beta - r\,\alpha$, which is an element of A that is not proportional to α. Observe that the α-string through β_0 consists of the same elements of A as the α-string through β. Let r_0, q_0 be the largest integers such that $\beta_0 - r_0\,\alpha$ and $\beta_0 + q_0\,\alpha$ are elements of A, as before. By construction, $r_0 = 0$ and $q_0 = q + r$. We also have that $|r_0 - q_0| \le 3$, as in (20.5.11). This means that

$$q + r \le 3. \tag{20.5.12}$$

Thus the α-string through β has at most 4 elements, as on p45 of [14].

20.6 Roots and linear subspaces

Let V be a vector space over the real numbers of positive finite dimension, as usual. Suppose for the moment that α is a nonzero element of V, and that σ_α is a symmetry on V with vector α. If V_0 is a linear subspace of V, then we might like to know if

$$\sigma_\alpha(V_0) \subseteq V_0. \tag{20.6.1}$$

Equivalently, this means that

$$\sigma_\alpha(V_0) = V_0, \tag{20.6.2}$$

because σ_α is its own inverse on V. If $\alpha \in V_0$, then it is easy to see that (20.6.1) holds, and hence (20.6.2) holds as well. Of course, (20.6.2) holds when V_0 is contained in the hyperplane of vectors in V that are fixed by σ_α. In fact, these are the only two ways in which (20.6.2) can hold, as in Exercise 1 on p45 of [14]. Indeed, if (20.6.1) holds, and if there is a $v_0 \in V_0$ such that $\sigma_\alpha(v_0) \neq v_0$, then $\sigma_\alpha(v_0) - v_0$ is a nonzero multiple of α that is contained in V_0.

Let A be a root system in V, and for each $\alpha \in A$, let σ_α be the symmetry on V with vector α that maps A onto itself. Let V_0 be a nontrivial linear subspace of V, and put

$$A_0 = A \cap V_0. \tag{20.6.3}$$

If V_0 is spanned by A_0, then A_0 is a root system in V_0. This follows from the fact that (20.6.2) holds for every $\alpha \in A_0$. This is related to Exercise 7 on p46 of [14].

Let A_1 be a nonempty subset of A that satisfies the following two conditions. First, if $\alpha \in A_1$, then $-\alpha \in A_1$. Second, if $\alpha, \beta \in A_1$ and $\alpha + \beta \in A$, then

$$\alpha + \beta \in A_1. \tag{20.6.4}$$

Under these conditions, A_1 is a root system in the linear subspace V_1 of V that it spans, as in Exercise 7 on p46 of [14]. Note that this includes the situation mentioned in the preceding paragraph. One way to see this is to check that if α and β are nonproportional elements of A_1, then A_1 contains the α-string through β in A, using the remarks in the previous section. This implies that $\sigma_\alpha(\beta) \in A_1$ in this case. Of course, if $\alpha, \beta \in A_1$ are proportional, then $\sigma_\alpha(\beta) = -\beta \in A_1$, by the first condition. It follows that for every $\alpha \in A_1$, σ_α maps A_1 into itself, and hence $\sigma_\alpha(A_1) = A_1$.

Let $(\cdot, \cdot)$ be an inner product on V that is invariant under the Weyl group of A. If c is a positive real number, then let $A(c)$ be the set of $\alpha \in A$ such that $(\alpha, \alpha) = c$. If $A(c) \neq \emptyset$, then one can verify that $A(c)$ is a root system in the linear subspace $V(c)$ of V that it spans. This is part of Exercise 11 on p47 of [14].

20.7 More on irreducibility

Let V be a vector space over the real numbers of positive finite dimension, let A be an irreducible root system in V, and let $(\cdot, \cdot)$ be an inner product on V

that is invariant under the Weyl group W of A. We would like to check that W acts irreducibly on V, as in the first part of Lemma B on p53 of [14]. More precisely, this means that there is no nontrivial proper linear subspace of V that is mapped into itself by the elements of W. To see this, let V_1 be a nonzero linear subspace of V that is mapped into itself by elements of W. If $\alpha \in A$, then let σ_α be the reflection on V associated to α with respect to $(\cdot, \cdot)$, as usual. By hypothesis,

$$\sigma_\alpha(V_1) \subseteq V_1, \tag{20.7.1}$$

so that either $\alpha \in V_1$ or V_1 is contained in the hyperplane of vectors that are fixed by σ_α, as in the previous section. Remember that the hyperplane of vectors that are fixed by σ_α is orthogonal to α. In the second case, we get that α is contained in the orthogonal complement V_2 of V_1 in V. Thus $A \subseteq V_1 \cup V_2$, which implies that $V_2 = \{0\}$, because A is supposed to be irreducible in V. This means that $V_1 = V$, as desired.

If $v \in V$, then the linear span of the set of images of v under elements of W is a linear subspace of V that is mapped into itself by elements of W. If $v \neq 0$, then it follows that this linear span is equal to V, as in the second part of Lemma B on p53 of [14]. If u is another nonzero element of V, then we get that

$$(\sigma(v), u) \neq 0 \tag{20.7.2}$$

for some $\sigma \in W$.

Suppose that $\alpha, \beta \in A$ satisfy

$$\|\alpha\| = \|\beta\|, \tag{20.7.3}$$

where $\|\cdot\|$ is the norm associated to $(\cdot, \cdot)$ on V. We would like to show that α is the image of β under an element of W, as in the second part of Lemma C on p53 of [14]. We may as well suppose that $(\alpha, \beta) \neq 0$, by replacing β by one of its images under an element of W if necessary, as in the preceding paragraph. If α and β are proportional, then $\alpha = \pm\beta$, by (20.7.3). There is nothing to do when $\alpha = \beta$, and if $\alpha = -\beta$, then $\alpha = \sigma_\beta(\beta)$, as desired. Suppose that α and β are not proportional, and let $n(\alpha, \beta)$, $n(\beta, \alpha)$ be as in Section 19.9. Observe that

$$n(\alpha, \beta) = n(\beta, \alpha) = \pm 1 \tag{20.7.4}$$

in this situation, as before. We may as well suppose that $n(\alpha, \beta) = n(\beta, \alpha) = 1$, by replacing β with $\sigma_\beta(\beta) = -\beta$ if necessary. Under these conditions, we get that

$$(\sigma_\alpha \circ \sigma_\beta \circ \sigma_\alpha)(\beta) = (\sigma_\alpha \circ \sigma_\beta)(\beta - \alpha) = \sigma_\alpha(-\beta - \alpha + \beta) = \alpha, \tag{20.7.5}$$

as desired.

Let $\alpha, \beta \in A$ be given, and let σ be an element of W such that

$$(\sigma(\alpha), \beta) \neq 0. \tag{20.7.6}$$

If $\sigma(\alpha)$ and β are proportional, then

$$\|\alpha\|^2/\|\beta\|^2 = \|\sigma(\alpha)\|^2/\|\beta\|^2 = 1,\ 4,\ \text{or } 1/4. \tag{20.7.7}$$

If $\sigma(\alpha)$ and β are not proportional, then

$$\|\alpha\|^2/\|\beta\|^2 = \|\sigma(\alpha)\|^2/\|\beta\|^2 = 1,\ 2,\ 3,\ 1/2,\ \text{or } 1/3, \tag{20.7.8}$$

as in Section 19.9. In particular, if A is reduced, then the only possible ratios are as in (20.7.8). In this case, one can check that there are at most two possible values for the norms of elements of A, as in the first part of Lemma C on p53 of [14]. If A is not reduced, then one can verify that there are at most three possible values for the norms of elements of A. In order to have three different values for the norms of elements of A, the ratio in (20.7.8) can only be 1, 2, or 1/2 when $\sigma(\alpha)$ and β are not proportional.

If $\alpha \in A$, then put $\widehat{\alpha} = 2\,\alpha/\|\alpha\|^2$, as in (19.7.9), so that

$$\|\widehat{\alpha}\| = 2/\|\alpha\|. \tag{20.7.9}$$

Remember that $\widehat{A} = \{\widehat{\alpha} : \alpha \in A\}$ is the inverse system of A in V with respect to $(\cdot,\cdot)$, as in Section 19.8. It is easy to see that the irreducibility of A in V implies that $\widehat{A}$ is irreducible in V too. If the elements of A have the same norm, then $\widehat{A}$ has the same property, by (20.7.9). In this case, $\widehat{A}$ is isomorphic to A, using a dilation on V. Otherwise, the number of distinct values of the norms of elements of $\widehat{A}$ is the same as for A. This corresponds to part of Exercise 11 on p55 of [14].

If $\langle\cdot,\cdot\rangle$ is another inner product on V, then there is a unique linear mapping T from V into itself such that

$$\langle u, v\rangle = (T(u), v) \tag{20.7.10}$$

for every $u, v \in V$. More precisely, T is self-adjoint and positive definite with respect to $(\cdot,\cdot)$, because of the symmetry and positivity properties of $\langle\cdot,\cdot\rangle$ on V. If $\langle\cdot,\cdot\rangle$ is also invariant under W, then one can check that T commutes with the elements of W, because $(\cdot,\cdot)$ is invariant under W too. It is well known that there is a basis for eigenvectors of T in V that is orthonormal with respect to $(\cdot,\cdot)$, because T is self-adjoint with respect to $(\cdot,\cdot)$. The eigenspaces of T are mapped into themselves by elements of W, because T commutes with elements of W. It follows that T is a constant multiple of the identity mapping on V, because W acts irreducibly on V. This means that $\langle\cdot,\cdot\rangle$ is a constant multiple of $(\cdot,\cdot)$ on V.

Suppose that A is reduced, so that there are at most two distinct values of the norms of elements of A. If there are two distinct values for the norms of the elements of A, then the elements of A whose norm is the larger value are called *long roots*, and the elements of A whose norm is the smaller value are called *short roots*, as on p53 of [14]. If the elements of A have the same norm, then it is customary to refer to them as long roots, as in [14].

20.8 Maximal roots

Let V be a vector space over the real numbers of positive finite dimension, let A be a root system in V, and let $(\cdot,\cdot)$ be an inner product on V that is invariant under the Weyl group of A. Also let B be a base for A, so that every element of A can be expressed as a linear combination of elements of B with integer coefficients, and where the coefficients are either all greater than or equal to 0, or all less than or equal to 0.

An element α of A is said to be *maximal* with respect to B if there is no element of A that can be expressed as the sum of α and some elements of B, which need not be distinct. Equivalently, this means that if $\gamma \in A$, and each of the coefficients of α associated to elements of B is less than or equal to the corresponding coefficient of γ, then $\alpha = \gamma$. In particular, α is maximal when the sum of its coefficients associated to elements of B is maximal, as an element of $\mathbf{Z}$.

Suppose from now on in this section that A is irreducible, and let α_0 be an element of A that is maximal with respect to B. It is easy to see that the coefficients of α_0 with respect to elements of B are nonnegative, by maximality. Let B_0 be the set of $\beta \in B$ such that the coefficient of α with respect to β is positive, so that the coefficients of α_0 with respect to $\beta \in B \setminus B_0$ are equal to 0. Note that $B_0 \neq \emptyset$, because $\alpha_0 \neq 0$. We would like to show that

$$B_0 = B, \tag{20.8.1}$$

which is part of Lemma A at the bottom of p52 of [14].

If β and γ are distinct elements of B, then $(\beta, \gamma) \leq 0$, as in (19.11.8). In particular, this holds when $\beta \in B_0$ and $\gamma \in B \setminus B_0$. If $B_0 \neq B$, then there are $\beta \in B_0$ and $\gamma \in B \setminus B_0$ such that $(\beta, \gamma) \neq 0$, because A is irreducible. It follows that $(\alpha_0, \gamma) < 0$ under these conditions, by the definition of B_0. Observe that α_0 is not proportional to γ in this situation. This implies that $\alpha_0 + \gamma \in A$, as in Section 19.9. This contradicts the maximality of α_0 with respect to B, so that (20.8.1) holds.

Next, we would like to check that

$$(\alpha_0, \beta) \geq 0 \tag{20.8.2}$$

for every $\beta \in B$, which is another part of Lemma A at the bottom of p52 of [14]. If the dimension of V is one, then B has only one element, α_0 is a positive integer multiple of that element of B, and (20.8.2) follows. Suppose now that the dimension of V is at least two. Let $\beta \in B$ be given, and note that α_0 is not proportional to β, because all of the coefficients of α_0 with respect to elements of B are positive. If $(\alpha_0, \beta) < 0$, then $\alpha_0 + \beta \in A$, as in Section 19.9 again. This would contradict the maximality of α_0 with respect to B, so that (20.8.2) holds. We also have that

$$(\alpha_0, \beta) > 0 \tag{20.8.3}$$

for at least one $\beta \in B$, because V is spanned by B.

We would like to show that α_0 is unique, as in Lemma A at the bottom of p52 of [14]. Let α_1 be another element of A that is maximal with respect to B. This implies that the coefficients of α_1 with respect to all elements of B are positive, as before. It follows that

$$(\alpha_0, \alpha_1) > 0, \tag{20.8.4}$$

by (20.8.2) and (20.8.3). If α_0 and α_1 are proportional, then it is easy to see that $\alpha_0 = \alpha_1$, as desired. Otherwise, if α_0 and α_1 are not proportional, then $\alpha_0 - \alpha_1 \in A$, as in Section 19.9. If the coefficients of $\alpha_0 - \alpha_1$ with respect to the elements of B are all nonnegative, then we get a contradiction with the maximality of α_1. Similarly, if the coefficients of $\alpha_0 - \alpha_1$ are all less than or equal to 0, then we get a contradiction with the maximality of α_0.

If $\alpha \in A$ and $\beta \in B$, then

(20.8.5) the coefficient of α associated to β is less than or equal to the coefficient of α_0 with respect to β.

To see this, one can first find an element α_1 of A that is maximal with respect to B such that the coefficient of α associated to β is less than or equal to the coefficient of α_1 associated to β for every $\beta \in B$. One can choose $\alpha_1 \in A$ so that the sum of its coefficients associated to elements of B is maximal, among elements of A whose coefficients are greater than or equal to the corresponding coefficients of α. The uniqueness of α_0 implies that $\alpha_0 = \alpha_1$, so that (20.8.5) holds. This is implicit in an argument near the top of p54 of [14]. It follows that the sum of the coefficients of α associated to elements of B is less than or equal to the sum of the coefficients of α_0, with equality only when $\alpha = \alpha_0$. This is another part of Lemma A at the bottom of p52 of [14].

20.9 More on maximality

Let V be a vector space over the real numbers of positive finite dimension, and let A be a root system in V. Also let $(\cdot, \cdot)$ be an inner product on V that is invariant under the Weyl group W of A, and let B be a base for A. Suppose for the moment that A is reduced. If τ is a linear functional on V, then there is an element σ of W such that $\tau(\sigma(\beta)) \geq 0$ for every $\beta \in B$, as in Section 19.14. Let $\alpha \in V$ be given, so that

$$\tau_\alpha(v) = (v, \alpha) \tag{20.9.1}$$

defines a linear functional on V. As before, there is a $\sigma \in W$ such that

$$(\sigma(\beta), \alpha) = \tau_\alpha(\sigma(\beta)) \geq 0 \tag{20.9.2}$$

for every $\beta \in B$. Equivalently, this means that

$$(\beta, \sigma^{-1}(\alpha)) \geq 0 \tag{20.9.3}$$

for every $\beta \in B$, because σ is an orthogonal transformation on V with respect to $(\cdot, \cdot)$. This corresponds to the formulation in part (a) of the theorem on p51 and Exercise 14 on p55 of [14].

Suppose now that A is irreducible as well as reduced, and let $\alpha_0 \in A$ be maximal with respect to B, as in the previous section. We would like to show that

$$\|\alpha_0\| \geq \|\alpha\| \tag{20.9.4}$$

for every $\alpha \in A$, where $\|\cdot\|$ is the norm on V associated to $(\cdot,\cdot)$, as in Lemma D on p53 of [14]. We may as well suppose that

$$(\beta, \alpha) \geq 0 \tag{20.9.5}$$

for every $\beta \in B$, by replacing α with $\sigma^{-1}(\alpha)$ for $\sigma \in W$ as in (20.9.3). Note that the coefficients of α associated to elements of B are less than or equal to the corresponding coefficients of α_0, as in (20.8.5). Combining this with (20.9.5), we get that

$$(\alpha_0 - \alpha, \alpha) \geq 0, \tag{20.9.6}$$

which is the same as saying that

$$(\alpha_0, \alpha) \geq (\alpha, \alpha). \tag{20.9.7}$$

This implies that

$$\|\alpha\|^2 = (\alpha, \alpha) \leq \|\alpha_0\| \, \|\alpha\|, \tag{20.9.8}$$

by the Cauchy–Schwarz inequality. It is easy to obtain (20.9.4) from this, as desired.

Let A be a root system in V again, that is not necessarily reduced. If $\alpha \in A$, then put $\widehat{\alpha} = 2\,\alpha/\|\alpha\|^2$, as in (19.7.9), and remember that $\widehat{A} = \{\widehat{\alpha} : \alpha \in A\}$ is the inverse system of A in V with respect to $(\cdot,\cdot)$, as in Section 19.8. Let B be a base for A, as before, and let B_1, B_2 be the sets of $\beta \in B$ such that $2\,\beta \notin A$ and $2\,\beta \in A$, respectively, as in Section 19.13. Remember that

$$\widetilde{B} = \{\widehat{\beta} : \beta \in B_1\} \cup \{\widehat{\beta}/2 : \beta \in B_2\} \tag{20.9.9}$$

is a base for $\widehat{A}$. If $\alpha, \gamma \in A$ satisfy

$$\|\alpha\| = \|\gamma\|, \tag{20.9.10}$$

then one can check that the coefficients of α associated to elements of B are less than or equal to the corresponding coefficients of γ if and only if the coefficients of $\widehat{\alpha}$ associated to elements of $\widetilde{B}$ are less than or equal to the corresponding coefficients of $\widehat{\gamma}$.

Suppose that A is reduced, so that $B_2 = \emptyset$, and $\widetilde{B}$ is the same as

$$\widehat{B} = \{\widehat{\beta} : \beta \in B\}. \tag{20.9.11}$$

Suppose that A is irreducible as well, which implies that $\widehat{A}$ is irreducible too, as in Section 20.7. Remember that there are at most two distinct values for the norms of the elements of A, as in Section 20.7. Let us suppose that there are two distinct values for the norms of elements of A, which means that there are two distinct values for the norms of elements of $\widehat{A}$.

Let $\widehat{\gamma_0}$ be a maximal root in $\widehat{A}$, as in the previous section. This implies that $\widehat{\gamma_0}$ is a long root in $\widehat{A}$, as before. It follows that the corresponding element γ_0 of A is a short root in A. If $\alpha \in A$, then the coefficients of $\widehat{\alpha}$ asociated to elements of $\widehat{B}$ are less than or equal to the corresponding coefficients of $\widehat{\gamma_0}$, as in (20.8.5). If α is a short root in A, then $\|\alpha\| = \|\gamma_0\|$, and it follows that the coefficients of α associated to elements of B are less than or equal to the coefficients of γ_0, as before. Note that γ_0 is uniquely determined by this property. This corresponds to part of Exercise 11 on p55 of [14].

20.10 Root systems of type A_n

Let n be a positive integer, and let $\mathbf{R}^{n+1}$ be the usual space of $(n+1)$-tuples of real numbers. The standard inner product is defined on $\mathbf{R}^{n+1}$ by

$$(u, v) = \sum_{j=1}^{n+1} u_j\, v_j, \tag{20.10.1}$$

as usual. Let $e_1, \ldots, e_{n+1}$ be the standard basis vectors in $\mathbf{R}^{n+1}$, so that the jth coordinate of e_l is equal to 1 when $j = l$, and to 0 otherwise. Of course, the set $\mathbf{Z}^{n+1}$ of $(n+1)$-tuples of integers is a subgroup of $\mathbf{R}^{n+1}$, as a commutative group with respect to addition. Put

$$V = \Big\{ v \in \mathbf{R}^{n+1} : \sum_{j=1}^{n+1} v_j = 0 \Big\}, \tag{20.10.2}$$

which is the hyperplane in $\mathbf{R}^{n+1}$ orthogonal to $e_1 + \cdots + e_{n+1}$.

Consider

$$A = \{\alpha \in V \cap \mathbf{Z}^{n+1} : (\alpha, \alpha) = 2\}. \tag{20.10.3}$$

Equivalently, it is easy to see that A consists exactly of the vectors of the form $e_j - e_l$, where $1 \le j, l \le n+1$ and $j \ne l$. Note that A is a finite set of nonzero elements of V whose linear span is equal to V.

Suppose for the moment that $\alpha \in \mathbf{R}^{n+1}$ satisfies $(\alpha, \alpha) = 2$. In this case, the reflection on $\mathbf{R}^{n+1}$ associated to α with respect to the standard inner product is given by

$$\sigma_\alpha(v) = v - (v, \alpha)\, \alpha \tag{20.10.4}$$

for every $v \in \mathbf{R}^{n+1}$. If $\alpha \in V$, then σ_α maps V onto itself, as in Section 20.6. If $\alpha \in \mathbf{Z}^{n+1}$, then $\sigma_\alpha(\mathbf{Z}^{n+1}) \subseteq \mathbf{Z}^{n+1}$, and hence

$$\sigma_\alpha(\mathbf{Z}^{n+1}) = \mathbf{Z}^{n+1}, \tag{20.10.5}$$

because σ_α is its own inverse. It follows that $\sigma_\alpha(A) = A$ when $\alpha \in A$, because σ_α is an orthogonal transformation on $\mathbf{R}^{n+1}$. Of course, $(v, \alpha) \in \mathbf{Z}$ when $\alpha, v \in \mathbf{Z}^{n+1}$, so that A defines a root system in V. This root system is said to be of *type* A_n. Clearly A is reduced, as a root system in V.

Suppose that $\alpha = e_j - e_l$ for some $j, l \in \{1, \ldots, n+1\}$, with $j \ne l$. If $v \in \mathbf{R}^{n+1}$, then

$$\sigma_\alpha(v) = v - (v_j - v_l)\,(e_j - e_l), \tag{20.10.6}$$

which interchanges the jth and lth coordinates of v, without affecting the other coordinates of v. It follows that the Weyl group of A consists of the linear mappings on V obtained from permuting the coordinates of elements of V.

Remember that the inverse system $\widehat{A}$ of A in V with respect to $(\cdot, \cdot)$ is defined in (19.8.4). In this case, $\widehat{A} = A$.

If $\alpha, \beta \in A$ and $n(\alpha, \beta) \in \mathbf{Z}$ is as in Sections 19.9 and 20.2, then

$$n(\alpha, \beta) = (\alpha, \beta) \tag{20.10.7}$$

in this situation, as in (20.2.2). Thus

$$n(\alpha, \beta)\, n(\beta, \alpha) = (\alpha, \beta)^2. \tag{20.10.8}$$

If $\alpha = \pm\beta$, then (20.10.7) is ± 2, and (20.10.8) is 4. Suppose that $\alpha = e_{j_1} - e_{j_2}$ and $\beta = e_{l_1} - e_{l_2}$ for some $j_1, j_2, l_1, l_2 \in \{1, \ldots, n+1\}$ with $j_1 \neq j_2$, $l_1 \neq l_2$. If $\{j_1, j_2\} \cap \{l_1, l_2\}$ has exactly one element, then (20.10.7) is ± 1, and (20.10.8) is 1. If $\{j_1, j_2\} \cap \{l_1, l_2\} = \emptyset$, then (20.10.7) and (20.10.8) are equal to 0.

Put

$$B = \{e_j - e_{j+1} : j = 1, \ldots, n\}, \tag{20.10.9}$$

which is a subset of A. It is easy to see that B is a basis for V, as a vector space over the real numbers. More precisely, one can check that B is a base for A as a root system in V. Indeed, if $1 \leq j < l \leq n+1$, then

$$e_j - e_l = \sum_{r=j}^{l-1} (e_r - e_{r+1}). \tag{20.10.10}$$

In particular, $e_1 - e_{n+1}$ is the unique maximal element of A with respect to B, as in Section 20.8.

Let $j, l \in \{1, \ldots, n\}$ be given, so that $e_j - e_{j+1}$ and $e_l - e_{l+1}$ are elements of (20.10.9). The corresponding entry of the Cartan matrix of A with respect to B is given by

$$n(e_j - e_{j+1}, e_l - e_{l+1}) = (e_j - e_{j+1}, e_l - e_{l+1}). \tag{20.10.11}$$

This is symmetric in j and l, and equal to 2 when $j = l$. As before, (20.10.11) is equal to -1 when $|j - l| = 1$, and to 0 when $|j - l| \geq 2$.

Similarly, let us consider the Coxeter graph of A with respect to B, as in Section 20.3. If $j, l \in \{1, \ldots, n\}$ and $j \neq l$, then the number of edges between $e_j - e_{j+1}$ and $e_l - e_{l+1}$ in the Coxeter graph is the square of (20.10.11). This is equal to 1 when $|j - l| = 1$, and to 0 when $|j - l| \geq 2$. Note that the Coxeter graph is connected, so that A is irreducible.

Let T be a one-to-one linear mapping from V onto itself such that $T(A) = A$. This implies that

$$(T(\alpha), T(\beta)) = (\alpha, \beta) \tag{20.10.12}$$

for every $\alpha, \beta \in A$, by (20.2.13) and (20.10.7). It follows that (20.10.12) holds for every $\alpha, \beta \in V$, because V is spanned by A.

Suppose that T also satisfies $T(B) = B$. If $n = 1$, then T is the identity mapping on V. If $n \geq 2$, then there is another such mapping T on V, which sends $e_j - e_{j+1}$ to $e_{n-j} - e_{n-j+1}$ for each $j = 1, \ldots, n$. Equivalently, T is the restriction to V of the mapping on $\mathbf{R}^{n+1}$ that sends $v = (v_1, \ldots, v_{n+1})$ to $-(v_{n+1}, \ldots, v_1)$.

This corresponds to some of the remarks on p64 and in Tables 1 and 2 on p66 of [14], and on p39-40 of [24].

20.11 Types B_n and C_n

Let n be a positive integer, and let us take $V = \mathbf{R}^n$, with its standard inner product $(\cdot, \cdot)$ and basis $e_1, \ldots, e_n$. Consider

$$A_1 = \{\alpha \in \mathbf{Z}^n : (\alpha, \alpha) = 1 \text{ or } 2\}. \tag{20.11.1}$$

Equivalently, A_1 consists of vectors of the form $\pm e_j$, $1 \le j \le n$, and $\pm e_j \pm e_l$, $1 \le j \ne l \le n$. Similarly, put

$$A_2 = \{\pm 2\, e_j : 1 \le j \le n\} \cup \{\pm e_j \pm e_l : 1 \le j \ne l \le n\}, \tag{20.11.2}$$

which is a subset of $\mathbf{Z}^n$ as well. Clearly A_1 and A_2 are finite sets of nonzero elements of V that span V. Note that the squares of the norms of the elements of A_2 are either 2 or 4.

If α is a nonzero element of V, then let σ_α be the reflection on V associated to α with respect to $(\cdot, \cdot)$, as usual. Suppose for the moment that α is a nonzero multiple of e_j for some $j = 1, \ldots, n$. In this case, $\sigma_\alpha = \sigma_{e_j}$ multiplies the jth coordinate of $v \in V$ by -1, and leaves the other coordinates of v unchanged. In particular, σ_α maps $\mathbf{Z}^n$, A_1, and A_2 onto themselves. Equivalently,

$$\sigma_\alpha(v) - v = -2\, v_j\, e_j \tag{20.11.3}$$

for every $v \in V$. If $\alpha = \pm e_j$ or $\pm 2\, e_j$ and $v \in \mathbf{Z}^n$, then it follows that $\sigma_\alpha(v) - v$ is an integer multiple of α. Thus this holds for every $v \in A_1$ or A_2.

If $\alpha \in V$ satisfies $(\alpha, \alpha) = 2$, then $\sigma_\alpha(v) = v - (v, \alpha)\, \alpha$ for every $v \in V$, as before. If we also have that $\alpha \in \mathbf{Z}^n$, then σ_α maps $\mathbf{Z}^n$ into itself, and hence onto itself. In this case, if $v \in \mathbf{Z}^n$, then $(v, \alpha) \in \mathbf{Z}$, so that $\sigma_\alpha(v) - v$ is an integer multiple of α. If $\alpha = e_j - e_l$, $1 \le j \ne l \le n$, then $\sigma_\alpha(v)$ interchanges the jth and lth coordinates of v, without affecting the other coordinates, as in the previous section. This implies that σ_α maps A_1 and A_2 onto themselves.

Suppose that $\alpha = \pm(e_j + e_l)$ for some $1 \le j \ne l \le n$, so that $(\alpha, \alpha) = 2$. In this case,

$$\sigma_\alpha(v) = v - (v_j + v_l)\,(e_j + e_l) \tag{20.11.4}$$

for every $v \in V$. This interchanges the jth and lth coordinates and multiplies them by -1, while leaving the other coordinates unchanged. Thus σ_α maps A_1 and A_2 onto themselves, so that A_1 and A_2 are root systems in V. More precisely, A_1 is said to be of *type* B_n, and A_2 is said to be of *type* C_n.

Consider

$$\begin{aligned} A_3 = A_1 \cup A_2 \quad &= \quad \{\pm e_j : 1 \le j \le n\} \cup \{\pm 2\, e_j : 1 \le j \le n\} \\ &\qquad \cup \{\pm e_j \pm e_l : 1 \le j \ne l \le n\}. \end{aligned} \tag{20.11.5}$$

If $\alpha \in A_3$, then σ_α maps A_1 and A_2 onto themselves, as in the previous paragraphs, and hence σ_α maps A_3 onto itself. We also have that $\sigma_\alpha(v) - v$ is an integer multiple of α for every $v \in \mathbf{Z}^n$, as before, and in particular for $v \in A_3$.

This means that A_3 is a root system in V as well, which is said to be of *type* BC_n. Note that A_1 and A_2 are reduced, and that A_3 is not reduced.

If α is a nonzero element of V, then put $\widehat{\alpha} = 2\,\alpha/(\alpha,\alpha)$, as in (19.7.9). Observe that

$$A_2 = \widehat{A_1} = \{\widehat{\alpha} : \alpha \in A_1\}, \tag{20.11.6}$$

which is the inverse system of A_1 in V with respect to $(\cdot,\cdot)$, as in Section 19.8. Of course, this means that $A_1 = \widehat{A_2}$ is the inverse system of A_2 in V with respect to $(\cdot,\cdot)$. It follows that $\widehat{A_3} = A_3$.

The Weyl groups of A_1, A_2, and A_3 are the same, because they are generated by the same reflections on V. This group consists of linear mappings on V that permute the coordinates of elements of V, while multiplying any collection of the coordinates by -1.

Put

$$B_1 = \{e_j - e_{j+1} : 1 \le j \le n-1\} \cup \{e_n\} \tag{20.11.7}$$

which is interpreted as being $\{e_1\}$ when $n = 1$. It is easy to see that this is a basis for V as a vector space over $\mathbf{R}$, and one can check that it is a base for A_1, as a root system in V. More precisely, if $1 \le j < n$, then

$$e_j = \sum_{r=j}^{n-1} (e_r - e_{r+1}) + e_n \tag{20.11.8}$$

and

$$e_j + e_n = \sum_{r=j}^{n-1} (e_r - e_{r+1}) + 2\,e_n. \tag{20.11.9}$$

If $1 \le j < l \le n$, then

$$e_j - e_l = \sum_{r=j}^{l-1} (e_r - e_{r+1}). \tag{20.11.10}$$

If $1 \le j < l < n$, then

$$e_j + e_l = \sum_{r=j}^{l-1} (e_r - e_{r+1}) + \sum_{r=l}^{n-1} 2\,(e_r - e_{r+1}) + 2\,e_n. \tag{20.11.11}$$

Similarly, put

$$B_2 = \{e_j - e_{j+1} : 1 \le j \le n-1\} \cup \{2\,e_n\}, \tag{20.11.12}$$

which is interpreted as being $\{2\,e_1\}$ when $n = 1$. This is a basis for V as a vector space over $\mathbf{R}$, and one can verify that it is a base for A_2 as a root system in V. Indeed, if $1 \le j < n$, then

$$2\,e_j = \sum_{r=j}^{n-1} 2\,(e_r - e_{r+1}) + 2\,e_n, \tag{20.11.13}$$

and $e_j + e_n$ can be expressed as in (20.11.9). If $1 \le j < l \le n$, then $e_j - e_l$ can be expressed as in (20.11.10), and $e_j + e_l$ can be expressed as in (20.11.11) when $l < n$. Note that B_1 is a base for A_3 as well, using (20.11.13).

If $n = 1$, then $A_1 = \{\pm e_1\}$ and $A_2 = \{\pm 2\, e_1\}$ are isomorphic to each other, and to the root system discussed in the previous section, with $n = 1$. If $n = 2$, then one can use the bases B_1 and B_2 to show that A_1 is isomorphic to A_2.

Let α and β be elements of A_1, A_2, or A_3, so that $n(\alpha, \beta) \in \mathbf{Z}$ can be defined as in Section 19.9. In fact,

$$n(\alpha, \beta) = 2\,(\alpha, \beta)\,(\beta, \beta)^{-1}, \tag{20.11.14}$$

as before, so that

$$n(\alpha, \beta)\, n(\beta, \alpha) = 2\,(\alpha, \beta)^2\,(\alpha, \alpha)^{-1}\,(\beta, \beta)^{-1}. \tag{20.11.15}$$

If $1 \le j, l \le n - 1$, then

$$n(e_j - e_{j+1}, e_l - e_{l+1}) = (e_j - e_{j+1}, e_l - e_{l+1}) \tag{20.11.16}$$

is symmetric in j and l, and equal to 2 when $j = l$. This is equal to -1 when $|j - l| = 1$, and to 0 when $|j - l| \ge 2$, as before. It follows that

$$n(e_j - e_{j+1}, e_l - e_{l+1})\, n(e_l - e_{l+1}, e_j - e_{j+1}) \tag{20.11.17}$$

is equal to 1 when $|j - 1| = 1$, and to 0 when $|j - l| \ge 2$.

If $1 \le j \le n - 1$, then

$$n(e_j - e_{j+1}, e_n) = 2\,(e_j - e_{j+1}, e_n), \tag{20.11.18}$$

which is 0 when $j < n - 1$, and -2 when $j = n - 1$. Similarly,

$$n(e_n, e_j - e_{j+1}) = (e_n, e_j - e_{j+1}), \tag{20.11.19}$$

which is 0 when $j < n - 1$ and -1 when $j = n - 1$. Thus

$$n(e_j - e_{j+1}, e_n)\, n(e_n, e_j - e_{j+1}) \tag{20.11.20}$$

is equal to 0 when $j < n - 1$, and to 2 when $j = n - 1$. Using this and the remarks in the preceding paragraph, one can determine the Cartan matrix and Coxeter graph of A_1 with respect to B_1. These are the same as for A_3 with respect to B_1.

If $1 \le j \le n - 1$ again, then

$$n(e_j - e_{j+1}, 2\, e_n) = (e_j - e_{j+1}, e_n), \tag{20.11.21}$$

which is 0 when $j < n - 1$ and -1 when $j = n - 1$. We also have that

$$n(2\, e_n, e_j - e_{j+1}) = 2\,(e_n, e_j - e_{j+1}), \tag{20.11.22}$$

which is 0 when $j < n-1$, and -2 when $j = n-1$. This implies that

$$n(e_j - e_{j+1}, 2\,e_n)\, n(2\,e_n, e_j - e_{j+1}) \tag{20.11.23}$$

is equal to 0 when $j < n-1$, and to 2 when $j = n-1$. This can be used to determine the Cartan matrix and Coxeter graph of A_2 with respect to B_2, in combination with the earlier remarks about (20.11.16) and (20.11.17). Note that the Coxeter graphs of A_1, A_2, and A_3 are connected, so that these root systems are irreducible.

If T is an automorphism of A_1 or A_3 and $T(B_1) = B_1$, then one can check that T is the identity mapping on V, using the Cartan matrix. Similarly, if T is an automorphism of A_2 and $T(B_2) = B_2$, then T is the identity mapping on V.

If $n \geq 2$, then the maximal root in A_1 with respect to B_1 is $e_1 + e_2$, which can be expressed in terms of B_1 as in (20.11.9) when $n = 2$, and (20.11.11) when $n > 2$. The maximal short root in A_1 with respect to B_1 is e_1, which can be expressed in terms of B_1 as in (20.11.8). The maximal root in A_2 with respect to B_2 is $2\,e_1$, which can be expressed in terms of B_2 as in (20.11.13). The maximal short root in A_2 with respect to B_2 is $e_1 + e_2$ when $n \geq 2$, which can be expressed in terms of B_2 as in (20.11.9) when $n = 2$, and (20.11.11) when $n > 2$.

This corresponds to some of the remarks on p64 and Tables 1 and 2 on p66 of [14], and on p39-40 of [24], as before. Root systems of type BC_n are mentioned in Exercise 3 on p66 of [14], and on p41 of [24].

20.12 Type D_n

Let $n \geq 2$ be an integer, and let us take $V = \mathbf{R}^n$ again, with its standard inner product $(\cdot,\cdot)$ and basis $e_1, \ldots, e_n$. Consider

$$A = \{\alpha \in \mathbf{Z}^n : (\alpha, \alpha) = 2\}, \tag{20.12.1}$$

which consists of the vectors of the form $\pm e_j \pm e_l$, $1 \leq j \neq l \leq n$. Of course, A is a finite set of nonzero elements of V that spans V.

If $\alpha \in V$ and $(\alpha, \alpha) = 2$, then the reflection σ_α on V associated to α with respect to $(\cdot,\cdot)$ is given by $\sigma_\alpha(v) = v - (v, \alpha)\,\alpha$, as before. If $\alpha \in \mathbf{Z}^n$ too, then σ_α maps $\mathbf{Z}^n$ onto itself, and hence σ_α maps A onto itself, because σ_α is an orthogonal transformation on V. We also have that $\sigma_\alpha(v) - v = (v, \alpha)\,\alpha$ is an integer multiple of α when $v \in \mathbf{Z}^n$ in this situation. Thus A is a root system in V, which is said to be of *type* D_n. Observe that A is reduced, as a root system in V.

If $\alpha = e_j - e_l$ for some $1 \leq j \neq l \leq n$, then $\sigma_\alpha(v)$ interchanges the jth and lth coordinates of $v \in V$, leaving the other coordinates unchanged, as before. If $\alpha = \pm(e_j + e_l)$ for some $1 \leq j \neq l \leq n$, then $\sigma_\alpha(v)$ interchanges the jth and lth coordinates and multiplies them by -1, leaving the other coordinates unchanged, as in the previous section. The Weyl group of A consists of linear mappings on V that permute the coordinates of $v \in V$, and multiply an even number of the coordinates by -1.

Let $\widehat{A}$ be the inverse system of A in V with respect to $(\cdot,\cdot)$, as in Section 19.8. Observe that $\widehat{A} = A$ in this situation.

It is easy to see that

$$B = \{e_j - e_{j+1} : 1 \le j \le n-1\} \cup \{e_{n-1} + e_n\} \tag{20.12.2}$$

is a basis for V, as a vector space over $\mathbf{R}$. One can check that B is a base for A, as a root system in V. More precisely, if $1 \le j < l \le n$, then

$$e_j - e_l = \sum_{r=j}^{l-1} (e_r - e_{r+1}), \tag{20.12.3}$$

as usual. If $1 \le j < n-1$, then

$$e_j + e_n = \sum_{r=j}^{n-2} (e_r - e_{r+1}) + (e_{n-1} + e_n). \tag{20.12.4}$$

If $1 \le j < l \le n-1$, then

$$\begin{aligned} e_j + e_l \quad = \quad & \sum_{r=j}^{l-1} (e_r - e_{r+1}) + \sum_{r=l}^{n-2} 2\,(e_r - e_{r+1}) + (e_{n-1} - e_n) \\ & + (e_{n-1} + e_n), \end{aligned} \tag{20.12.5}$$

where the second sum on the right is interpreted as being equal to 0 when $l = n-1$.

If $\alpha, \beta \in A$, then $n(\alpha, \beta) \in \mathbf{Z}$ can be defined as in Section 19.9, and is equal to (α, β) in this situation. If $1 \le j, l \le n-1$, then

$$n(e_j - e_{j+1}, e_l - e_{l+1}) = (e_j - e_{j+1}, e_l - e_{l+1}) \tag{20.12.6}$$

is equal to 2 when $j = l$, to -1 when $|j - l| = 1$, and to 0 when $|j - l| \ge 2$, as before. Thus

$$n(e_j - e_{j+1}, e_l - e_{l+1})\, n(e_l - e_{l+1}, e_j - e_{j+1}) \tag{20.12.7}$$

is equal to 1 when $|j - l| = 1$, and to 0 when $|j - l| \ge 2$. If $1 \le j \le n-1$, then

$$n(e_j - e_{j+1}, e_{n-1} + e_n) = (e_j - e_{j+1}, e_{n-1} + e_n) \tag{20.12.8}$$

is equal to 0 when $j \le n-3$ and when $j = n-1$, and equal to -1 when $j = n-2$. It follows that

$$n(e_j - e_{j+1}, e_{n-1} + e_n)\, n(e_{n-1} + e_n, e_j - e_{j+1}) \tag{20.12.9}$$

is equal to 0 when $j \le n-3$ and $j = n-1$, and to 1 when $j = n-1$. This can be used to determine Cartan matrix and Coxeter graph of A with respect to B. If $n \ge 3$, then the Coxeter graph is connected, so that A is irreducible in

V. In this case, the maximal root in A with respect to B is $e_1 + e_2$, which can expressed in terms of B as in (20.12.5).

If $n = 2$, then A is isomorphic to the sum of two root systems of rank one. If $n = 3$, then A is isomorphic to the corresponding root system in Section 20.10. Thus one often restricts one's attention to $n \geq 4$.

As usual, one can look for automorphisms T of A that map B onto itself, other than the identity mapping. One way to do this is to interchange $e_{n-1} - e_n$ with $e_{n-1} + e_n$, while fixing the other elements of B. If $n = 4$, then one can permute any of the basis elements $e_1 - e_2$, $e_3 - e_4$, and $e_3 + e_4$.

This corresponds to some remarks on p64 and Tables 1 and 2 on p66 of [14] again, and on p39-40 of [24].

20.13 Complex numbers

Let V be a vector space over the real numbers of positive finite dimension, and let $(\cdot, \cdot)$ be an inner product on V. If α is a nonzero element of V, then let σ_α be the reflection on V associated to α with respect to $(\cdot, \cdot)$. Let β be another nonzero element of V. If α and β are proportional in V, then $\sigma_\alpha = \sigma_\beta$ on V. Otherwise, if α and β are not proportional in V, then they span a two-dimensional linear subspace V_0 of V. Note that σ_α and σ_β map V_0 onto itself, as in Section 20.6. Of course, σ_α and σ_β fix every element of the orthogonal complement of V_0 in V.

The complex plane $\mathbf{C}$ may be considered as a two-dimensional vector space over the real numbers. More precisely, $\mathbf{C}$ can be identified with $\mathbf{R}^2$ in the usual way, using the real and imaginary parts of a complex number. If $u, v \in \mathbf{C}$, then put

$$(u, v) = \operatorname{Re}(u\,\overline{v}), \tag{20.13.1}$$

which is the real part of u times the complex conjugate of v. This is the standard inner product on $\mathbf{C}$, as a vector space over $\mathbf{R}$, and which corresponds to the standard inner product on $\mathbf{R}^2$. The norm on $\mathbf{C}$ associated to (20.13.1) is the same as the standard absolute value function $|\cdot|$ on $\mathbf{C}$. Note that

$$(a\,u, a\,v) = |a|^2\,(u, v) \tag{20.13.2}$$

for every $a, u, v \in \mathbf{C}$. As before, a real-linear mapping from $\mathbf{C}$ into itself is a linear mapping from $\mathbf{C}$ into itself, as a vector space over $\mathbf{R}$. Complex conjugation on $\mathbf{C}$ is a real-linear mapping from $\mathbf{C}$ into itself that preserves (20.13.2). This is the same as the reflection on $\mathbf{C}$, as a vector space over $\mathbf{R}$, associated to a nonzero imaginary number with respect to (20.13.1).

If a is a nonzero complex number, then put

$$\rho_a(z) = a\,\overline{(z/a)} = (a/\overline{a})\,\overline{z} \tag{20.13.3}$$

for every $z \in \mathbf{C}$. This defines a real-linear mapping ρ_a from $\mathbf{C}$ into itself, with

$$\rho_{t\,a} = \rho_a \tag{20.13.4}$$

for every $t \in \mathbf{R} \setminus \{0\}$. Observe that ρ_a is an orthogonal transformation on $\mathbf{C}$, as a vector space over $\mathbf{R}$, with respect to (20.13.1). If $\alpha \in \mathbf{C} \setminus \{0\}$, then let σ_α be the reflection on $\mathbf{C}$, as a vector space over $\mathbf{R}$, associated to α with respect to (20.13.1). Observe that

$$\rho_a = \sigma_{a\,i} \tag{20.13.5}$$

for every $a \in \mathbf{C} \setminus \{0\}$. Equivalently,

$$\sigma_\alpha = \rho_{\alpha\,i} = -\rho_\alpha \tag{20.13.6}$$

for every $\alpha \in \mathbf{C} \setminus \{0\}$. Thus

$$\sigma_\alpha(z) = -\rho_\alpha(z) = -\alpha\,\overline{(z/\alpha)} = -(\alpha/\overline{\alpha})\,\overline{z} \tag{20.13.7}$$

for every $\alpha \in \mathbf{C} \setminus \{0\}$ and $z \in \mathbf{C}$.

If $\alpha, \beta \in \mathbf{C} \setminus \{0\}$ and $z \in \mathbf{C}$, then

$$\sigma_\alpha(\sigma_\beta(z)) = -(\alpha/\overline{\alpha})\,\overline{\sigma_\beta(z)} = (\alpha\,\overline{\beta}/(\overline{\alpha}\,\beta))\,z. \tag{20.13.8}$$

This is related to Exercise 3 on p46 of [14]. This is also related to Weyl groups of rank two root systems, as in Exercise 4 on p46 of [14], and some remarks on p27 of [24].

Let $\alpha \in \mathbf{C} \setminus \{0\}$ and $z \in \mathbf{C}$ be given. Observe that

$$\begin{aligned} \sigma_\alpha(z) - z = -\alpha\,\overline{(z/\alpha)} - z &= -\alpha\,\overline{(z/\alpha)} - \alpha(z/\alpha) \\ &= -2\,\mathrm{Re}(z/\alpha)\,\alpha = -2\,(z,\alpha)\,|\alpha|^{-2}\,\alpha. \end{aligned} \tag{20.13.9}$$

Of course, the right side corresponds to the usual expression for reflections with respect to an inner product.

20.14 Type A_2

Some very nice pictures of a root system in the plane that is isomorphic to the one in Section 20.10 with $n = 2$ can be found on p44 of [14] and p26 of [24]. This root system can also be described as the set A of cube roots of unity and their negatives in the complex plane. Remember that points on the unit circle in $\mathbf{C}$ can be expressed as $\exp(i\,t)$ with $t \in \mathbf{R}$, using the complex exponential function. The elements of A can be expressed as $\exp(i\,t)$, where t is an integer multiple of $\pi/3$. In particular, A is a subgroup of the unit circle in $\mathbf{C}$, as a commutative group with respect to multiplication.

It is well known that

$$\exp(\pi\,i/3) = 1/2 + (\sqrt{3}/2)\,i \tag{20.14.1}$$

and

$$\exp(2\,\pi\,i/3) = -1/2 + (\sqrt{3}/2)\,i. \tag{20.14.2}$$

Indeed,

$$(1/2 + (\sqrt{3}/2)\, i)^2 = 1/4 - 3/4 + 2\,(1/2)\,(\sqrt{3}/2)\, i = -1/2 + (\sqrt{3}/2)\, i \tag{20.14.3}$$

and

$$(1/2 + (\sqrt{3}/2)\, i)^3 = (1/2 + (\sqrt{3}/2)\, i)^2\,(1/2 + (\sqrt{3}/2)\, i) = (-1/2 + (\sqrt{3}/2)\, i)\,(1/2 + (\sqrt{3}/2)\, i) = -1/4 - 3/4 = -1. \tag{20.14.4}$$

Put $\alpha = 1$ and $\beta = \exp(2\,\pi\, i/3)$, so that $\alpha + \beta = \exp(\pi\, i/3)$, as indicated in the pictures on p44 of [14] and p26 of [24]. Thus A consists of $\pm\alpha$, $\pm\beta$, and $\pm(\alpha + \beta)$. Of course, A is a finite set of nonzero elements of $\mathbf{C}$, whose linear span in $\mathbf{C}$, as a vector space over $\mathbf{R}$, is equal to $\mathbf{C}$.

If $\gamma \in \mathbf{C} \setminus \{0\}$, then let σ_γ be the reflection on $\mathbf{C}$, as a vector space over $\mathbf{R}$, associated to γ with respect to the standard inner product, as before. Thus one should check that $\sigma_\gamma(A) = A$ for every $\gamma \in A$. This is clear from the pictures in [14, 24], and can be verified using (20.13.7) as well. One should also check that $\sigma_\gamma(z) - z$ is an integer multiple of $\gamma \in A$ for every $z \in A$, which means that $2\,(z, \gamma) \in \mathbf{Z}$ for every $z \in A$. This can be seen using the expressions for the elements of A mentioned earlier, or more geometrically.

Clearly A is reduced, as a root system in the plane. It is easy to see that $B = \{\alpha, \beta\}$ is a base for A, as in [14, 24]. If we take $n = 2$ in Section 20.10, then we have seen that $\{e_1 - e_2, e_2 - e_3\}$ is a base for the root system discussed there. One can check that these root systems are isomorphic, using a linear mapping which sends one base to the other. Note that the inner product in Section 20.10 corresponds to twice the standard inner product on $\mathbf{C}$ in this way.

20.15 Dynkin diagrams

Let V be a vector space over the real numbers of positive finite dimension, and let A be a root system in V. If $\alpha, \beta \in A$, then let $n(\alpha, \beta) \in \mathbf{Z}$ be as in Section 19.9. Let $(\cdot, \cdot)$ be an inner product on V that is invariant under the Weyl group of A, and let $\|\cdot\|$ be the corresponding norm on V. If $\alpha, \beta \in A$, then

$$n(\alpha, \beta) = 2\,(\alpha, \beta)/\|\beta\|^2, \tag{20.15.1}$$

as before. In particular, $n(\alpha, \beta) = 0$ if and only if $(\alpha, \beta) = 0$, which is symmetric in α and β. Otherwise, if $n(\beta, \alpha) \neq 0$, then

$$n(\alpha, \beta)/n(\beta, \alpha) = \|\alpha\|^2/\|\beta\|^2. \tag{20.15.2}$$

In this case, $\|\alpha\|$ is greater than, equal to, or less than $\|\beta\|$ exactly when (20.15.2) is greater than, equal to, or less than 1, respectively.

Let B be a base for A. The corresponding *Dynkin diagram* adds some information to the Coxeter graph of A with respect to B, so that the Cartan matrix of A with respect to B is determined. More precisely, if α and β are distinct elements of B, and if there is more than one edge between α and β in the Coxeter graph, then $n(\alpha, \beta), n(\beta, \alpha) \neq 0$, and (20.15.2) is not equal to 1. In this situation, one can add a marking to the edges between α and β, to indicate whether (20.15.2) is greater than or less than 1. This is equivalent to indicating whether $\|\alpha\|$ is greater than or less than $\|\beta\|$, as on p57 of [14] and p39 of [24].

Alternatively, suppose that A is irreducible, so that the Coxeter graph is connected. As on p38 of [24], one can label each $\alpha \in B$ with a positive real number that is proportional to $\|\alpha\|^2$. If α and β are distinct elements of B, and if there is at least one edge between α and β in the Coxeter graph, then $n(\alpha, \beta), n(\beta, \alpha) \neq 0$, and (20.15.2) is the same as the ratio of the labels of α and β. In this case, the number of edges between α and β in the Coxeter graph is the same as this ratio. Two sets of labels of the elements of B are considered to be equivalent when they differ by a single positive multiplicative constant.

Let B_0 be a nonempty subset of B, and let V_0 be the linear subspace spanned by B_0. Thus $A_0 = A \cap V_0$ is a root system in V_0, as in Section 20.6, and Exercise 2 on p54 of [14]. More precisely, B_0 is a base for A_0. If $\alpha \in A$, then let σ_α be the symmetry on V with vector α that maps A onto itself. If $\alpha \in A_0$, then σ_α maps V_0 onto itself, as before. This implies that σ_α maps A_0 onto itself, so that the restriction of σ_α to V_0 is the symmetry on V_0 with vector α that maps A_0 onto itself. If $\alpha, \beta \in A_0$, then it follows that the analogue of $n(\alpha, \beta)$ for A_0 is the same as for A. Similarly, the restriction of $(\cdot, \cdot)$ to V_0 is invariant under the Weyl group of A_0. The Cartan matrix of A_0 with respect to B_0 is the same as the restriction to $B_0 \times B_0$ of the Cartan matrix of A with respect to B. If α and β are distinct elements of B_0, then the number of edges between α and β in the Coxeter graph of A_0 with respect to B_0 is the same as in the Coxeter graph of A with respect to B. One could also use the same additional markings or labellings for the Dynkin diagram of A_0 with respect to B_0 as for A with respect to B. This corresponds to Exercise 6 on p54 of [14].

Chapter 21

Root systems, 3

21.1 More on type A_2

Let $(\cdot,\cdot)$ be the standard inner product on the complex plane, considered as a vector space over the real numbers, as in Section 20.13. Also let $A_{2,1}$ be the root system in $\mathbf{C}$ discussed in Section 20.14, consisting of the cube roots of unity and their negatives. Equivalently, $A_{2,1}$ consists of complex numbers of the form $\exp(j\,\pi\,i/3)$, with $j \in \mathbf{Z}$. Observe that

$$\exp(\pi\,i/3) + \exp(2\,\pi\,i/3) = \sqrt{3}\,i, \tag{21.1.1}$$

by (20.14.1) and (20.14.2). If $j \in \mathbf{Z}$, then it follows that

$$\exp(j\,\pi\,i/3) + \exp((j+1)\,\pi\,i/3) = \sqrt{3}\,i\,\exp((j-1)\,\pi\,i/3). \tag{21.1.2}$$

Put

$$A_{2,2} = \sqrt{3}\,i\,A_{2,1} = \{\sqrt{3}\,i\,z : z \in A_{2,1}\}. \tag{21.1.3}$$

This is the same as the set of complex numbers that can be expressed as in (21.1.2) for some $j \in \mathbf{Z}$. It is clear from (21.1.3) that $A_{2,2}$ is a root system in $\mathbf{C}$, as a vector space over $\mathbf{R}$, that is isomorphic to $A_{2,1}$. If $w \in A_{2,2}$, then it is easy to see that

$$w/\overline{w} \in A_{2,1}. \tag{21.1.4}$$

Of course, this also holds when $w \in A_{2,1}$.

If $\gamma \in \mathbf{C} \setminus \{0\}$, then let σ_γ be the reflection on $\mathbf{C}$, as a vector space over $\mathbf{R}$, associated to γ with respect to $(\cdot,\cdot)$, as before. Thus $\sigma_\gamma(z) = -(\gamma/\overline{\gamma})\,\overline{z}$ for every $z \in \mathbf{C}$, as in Section 20.13. If $\gamma \in A_{2,1}$ or $A_{2,2}$, then one can check that σ_γ maps $A_{2,1}$ and $A_{2,2}$ onto themselves, using (21.1.4).

Remember that $\sigma_\gamma(z) - z = -2\,(z,\gamma)\,|\gamma|^{-2}\,\gamma$ for every $\gamma \in \mathbf{C}\setminus\{0\}$ and $z \in \mathbf{C}$, as in Section 20.13. Let us check that

$$2\,(z,\gamma)\,|\gamma|^{-2} = 2\,\mathrm{Re}(z/\gamma) \in \mathbf{Z} \tag{21.1.5}$$

for every $\gamma, z \in A_{2,1} \cup A_{2,2}$. This was already mentioned in Section 20.14 when $\gamma, z \in A_{2,1}$. If $\gamma, z \in A_{2,2}$, then this follows from the previous case, because γ and z are products of elements of $A_{2,1}$ by $\sqrt{3}\, i$. If $\gamma \in A_{2,1}$ and $z \in A_{2,2}$, then (21.1.5) can be reduced to the case where $z \in A_{2,1}$, because elements of $A_{2,2}$ can be expressed as sums of elements of $A_{2,1}$, as in (21.1.2). The case where $\gamma \in A_{2,2}$ and $z \in A_{2,1}$ is a more precise version of this, because of the additional factor of $|\gamma|^{-2} = 1/3$. If $\gamma = \sqrt{3}\, i$ and $z \in A_{2,1}$, then (21.1.5) can be verified directly. Otherwise, if γ is the product of $\sqrt{3}\, i$ and any element of $A_{2,1}$, then one can reduce to the case where $\gamma = \sqrt{3}\, i$.

21.2 Type G_2

Some very nice pictures can be found on p44 of [14] and p27 of [24]. Let us continue with the notation in the previous section, and put

$$A = A_{2,1} \cup A_{2,2}. \tag{21.2.1}$$

It is easy to see that this defines a root system in the complex plane, as a vector space over the real numbers, using the remarks in the previous section. This root system is said to be of *type* G_2, and this description of it corresponds to the one on p40 of [24]. More precisely, A is reduced as a root system in $\mathbf{C}$.

Put $\alpha = 1 \in A_{2,1}$ and

$$\beta = \sqrt{3}\, i \, \exp(\pi\, i/3) = \sqrt{3}\, i\, (1/2 + (\sqrt{3}/2)\, i) = -3/2 + (\sqrt{3}/2)\, i, \tag{21.2.2}$$

which is an element of $A_{2,2}$. Note that this choice of α is the same as in Section 20.14, but this choice of β is different. Of course, $B = \{\alpha, \beta\}$ is a basis for $\mathbf{C}$ as a vector space over $\mathbf{R}$, and in fact it is a base for A, as in [14, 24]. Indeed,

$$\beta + \alpha = -1/2 + (\sqrt{3}/2)\, i = \exp(2\,\pi\, i/3) \tag{21.2.3}$$

and

$$\beta + 2\,\alpha = 1/2 + (\sqrt{3}/2)\, i = \exp(\pi\, i/3). \tag{21.2.4}$$

Similarly,

$$\begin{aligned} \beta + 3\,\alpha = 3/2 + (\sqrt{3}/2)\, i &= \sqrt{3}\, i\, (1/2 - (\sqrt{3}/2)\, i) \\ &= \sqrt{3}\, i\, \exp(-\pi\, i/3). \end{aligned} \tag{21.2.5}$$

We also have that

$$2\,\beta + 3\,\alpha = \sqrt{3}\, i. \tag{21.2.6}$$

These expressions for elements of A are indicated in the picture on p27 of [24], and the other elements of A can be obtained by multiplying by -1.

If $z, w \in A$, then $n(z, w) = 2\,(z, w)\,|w|^{-2} \in \mathbf{Z}$, as in Section 19.9. Observe that

$$n(\alpha, \beta) = 2\,(\alpha, \beta)\,|\beta|^{-2} = 2\ \mathrm{Re}(\alpha\,\overline{\beta})\,|\beta|^{-2} = -1 \tag{21.2.7}$$

and

$$n(\beta, \alpha) = 2\,(\alpha, \beta)\,|\alpha|^{-2} = -3. \tag{21.2.8}$$

Thus the number of edges between α and β in the Coxeter graph of A with respect to B is

$$n(\alpha, \beta)\, n(\beta, \alpha) = 3. \tag{21.2.9}$$

The corresponding Dynkin diagram may be depicted as on p38 of [24], where α has the label $|\alpha|^2 = 1$ and β has the label $|\beta|^2 = 3$. Alternatively, the Dynkin diagram may be depicted as on p57f of [14] and p39 of [24], where the edges are marked to indicate that $|\alpha| < |\beta|$.

Let T be a one-to-one linear mapping from $\mathbf{C}$ onto itself, as a vector space over $\mathbf{R}$. Remember that T is an automorphism of the root system A if $T(A) = A$. In this case, if T maps B onto itself, then T preserves the Cartan matrix of A with respect to B, as in Section 20.2. It is easy to see that this only happens when T is the identity mapping on $\mathbf{C}$ in this situation. This is mentioned in Table 1 on p66 of [14], and on p39 of [24].

If $z \in \mathbf{C} \setminus \{0\}$, then put $\widehat{z} = 2\,z/|z|^2$, as in (19.7.9). If $E \subseteq \mathbf{C} \setminus \{0\}$, then let $\widehat{E}$ be the set of $\widehat{z}$, $z \in E$. Thus

$$\widehat{A_{2,1}} = 2\,A_{2,1} = \{2\,z : z \in A_{2,1}\} \tag{21.2.10}$$

and

$$\widehat{A_{2,2}} = (2/3)\,A_{2,2} = \{(2/3)\,z : z \in A_{2,2}\}. \tag{21.2.11}$$

Observe that

$$\widehat{A_{2,1}} = (2/\sqrt{3})\,i\,A_{2,2} \tag{21.2.12}$$

and

$$\widehat{A_{2,2}} = (2/\sqrt{3})\,i\,A_{2,1}. \tag{21.2.13}$$

This implies that

$$\widehat{A} = \widehat{A_{2,1}} \cup \widehat{A_{2,2}} = (2/\sqrt{3})\,i\,A. \tag{21.2.14}$$

Remember that $\widehat{A}$ is the inverse system of A in $\mathbf{C}$ with respect to $(\cdot, \cdot)$, as in Section 19.8. It follows that $\widehat{A}$ is isomorphic to A, as root systems in $\mathbf{C}$. This corresponds to part of Exercise 5 on p63 of [14].

21.3 Another description

Let us now consider the description on p65 of [14], of a root system that is isomorphic to the one in the previous section. Let $(\cdot, \cdot)$ be the standard inner product on $\mathbf{R}^3$, and let e_1, e_2, and e_3 be the standard basis vectors in $\mathbf{R}^3$. Put

$$V = \{v \in \mathbf{R}^3 : v_1 + v_2 + v_3 = 0\}, \tag{21.3.1}$$

which is the two-dimensional linear subspace of $\mathbf{R}^3$ orthogonal to $e_1 + e_2 + e_3$. Consider

$$A_1 = \{\alpha \in V \cap \mathbf{Z}^3 : (\alpha, \alpha) = 2\}, \tag{21.3.2}$$

$$A_2 = \{\alpha \in V \cap \mathbf{Z}^3 : (\alpha, \alpha) = 6\}, \tag{21.3.3}$$

and

$$A = A_1 \cup A_2. \tag{21.3.4}$$

Thus V is the same as in Section 20.10 with $n = 2$, and A_1 is the root system discussed there in this case. As before, the elements of A_1 are of the form $e_j - e_l$, where $1 \le j \ne l \le 3$. Observe that $\alpha \in \mathbf{Z}^3$ satisfies $(\alpha, \alpha) = 6$ exactly when two of the coordinates of α are ± 1, and the third coordinate is ± 2. It follows that $\alpha \in A_2$ exactly when one of the coordinates of α is 2 and the other two coordinates are -1, or one of the coordinates is -2 and the other two coordinates are 1. In particular, A is a finite set of nonzero elements of V whose linear span is V.

If α is a nonzero element of $\mathbf{R}^3$, then let σ_α be the reflection on $\mathbf{R}^3$ associated to α with respect to $(\cdot, \cdot)$, as usual. If $\alpha \in V$, then

$$\sigma_\alpha(V) = V, \tag{21.3.5}$$

as in Section 20.6. Suppose for the moment that $(\alpha, \alpha) = 2$, so that $\sigma_\alpha(v) = v - (v, \alpha)\, \alpha$ for every $v \in \mathbf{R}^3$. If $\alpha \in \mathbf{Z}^3$, then $\sigma_\alpha(\mathbf{Z}^3) = \mathbf{Z}^3$, as in Section 20.10. If $\alpha \in V \cap \mathbf{Z}^3$, then it follows that σ_α maps A_1 and A_2 onto themselves, because σ_α is an orthogonal transformation on $\mathbf{R}^3$. Of course, this implies that σ_α maps A onto itself. If $\alpha, v \in \mathbf{Z}^3$, then $(v, \alpha) \in \mathbf{Z}$, so that $\sigma_\alpha(v) - v = (v, \alpha)\, \alpha$ is an integer multiple of α. If $\alpha = e_j - e_l$, $1 \le j \ne l \le 3$, then $\sigma_\alpha(v)$ interchanges the jth and lth coordinates of v, without affecting the other coordinate, as before.

Suppose now that $\alpha \in A_2$, so that

$$\sigma_\alpha(v) = v - (v, \alpha)\, \alpha/3 \tag{21.3.6}$$

for every $v \in \mathbf{R}^3$. If $\beta \in A$, then we would like to check that

$$(\beta, \alpha)/3 \in \mathbf{Z}. \tag{21.3.7}$$

Suppose first that $\beta \in A_1$, so that $\beta = e_j - e_l$ for some $1 \le j \ne l \le n$. If $\alpha_j = \alpha_l$, then $(\beta, \alpha) = 0$. Otherwise, if $\alpha_j \ne \alpha_l$, then one can check that

$$(\beta, \alpha) = \pm 3. \tag{21.3.8}$$

If $\beta = \pm\alpha \in A_2$, then (21.3.7) clearly holds. If $\beta \in A_2$ and $\beta \ne \pm\alpha$, then one can verify that (21.3.8) holds.

It follows from (21.3.7) that σ_α maps A into $\mathbf{Z}^3$. This implies that σ_α maps A_1 and A_2 into themselves, because σ_α is an orthogonal transformation on $\mathbf{R}^3$ that maps V to itself. This means that σ_α maps A_1 and A_2 onto themselves, because σ_α is its own inverse, so that σ_α maps A onto itself as well. If $\beta \in A$, then $\sigma_\alpha(\beta) - \beta$ is an integer multiple of α, by (21.3.7). This shows that A is a root system in V, and it is easy to see that A is reduced.

As a base for A, one can take

$$\{e_1 - e_2,\ -2\, e_1 + e_2 + e_3\}, \tag{21.3.9}$$

as on p65 of [14]. Indeed,

$$(21.3.10) \qquad (e_1 - e_2) + (-2\,e_1 + e_2 + e_3) = e_3 - e_1,$$
$$(21.3.11) \qquad 2\,(e_1 - e_2) + (-2\,e_1 + e_2 + e_3) = e_3 - e_2,$$
$$(21.3.12) \qquad 3\,(e_1 - e_2) + (-2\,e_1 + e_2 + e_3) = e_1 - 2\,e_2 + e_3,$$
$$(21.3.13) \qquad 3\,(e_1 - e_2) + 2\,(-2\,e_1 + e_2 + e_3) = -e_1 - e_2 + 2\,e_3.$$

Note that (21.3.13) is the maximal root in A with respect to (21.3.9), and that (21.3.11) is the maximal short root, as in Table 2 of p66 of [14].

If $z, w \in A$, then $n(z, w) = 2\,(z, w)\,(w, w)^{-2} \in \mathbf{Z}$, as in Section 19.9. It is easy to see that

$$(21.3.14) \qquad n(e_1 - e_2, -2\,e_1 + e_2 + e_3) = -1,$$
$$(21.3.15) \qquad n(-2\,e_1 + e_2 + e_3, e_1 - e_2) = -3.$$

In particular, their product is 3, which is the number of edges between the two vertices in the Coxeter graph of A.

Consider the linear mapping from the complex plane, as a vector space over the real numbers, onto V which sends the elements α and β of the base in the previous section to the first and second elements of (21.3.9), respectively. One can check that this defines an isomorphism between the root systems discussed in this and the previous section. More precisely, the subsystems $A_{2,1}$ and $A_{2,2}$ in the previous section correspond to A_1 and A_2 in this section. This is related to Exercise 4 on p67 of [14]. Observe that the restriction to V of the standard inner product on $\mathbf{R}$ corresponds to twice the standard inner product on $\mathbf{C}$ with respect to this isomorphism.

21.4 Type F_4

In this section, we take $V = \mathbf{R}^4$, with its standard inner product $(\cdot, \cdot)$ and basis e_1, e_2, e_3, e_4. Put

$$(21.4.1) \qquad A_1 = \{\alpha \in \mathbf{Z}^4 : (\alpha, \alpha) = 1 \text{ or } 2\},$$

as in Section 20.11, with $n = 4$. The elements of A_1 with $(\alpha, \alpha) = 1$ are of the form $\pm e_j$ for some $j = 1, 2, 3, 4$, and the elements of A_1 with $(\alpha, \alpha) = 2$ are of the form $\pm e_j \pm e_l$ for some $1 \le j \ne l \le n$, as before. We have seen that A_1 is a reduced root system in V.

Let $\widetilde{L}_4$ be the subgroup of $\mathbf{R}^4$, as a commutative group with respect to addition, generated by e_1, e_2, e_3, e_4, and $(1/2)\,(e_1 + e_2 + e_3 + e_4)$. Of course, $L_4 = \mathbf{Z}^4$ is the subgroup of $\mathbf{R}^4$ generated by e_1, e_2, e_3, e_4, so that $\widetilde{L}_4$ is the same as the subgroup of $\mathbf{R}^4$ generated by $\mathbf{Z}^4$ and $(1/2)\,(e_1+e_2+e_3+e_4)$. Equivalently,

$$(21.4.2) \qquad \widetilde{L}_4 = \mathbf{Z}^4 \cup (\mathbf{Z}^4 + (1/2, 1/2, 1/2, 1/2)).$$

Consider

$$(21.4.3) \qquad A = \{\alpha \in \widetilde{L}_4 : (\alpha, \alpha) = 1 \text{ or } 2\}.$$

Note that

$$A \cap \mathbf{Z}^n = A_1. \tag{21.4.4}$$

One can check that

$$\begin{aligned} A \cap (\mathbf{Z}^4 + (1/2, 1/2, 1/2, 1/2)) \\ = \quad \{\alpha \in \mathbf{R}^4 : \alpha_j = \pm 1/2 \text{ for every } j = 1, 2, 3, 4\}. \end{aligned} \tag{21.4.5}$$

More precisely, it is easy to see that if $\alpha_j = \pm 1/2$ for each $j = 1, 2, 3, 4$, then $\alpha \in \widetilde{L}_4$ and $(\alpha, \alpha) = 1$, so that $\alpha \in A$. If $\alpha \in \mathbf{Z}^4 + (1/2, 1/2, 1/2, 1/2)$ and $\alpha_j \neq \pm 1/2$ for some $j = 1, 2, 3, 4$, then one can verify that $(\alpha, \alpha) \geq 3$.

Of course, A is a finite set of nonzero elements of V, whose linear span is V. If $\alpha \in V \setminus \{0\}$, then let σ_α be the reflection on V associated to α with respect to $(\cdot, \cdot)$, as usual. Suppose first that $\alpha = \pm e_j$ for some $j = 1, 2, 3, 4$, so that $\sigma_\alpha = \sigma_{e_j}$ multiplies the jth coordinate of $v \in V$ by -1, and leaves the other coordinates of v unchanged. Clearly σ_α maps $\mathbf{Z}^4$, $\widetilde{L}_4$, A_1, and A onto themselves. If $v \in \widetilde{L}_4$, then $2\, v_j \in \mathbf{Z}$, and $\sigma_\alpha(v) - v = -2\, v_j\, e_j$ is an integer multiple of α.

Suppose now that $\alpha = \pm e_j \pm e_l$ for some $1 \leq j \neq l \leq 4$, so that $\sigma_\alpha(v) = v - (v, \alpha)\, \alpha$ for every $v \in V$. More precisely, we have seen that σ_α interchanges the jth and lth coordinates of $v \in V$ in this case, and may multiply them by -1, while leaving the other coordinates of v unchanged. In particular, σ_α maps $\mathbf{Z}^4$, $\widetilde{L}_4$, A_1, and A onto themselves. If $v \in \widetilde{L}_4$, then one can check that

$$(v, \alpha) \in \mathbf{Z}. \tag{21.4.6}$$

This implies that $\sigma_\alpha(v) - v = -(v, \alpha)\, \alpha$ is an integer multiple of α when $v \in \widetilde{L}_4$, and in particular when $v \in A$.

Suppose that α is an element of (21.4.5), so that $\alpha_j = \pm 1/2$ for each $j = 1, 2, 3, 4$. If $v \in \widetilde{L}_4$, then one can verify that

$$2\,(v, \alpha) \in \mathbf{Z}. \tag{21.4.7}$$

More precisely, if $v \in \mathbf{Z}^4$, then this follows from the fact that $2\,\alpha \in \mathbf{Z}^4$. If $v = (1/2, 1/2, 1/2, 1/2)$, then (21.4.7) can be checked directly. This implies that (21.4.7) holds for all $v \in \widetilde{L}_4$.

Note that $\sigma_\alpha(v) = v - 2\,(v, \alpha)\, \alpha$ for every $v \in V$, because $(\alpha, \alpha) = 1$. It follows that σ_α maps $\widetilde{L}_4$ into itself, by (21.4.7). Thus σ_α maps $\widetilde{L}_4$ onto itself, because σ_α is its own inverse on V. This means that σ_α maps A onto itself, because σ_α is an orthogonal transformation on V. If $v \in \widetilde{L}_4$, then $\sigma_\alpha(v) - v$ is an integer multiple of α, by (21.4.7).

This shows that A is a root system in V, which is said to be of *type* F_4. This follows the descriptions on p65 of [14], and p40 of [24]. Observe that A is reduced, as a root system in V.

Put

$$V_0 = \{v \in V : v_1 = 0\} \tag{21.4.8}$$

and

$$A_0 = A \cap V_0 = A_1 \cap V_0. \tag{21.4.9}$$

Observe that A_0 is a reduced root system in V_0, which is isomorphic to the analogue of A_1 in $\mathbf{R}^3$.

Put

$$B = \{e_2 - e_3,\, e_3 - e_4,\, e_4,\, (1/2)\,(e_1 - e_2 - e_3 - e_4)\} \tag{21.4.10}$$

and

$$B_0 = B \cap V_0 = \{e_2 - e_3,\, e_3 - e_4,\, e_4\}. \tag{21.4.11}$$

It is easy to see that B_0 is a basis for V_0. In fact, B_0 is a base for A_0 as a root system in V_0, as in Section 20.11. We also have that B is a basis for V, because B_0 is a basis for V_0. One can check that B is a base for A, as in [14, 24].

More precisely, note that e_2 and e_3 can be expressed as sums of elements of B_0, as in Section 20.11. Using this, one can express any element of A of the form $(1/2)\,(e_1 \pm e_2 \pm e_3 \pm e_4)$ as $(1/2)\,(e_1 - e_2 - e_3 - e_4)$ plus possibly some elements of B_0. If $l = 2, 3, 4$, then $e_1 - e_l$ can be expressed as the sum of

$$2\,((1/2)\,(e_1 - e_2 - e_3 - e_4)) = e_1 - e_2 - e_3 - e_4 \tag{21.4.12}$$

and elements of B_0. Similarly, one can use this to express e_1 and $e_1 + e_l$, $l = 2, 3, 4$, as sums of (21.4.12) and elements of B_0.

The maximal root in A with respect to B is

$$\begin{aligned} &2\,(e_2 - e_3) + 3\,(e_3 - e_4) + 4\,e_4 + 2\,((1/2)\,(e_1 - e_2 - e_3 - e_4)) \\ &= e_1 + e_2, \end{aligned} \tag{21.4.13}$$

as in Table 2 on p66 of [14]. The maximal short root is

$$\begin{aligned} &(e_2 - e_3) + 2\,(e_3 - e_4) + 3\,e_4 + 2\,((1/2)\,(e_1 - e_2 - e_3 - e_4)) \\ &= e_1. \end{aligned} \tag{21.4.14}$$

If $\alpha, \beta \in A$, then $n(\alpha, \beta) = 2\,(\alpha, \beta)\,(\beta, \beta)^{-1} \in \mathbf{Z}$, as in Section 19.9. If $\alpha, \beta \in B$ and $\alpha \neq \beta$, then the number of edges between α and β in the Coxeter graph of A with respect to B is $n(\alpha, \beta)\, n(\beta, \alpha)$. In particular, if $(\alpha, \beta) = 0$, then $n(\alpha, \beta) = n(\beta, \alpha) = 0$, and there are no edges between α and β in the Coxeter graph of A with respect to B. Clearly

$$\begin{aligned} (e_2 - e_3, e_4) &= (e_2 - e_3, (1/2)\,(e_1 - e_2 - e_3 - e_4)) \\ &= (e_3 - e_4, (1/2)\,(e_1 - e_2 - e_3 - e_4)) = 0. \end{aligned} \tag{21.4.15}$$

Thus there are no edges between $e_2 - e_3$ and e_4, or between either $e_2 - e_3$ or $e_3 - e_4$ and $(1/2)\,(e_1 - e_2 - e_3 - e_4)$ in the Coxeter graph of A with respect to B.

It is easy to see that

$$n(e_2 - e_3, e_3 - e_4) = n(e_3 - e_4, e_2 - e_3) = -1 \tag{21.4.16}$$

and

$$n(e_4, (1/2)\,(e_1 - e_2 - e_3 - e_4)) = n((1/2)\,(e_1 - e_2 - e_3 - e_4), e_4) = -1. \tag{21.4.17}$$

This implies that there is one edge between $e_2 - e_3$ and $e_3 - e_4$, and one edge between e_4 and $(1/2)\,(e_1 - e_2 - e_3 - e_4)$, in the Coxeter graph of A with respect to B.

We also have that

$$n(e_3 - e_4, e_4) = -2 \tag{21.4.18}$$

and

$$n(e_4, e_3 - e_4) = -1. \tag{21.4.19}$$

This means that there are two edges between $e_3 - e_4$ and e_4 in the Coxeter graph of A with respect to B. The corresponding Dynkin diagram may be depicted as on p38 of [24], where $e_2 - e_3$ and $e_3 - e_4$ are labelled with 2, and e_4 and $(1/2)\,(e_1 - e_2 - e_3 - e_4)$ are labelled with 1. The Dynkin diagram may be depicted as on p57f of [14] and p39 of [24] as well, where the edges between $e_3 - e_4$ and e_4 are marked to indicate that $(e_3 - e_4, e_3 - e_4) = 2 > 1 = (e_4, e_4)$.

Let T be an automorphism of A as a root system, so that T is a one-to-one linear mapping from V onto itself that maps A onto itself. If $T(B) = B$, then T preserves the Cartan matrix of A with respect to B, as in Section 20.2. It it easy to see that this can only happen when T is the identity mapping on V, as indicated in Table 1 on p66 of [14], and on p39 of [24].

21.5 Inverse systems

Let V be a vector space over the real numbers of positive finite dimension, and let A be a root system in V. If $\alpha, \beta \in A$, then we let $n(\alpha, \beta) \in \mathbf{Z}$ be as in Section 19.9, as usual. Let $(\cdot, \cdot)$ be an inner product on V that is invariant under the Weyl group of A, so that $n(\alpha, \beta) = 2\,(\alpha, \beta)\,(\beta, \beta)^{-1}$ for every $\alpha, \beta \in A$. If $v \in V \setminus \{0\}$, then put $\widehat{v} = 2\,v\,(v, v)^{-1}$, as in (19.7.9). Note that

$$(\widehat{v}, \widehat{v}) = 4/(v, v). \tag{21.5.1}$$

Remember that $\widehat{A} = \{\widehat{\alpha} : \alpha \in A\}$ is the inverse system of A in V with respect to $(\cdot, \cdot)$, as in Section 19.8. If $\alpha, \beta \in A$, then $\widehat{\alpha}, \widehat{\beta} \in \widehat{A}$, and $n(\widehat{\alpha}, \widehat{\beta})$ can be defined as before. Observe that

$$n(\widehat{\alpha}, \widehat{\beta}) = 2\,(\widehat{\alpha}, \widehat{\beta})\,(\widehat{\beta}, \widehat{\beta})^{-1} = 2\,(\alpha, \beta)\,(\alpha, \alpha)^{-1} = n(\beta, \alpha). \tag{21.5.2}$$

It follows that

$$n(\widehat{\alpha}, \widehat{\beta})\,n(\widehat{\beta}, \widehat{\alpha}) = n(\alpha, \beta)\,n(\beta, \alpha) \tag{21.5.3}$$

for every $\alpha, \beta \in A$. Of course, if $(\alpha, \alpha) = (\beta, \beta)$, then

$$n(\widehat{\alpha}, \widehat{\beta}) = n(\alpha, \beta). \tag{21.5.4}$$

Let B be a base for A. Suppose for the moment that A is reduced, so that $\widehat{B} = \{\widehat{\alpha} : \alpha \in B\}$ is a base for $\widehat{A}$, as in Section 19.13. In this case, the Coxeter graph of A with respect to B corresponds to the Coxeter graph of $\widehat{A}$ with respect to $\widehat{B}$ under the mapping $\alpha \mapsto \widehat{\alpha}$, by (21.5.3). If A is not reduced, then one can get a base for $\widehat{A}$ from B as in Section 19.13. One can check that the Coxeter graphs for A and $\widehat{A}$ with respect to these bases correspond to each other in this situation as well.

If the elements of A have the same norm with respect to $(\cdot, \cdot)$, then there is a dilation on V that sends A onto $\widehat{A}$. This dilation sends $\alpha \in A$ to $\widehat{\alpha} \in \widehat{A}$.

If A is as in Section 21.2, then the elements of A do not all have the same norm, but we saw that $\widehat{A}$ is isomorphic to A. Alternatively, let $B = \{\alpha, \beta\}$ be a base for A, so that $\widehat{B} = \{\widehat{\alpha}, \widehat{\beta}\}$ is a base for $\widehat{A}$. Consider the mapping ϕ from B onto $\widehat{B}$ defined by $\phi(\alpha) = \widehat{\beta}$ and $\phi(\beta) = \widehat{\alpha}$. Using ϕ, the Cartan matrix of A with respect to B corresponds to the Cartan matrix of $\widehat{A}$ with respect to $\widehat{B}$, because of (21.5.2). Thus ϕ extends to an isomorphism between A and $\widehat{A}$, as in Section 20.2.

Let us now return to the situation considered in the previous section. Note that $\widehat{v} = 2\,v$ when $v \in V$ satisfies $(v, v) = 1$, and $\widehat{v} = v$ when $(v, v) = 2$. If A_1 is as in (21.4.1), then its inverse system $\widehat{A_1}$ in $V = \mathbf{R}^4$ with respect to the standard inner product consists of elements of the form $\pm 2\,e_j$ for $j = 1, 2, 3, 4$ and $\pm e_j \pm e_l$ for $1 \le j \ne l \le 4$, as in Section 20.11. If A is as in (21.4.3), then the inverse system $\widehat{A}$ of A in V with respect to the standard inner product consists of the elements of $\widehat{A_1}$, and elements of the form $\pm e_1 \pm e_2 \pm e_3 \pm e_4$.

Let B be the base for A in (21.4.10). The corresponding base $\widehat{B}$ for $\widehat{A}$ is given by

(21.5.5) $$\widehat{B} = \{e_2 - e_3,\, e_3 - e_4,\, 2\,e_4,\, e_1 - e_2 - e_3 - e_4\}.$$

Let ϕ be the one-to-one mapping from B onto $\widehat{B}$ that interchanges the ordering in these lists. One can verify that the Cartan matrix of A with respect to B corresponds to the Cartan matrix of $\widehat{A}$ with respect to $\widehat{B}$, using ϕ. This means that ϕ extends to an isomorphism between A and $\widehat{A}$, as in Section 20.2 again.

This corresponds to part of Exercise 5 on p63 of [14]. Of course, the Dynkin diagram of the inverse system can be obtained by changing the labels on the vertices, or the markings of the multiple edges. In the previous two cases, the resulting Dynkin diagram is easily seen to be isomorphic to the initial one.

21.6 Type E_8

Let us take $V = \mathbf{R}^8$, with its standard inner product $(\cdot, \cdot)$ and basis $e_1, \ldots, e_8$. Put

(21.6.1) $$A_1 = \{\alpha \in \mathbf{Z}^8 : (\alpha, \alpha) = 2\},$$

as in Section 20.12, with $n = 8$. The elements of A_1 are of the form $\pm e_j \pm e_l$ with $1 \le j \ne l \le 8$, as before. Remember that A is a reduced root system in V.

Of course, $L_8 = \mathbf{Z}^8$ is the subgroup of $\mathbf{R}^8$, as a commutative group with respect to addition, generated by $e_1, \ldots, e_8$. Let $\widetilde{L}_8$ be the subgroup of $\mathbf{R}^8$ generated by $e_1, \ldots, e_8$ and $(1/2)\,(e_1 + \cdots + e_8)$. Thus

$$\widetilde{L}_8 = \mathbf{Z}^8 \cup (\mathbf{Z}^8 + (1/2, \ldots, 1/2)). \tag{21.6.2}$$

If $\alpha \in \mathbf{R}^8$ satisfies $\alpha_j = \pm 1/2$ for every $j = 1, \ldots, 8$, then α is an element of $\mathbf{Z}^8 + (1/2, \ldots, 1/2)$ and $(\alpha, \alpha) = 2$. If $\alpha \in \mathbf{Z}^8 + (1/2, \ldots, 1/2)$ and $\alpha_j \neq \pm 1/2$ for some $j = 1, \ldots, 8$, then it is easy to see that $(\alpha, \alpha) \geq 4$.

Let $L_{8,e}$ be the set of $v \in \mathbf{Z}^8$ such that

$$\sum_{j=1}^{8} v_j \in 2\,\mathbf{Z}, \tag{21.6.3}$$

and let $\widetilde{L}_{8,e}$ be the set of $v \in \widetilde{L}_8$ such that (21.6.3) holds. These are subgroups of $\mathbf{Z}^8$ and $\widetilde{L}_8$, respectively. Note that

$$(1/2)\,(e_1 + \cdots + e_8) \in \widetilde{L}_{8,e}, \tag{21.6.4}$$

because the sum of its coordinates is 4. It follows that

$$\widetilde{L}_{8,e} = L_{8,e} \cup (L_{8,e} + (1/2, \ldots, 1/2)). \tag{21.6.5}$$

We also have that $A_1 \subseteq L_{8,e}$.

Suppose that $\alpha \in \mathbf{R}^8$ satisfies $\alpha_j = \pm 1/2$ for each $j = 1, \ldots, 8$, and let r be the number of j such that $\alpha_j = 1/2$. In this case,

$$\sum_{j=1}^{8} \alpha_j = (1/2)\,(r - (8 - r)) = r - 4. \tag{21.6.6}$$

This means that $\alpha \in \widetilde{L}_{8,e}$ exactly when r is even.

Consider

$$A = \{\alpha \in \widetilde{L}_{8,e} : (\alpha, \alpha) = 2\}. \tag{21.6.7}$$

Observe that

$$A \cap L_{8,e} = A_1. \tag{21.6.8}$$

Using the previous remarks, we get that $\alpha \in A \cap (L_{8,e} + (1/2, \ldots, 1/2))$ if and only if $\alpha_j = \pm 1/2$ for every $j = 1, \ldots, 8$, and $\alpha_j = 1/2$ for an even number of j. Clearly A is a finite set of nonzero elements of V whose linear span is V.

Let us check that

$$(v, w) \in \mathbf{Z} \tag{21.6.9}$$

for every $v, w \in \widetilde{L}_{8,e}$. Of course, (21.6.9) holds when $v, w \in \mathbf{Z}^8$. If $w = (1/2, \ldots, 1/2)$, then (21.6.9) holds for every $v \in L_{8,e}$, by (21.6.3). If $v = (1/2, \ldots, 1/2)$ as well, then $(v, w) = 2$. It follows that (21.6.9) holds for every $v, w \in \widetilde{L}_{8,e}$, by (21.6.5).

If $\alpha \in V$ satisfies $(\alpha, \alpha) = 2$, then the reflection σ_α on V associated to α with respect to $(\cdot, \cdot)$ is given by $\sigma_\alpha(v) = v - (v, \alpha)\, \alpha$, as before. If $\alpha \in A$, then σ_α maps $\widetilde{L}_{8,e}$ into itself, because of (21.6.9). This implies that σ_α maps $\widetilde{L}_{8,e}$ onto itself, because σ_α is its own inverse. It follows that σ_α maps A onto itself, because σ_α is an orthogonal transformation on V. If $v \in \widetilde{L}_{8,e}$, then $\sigma_\alpha(v) - v$ is an integer multiple of α, by (21.6.9).

Thus A is a root system in V, which is said to be of *type* E_8. This follows the descriptions on p65 of [14], and p41 of [24]. Note that A is reduced, as a root system in V.

Put

$$V_0 = \{v \in V : v_8 = 0\} \tag{21.6.10}$$

and

$$A_0 = A \cap V_0. \tag{21.6.11}$$

Equivalently,

$$A_0 = A_1 \cap V_0, \tag{21.6.12}$$

because $\widetilde{L}_{8,e} \cap V_0 = L_{8,e} \cap V_0$. This is a reduced root system in V_0, which is isomorphic to the one in Section 20.12 with $n = 7$.

Put

$$\begin{aligned} B \;=\; & \{(1/2)\,(e_1 + e_8 - (e_2 + \cdots + e_7)),\, e_1 + e_2,\, e_2 - e_1, \\ & e_3 - e_2,\, e_4 - e_3,\, e_5 - e_4,\, e_6 - e_5,\, e_7 - e_6\} \end{aligned} \tag{21.6.13}$$

and

$$\begin{aligned} B_0 = B \cap V_0 \;=\; & \{e_1 + e_2,\, e_2 - e_1,\, e_3 - e_2,\, e_4 - e_3, \\ & e_5 - e_4,\, e_6 - e_5,\, e_7 - e_6\}. \end{aligned} \tag{21.6.14}$$

Observe that B_0 is a basis for V_0. More precisely, B_0 is a base for A_0, as a root system in V_0. This is similar to the base discussed in Section 20.12, with $n = 7$, ordering the standard basis vectors in V_0 the other way. If $1 \le l < j \le 7$, then $e_j - e_l$ and $e_j + e_l$ can be expressed as sums of elements of B_0, as before.

It is easy to see that B is a basis for V, because B_0 is a basis for V_0. In fact, B is a base for A, as on p65 of [14]. More precisely, suppose first that $\alpha \in A$ satisfies $\alpha_j = \pm 1/2$ for $j = 1, \ldots, 7$, and $\alpha_8 = 1/2$. One can express α as $(1/2)\,(e_1 + e_8 - (e_2 + \cdots + e_7))$ plus possibly some elements elements of B_0.

One can express $e_8 - e_7$ as the sum of

$$2\,((1/2)\,(e_1 + e_8 - (e_2 + \cdots e_7))) = e_8 + e_1 - (e_2 + \cdots + e_7) \tag{21.6.15}$$

and elements of B_0. Using this, one can express $e_8 - e_l$ as the sum of (21.6.15) and elements of B_0 for every $l = 1, \ldots, 7$. One can use this to express $e_8 + e_l$ as the sum of (21.6.15) and elements of B_0 for every $l = 1, \ldots, 7$.

The maximal root in A with respect to B is

$$\begin{aligned} & 2\,((1/2)\,(e_1 + e_8 - (e_2 + \cdots + e_7))) + 3\,(e_1 + e_2) + 4\,(e_2 - e_1) \\ & \quad + 6\,(e_3 - e_2) + 5\,(e_4 - e_3) + 4\,(e_5 - e_4) + 3\,(e_6 - e_5) + 2\,(e_7 - e_6) \\ = \; & e_8 + e_7, \end{aligned} \tag{21.6.16}$$

as in Table 2 on p66 of [14].

If $\alpha, \beta \in A$, then let $n(\alpha, \beta) \in \mathbf{Z}$ be as in Section 19.9, so that $n(\alpha, \beta) = 2\,(\alpha, \beta)\,(\beta, \beta)^{-1} = (\alpha, \beta)$. If $\alpha, \beta \in B$ and $\alpha \neq \beta$, then $n(\alpha, \beta)\, n(\beta, \alpha) = (\alpha, \beta)^2$ is the number of edges between α and β in the Coxeter graph of A with respect to B. Observe that

$$((1/2)\,(e_1 + e_8 - (e_2 + \cdots + e_7)), e_2 - e_1) = -1. \tag{21.6.17}$$

However, $(1/2)\,(e_1 + e_8 - (e_2 + \cdots + e_7))$ is orthogonal to the elements of B other than $e_2 - e_1$ and itself.

The inner products between distinct elements of B_0 can be determined as in Section 20.12. More precisely,

$$(e_1 + e_2, e_3 - e_2) = -1, \tag{21.6.18}$$

and $e_1 + e_2$ is orthogonal to the elements of B_0 other than $e_3 - e_2$ and itself. Similarly,

$$(e_j - e_{j-1}, e_l - e_{l-1}) \tag{21.6.19}$$

is equal to -1 when $|j - l| = 1$, and to 0 when $|j - l| \geq 2$. The Coxeter graph or Dynkin diagram of A can be depicted as on p58 of [14], or p37, 39 of [24].

Let T be an automorphism of A as a root system in V, and suppose that $T(B) = B$. This implies that T preserves the Cartan matrix of A with respect to B, as in Section 20.2, so that T preserves the Coxeter graph of A with respect to B too. One can check that this can only happen when T is the identity mapping on V, as indicated in Table 1 on p66 of [14], and on p39 of [24].

21.7 Type E_7

Let us continue with the same notation and hypotheses as in the previous section. Observe that

$$(1/2)\,(e_1 + e_8 - (e_2 + \cdots + e_7)) \in \mathbf{Z}^8 + (1/2, \ldots, 1/2) \subseteq \widetilde{L}_8, \tag{21.7.1}$$

so that

$$\mathbf{Z}^8 + (1/2, -1/2, \ldots, -1/2, 1/2) = \mathbf{Z}^8 + (1/2, \ldots, 1/2). \tag{21.7.2}$$

Thus

$$\widetilde{L}_8 = \mathbf{Z}^8 \cup (\mathbf{Z}^8 + (1/2, -1/2, \ldots, -1/2, 1/2)), \tag{21.7.3}$$

which is the same as the subgroup of $\mathbf{R}^8$, as a commutative group with respect to addition, generated by $e_1, \ldots, e_8$ and $(1/2)\,(e_1 + e_8 - (e_2 + \cdots + e_7))$. More precisely,

$$(1/2)\,(e_1 + e_8 - (e_2 + \cdots + e_7)) \in \widetilde{L}_{8,e}, \tag{21.7.4}$$

with the sum of its coordinates equal to -2, and in fact

$$(1/2)\,(e_1 + e_8 - (e_2 + \cdots + e_7)) \in L_{8,e} + (1/2, \ldots, 1/2). \tag{21.7.5}$$

This implies that

$$(21.7.6) \qquad L_{8,e} + (1/2, -1/2, \ldots, -1/2, 1/2) = L_{8,e} + (1/2, \ldots, 1/2),$$

so that

$$(21.7.7) \qquad \widetilde{L}_{8,e} = L_{8,e} \cup (L_{8,e} + (1/2, -1/2, \ldots, -1/2, 1/2)).$$

Remember that $V = \mathbf{R}^8$, and put

$$(21.7.8) \qquad V_7 = \{v \in V : v_7 = -v_8\}.$$

Note that $(1/2)\,(e_1 + e_8 - (e_2 + \cdots + e_7)) \in V_7$. The elements of

$$(21.7.9) \qquad A_1 \cap V_7 = \{\alpha \in \mathbf{Z}^8 \cap V_7 : (\alpha, \alpha) = 2\}$$

are of the form $\pm e_j \pm e_l$ with $1 \le j \ne l \le 6$, or $\pm(e_7 - e_8)$. It is easy to see that $A_1 \cap V_7$ spans V_7. In fact, $A_1 \cap V_7$ is a reduced root system in V_7, as in Section 20.6.

Consider

$$(21.7.10) \qquad A_7 = A \cap V_7 = \{\alpha \in \widetilde{L}_{8,e} \cap V_7 : (\alpha, \alpha) = 2\}.$$

Clearly

$$(21.7.11) \qquad A_7 \cap L_{8,e} = (A \cap L_{8,e}) \cap V_7 = A_1 \cap V_7.$$

Observe that

$$(21.7.12) \qquad \begin{aligned} & A_7 \cap (L_{8,e} + (1/2, -1/2, \ldots, -1/2, 1/2)) \\ = \;\; & (A \cap (L_{8,e} + (1/2, \ldots, 1/2))) \cap V_7 \end{aligned}$$

consists of $\alpha \in \mathbf{R}^8$ such that $\alpha_j = \pm 1/2$ for every $j = 1, \ldots, 8$, $\alpha_j = 1/2$ for an even number of j, and $\alpha_7 = -\alpha_8$. Of course, V_7 is spanned by A_7, because V_7 is spanned by $A_1 \cap V_7$. Thus A_7 is a root system in V_7, as in Section 20.6. This root system is said to be of *type* E_7. Note that A_7 is reduced, as a root system in V_7.

Put

$$(21.7.13) \qquad V_{7,0} = V_7 \cap V_0 = \{v \in V : v_7 = v_8 = 0\}$$

and

$$(21.7.14) \qquad A_{7,0} = A_7 \cap V_{7,0} = A \cap V_{7,0}.$$

Equivalently,

$$(21.7.15) \qquad A_{7,0} = A_1 \cap V_{7,0},$$

because $\widetilde{L}_{8,e} \cap V_{7,0} = L_{8,e} \cap V_{7,0}$. This is a reduced root system in $V_{7,0}$, which is isomorphic to the one in Section 20.12 with $n = 6$.

Put

$$(21.7.16) \qquad \begin{aligned} B_7 \;\; = \;\; & \{(1/2)\,(e_1 + e_8 - (e_2 + \cdots + e_7)),\, e_1 + e_2, \\ & e_2 - e_1,\, e_3 - e_2,\, e_4 - e_3,\, e_5 - e_4,\, e_6 - e_5\}, \end{aligned}$$

and
(21.7.17) $B_{7,0} = \{e_1 + e_2, e_2 - e_1, e_3 - e_2, e_4 - e_3, e_5 - e_4, e_6 - e_5\}$.

Thus B, B_0 in the previous section can be expressed as

$$B = B_7 \cup \{e_7 - e_6\}, \quad B_0 = B_{7,0} \cup \{e_7 - e_6\}. \tag{21.7.18}$$

It is easy to see that $B_{7,0}$ is a basis for $V_{7,0}$, and in fact $B_{7,0}$ is a base for $A_{7,0}$. This is similar to the base discussed in Section 20.12, ordering the standard basis vectors in $V_{7,0}$ the other way, as before.

Observe that B_7 is a basis for V_7, because $B_{7,0}$ is a basis for $V_{7,0}$. More precisely, B_7 is a base for A_7, because B is a base for A, as in Section 20.15. This is how the root system of type E_7 is described on p65 of [14], and p41 of [24].

The maximal root in A_7 with respect to B_7 is

$$\begin{aligned} & 2\,((1/2)\,(e_1 + e_8 - (e_2 + \cdots + e_7))) + 2\,(e_1 + e_2) + 3\,(e_2 - e_1) \\ & +4\,(e_3 - e_2) + 3\,(e_4 - e_3) + 2\,(e_5 - e_4) + (e_6 - e_5) \\ = \; & e_8 - e_7, \end{aligned} \tag{21.7.19}$$

as in Table 2 on p66 of [14].

The Coxeter graph of A_7 with respect to B_7 corresponds to a subgraph of the Coxeter graph of A with respect to B, and similarly for the Dynkin diagram, as in Section 20.15. These can be depicted as on p58 of [14], or p37, 39 of [24].

If T is an automorphism of A_7 as a root system in V_7, and if $T(B_7) = B_7$, then T preserves the Cartan matrix of A_7 with respect to B_7, as in Section 20.2. This implies that T preserves the Coxeter graph of A with respect to B too. One can verify that this can only happen when T is the identity mapping on V_7, as in Table 1 on p66 of [14], and on p39 of [24].

21.8 Type E_6

We continue with the same notation and hypotheses as in the previous two sections. Remember that $V = \mathbf{R}^8$, and put

$$V_6 = \{v \in V : v_6 = v_7 = -v_8\}, \tag{21.8.1}$$

which is a linear subspace of V_7. Note that $(1/2)\,(e_1 + e_8 - (e_2 + \cdots + e_7)) \in V_6$. Put

$$V_{6,0} = V_6 \cap V_0 = \{v \in V : v_6 = v_7 = v_8 = 0\}, \tag{21.8.2}$$

which is a linear subspace of $V_{7,0}$.

The elements of

$$A_1 \cap V_6 = \{\alpha \in \mathbf{Z}^8 \cap V_6 : (\alpha, \alpha) = 2\} \tag{21.8.3}$$

are of the form $\pm e_j \pm e_l$ with $1 \le j \ne l \le 5$. Thus

$$A_1 \cap V_6 = A_1 \cap V_{6,0}, \tag{21.8.4}$$

and the linear span of (21.8.4) is $V_{6,0}$. More precisely, (21.8.4) is a reduced root system in $V_{6,0}$, which is isomorphic to the one in Section 20.12 with $n = 5$.

Consider

(21.8.5) $$A_6 = A \cap V_6 = \{\alpha \in \widetilde{L}_{8,e} \cap V_6 : (\alpha, \alpha) = 2\}.$$

Note that $A_6 \subseteq A_7$, and that

(21.8.6) $$A_6 \cap L_{8,e} = (A \cap L_{8,e}) \cap V_6 = A_1 \cap V_6.$$

Of course, A_6 is the union of (21.8.6) and

(21.8.7) $$\begin{aligned} & A_6 \cap (L_{8,e} + (1/2, -1/2, \ldots, -1/2, 1/2)) \\ = \;& (A \cap (L_{8,e} + (1/2, \ldots, 1/2))) \cap V_6. \end{aligned}$$

An element α of $\mathbf{R}^8$ is in (21.8.7) if and only if $\alpha_j = \pm 1/2$ for every $j = 1, \ldots, 8$, $\alpha_j = 1/2$ for an even number of j, and $\alpha_6 = \alpha_7 = -\alpha_8$. In particular, $(1/2)\,(e_1 + e_8 - (e_2 + \cdots + e_7))$ is an element of (21.8.7). It follows that V_6 is spanned by A_6, because $V_{6,0}$ is spanned by (21.8.6), as in the preceding paragraph. This implies that A_6 is a root system in V_6, as in Section 20.6. This root system is reduced, and said to be of *type* E_6.

Put

(21.8.8) $$A_{6,0} = A_6 \cap V_{6,0} = A \cap V_{6,0}.$$

Equivalently,

(21.8.9) $$A_{6,0} = A_1 \cap V_{6,0},$$

because $\widetilde{L}_{8,e} \cap V_{6,0} = L_{8,e} \cap V_{6,0}$.

Put

(21.8.10) $$\begin{aligned} B_6 \;=\; & \{(1/2)\,(e_1 + e_8 - (e_2 + \cdots + e_7)),\, e_1 + e_2, \\ & e_2 - e_1,\, e_3 - e_2,\, e_4 - e_3,\, e_5 - e_4\} \end{aligned}$$

and

(21.8.11) $$B_{6,0} = \{e_1 + e_2,\, e_2 - e_1,\, e_3 - e_2,\, e_4 - e_3,\, e_5 - e_4\}.$$

This means that

(21.8.12) $$B_7 = B_6 \cup \{e_6 - e_5\}, \quad B_{7,0} = B_{6,0} \cup \{e_6 - e_5\}.$$

Observe that $B_{6,0}$ is a basis for $V_{6,0}$, and in fact a base for $A_{6,0}$. This is similar to the base discussed in Section 20.12, as before.

It is easy to see that B_6 is a basis for V_6, because $B_{6,0}$ is a basis for $V_{6,0}$. In fact, B_6 is a base for A_6, because B_7 is a base for A_7, as in Section 20.15. Of course, one could also use the fact that B is a base for A here. The root system of type E_6 is described in this way on p65 of [14], and p41 of [24].

The maximal root in A_6 with respect to B_6 is

(21.8.13) $$\begin{aligned} & (1/2)\,(e_1 + e_8 - (e_2 + \cdots + e_7)) + 2\,(e_1 + e_2) \\ & +2\,(e_2 - e_1) + 3\,(e_3 - e_2) + 2\,(e_4 - e_3) + (e_5 - e_4) \\ = \;& (1/2)\,(e_1 + e_2 + e_3 + e_4 + e_5 - e_6 - e_7 + e_8), \end{aligned}$$

as in Table 2 on p66 of [14].

The Coxeter graph of A_6 with respect to B_6 corresponds to a subgraph of the Coxeter graph of A_7 with respect to B_7, and similarly for the Dynkin diagram, as in Section 20.15. One can also look at these in terms of their analogues for A and B. The Coxeter graph and Dynkin diagram of A_6 with respect to B_6 may be depicted as on p58 of [14], or p37, 39 of [24].

If T is an automorphism of A_6 as a root system in V_6, and $T(B_6) = B_6$, then T preserves the Cartan matrix of A_6 with respect to B_6, and hence the Coxeter graph. There is exactly one automorphism T with this property, other than the identity mapping, which interchanges some elements of B_6, and satisfies $T^2 = I$. This is mentioned in Table 1 on p66 of [14], and on p39 of [24].

21.9 Irreducible root systems

Let V be a vector space over the real numbers of positive finite dimension, and let A be an irreducible reduced root system in V. It is well known that A is isomorphic to one of the root systems that has been described previously. More precisely, A is isomorphic to one of the following:

(21.9.1) a root system of type A_n, with $n \geq 1$, as in Section 20.10;

(21.9.2) a root system of type B_n, with $n \geq 2$, as in Section 20.11;

(21.9.3) a root system of type C_n, with $n \geq 3$, as in Section 20.11;

(21.9.4) a root system of type D_n, with $n \geq 4$, as in Section 20.12;

(21.9.5) a root system of type E_6, E_7, or E_8, as in Sections 21.6 – 21.8;

(21.9.6) a root system of type F_4, as in Section 21.4;

(21.9.7) a root system of type G_2, as in Sections 21.2 and 21.3.

Equivalently, if B is a base for A, then the corresponding Dynkin diagram is isomorphic to one of the Dynkin diagrams in this list. This is the theorem on p57f of [14], which corresponds to Theorem 4 on p38 of [24]. The restrictions on n in the first four types ensures that there are no repetitions. If A is irreducible but not reduced, then it is well known that A is isomorphic to a root system of type BC_n, with $n \geq 1$, as in Section 20.11. This corresponds to Exercise 3 on p66 of [14], and is also mentioned on p41 of [24].

Suppose that A is an irreducible reduced root system again, and let B be a base for A. If T is an automorphism of A that maps B onto itself, then T preserves the Cartan matrix of A with respect to B, as in Section 20.2. Conversely, any one-to-one mapping from B onto itself that preserves the Cartan matrix corresponds to a unique automorphism T of A that maps B onto itself, as before. Equivalently, automorphisms of A that map B onto itself correspond to automorphisms of the Dynkin diagram of A with respect to B.

Remember that there are pairs of vertices in the Coxeter graph of A with respect to B with multiple edges in the cases (21.9.2), (21.9.3), (21.9.6), and (21.9.7). In these cases, the only automorphism of the Dynkin diagram is the identity mapping, as before. This implies that the automorphism group of A is the same as the Weyl group of A.

In the cases (21.9.1), (21.9.4), and (21.9.5), there is at most one edge between any pair of vertices in the Coxeter graph. This means that the Coxeter graph determines the Cartan matrix of A with respect to B, or equivalently the Dynkin diagram. In these cases, automorphisms of A that map B onto itself correspond exactly to automorphisms of the Coxeter graph.

If A is of type A_1, E_7, or E_8, then the only automorphism of the Coxeter graph is the identity mapping. Thus the automorphism group of A is the same as the Weyl group of A in these cases.

21.10 Connected Coxeter graphs

Let V be a vector space over the real numbers of positive finite dimension, let A be a root system in V, and let B be a base for A. Also let $(\cdot, \cdot)$ be an inner product on V that is invariant under the Weyl group of A, and let $\|\cdot\|$ be the corresponding norm on V. If $\alpha \in B$, then put

(21.10.1) $$e_\alpha = \alpha/\|\alpha\|.$$

If $\alpha, \beta \in B$ and $\alpha \neq \beta$, then

(21.10.2) $$(e_\alpha, e_\beta) = (\alpha, \beta)\, \|\alpha\|^{-1}\, \|\beta\|^{-1} \le 0,$$

where the second step is as in Section 19.11. In this case,

(21.10.3) $$4\,(e_\alpha, e_\beta)^2 = 4\,(\alpha, \beta)^2\, \|\alpha\|^{-2}\, \|\beta\|^{-2}$$

is the same as the number of edges between α and β in the Coxeter graph of A with respect to B, as in Section 20.3.

Now let B be a nonempty finite set, and let Γ be a Coxeter graph, with B as the set of vertices in Γ. Thus every pair of distinct elements of B is connected by 0, 1, 2, or 3 edges in Γ. Let V be a vector space over the real numbers, with dimension equal to the number of elements of B. Suppose that for each $\alpha \in B$, e_α is a nonzero element of V, and that the collection of e_α, $\alpha \in B$, is a basis for V. Under these conditions, there is a unique symmetric bilinear form (v, w) on V with the following properties. First,

(21.10.4) $$(e_\alpha, e_\alpha) = 1$$

for every $\alpha \in B$. Second, if $\alpha, \beta \in B$ and $\alpha \neq \beta$, then

(21.10.5) $$(e_\alpha, e_\beta) \le 0$$

and

(21.10.6) $$4\,(e_\alpha, e_\beta)^2 = \text{ the number of edges between } \alpha \text{ and } \beta \text{ in } \Gamma.$$

We may also be interested in situations where

(21.10.7) $$(v, w) \text{ is positive definite on } V.$$

If Γ is the Coxeter graph of a root system, then we can take e_α to be as in (21.10.1). Thus (21.10.7) holds in this situation, as on p37 of [24]. The properties of the e_α's in the preceding paragraph, including (21.10.7), correspond to the definition of an admissible set of vectors in a finite-dimensional inner product space on p60 of [14].

If Γ is a connected Coxeter graph for which (21.10.7) holds, then it is well known that Γ isomorphic to the Coxeter graph of one of the root systems (21.9.1) – (21.9.7). More precisely, the Coxeter graphs associated to root systems of type B_n and C_n are the same, and otherwise these Coxeter graphs are distinct. In particular, Coxeter graphs of irreducible root systems are of this form, as in Theorem 3 on p37 of [24]. This is shown in the proof of the theorem on p57f of [14]. Using this, it is not difficult to obtain the analogous statement for Dynkin diagrams, as on p62f of [14], and p39 of [24].

21.11 Lengths in the Weyl group

Let V be a vector space over the real numbers of positive finite dimension, let A be a reduced root system in V, and let B be a base for A. If $\alpha \in A$, then σ_α denotes the symmetry on V with vector α that maps A onto itself, as usual. Remember that the Weyl group W of A is generated by the symmetries σ_β with $\beta \in B$, as in Section 19.14.

Suppose that $\sigma \in W$ can be expressed as

(21.11.1) $$\sigma = \sigma_{\beta_1} \circ \cdots \circ \sigma_{\beta_r}$$

for some $\beta_1, \ldots, \beta_r \in B$, where $r \geq 0$ is as small as possible. In this case, the expression on the right side of (21.11.1) is said to be *reduced*, and the *length* of σ with respect to B is defined by

(21.11.2) $$\mathrm{length}(\sigma) = r,$$

as on p51 of [14]. More precisely, the right side of (21.11.1) is interpreted as being the identity mapping on V when $r = 0$, so that $\mathrm{length}(\sigma) = 0$ exactly when σ is the identity mapping.

Let $A^+ = A^{B,+}$ be the set of $\alpha \in A$ that can be expressed as a linear combination of elements of B whose coefficients are nonnegative integers, so that $A = A^+ \cup (-A^+)$. If $\sigma \in W$, then put

(21.11.3) $$n(\sigma) = \#\{\alpha \in A^+ : \sigma(\alpha) \in -A^+\},$$

which is to say the number of elements of the set on the right, as on p51 of [14]. Lemma A at the top of p52 of [14] states that

(21.11.4) $$\mathrm{length}(\sigma) = n(\sigma)$$

for every $\sigma \in W$. Of course, if $\mathrm{length}(\sigma) = 0$, then σ is the identity mapping on V, and $n(\sigma) = 0$ too.

Suppose now that $\mathrm{length}(\sigma) > 0$, and that the statement holds for elements of W with smaller length. Let (21.11.1) be a reduced expression for σ, so that (21.11.2) holds. Under these conditions, we have that

$$\sigma(\beta_r) \in -A^+, \tag{21.11.5}$$

as mentioned just after (20.1.8). Equivalently,

$$(\sigma_{\beta_1} \circ \cdots \circ \sigma_{\beta_{r-1}})(\beta_r) \in A^+, \tag{21.11.6}$$

because $\sigma_{\beta_r}(\beta_r) = -\beta_r$.

Remember that σ_{β_r} maps $A^+ \setminus \{\beta_r\}$ onto itself, as in (19.12.8). Using this, we get that

$$n(\sigma_{\beta_1} \circ \cdots \circ \sigma_{\beta_{r-1}}) = n(\sigma) - 1. \tag{21.11.7}$$

More precisely, the number of $\alpha \in A^+ \setminus \{\beta_r\}$ that are mapped into $-A^+$ by $\sigma_{\beta_1} \circ \cdots \circ \sigma_{\beta_{r-1}}$ is the same as for σ, because σ_{β_r} maps $A^+ \setminus \{\beta_r\}$ onto itself. The case where $\alpha = \beta_r$ corresponds to the remarks in the preceding paragraph.

The length of $\sigma_{\beta_1} \circ \cdots \circ \sigma_{\beta_{r-1}}$ with respect to B is clearly less than or equal to $r - 1$. In fact,

$$\mathrm{length}(\sigma_{\beta_1} \circ \cdots \circ \sigma_{\beta_{r-1}}) = r - 1 = \mathrm{length}(\sigma) - 1, \tag{21.11.8}$$

because otherwise σ would have length less than r with respect to B. Arguing by induction, we have that

$$\mathrm{length}(\sigma_{\beta_1} \circ \cdots \circ \sigma_{\beta_{r-1}}) = n(\sigma_{\beta_1} \circ \cdots \circ \sigma_{\beta_{r-1}}). \tag{21.11.9}$$

Thus (21.11.4) follows from (21.11.7), (21.11.8), and (21.11.9), as desired.

If $\sigma \in W$ and $\beta \in B$, then

$$n(\sigma \circ \sigma_\beta) = n(\sigma) \pm 1. \tag{21.11.10}$$

Indeed, the number of $\alpha \in A^+ \setminus \{\beta\}$ that are mapped into $-A^+$ by σ is the same as for $\sigma \circ \sigma_\beta$, because σ_β maps $A \setminus \{\beta\}$ onto itself, as before. Of course,

$$(\sigma \circ \sigma_\beta)(\beta) = \sigma(\sigma_\beta(\beta)) = -\sigma(\beta), \tag{21.11.11}$$

so that exactly one of $\sigma(\beta)$ and $(\sigma \circ \sigma_\beta)(\beta)$ is in A^+. This implies (21.11.10).

Exercise 5 on p54 of [14] states that if $\sigma \in W$ can be expressed as the composition of r symmetries associated to elements of B, then r has the same parity as $\mathrm{length}(\sigma)$. More precisely, it is easy to see that r has the same parity as $n(\sigma)$, by (21.11.11). Thus r has the same parity as $\mathrm{length}(\sigma)$, by (21.11.4).

Exercise 6 on p54 of [14] says that

$$\sigma \mapsto (-1)^{\mathrm{length}(\sigma)} \tag{21.11.12}$$

defines a group homomorphism from W into the multiplicative group $\{\pm 1\}$. This follows from the fact that if $\sigma \in W$ can be expressed as the composition of r symmetries associated to elements of β, then

$$(-1)^r = (-1)^{\mathrm{length}(\sigma)}, \tag{21.11.13}$$

as in the preceding paragraph. Alternatively, the determinant of any symmetry on V is equal to -1, so that (21.11.12) is the same as the restriction of the determinant to W.

21.12 Nonnegative linear functionals

Let us continue with the same notation and hypotheses as in the previous section. Note that

$$\mathrm{length}(\sigma^{-1}) = \mathrm{length}(\sigma) \tag{21.12.1}$$

for every $\sigma \in W$, because the inverse of a symmetry on V is itself. Similarly,

$$n(\sigma^{-1}) = n(\sigma) \tag{21.12.2}$$

for every $\sigma \in W$. This can be verified directly from the definition (21.11.3) of $n(\sigma)$, and it is compatible with (21.11.4) and (21.12.1) as well.

Let us say that a linear functional λ on V is nonnegative with respect to B if

$$\lambda(\beta) \geq 0 \quad \text{for every } \beta \in B. \tag{21.12.3}$$

Of course, this implies that

$$\lambda(\alpha) \geq 0 \quad \text{for every } \alpha \in A^+. \tag{21.12.4}$$

Remember that the Weyl chamber associated to B consists of the $\lambda \in V'$ such that $\lambda(\beta) > 0$ for every $\beta \in B$, as in Section 19.15. The set of linear functionals on V that are nonnegative with respect to B is the same as the closure in V' of the Weyl chamber associated to B. This uses the topology on V' that corresponds to the standard topology on a Euclidean space of the same dimension, using any linear isomorphism.

Suppose that $\lambda \in V'$ is nonnegative with respect to B, $\sigma \in W$, and $\lambda \circ \sigma$ is nonnegative with respect to B too. Under these conditions, σ can be expressed as the composition of finitely many symmetries on V with vector in B that map A onto itself, in such a way that λ is invariant under each of these symmetries. In particular,

$$\lambda \circ \sigma = \lambda. \tag{21.12.5}$$

This corresponds to Lemma B on p52 of [14].

If the length of σ with respect to B is 0, then σ is the identity mapping on V, and the statement in the preceding paragraph is trivial. Suppose that $\mathrm{length}(\sigma) > 0$, which is the same as saying that $\mathrm{length}(\sigma^{-1}) > 0$. Thus $n(\sigma^{-1})$

is positive, by (21.11.4), so that there is an $\alpha \in A^+$ such that $\sigma^{-1}(\alpha) \in -A^+$, by the definition (21.11.3) of $n(\sigma^{-1})$. More precisely, there is a $\beta \in B$ such that

$$\sigma^{-1}(\beta) \in -A^+, \tag{21.12.6}$$

because otherwise σ^{-1} would map A^+ into itself. Alternatively, this can be obtained as in (20.1.8).

Because $\lambda \circ \sigma$ is nonnegative with respect to B, we have that

$$\lambda(\beta) = (\lambda \circ \sigma)(\sigma^{-1}(\beta)) \leq 0. \tag{21.12.7}$$

This implies that

$$\lambda(\beta) = 0, \tag{21.12.8}$$

because $\lambda(\beta) \geq 0$, by hypothesis. It follows that

$$\lambda \circ \sigma_\beta = \lambda \tag{21.12.9}$$

on V, because $\sigma_\beta(v) - v$ is a multiple of β for every $v \in V$.

Let us check that

$$\text{length}(\sigma^{-1} \circ \sigma_\beta) = \text{length}(\sigma^{-1}) - 1. \tag{21.12.10}$$

Equivalently, this means that

$$n(\sigma^{-1} \circ \sigma_\beta) = n(\sigma^{-1}) - 1, \tag{21.12.11}$$

by (21.11.4). Remember that σ_β maps $A^+ \setminus \{\beta\}$ onto itself, as in (19.12.8). One can use this to get (21.12.11), because of (21.12.6) and the fact that $\sigma_\beta(\beta) = -\beta$. Alternatively, if β is obtained from σ^{-1} as in (20.1.8), then (21.12.10) holds by construction, as in (21.11.8).

Observe that

$$\lambda \circ (\sigma_\beta \circ \sigma) = (\lambda \circ \sigma_\beta) \circ \sigma = \lambda \circ \sigma, \tag{21.12.12}$$

by (21.12.9). Thus $\lambda \circ (\sigma_\beta \circ \sigma)$ is nonnegative with respect to B, by hypothesis. We also have that

$$\text{length}(\sigma_\beta \circ \sigma) = \text{length}(\sigma) - 1, \tag{21.12.13}$$

by (21.12.1), (21.12.10), and the fact that σ_β is its own inverse. This permits us to use induction to obtain the initial statement about σ.

If λ is strictly positive on B, then σ has to be the identity mapping on V. More precisely, (21.12.7) cannot hold in this situation. This corresponds to Exercise 12 on p55 of [14].

Alternatively, if λ is strictly positive on B, then B is the same as the base B_λ for A associated to λ as in Section 19.11. If $\sigma \in W$, then $\sigma(B)$ is a base for A too. If $\lambda \circ \sigma$ is strictly positive on B, then λ is strictly positive on $\sigma(B)$. This implies that $\sigma(B) = B_\lambda$, as before, so that $\sigma(B) = B$. It follows that σ is the identity mapping on V, as in Section 20.1.

Remember that $\tau \in V'$ is said to be regular with respect to A if $\tau(\alpha) \neq 0$ for each $\alpha \in A$, as in Section 19.15. In this case, there is a unique base B_τ for

A on which τ is strictly positive, as in Section 19.11. If $\sigma \in W$ and $\tau \circ \sigma = \tau$, then τ is strictly positive on $\sigma(B_\tau)$, so that $\sigma(B_\tau) = B_\tau$. This implies that σ is the identity mapping on V, as before.

Let $(\cdot, \cdot)$ be an inner product on V that is invariant under W. If $u \in V$, then let $\mu_u(v) = (v, u)$ be the corresponding linear functional on V with respect to $(\cdot, \cdot)$. If σ is an orthogonal transformation on V with respect to $(\cdot, \cdot)$, then

$$\mu_u(\sigma(v)) = (\sigma(v), u) = (v, \sigma^{-1}(u)) = \mu_{\sigma^{-1}(u)}(v) \tag{21.12.14}$$

for every $v \in V$, so that $\mu_u \circ \sigma = \mu_{\sigma^{-1}(u)}$ on V. In particular, this holds when $\sigma \in W$. If $\sigma(u) = u$, then $\sigma^{-1}(u) = u$, and $\mu_u \circ \sigma = \mu_u$.

Note that μ_u is regular with respect to A exactly when u is not orthogonal to any element of A with respect to $(\cdot, \cdot)$. In this case, if $\sigma(u) = u$, then we get that σ is the identity mapping on V, because $\mu_u \circ \sigma = \sigma$, as before.

If $\sigma \in W$ is a reflection on V with respect to $(\cdot, \cdot)$, then σ is the reflection associated to an element of A, as in Exercise 13 on p55 of [14]. To see this, it suffices to show that the hyperplane in V of vectors fixed by σ is contained in the hyperplane of vectors fixed by σ_α for some $\alpha \in A$. Otherwise, for each $\alpha \in A$, the intersection of the hyperplane in V of vectors fixed by σ with the hyperplane of vectors fixed by σ_α is a hyperplane in the hyperplane of vectors fixed by σ. Because A has only finitely many elements, there is an element u of the hyperplane of vectors fixed by σ that is not in the hyperplane of vectors fixed by σ_α for any $\alpha \in A$, as in Section 18.12.

Equivalently, this means that u is not orthogonal to any $\alpha \in A$ with respect to $(\cdot, \cdot)$. By construction, $\sigma(u) = u$, so that σ is the identity mapping on V, as before. This contradicts the hypothesis that σ be a reflection on V.

21.13 The mapping $\alpha \mapsto -\alpha$

Let V be a vector space over the real numbers of positive finite dimension, and let A be a root system in V. It is easy to see that the mapping

$$\alpha \mapsto -\alpha \tag{21.13.1}$$

on V is an automorphism of A, as in the first part of Exercise 6 on p67 of [14]. The second part of the exercise is to try to decide for which irreducible reduced root systems (21.13.1) is an element of the Weyl group of A. Of course, this holds automatically when the automorphism group of A is the same as the Weyl group of A. Remember that this happens for root systems of type B_n and C_n, as well as types A_1, F_4, G_2, E_7, and E_8, as in Section 21.9.

If $n \geq 2$, then (21.13.1) is not in the Weyl group of the root system of type A_n. This can be seen using the description of the Weyl group in Section 20.10.

The Weyl group of root systems of type D_n consist of linear mappings on $V = \mathbf{R}^n$ that permute the coordinates, and multiply an even number of coordinates by -1, as in Section 20.12. Thus (21.13.1) is an element of the Weyl group exactly when n is even.

To deal with type E_6, let us take $V = \mathbf{R}^8$, equipped with the standard inner product $(\cdot, \cdot)$, and put

$$V_6 = \{v \in V : v_6 = v_7 = -v_8\}, \tag{21.13.2}$$

$$V_7 = \{v \in V : v_7 = -v_8\}, \tag{21.13.3}$$

as in Sections 21.7 and 21.6. Consider the line

$$Z = \{v \in V : v_1 = \cdots = v_5 = 0,\, v_7 = -v_6/2 = -v_8\} \tag{21.13.4}$$

in V_7. If $v \in V_6$ and $z \in Z$, then

$$\begin{aligned} (v, z) = \sum_{j=1}^{n} v_j\, z_j &= v_6\, z_6 + v_7\, z_7 + v_8\, z_8 \\ &= v_7\,(-2\, z_7) + v_7\, z_7 + (-v_7)\,(-z_7) = 0. \end{aligned} \tag{21.13.5}$$

Thus Z is the orthogonal complement of V_6 in V_7, with respect to the standard inner product on V.

Let A_6 and A_7 be the root systems in V_6 and V_7 of types E_6 and E_7, respectively, as in Sections 21.8 and 21.7. If $\alpha \in A_6$, then the reflection on V_6 associated to α is the same as the restriction to V_6 of the reflection on V_7 associated to α. The restriction to Z of the reflection on V_7 associated to $\alpha \in V_6$ is the identity mapping on Z, because Z is orthogonal to α.

Remember that $A_6 = A_7 \cap V_6 \subseteq A_7$, by construction. If T is a one-to-one linear mapping from V_6 onto itself, then let $\widetilde{T}$ be the extension of T to a one-to-one linear mapping from V_7 onto itself whose restriction to Z is the identity mapping on Z. If T is in the Weyl group of A_6, then it follows that $\widetilde{T}$ is in the Weyl group of A_7.

Consider the mapping T from V_6 into itself defined by $T(v) = -v$ for every $v \in V_6$. If T is in the Weyl group of A_6, then $\widetilde{T}$ is in the Weyl group of A_7, as before. Remember that the mapping on V_7 that sends $v \in V_7$ to $-v$ is in the Weyl group of A_7, as mentioned earlier. It follows that the composition of this mapping with $\widetilde{T}$ is in the Weyl group of A_7 as well.

The composed mapping on V_7 just mentioned sends every element of V_6 to itself, and sends $z \in Z$ to $-z$. Note that this is a reflection on V_7. If this composed mapping is an element of the Weyl group of A_7, then it is the reflection associated to an element of A_7, as in the previous section. This is not possible, because there are no elements of A_7 in Z. Thus the mapping $v \mapsto -v$ on V_6 is not an element of the Weyl group of A_6.

21.14 Another mapping on V

Let V be a vector space over the real numbers of positive finite dimension again, and let A be a reduced root system in V. Also let B be a base for A, and observe that $-B$ is a base for A as well. It follows that there is an element σ of the Weyl group W of A such that

$$\sigma(B) = -B, \tag{21.14.1}$$

as in Section 19.14. In fact, σ is unique, as in Section 20.1.

Let $A^+ = A^{B,+}$ be the set of $\alpha \in A$ that can be expressed as linear combinations of elements of B whose coefficients are nonnegative integers, as before. Of course, (21.14.1) implies that

$$\sigma(A^+) = -A^+. \tag{21.14.2}$$

If $n(\sigma)$ is as in (21.11.3), then (21.14.2) is the same as saying that

$$n(\sigma) = \#A^+. \tag{21.14.3}$$

Note that this is the largest possible value of $n(\sigma)$. Remember that this is equal to the length of σ with respect to B, as in (21.11.4).

If σ is any element of W that satisfies (21.14.2), then σ satisfies (21.14.1). Indeed, (21.14.2) implies that

$$\sigma(B) \subseteq -A^+ = A^{-B,+}. \tag{21.14.4}$$

This implies that (21.14.1) holds, because $\sigma(B)$ is a base for A, as in (19.15.7).

Let $\beta_0 \in B$ be given, and let V_0 be the hyperplane in V spanned by $\beta \in B$ with $\beta \neq \beta_0$. If $v \in V$, then v can be expressed in a unique way as a linear combination of elements of B, and we let $\tau_0(v) \in \mathbf{R}$ be the coefficient of β_0 in this expression for v. Thus V_0 is the same as the kernel of τ_0. If $\beta \in B \setminus \{\beta_0\}$ and $v \in V$, then $\sigma_\beta(v) - v \in V_0$, so that

$$\tau_0 \circ \sigma_\beta = \tau_0 \tag{21.14.5}$$

on V. If σ is an element of the subgroup of W generated by σ_β with $\beta \in B \setminus \{\beta_0\}$, then it follows that

$$\tau_0 \circ \sigma = \tau_0 \tag{21.14.6}$$

on V too. In particular, this means that

$$\tau_0(\sigma(\beta_0)) = \tau_0(\beta_0) = 1. \tag{21.14.7}$$

This implies that σ does not satisfy (21.14.2).

This corresponds to Exercise 9 on p54 of [14].

21.15 Invertibility of Cartan matrices

Let k be a field, and let V be a vector space over k of positive finite dimension r. Also let k^r be the space of r-tuples of elements of k, as usual, which is an r-dimensional vector space over k with respect to coordinatewise addition and scalar multiplication. If $v_1, \ldots, v_r$ is a basis for V, then we get a one-to-one linear mapping from k^r onto V, which sends $t = (t_1, \ldots, t_r) \in k^r$ to $\sum_{j=1}^r t_j \, v_j$. Similarly, if $\lambda_1, \ldots, \lambda_r$ are linear functionals on V that form a basis for the dual space V', then we get a one-to-one mapping from V onto k^r, which sends $v \in V$ to $(\lambda_1(v), \ldots, \lambda_r(v)) \in k^r$. Thus the composition of these two mappings is a one-to-one linear mapping from k^r onto itself. The composition of these two mappings corresponds to the $r \times r$ matrix with entries $\lambda_l(v_j)$, $j, l = 1, \ldots, r$, with respect to the standard basis in k^r. Thus this matrix is invertible, as an $r \times r$ matrix with entries in k, under these conditions.

Now let V be a vector space over the real numbers of positive finite dimension, and let A be a root system in V. As before, let σ_α be the symmetry on V with vector $\alpha \in A$ that maps A onto itself, and let λ_α be the corresponding linear functional on V. Remember that $n(\alpha, \beta) = \lambda_\beta(\alpha)$ is an integer for every $\alpha, \beta \in A$, by the definition of a root system. Let $(\cdot, \cdot)$ be an inner product on V that is invariant under the Weyl group of A, so that σ_α is the reflection on V with respect to $(\cdot, \cdot)$ associated to $\alpha \in A$, and $\lambda_\alpha(v) = 2 \, (v, \alpha) \, (\alpha, \alpha)^{-1}$ for every $v \in V$. Thus $n(\alpha, \beta) = 2 \, (\alpha, \beta) \, (\beta, \beta)^{-1}$ for every $\alpha, \beta \in A$.

Let B be a base for A, so that B is a basis for V in particular. Using the inner product, we can identify V with its dual space, and it follows that λ_β, $\beta \in B$, is a basis for V'. This implies that the Cartan matrix $n(\alpha, \beta)$, $\alpha, \beta \in B$, is invertible, as before, and as on p55 of [14]. Equivalently, the determinant of the Cartan matrix is nonzero. Of course, the determinant is an integer.

More precisely, the Cartan matrix may be considered as the product of the symmetric matrix (α, β) and the diagonal matrix with diagonal entries $2 \, (\beta, \beta)^{-1}$. The symmetric matrix (α, β) is positive definite, because of the positivity of the inner product, and the fact that B is a basis for V. Thus its determinant is a positive real number. The determinant of the diagonal matrix is postive too, because the diagonal entries of the matrix are positive. This means that the determinant of the Cartan matrix is positive as well.

Chapter 22

Roots and Lie algebras

22.1 A basic situation

Let k be a field of characteristic 0, and let $(A, [\cdot,\cdot]_A)$ be a Lie algebra over k with positive finite dimension as a vector space over k. Also let B be a Lie subalgebra of A such that every element of B is ad-diagonalizable as an element of A. This implies that B is commutative as a Lie algebra, as in Section 17.1. Let B' be the dual space of linear functionals on B, as a vector space over k, as usual. If $\alpha \in B'$, then put

(22.1.1) $A_\alpha = \{x \in A : \mathrm{ad}_w(x) = [w, x]_A = \alpha(w)\, x \text{ for every } w \in B\},$

as before, which is a linear subspace of A. This is the same as the centralizer $C_A(B)$ of B in A when $\alpha = 0$. In particular, $B \subseteq A_0$, because B is commutative as a Lie algebra. Let us suppose for the rest of the section that

(22.1.2) $$A_0 = C_A(B) = B$$

and

(22.1.3) $$Z(A) = \{0\},$$

where $Z(A)$ is the center of A as a Lie algebra.

It follows that $B \neq \{0\}$, because $A \neq \{0\}$, by hypothesis. Put

(22.1.4) $$\Phi_B = \{\alpha \in B' : \alpha \neq 0 \text{ and } A_\alpha \neq \{0\}\},$$

so that $\Phi_B \cup \{0\}$ is the same as the set of $\alpha \in B'$ such that $A_\alpha \neq \{0\}$, as before. Remember that A corresponds to the direct sum of the subspaces A_α with $\alpha \in \Phi_B \cup \{0\}$, as a vector space over k, and in particular that Φ_B has only finitely many elements, as in Section 17.2. If $x \in A_\alpha$ and $y \in A_\beta$ for some $\alpha, \beta \in B'$, then

(22.1.5) $$[x, y]_A \in A_{\alpha+\beta},$$

as before. We also have that the linear span of Φ_B in B' is equal to B', because of (22.1.3), as in Section 17.5. Let $b(\cdot,\cdot)$ be a nondegenerate bilinear form on A, and suppose that $b(\cdot,\cdot)$ is associative on A, or equivalently invariant under the adjoint representation on A, as in Sections 6.10 and 7.7. This implies that the restriction of $b(\cdot,\cdot)$ to (22.1.2) is nondegenerate, as in Section 17.3.

Of course, there is a natural embedding of $\mathbf{Q}$ into k, because k has characteristic 0, so that B' may also be considered as a vector space over $\mathbf{Q}$. Let $E_{\mathbf{Q}}$ be the linear subspace of B', as a vector space over $\mathbf{Q}$, spanned by Φ_B, as in Section 17.12. If $\alpha_1, \ldots, \alpha_n$ are elements of Φ_B that form a basis for B', as a vector space over k, then $\alpha_1, \ldots, \alpha_n$ form a basis for $E_{\mathbf{Q}}$, as a vector space over $\mathbf{Q}$, as in Section 17.10. Using this, we can get a vector space $E_{\mathbf{R}}$ over $\mathbf{R}$ of the same dimension n that contains $E_{\mathbf{Q}}$, as in Section 17.13. In particular, Φ_B is contained in $E_{\mathbf{R}}$, and the linear span of Φ_B in $E_{\mathbf{R}}$, as a vector space over $\mathbf{R}$, is equal to $E_{\mathbf{R}}$.

If $\alpha \in B'$, then there is a unique $t_{b,\alpha} \in B$ such that $\alpha(w) = b(w, t_{b,w})$ for every $w \in B$, because $b(\cdot,\cdot)$ is nondegenerate on B. Remember that $\alpha(t_{b,\alpha}) = b(t_{b,\alpha}, t_{b,\alpha}) \neq 0$ when $\alpha \in \Phi_B$, as in Section 17.6. In this case, we put

$$h_\alpha = 2\,\alpha(t_{b,\alpha})^{-1}\,t_{b,\alpha}, \tag{22.1.6}$$

as before, so that $\alpha(h_\alpha) = 2$. If $\beta \in \Phi_B$, then $\beta - \beta(h_\alpha)\,\alpha \in \Phi_B$, as in Section 17.8. We have also seen that $\beta(h_\alpha)$ corresponds to an integer in this situation, with respect to the standard embedding of $\mathbf{Q}$ into k.

Of course,

$$\beta \mapsto \beta(h_\alpha) \tag{22.1.7}$$

defines a linear functional on B', as a vector space over k. If $\beta \in E_{\mathbf{Q}}$, then $\beta(h_\alpha)$ is in the image of $\mathbf{Q}$ in k, by the remarks in the previous paragraphs. Let λ_α be the corresponding linear functional on $E_{\mathbf{Q}}$, as a vector space over $\mathbf{Q}$. This extends to a linear functional on $E_{\mathbf{R}}$, as a vector space over $\mathbf{R}$, in a natural way, that we shall also denote by λ_α. As before, we have that

$$\beta - \lambda_\alpha(\beta)\,\alpha \in \Phi_B \tag{22.1.8}$$

and $\lambda_\alpha(\beta) \in \mathbf{Z}$ for every $\beta \in \Phi_B$.

It follows that Φ_B is a root system in $E_{\mathbf{R}}$, as in Section 19.3. More precisely, if $\alpha \in \Phi_B$, then the corresponding symmetry on $E_{\mathbf{R}}$ is defined by

$$\sigma_\alpha(\beta) = \beta - \lambda_\alpha(\beta)\,\alpha \tag{22.1.9}$$

for every $\beta \in E_{\mathbf{R}}$. Note that the definition of a root system is extended to finite-dimensional vector spaces over the complex numbers in Definition 7 on p41 of [24]. If $k = \mathbf{C}$, then one can consider Φ_B as a root system in B' as a vector space over $\mathbf{C}$.

This root system is reduced, in the sense that for each $\alpha \in \Phi_B$, the only multiples of α in Φ_B are $\pm\alpha$. This was discussed in Sections 17.7 and 17.8, for multiples of α by elements of k, and by elements of $\mathbf{Q}$ in particular. One should also consider multiples of α by real numbers in $E_{\mathbf{R}}$, but it is easy to reduce to considering multiples by elements of $\mathbf{Q}$, because Φ_B is contained in $E_{\mathbf{Q}}$. Of course, in any root system, one only has to consider multiples by ± 2 or $\pm 1/2$.

Let $(\cdot,\cdot)$ be any inner product on $E_{\mathbf{R}}$ that is invariant under the Weyl group of Φ_B. If $\alpha \in \Phi_B$, then it follows that (22.1.9) is the reflection on $E_{\mathbf{R}}$ associated to α with respect to $(\cdot,\cdot)$. This means that

$$\lambda_\alpha(\beta) = 2\,(\beta,\alpha)\,(\alpha,\alpha)^{-1} \tag{22.1.10}$$

for every $\beta \in E_{\mathbf{R}}$. In particular, this corresponds to $\beta(h_\alpha)$ when $\beta \in \Phi_B$ too.

Suppose for the moment that A is semisimple as a Lie algebra over k, so that we can take $b(\cdot,\cdot)$ to be the Killing form on A, as in Section 17.11. This leads to an inner product $(\cdot,\cdot)_{E_{\mathbf{R}}}$ on $E_{\mathbf{R}}$, as in Section 17.13. More precisely, a bilinear form $(\cdot,\cdot)_{E_{\mathbf{Q}}}$ was defined on $E_{\mathbf{Q}}$ in Section 17.12, which was extended to $E_{\mathbf{R}}$. If $\alpha, \beta \in \Phi_B$, then

$$\lambda_\alpha(\beta) = 2\,(\alpha,\beta)_{E_{\mathbf{Q}}}\,(\alpha,\alpha)_{E_{\mathbf{Q}}}^{-1}, \tag{22.1.11}$$

by (17.10.8) and the definition of $(\cdot,\cdot)_{E_{\mathbf{Q}}}$. Of course, this implies that

$$\lambda_\alpha(\beta) = 2\,(\alpha,\beta)_{E_{\mathbf{R}}}\,(\alpha,\alpha)_{E_{\mathbf{R}}}^{-1}. \tag{22.1.12}$$

In fact, this holds for every $\alpha \in \Phi_B$ and $\beta \in E_{\mathbf{R}}$, because $E_{\mathbf{R}}$ is spanned by Φ_B, and both sides are linear in β. This means that (22.1.9) is the same as the reflection on $E_{\mathbf{R}}$ associated to $\alpha \in \Phi_B$ with respect to $(\cdot,\cdot)_{E_{\mathbf{R}}}$ in this situation. This corresponds to the theorem on p40 of [14].

22.2 Inverse roots and B

Let us continue with the same notation and hypotheses as in the previous section, except for the last paragraph. Let $\alpha_1, \ldots, \alpha_n$ be elements of Φ_B that form a basis for B' as a vector space over k, so that $\alpha_1, \ldots, \alpha_n$ form a basis for $E_{\mathbf{Q}}$ as a vector space over $\mathbf{Q}$, as before. Thus $\alpha_1, \ldots, \alpha_n$ is a basis for $E_{\mathbf{R}}$ too, as a vector space over $\mathbf{R}$, by construction.

Let $E'_{\mathbf{Q}}$ and $E'_{\mathbf{R}}$ be the dual spaces of linear functionals on $E_{\mathbf{Q}}$ and $E_{\mathbf{R}}$, as vector spaces over $\mathbf{Q}$ and $\mathbf{R}$, respectively. Of course, any linear functional on $E_{\mathbf{Q}}$ or $E_{\mathbf{R}}$ is uniquely determined by its values on $\alpha_1, \ldots, \alpha_n$. Linear functionals on $E_{\mathbf{Q}}$ may take arbitrary values in $\mathbf{Q}$ on $\alpha_1, \ldots, \alpha_n$, and linear functionals on $E_{\mathbf{R}}$ may take arbitrary values in $\mathbf{R}$ on $\alpha_1, \ldots, \alpha_n$. Every linear functional on $E_{\mathbf{Q}}$ has a natural unique extension to a linear functional on $E_{\mathbf{R}}$. If μ is a linear functional on $E_{\mathbf{R}}$, and μ maps $E_{\mathbf{Q}} \subseteq E_{\mathbf{R}}$ into $\mathbf{Q}$, then the restriction of μ to $E_{\mathbf{Q}}$ is a linear functional on $E_{\mathbf{Q}}$. Thus we may identify $E'_{\mathbf{Q}}$ with

$$\{\mu \in E'_{\mathbf{R}} : \mu(E_{\mathbf{Q}}) \subseteq \mathbf{Q}\}. \tag{22.2.1}$$

This is a linear subspace of $E'_{\mathbf{R}}$, as a vector space over $\mathbf{Q}$.

If $w \in B$, then put

$$T(w) = (\alpha_1(w), \ldots, \alpha_n(w)), \tag{22.2.2}$$

which is an element of the space k^n of n-tuples of elements of k. This defines a linear mapping from B into k^n, as a vector space over k with respect to coordinatewise addition and scalar multiplication, because α_j is a linear functional on B as a vector space over k for each $j = 1, \ldots, n$. More precisely, T is a one-to-one mapping from B onto k^n, because $\alpha_1, \ldots, \alpha_n$ is a basis for B', as a vector space over k.

Remember that k has characteristic 0, so that there is a standard embedding of $\mathbf{Q}$ into k. Let us identify $\mathbf{Q}$ with its image in k under the standard embedding, so that $\mathbf{Q}^n$ may be identified with a subset of k^n. Of course, $\mathbf{Q}^n$ is a linear subspace of k^n, as a vector space over $\mathbf{Q}$. Put

$$C_{\mathbf{Q}} = T^{-1}(\mathbf{Q}^n), \tag{22.2.3}$$

which is a linear subspace of B, as a vector space over $\mathbf{Q}$. Equivalently, $C_{\mathbf{Q}}$ consists of the $w \in B$ such that $\alpha_j(w) \in \mathbf{Q}$ for every $j = 1, \ldots, n$. This is the same as

$$C_{\mathbf{Q}} = \{w \in B : \beta(w) \in \mathbf{Q} \text{ for every } \beta \in E_{\mathbf{Q}}\}, \tag{22.2.4}$$

by the definition of $E_{\mathbf{Q}}$. Note that the dimension of $C_{\mathbf{Q}}$, as a vector space over $\mathbf{Q}$, is equal to n, and that the linear span of $C_{\mathbf{Q}}$ in B, as a vector space over k, is equal to B. The standard basis for $\mathbf{Q}^n$ corresponds to a basis for $C_{\mathbf{Q}}$, as a vector space over $\mathbf{Q}$, which is also a basis for B, as a vector space over k.

If $\beta \in E_{\mathbf{Q}} \subseteq B'$, then β is a linear functional on B, as a vector space over k, that maps $C_{\mathbf{Q}}$ into $\mathbf{Q}$. This implies that the restriction of β to $C_{\mathbf{Q}}$ is a linear functional on $C_{\mathbf{Q}}$, as a vector space over $\mathbf{Q}$. Of course, β is uniquely determined, as an element of B', by its restriction to $C_{\mathbf{Q}}$, because the linear span of $C_{\mathbf{Q}}$ in B, as a vector space over k, is equal to B. It is easy to see that every linear functional on $C_{\mathbf{Q}}$, as a vector space over $\mathbf{Q}$, corresponds to some $\beta \in E_{\mathbf{Q}}$ in this way, using T. Thus the dual space $C'_{\mathbf{Q}}$ of linear functionals on $C_{\mathbf{Q}}$, as a vector space over $\mathbf{Q}$, can be identified with $E_{\mathbf{Q}}$.

If $w \in B$, then

$$\beta \mapsto \beta(w) \tag{22.2.5}$$

defines a linear functional on the dual B' of B, as a vector space over k. This defines a one-to-one linear mapping from B onto the dual of B', as vector spaces over k. Similarly, if $w \in C_{\mathbf{Q}}$, then (22.2.5) defines a linear functional on $E_{\mathbf{Q}}$, as a vector space over $\mathbf{Q}$. This defines a one-to-one linear mapping from $C_{\mathbf{Q}}$ onto $E'_{\mathbf{Q}}$, as vector spaces over $\mathbf{Q}$.

Let $\alpha \in \Phi_B$ be given, and let $h_\alpha \in B$ be as in the previous section. Remember that $\beta(h_\alpha) \in \mathbf{Z}$ for every $\beta \in \Phi_B$, so that

$$h_\alpha \in C_{\mathbf{Q}} \tag{22.2.6}$$

in particular. The linear functional λ_α on $E_{\mathbf{Q}}$ that corresponds to h_α as in the preceding paragraph is the same as in the previous section. Note that λ_α, considered as a linear functional on $E_{\mathbf{R}}$, is the inverse root associated to α, as in Section 19.8.

Put

(22.2.7) $$\Phi'_B = \{\lambda_\alpha : \alpha \in \Phi_B\},$$

which is a subset of $E'_{\mathbf{Q}} \subseteq E'_{\mathbf{R}}$. As a subset of $E'_{\mathbf{R}}$, this is the inverse system of Φ_B, as in Section 19.8.

In [24], $k = \mathbf{C}$, and the notion of root systems is extended to complex vector spaces, so that h_α is identified directly with the inverse root of α, as in part (b) of Theorem 2 on p43f.

In [14], the Killing form on a semisimple Lie algebra A is used to get an inner product on $E_{\mathbf{R}}$, as in the previous section. Using this, the inverse root of $\alpha \in \Phi_B$ is identified with an element of $E_{\mathbf{R}}$. More precisely, the inverse root of α corresponds to an element of $E_{\mathbf{Q}}$, and thus an element of B'. This corresponds to $h_\alpha \in B$ using the Killing form, as on p43 of [14].

22.3 Semigroups and submodules

Let Ξ be a commutative semigroup, with the semigroup operation expressed additively. Also let Ψ be a nonempty subset of Ξ. If $\alpha \in \Xi$ and n is a positive integer, then $n \cdot \alpha$ is the sum of n α's in Ξ, as usual.

Let k be a commutative ring with a multiplicative identity element, and let $(A, [\cdot,\cdot]_A)$ be a Lie algebra over k. Suppose that for each $\alpha \in \Psi$, A_α is a submodule of A, as a module over k. We ask that A correspond to the direct sum of the A_α's, $\alpha \in \Psi$, as a module over k, so that every element of A can be expressed in a unique way as a sum of elements of the A_α's. It is convenient to put

(22.3.1) $$A_\alpha = \{0\} \quad \text{when } \alpha \in \Xi \setminus \Psi,$$

so that A_α is defined as a submodule of A, as a module over k, for every $\alpha \in \Xi$.

If $x \in A_\alpha$ and $y \in A_\beta$ for some $\alpha, \beta \in \Xi$, then we ask that

(22.3.2) $$[x, y]_A \in A_{\alpha+\beta}.$$

Of course, this holds trivially when α or β is in $\Xi \setminus \Psi$, by (22.3.1). Observe that

(22.3.3) $$[x, y]_A = 0 \quad \text{when } \alpha + \beta \notin \Psi,$$

by (22.3.1) and (22.3.2). If Ξ has an additive identity element 0, then (22.3.2) implies that A_0 is a Lie subalgebra of A.

If $x \in A_\alpha$ for some $\alpha \in \Psi$, then

(22.3.4) $$\mathrm{ad}_x(A_\gamma) \subseteq A_{\alpha+\gamma}$$

for every $\gamma \in \Xi$. If $n \in \mathbf{Z}_+$, then we get that

(22.3.5) $$(\mathrm{ad}_x)^n(A_\gamma) \subseteq A_{n\cdot\alpha+\gamma},$$

where $(\mathrm{ad}_x)^n$ is the nth power of ad_x on A, with respect to composition of mappings. Suppose that $\gamma \in \Psi$ and $n(\gamma) \in \mathbf{Z}_+$ have the property that

(22.3.6) $$n(\gamma) \cdot \alpha + \gamma \notin \Psi.$$

This implies that $(\mathrm{ad}_x)^{n(\gamma)} = 0$ on A_γ, and hence that $(\mathrm{ad}_x)^n = 0$ on A_γ for every integer $n \geq n(\gamma)$. If Ψ has only finitely many elements, and for each $\gamma \in \Psi$ there is an $n(\gamma) \in \mathbf{Z}_+$ such that (22.3.6) holds, then it follows that $(\mathrm{ad}_x)^n = 0$ on A when $n \geq \max_{\gamma \in \Psi} n(\gamma)$, so that x is ad-nilpotent as an element of A.

In some situations, we may have that

$$n \mapsto n \cdot \alpha + \gamma \tag{22.3.7}$$

is injective as a mapping from $\mathbf{Z}_+$ into Ξ. In particular, this holds for every $\gamma \in \Xi$ when Ξ is a commutative group without torsion, and $\alpha \neq 0$. Suppose that Ψ has only finitely many elements, so that the injectivity of (22.3.7) implies that

$$n \cdot \alpha + \gamma \in \Psi \tag{22.3.8}$$

for only finitely many $n \in \mathbf{Z}_+$. This means that $(\mathrm{ad}_x)^n = 0$ on A_γ for all but finitely many $n \in \mathbf{Z}_+$, as before. If this holds for every $\gamma \in \Psi$, then it follows that $(\mathrm{ad}_x)^n = 0$ on A for all but finitely many $n \in \mathbf{Z}_+$.

As usual, one may say that Ξ is a semigroup with cancellation if for every $\alpha, \beta, \gamma \in \Xi$ with

$$\alpha + \gamma = \beta + \gamma, \tag{22.3.9}$$

we have that $\alpha = \beta$. Note that this holds when Ξ is a subsemigroup of a group.

Suppose now that Ξ has an additive identity element 0. If $\alpha \in \Xi$ satisfies $n \cdot \alpha = 0$ for some $n \in \mathbf{Z}_+$, then α is said to be a torsion element of Ξ. If 0 is the only torsion element of Ξ, then one may say that Ξ is torsion-free, or that Ξ has no nontrivial torsion.

Suppose that Ξ is a semigroup with cancellation. If $\alpha, \gamma \in \Xi$ and α is not a torsion element, then it is easy to see that (22.3.8) is injective as a mapping from $\mathbf{Z}_+$ into Ξ. If $x \in A_\alpha$ and Ψ has only finitely many elements, then it follows that x is ad-nilpotent as an element of A, as before.

22.4 Semigroups and algebras

Let Ξ be a commutative semigroup, where the semigroup operation is expressed additively, and let Ψ be a nonempty subset of Ξ. Also let k be a commutative ring with a multiplicative identity element, and let A be an algebra over k in the strict sense, where multiplication of $x, y \in A$ is expressed as $x\,y$. Suppose that for each $\alpha \in \Psi$, A_α is a submodule of A, as a module over k, and that A corresponds to the direct sum of the A_α's, $\alpha \in \Psi$, as a module over k. As before, it is convenient to put $A_\alpha = \{0\}$ when $\alpha \in \Xi \setminus \Psi$.

Suppose that

$$x\,y \in A_{\alpha+\beta} \tag{22.4.1}$$

when $x \in A_\alpha$ and $y \in A_\beta$ for some $\alpha, \beta \in \Xi$. Thus

$$x\,y = 0 \tag{22.4.2}$$

when α, β, or $\alpha+\beta$ is not in Ψ. If Ξ has an additive identity element 0, then A_0 is a subalgebra of A, by (22.4.1). Of course, the remarks in the previous section correspond to the case where A is a Lie algebra over k.

Note that

(22.4.3) $$x\,y - y\,x \in A_{\alpha+\beta}$$

when $x \in A_\alpha$ and $y \in A_\beta$ for some $\alpha, \beta \in \Xi$, by (22.4.1). If A is an associative algebra over k, then A may be considered as a Lie algebra with respect to the corresponding commutator bracket, as usual.

Suppose that A is an associative algebra over k, and that $x \in A_\alpha$ for some $\alpha \in \Psi$. If $n \in \mathbf{Z}_+$, then

(22.4.4) $$x^n \in A_{n\cdot\alpha},$$

by (22.4.1). In particular, if $n\cdot\alpha \not\in \Psi$, then $x^n = 0$. If $n \mapsto n\cdot\alpha$ is injective as a mapping from $\mathbf{Z}_+$ into Ξ, and Ψ has only finitely many elements, then $n\cdot\alpha \in \Psi$ for only finitely many $n \in \mathbf{Z}_+$, so that x is nilpotent in A. If Ξ is a semigroup with cancellation and an additive identity element 0, and if α is not a torsion element of Ξ, then $n \mapsto n\cdot\alpha$ is an injective mapping from $\mathbf{Z}_+$ into Ξ, as before.

Let A be an algebra over k in the strict sense again. If Ψ_0 is a subset of Ξ, then let $A(\Psi_0)$ be the subset of A consisting of elements that can be expressed as a sum of elements of A_α, for finitely many $\alpha \in \Psi_0$. This is a submodule of A, as a module over k, which may be interpreted as being $\{0\}$ when $\Psi_0 = \emptyset$, and which corresponds to the direct sum of the A_α's, $\alpha \in \Psi_0$, as a module over k. Of course,

(22.4.5) $$A(\Psi_0) = A(\Psi_0 \cap \Psi),$$

and one may wish to restrict one's attention to $\Psi_0 \subseteq \Psi$. However, it is sometimes convenient for $A(\Psi_0)$ to be defined for any $\Psi_0 \subseteq \Xi$.

Suppose that $\Psi_0 \subseteq \Xi$ has the property that

(22.4.6) $$\text{if } \alpha, \beta \in \Psi_0 \text{ and } \alpha + \beta \in \Psi, \text{ then } \alpha + \beta \in \Psi_0.$$

In particular, if Ξ_0 is a subsemigroup of Ξ, then $\Xi_0 \cap \Psi$ has this property. Under these conditions, $A(\Psi_0)$ is a subalgebra of A, as an algebra over k in the strict sense.

Suppose that $\Psi_1 \subseteq \Xi$ has the property that

(22.4.7) $$\text{if } \alpha \in \Psi_1 \text{ and } \beta, \alpha + \beta \in \Psi, \text{ then } \alpha + \beta \in \Psi_1.$$

In this case, $A(\Psi_1)$ is a two-sided ideal in A. If $\Xi_1 \subseteq \Xi$ has the property that

(22.4.8) $$\text{if } \alpha \in \Xi_1 \text{ and } \beta \in \Xi, \text{ then } \alpha + \beta \in \Xi_1,$$

then $\Xi_1 \cap \Psi$ satisfies (22.4.7).

Similarly, suppose that $\Psi_2 \subseteq \Xi$ satisfies (22.4.6), and that $\Psi_1 \subseteq \Psi_2$ satisfies

(22.4.9) $$\text{if } \alpha \in \Psi_1 \text{ and } \beta, \alpha + \beta \in \Psi_2, \text{ then } \alpha + \beta \in \Psi_1.$$

In this situation, $A(\Psi_1)$ is a two-sided ideal in $A(\Psi_2)$, as an algebra over k in the strict sense.

22.5 Some nilpotency properties

Let us continue with the same notation and hypotheses as in the previous section. In particular, Ξ is a commutative semigroup, and A is an algebra over k in the strict sense. If $\Psi_1, \ldots, \Psi_r \subseteq \Xi$ for some $r \in \mathbf{Z}_+$, then put

$$\Psi_1 + \cdots + \Psi_r = \left\{ \sum_{j=1}^{r} \alpha_j : \alpha_j \in \Psi_j \text{ for each } j = 1, \ldots, r \right\}, \tag{22.5.1}$$

as usual. This subset of Ξ may be denoted $\sum_{j=1}^{r} \Psi_j$ as well. Note that

$$A(\Psi_1) \cdot A(\Psi_2) \subseteq A(\Psi_1 + \Psi_2) \tag{22.5.2}$$

for every $\Psi_1, \Psi_2 \subseteq \Xi$, by (22.4.1), where the left side is the set of finite sums of products of elements of $A(\Psi_1)$ and $A(\Psi_2)$, as in Section 9.2.

If $\Psi_0 \subseteq \Xi$, then (22.4.6) may be expressed as

$$(\Psi_0 + \Psi_0) \cap \Psi \subseteq \Psi_0. \tag{22.5.3}$$

Of course, $\Xi_0 \subseteq \Xi$ is a subsemigroup of Ξ when

$$\Xi_0 + \Xi_0 \subseteq \Xi_0. \tag{22.5.4}$$

Similarly, if $\Psi_1 \subseteq \Xi$, then (22.4.7) may be expressed as

$$(\Psi_1 + \Psi) \cap \Psi \subseteq \Psi_1. \tag{22.5.5}$$

If $\Xi_1 \subseteq \Xi$, then (22.4.8) may be expressed as

$$\Xi_1 + \Xi \subseteq \Xi_1. \tag{22.5.6}$$

If $\Psi_1 \subseteq \Psi_2 \subseteq \Xi$, then (22.4.9) may be expressed as

$$(\Psi_1 + \Psi_2) \cap \Psi_2 \subseteq \Psi_1. \tag{22.5.7}$$

If $r \in \mathbf{Z}_+$, and $\Psi_j \subseteq \Xi$, $x_j \in A(\Psi_j)$ for each $j = 1, \ldots, r$, then the product of $x_1, \ldots, x_r$ in A, with any ordering or grouping, is an element of $A\Big(\sum_{j=1}^{r} \Psi_j\Big)$. In particular, if

$$\Big(\sum_{j=1}^{r} \Psi_j\Big) \cap \Psi = \emptyset, \tag{22.5.8}$$

then any such product of $x_1, \ldots, x_n$ in A is equal to 0.

Let Ψ_0 be a subset of Ξ, and put

$$\Psi_0(r) = \sum_{j=1}^{r} \Psi_0 \tag{22.5.9}$$

for each $r \in \mathbf{Z}_+$, which is the subset of Ξ consisting of sums of r elements of Ψ_0. If $x_1, \ldots, x_r$ are elements of $A(\Psi_0)$, then the product of $x_1, \ldots, x_r$ in A, with any grouping, is an element of $A(\Psi_0(r))$, as in the preceding paragraph. If

$$\Psi_0(r) \cap \Psi = \emptyset, \tag{22.5.10}$$

then such a product of $x_1, \ldots, x_r$ in A is equal to 0.

If $y \in A = A(\Psi)$, then the product of $x_1, \ldots, x_r, y$ in A, with any ordering or grouping, is an element of $A(\Psi_0(r) + \Psi)$, as before. If

$$(\Psi_0(r) + \Psi) \cap \Psi = \emptyset, \tag{22.5.11}$$

then such a product of $x_1, \ldots, x_r, y$ in A is equal to 0.

Suppose now that A is a Lie algebra over k, so that (22.5.2) can be expressed as

$$[A(\Psi_1), A(\Psi_2)] \subseteq A(\Psi_1 + \Psi_2) \tag{22.5.12}$$

for every $\Psi_1, \Psi_2 \subseteq \Xi$. Equivalently, if $x \in \Psi_1$, then

$$\mathrm{ad}_x(A(\Psi_2)) \subseteq A(\Psi_1 + \Psi_2). \tag{22.5.13}$$

If $\Psi_0 \subseteq \Xi$, $x \in A(\Psi_0)$, and $r \in \mathbf{Z}_+$, then

$$\mathrm{ad}_x(A(\Psi_0(r) + \Psi)) \subseteq A(\Psi_0(r+1) + \Psi). \tag{22.5.14}$$

Thus

$$(\mathrm{ad}_x)^r(A) \subseteq A(\Psi_0(r) + \Psi) \tag{22.5.15}$$

for every $r \geq 1$. In particular, if $x \in A(\Psi_0)$ and $r \in \mathbf{Z}_+$ satisfies (22.5.11), then we get that $(\mathrm{ad}_x)^r = 0$ on A.

Suppose that Ψ_0 satisfies (22.5.3), so that $A(\Psi_0)$ is a Lie subalgebra of A. Let $(A(\Psi_0))^j$, $j \geq 0$, be the lower central series in $A(\Psi_0)$, as in Section 9.5. If $r \in \mathbf{Z}_+$, then

$$(A(\Psi_0))^{r-1} \subseteq A(\Psi_0(r)), \tag{22.5.16}$$

as before. If (22.5.10) holds, then

$$(A(\Psi_0))^{r-1} = \{0\}, \tag{22.5.17}$$

so that $A(\Psi_0)$ is nilpotent as a Lie algebra.

Suppose that Ξ has an additive identity element 0, so that A_0 is a Lie subslagebra of A. If $\Psi_1, \Psi_2 \subseteq \Xi$, then

$$(\Psi_1 \cup \{0\}) + (\Psi_2 \cup \{0\}) = (\Psi_1 + \Psi_2) \cup \Psi_1 \cup \Psi_2 \cup \{0\}. \tag{22.5.18}$$

If A_0 is commutative as a Lie algebra, then

$$[A(\Psi_1 \cup \{0\}), A(\Psi_2 \cup \{0\})] \subseteq A((\Psi_1 + \Psi_2) \cup \Psi_1 \cup \Psi_2). \tag{22.5.19}$$

Suppose that $\Psi_0 \subseteq \Xi$ satisfies (22.5.3) again. This implies that $\Psi_0 \cup \{0\}$ satisfies the analogous condition,

$$((\Psi_0 \cup \{0\}) + (\Psi_0 \cup \{0\})) \cap \Psi \subseteq \Psi_0 \cup \{0\}. \tag{22.5.20}$$

Thus $A(\Psi_0 \cup \{0\})$ is a Lie subalgebra of A too, and it is easy to see that $A(\Psi_0)$ is an ideal in $A(\Psi_0 \cup \{0\})$. If A_0 is commutative as a Lie algebra, then

$$[A(\Psi_0 \cup \{0\}), A(\Psi_0 \cup \{0\})] \subseteq A(\Psi_0). \tag{22.5.21}$$

It follows that $A(\Psi_0 \cup \{0\})$ is solvable as a Lie algebra over k when (22.5.10) holds for some r, so that $A(\Psi_0)$ is nilpotent as a Lie algebra.

If

$$[A_0, A_\alpha] = A_\alpha \tag{22.5.22}$$

for every $\alpha \in \Psi_0$, then

$$[A_0, A(\Psi_0)] = A(\Psi_0). \tag{22.5.23}$$

If A_0 is commutative as a Lie algebra, then we get that

$$[A(\Psi_0 \cup \{0\}), A(\Psi_0 \cup \{0\})] = A(\Psi_0). \tag{22.5.24}$$

22.6 Roots and submodules

Let V be a vector space over the real numbers of positive finite dimension, and let Φ be a root system in V. Also let Θ be the subgroup of V, as a commutative group with respect to addition, generated by Φ. We would like to consider situations like those in Section 22.3, with

$$\Xi = \Theta, \quad \Psi = \Phi \cup \{0\}. \tag{22.6.1}$$

Note that Θ has no nontrivial torsion, because V has none.

Let k be a commutative ring with a multiplicative identity element, and let $(A, [\cdot,\cdot]_A)$ be a Lie algebra over k. If $\alpha \in \Phi \cup \{0\}$, then we ask that A_α be a submodule of A, as a module over k, and that A correspond to the direct sum of the A_α's, $\alpha \in \Phi \cup \{0\}$, as a module over k. As before, we put $A_\alpha = \{0\}$ when $\alpha \in \Theta \setminus (\Phi \cup \{0\})$, and we ask that

$$[A_\alpha, A_\beta] \subseteq A_{\alpha+\beta} \tag{22.6.2}$$

for every $\alpha, \beta \in \Theta$, as in (22.3.2). Thus A_0 is a Lie subalgebra of A, as before. If $x \in A_\alpha$ for some nonzero $\alpha \in \Theta$, then x is ad-nilpotent in A, as in Section 22.3.

If $\Psi_0 \subseteq \Theta$, then let $A(\Psi_0)$ be the subset of A consisting of finite sums of elements of A_α, $\alpha \in \Psi_0$, as in Section 22.4. Let $\Delta \subseteq \Phi$ be a base for Φ, as a root system in V, and let $\Phi^+ = \Phi^{\Delta,+}$ be the set of positive roots in Φ with respect to Δ. Thus Φ^+ consists of the $\alpha \in \Phi$ that can be expressed as a linear combination of elements of Δ whose coefficients are nonnegative integers, and $\Phi = \Phi^+ \cup (-\Phi^+)$. Note that

$$(\Phi^+ + \Phi^+) \cap (\Phi \cup \{0\}) \subseteq \Phi^+, \tag{22.6.3}$$

so that $A(\Phi^+)$ is a Lie subalgebra of A, as before. Similarly,

$$((-\Phi^+) + (-\Phi^+)) \cap (\Phi \cup \{0\}) \subseteq -\Phi^+, \tag{22.6.4}$$

and $A(-\Phi^+)$ is a Lie subalgebra of A too.

It is easy to see that

$$\Big(\sum_{j=1}^{r} \Phi^+\Big) \cap (\Phi \cup \{0\}) = \emptyset \tag{22.6.5}$$

when r is sufficiently large, because Φ has only finitely many elements. In fact,

$$\Big(\Big(\sum_{j=1}^{r} \Phi^+\Big) + (\Phi \cup \{0\})\Big) \cap (\Phi \cup \{0\}) = \emptyset \tag{22.6.6}$$

when r is sufficiently large. This implies that $A(\Phi^+)$ is nilpotent as a Lie algebra over k, and that the elements of $A(\Phi^+)$ are ad-nilpotent in A, as in the previous section. Similarly, $A(-\Phi^+)$ is nilpotent as a Lie algebra over k, and the elements of $A(-\Phi^+)$ are ad-nilpotent in A. This corresponds to some remarks near the top of p84 of [14], and part (b) of Theorem 4 on p47 of [24].

Observe that

$$((\Phi^+ \cup \{0\}) + (\Phi^+ \cup \{0\})) \cap (\Phi \cup \{0\}) \subseteq \Phi^+ \cup \{0\} \tag{22.6.7}$$

and

$$(((-\Phi^+) \cup \{0\}) + ((-\Phi^+) \cup \{0\})) \cap (\Phi \cup \{0\}) \subseteq (-\Phi^+) \cup \{0\}, \tag{22.6.8}$$

so that $A(\Phi^+ \cup \{0\})$ and $A((-\Phi^+) \cup \{0\})$ are Lie subalgebras of A. As in the previous section, $A(\Phi^+)$ is an ideal in $A(\Phi^+ \cup \{0\})$, and $A(-\Phi^+)$ is an ideal in $A((-\Phi^+) \cup \{0\})$.

If A_0 is commutative as a Lie algebra over k, then

$$[A(\Phi^+ \cup \{0\}), A(\Phi^+ \cup \{0\})] \subseteq A(\Phi^+) \tag{22.6.9}$$

and

$$[A((-\Phi^+) \cup \{0\}), A((-\Phi^+) \cup \{0\})] \subseteq A(-\Phi^+), \tag{22.6.10}$$

as in (22.5.21). This implies that $A(\Phi^+ \cup \{0\})$ and $A((-\Phi^+) \cup \{0\})$ are solvable as Lie algebras over k, because $A(\Phi^+)$ and $A(-\Phi^+)$ are nilpotent as Lie algebras over k. This corresponds to some of the remarks near the top of p84 of [14] again, and part of part (c) of Theorem 4 on p47 of [24].

If

$$[A_0, A_\alpha] = A_\alpha \tag{22.6.11}$$

for every $\alpha \in \Phi$, then

$$[A_0, A(\Phi^+)] = A(\Phi^+) \tag{22.6.12}$$

and

$$[A_0, A(-\Phi^+)] = A(-\Phi^+). \tag{22.6.13}$$

If A_0 is commutative as a Lie algebra over k, then it follows that

$$[A(\Phi^+ \cup \{0\}), A(\Phi^+ \cup \{0\})] = A(\Phi^+) \tag{22.6.14}$$

and

$$[A((-\Phi^+) \cup \{0\}), A((-\Phi^+) \cup \{0\})] = A(-\Phi^+), \tag{22.6.15}$$

as in (22.5.24). This corresponds to the second part of part (c) of Theorem 4 on p47 of [24].

22.7 Borel subalgebras

Let k be a commutative ring with a multiplicative identity element, and let $(A, [\cdot,\cdot]_A)$ be a Lie algebra over k. A Lie subalgebra B of A is said to be a *Borel subalgebra* if B is solvable as a Lie algebra over k, and B is maximal with respect to inclusion among Lie subalgebras of A that are solvable as Lie algebras. If solvable subalgebras in A satisfy an ascending chain condition, then every solvable subalgebra of A is contained in a Borel subalgebra. In particular, this holds for finite-dimensional Lie algebras over fields.

Let A be an algebra over k in the strict sense for the moment, where multiplication of $a, b \in A$ is expressed as $a\,b$, and let A_1, A_2 be subalgebras of A. In particular, A_1 and A_2 are submodules of A, as a module over k, so that $A_1 + A_2$ is a submodule of A. Let $a_1, b_1 \in A_1$ and $a_2, b_2 \in A_2$ be given, so that

$$(a_1 + a_2)\,(b_1 + b_2) = a_1\,b_1 + a_1\,b_2 + a_2\,b_1 + a_2\,b_2. \tag{22.7.1}$$

Of course, $a_1\,b_1 \in A_1$ and $a_2\,b_2 \in A_2$, by hypothesis. If A_1 is a right ideal in A, then $a_1\,b_2 \in A_1$, and if A_2 is a left ideal in A, then $a_1\,b_2 \in A_2$. Similarly, if A_1 is a left ideal in A, then $a_2\,b_1 \in A_1$, and if A_2 is a right ideal in A, then $a_2\,b_1 \in A_2$. It follows that (22.7.1) is an element of $A_1 + A_2$ when either A_1 is a right ideal in A or A_2 is a left ideal in A, and either A_1 is a left ideal in A, or A_2 is a right ideal in A. In particular, this holds when A_1 or A_2 is a two-sided ideal in A. This means that $A_1 + A_2$ is a subalgebra of A under these conditions.

Let A be a Lie algebra over k again, let A_1 be a Lie subalgebra of A, and let A_2 be an ideal in A. Thus $A_1 + A_2$ is a Lie subalgebra of A, as in the preceding paragraph. If A_1 and A_2 are both solvable as Lie algebras over k, then $A_1 + A_2$ is solvable as well. This was mentioned in Section 9.4 when A_1 and A_2 are both ideals in A, and essentially the same argument works in this situation. More precisely, note that A_2 is an ideal in $A_1 + A_2$. It suffices to verify that $(A_1 + A_2)/A_2$ is solvable as a Lie algebra, because A_2 is solvable, as in Section 9.3. Let q_2 be the canonical quotient mapping from $A_1 + A_2$ onto

$(A_1 + A_2)/A_2$, which is essentially the same as the restriction of the canonical quotient mapping from A onto A/A_2 to $A_1 + A_2$.

It is easy to see that $A_1 \cap A_2$ is an ideal in A_1, because A_2 is an ideal in A. In fact, $A_1 \cap A_2$ is the same as the kernel of the restriction of q_2 to A_1, as a subalgebra of $A_1 + A_2$. Note that $q_2(A_1) = q_2(A_1 + A_2)$. The restriction of q_2 to A_1 can be identified with the canonical quotient mapping from A_1 onto $A_1/(A_1 \cap A_2)$, as a Lie algebra homomorphism. This leads to a natural Lie algebra isomorphism between $A_1/(A_1 \cap A_2)$ and $(A_1 + A_2)/A_2$. By hypothesis, A_1 is solvable, which implies that $A_1/(A_1 \cap A_2)$ is solvable, as in Section 9.3. This means that $(A_1 + A_2)/A_2$ is solvable, as desired.

If A_1 is a Borel subalgebra of A, then we get that $A_1 = A_1 + A_2$, which means that

$$A_2 \subseteq A_1. \tag{22.7.2}$$

If A has a solvable radical $\operatorname{Rad} A$, as in Section 9.4, then it follows that

$$\operatorname{Rad} A \subseteq A_1. \tag{22.7.3}$$

This corresponds to part of the proof of Lemma B on p83 of [14].

Let A_0 be a solvable ideal in A, and let q_0 be the canonical quotient mapping from A onto A/A_0. If B is a Lie subalgebra of A that is solvable as a Lie algebra over k, then $q_0(B)$ is solvable too, as in Section 9.3. If B_0 is a solvable Lie subalgebra of A/A_0, then $q_0^{-1}(B_0)$ is a solvable Lie subalgebra of A, as before. If B is a Borel subalgebra of A, then $A_0 \subseteq B$, as in the preceding paragraph. This leads to a natural one-to-one correspondence between Borel subalgebras of A and A/A_0, as in Lemma B on p83 of [14].

Let B be a Lie subalgebra of A, and let x be an element of the normalizer $N_A(B)$ of B in A. Under these conditions, it is easy to see that

$$B(x) = \{t\,x + y : t \in k,\ y \in B\} \tag{22.7.4}$$

is a Lie subalgebra of A, with

$$[B(x), B(x)] \subseteq B. \tag{22.7.5}$$

If B is solvable, then it follows that $B(x)$ is solvable as well. If B is a Borel subalgebra of A, then we get that $B = B(x)$, so that $x \in B$. This means that $N_A(B) = B$ when B is a Borel subalgebra of A, as in Lemma A on p83 of [14].

22.8 Some diagonalizability conditions

Let Ξ be a commutative semigroup, with the semigroup operation expressed additively, and with an additive identity element 0. Also let Φ be a set of nonzero elements of Ξ. We would like to consider the same type of situation as in Section 22.3, with $\Psi = \Phi \cup \{0\}$.

Let k be a commutative ring with a multiplicative identity element again, and let $(A, [\cdot,\cdot]_A)$ be a Lie algebra over k. As before, suppose that A_α is a submodule of A, as a module over k, for each $\alpha \in \Phi \cup \{0\}$, and that A corresponds to the direct sum of the A_α's, as a module over k. We put $A_\alpha = \{0\}$ when $\alpha \in \Xi \setminus (\Phi \cup \{0\})$, and ask that

$$[A_\alpha, A_\beta] \subseteq A_{\alpha+\beta} \tag{22.8.1}$$

for every $\alpha, \beta \in \Xi$, as in (22.3.2). In particular, this means that A_0 is a Lie subalgebra of A.

Let $\mathrm{Hom}_k(A_0, k)$ be the space of homomorphisms from A_0 into k, as modules over k. Remember that this is a module over k, with respect to pointwise addition and scalar multiplication. Suppose that

(22.8.2) ϕ is a semigroup homomorphism from Ξ into $\mathrm{Hom}_k(A_0, k)$,

as a commutative semigroup with respect to addition. Note that

$$\phi(0) = 0 \tag{22.8.3}$$

in $\mathrm{Hom}_k(A_0, k)$, because the additive identity element in a group is the only element of the group whose sum with itself is equal to itself.

If $\alpha \in \Xi$, then it is convenient to let

$$\phi_\alpha = \phi(\alpha) \tag{22.8.4}$$

be the corresponding element of $\mathrm{Hom}_k(A_0, k)$. Thus, if $w \in A_0$, then $\phi_\alpha(w)$ is an element of k.

If $\alpha \in \Phi \cup \{0\}$, $w \in A_0$, and $x \in A_\alpha$, then we ask that

$$\mathrm{ad}_w(x) = [w, x]_A = \phi_\alpha(w)\, x. \tag{22.8.5}$$

In particular, this is equal to 0 when $\alpha = 0$. This means that A_0 is commutative as a Lie algebra. If $\alpha \in \Xi \setminus (\Phi \cup \{0\})$ and $x \in A_\alpha$, then $x = 0$, so that (22.8.5) holds trivially.

Note that (22.8.1) follows from (22.8.5) when α or β is 0. If $w \in A_0$, and $x \in A_\alpha$, $y \in A_\beta$ for some $\alpha, \beta \in \Xi$, then

$$\begin{aligned} [w, [x, y]_A]_A &= [[w, x]_A, y]_A + [x, [w, y]_A]_A \\ &= \phi_\alpha(w)\, [x, y]_A + \phi_\beta(w)\, [x, y]_A = \phi_{\alpha+\beta}(w)\, [x, y]_A. \end{aligned} \tag{22.8.6}$$

Of course, this is compatible with (22.8.1) and (22.8.5).

If $w \in A_0$ satisfies

$$\phi_\alpha(w) = 0 \tag{22.8.7}$$

for every $\alpha \in \Phi$, then w is in the center $Z(A)$ of A as a Lie algebra. In particular, if $Z(A) = \{0\}$, then $w = 0$.

If $\alpha \in \Xi$, then $[A_0, A_\alpha] \subseteq A_\alpha$, as in (22.8.1). If there is a $w \in A_0$ such that $\phi_\alpha(w)$ has a multiplicative inverse in k, then we get that

$$[A_0, A_\alpha] = A_\alpha. \tag{22.8.8}$$

22.9 Diagonalizability and subspaces

Let k be a field, and let $(A, [\cdot,\cdot]_A)$ be a finite-dimensional Lie algebra over k. Suppose that B is a Lie subalgebra of A such that every element of B is ad-diagonalizable as an element of A. This implies that B is commutative as a Lie algebra, as in Section 17.1. Let B' be the dual of B, as a vector space over k, and for each $\alpha \in B'$, let A_α be the set of $x \in A$ such that $\mathrm{ad}_w(x) = \alpha(w)\,x$ for every $w \in B$. Consider the set Φ_B of $\alpha \in B'$ such that $\alpha \neq 0$ and $A_\alpha \neq \{0\}$. Under these conditions, Φ_B has only finitely many elements, and A corresponds to the direct sum of the subspaces A_α with $\alpha \in \Phi_B \cup \{0\}$, as a vector space over k, as in Section 17.2. Remember that $[A_\alpha, A_\beta] \subseteq A_{\alpha+\beta}$ for every $\alpha, \beta \in B'$, as before. In this situation, we can take Ξ_B to be a subsemigroup of B', as a commutative group with respect to addition, with

(22.9.1) $$\Phi_B \cup \{0\} \subseteq \Xi_B.$$

Note that

(22.9.2) $$[B, A_\alpha] = A_\alpha$$

for every $\alpha \in \Phi_B$. It follows that $[A_0, A_\alpha] = A_\alpha$ for every $\alpha \in \Phi_B$, because $B \subseteq A_0$, by the commutativity of B as a Lie algebra.

As before, A_0 is the centralizer $C_A(B)$ of B in A. Suppose that $C_A(B) = B$, so that $A_0 = B$, and

(22.9.3) $$\mathrm{Hom}_k(A_0, k) = A_0' = B'.$$

In this case, we can take ϕ to be the obvious inclusion mapping of Ξ_B into (22.9.3), so that (22.8.5) follows from the definition of A_α.

Let us return for the moment to the situation before the preceding paragraph, so that we do not necessarily ask the centralizer of B in A to be B. Let C be a linear subspace of A such that

(22.9.4) $$[B, C] \subseteq C.$$

In particular, this holds when C is a Lie subalgebra of A that contains B. If $w \in B$, then

(22.9.5) $$\mathrm{ad}_w(C) \subseteq C,$$

and ad_w is diagonalizable on A, by hypothesis. This implies that the restriction of ad_w to C is diagonalizable on C, as in Section 10.6.

If $u, v \in B$, then $[u, v]_A = 0$, which implies that ad_u and ad_v commute on A, as in Section 2.4. Thus the restrictions of ad_u and ad_v to C commute as well. This means that the restrictions of ad_u, $u \in B$, to C are simultaneously diagonalizable on C, by standard arguments. Put

(22.9.6) $$\Psi_C = \{\alpha \in B' : A_\alpha \cap C \neq \{0\}\},$$

which is contained in $\Phi_B \cup \{0\}$. It follows that C corresponds to the direct sum of $A_\alpha \cap C$ with $\alpha \in \Psi_C$, as a vector space over k. If C is a Lie subalgebra of A, then

(22.9.7) $$[A_\alpha \cap C, A_\beta \cap C] \subseteq A_{\alpha+\beta} \cap C$$

for every $\alpha, \beta \in B'$. Of course,

$$\mathrm{ad}_w(A_\alpha \cap C) = A_\alpha \cap C \tag{22.9.8}$$

when $w \in B$, $\alpha \in B'$, and $\alpha(w) \neq 0$.

22.10 Injectivity on Ψ

Let us consider some situations as in Section 22.8, with k a field. Thus we let Ξ be a commutative semigroup, with the semigroup operation expressed additively, and with an additive identity element 0. We also let Φ be a finite set of nonzero elements in Ξ, and start with situations as in Section 22.3, with $\Psi = \Phi \cup \{0\}$.

Let $(A, [\cdot,\cdot]_A)$ be a finite-dimensional Lie algebra over k, and let A_α be a linear subspace of A, as a vector space over k, for each $\alpha \in \Phi \cup \{0\}$. Suppose that A corresponds to the direct sum of the A_α's, $\alpha \in \Phi \cup \{0\}$, and put $A_\alpha = \{0\}$ when $\alpha \in \Xi \setminus (\Phi \cup \{0\})$. As before, we ask that $[A_\alpha, A_\beta] \subseteq A_{\alpha+\beta}$ for every $\alpha, \beta \in \Xi$, which implies that A_0 is a Lie subalgebra of A.

Suppose that

$$\phi \text{ is a semigroup homomorphism from } \Xi \text{ into } A_0', \tag{22.10.1}$$

where A_0' is the dual of A_0 as a vector space over k, considered as a commutative semigroup with respect to addition in (22.10.1). As before, $\phi(0) = 0$ in A_0', because A_0' is a group with respect to addition. If $\alpha \in \Xi$, then it is convenient to put $\phi_\alpha = \phi(\alpha)$ again. We ask that $\mathrm{ad}_w(x) = [w,x]_A = \phi_\alpha(w)\,x$ for every $\alpha \in \Phi \cup \{0\}$, $w \in A_0$, and $x \in A_\alpha$, which holds trivially when $\alpha \in \Xi \setminus (\Phi \cup \{0\})$. This implies that A_0 is commutative as a Lie subalgebra of A.

Note that $[A_0, A_\alpha] = A_\alpha$ for every $\alpha \in \Phi$ such that $\phi_\alpha \neq 0$, as in (22.8.8). More precisely, if $\phi_\alpha \neq 0$, then there is a $w \in A_0$ such that $\phi_\alpha(w) \neq 0$, and $\mathrm{ad}_w(A_\alpha) = A_\alpha$.

Let us take $B = A_0$, so that every element of B is ad-diagonalizable, by hypothesis. If ρ is an element of the dual $B' = A_0'$ of B, then put

$$\widetilde{A}_\rho = \{x \in A : \text{ for every } w \in B,\ \mathrm{ad}_w(x) = [w,x]_A = \rho(w)\,x\}, \tag{22.10.2}$$

which is a linear subspace of A. Thus

$$A_\alpha \subseteq \widetilde{A}_{\phi_\alpha} \tag{22.10.3}$$

for every $\alpha \in \Xi$. If ρ is any element of B', then it follows that $\widetilde{A}_\rho$ corresponds to the direct sum of A_α with $\alpha \in \Phi \cup \{0\}$ and $\phi_\alpha = \rho$. This means that $\widetilde{A}_\rho = \{0\}$ when $\rho \neq \phi_\alpha$ for every $\alpha \in \Phi \cup \{0\}$.

Suppose that

$$\text{for every } \alpha \in \Phi, \text{ we have that } \phi_\alpha \neq 0. \tag{22.10.4}$$

This implies that

(22.10.5) $$A_0 = \widetilde{A}_0,$$

as in the preceding paragraph. Note that $\widetilde{A}_0$ is the same as the centralizer of B in A, as before. Thus the centralizer $C_A(A_0)$ of A_0 in A is equal to A_0 in this case. We also get that $[A_0, A_\alpha] = A_\alpha$ for every $\alpha \in \Phi$ when (22.10.4) holds.

Suppose now that

(22.10.6) $$\phi \text{ is injective on } \Phi \cup \{0\},$$

so that $\phi_\alpha \neq \phi_\beta$, as elements of A_0', for every $\alpha, \beta \in \Phi \cup \{0\}$ with $\alpha \neq \beta$. Of course, (22.10.6) is the same as saying that (22.10.4) holds, and that ϕ is injective on Φ. It follows that

(22.10.7) $$A_\alpha = \widetilde{A}_{\phi_\alpha}$$

for every $\alpha \in \Phi \cup \{0\}$, as before.

Let C be a linear subspace of A such that

(22.10.8) $$[A_0, C] \subseteq C,$$

and put

(22.10.9) $$\widetilde{\Psi}_C = \{\rho \in B' : \widetilde{A}_\rho \cap C \neq \{0\}\},$$

which corresponds to (22.9.6) with the notation in this section. As in the previous section, C corresponds to the direct sum of $\widetilde{A}_\rho \cap C$ with $\rho \in \widetilde{\Psi}_C$, as a vector space over k. Note that this does not use (22.10.4) or (22.10.6). Put

(22.10.10) $$\Psi_C = \{\alpha \in \Phi \cup \{0\} : A_\alpha \cap C \neq \{0\}\}.$$

If (22.10.6) holds, then C corresponds to the direct sum of $A_\alpha \cap C$ with $\alpha \in \Psi_C$, as a vector space over k.

22.11 Some additional conditions

Let V be a vector space over the real numbers of positive finite dimension, and let Φ be a root system in V. Thus, for every $\alpha \in \Phi$, there is a unique symmetry σ_α on V with vector α that maps Φ onto itself. Let λ_α be the linear functional on V that is equal to 0 on the hyperplane fixed by σ_α and satisfies $\lambda_\alpha(\alpha) = 2$, as before. Equivalently, $\sigma_\alpha(v) = v - \lambda_\alpha(v)\, \alpha$ for every $v \in V$. Remember that $\lambda_\alpha(\beta) \in \mathbf{Z}$ for every $\alpha, \beta \in \Phi$, by definition of a root system.

Let Θ be the subgroup of V, as a commutative group with respect to addition, generated by Φ. This is the same as the subsemigroup of V generated by Φ. We would like to consider situations like those discussed in Section 22.8, with $\Xi = \Theta$. Note that the elements of Θ can be expressed as linear combinations of the elements of any base for Φ with coefficients in $\mathbf{Z}$.

Let k be a commutative ring with a multiplicative identity element, and let $(A, [\cdot,\cdot]_A)$ be a Lie algebra over k. If $\alpha \in \Phi \cup \{0\}$, then we suppose that A_α is a submodule of A, as a module over k, and that A corresponds to the direct sum of the A_α's, as a module over k. As usual, it is convenient to put $A_\alpha = \{0\}$

when $\alpha \in \Theta \setminus (\Phi \cup \{0\})$, and we ask that $[A_\alpha, A_\beta] \subseteq A_{\alpha+\beta}$ for every $\alpha, \beta \in \Theta$. We also ask that ϕ be a group homomorphism from Θ into $\mathrm{Hom}_k(A_0, k)$, as a commutative group with respect to addition, such that $\mathrm{ad}_w(x) = \phi_\alpha(w)\, x$ for every $w \in A_0$ and $x \in A_\alpha$, $\alpha \in \Phi \cup \{0\}$, where $\phi_\alpha = \phi(\alpha)$. This implies that A_0 is a Lie subalgebra of A that is commutative as a Lie algebra over k, as before.

If $\alpha \in \Phi$, then $-\alpha \in \Phi$, and $[A_\alpha, A_{-\alpha}] \subseteq A_0$. We may be interested in situations where there is an $h_\alpha \in A_0$ such that

$$[A_\alpha, A_{-\alpha}] = \{t\, h_\alpha : t \in k\}. \tag{22.11.1}$$

We may also ask that

$$\phi_\alpha(h_\alpha) = 2 (= 1 + 1) \tag{22.11.2}$$

in k. In particular, (22.11.1) implies that there are $x_\alpha \in A_\alpha$ and $y_\alpha \in A_{-\alpha}$ such that

$$[x_\alpha, y_\alpha]_A = h_\alpha. \tag{22.11.3}$$

More precisely, we may ask that

$$A_\alpha \text{ and } A_{-\alpha} \text{ are generated by } x_\alpha \text{ and } y_\alpha, \text{ respectively}, \tag{22.11.4}$$

as modules over k, so that every element of A_α or $A_{-\alpha}$ can be expressed as a multiple of x_α or y_α by an element of k, as appropriate. Of course, (22.11.3) and (22.11.4) imply (22.11.1). If $\beta \in \Phi$, then we may ask that

$$\phi_\beta(h_\alpha) = \lambda_\alpha(\beta) \cdot 1 \tag{22.11.5}$$

in k, which reduces to (22.11.2) when $\alpha = \beta$.

In the situation considered in Section 22.1, we take $V = E_{\mathbf{R}}$ and $\Phi = \Phi_B$. More precisely, k is a field of characteristic 0 in this case, and Φ may be considered as a subset of the dual of $A_0 = B$, as a vector space over k. Remember that $E_{\mathbf{Q}}$ is the linear subspace of the dual of A_0, as a vector space over $\mathbf{Q}$, spanned by Φ. By construction, $E_{\mathbf{Q}}$ is also a linear subspace of $V = E_{\mathbf{R}}$, as a vector space over $\mathbf{Q}$. In particular,

$$\Theta \subseteq E_{\mathbf{Q}}. \tag{22.11.6}$$

Thus ϕ may be taken to be the obvious inclusion mapping of Θ into the dual of A_0. The one-dimensionality of $[A_\alpha, A_{-\alpha}]$ for $\alpha \in \Phi$ was discussed in Section 17.5, and h_α was defined in Section 17.6. The one-dimensionality of A_α, $A_{-\alpha}$ was discussed in Section 17.7, and (22.11.5) follows from the definition of λ_α in Section 22.1.

We also have that

$$A_0 \text{ is spanned by the } h_\alpha\text{'s, } \alpha \in \Phi, \tag{22.11.7}$$

as a vector space over k, in the situation considered in Section 22.1. More precisely, $A_0 = B$ is spanned by $t_{b,\alpha}$, $\alpha \in \Phi$, because the dual of B is spanned by Φ.

Similarly, if $\Delta \subseteq \Phi$ is a base for Φ, then

$$A_0 \text{ is spanned by the } h_\alpha\text{'s}, \ \alpha \in \Delta, \tag{22.11.8}$$

as a vector space over k, in the situation considered in Section 22.1. To see this, it suffices to check that A_0 is spanned by $t_{b,\alpha}$, $\alpha \in \Delta$, because h_α was defined to be the product of $t_{b,\alpha}$ by a nonzero element of k. This reduces to the previous case, because every element of Φ can be expressed as a linear combination of elements of Δ with integer coefficients.

In fact,

$$h_\alpha, \ \alpha \in \Delta, \ \text{ form a basis for } A_0 \tag{22.11.9}$$

as a vector space over k, in the situation considered in Section 22.1. To see this, remember that the number of elements of Δ is the same as the dimension of $V = E_{\mathbf{R}}$ as a vector space over $\mathbf{R}$. This is the same as the dimension of $E_{\mathbf{Q}}$, as a vector space over $\mathbf{Q}$. This is also the same as the dimension of the dual of $A_0 = B$, as a vector space over k. Of course, this is the same as the dimension of A_0, as a vector space over k.

If $\alpha, \beta \in \Phi$, then ad_{x_α} maps A_β into $A_{\alpha+\beta}$, as before. In the situation considered in Section 22.1, if we also have that $\alpha + \beta \in \Phi$, then

$$\text{the restriction of } \mathrm{ad}_{x_\alpha} \text{ to } A_\beta \text{ is a one-to-one mapping onto } A_{\alpha+\beta}, \tag{22.11.10}$$

as in Section 17.9.

22.12 Standard Borel subalgebras

Let V be a vector space over the real numbers of positive finite dimension, and let Φ be a root system in V. Also let Θ be the subgroup of V, as a commutative group with respect to addition, generated by Φ. We would like to consider situations with some of the conditions mentioned in the previous section, with k a field. Let $(A, [\cdot,\cdot]_A)$ be a finite-dimensional Lie algebra over k, and let A_α be a linear subspace of A, as a vector space over k, for each $\alpha \in \Phi \cup \{0\}$. As before, we suppose that A corresponds to the direct sum of the A_α's, $\alpha \in \Phi \cup \{0\}$, as a vector space over k, and we put $A_\alpha = \{0\}$ when $\alpha \in \Theta \setminus (\Phi \cup \{0\})$, for convenience. We suppose that $[A_\alpha, A_\beta] \subseteq A_{\alpha+\beta}$ for every $\alpha, \beta \in \Theta$, and that there is a group homomorphism ϕ from Θ into the dual A_0' of A_0 as a vector space over k such that $\mathrm{ad}_w(x) = \phi_\alpha(w)\, x$ for every $w \in A_0$ and $x \in A_\alpha$, $\alpha \in \Phi \cup \{0\}$. Here $\phi_\alpha = \phi(\alpha)$ for every $\alpha \in \Theta$, as usual.

Suppose that for each $\alpha \in \Phi$ there are $x_\alpha \in A_\alpha$ and $y_\alpha \in A_{-\alpha}$ such that A_α, $A_{-\alpha}$ are spanned in A by x_α, y_α, respectively. Put $h_\alpha = [x_\alpha, y_\alpha]_A$ for every $\alpha \in \Phi$, so that $h_\alpha \in A_0$. We ask that

$$\phi_\alpha(h_\alpha) = 2 \cdot 1 \tag{22.12.1}$$

in k for every $\alpha \in \Phi$, as before. Suppose in addition that

$$\phi \text{ is injective on } \Phi \cup \{0\}, \tag{22.12.2}$$

so that $\phi_\alpha \neq \phi_\beta$ when α and β are distinct elements of $\Phi \cup \{0\}$. Note that this holds in the situation considered in Section 22.1, as in the previous section.

In particular, we are in the type of situation considered in Section 22.6. Let $\Delta \subseteq \Phi$ be a base for Φ, as a root system in V, and let Φ^+ be the set of positive roots in Φ with respect to Δ, as before. If $\Psi_0 \subseteq \Theta$, then we let $A(\Psi_0)$ be the linear subspace of A spanned by A_α with $\alpha \in \Psi_0$, as in Section 22.4. Remember that A_0 is commutative as a Lie subalgebra of A, as in Section 22.8. It follows that $A(\Phi^+ \cup \{0\})$ is a solvable Lie subalgebra of A, as in Section 22.6.

Let C be a Lie subalgebra of A such that

$$A(\Phi^+ \cup \{0\}) \subseteq C \tag{22.12.3}$$

In particular, this means that $A_0 \subseteq C$, so that $[A_0, C] \subseteq C$. If we put

$$\Psi_C = \{\alpha \in \Phi \cup \{0\} : A_\alpha \cap C \neq \{0\}\}, \tag{22.12.4}$$

then C corresponds to the direct sum of $A_\alpha \cap C$ with $\alpha \in \Psi_C$, as in Section 22.10. Note that this uses (22.12.2).

Suppose that $A(\Phi^+ \cup \{0\})$ is a proper subset of C. This implies that Ψ_C is not contained in $\Phi^+ \cup \{0\}$, as in the preceding paragraph. This means that there is an $\alpha \in \Psi_C \cap (-\Phi^+)$, because $\Phi = \Phi^+ \cup (-\Phi^+)$. It follows that $x_\alpha \in C$, because A_α is spanned by x_α.

Under these conditions, $-\alpha \in \Phi^+$, and $y_\alpha, h_\alpha \in A(\Phi^+ \cup \{0\})$, so that y_α, h_α are elements of C too. Suppose that the characteristic of k is not 2, which implies that

$$\phi_\alpha(h_\alpha) \neq 0. \tag{22.12.5}$$

In particular, $x_\alpha, y_\alpha, h_\alpha \neq 0$, and their linear span in A is a Lie subalgebra of A that is isomorphic to $sl_2(k)$, as a Lie algebra over k. Remember that this Lie subalgebra is not solvable in this case. It follows that C is not solvable as a Lie algebra over k.

Equivalently, if the characteristic of k is not 2, and if C is solvable as a Lie algebra, then $A(\Phi^+ \cup \{0\}) = C$. This means that $A(\Phi^+ \cup \{0\})$ is a Borel subalgebra of A when the characteristic of k is not 2. This may be called the *standard Borel subalgebra* of A with respect to Φ, Δ, and the A_α's. This corresponds to some remarks near the top of p84 in [14], and at the bottom of p47 of [24].

22.13 Subalgebras and derivations

Let k be a commutative ring with a multiplicative identity element, and let A be an algebra over k in the strict sense, where multiplication of $x, y \in A$ is expressed as $x\,y$. If B and C are submodules of A, as a module over k, then remember that their product $B \cdot C$ is defined to be the subset of A consisting of finite sums of elements of A of the form $x\,y$, with $x \in B$ and $y \in C$. This is a submodule of A too, as a module over k, as in Section 9.2.

Let B be a submodule of A again, as a module over k, and put $B_1 = B$. If $B_1, \ldots, B_l \subseteq A$ have been defined for some positive integer l, then let $B_{l+1} \subseteq A$ be the set of finite sums of elements of $B_j \cdot B_{l+1-j}$, $j = 1, \ldots, l$. Continuing in this way, we can define B_l as a submodule of A, as a module over k, for every $l \in \mathbf{Z}_+$. Equivalently, B_l consists of finite sums of elements of A that can be expressed as the product of l elements of B, with some grouping of the factors.

Let $B_\infty \subseteq A$ be the set of finite sums of elements of B_l, $l \in \mathbf{Z}_+$. It is easy to see that B_∞ is a submodule of A as a module over k, and in fact a subalgebra of A. Of course, $B = B_1 \subseteq B_\infty$, by construction. More precisely, B_∞ is the smallest subalgebra of A that contains B. We may call B_∞ the subalgebra of A generated by B.

Let δ be a derivation on A such that

$$\delta(B) \subseteq B. \tag{22.13.1}$$

One can check that

$$\delta(B_l) \subseteq B_l \tag{22.13.2}$$

for every $l \in \mathbf{Z}_+$, by induction. This implies that

$$\delta(B_\infty) \subseteq B_\infty. \tag{22.13.3}$$

22.14 Reducibility and semigroups

Let us return to the type of situation considered in Section 22.3. Thus we let Ξ be a commutative semigroup, with the semigroup operation expressed additively, and we let Ψ be a nonempty subset of Ξ. Also let k be a commutative ring with a multiplicative identity element, and let $(A, [\cdot,\cdot]_A)$ be a Lie algebra over k. Suppose that A_α is a submodule of A, as a module over k, for each $\alpha \in \Psi$, and that A corresponds to the direct sum of the A_α's, $\alpha \in \Psi$, as a module over k. It is convenient to put $A_\alpha = \{0\}$ when $\alpha \in \Xi \setminus \Psi$, as before. We ask that $[A_\alpha, A_\beta] \subseteq A_{\alpha+\beta}$ for every $\alpha, \beta \in \Psi$, which holds trivially when α or β is in $\Xi \setminus \Psi$. If Ξ has an additive identity element 0, then it follows that A_0 is a Lie subalgebra of A.

If $\Psi_0 \subseteq \Xi$, then let $A(\Psi_0)$ be the subset of A consisting of finite sums of elements of A_α, $\alpha \in \Psi_0$, as in Section 22.4. If $(\Psi_0 + \Psi_0) \cap \Psi \subseteq \Psi_0$, then $A(\Psi_0)$ is a Lie subalgebra of A, as before.

Let Ψ_1, Ψ_2 be nonempty subsets of Ψ. If

$$(\Psi_j + \Psi_j) \cap \Psi \subseteq \Psi_j \tag{22.14.1}$$

for $j = 1, 2$, then $A(\Psi_1)$, $A(\Psi_2)$ are Lie subalgebras of A, as in the preceding paragraph. If

$$\Psi_1 \cup \Psi_2 = \Psi \tag{22.14.2}$$

and

$$\Psi_1 \cap \Psi_2 = \emptyset, \tag{22.14.3}$$

then A corresponds to the direct sum of $A(\Psi_1)$ and $A(\Psi_2)$, as a module over k. If

$$(\Psi_1 + \Psi_2) \cap \Psi = \emptyset, \tag{22.14.4}$$

then it follows that

$$[A(\Psi_1), A(\Psi_2)] = \{0\}. \tag{22.14.5}$$

If all four of these conditions hold, then A corresponds to the direct sum of $A(\Psi_1)$ and $A(\Psi_2)$, as a Lie algebra over k.

Suppose from now on in this section that Ξ has an additive identity element 0, and that $0 \in \Psi$. In this case, (22.14.2) implies that 0 is an element of Ψ_1 or Ψ_2. This means that (22.14.4) does not hold, because $\Psi_1, \Psi_2 \neq \emptyset$.

Let Φ_1, Φ_2 be nonempty subsets of

$$\Phi = \Psi \setminus \{0\}. \tag{22.14.6}$$

If $j \in \{1, 2\}$ and

$$(\Phi_j + \Phi_j) \cap \Psi \subseteq \Phi_j \cup \{0\}, \tag{22.14.7}$$

then

$$((\Phi_j \cup \{0\}) + (\Phi_j \cup \{0\})) \cap \Psi \subseteq \Phi_j \cup \{0\}, \tag{22.14.8}$$

and $A(\Phi_j \cup \{0\})$ is a Lie subalgebra of A, as before. Let

(22.14.9) A^j be the Lie subalgebra of A generated by $A(\Phi_j)$,

so that

$$A^j \subseteq A(\Phi_j \cup \{0\}) \tag{22.14.10}$$

in this situation.

If

$$(\Phi_1 + \Phi_2) \cap \Psi = \emptyset, \tag{22.14.11}$$

then

$$[A(\Phi_1), A(\Phi_2)] = \{0\}, \tag{22.14.12}$$

as before. Equivalently, this means that

$$A(\Phi_1) \subseteq C_A(A(\Phi_2)), \quad A(\Phi_2) \subseteq C_A(A(\Phi_1)). \tag{22.14.13}$$

This implies that

$$A^1 \subseteq C_A(A(\Phi_2)), \quad A^2 \subseteq C_A(A(\Phi_1)), \tag{22.14.14}$$

because the centralizer $C_A(E)$ of any $E \subseteq A$ in A is a Lie subalgebra of A, as in Section 7.6. This is the same as saying that

$$A(\Phi_2) \subseteq C_A(A^1), \quad A(\Phi_1) \subseteq C_A(A^2). \tag{22.14.15}$$

It follows that

$$A^2 \subseteq C_A(A^1), \quad A^1 \subseteq C_A(A^2), \tag{22.14.16}$$

as before, which are of course equivalent.

If $w \in A_0$, then

(22.14.17) $$\mathrm{ad}_w(A(\Phi_j)) \subseteq A(\Phi_j)$$

for $j = 1, 2$, because $\mathrm{ad}_w(A_\alpha) \subseteq A_\alpha$ for every $\alpha \in \Psi$, by hypothesis. This implies that

(22.14.18) $$\mathrm{ad}_w(A^j) \subseteq A^j$$

for $j = 1, 2$, as in the previous section, because ad_w is a derivation on A.

Let us check that

(22.14.19) $$A^j \text{ is an ideal in } A \text{ for } j = 1, 2$$

when (22.14.11) holds. Of course, this is the same as saying that the normalizer $N_A(A^j)$ of A^j in A is equal to A. By construction, $A(\Phi_j) \subseteq A^j \subseteq N_A(A^j)$ for $j = 1, 2$. Using (22.14.14), we get that $A(\Phi_2) \subseteq N_A(A^1)$ and $A(\Phi_1) \subseteq N_A(A^2)$. We also have that $A_0 \subseteq N_A(A^j)$ for $j = 1, 2$, by (22.14.18), so that $N_A(A^j) = A$, as desired.

If

(22.14.20) $$\text{for each } j = 1, 2, \text{ there is an } \alpha_j \in \Phi_j \text{ such that } A_{\alpha_j} \neq \{0\},$$

then

(22.14.21) $$A^j \neq \{0\} \text{ for } j = 1, 2.$$

If (22.14.7) holds for $j = 1, 2$, (22.14.20) holds, and

(22.14.22) $$\Phi_1 \cap \Phi_2 = \emptyset,$$

then

(22.14.23) $$A^j \neq A \text{ for } j = 1, 2,$$

by (22.14.10). If (22.14.11) holds too, and k is a field, then it follows that A is not simple as a Lie algebra, because of (22.14.19). This is related to the proposition on p73 of [14], and to part of the corollary to Theorem 9 on p50 of [24].

Note that

(22.14.24) $$A^1 \cap A^2 \subseteq A_0$$

when (22.14.7) holds for $j = 1, 2$ and (22.14.22) holds, because of (22.14.10). If (22.14.11) holds as well,

(22.14.25) $$\Phi_1 \cup \Phi_2 = \Phi,$$

and

(22.14.26) $$A_0 \text{ is commutative as a Lie algebra over } k,$$

then

(22.14.27) $$A^1 \cap A^2 \subseteq Z(A),$$

where $Z(A)$ is the center of A as a Lie algebra, as usual. More precisely, if $x \in A^1 \cap A^2$, then $[x, y]_A = 0$ for every $y \in A^1$ or A^2, by (22.14.16). This holds when $y \in A_0$ too, by (22.14.24) and (22.14.26). It follows that this holds for every $y \in A$, because of (22.14.25), as desired.

If $Z(A) = \{0\}$, then (22.14.27) implies that

$$A^1 \cap A^2 = \{0\}. \tag{22.14.28}$$

If we also have that

(22.14.29) every element of A can be expressed as the sum of elements of A^1 and A^2,

then A corresponds to the direct sum of A^1 and A^2, as a module over k. If (22.14.11) holds too, then A corresponds to the direct sum of A^1 and A^2 as a Lie algebra over k, because of (22.14.16). If (22.14.25) holds, and every element of A_0 can be expressed as a sum of elements of A^1 and A^2, then (22.14.29) holds.

If $j \in \{1, 2\}$, $\alpha, \beta \in \Phi_j$, and $\alpha + \beta = 0$, then

$$[A_\alpha, A_\beta] \subseteq A^j \cap A_0. \tag{22.14.30}$$

If (22.14.7) and (22.14.26) hold, then one can check that set of elements of A that can be expressed as finite sums of elements of $A(\Phi_j)$ and $[A_\alpha, A_\beta]$ with $\alpha, \beta \in \Phi_j$ and $\alpha + \beta = 0$ is a Lie subalgebra of A. It follows that this is the same as A^j in this case.

22.15 Reducibility and roots

Let V be a vector space over the real numbers of positive finite dimension, and let Φ be a root system in V. Also let Θ be the subgroup of V, as a group with respect to addition, generated by Φ. We would like to consider situations like those in the previous section, with $\Xi = \Theta$ and $\Psi = \Phi \cup \{0\}$. Thus we let k, A, and A_α be as before.

Suppose that Φ is reducible as a root system in V, as in Section 20.4. Thus V is the direct sum of two nontrivial linear subspaces V_1 and V_2, as a vector space over $\mathbf{R}$, and

$$\Phi \subseteq V_1 \cup V_2. \tag{22.15.1}$$

Put $\Phi_j = \Phi \cap V_j$ for $j = 1, 2$, so that $\Phi = \Phi_1 \cup \Phi_2$. If $\alpha \in \Phi_1$ and $\beta \in \Phi_2$, then $\alpha \neq \beta$, because $V_1 \cap V_2 = \{0\}$, and

$$\alpha + \beta \notin \Phi \cup \{0\}, \tag{22.15.2}$$

because $\alpha + \beta \notin V_1 \cup V_2$. This means that (22.14.7), (22.14.11), (22.14.22), and (22.14.25) hold in this situation.

If $j \in \{1, 2\}$ and $\alpha \in \Phi_j$, then $-\alpha \in \Phi_j$, and

$$[A_\alpha, A_{-\alpha}] \subseteq A^j \cap A_0, \tag{22.15.3}$$

as in (22.14.30). Suppose from now on in this section that A_0 is commutative as a Lie algebra over k, as in (22.14.26). This implies that the set of elements of

A that can be expressed as finite sums of elements of $A(\Phi_j)$ and $[A_\alpha, A_{-\alpha}]$ with $\alpha \in \Phi_j$ is a Lie subalgebra of A, as in the previous section. This Lie subalgebra is the same as A^j under these conditions, as before.

We can describe A^j, $j = 1, 2$, more precisely with some additional conditions, as in Section 22.11. Suppose that for each $\alpha \in \Phi$, there is an $h_\alpha \in A_0$ such that $[A_\alpha, A_{-\alpha}]$ is the set of multiples of h_α by elements of k, as before. This means that A^j consists of sums of elements of $A(\Phi_j)$ and linear combinations of the h_α's, $\alpha \in \Phi_j$, with coefficients in k, for $j = 1, 2$.

Let Δ_1 and Δ_2 be bases for Φ_1 and Φ_2 in V_1 and V_2, respectively. This implies that $\Delta_1 \cup \Delta_2$ is a base for Φ, as in Section 20.4. In the situation considered in Section 22.1, k is a field, and h_α, $\alpha \in \Delta_1 \cup \Delta_2$, form a basis for A_0 as a vector space over k, as in Section 22.11. If $\alpha \in \Phi_j$ for $j = 1, 2$, then h_α can be expressed as a linear combination of h_β, $\beta \in \Delta_j$, in A_0 in this case. This follows from the fact that α can be expressed as a linear combination of the elements of Δ_j with integer coefficients, so that $t_{b,\alpha}$ can be expressed as a linear combination of $t_{b,\beta}$, $\beta \in \Delta_j$, where $t_{b,\gamma}$ is as in Section 22.1.

Under these conditions, A^j consists of sums of elements of $A(\Phi_j)$ and linear combinations of the h_α's, now with $\alpha \in \Delta_j$, for $j = 1, 2$. It follows that every element of A can be expressed in a unique way as a sum of elements of A^1 and A^2, so that A corresponds to the direct sum of A^1 and A^2, as a Lie algebra over k.

As before, this is related to the proposition on p73 of [14], and to part of the corollary to Theorem 9 on p50 of [24].

Chapter 23

Roots and Lie algebras, 2

23.1 Inverse roots and homomorphisms

Let V be a vector space over the real numbers of positive finite dimension, and let Φ be a root system in V. If $\alpha \in \Phi$, then there is a unique symmetry σ_α on V with vector α that maps Φ onto itself, as usual. Let λ_α be the linear functional on V that is equal to 0 on the hyperplane fixed by σ_α and satisfies $\lambda_\alpha(\alpha) = 2$, so that $\sigma_\alpha(v) = v - \lambda_\alpha(v)\,\alpha$ for every $v \in V$. Remember that

(23.1.1) $$\Phi' = \{\lambda_\alpha : \alpha \in \Phi\}$$

is a root system in the dual V' of V, as in Section 19.8.

Note that

(23.1.2) $$\alpha \mapsto \lambda_\alpha$$

is a one-to-one mapping from Φ onto Φ'. More precisely, if $(\cdot,\cdot)$ is an inner product on V that is invariant under the Weyl group of Φ and $\alpha \in \Phi$, then λ_α corresponds to $\widehat{\alpha} = 2\,\alpha\,(\alpha,\alpha)^{-1}$ with respect to $(\cdot,\cdot)$, and $\widehat{\widehat{\alpha}} = \alpha$. Alternatively, the symmetry on V' with vector λ_α that maps Φ' onto itself corresponds to the dual of σ_α, and the associated linear functional on V' corresponds to α in a natural way.

Let $\Theta = \Theta_\Phi$ be the subgroup of V, as a commutative group with respect to addition, generated by Φ. If Δ is a base for Φ, then Θ consists of the linear combinations of elements of Δ with coefficients in $\mathbf{Z}$.

Let $\mathrm{Hom}(\Theta, \mathbf{Z})$ be the collection of homomorphisms from Θ in $\mathbf{Z}$, as commutative groups with respect to addition. Of course, commutative groups may be considered as modules over $\mathbf{Z}$, and group homomorphisms between them may be considered as module homomorphisms. Thus we may also use $\mathrm{Hom}_{\mathbf{Z}}(\Theta, \mathbf{Z})$ for space of homomorphisms from Θ into $\mathbf{Z}$, as commutative groups or modules over $\mathbf{Z}$. This is a commutative group with respect to pointwise addition of functions into $\mathbf{Z}$, or equivalently a module over $\mathbf{Z}$.

Elements of $\mathrm{Hom}(\Theta, \mathbf{Z})$ are uniquely determined by their restrictions to Δ. Every $\mathbf{Z}$-valued function on Δ can be extended to a homomorphism from Θ

into $\mathbf{Z}$. Similarly, linear functionals on V are uniquely determined by their restrictions to Δ, and every real-valued function on Δ can be extended to a linear functional on V. If λ is a linear functional on V that maps Θ into $\mathbf{Z}$, then the restriction of λ to Θ defines an element of $\mathrm{Hom}(\Theta, \mathbf{Z})$. Every element of $\mathrm{Hom}(\Theta, \mathbf{Z})$ is the restriction to Θ of a unique linear functional on V that maps Θ into $\mathbf{Z}$, which can be obtained from its restriction to Δ, as before.

Thus $\mathrm{Hom}(\Theta, \mathbf{Z})$ can be identified with the set of linear functionals on V that map Θ into $\mathbf{Z}$. This is a subgroup of the dual space V', as a commutative group with respect to addition. If $\alpha \in \Phi$, then λ_α maps Φ into $\mathbf{Z}$, by the definition of a root system. This means that λ_α maps Θ into $\mathbf{Z}$, so that the restriction of λ_α to Θ is an element of $\mathrm{Hom}(\Theta, \mathbf{Z})$.

Let $\Theta_{\Phi'}$ be the subgroup of V', as a commutative group with respect to addition, generated by Φ'. Note that every element of $\Theta_{\Phi'}$ maps Θ into $\mathbf{Z}$, so that its restriction to Θ is an element of $\mathrm{Hom}(\Theta, \mathbf{Z})$.

As before, $\Theta_{\Phi'}$ consists of linear combinations of elements of a base for Φ' with coefficients in $\mathbf{Z}$. If Φ is reduced as a root system in V, then

$$\Delta' = \{\lambda_\alpha : \alpha \in \Delta\} \tag{23.1.3}$$

is a base for Φ', as in Section 19.13.

In the types of situations considered in Section 22.11, one can ask for a homomorphism from $\Theta_{\Phi'}$ into A_0, as commutative groups with respect to addition, that sends λ_α to h_α for every $\alpha \in \Phi$. In particular, this happens in the type of situation considered in Section 22.1, as in Section 22.2.

23.2 Bases and submodules

Let us return to the type of situation considered in Section 22.6, and look at some additional properties related to a base for the root system. Thus we let V be a vector space over the real numbers of positive finite dimension, and let Φ be a root system in V. Also let Δ be a base for Φ, and let $\Phi^+ = \Phi^{\Delta,+}$ be the set of positive roots in Φ with respect to Δ. Let Θ be the subgroup of V, as a commutative group with respect to addition, generated by Φ, as before. Of course, this is the same as the subgroup of V generated by Δ.

Let k be a commutative ring with a multiplicative identity element, and let $(A, [\cdot,\cdot]_A)$ be a Lie algebra over k. Suppose that A_α is a submodule of A, as a module over k, for each $\alpha \in \Phi \cup \{0\}$, and that A corresponds to the direct sum of the A_α's, as a module over k. Put $A_\alpha = \{0\}$ when $\alpha \in \Theta \setminus (\Phi \cup \{0\})$, as before, and suppose that $[A_\alpha, A_\beta] \subseteq A_{\alpha+\beta}$ for every $\alpha, \beta \in \Theta$. Of course, this implies that

$$[A_\alpha, A_{-\alpha}] \subseteq A_0 \tag{23.2.1}$$

for every $\alpha \in \Theta$. In particular, A_0 is a Lie subalgebra of A, as before.

If $\alpha, \beta \in \Delta$, then $\alpha - \beta \not\in \Phi$, by the definition of a base for a root system. If $\alpha \neq \beta$ too, then $\alpha - \beta \not\in \Phi \cup \{0\}$, so that

$$[A_\alpha, A_{-\beta}] = \{0\}. \tag{23.2.2}$$

This corresponds to part of the proposition on p96 of [14], and part of part (b) of Theorem 6 on p48 of [24].

If $\alpha \in \Phi$, then let σ_α be the symmetry on V with vector α that maps Φ onto itself, and let λ_α be the corresponding linear functional on V, so that $\sigma_\alpha(v) = v - \lambda_\alpha(v)\,\alpha$ for every $v \in V$. Let $\alpha, \beta \in \Delta$ be given, with $\alpha \neq \beta$. Remember that $\lambda_\alpha(\beta) \in \mathbf{Z}$, by definition of a root system, and that $\lambda_\alpha(\beta) \leq 0$ in this case, as in Section 20.2. Observe that

$$\beta - \lambda_\alpha(\beta)\,\alpha + \alpha = \sigma_\alpha(\beta - \alpha), \tag{23.2.3}$$

because $\sigma_\alpha(\alpha) = -\alpha$. This implies that

$$\beta - \lambda_\alpha(\beta)\,\alpha + \alpha \in \Theta \setminus (\Phi \cup \{0\}), \tag{23.2.4}$$

because $\lambda_\alpha(\beta) \in \mathbf{Z}$ and $\alpha - \beta \notin \Phi \cup \{0\}$, as before. It follows that

$$A_{\beta - \lambda_\alpha(\beta)\,\alpha + \alpha} = \{0\} \tag{23.2.5}$$

under these conditions. Similarly,

$$-\beta - \lambda_\alpha(\beta)\,(-\alpha) - \alpha = -(\beta - \lambda_\alpha(\beta)\,\alpha + \alpha) \in \Theta \setminus (\Phi \cup \{0\}), \tag{23.2.6}$$

so that

$$A_{-\beta - \lambda_\alpha(\beta)\,(-\alpha) - \alpha} = \{0\}. \tag{23.2.7}$$

This corresponds to another part of the proposition on p96 of [14], and to part (c) of Theorem 6 on p48 of [24].

Let $\alpha, \beta \in \Theta$ be given, so that

$$[[A_\alpha, A_\beta], A_{-\alpha-\beta}] \subseteq [A_{\alpha+\beta}, A_{-\alpha-\beta}] \subseteq A_0. \tag{23.2.8}$$

Using the Jacobi identity, we get that

$$[[A_\alpha, A_\beta], A_{-\alpha-\beta}] \subseteq [[A_\beta, A_{-\alpha-\beta}], A_\alpha] + [[A_{-\alpha-\beta}, A_\alpha], A_\beta]. \tag{23.2.9}$$

This implies that

$$[[A_\alpha, A_\beta], A_{-\alpha-\beta}] \subseteq [A_\alpha, A_{-\alpha}] + [A_\beta, A_{-\beta}]. \tag{23.2.10}$$

23.3 Some generating submodules

Let us continue with the same notation and hypotheses as in the previous section. If $\Psi_0 \subseteq \Theta$, then let $A(\Psi_0)$ be the subset of A consisting of finite sums of elements of A_α, $\alpha \in \Psi_0$, as before. This is a submodule of A, as a module over k.

Suppose that for each $\alpha \in \Delta$ and $\beta \in \Phi^+$ with $\alpha + \beta \in \Phi$ we have that

$$[A_\alpha, A_\beta] = A_{\alpha+\beta}. \tag{23.3.1}$$

Of course, $\alpha + \beta \in \Phi^+$ in this case. This condition holds in the situation considered in Section 22.1, as in Section 17.9. Note that $\alpha + \beta \neq 0$ when α, β are elements of Φ^+, because of the nonnegativity of the coefficients of α and β when expressed as linear combinations of elements of Δ. If $\alpha + \beta \notin \Phi$, then $A_{\alpha+\beta} = \{0\}$, by construction, and (23.3.1) holds automatically, by hypothesis.

Let $\beta \in \Phi^+$ be given, and remember that β can be expressed as $\sum_{j=1}^{r} \alpha_j$ for some $\alpha_1, \ldots, \alpha_r \in \Delta$, where

$$\beta_l = \sum_{j=1}^{l} \alpha_j \in \Phi \tag{23.3.2}$$

for each $l = 1, \ldots, r$, as in Section 19.12. If $l < r$, then we get that

$$A_{\beta_{l+1}} = [A_{\alpha_{l+1}}, A_{\beta_l}], \tag{23.3.3}$$

as in (23.3.1), because $\beta_l \in \Phi^+$.

Remember that $A(\Phi^+)$ is a Lie subalgebra of A, as in Section 22.6. If (23.3.1) holds for every $\alpha \in \Delta$ and $\beta \in \Phi^+$ with $\alpha + \beta \in \Phi$, then

(23.3.4) $A(\Phi^+)$ is generated by the submodules A_α, $\alpha \in \Delta$, as a Lie algebra over k.

More precisely, if $\beta \in \Phi^+$, then one can use (23.3.3) to get that A_β is contained in the Lie subalgebra of A generated by A_α, $\alpha \in \Delta$. This corresponds to part of the proof of the proposition on p74 of [14], and is related to part of part (a) of Theorem 6 on p48 of [24].

Similarly, suppose that

$$[A_{-\alpha}, A_{-\beta}] = A_{-\alpha-\beta} \tag{23.3.5}$$

for every $\alpha \in \Delta$ and $\beta \in \Phi^+$ with $\alpha + \beta \in \Phi$. This also holds in the situation considered in Section 22.1, as in Section 17.9. If $\alpha+\beta \notin \Phi$, then $-\alpha-\beta \notin \Phi$, so that $A_{-\alpha-\beta} = \{0\}$, and (23.3.5) holds automatically, by hypothesis. If $\beta \in \Phi^+$, and $\alpha_1, \ldots, \alpha_r \in \Delta$, $\beta_l \in \Phi^+$ are as in (23.3.2), then we get that

$$A_{-\beta_{l+1}} = [A_{-\alpha_{l+1}}, A_{-\beta_l}] \tag{23.3.6}$$

when $l < r$.

We also have that $A(-\Phi^+)$ is a Lie subalgebra of A, as in Section 22.6 again. If (23.3.5) holds for every $\alpha \in \Delta$ and $\beta \in \Phi^+$ with $\alpha + \beta \in \Phi$, then

(23.3.7) $A(-\Phi^+)$ is generated by the submodules $A_{-\alpha}$, $\alpha \in \Delta$, as a Lie algebra over k.

This can be obtained from (23.3.6), as before. This corresponds to another part of the proof of the proposition on p74 of [14], and is related to another part of part (a) of Theorem 6 on p48 of [24].

If $\alpha \in \Delta$, $\beta \in \Phi^+$, and (23.3.1) holds, then

$$[A_{\alpha+\beta}, A_{-\alpha-\beta}] \subseteq [A_\alpha, A_{-\alpha}] + [A_\beta, A_{-\beta}], \tag{23.3.8}$$

by (23.2.10). Suppose that (23.3.1) holds for every $\alpha \in \Delta$ and $\beta \in \Phi^+$ with $\alpha + \beta \in \Phi$ again. If $\beta \in \Phi^+$, then

(23.3.9) $[A_\beta, A_{-\beta}]$ is contained in the submodule of A_0 generated by $[A_\alpha, A_{-\alpha}]$, $\alpha \in \Delta$, as a module over k.

To see this, one can express β as in (23.3.2) with $l = r$, as before. If $l < r$, then

$$[A_{\beta_{l+1}}, A_{-\beta_{l+1}}] \subseteq [A_{\alpha_{l+1}}, A_{-\alpha_{l+1}}] + [A_{\beta_l}, A_{-\beta_l}], \tag{23.3.10}$$

by (23.3.3) and (23.3.8). One can use this repeatedly to get (23.3.9). Of course, one can use an analogous argument when (23.3.5) holds for every $\alpha \in \Delta$ and $\beta \in \Phi^+$ with $\alpha + \beta \in \Phi$, instead of (23.3.1).

In the situation considered in Section 22.1,

(23.3.11) A_0 is generated by $[A_\alpha, A_{-\alpha}]$, $\alpha \in \Phi^+$, as a module over k.

as in (22.11.7). More precisely,

(23.3.12) A_0 is generated by $[A_\alpha, A_{-\alpha}]$, $\alpha \in \Delta$, as a module over k.

in this case, as in (22.11.8). If (23.3.9) holds for every $\beta \in \Phi^+$, then (23.3.11) implies (23.3.12).

Suppose that (23.3.1) and (23.3.5) hold for every $\alpha \in \Delta$ and $\beta \in \Phi^+$ with $\alpha + \beta \in \Phi$. If (23.3.11) holds too, then we get that

(23.3.13) A is generated by the submodules A_α and $A_{-\alpha}$, $\alpha \in \Delta$, as a Lie algebra over k.

This corresponds to the proposition on p74 of [14], which is related to another part of part (a) of Theorem 6 on p48 of [24].

23.4 Some generators

Let us continue with the same notation and basic hypotheses as in the previous two sections. Suppose now that for each $\alpha \in \Delta$, there is an $x_\alpha \in A_\alpha$ such that

(23.4.1) A_α is generated by x_α as a module over k,

so that every element of A_α can be expressed as a multiple of x_α by an element of k. This holds in the situation considered in Section 22.1, as in Section 17.7. If $\alpha \in \Delta$ and $\beta \in \Phi^+$ satisfy $\alpha + \beta \in \Phi$, then (23.3.1) is the same as saying that

$$\mathrm{ad}_{x_\alpha}(A_\beta) = A_{\alpha+\beta}. \tag{23.4.2}$$

Suppose that this holds for all such α and β, let $\beta \in \Phi^+$ be given, and let $\alpha_1, \ldots, \alpha_r \in \Delta$ be as before, so that (23.3.2) holds for every $l = 1, \ldots, r$, and $\beta_r = \beta$. If $l < r$, then

(23.4.3) $$A_{\beta_{l+1}} = \mathrm{ad}_{x_{\alpha_{l+1}}}(A_{\beta_l}),$$

by (23.4.2). This implies that A_{β_l} is generated by a single element as a module over k for each $l = 1, \ldots, r$. In particular, A_β is generated by a single element, as a module over k, because $\beta = \beta_r$.

In this situation, (23.3.4) is the same as saying that

(23.4.4) $A(\Phi^+)$ is generated by x_α, $\alpha \in \Delta$, as a Lie algebra over k.

This corresponds to part of part (a) of Theorem 6 on p48 of [24].

Similarly, suppose that for each $\alpha \in \Delta$ there is a $y_\alpha \in A_{-\alpha}$ such that

(23.4.5) $A_{-\alpha}$ is generated by y_α as a module over k.

This holds in the situation considered in Section 22.1, as in Section 17.7 again. If $\alpha \in \Delta$, $\beta \in \Phi^+$, and $\alpha + \beta \in \Phi$, then (23.3.5) is the same as saying that

(23.4.6) $$\mathrm{ad}_{y_\alpha}(A_{-\beta}) = A_{-\alpha-\beta}.$$

If this holds for all such α and β, then we get that $A_{-\beta}$ is generated by a single element as a module over k for every $\beta \in \Phi^+$, as before.

In this case, (23.3.7) is the same as saying that

(23.4.7) $A(-\Phi^+)$ is generated by y_α, $\alpha \in \Delta$, as a Lie algebra over k.

This corresponds to another part of part (a) of Theorem 6 on p48 of [24].

Suppose that (23.4.1) and (23.4.5) hold for every $\alpha \in \Delta$, so that

(23.4.8) $[A_\alpha, A_{-\alpha}]$ is generated by $[x_\alpha, y_\alpha]_A$ as a module over k

for every $\alpha \in \Delta$. In this situation, (23.3.12) is the same as saying that

(23.4.9) A_0 is generated by $[x_\alpha, y_\alpha]_A$, $\alpha \in \Delta$, as a module over k.

If (23.4.2) and (23.4.6) hold for every $\alpha \in \Delta$ and $\beta \in \Phi^+$ with $\alpha + \beta \in \Phi$, and if (23.4.9) holds, then we get that

(23.4.10) A is generated by x_α and y_α, $\alpha \in \Delta$, as a Lie algebra over k.

This corresponds to the second formulation of the proposition on p74 of [14], and to another part of part (a) of Theorem 6 on p48 of [24].

23.5 Some relations

Let us continue with the same notation and basic hypotheses as in the previous three sections. If $\alpha \in \Phi$, then let σ_α be the symmetry on V with vector α that maps Φ onto itself, and let λ_α be the corresponding linear functional on V. Thus λ_α is equal to 0 on the hyperplane fixed by σ_α and satisfies $\lambda_\alpha(\alpha) = 2$, so that $\sigma_\alpha(v) = v - \lambda_\alpha(v)\,\alpha$ for every $v \in V$. Suppose that ϕ is a group homomorphism from Θ into $\mathrm{Hom}_k(A_0, k)$, as a commutative group with respect to addition, such that $\mathrm{ad}_w(x) = \phi_\alpha(w)\,x$ for every $w \in A_0$ and $x \in A_\alpha$, $\alpha \in \Phi \cup \{0\}$, where $\phi_\alpha = \phi(\alpha)$, as before. In particular, this means that A_0 is commutative as a Lie subalgebra of A.

Suppose that for each $\alpha \in \Delta$, $x_\alpha \in A_\alpha$ and $y_\alpha \in A_{-\alpha}$, and put

$$h_\alpha = [x_\alpha, y_\alpha]_A \tag{23.5.1}$$

which is an element of A_0. We also suppose that

$$\phi_\beta(h_\alpha) = \lambda_\alpha(\beta) \cdot 1 \tag{23.5.2}$$

in k for every $\alpha \in \Delta$ and $\beta \in \Phi$. Remember that $\lambda_\alpha(\beta) \in \mathbf{Z}$ for every $\alpha, \beta \in \Phi$. In the situation considered in Section 22.1, we can choose x_α, y_α so that (23.5.1) satisfies (23.5.2), as in Section 22.11. These choices of x_α and y_α satisfy the other conditions mentioned in the previous section in that situation too, as before.

If $\alpha, \beta \in \Delta$, then

$$[h_\alpha, h_\beta]_A = 0, \tag{23.5.3}$$

because A_0 is commutative as a Lie algebra over k. If $\alpha \neq \beta$, then

$$[x_\alpha, y_\beta]_A = 0, \tag{23.5.4}$$

as in (23.2.2). We also have that

$$[h_\alpha, x_\beta]_A = \phi_\beta(h_\alpha)\,x_\beta = \lambda_\alpha(\beta) \cdot x_\beta \tag{23.5.5}$$

for every $\alpha, \beta \in \Delta$, using (23.5.2) and the fact that $x_\beta \in A_\beta$, by construction. Similarly,

$$[h_\alpha, y_\beta]_A = \phi_{-\beta}(h_\alpha)\,y_\beta = -\lambda_\alpha(\beta) \cdot y_\beta \tag{23.5.6}$$

for every $\alpha, \beta \in \Delta$, because $y_\beta \in A_{-\beta}$. These relations, including (23.5.1), are called the *Weyl relations*, as in part (b) of Theorem 6 on p48 of [24].

Let $\alpha, \beta \in \Delta$ be given, with $\alpha \neq \beta$. Remember that $\lambda_\alpha(\beta) \leq 0$, as in Section 20.2. Observe that

$$\mathrm{ad}_{x_\alpha}^{-\lambda_\alpha(\beta)+1}(x_\beta) = 0, \tag{23.5.7}$$

by (23.2.5). Similarly,

$$\mathrm{ad}_{y_\alpha}^{-\lambda_\alpha(\beta)+1}(y_\beta) = 0, \tag{23.5.8}$$

by (23.2.7). This corresponds to part (c) of Theorem 6 on p48 of [24], and the Weyl relations together with these additional relations are in the proposition on p96 of [14].

23.6 Isomorphisms and diagonalizability

Let k be a field, and let $(A_1, [\cdot,\cdot]_{A_1})$ and $(A_2, [\cdot,\cdot]_{A_2})$ be finite-dimensional Lie algebras over k. Also let T be a Lie algebra isomorphism from A_1 onto A_2. Suppose that B_1 is a Lie subalgebra of A_1 such that every element of B_1 is ad-diagonalizable as an element of A_1. This implies that B_1 is commutative as a Lie algebra over k, as in Section 17.1. It follows that

$$B_2 = T(B_1) \tag{23.6.1}$$

has the analogous properties in A_2.

Let B_1', B_2' be the duals of B_1, B_2, respectively, as vector spaces over k. The restriction T_B of T to B_1 is a one-to-one linear mapping from B_1 onto B_2. If $\alpha_2 \in B_2'$, then

$$T_B'(\alpha_2) = \alpha_2 \circ T_B \in B_1', \tag{23.6.2}$$

as usual. This defines the dual linear mapping T_B' from B_2' into B_1'. More precisely, T_B' is a one-to-one mapping from B_2' onto B_1' in this situation.

If $\alpha_j \in B_j'$, $j = 1, 2$, then let A_{j,α_j} be the set of $x_j \in A_j$ such that

$$\mathrm{ad}_{A_j, w_j}(x_j) = [w_j, x_j]_{A_j} = \alpha_j(w_j)\, x_j \tag{23.6.3}$$

for every $w_j \in B_j$, as before. Thus A_{j,α_j} is a linear subspace of A_j, as a vector space over k. Observe that $x_1 \in A_1$, $w_1 \in B_1$, and $\alpha_1 \in B_1'$ satisfy

$$[w_1, x_1]_{A_1} = \alpha_1(w_1)\, x_1 \tag{23.6.4}$$

exactly when

$$[T(w_1), T(x_1)]_{A_2} = \alpha_1(w_1)\, T(x_1). \tag{23.6.5}$$

Let $\alpha_2 \in B_2'$ be given, and let us apply this to $\alpha_1 = T_B'(\alpha_2)$. This implies that $x_1 \in A_1$ and $w_1 \in B_1$ satisfy

$$[w_1, x_1]_{A_1} = (T_B'(\alpha_2))(w_1)\, x_1 \tag{23.6.6}$$

exactly when

$$[T(w_1), T(x_1)]_{A_2} = \alpha_2(T(w_1))\, T(x_1), \tag{23.6.7}$$

because $(T_B'(\alpha_2))(w_1) = \alpha_2(T_B(w_1)) = \alpha_2(T(w_1))$.

Using this, it is easy to see that

$$T(A_{1,T_B'(\alpha_2)}) = A_{2,\alpha_2} \tag{23.6.8}$$

for every $\alpha_2 \in B_2'$. Put

$$\Phi_{j,B_j} = \{\alpha_j \in B_j' : \alpha_j \neq 0 \text{ and } A_{j,\alpha_j} \neq \{0\}\} \tag{23.6.9}$$

for $j = 1, 2$, as before. It follows that

$$T_B'(\Phi_{2,B_2}) = \Phi_{1,B_1}, \tag{23.6.10}$$

by (23.6.8). Remember that Φ_{j,B_j} has finitely many elements, as in Section 17.2.

Suppose now that k has characteristic 0. Let $E_{j,\mathbf{Q}}$ be the linear subspace of B_j', as a vector space over $\mathbf{Q}$, spanned by Φ_{j,B_j} for $j = 1, 2$, as before. Using (23.6.10), we get that

(23.6.11) $$T_B'(E_{2,\mathbf{Q}}) = E_{1,\mathbf{Q}}.$$

Thus the restriction of T_B' to $E_{2,\mathbf{Q}}$ is a one-to-one mapping onto $E_{1,\mathbf{Q}}$ that is linear over $\mathbf{Q}$.

Let $E_{j,\mathbf{R}}$ be the vector space over $\mathbf{R}$ obtained from $E_{j,\mathbf{Q}}$ as in Section 17.13, for $j = 1, 2$. More precisely, $E_{j,\mathbf{Q}}$ corresponds to a linear subspace of $E_{j,\mathbf{R}}$, as a vector space over $\mathbf{Q}$, and any basis for $E_{j,\mathbf{Q}}$, as a vector space over $\mathbf{Q}$, is also a basis for $E_{j,\mathbf{R}}$, as a vector space over $\mathbf{R}$. The restriction of T_B' to $E_{2,\mathbf{Q}}$ leads to a one-to-one mapping from $E_{2,\mathbf{R}}$ onto $E_{1,\mathbf{R}}$ that is linear over $\mathbf{R}$. This mapping agrees with T_B' on $E_{2,\mathbf{Q}}$, and in particular maps Φ_{2,B_2} onto Φ_{1,B_1}.

If Φ_{1,B_1} is a root system in $E_{1,\mathbf{R}}$, then Φ_{2,B_2} is a root system in $E_{2,\mathbf{R}}$. In this case, the linear mapping from $E_{2,\mathbf{R}}$ onto $E_{1,\mathbf{R}}$ obtained from T_B' as in the preceding paragraph is an isomorphism between these root systems. Remember that Φ_{j,B_j} is a root system in $E_{j,\mathbf{R}}$ when A_j, B_j satisfy the conditions in Section 22.1.

23.7 Automorphisms and $sl_2(k)$

Let k be a field of characteristic 0, and let $(A, [\cdot,\cdot]_A)$ be a finite-dimensional Lie algebra over k. If $w \in A$ is ad-nilpotent, then the exponential of ad_w defines a Lie algebra automorphism of A, as in Section 14.11. If $u \in A$ and $[w, u]_A = 0$, then it is easy to see that

(23.7.1) $$(\exp \mathrm{ad}_w)(u) = u.$$

Let x, y be elements of A, and put

(23.7.2) $$h = [x, y]_A.$$

Suppose that

(23.7.3) $$[h, x]_A = 2 \cdot x, \quad [h, y]_A = -2 \cdot y.$$

Let C be the linear span of x, y, and h in A, which is a Lie subalgebra of A that is isomorphic to $sl_2(k)$, as a Lie algebra over k. Using (23.7.3), we get that x and y are ad-nilpotent as elements of A, as in Section 14.2. More precisely, this uses the adjoint representation of A.

Of course, $-y$ is ad-nilpotent as an element of A too. Thus the exponentials of ad_x and $-\mathrm{ad}_y$ define Lie algebra automorphisms on A, as before. It follows that

(23.7.4) $$\theta = (\exp \mathrm{ad}_x) \circ (\exp -\mathrm{ad}_y) \circ (\exp \mathrm{ad}_x)$$

is a Lie algebra automorphism on A too. If $u \in A$ satisfies

(23.7.5) $$[x, u]_A = [y, u]_A = 0,$$

then

(23.7.6) $$(\exp \mathrm{ad}_x)(u) = (\exp -\mathrm{ad}_y)(u) = u,$$

as in (23.7.1). This implies that

(23.7.7) $$\theta(u) = u.$$

Clearly ad_x and ad_y map C into itself, because C is a Lie subalgebra of A that contains x and y. The restrictions of $\mathrm{ad}_x = \mathrm{ad}_{A,x}$ and $\mathrm{ad}_y = \mathrm{ad}_{A,y}$ to C are the same as $\mathrm{ad}_{C,x}$ and $\mathrm{ad}_{C,y}$, respectively, corresponding to the adjoint representation on C. It is easy to see that the restrictions of $\exp \mathrm{ad}_x = \exp \mathrm{ad}_{A,x}$ and $\exp(-\mathrm{ad}_y) = \exp(-\mathrm{ad}_{A,y})$ to C are the same as $\exp \mathrm{ad}_{C,x}$ and $\exp(-\mathrm{ad}_{C,y})$. This means that the restriction of θ to C is the same as

(23.7.8) $$(\exp \mathrm{ad}_{C,x}) \circ (\exp -\mathrm{ad}_{C,y}) \circ (\exp \mathrm{ad}_{C,x}).$$

Using this, we get that

(23.7.9) $$\theta(x) = -y, \quad \theta(y) = -x, \quad \theta(h) = -h.$$

More precisely, we can take θ to be as in (23.7.8) here, as in the preceding paragraph. This permits one to obtain (23.7.9) as in Section 15.7, because C is isomorphic to $sl_2(k)$ as a Lie algebra over k, with its usual basis. Note that (23.7.4) is an inner automorphism of A, as in Section 14.11.

23.8 Automorphisms and roots

Let k be a field of characteristic 0 again, and let $(A, [\cdot,\cdot]_A)$ be a finite-dimensional Lie algebra over k. Also let B be a Lie subalgebra of A, all of whose elements are ad-diagonalizable as elements of A. If α is an element of the dual B' of B, as a vector space over k, then we let A_α be the set of $x \in A$ such that $[w, x]_A = \alpha(w)\, x$ for every $w \in B$, as before. The set of $\alpha \in B'$ such that $\alpha \neq 0$ and $A_\alpha \neq \{0\}$ is denoted Φ_B, as usual.

Let $\alpha \in \Phi_B$ be given, and suppose that $x_\alpha \in A_\alpha$ and $y_\alpha \in A_{-\alpha}$ have the property that $h_\alpha = [x_\alpha, y_\alpha]_A$ satisfies $\alpha(h_\alpha) = 2$. Thus $[h_\alpha, x_\alpha]_A = \alpha(h_\alpha)\, x_\alpha = 2\, x_\alpha$, and $[h_\alpha, y_\alpha]_A = -\alpha(h_\alpha)\, y_\alpha = -2\, y_\alpha$. In particular, x_α and y_α are ad-nilpotent as elements of A, as in Sections 14.2 and 17.2. This implies that $-y_\alpha$ is ad-nilpotent as an element of A, and that the exponentials of ad_{x_α} and $-\mathrm{ad}_{y_\alpha}$ define Lie algebra automorphisms of A, as in Section 14.11. Note that there are such x_α, y_α in the situation considered in Section 22.1, as in Section 17.6.

Put

(23.8.1) $$\theta_\alpha = (\exp \mathrm{ad}_{x_\alpha}) \circ (\exp -\mathrm{ad}_{y_\alpha}) \circ (\exp \mathrm{ad}_{x_\alpha}),$$

which defines a Lie algebra automorphism on A. If $u \in A$ satisfies $[x_\alpha, u]_A = [y_\alpha, u]_A = 0$, then

(23.8.2) $$\theta_\alpha(u) = u,$$

as in the previous section. In particular, this holds for every $u \in B$ with $\alpha(u) = 0$, because $x_\alpha \in A_\alpha$ and $y_\alpha \in A_{-\alpha}$. We also have that

$$\theta_\alpha(h_\alpha) = -h_\alpha, \tag{23.8.3}$$

as before. This implies that

$$\theta_\alpha(B) = B, \tag{23.8.4}$$

because B is spanned by the kernel of α and h_α.

Let $\theta_{\alpha,B}$ be the restriction of θ_α to B, which is a one-to-one linear mapping from B onto itself. If $\beta \in B'$, then

$$\theta'_{\alpha,B}(\beta) = \beta \circ \theta_{\alpha,B} \in B', \tag{23.8.5}$$

and $\theta'_{\alpha,B}$ is a one-to-one linear mapping from B' onto itself. As in Section 23.6,

$$\theta_\alpha(A_{\theta'_{\alpha,B}(\beta)}) = A_\beta \tag{23.8.6}$$

for every $\beta \in B'$. This implies that

$$\theta'_{\alpha,B}(\Phi_B) = \Phi_B, \tag{23.8.7}$$

as before.

It is easy to see that

$$\theta_\alpha(u) = u - \alpha(u)\, h_\alpha \tag{23.8.8}$$

for every $u \in B$, using (23.8.2), (23.8.3), and the fact that $\alpha(h_\alpha) = 2$. If $\beta \in B'$, then we get that

$$\theta'_{\alpha,B}(\beta) = \beta - \beta(h_\alpha)\, \alpha. \tag{23.8.9}$$

Let $E_{\mathbf{Q}}$ be the linear subspace of B', as a vector space over $\mathbf{Q}$, spanned by Φ_B, as before. Thus

$$\theta'_{\alpha,B}(E_{\mathbf{Q}}) = E_{\mathbf{Q}}, \tag{23.8.10}$$

as in Section 23.6, by (23.8.7).

Suppose that for each $\beta \in \Phi_B$, $\beta(h_\alpha)$ corresponds to an element of $\mathbf{Q}$ with respect to the standard embedding into k, which holds in the situation considered in Section 22.1. This implies that $\beta(h_\alpha)$ is in the image of $\mathbf{Q}$ in k when $\beta \in E_{\mathbf{Q}}$, by definition of $E_{\mathbf{Q}}$. Let λ_α be the linear functional on $E_{\mathbf{Q}}$, as a vector space over $\mathbf{Q}$, corresponding to $\beta \mapsto \beta(h_\alpha)$. If $\beta \in E_{\mathbf{Q}}$, then (23.8.9) can be expressed as

$$\theta'_{\alpha,B}(\beta) = \beta - \lambda_\alpha(\beta)\, \alpha. \tag{23.8.11}$$

Let $E_{\mathbf{R}}$ be the vector space over $\mathbf{R}$ obtained from $E_{\mathbf{Q}}$ as in Sections 17.13 and 23.6, so that $E_{\mathbf{Q}}$ corresponds to a linear subspace of $E_{\mathbf{R}}$, as a vector space over $\mathbf{Q}$, and any basis for $E_{\mathbf{Q}}$, as a vector space over $\mathbf{Q}$, is a basis for $E_{\mathbf{R}}$ too, as a vector space over $\mathbf{R}$. The restriction of $\theta'_{\alpha,B}$ to $E_{\mathbf{Q}}$ leads to a one-to-one mapping from $E_{\mathbf{R}}$ onto itself that is linear over $\mathbf{R}$, as in Section 23.6.

There is a natural extension of λ_α to a linear functional on $E_{\mathbf{R}}$, that we shall denote as λ_α as well. The mapping on $E_{\mathbf{R}}$ corresponding to the restriction of $\theta'_{\alpha,B}$ to $E_{\mathbf{Q}}$ can be given by the same expression as in (23.8.11), using this extension of λ_α to $E_{\mathbf{R}}$. This defines a symmetry on $E_{\mathbf{R}}$ with vector α that maps Φ_B onto itself.

In the situation considered in Section 22.1, Φ_B is a root system in $E_{\mathbf{R}}$, and every $\alpha \in \Phi_B$ can be handled in this way. It follows that every element of the Weyl group of Φ_B corresponds to a Lie algebra automorphism of A that maps B onto itself as in Section 23.6 in this case. This corresponds to the first part of the remark on p47 of [24]. This also corresponds to some remarks on p77 of [14]. More precisely, every element of the Weyl group of Φ_B corresponds to an inner automorphism of A that maps B into itself in this way, because (23.8.1) is an inner automorphism of A, as in the previous section.

23.9 Automorphisms and bases for Φ_B

We would like to consider some conditions combining those in Section 22.12 and the previous section, and which hold in the situation described in Section 22.1, as usual. We begin as in the previous section, so that $(A, [\cdot,\cdot]_A)$ is a finite-dimensional Lie algebra over a field k of characteristic 0. Let B, A_α for $\alpha \in B'$, and Φ_B be as before. Remember that B is commutative as a Lie subalgebra of A, as in Section 17.1, and that A corresponds to the direct sum of the linear subspaces A_α, $\alpha \in \Phi_B \cup \{0\}$, as a vector space over k, as in Section 17.2. We also have that $[A_\alpha, A_\beta] \subseteq A_{\alpha+\beta}$ for every $\alpha, \beta \in B'$, as before.

Of course, $B \subseteq A_0$, because B is commutative as a Lie subalgebra of A. We ask that $B = A_0$, which will be compatible with Section 22.12. This is the same as saying that B is equal to its centralizer in A, as usual.

Suppose that for each $\alpha \in \Phi_B$, we have elements x_α of A_α and y_α of $A_{-\alpha}$ such that $h_\alpha = [x_\alpha, y_\alpha]_A$ satisfies $\alpha(h_\alpha) = 2$, as in the previous section. Suppose also that A_α, $A_{-\alpha}$ are spanned by x_α, y_α, respectively, as in Section 22.12.

Let $E_{\mathbf{Q}}$ be the linear subapce of B', as a vector space over $\mathbf{Q}$, spanned by Φ_B, and let $E_{\mathbf{R}}$ be the vector space over $\mathbf{R}$ obtained from $E_{\mathbf{Q}}$ in the usual way, as in the previous section. Suppose that for each $\alpha, \beta \in \Phi_B$, $\beta(h_\alpha)$ corresponds to an element of $\mathbf{Q}$ with respect to the standard embedding into k, as in the previous section. If $\alpha \in \Phi_B$, then we get a linear functional λ_α on $E_{\mathbf{Q}}$, as a vector space over $\mathbf{Q}$, corresponding to $\beta \mapsto \beta(h_\alpha)$, as before. This has a natural extension to a linear functional on $E_{\mathbf{R}}$, which is denoted λ_α too, as before. This can be used to get a symmetry on $E_{\mathbf{R}}$ with vector α that maps Φ_B onto itself, as in the prevous section.

We would like Φ_B to be a root system in $E_{\mathbf{R}}$. This amounts to asking that for every $\alpha, \beta \in \Phi_B$, $\beta(h_\alpha)$ corresponds to an integer with respect to the standard embedding into k, so that $\lambda_\alpha(\beta) \in \mathbf{Z}$. Under these conditions, we can take $V = E_{\mathbf{R}}$ and $\Phi = \Phi_B$ in Section 22.12.

If Θ is the subgroup of $E_{\mathbf{R}}$, as a commutative group with respect to addition, generated by Φ_B, then Θ is in fact a subgroup of $E_{\mathbf{Q}}$, and thus of B'. Equivalently, Θ is a subgroup of the dual A_0' of A_0, as a vector space over k. The group homomorphism ϕ from Θ into A_0' mentioned in Section 22.12 may be taken to be the obvious inclusion mapping of Θ into A_0' here.

If $\Psi_0 \subseteq \Phi_B \cup \{0\}$, then we take $A(\Psi_0)$ to be the linear subspace of A spanned by A_α, $\alpha \in \Psi_0$, as in Section 22.12. Let Δ be a base for Φ_B, as a root system in $E_{\mathbf{R}}$. This leads to the set $\Phi_B^{\Delta,+}$ of positive roots in Φ_B with respect to Δ, which can be expressed as linear combinations of elements of Δ with nonnegative coefficients. Remember that $A(\Phi_B^{\Delta,+} \cup \{0\})$ is a solvable Lie subalgebra of A, and in fact a Borel subalgebra of A, as in Section 22.12. This may be called the standard Borel subalgebra of A associated to B and Δ, as before.

If σ is an element of the Weyl group of Φ_B, then there is an inner automorphism θ of A that corresponds to σ as in the previous section. More precisely, $\theta(B) = B$, and we let θ_B be the restriction of θ to B, which is a one-to-one linear mapping from B onto itself. If $\beta \in B'$, then $\theta_B'(\beta) = \beta \circ \theta_B \in B'$, and θ_B' is a one-to-one linear mapping from B' onto itself. As before, θ maps $A_{\theta_B'(\beta)}$ onto A_β for every $\beta \in B'$, which implies that θ_B' maps Φ_B onto itself. It follows that θ_B' maps $E_{\mathbf{Q}}$ onto itself, as in the previous section.

The restriction of θ_B' to $E_{\mathbf{Q}}$ leads to a one-to-one linear mapping from $E_{\mathbf{R}}$ onto itself, as before. We can choose θ so that this linear mapping on $E_{\mathbf{R}}$ is σ. Indeed, if $\alpha \in \Phi_B$, then the automorphism θ_α in (23.8.1) corresponds in this way to the symmetry on $E_{\mathbf{R}}$ with vector α that maps Φ_B onto itself. If σ is any element of the Weyl group of Φ, then σ can be expressed as the composition of finitely many such symmetries on $\mathbf{E_R}$. One can take θ to be the composition of the corresponding θ_α's in the other order, because the dual of a composition of linear mappings is the composition of the dual linear mappings in the other order.

If $\Psi_0 \subseteq \Phi_B \cup \{0\}$, then $\theta_B'(\Psi_0) = \sigma(\Psi_0) \subseteq \Phi_B \cup \{0\}$, and

$$\theta(A(\sigma(\Psi_0))) = \theta(A(\theta_B'(\Psi_0))) = A(\Psi_0). \tag{23.9.1}$$

Let Δ be a base for Φ_B again, so that $\sigma(\Delta)$ is a base for Φ_B too. Thus $\Phi_B^{\sigma(\Delta),+}$ can be defined in the same way as before, and in fact

$$\sigma(\Phi_B^{\Delta,+}) = \Phi_B^{\sigma(\Delta),+}. \tag{23.9.2}$$

This implies that

$$\theta(A(\Phi_B^{\sigma(\Delta),+})) = A(\Phi_B^{\Delta,+}), \tag{23.9.3}$$

by (23.9.1).

Suppose that Φ_B is reduced as a root system in $E_{\mathbf{R}}$. This implies that every base for Φ_B can be expressed as $\sigma(\Delta)$ for some σ in the Weyl group of Φ_B, as in Section 19.14. It follows that the standard Borel subalgebra of A associated to any base of Φ_B is related to $A(\Phi_B^{\Delta,+} \cup \{0\})$ by an inner automorphism of A, as in (23.9.3). This basically corresponds to the second part of Lemma C on p84 of [14].

More precisely, that result also states that θ can be taken to be an element of the subgroup $\mathcal{E}(A)$ of the group $\mathrm{Int}(A)$ of all inner automorphisms of A defined in Section 24.3. To see this, it is enough to check that if $\alpha \in \Phi_B$, then the automorphism θ_α in (23.8.1) is an element of $\mathcal{E}(A)$. To get this, it is enough to verify that $\exp \mathrm{ad}_{x_\alpha}$ and $\exp(-\mathrm{ad}_{y_\alpha})$ are elements of $\mathcal{E}(A)$. This reduces to showing that x_α and y_α are strongly ad-nilpotent in A, in the sense described in Section 24.3, by definition of $\mathcal{E}(A)$. This is easy to do, using the properties of x_α and y_α mentioned in the previous section.

23.10 Sums and diagonalizability

Let k be a field, and let $(A, [\cdot,\cdot]_A)$ be a finite-dimensional Lie algebra over k. Also let B be a Lie subalgebra of A such that every element of B is ad-diagonalizable as an element of A, which implies that B is commutative as a Lie algebra, as in Section 17.1. As usual, B' denotes the dual of B, as a vector space over k, and if $\alpha \in B'$, then A_α is the set of $x \in A$ such that $[w, x]_A = \alpha(w)\, x$ for every $w \in B$. Let Φ_B be the set of $\alpha \in B'$ such that $\alpha \neq 0$ and $A_\alpha \neq \{0\}$, as before. Remember that Φ_B has only finitely many elements, and that A corresponds to the direct sum of the linear subspaces A_α, $\alpha \in \Phi_B \cup \{0\}$, as a vector space over k, as in Section 17.2.

If C is an ideal in A, then $\mathrm{ad}_w(C) \subseteq C$ for every $w \in B$, and the restrictions of ad_w, $w \in B$, to C are simultaneously diagonalizable, as in Section 22.9. This means that C corresponds to the direct sum of the linear subspaces $A_\alpha \cap C$, as a vector space over k, where $\alpha \in \Phi_B \cup \{0\}$ and $A_\alpha \cap C \neq \{0\}$, as before.

Let $C_1, \ldots, C_n$ be finitely many nontrivial ideals in A, and suppose that A corresponds to their direct sum, as a vector space over k, and thus as a Lie algebra. Each C_j corresponds to a direct sum of subspaces of the form $A_\alpha \cap C_j$, as a vector space over k, as in the preceding paragraph. It follows that for each $\alpha \in \Phi_B \cup \{0\}$, A_α corresponds to the direct sum of linear subspaces of the form $A_\alpha \cap C_j$, $j = 1, \ldots, n$, as a vector space over k.

Let us suppose from now on in this section that B is equal to its centralizer in A, which means that $B = A_0$. This implies that B corresponds to the direct sum of the linear subspaces

$$B_j = B \cap C_j = A_0 \cap C_j, \tag{23.10.1}$$

$j = 1, \ldots, n$, as in the previous paragraph. It is easy to see that every element of the centralizer of B_j in C_j is contained in the centralizer of B in A, for each $j = 1, \ldots, n$. Thus

$$\text{the centralizer of } B_j \text{ in } C_j \text{ is equal to } B_j \tag{23.10.2}$$

for every $j = 1, \ldots, n$.

If $j \in \{1, \ldots, n\}$, then put

$$\widetilde{B}'_j = \{\alpha \in B' : \alpha(w_l) = 0 \text{ for every } w_l \in B_l,\ 1 \le l \neq j \le n\}. \tag{23.10.3}$$

This is a linear subspace of B', and B' corresponds to the direct sum of $\widetilde{B}'_j$, $1 \le j \le n$, as a vector space over k. The mapping from $\alpha \in \widetilde{B}'_j$ to the restriction of α to B_j is a one-to-one linear mapping from $\widetilde{B}'_j$ onto the dual B'_j of B_j for each

$j = 1, \ldots, n$, because B corresponds to the direct sum of the B_j's, $1 \le j \le n$, as a vector space over k.

Let $\alpha \in B'$ and $j \in \{1, \ldots, n\}$ be given, and suppose that

$$\text{there is a } w_j \in B_j \text{ such that } \alpha(w_j) \neq 0. \tag{23.10.4}$$

If $x \in A$, then $[w_j, x]_A \in C_j$, because $B_j \subseteq C_j$, and C_j is an ideal in A. If $x \in A_\alpha$, then we get that $\alpha(w_l)\, x \in C_j$, so that $x \in C_j$. Thus

$$A_\alpha \subseteq C_j \tag{23.10.5}$$

when (23.10.4) holds.

Suppose that there are also an $l \in \{1, \ldots, n\}$ and a $w_l \in B_l$ such that $j \neq l$ and $\alpha(w_l) \neq 0$. This implies that $A_\alpha \subseteq C_l$, as before, so that $A_\alpha = \{0\}$, because $C_j \cap C_l = \{0\}$, by hypothesis.

If $\alpha \in \Phi_B$, then (23.10.4) holds for some $j \in \{1, \ldots, n\}$, because $\alpha \neq 0$ and B corresponds to the direct sum of the B_j's. If $1 \le l \le n$ and $j \neq l$, then it follows from the remarks in the preceding paragraph that $\alpha(w_l) = 0$ for every $w_l \in B_l$, because $A_\alpha \neq \{0\}$. This means that $\alpha \in \widetilde{B}'_j$, so that

$$\Phi_B \subseteq \bigcup_{j=1}^{n} \widetilde{B}'_j. \tag{23.10.6}$$

Let $j \in \{1, \ldots, n\}$ be given, and put

$$\Phi_{B,j} = \Phi_B \cap \widetilde{B}'_j. \tag{23.10.7}$$

If $\alpha \in \Phi_{B,j}$, then (23.10.4) holds, because $\alpha \neq 0$ and $\alpha \in \widetilde{B}'_j$. This implies that (23.10.5) holds, as before. Of course,

$$\Phi_B = \bigcup_{j=1}^{n} \Phi_{B,j}, \tag{23.10.8}$$

by (23.10.6). Note that

$$\Phi_{B,j} \cap \Phi_{B,l} = \emptyset \tag{23.10.9}$$

when $1 \le j \neq l \le n$, because $\widetilde{B}'_j \cap \widetilde{B}'_l = \{0\}$, by construction.

Let $\alpha \in \widetilde{B}'_j$ be given for some $j \in \{1, \ldots, n\}$, and suppose that $\alpha \neq 0$, so that (23.10.4) holds. Under these conditions,

$$A_\alpha = \{x_j \in C_j : [u_j, x_j]_A = \alpha(u_j)\, x_j \text{ for every } u_j \in B_j\}. \tag{23.10.10}$$

More precisely, A_α is contained in the right side, by (23.10.5). If $x_j \in C_j$ and $w_l \in B_l$ for some $1 \le l \neq j \le n$, then $[w_l, x_j]_A = 0$ and $\alpha(w_l) = 0$. This implies that the right side of (23.10.10) is contained in A_α, as desired.

Suppose now that k has characteristic 0, and that $\Phi_B \neq \emptyset$. Let $E_{\mathbf{Q}}$ be the linear subspace of B', as a vector space over $\mathbf{Q}$, spanned by Φ_B, as usual.

Similarly, if $\Phi_{B,j} \neq \emptyset$ for some $j \in \{1, \ldots, n\}$, then let $E_{\mathbf{Q},j}$ be the linear subspace of $\widetilde{B}'_j$, as a vector space over $\mathbf{Q}$, spanned by $\Phi_{B,j}$. Thus

$$E_{\mathbf{Q},j} \subseteq E_{\mathbf{Q}}, \tag{23.10.11}$$

and it is easy to see that $E_{\mathbf{Q}}$ corresponds to the direct sum of the $E_{\mathbf{Q},j}$'s for these j's, as a vector space over $\mathbf{Q}$.

Let $E_{\mathbf{R}}$ be the vector space over $\mathbf{R}$ obtained from $E_{\mathbf{Q}}$ in the usual way, so that $E_{\mathbf{Q}}$ corresponds to a linear subspace of $E_{\mathbf{R}}$, as a vector space over $\mathbf{Q}$, and any basis for $E_{\mathbf{Q}}$, as a vector space over $\mathbf{Q}$, is a basis for $E_{\mathbf{R}}$, as a vector space over $\mathbf{R}$. Similarly, we can get a vector space $E_{\mathbf{R},j}$ over $\mathbf{R}$ from $E_{\mathbf{Q},j}$ for each $j \in \{1, \ldots, n\}$ such that $\Phi_{B,j} \neq \emptyset$. More precisely, $E_{\mathbf{R},j}$ is a linear subspace of $E_{\mathbf{R}}$, and $E_{\mathbf{R}}$ corresponds to the direct sum of the $E_{\mathbf{R},j}$'s for these j's.

Suppose that Φ_B is a root system in $E_{\mathbf{R}}$. This implies that $\Phi_{B,j}$ is a root system in $E_{\mathbf{R},j}$ when $\Phi_{B,j} \neq \emptyset$. If this happens for more that one $j \in \{1, \ldots, n\}$, then it follows that Φ_B is reducible as a root system in $E_{\mathbf{R}}$. This is related to the corollary on p74 of [14], and to part of the corollary to Theorem 9 on p50 of [24].

23.11 Reducibility and diagonalizability

Let us return to the same type of situation as at the beginning of the previous section. Thus we let k be a field, and $(A, [\cdot, \cdot]_A)$ be a finite-dimensional Lie algebra over k. We also let B be a Lie subalgebra of A such that every element of B is ad-diagonalizable as an element of A, which implies that B is commutative as a Lie algebra, as before. If α is an element of the dual B' of B, as a vector space over k, then A_α is the set of $x \in A$ such that $[w, x]_A = \alpha(w)\, x$ for every $w \in B$. We let Φ_B be the set of $\alpha \in B'$ such that $\alpha \neq 0$ and $A_\alpha \neq \{0\}$, which is a finite set with the property that A corresponds to the direct sum of A_α, $\alpha \in \Phi_B \cup \{0\}$, as a vector space over k.

Remember that $[A_\alpha, A_\beta] \subseteq A_{\alpha+\beta}$ for every $\alpha, \beta \in B'$, as in Section 17.2. Let Ξ_B be a subsemigroup of B', as a commutative group with respect to addition, that contains $\Phi_B \cup \{0\}$. In particular, we are in the same type of situation as in Section 22.3, with $\Xi = \Xi_B$ and $\Psi = \Phi_B \cup \{0\}$. If $\Psi_0 \subseteq \Xi_B$, then let $A(\Psi_0)$ be the subset of A_0 consisting of finite sums of elements of A_α, $\alpha \in \Psi_0$, as in Section 22.4. If

$$(\Psi_0 + \Psi_0) \cap (\Phi_B \cup \{0\}) \subseteq \Psi_0, \tag{23.11.1}$$

then $A(\Psi_0)$ is a Lie subalgebra of A, as before.

Let $\widehat{B}'_1$, $\widehat{B}'_2$ be complementary linear subspaces of B', so that

$$\widehat{B}'_1 \cap \widehat{B}'_2 = \{0\} \tag{23.11.2}$$

and

$$\widehat{B}'_1 + \widehat{B}'_2 = B'. \tag{23.11.3}$$

Suppose that

$$\Phi_B \subseteq \widehat{B}'_1 \cup \widehat{B}'_2, \tag{23.11.4}$$

and put

$$\Phi_{B,j} = \Phi_B \cap \widehat{B}'_j \tag{23.11.5}$$

for $j = 1, 2$. Note that $\Phi_B = \Phi_{B,1} \cup \Phi_{B,2}$ and

$$\Phi_{B,1} \cap \Phi_{B,2} = \emptyset, \tag{23.11.6}$$

by (23.11.2). If $\alpha \in \Phi_{B,1}$ and $\beta \in \Phi_{B,2}$, then

$$\alpha + \beta \not\in \Phi_B \cup \{0\}, \tag{23.11.7}$$

because $\alpha + \beta \not\in \widehat{B}'_1 \cup \widehat{B}'_2$. It follows that

$$[A_\alpha, A_\beta] = \{0\} \tag{23.11.8}$$

in this case.

We are now in a situation like one considered in Section 22.14, with $\Phi = \Phi_B$ and $\Phi_j = \Phi_{B,j}$ for $j = 1, 2$. More precisely, (22.14.7), (22.14.11), (22.14.22), and (22.14.25) hold under these conditions, as in the preceding paragraph. In particular, $A(\Phi_{B,j} \cup \{0\})$ is a Lie subalgebra of A for $j = 1, 2$, as before. Let A^j be the Lie subalgebra of A generated by $A(\Phi_{B,j})$ for $j = 1, 2$, as before, which is contained in $A(\Phi_{B,j} \cup \{0\})$. Remember that

$$[A^1, A^2] = \{0\}, \tag{23.11.9}$$

and that A^j is an ideal in A for $j = 1, 2$, as a Lie algebra over k.

Put

$$B_1 = \{w \in B : \beta(w) = 0 \text{ for every } \beta \in \widehat{B}'_2\}, \tag{23.11.10}$$

$$B_2 = \{w \in B : \beta(w) = 0 \text{ for every } \beta \in \widehat{B}'_1\}. \tag{23.11.11}$$

These are complementary linear subspaces of B, because $\widehat{B}'_1$, $\widehat{B}'_2$ are complementary linear subspaces of B', by hypothesis. Observe that

$$[B_1, A_\beta] = \{0\} \tag{23.11.12}$$

for every $\beta \in \Phi_{B,2}$, and similarly that

$$[B_2, A_\beta] = \{0\} \tag{23.11.13}$$

for every $\beta \in \Phi_{B,1}$, by the definition of A_β. Equivalently, this means that

$$[B_1, A(\Phi_{B,2})] = [B_2, A(\Phi_{B,1})] = \{0\}, \tag{23.11.14}$$

which is the same as saying that

$$A(\Phi_{B,1}) \subseteq C_A(B_2), \quad A(\Phi_{B,2}) \subseteq C_A(B_1). \tag{23.11.15}$$

It follows that

$$A^1 \subseteq C_A(B_2), \quad A^2 \subseteq C_A(B_1), \tag{23.11.16}$$

because the centralizer $C_A(E)$ of $E \subseteq A$ is a Lie subalgebra of A.

Suppose from now on in this section that B is its own centralizer in A, so that $B = A_0$. In particular, this means that A_0 is commutative as a Lie algebra over k. This implies that $A^1 \cap A^2$ is contained in the center $Z(A)$ of A as a Lie algebra, as in Section 22.14.

If $j \in \{1, 2\}$ and $\alpha \in \Phi_{B,j}$, then

$$[A_\alpha, A_{-\alpha}] \subseteq A^j \cap A_0 = A^j \cap B. \tag{23.11.17}$$

Note that $A_{-\alpha} = \{0\}$ unless $-\alpha \in \Phi_{B,j}$ too. As in Section 22.14, A^j is the same as the set of elements of A that can be expressed as finite sums of elements of $A(\Phi_{B,j})$ and $[A_\alpha, A_{-\alpha}]$ with $\alpha \in \Phi_{B,j}$, because A_0 is commutative as a Lie algebra over k.

Suppose for the moment that $\alpha \in \Phi_{B,1}$, $\beta \in \Phi_{B,2}$, $x_\alpha \in A_\alpha$, $y_\alpha \in A_{-\alpha}$, and $z_\beta \in A_\beta$. This implies that

$$[x_\alpha, z_\beta]_A = [y_\alpha, z_\beta]_A = 0, \tag{23.11.18}$$

because $\pm\alpha + \beta \notin \widehat{B}'_1 \cup \widehat{B}'_2$. It follows that

$$[[x_\alpha, y_\alpha]_A, z_\beta]_A = 0, \tag{23.11.19}$$

by the Jacobi identity. We also have that $[x_\alpha, y_\alpha]_A \in A_0 = B$, so that

$$[[x_\alpha, y_\alpha]_A, z_\beta]_A = \beta([x_\alpha, y_\alpha]_A)\, z_\beta, \tag{23.11.20}$$

by definition of A_β. If $z_\beta \neq 0$, then we get that

$$\beta([x_\alpha, y_\alpha]_A) = 0. \tag{23.11.21}$$

Of course, we can always choose z_β to be a nonzero element of A_β, because $\beta \in \Phi_{B,2} \subseteq \Phi_B$. This shows that (23.11.21) holds for every $x_\alpha \in A_\alpha$ and $y_\alpha \in A_{-\alpha}$ when $\beta \in \Phi_{B,2}$. This argument works as well when $\alpha \in \Phi_{B,2}$ and $\beta \in \Phi_{B,1}$.

Let us suppose from now on in this section that $Z(A) = \{0\}$. This implies that the linear span of Φ_B in B' is equal to B', as in Section 17.5. It follows that the linear span of $\Phi_{B,j}$ in $\widehat{B}'_j$ is equal to $\widehat{B}'_j$ for $j = 1, 2$ in this situation. This means that (23.11.21) holds for every $x_\alpha \in A_\alpha$ and $y_\alpha \in A_{-\alpha}$ when $\alpha \in \Phi_{B,j}$ and $\beta \in \widehat{B}'_2$, and when $\alpha \in \Phi_{B,2}$ and $\beta \in \widehat{B}'_1$. This is the same as saying that

$$[A_\alpha, A_{-\alpha}] \subseteq B_j \tag{23.11.22}$$

for $j = 1, 2$ and $\alpha \in \Phi_{B,j}$.

Using (23.11.22), we get that

$$A^j \subseteq A(\Phi_{B,j}) + B_j \tag{23.11.23}$$

for $j = 1, 2$. One can check that $A(\Phi_{B,j}) + B_j$ is a Lie subalgebra of A for $j = 1, 2$, because B is commutative as a Lie subalgebra of A, and $[B, A(\Phi_{B,j})] \subseteq A(\Phi_{B,j})$ for $j = 1, 2$. We also have that

$$[A(\Phi_{B,1}) + B_1, A(\Phi_{B,2}) + B_2] = \{0\}, \tag{23.11.24}$$

because of (23.11.8), (23.11.14), and the fact that B is commutative as a Lie algebra. It is easy to see that

$$A(\Phi_{B,1}) + B_1, \quad A(\Phi_{B,2}) + B_2 \tag{23.11.25}$$

are complementary linear subspaces of A, because B_1, B_2 are complementary linear subspaces of $B = A_0$. It follows that these are ideals in A, and that A corresponds to their direct sum, as a Lie algebra over k.

This is related to the proposition on p73 of [14], and to part of the corollary to Theorem 9 on p50 of [24], as before.

Chapter 24

Strong ad-nilpotence and automorphisms

24.1 Invariant subspaces and nilpotent vectors

Let k be a field, let V be a vector space over k, and let T be a linear mapping from V into itself. Remember that

(24.1.1) $$V_0 = \{v \in V : T^l(v) = 0 \text{ for some } l \in \mathbf{Z}_+\}$$

is a linear subspace of V, as in Section 10.7. Clearly

(24.1.2) $$T(V_0) \subseteq V_0.$$

In fact,

(24.1.3) $$T^{-1}(V_0) = V_0.$$

More precisely, if $v \in V$ and $T(v) \in V_0$, then it is easy to see that $v \in V_0$.

Let W be a linear subspace of V, and suppose that

(24.1.4) $$T(W) \subseteq W.$$

Put

(24.1.5) $$W_0 = W \cap V_0 = \{w \in W : T^l(w) = 0 \text{ for some } l \in \mathbf{Z}_+\},$$

which is a linear subspace of W. Of course,

(24.1.6) $$T(W_0) \subseteq W_0,$$

as in (24.1.2). Similarly,

(24.1.7) $$W \cap T^{-1}(W_0) = W_0,$$

as in (24.1.3).

Let q be the canonical quotient mapping from V onto the quotient vector space V/W. As usual, there is a unique linear mapping $T_{V/W}$ from V/W into itself such that

$$T_{V/W} \circ q = q \circ T \tag{24.1.8}$$

on V. This implies that

$$(T_{V/W})^l \circ q = q \circ T^l \tag{24.1.9}$$

on V for every positive integer l.

Put

$$(V/W)_0 = \{z \in V/W : (T_{V/W})^l(z) = 0 \text{ for some } l \in \mathbf{Z}_+\}, \tag{24.1.10}$$

which is a linear subspace of V/W, as before. If $v \in V$, then

$$(T_{V/W})^l(q(v)) = q(T^l(v)) \tag{24.1.11}$$

for every positive integer l, as in (24.1.9). Thus (24.1.10) consists of the $q(v)$ with $v \in V$ such that (24.1.11) is equal to 0 for some $l \geq 1$. Equivalently, this means that

$$T^l(v) \in W \tag{24.1.12}$$

for some $l \geq 1$. In particular,

$$q(V_0) \subseteq (V/W)_0. \tag{24.1.13}$$

Let q_0 be the canonical quotient mapping from W onto the quotient vector space W/W_0. As before, there is a unique linear mapping T_{W/W_0} from W/W_0 into itself such that

$$T_{W/W_0} \circ q_0 = q_0 \circ T \tag{24.1.14}$$

on W. Thus

$$(T_{W/W_0})^l \circ q_0 = q_0 \circ T^l \tag{24.1.15}$$

on W for every positive integer l, as before. Observe that the kernel of T_{W/W_0} is trivial in W/W_0, because of (24.1.7).

24.2 Finite-dimensional spaces

Let us continue with the same notation and hypotheses as in the previous section. Suppose in addition that the dimension of W is finite, as a vector space over k. Of course, this implies that the dimension of W/W_0 is finite. Remember that the kernel of T_{W/W_0} is trivial in W/W_0. It follows that T_{W/W_0} maps W/W_0 onto itself.

If $w \in W$ and $l \in \mathbf{Z}_+$, then we get that there is a $u_l \in W$ such that

$$(T_{W/W_0})^l(q_0(u_l)) = q_0(w). \tag{24.2.1}$$

Equivalently, this means that

$$q_0(T^l(u_l)) = q_0(w). \tag{24.2.2}$$

This is the same as saying that

$$T^l(u_l) - w \in W_0. \tag{24.2.3}$$

Let $v \in V$ be given, and suppose that $q(v) \in (V/W)_0$. This implies that $T^l(v) \in W$ for some positive integer l, as in (24.1.12). It follows that there is a $u_l \in W$ such that

$$T^l(u_l) - T^l(v) \in W_0, \tag{24.2.4}$$

as in the preceding paragraph. Equivalently, this means that

$$T^l(v - u_l) \in W_0. \tag{24.2.5}$$

Hence there is a positive integer r such that

$$T^r(T^l(v - u_l)) = 0, \tag{24.2.6}$$

by the definition (24.1.5) of W_0.

Thus $T^{l+r}(v - u_l) = 0$, so that

$$v - u_l \in V_0. \tag{24.2.7}$$

Of course, $q(v) = q(v - u_l)$, because $u_l \in W$. It follows that

$$q(v) = q(v - u_l) \in q(V_0). \tag{24.2.8}$$

Combining this with (24.1.13), we get that

$$q(V_0) = (V/W)_0 \tag{24.2.9}$$

under these conditions.

Alternatively, suppose that V has finite dimension, as a vector space over k. It is well known that the characteristic polynomial of T on V is equal to the product of the characteristic polynomial of the restriction of T to W and the characteristic polynomial of $T_{V/W}$ on V/W. In particular, the order of vanishing of the characteristic polynomial of T on V at 0 is the same as the sum of the orders of vanishing of the characteristic polynomials of the restriction of T to W and $T_{V/W}$ at 0. This means that the dimension of V_0 is equal to the sum of the dimensions of W_0 and $(V/W)_0$, as vector spaces over k. Note that the kernel of the restriction of q to V_0 is equal to W_0, because $W_0 = W \cap V_0$, as in (24.1.5). This implies that the dimension of V_0 is equal to the sum of the dimensions of W_0 and $q(V_0)$ too. Hence the dimension of $q(V_0)$ is equal to the dimension of $(V/W)_0$. This permits one to obtain (24.2.9) from (24.1.13).

24.3 Strong ad-nilpotence

Let k be a field of characteristic 0, and let $(A, [\cdot,\cdot]_A)$ be a finite-dimensional Lie algebra over k. An element x of A is said to be *strongly* ad-*nilpotent* if there are a $y \in A$, $\alpha \in k$, and $l \in \mathbf{Z}_+$ such that $\alpha \neq 0$ and

$$(\mathrm{ad}_y - \alpha\, I)^l(x) = 0, \tag{24.3.1}$$

where I is the identity mapping on A. This definition is given on p82 of [14], where k is also taken to be algebraically closed. In that case, if x is strongly ad-nilpotent, then x is ad-nilpotent in A, by the remarks in Section 18.1, as in [14].

Otherwise, let k_1 be an algebraically closed field that contains k. We may as well identify A with k^n for some positive integer n as a vector space over k, using a basis for A. Let A_1 be k_1^n, as a vector space over k_1. We can extend the Lie bracket on A to A_1, so that A_1 becomes a Lie algebra over k_1. If $x \in A$ is strongly ad-nilpotent as an element of A, then x is strongly ad-nilpotent as an element of A_1 too. This implies that x is ad-nilpotent as an element of A_1, as before. It follows that x is ad-nilpotent as an element of A as well. Another approach to this will be given in Section 24.5.

If A is semisimple, and $x \in A$ is ad-nilpotent, then x is strongly ad-nilpotent, as in Sections 14.1 and 14.2.

Let $\mathcal{N}(A)$ be the set of $x \in A$ such that x is strongly ad-nilpotent in A. If B is a Lie subalgebra of A, then it is easy to see that

$$\mathcal{N}(B) \subseteq \mathcal{N}(A), \tag{24.3.2}$$

as on p82 of [14]. Note that $\mathcal{N}(A)$ is invariant under Lie algebra automorphisms of A.

If $x \in A$ is ad-nilpotent in A, then the exponential $\exp \mathrm{ad}_x$ of ad_x on A defines a Lie algebra automorphism of A, as in Section 14.11. Remember that $\mathrm{Int}\, A$ denotes the subgroup of the automorphism group of A generated by these automorphisms. Let $\mathcal{E}(A)$ be the subgroup of $\mathrm{Int}\, A$ generated by exponentials of strongly ad-nilpotent elements of A. One can check that $\mathcal{E}(A)$ is a normal subgroup of the group of all Lie algebra automorphisms of A, because $\mathcal{N}(\mathcal{A})$ is invariant under Lie algebra automorphisms of A, as on p82 of [14]. If A is semisimple, then $\mathcal{E}(A) = \mathrm{Int}\, A$, because $\mathcal{N}(A)$ contains all ad-nilpotent elements of A, as before.

Let B be a Lie subalgebra of A, and let x be an element of B. Thus $\mathrm{ad}_{B,x}$ is the same as the restriction of $\mathrm{ad}_{A,x}$ to B. Suppose that $x \in \mathcal{N}(B)$, so that $x \in \mathcal{N}(A)$, and $\mathrm{ad}_{A,x}$ is nilpotent on A. Note that $\exp \mathrm{ad}_{B,x}$ is the same as the restriction of $\exp \mathrm{ad}_{A,x}$ to B.

Let $\mathcal{E}(A, B)$ be the subgroup of $\mathcal{E}(A)$ generated by elements of the form $\exp \mathrm{ad}_{A,x}$ with $x \in \mathcal{N}(B)$. The restriction of every element of $\mathcal{E}(A, B)$ to B is an element of $\mathcal{E}(B)$. It is easy to see that every element of $\mathcal{E}(B)$ can be obtained from an element of $\mathcal{E}(A, B)$ in this way. This corresponds to some remarks on p82 of [14].

24.4 Strong ad-nilpotence and homomorphisms

Let k be a field of characteristic 0, and let $(A, [\cdot,\cdot]_A)$, $(C, [\cdot,\cdot]_C)$ be finite-dimensional Lie algebras over k. Also let ψ be a Lie algebra homomorphism from A into C. If $y \in A$, then

$$\psi \circ \mathrm{ad}_{A,y} = \mathrm{ad}_{C,\psi(y)} \circ \psi, \tag{24.4.1}$$

as in Section 14.8. This implies that

$$\psi \circ (\mathrm{ad}_{A,y} - \alpha\, I_A) = (\mathrm{ad}_{C,\psi(y)} - \alpha\, I_C) \circ \psi \tag{24.4.2}$$

for every $\alpha \in k$, where I_A, I_C are the identity mappings on A, C, respectively. It follows that

$$\psi \circ (\mathrm{ad}_{A,y} - \alpha\, I_A)^l = (\mathrm{ad}_{C,\psi(y)} - \alpha\, I_C)^l \circ \psi \tag{24.4.3}$$

for every $l \in \mathbf{Z}_+$.

Suppose that $x \in A$ is strongly ad-nilpotent in A, so that there are $y \in A$, $\alpha \in k$, and $l \in \mathbf{Z}_+$ such that $\alpha \neq 0$ and

$$(\mathrm{ad}_{A,y} - \alpha\, I_A)^l(x) = 0, \tag{24.4.4}$$

as in (24.3.1). This implies that

$$(\mathrm{ad}_{C,\psi(y)} - \alpha\, I_C)^l(\psi(x)) = 0, \tag{24.4.5}$$

by (24.4.3). This means that $\psi(x)$ is strongly ad-nilpotent in C, so that

$$\psi(\mathcal{N}(A)) \subseteq \mathcal{N}(C). \tag{24.4.6}$$

In particular, x and $\psi(x)$ are ad-nilpotent in A and C, respectively, as before. We also get that

$$\psi \circ (\exp \mathrm{ad}_{A,x}) = (\exp \mathrm{ad}_{C,\psi(x)}) \circ \psi, \tag{24.4.7}$$

as in Section 14.12.

Let $y \in A$ and $\alpha \in k$ be given again, and observe that

$$\{x \in A : (\mathrm{ad}_{A,y} - \alpha\, I_A)^l(x) = 0 \text{ for some } l \in \mathbf{Z}_+\} \tag{24.4.8}$$

is a linear subspace of A. This corresponds to (24.1.1), with $V = A$ and $T = \mathrm{ad}_{A,y} - \alpha\, I_A$. Similarly,

$$\{z \in C : (\mathrm{ad}_{C,\psi(y)} - \alpha\, I_C)^l(z) = 0 \text{ for some } l \in \mathbf{Z}_+\} \tag{24.4.9}$$

is a linear subspace of C. Clearly ψ maps (24.4.8) into (24.4.9), because of (24.4.3). If, in the notation of Section 24.1, we take W to be the kernel of ψ, then (24.1.4) holds, because the kernel of ψ is an ideal in A.

Suppose now that ψ maps A onto C, so that V/W corresponds to C, and the quotient mapping q from V onto V/W corresponds to ψ. Note that the linear mapping $T_{V/W}$ induced on V/W by T as in Section 24.1 corresponds to $\mathrm{ad}_{C,\psi(y)} - \alpha\, I_C$, and that (24.1.10) corresponds to (24.4.9). In this case, ψ maps (24.4.8) onto (24.4.9), as in (24.2.9). It follows that

$$\psi(\mathcal{N}(A)) = \psi(\mathcal{N}(C)) \tag{24.4.10}$$

under these conditions. This corresponds to some remarks on p82 of [14].

If $\sigma_C \in \mathcal{E}(C)$, then there is a $\sigma_A \in \mathcal{E}(A)$ such that

$$\psi \circ \sigma_A = \sigma_C \circ \psi. \tag{24.4.11}$$

This can be obtained from (24.4.7) and (24.4.10). This corresponds to the lemma on p82 of [14].

24.5 Another criterion for nilpotence

Let k be a field of characteristic 0, let $\mathcal{A}$ be an associative algebra over k, and let δ be a derivation on $\mathcal{A}$. If $\lambda \in k$, then put

$$\mathcal{E}_\lambda(\delta) = \{a \in \mathcal{A} : (\delta - \lambda\, I)^l(a) = 0 \text{ for some } l \in \mathbf{Z}_+\}, \tag{24.5.1}$$

as in Sections 10.7 and 10.9, where I is the identity mapping on $\mathcal{A}$. If $b \in \mathcal{E}_\lambda(\delta)$ and $c \in \mathcal{E}_\mu(\delta)$ for some $\mu \in k$, then $b\,c \in \mathcal{E}_{\lambda+\mu}(\delta)$, as in Section 10.9. It follows that

$$b^j \in \mathcal{E}_{j\cdot\lambda}(\delta) \tag{24.5.2}$$

for every positive integer j.

Suppose that $\lambda \neq 0$, so that the elements of k of the form $j \cdot \lambda$, $j \in \mathbf{Z}_+$, are distinct, because k has characteristic 0. If, for each $j \in \mathbf{Z}_+$, we have that $b^j \neq 0$, then the b^j's are linearly independent in $\mathcal{A}$, as in Section 10.7. If $\mathcal{A}$ has finite dimension as a vector space over k, then it follows that $b^j = 0$ for some $j \geq 1$. This extends the remarks at the beginning of Section 14.2.

If $a \in \mathcal{A}$, then $\delta_a(x) = [a, x] = a\,x - x\,a$ defines a derivation on $\mathcal{A}$. Thus if $b \in \mathcal{E}_\lambda(\delta_a)$ for some nonzero $\lambda \in k$ and $\mathcal{A}$ has finite dimension as a vector space over k, then b is nilpotent in $\mathcal{A}$.

Remember that $\mathcal{A}$ may be considered as a Lie algebra over k, with respect to the commutator bracket corresponding to multiplication in $\mathcal{A}$. If $b \in \mathcal{A}$ is strongly ad-nilpotent in $\mathcal{A}$ as a Lie algebra, then b is nilpotent in $\mathcal{A}$, as in the preceding paragraph.

Let $(A, [\cdot,\cdot]_A)$ be a finite-dimensional Lie algebra over k. If $x \in A$ is strongly ad-nilpotent, then ad_x is strongly ad-nilpotent as an element of the Lie algebra of linear mappings from A into itself. This follows from (24.4.6), using the adjoint representation of A. This implies that ad_x is nilpotent as a linear mapping on A, as in the previous paragraph.

24.6 Nilpotence and automorphisms

Let k be a field, and let $f(t) = \sum_{j=0}^n f_j\, t^j$ be a polynomial function of $t \in k$ with coefficients in a vector space over k. If $f_j \neq 0$ for some j, then $f(t) = 0$ for at most n $t \in k$, by standard arguments.

Suppose from now on in this section that k has characteristic 0. Let $\mathcal{A}$ be an associative algebra over k with a multiplicative identity element e, and let a be a nilpotent element of $\mathcal{A}$. Thus $\exp(t\,a)$ defines a polynomial function of $t \in k$ with values in $\mathcal{A}$. If $a \neq 0$, then $\exp(t\,a) = e$ for only finitely many $t \in k$, as in the previous paragraph.

Let $(A, [\cdot,\cdot]_A)$ be a Lie algebra over k. If $x \in A$ is ad-nilpotent, then $\exp(t\ \mathrm{ad}_x)$ defines a polynomial function of $t \in k$ with values in the algebra of linear mappings from A into itself. If $\mathrm{ad}_x \neq 0$ as a linear mapping from A into itself, then $\exp(t\ \mathrm{ad}_x)$ is equal to the identity mapping on A for only finitely many $t \in k$, as before.

Let $y \in A$ be given, and for each $\alpha \in k$, let $A_{y,\alpha}$ be the set of $x \in A$ such that $(\mathrm{ad}_y - \alpha\, I)^l(x) = 0$ for some positive integer l, as in Section 18.1. Remember that $A_{y,\alpha} \neq \{0\}$ exactly when α is an eigenvalue of ad_y on A. In particular, if y is ad-nilpotent as an element of A, then $A_{y,\alpha} = \{0\}$ when $\alpha \neq 0$.

If A is nilpotent as a Lie algebra over k, then every $y \in A$ is ad-nilpotent, and it follows that 0 is the only element of A that is strongly ad-nilpotent. This implies that $\mathcal{E}(A)$ contains only the identity mapping on A, as in Exercise 1 on p87 of [14].

Suppose now that k is algebraically closed, and that A has finite dimension, as a vector space over k. If $y \in A$, then A corresponds to the direct sum of the linear subspaces $A_{y,\alpha}$, where $\alpha \in k$ is an eigenvalue of ad_y on A, as a vector space over k, as in Section 18.1.

If ad_y is not nilpotent on A, then it follows that ad_y has a nonzero eigenvalue $\alpha \in k$. This means that there is an $x \in A$ such that $x \neq 0$ and $\mathrm{ad}_y(x) = \alpha\, x$, so that x is strongly ad-nilpotent in particular. Note that $\mathrm{ad}_x(y) = -\mathrm{ad}_y(x) = -\alpha\, x \neq 0$, so that $\mathrm{ad}_x \neq 0$. Of course, $t\ \mathrm{ad}_x$ is strongly ad-nilpotent for every $t \in k$ too, so that

$$\exp(t\,\mathrm{ad}_x) \in \mathcal{E}(A) \tag{24.6.1}$$

for every $t \in k$.

If A is not nilpotent as a Lie algebra, then there is a $y \in A$ that is not ad-nilpotent, by Engel's theorem. Under these conditions, we get that $\mathcal{E}(A)$ is nontrivial, as in Exercise 1 on p87 of [14].

24.7 Conjugacy and solvability

Let k be an algebraically closed field of characteristic 0, and let $(A, [\cdot,\cdot]_A)$ be a finite-dimensional solvable Lie algebra over k. If C_1, C_2 are Cartan subalgebras of A, then there is an element of the group $\mathcal{E}(A)$ defined in Section 24.3 that maps C_1 onto C_2. This is the theorem on p82 of [14], which is related to Theorem 2 on p12 of [24].

Of course, if A is nilpotent as a Lie algebra, then A may be considered as a Cartan subalgebra of itself. More precisely, A is the only Cartan subalgebra of itself in this case, because Cartan subalgebras are maximal among nilpotent Lie subalgebras, as mentioned at the beginning of Section 18.11.

To prove the theorem, one can use induction on the dimension of A. We may also suppose that A is not nilpotent as a Lie algebra over k, as in the preceding paragraph. In particular, this means that the dimension of A is at least two.

Because $A \neq \{0\}$ is solvable as a Lie algebra, A has nontrivial ideals that are commutative as Lie algebras. Let A_0 be a nontrivial ideal in A that is commutative as a Lie algebra, and with minimal dimension among such ideals.

Let q_0 be the natural quotient mapping from A onto A/A_0, and note that A/A_0 is a solvable Lie algebra over k, with dimension strictly less than the dimension of A. Under these conditions, $q_0(C_1)$ and $q_0(C_2)$ are Cartan subalgebras of A/A_0, as in Section 18.11.

Our induction hypothesis implies that there is an element σ_0 of $\mathcal{E}(A/A_0)$ such that

$$\sigma_0(q_0(C_1)) = q_0(C_2). \tag{24.7.1}$$

This leads to an element σ of $\mathcal{E}(A)$ such that

$$q_0 \circ \sigma = \sigma_0 \circ q_0, \tag{24.7.2}$$

as in Section 24.4.

Put

$$B_1 = q_0^{-1}(q_0(C_1)), \quad B_2 = q_0^{-1}(q_0(C_2)). \tag{24.7.3}$$

These are Lie subalgebras of A, with

$$C_1 \subseteq B_1, \quad C_2 \subseteq B_2. \tag{24.7.4}$$

It is easy to see that

$$\sigma(B_1) = B_2, \tag{24.7.5}$$

using (24.7.1) and (24.7.2).

Note that C_1, C_2 may be considered as Cartan subalgebras of B_1, B_2, respectively, as in Section 18.11. It follows that $\sigma(C_1)$ may be considered as a Cartan subalgebra of B_2, by (24.7.5).

Suppose for the moment that

$$B_2 \neq A. \tag{24.7.6}$$

In this case, our induction hypothesis implies that there is an element τ_2 of $\mathcal{E}(B_2)$ such that

$$\tau_2(\sigma(C_1)) = C_2. \tag{24.7.7}$$

As in Section 24.3, there is an element τ of $\mathcal{E}(A, B_2) \subseteq \mathcal{E}(A)$ whose restriction to B_2 is equal to τ_2. In particular, this implies that

$$\tau(\sigma(C_1)) = C_2. \tag{24.7.8}$$

This completes the proof of the theorem in this case, because $\tau \circ \sigma \in \mathcal{E}(A)$.

24.8 The case where $A = B_2$

Let us continue with the same notation and hypotheses as in the previous section, except that we suppose now that $A = B_2$. In this case, $\sigma(B_1) = B_2 = A$, so that $B_1 = A$ as well. Equivalently, this means that

$$C_1 + A_0 = C_2 + A_0 = A. \tag{24.8.1}$$

If $x \in A$ and $\alpha \in k$, then let $A_{x,\alpha}$ be the set of $y \in A$ such that

$$(\mathrm{ad}_x - \alpha\, I)^l(y) = 0 \tag{24.8.2}$$

for some positive integer l, as in Section 18.1, and where I is the identity mapping on A. This is a linear subspace of A, and A corresponds to the direct sum of $A_{x,\alpha}$, as a vector space over k, where $\alpha \in k$ is an eigenvalue of ad_x on A, as before, because k is algebraically closed, by hypothesis.

Remember that A_0 is an ideal in A, so that $\mathrm{ad}_x(A_0) \subseteq A_0$. If $\alpha \in k$, then $A_0 \cap A_{x,\alpha}$ consists of $y \in A_0$ such that (24.8.2) holds for some $l \in \mathbf{Z}_+$, which is the analogue of $A_{x,\alpha}$ for the restriction of ad_x to A_0. As before, A_0 corresponds to the direct sum of $A_0 \cap A_{x,\alpha}$, where $\alpha \in k$ is an eigenvalue of ad_x on A_0, as a vector space over k.

Remember that $[A_{x,\alpha}, A_{x,\beta}] \subseteq A_{x,\alpha+\beta}$ for every $\alpha, \beta \in k$, as in Section 18.1. This implies that

$$[A_{x,0}, A_0 \cap A_{x,\alpha}] \subseteq A_0 \cap A_{x,\alpha} \tag{24.8.3}$$

for every $\alpha \in k$, because A_0 is an ideal in A.

Because C_2 is a Cartan subalgebra of A, there is an $x \in A$ such that

$$C_2 = A_{x,0}, \tag{24.8.4}$$

as in Section 18.8. In this case, one can check that

$$A_0 \cap A_{x,\alpha} \text{ is an ideal in } A \tag{24.8.5}$$

for every $\alpha \in k$. More precisely, this uses (24.8.1), (24.8.3), and the fact that A_0 is commutative as a Lie subalgebra of A.

If

$$A_0 \cap A_{x,\alpha} \neq \{0\} \tag{24.8.6}$$

for some $\alpha \in k$, then

$$A_0 \cap A_{x,\alpha} = A_0, \tag{24.8.7}$$

because A_0 is supposed to be minimal among nontrivial ideals that are commutative as Lie subalgebras of A. Note that (24.8.6) holds for some $\alpha \in k$, because $A_0 \neq \{0\}$, and A_0 corresponds to the direct sum of $A_0 \cap A_{x,\alpha}$ over some $\alpha \in k$, as a vector space over k.

If (24.8.7) holds with $\alpha = 0$, then $A_0 \subseteq A_{x,0} = C_2$, which means that $A = C_2$, by (24.8.1). This would imply that A is nilpotent as a Lie algebra, by definition of a Cartan subalgebra. However, A is not supposed to be nilpotent, as in the previous section, and so we get that $A_0 \cap A_{x,0} = \{0\}$.

It follows that (24.8.7) holds for some nonzero $\alpha \in k$, so that $A_0 \subseteq A_{x,\alpha}$. This implies that

$$A_0 = A_{x,\alpha}, \tag{24.8.8}$$

because of (24.8.1), (24.8.4), and the fact that A corresponds to the direct sum of $A_{x,\beta}$ over some $\beta \in k$, as a vector space over k.

Using (24.8.1), we get that x can be expressed as

$$x = y + z, \tag{24.8.9}$$

with $y \in C_1$ and $z \in A_0$. More precisely, $z \in A_{x,\alpha}$, by (24.8.8).

It is easy to see that $\mathrm{ad}_x(A_{x,\alpha}) \subseteq A_{x,\alpha}$, by the definition of $A_{x,\alpha}$. Because $z \in A_{x,\alpha}$ and $\alpha \neq 0$, one can express z as

$$z = \mathrm{ad}_x(w), \tag{24.8.10}$$

where w is a linear combination of $(\mathrm{ad}_x)^j(z)$, for finitely many positive integers j. In particular, this implies that $w \in A_{x,\alpha}$.

Equivalently, $w \in A_0$, so that $\mathrm{ad}_w(A) \subseteq A_0$, because A_0 is an ideal in A. This implies that

$$\mathrm{ad}_w \circ \mathrm{ad}_w = 0 \tag{24.8.11}$$

on A, because A_0 is commutative as a Lie subalgebra of A.

Thus

$$\exp(\mathrm{ad}_w) = I + \mathrm{ad}_w, \tag{24.8.12}$$

so that

$$(\exp(\mathrm{ad}_w))(x) = x + \mathrm{ad}_w(x) = x - \mathrm{ad}_x(w) = x - z = y. \tag{24.8.13}$$

Put

$$C = (\exp(\mathrm{ad}_w))(C_2), \tag{24.8.14}$$

which is a Cartan subalgebra of A, because C_2 is a Cartan subalgebra of A, and $\exp(\mathrm{ad}_w)$ is an automorphism of A. One can check that

$$C = A_{y,0}, \tag{24.8.15}$$

using (24.8.4) and (24.8.13).

Remember that $y \in C_1$, by construction, so that ad_y maps C_1 into itself. More precisely, ad_y is nilpotent on C_1, because C_1 is a Cartan subalgebra of A, and thus nilpotent as a Lie algebra. It follows that

$$C_1 \subseteq C, \tag{24.8.16}$$

by (24.8.15).

This implies that

$$C_1 = C, \tag{24.8.17}$$

by the characterization of Cartan subalgebras as minimal Engel subalgebras, as in Section 18.8. Alternatively, one can use the fact that Cartan subalgebras are maximal among nilpotent Lie subalgebras of A, as in Section 18.11.

Remember that $w \in A_{x,\alpha}$, so that w is strongly ad-nilpotent in A, and $\exp(\mathrm{ad}_w) \in \mathcal{E}(A)$. It follows that there is an element of $\mathcal{E}(A)$ that maps C_1 onto C_2, by (24.8.14) and (24.8.17). This completes the proof of the theorem stated at the beginning of the previous section.

24.9 Conjugacy in arbitrary Lie algebras

Let k be an algebraically closed field of characteristic 0 again, and let $(A, [\cdot,\cdot]_A)$ be a finite-dimensional Lie algebra over k. If B_1, B_2 are Borel subalgebras of A, then the theorem on p84 of [14] states that

(24.9.1) there is an element of $\mathcal{E}(A)$ that maps B_1 onto B_2.

This is closely related to Theorem 5 on p48 of [24].

If C_1, C_2 are Cartan subalgebras of A, then the corollary on p84 states that

(24.9.2) there is an element of $\mathcal{E}(A)$ that maps C_1 onto C_2.

This is closely related to Theorem 2 on p12 of [24].

To obtain the corollary from the theorem, remember that Cartan subalgebras are nilpotent, and solvable in particular. This implies that there are Borel subalgebras B_1, B_2 of A that contain C_1, C_2, respectively. Using the theorem, we get $\sigma \in \mathcal{E}(A)$ such that $\sigma(B_1) = B_2$. It follows that

(24.9.3) $$\sigma(C_1) \subseteq B_2.$$

Of course, $\sigma(C_1)$ is a Cartan subalgebra of A as well. As in Section 18.11, $\sigma(C_1)$ and C_2 may also be considered as Cartan subalgebras of B_2. Because B_2 is solvable as a Lie algebra over k, there is an element of $\mathcal{E}(B_2)$ that maps $\sigma(C_1)$ onto C_2, as in Section 24.7.

Every element of $\mathcal{E}(B_2)$ can be obtained as the restriction of an element of $\mathcal{E}(A, B_2) \subseteq \mathcal{E}(A)$ to B_2, as in Section 24.3. This implies that there is an element of $\mathcal{E}(A)$ that maps $\sigma(C_1)$ onto C_2. It follows that there is an element of $\mathcal{E}(A)$ that maps C_1 onto C_2, as desired.

24.9.1 The beginning of the proof of the theorem

Let us now begin the proof of the theorem. Note that the theorem holds trivially when A is solvable as a Lie algebra, in which case A is the only Borel subalgebra of itself.

To prove the theorem, one uses induction on the dimension of A as a vector space over k. If the dimension of A is one, then the theorem is trivial, as in the preceding paragraph.

Remember that $\operatorname{Rad} A$ denotes the solvable radical of A, as in Section 9.4. If B_1, B_2 are Borel subalgebras of A, then

(24.9.4) $$\operatorname{Rad} A \subseteq B_1, B_2,$$

as in Section 22.7.

Remember that $\operatorname{Rad} A$ is an ideal in A, and let q be the natural quotient mapping from A onto $A/\operatorname{Rad}(A)$. Note that $q(B_1)$, $q(B_2)$ are Borel subalgebras of $A/\operatorname{Rad} A$, as in Section 22.7. We also have that

(24.9.5) $$B_j = q^{-1}(q(B_j)) \quad \text{for } j = 1, 2,$$

by (24.9.4).

If $\operatorname{Rad} A \neq \{0\}$, then the dimension of $A/\operatorname{Rad} A$ is less than the dimension of A, and our induction hypothesis implies that there is an element σ of $\mathcal{E}(A/\operatorname{Rad} A)$ such that

(24.9.6) $$\sigma(q(B_1)) = q(B_2).$$

This leads to an element σ_A of $\mathcal{E}(A)$ such that

(24.9.7) $$q \circ \sigma_A = \sigma \circ q,$$

as in Section 24.4.

It is easy to see that

(24.9.8) $$\sigma_A(B_1) = B_2,$$

using (24.9.5), (24.9.6), and (24.9.7). This completes the proof when $\operatorname{Rad} A \neq \{0\}$.

Thus we may suppose from now on that $\operatorname{Rad} A = \{0\}$, so that A is semisimple as a Lie algebra over k. Of course, we may suppose that $A \neq \{0\}$ too.

24.9.2 Standard Borel subalgebras of A

Let A_0 be a toral subalgebra of A, as in Section 17.1, so that every element of A_0 is ad-diagonalizable as an element of A. Remember that A_0 is commutative as a Lie algebra, as before. More precisely, let A_0 be a toral subalgebra of A that is maximal with respect to inclusion. Note that $A_0 \neq \{0\}$, as in Section 17.1, because $A \neq \{0\}$, and using our hypotheses on k. We also have that the centralizer of A_0 in A is equal to A_0, as in Section 17.4.

Let A_0' be the dual of A_0, as a vector space over k, as usual. If $\alpha \in A_0'$, then let A_α be the set of $x \in A$ such that $\operatorname{ad}_w(x) = \alpha(w)\, x$ for every $w \in A_0$. This is the same as A_0 when $\alpha = 0$, because A_0 is its own centralizer in A, as in the preceding paragraph.

Let $\Phi = \Phi_{A_0}$ be the set of $\alpha \in A_0'$ such that $\alpha \neq 0$ and $A_\alpha \neq \{0\}$. Remember that A corresponds to the direct sum of the subspaces A_α, $\alpha \in \Phi \cup \{0\}$, as a vector space over k, as in Section 17.2. If $\alpha, \beta \in A_0'$, then $[A_\alpha, A_\beta] \subseteq A_{\alpha+\beta}$, as before.

If $\alpha \in \Phi$, then A_α has dimension one as a vector space over k, as in Section 17.7. We may choose $x_\alpha \in A_\alpha$ and $y_\alpha \in A_{-\alpha}$ so that $h_\alpha = [x_\alpha, y_\alpha]_A$ satisfies $\alpha(h_\alpha) = 2$, as in Section 17.6.

Let $E_{\mathbf{Q}}$ be the linear subspace of A_0', as a vector space over $\mathbf{Q}$, spanned by Φ, as in Section 17.12. Let $E_{\mathbf{R}}$ be the corresponding vector space over $\mathbf{R}$, as in Section 17.13. Remember that Φ is a reduced root system in $E_{\mathbf{R}}$, as in Section 22.1.

If $\Psi_0 \subseteq \Phi \cup \{0\}$, then let $A(\Psi_0)$ be the linear subspace of A spanned by A_α, $\alpha \in \Psi_0$, as in Section 22.4. Let Δ be a base for Φ, as a root system in $E_{\mathbf{R}}$, and let $\Phi^+ = \Phi^{\Delta,+}$ be the corresponding set of positive roots, which are the elements of Φ that can be expressed as linear combinations of elements of Δ with nonnegative coefficients. Remember that

(24.9.9) $$B_\Delta = A(\Phi^+ \cup \{0\})$$

is a Borel subalgebra of A, as in Section 22.12, which is the standard Borel subalgebra associated to A_0 and Δ.

Let B be any other Borel subalgebra of A. It suffices to show that there is an element of $\mathcal{E}(A)$ that maps B_Δ onto B.

If $B_\Delta \subseteq B$, then $B_\Delta = B$, because B_Δ is maximal among solvable Lie subalgebras of A. Of course, the problem is trivial in this case.

24.9.3 The second induction hypothesis

To continue the proof, we also use induction on the dimension of $B_\Delta \cap B$, as a vector space over k, as on p84 of [14]. If the dimension is equal to the dimension of B_Δ, then $B_\Delta \cap B = B_\Delta$, so that $B_\Delta \subseteq B$, and thus $B_\Delta = B$, as before. If $\widetilde{B}$ is a Borel subalgebra of A such that

$$\dim(B_\Delta \cap \widetilde{B}) > \dim B_\Delta \cap B, \tag{24.9.10}$$

then we suppose from now on that there is an element of $\mathcal{E}(A)$ that maps B_Δ onto $\widetilde{B}$.

Of course, B_Δ depends on the choice of the maximal toral subalgebra A_0 of A, as well as the base Δ for the corresponding root system Φ, as in the previous subsection. In Section 24.12, we shall consider another maximal toral subalgebra of A. Thus A_0 should be considered as an arbitrary maximal toral subalgebra of A here, and Δ as an arbitrary base for the corresponding root system Φ.

As in [14], we consider separately the cases where $B_\Delta \cap B$ is nontrivial or equal to $\{0\}$. In the first case, we consider the subcases where $B_\Delta \cap B$ does or does not have nonzero elements that are ad-nilpotent in A. These two subcases are discussed in the next two sections.

24.10 The first subcase

Let us continue with the same notation and hypotheses as in the previous section. In this section, we suppose that

$$B_\Delta \cap B \neq \{0\}, \tag{24.10.1}$$

and that

(24.10.2) $B_\Delta \cap B$ has a nonzero element that is ad-nilpotent in A.

This corresponds to Case (i) of (1) on p85 of [14].

We may as well suppose too that

$$B_\Delta \cap B \neq B_\Delta, B. \tag{24.10.3}$$

Otherwise, we would have $B_\Delta \subseteq B$ or $B \subseteq B_\Delta$, which would imply that $B_\Delta = B$.

Put

(24.10.4) $$N_\Delta = A(\Phi^+),$$

so that $N_\Delta \subseteq B_\Delta$. Remember that N_Δ is a Lie subalgebra of A that is nilpotent as a Lie algebra over k, and that the elements of N_Δ are ad-nilpotent in A, as in Section 22.6.

If $\alpha \in A_0'$ and $\alpha \neq 0$, then it is easy to see that $[A_0, A_\alpha] = A_\alpha$. This implies that

(24.10.5) $$[B_\Delta, B_\Delta] = N_\Delta,$$

as in Section 22.6.

We would like to check that

(24.10.6) $$N_\Delta = \{v \in B_\Delta : \mathrm{ad}_v \text{ is nilpotent on } A\}.$$

We have seen that N_Δ is contained in the right side, and so we only have to verify that the right side is contained in N_Δ. Note that B_Δ corresponds to the direct sum of A_0 and N_Δ, as a vector space over k.

Let $v \in B_\Delta$ be given, so that v can be expressed as

(24.10.7) $$v = w + u,$$

with $w \in A_0$ and $u \in N_\Delta$. Suppose that $v \notin N_\Delta$, so that $w \neq 0$. We would like to check that ad_v is not nilpotent on A.

Remember that the linear span of Φ in A_0', as a vector space over k, is equal to A_0', as in Section 17.5. This implies that the linear span of Δ in A_0' is equal to A_0', because every element of Φ can be expressed as a linear combination of elements of Δ with coefficients in $\mathbf{Z}$. It follows that $\alpha(w) \neq 0$ for some $\alpha \in \Delta$, because w is a nonzero element of A_0.

Observe that ad_v maps N_Δ into itself, and that N_Δ corresponds to the direct sum of A_β, $\beta \in \Phi^+$, as a vector space over k. If $z \in N_\Delta$, then the component of $\mathrm{ad}_u(z)$ in A_α is equal to 0. This implies that the component of $\mathrm{ad}_v(z)$ in A_α is the same as the component of $\mathrm{ad}_w(z)$ in A_α, which is $\alpha(w)$ times the component of z in A_α. One can use this to get that ad_v is not nilpotent on N_Δ, because $A_\alpha \neq \{0\}$.

24.10.1 Nilpotent elements of $B_\Delta \cap B$

Let N be the set of elements of $B_\Delta \cap B$ that are ad-nilpotent in A, so that $N \neq \{0\}$, by hypothesis. Observe that

(24.10.8) $$N = N_\Delta \cap B,$$

by (24.10.6).

Thus N is a linear subspace of A, and in fact a Lie subalgebra of A. We also have that

(24.10.9) $$[B_\Delta \cap B, B_\Delta \cap B] \subseteq [B_\Delta, B_\Delta] \cap B = N_\Delta \cap B = N.$$

In particular, N is an ideal in $B_\Delta \cap B$, as a Lie algebra over k.

Of course, $x \mapsto \mathrm{ad}_x = \mathrm{ad}_{A,x}$ defines a representation of B on A, as a vector space over k. If $x \in [B, B]$, then ad_x is nilpotent on A, because B is solvable, as in Section 14.14. This implies that

$$B_\Delta \cap [B, B] \subseteq N. \tag{24.10.10}$$

Note that N is nilpotent as a Lie algebra over k, because N_Δ is nilpotent. This means that N is solvable as a Lie algebra over k in particular. It follows that N is not an ideal in A, because A is semisimple, and $N \neq \{0\}$.

Let M be the normalizer of N in A, so that M is a proper Lie subalgebra of A. Clearly

$$B_\Delta \cap B \subseteq M, \tag{24.10.11}$$

because N is an ideal in $B_\Delta \cap B$.

Let us check that

$$B_\Delta \cap B \neq B_\Delta \cap M. \tag{24.10.12}$$

Of course, $B_\Delta \cap B$ is a linear subspace of B_Δ, so that the quotient

$$B_\Delta/(B_\Delta \cap B) \tag{24.10.13}$$

may be considered as a vector space over k. If $x \in N$, then ad_x maps B_Δ and $B_\Delta \cap B$ into themselves, because $x \in B_\Delta \cap B$. This leads to an induced linear mapping from (24.10.13) into iself. More precisely, this induced linear mapping is nilpotent, because ad_x is nilpotent.

The collection of linear mappings from (24.10.13) into itself induced by ad_x, $x \in N$, is a Lie subalgebra of the algebra of all linear mappings from (24.10.13) into itself, because N is a Lie algebra over k. Note that (24.10.13) is nontrivial, by (24.10.3). It follows that there is a nonzero element of (24.10.13) that is sent to 0 by the mapping induced by ad_x for every $x \in N$, as in Section 9.9.

Equivalently, this means that there is a $y \in B_\Delta$ such that $y \notin B$ and $\mathrm{ad}_x(y) \in B_\Delta \cap B$ for every $x \in N$. We also have that $\mathrm{ad}_x(y) \in N_\Delta$ for every $x \in N$, because N_Δ is an ideal in B_Δ. This implies that

$$[y, x] = -\mathrm{ad}_x(y) \in N \tag{24.10.14}$$

for every $x \in N$, so that $y \in M$. It follows that (24.10.12) holds, because $y \in B_\Delta$ and $y \notin B$.

Similarly, let us verify that

$$B_\Delta \cap B \neq B \cap M. \tag{24.10.15}$$

The quotient $B/(B_\Delta \cap B)$ is a nontrivial vector space over k, on which ad_x induces a linear mapping for every $x \in N$. Using the same type of argument as before, we get that there is a $z \in B$ such that $z \notin B_\Delta$ and $\mathrm{ad}_x(z) \in B_\Delta \cap B$ for every $x \in N$.

If $x \in N$, then $[x, z] \in [B, B]$, because $N \subseteq B$ and $z \in B$. This means that

$$[x, z] \in B_\Delta \cap [B, B] \subseteq N, \tag{24.10.16}$$

using (24.10.10) in the second step. It follows that $z \in M$. Thus z is an element of the right side of (24.10.15), and not the left.

24.10.2 Some Borel subalgebras of M and A

Note that $B_\Delta \cap M$, $B \cap M$ are solvable as Lie algebras over k, because B_Δ, B are solvable. Let C_Δ, C be Borel subalgebras of M such that

$$B_\Delta \cap M \subseteq C_\Delta, \quad B \cap M \subseteq C. \tag{24.10.17}$$

Remember that M is a proper Lie subalgebra of A, so that the dimension of M is less than the dimension of A. Thus our induction hypothesis implies that there is an element of $\mathcal{E}(M)$ that maps C onto C_Δ.

Every element of $\mathcal{E}(M)$ can be obtained by restricting an element of $\mathcal{E}(A, M)$ to M. It follows that there is a $\sigma \in \mathcal{E}(A, M) \subseteq \mathcal{E}(A)$ such that

$$\sigma(C) = C_\Delta. \tag{24.10.18}$$

Let B_1 be a Borel subalgebra of A that contains C_Δ. Note that

$$B_\Delta \cap B \subseteq B_\Delta \cap M \subseteq B_\Delta \cap C_\Delta \subseteq B_\Delta \cap B_1, \tag{24.10.19}$$

by (24.10.11) and (24.10.17). We also have that

$$B_\Delta \cap B \neq B_\Delta \cap B_1, \tag{24.10.20}$$

by (24.10.12). This implies that the dimension of $B_\Delta \cap B$ is strictly less than the dimension of $B_\Delta \cap B_1$. This permits us to use our second induction hypothesis, to get an element τ of $\mathcal{E}(A)$ such that

$$\tau(B_1) = B_\Delta. \tag{24.10.21}$$

Combining (24.10.18) and (24.10.21), we obtain that

$$\tau(\sigma(C)) = \tau(C_\Delta) \subseteq \tau(B_1) = B_\Delta. \tag{24.10.22}$$

Observe that

$$\begin{aligned} \tau(\sigma(B_\Delta \cap B)) &\subseteq \tau(\sigma(B \cap M)) \\ &\subseteq \tau(\sigma(C)) \cap \tau(\sigma(B)) \subseteq B_\Delta \cap \tau(\sigma(B)), \end{aligned} \tag{24.10.23}$$

by (24.10.11), (24.10.17), and (24.10.22). We also have that the first inclusion is strict, by (24.10.15).

This shows that the dimension of $B_\Delta \cap B$ is strictly less than the dimension of $B_\Delta \cap \tau(\sigma(B))$. Of course, $\tau(\sigma(B))$ is a Borel subalgebra of A too. Thus we may use our second induction hypothesis again, to get that there is an element of $\mathcal{E}(A)$ that maps B_Δ onto $\tau(\sigma(B))$. This means that there is an element of $\mathcal{E}(A)$ that maps B_Δ onto B, as desired.

24.11 The second subcase

We continue with the same notation and hypotheses as in Section 24.9. In this section, we continue to suppose that $B_\Delta \cap B \neq \{0\}$ as well, and now also that

$$B_\Delta \cap B \text{ does not have any nonzero elements that are ad-nilpotent in } A. \tag{24.11.1}$$

This corresponds to Case (ii) of (1) on p85 of [14].

Let B_0 be a Borel subalgebra of A, and let $x \in B_0$ be given. Remember that there are unique $x_1, x_2 \in A$ such that $x = x_1 + x_2$, $[x_1, x_2]_A = 0$, and ad_{x_1}, ad_{x_2} are the diagonalizable and nilpotent parts of ad_x, as a linear mapping from A into itself, as in Section 14.3. We also have that

$$\mathrm{ad}_{x_1}(B_0), \mathrm{ad}_{x_2}(B_0) \subseteq B_0, \tag{24.11.2}$$

because $\mathrm{ad}_x(B_0) \subseteq B_0$, as in Section 10.8. This means that x_1, x_2 are elements of the normalizer of B_0 in A. It follows that

$$x_1, x_2 \in B_0, \tag{24.11.3}$$

because the normalizer of a Borel subalgebra of A is itself, as in Section 22.7.

If $x \in B_\Delta \cap B$, then the ad-diagonalizable and ad-nilpotent parts of x are elements of $B_\Delta \cap B$ too, by the remarks in the preceding paragraph. This implies that the ad-nilpotent part of x is 0, by hypothesis. This means that every element of $B_\Delta \cap B$ is ad-diagonalizable in A under these conditions.

Of course,

$$T = B_\Delta \cap B \tag{24.11.4}$$

is a Lie subalgebra of A, and in fact a toral subalgebra of A, as in Section 17.1. In particular, T is commutative as a Lie algebra over k, as before. It follows that ad_x, $x \in T$, can be simultaneously diagonalized on A.

Let N_Δ be as in (24.10.4), and note that

$$N_\Delta \cap T = \{0\}, \tag{24.11.5}$$

by hypothesis. Thus

$$[B_\Delta, B_\Delta] \cap T = \{0\}, \tag{24.11.6}$$

by (24.10.5). Of course, this implies that

$$[B_\Delta, T] \cap T = \{0\}, \tag{24.11.7}$$

because $T \subseteq B_\Delta$. It follows that the normalizer of T in B_Δ is the same as the centralizer of T in B_Δ, which is to say that

$$N_{B_\Delta}(T) = C_{B_\Delta}(T). \tag{24.11.8}$$

24.11.1 Reducing to $T \subseteq A_0$

Let C be a Cartan subalgebra of $C_{B_\Delta}(T)$, as a Lie algebra over k. Observe that T is contained in the normalizer $N_{C_{B_\Delta}}(T)(C)$ of C in $C_{B_\Delta}(T)$, by definition of $C_{B_\Delta}(T)$. This implies that

(24.11.9) $$T \subseteq C,$$

because $N_{C_B(T)}(C) = C$, by the definition of a Cartan subalgebra.

Of course, $C_{B_\Delta}(T) \subseteq B_\Delta$, by definition. Let u be an element of the normalizer $N_{B_\Delta}(C)$ of C in B_Δ, and let $t \in T$ be given. Clearly

(24.11.10) $$\mathrm{ad}_t(u) = [t, u]_A \in C,$$

because $t \in C$. This implies that

(24.11.11) $$\mathrm{ad}_t(\mathrm{ad}_t(u)) = 0,$$

because $C \subseteq C_{B_\Delta}(T)$. It follows that

(24.11.12) $$\mathrm{ad}_t(u) = 0,$$

because ad_t is diagonalizable on A, as before.

This shows that $u \in C_{B_\Delta}(T)$, so that

(24.11.13) $$N_{B_\Delta}(C) \subseteq C_{B_\Delta}(T).$$

Using this, it is easy to see that

(24.11.14) $$N_{B_\Delta}(C) = N_{C_{B_\Delta}(T)}(C),$$

by definition of the normalizer. This means that

(24.11.15) $$N_{B_\Delta}(C) = C,$$

because C is a Cartan subalgebra of $C_{B_\Delta}(T)$. Of course, C is nilpotent as a Lie algebra over k, because it is a Cartan subalgebra of $C_{B_\Delta}(T)$. It follows that C is a Cartan subalgebra of B_Δ as well.

Remember that A_0 is a maximal toral subalgebra of A, as in Section 24.9. This implies that A_0 is a Cartan subalgebra of A, as in Section 18.10. We also have that $A_0 \subseteq B_\Delta$, by the definition (24.9.9) of B_Δ. It follows that A_0 is a Cartan subalgebra of B_Δ, as in Section 18.11.

Because B_Δ is solvable as a Lie algebra over k, and A_0, C are Cartan subalgebras of B_Δ, there is an element of $\mathcal{E}(B_\Delta)$ that maps C onto A_0, as in Section 24.7. This implies that there is an element of $\mathcal{E}(A, B_\Delta) \subseteq \mathcal{E}(A)$ that maps C onto A_0, as in Section 24.3. In particular, this element of $\mathcal{E}(A, B_\Delta)$ maps T into A_0. Using this, we can reduce to the case where

(24.11.16) $$T \subseteq A_0.$$

24.11.2 The case where $T = A_0$

Suppose for the moment that $T = A_0$. Remember that $A_0 \neq \{0\}$, as in Section 24.9. We also have $A \neq A_0$, because A is semisimple, and A_0 is commutative as a Lie algebra. This implies that $\Phi \neq \emptyset$, so that $B_\Delta \neq A_0$. Thus A_0 is not a Borel subalgebra of A, and $A_0 \neq B$.

If $T = A_0$, then $A_0 \subseteq B$. If $x \in A_0$, then it follows that ad_x maps B into itself. This implies that the restrictions of the ad_x's, $x \in A_0$, to B are simultaneously diagonalizable on B. Remember that for each $\alpha \in \Phi$, A_α has dimension one as a vector space over k. This means that B corresponds, as a vector space over k, to the direct sum of A_0 and some collection of A_α's. In particular, there is at least one $\alpha_0 \in \Phi$ such that

$$A_{\alpha_0} \subseteq B, \tag{24.11.17}$$

because $B \neq A_0$. More precisely, $\alpha_0 \notin \Phi^+$, because $B_\Delta \cap B = T \subseteq A_0$. Thus $\alpha_0 \in -\Phi^+$.

Let θ_{α_0} be the Lie algebra automorphism of A corresponding to α_0 as in (23.8.1). Note that the Lie subalgebra of A denoted B in Section 23.8 corresponds to A_0 here. It is easy to see that $\theta_{\alpha_0} \in \mathcal{E}(A)$, because x_α, y_α are strongly ad-nilpotent in A, as mentioned in Section 23.9. We also have that

$$\theta_{\alpha_0}(A_0) = A_0 \tag{24.11.18}$$

and

$$\theta_{\alpha_0}(A_{\alpha_0}) = A_{-\alpha_0}. \tag{24.11.19}$$

More precisely, (24.11.18) corresponds to (23.8.4), and can also be obtained from (23.8.6), while (24.11.19) can be obtained from (23.7.9) or (23.8.6).

It follows that $\theta_{\alpha_0}(B)$ is a Borel subalgebra of A with

$$A_0 + A_{-\alpha_0} \subseteq \theta_{\alpha_0}(B). \tag{24.11.20}$$

Of course, $A_0 + A_{-\alpha_0} \subseteq B_\Delta$, because $-\alpha_0 \in \Phi^+$. Thus

$$A_0 + A_{-\alpha_0} \subseteq B_\Delta \cap \theta_{\alpha_0}(B). \tag{24.11.21}$$

In particular, the dimension of $B_\Delta \cap \theta_{\alpha_0}(B)$ is strictly larger than the dimension of $B_\Delta \cap B = T = A_0$, so that our second induction hypothesis implies that there is an element of $\mathcal{E}(A)$ that maps B_Δ onto $\theta_{\alpha_0}(B)$. This implies that there is an element of $\mathcal{E}(A)$ that maps B_Δ onto B, as desired.

24.11.3 The case where $T \neq A_0$, $B \subseteq C_A(T)$

Thus we suppose from now on in this section that

$$T \neq A_0. \tag{24.11.22}$$

Suppose for the moment that

$$B \subseteq C_A(T). \tag{24.11.23}$$

Remember that $T = B_\Delta \cap B \neq \{0\}$, by hypothesis. This implies that

$$C_A(T) \neq A, \tag{24.11.24}$$

because otherwise T would be contained in the center of A, which would contradict the semisimplicity of A.

Observe that

$$A_0 \subseteq C_A(T), \tag{24.11.25}$$

because $T \subseteq A_0$ and A_0 is commutative as a Lie algebra. Let B_1 be a Borel subalgebra of $C_A(T)$, as a Lie algebra over k, that contains A_0. Of course, B may be considered as a Borel subalgebra of $C_A(T)$ too, as in Section 18.11. Thus our first induction hypothesis implies that there is an element of $\mathcal{E}(C_A(T))$ that maps B onto B_1. It follows that there is an element σ of $\mathcal{E}(A, C_A(T)) \subseteq \mathcal{E}(A)$ such that

$$\sigma(B) = B_1, \tag{24.11.26}$$

as in Section 24.3.

Using (24.11.26) we get that B_1 is a Borel subalgebra of A. Note that

$$A_0 \subseteq B_\Delta \cap B_1, \tag{24.11.27}$$

while $B_\Delta \cap B = T$ is a proper linear subspace of A_0. This means that the dimension of $B_\Delta \cap B$ is strictly less than the dimension of $B_\Delta \cap B_1$, so that our second induction hypothesis implies that there is an element of $\mathcal{E}(A)$ that maps B_Δ onto B_1. It follows that there is an element of $\mathcal{E}(A)$ that maps B_Δ onto B, by (24.11.26).

24.11.4 The case where $T \neq A_0$, $B \not\subseteq C_A(T)$

Suppose for the rest of the section that (24.11.23) does not hold. This means that there is a $t_1 \in T$ such that ad_{t_1} is not identically zero on B. Note that ad_{t_1} maps B into itself, because $T \subseteq B$ and B is a Lie subalgebra of A. We also have that ad_{t_1} is diagonalizable on B, because it is diagonalizable on A. It follows that there is an $a_1 \in k$ and $x_1 \in B$ such that $a_1 \neq 0$, $x_1 \neq 0$, and

$$\mathrm{ad}_{t_1}(x_1) = a_1\, x_1. \tag{24.11.28}$$

Remember that if $\Psi_0 \subseteq \Phi \cup \{0\}$, then $A(\Psi_0)$ is the linear subspace of A spanned by A_α, $\alpha \in \Psi_0$, as in Subsection 24.9.2. Put

$$\Psi_1 = \{\alpha \in \Phi : \alpha(t_1) = a_1\} \tag{24.11.29}$$

and

$$\Psi_2 = \{\alpha \in \Phi : \alpha(t_1) = n \cdot a_1 \text{ for some } n \in \mathbf{Z}_+\}, \tag{24.11.30}$$

so that $\Psi_1 \subseteq \Psi_2$. One can use (24.11.28) to check that

$$x_1 \in A(\Psi_1). \tag{24.11.31}$$

One can also verify that $A(\Psi_2)$, $A(\Psi_2 \cup \{0\})$ are Lie subalgebras of A, with $A(\Psi_2)$ nilpotent, and $A(\Psi_2 \cup \{0\})$ solvable. More precisely, this can be obtained as in Section 22.5.

Let B_2 be a Borel subalgebra of A that contains $A(\Psi_2 \cup \{0\})$. Thus

$$A_0 \subseteq B_\Delta \cap B_2, \tag{24.11.32}$$

which implies that the dimension of $B_\Delta \cap B = T$ is strictly less than the dimension of $B_\Delta \cap B_2$, because T is a proper linear subspace of A_0. Using our second induction hypothesis, we get that there is an element σ_2 of $\mathcal{E}(A)$ such that

$$\sigma_2(B_\Delta) = B_2. \tag{24.11.33}$$

Observe that

$$x_1 \in B_2 \cap B, \tag{24.11.34}$$

using (24.11.31). Clearly $T \subseteq A_0 \subseteq B_2$, so that

$$T \subseteq B_2 \cap B. \tag{24.11.35}$$

Of course, x_1 is not in T, by (24.11.28). This implies that $B_\Delta \cap B = T$ is a proper linear subspace of $B_2 \cap B$. In particular, the dimension of $B_\Delta \cap B$ is strictly less than the dimension of $B_2 \cap B$.

It follows that the dimension of $B_\Delta \cap B$ is strictly less than the dimension of

$$\sigma_2^{-1}(B_2 \cap B) = B_\Delta \cap \sigma_2^{-1}(B). \tag{24.11.36}$$

Note that $\sigma_2^{-1}(B)$ is a Borel subalgebra of A, so that our second induction hypothesis implies that there is an element of $\mathcal{E}(A)$ that maps B_Δ onto $\sigma_2^{-1}(B)$. This implies that there is an element of $\mathcal{E}(A)$ that maps B_Δ onto B, as desired.

24.12 The second case

We continue with the same notation and hypotheses as in Section 24.9 again. The arguments in the previous two sections show that if $B_\Delta \cap B \neq \{0\}$, then there is an element of $\mathcal{E}(A)$ that maps B_Δ onto B. More precisely, this works for any choice of maximal toral subalgebra A_0 of A, and base Δ for the corresponding root system Φ, as in Subsection 24.9.3.

In this section, we suppose that

$$B_\Delta \cap B = \{0\}. \tag{24.12.1}$$

This corresponds to (2) on p86 of [14].

Remember that A corresponds to the direct sum of A_α, $\alpha \in \Phi \cup \{0\}$, as a vector space over k, as in Subsection 24.9.2. In particular, the dimension of A, as a vector space over k, is given by

$$\dim A = \dim A_0 + \#\Phi, \tag{24.12.2}$$

where $\#\Phi$ is the number of elements of Φ, because A_α has dimension one as a vector space over k when $\alpha \in \Phi$. Similarly,

$$\dim B_\Delta = \dim A(\Phi^+ \cup \{0\}) = \dim A_0 + \#\Phi^+. \tag{24.12.3}$$

Note that

$$\#\Phi^+ = \#\Phi/2, \tag{24.12.4}$$

because Φ is the union of Φ^+ and $-\Phi^+$, which are disjoint. Thus

$$\dim B_\Delta = \dim A_0 + \#\Phi/2. \tag{24.12.5}$$

It follows that

$$(\dim A)/2 < \dim B_\Delta, \tag{24.12.6}$$

because $A_0 \neq \{0\}$. We also have that

$$\dim B_\Delta + \dim B \leq \dim A, \tag{24.12.7}$$

by (24.12.1). This means that

$$\dim B < (\dim A)/2. \tag{24.12.8}$$

Suppose for the moment that every element of B is ad-nilpotent in A. Of course, this implies that every element of B is ad-nilpotent in B. It follows that B is nilpotent as a Lie algebra over k, as in Section 9.10.

Remember that the normalizer of B in A is equal to B, because B is a Borel subalgebra of A, as in Section 22.7. This means that B is a Cartan subalgebra of A.

Under these conditions, we get that B is a toral subalgebra of A, as in Section 18.10. Thus the elements of B are ad-diagonalizble in A. This implies that $B = \{0\}$, because the elements of B are also supposed to be ad-nilpotent in A. This contradicts the hypothesis that B be a Borel subalgebra of A, since $A \neq \{0\}$.

Thus we may suppose now that B has an element that is not ad-nilpotent in A. Remember that B contains the ad-diagonalizable and ad-nipotent parts of its elements, as in (24.11.3). It follows that B has a nonzero element x_0 that is ad-diagonalizable in A.

Let T_0 be a maximal toral subalgebra of A that contains x_0. Using any base for the root system corresponding to T_0, we get a standard Borel subalgebra B_0 of A with respect to T_0, as in Subsection 24.9.2. Note that $T_0 \subseteq B_0$, so that

$$B_0 \cap B \neq \{0\}. \tag{24.12.9}$$

This implies that there is an element of $\mathcal{E}(A)$ that maps B_0 onto B, as mentioned at the beginning of the section. In particular,

$$\dim B = \dim B_0. \tag{24.12.10}$$

However, $\dim B_0 > (\dim A)/2$, as in (24.12.6). This contradicts (24.12.8).

This shows that (24.12.1) is not possible. It follows that there is an element of $\mathcal{E}(A)$ that maps B_Δ onto B. This completes the proof of the theorem stated at the beginning of Section 24.9.

24.13 Some consequences

Let k be an algebraically closed field of characteristic 0 again, and let $(A, [\cdot,\cdot]_A)$ be a finite-dimensional Lie algebra over k. The *rank* of A as a Lie algebra over k may be defined as the dimension of any Cartan subalgebra of A, as on p86 of [14]. The corollary stated at the beginning of Section 24.9 implies that

(24.13.1) the rank of A does not depend on the choice of the Cartan subalgebra.

The rank of a finite-dimensional complex Lie algebra is defined another way in Definition 2 on p11 of [24], and Corollary 1 on p13 of [24] states that these two definitions are equivalent.

Suppose now that $A \neq \{0\}$ is semisimple, as a Lie algebra over k. Let A_0 be a maximal toral subalgebra of A, and let Φ be the corresponding root system, as in Subsection 24.9.2. Also let Δ be a base for Φ, and B_Δ be the standard Borel subalgebra of A associated to A_0 and Δ, as in Subsection 24.9.2.

Suppose that N is a Lie subalgebra of A such that every element of N is ad-nilpotent as an element of A. In particular, every element of N is ad-nilpotent as an element of N, so that N is nilpotent as a Lie algebra over k, as in Section 9.10. Of course, this implies that N is solvable as a Lie algebra over k, so that there is a Borel subalgebra B of A that contains N.

The theorem stated at the beginning of Section 24.9 implies that there is an element σ of $\mathcal{E}(A)$ such that $\sigma(B) = B_\Delta$. In particular, $\sigma(N) \subseteq B_\Delta$. In fact,

$$\sigma(N) \subseteq N_\Delta, \tag{24.13.2}$$

where N_Δ is as in (24.10.4). This follows from (24.10.6), because the elements of $\sigma(N)$ are ad-nilpotent in A. This corresponds to Exercise 2 on p87 of [14], and the corollary to Theorem 5 on p48 of [24].

Note that the standard Borel subalgebras of A associated to A_0 and any base for Φ contain A_0, by construction. Conversely, let B be any Borel subalgebra of A such that

$$A_0 \subseteq B. \tag{24.13.3}$$

Under these conditions,

(24.13.4) B is a standard Borel subalgebra of A with respect to A_0 and some base for Φ,

as mentioned on p86 of [14].

To see this, let Δ be a base for Φ again, and let B_Δ be the corresponding standard Borel subalgebra of A, as before. Remember that there is an element σ of $\mathcal{E}(A)$ such that $\sigma(B_\Delta) = B$, by the theorem stated at the beginning of Section 24.9. In particular,

$$\sigma(A_0) \subseteq \sigma(B_\Delta) \subseteq B. \tag{24.13.5}$$

Remember that A_0 is a Cartan subalgebra of A, as in Section 18.10. Of course, this implies that $\sigma(A_0)$ is a Cartan subalgebra of A too. It follows that A_0 and $\sigma(A_0)$ may be considered as Cartan subalgebras of B, as in Section 18.11.

Thus there is an element of $\mathcal{E}(B)$ that maps $\sigma(A_0)$ onto A_0, as in Section 24.7. This implies that there is an element τ of $\mathcal{E}(A, B) \subseteq \mathcal{E}(A)$ such that

$$\tau(\sigma(A_0)) = A_0, \tag{24.13.6}$$

as in Section 24.3. Note that

$$\tau(\sigma(B_\Delta)) = \tau(B) = B. \tag{24.13.7}$$

Put $\sigma_1 = \tau \circ \sigma \in \mathcal{E}(A)$, so that $\sigma_1(A_0) = A_0$ and $\sigma_1(B_\Delta) = B$. Let σ_0 be the restriction of σ_1 to A_0, and let σ_0' be the corresponding dual linear mapping from the dual A_0' of A_0 into itself. If $\alpha \in A_0'$ and A_α is as in Subsection 24.9.2, then

$$\sigma_1(A_{\sigma_0'(\alpha)}) = A_\alpha \tag{24.13.8}$$

for every $\alpha \in A_0'$, as in Section 23.6. In particular,

$$\sigma_0'(\Phi) = \Phi, \tag{24.13.9}$$

as before.

Let $E_{\mathbf{Q}}$ be the linear subspace of A_0', as a vector space over $\mathbf{Q}$, spanned by Φ, as in Subsection 24.9.2. Thus

$$\sigma_0'(E_{\mathbf{Q}}) = E_{\mathbf{Q}}, \tag{24.13.10}$$

by (24.13.9), as in Section 23.6. This leads to a one-to-one linear mapping from the corresponding real vector space $E_{\mathbf{R}}$ onto itself, which is an automorphism of Φ as a root system in $E_{\mathbf{R}}$, as before. Using this, one can check that

$$\widetilde{\Delta} = (\sigma_0')^{-1}(\Delta) \tag{24.13.11}$$

is a base for Φ as a root system in $E_{\mathbf{R}}$ too.

Let $B_{\widetilde{\Delta}}$ be the standard Borel subalgebra of A associated to A_0 and $\widetilde{\Delta}$ as in Subsection 24.9.2. One can verify that

$$\sigma_1(B_\Delta) = B_{\widetilde{\Delta}}, \tag{24.13.12}$$

using (24.13.8). This means that

$$B = B_{\widetilde{\Delta}}, \tag{24.13.13}$$

as desired, because $\sigma_1(B_\Delta) = B$, by construction.

24.14 The case of $sl_2(k)$

Exercise 4 on p87 of [14] asks one to consider simplifications of the proof of the theorem stated at the beginning of Section 24.9, in the case where the Lie algebra is $sl_2(k)$. Let us begin with a preliminary remark.

Let k be an algebraically closed field, and let $(A, [\cdot,\cdot]_A)$ be a Lie algebra over k of finite dimension at least 2. Suppose that x is a nonzero element of A, so that the quotient

$$A/\{t\,x : t \in k\} \tag{24.14.1}$$

may be considered as a vector space over k of positive finite dimension. Note that ad_x induces a linear mapping from (24.14.1) into itself. This mapping has a nonzero eigenvector in (24.14.1), because k is algebraically closed.

Equivalently, there is an element y of A such that x and y are linearly independent in A, and $\mathrm{ad}_x(y)$ can be expressed as a linear combination of x and y. This means that the linear span of x and y is a 2-dimensional Lie subalgebra of A, which is solvable as a Lie algebra over k. It follows that

(24.14.2) every Borel subalgebra of A has dimension at least two

under these conditions.

Now let k be an algebraically closed field of characteristic 0, as in Section 24.9. Note that the Borel subalgebras of $sl_2(k)$ are proper subalgebras of $sl_2(k)$, because $sl_2(k)$ is not solvable. This implies that every Borel subalgebra of $sl_2(k)$ has dimension two as a vector space over k, by (24.14.2). Conversely, every two-dimensional Lie subalgebra of $sl_2(k)$ is solvable, and thus a Borel subalgebra.

Let $x = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}$, $y = \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix}$, and $h = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$ be the usual basis for $sl_2(k)$, as a vector space over k. Thus $[x, y] = h$, $[h, x] = 2 \cdot x$, and $[h, y] = -2 \cdot y$, as before. The linear span of h is a maximal toral subalgebra of $sl_2(k)$, for which Φ corresponds to the linear functionals defined by multiplication by 2 and -2. The linear functional defined by multiplication by 2 may be considered as a base for Φ as a root system, for which the corresponding standard Borel subalgebra B_Δ of $sl_2(k)$ is spanned by h and x.

Let B be any Borel subalgebra of $sl_2(k)$, so that B has dimension two as a vector space over k, as before. In particular, $B_\Delta \cap B \neq \{0\}$ in this case. We would like to show that there is an element of $\mathcal{E}(sl_2(k))$ that maps B_Δ onto B. Of course, this is trivial when $B = B_\Delta$, and so we may suppose that $B \neq B_\Delta$.

Suppose for the moment that $x \in B$. If $B \subseteq B_\Delta$, then $B = B_\Delta$, and so we may suppose that $B \not\subseteq B_\Delta$. Thus

$$a\,x + b\,y + c\,h \in B \tag{24.14.3}$$

for some $a, b, c \in k$, with $b \neq 0$. This implies that

$$[x, a\,x + b\,y + c\,h] = b\,h - 2\,c\,x \in B, \tag{24.14.4}$$

because $x \in B$ and B is a Lie subalgebra of $sl_2(k)$. It follows that $h \in B$, because $x \in B$. This means that $y \in B$, by (24.14.3), which is to say that $B = sl_2(k)$. This is a contradiction, because $sl_2(k)$ is not solvable.

Thus we may suppose that $x \notin B$. It follows that

$$a\,x + h \in B \tag{24.14.5}$$

for some $a \in k$, because $B_\Delta \cap B \neq \{0\}$. One can use the exponential of a multiple of ad_x to reduce to the case where $h \in B$. Using this, one can check that either $B = B_\Delta$, or B is spanned by y and h. If B is spanned by y and h, then $B = \sigma(B_\Delta)$, where $\sigma \in \mathcal{E}(sl_2(k))$ is as in Section 15.7.

24.15 Automorphisms and semisimplicity

Let k be an algebraically closed field of characteristic 0, and let $(A, [\cdot,\cdot]_A)$ be a semisimple Lie algebra over k of positive finite dimension. Also let A_0 be a maximal toral subalgebra of A, and let Φ be the corresponding root system, as in Subsection 24.9.2. Choose a base Δ for Φ, and let B_Δ be the standard Borel subalgebra of A associated to A_0 and Δ, as before.

Suppose that τ is an automorphism of A, as a Lie algebra over k. Thus $\tau(B)$ is another Borel subalgebra of A. The theorem stated at the beginning of Section 24.9 implies that there is an element σ_1 of $\mathcal{E}(A)$ such that

$$\sigma_1(\tau(B_\Delta)) = B_\Delta. \tag{24.15.1}$$

Remember that A_0 is a Cartan subalgebra of A, as in Section 18.10. This implies that $\sigma_1(\tau(A_0))$ is a Cartan subalgebra of A as well. It follows that A_0 and $\sigma_1(\tau(A_0))$ are Cartan subalgebras of B_Δ too, as a Lie algebra over k, as in Section 18.11. Thus there is an element of $\mathcal{E}(B_\Delta)$ that maps $\sigma_1(\tau(A_0))$ onto A_0, as in Section 24.7. This means that there is an element σ_2 of $\mathcal{E}(A, B_\Delta) \subseteq \mathcal{E}(A)$ with

$$\sigma_2(\sigma_1(\tau(A_0))) = A_0, \tag{24.15.2}$$

as in Section 24.3.

Put

$$\tau_2 = \sigma_2 \circ \sigma_1 \circ \tau, \tag{24.15.3}$$

which is an automorphism of A that maps A_0 onto itself. Let $\tau_{2,0}$ be the restriction of τ_2 to A_0, and let $\tau'_{2,0}$ be the corresponding dual linear mapping from A'_0 into itself. Thus

$$\tau_2(A_{\tau'_{2,0}(\alpha)}) = A_\alpha \tag{24.15.4}$$

for every $\alpha \in A'_0$, as in Section 23.6, where A_α is as in Subsection 24.9.2. This implies that

$$\tau'_{2,0}(\Phi) = \Phi, \tag{24.15.5}$$

as before.

It follows that

$$\tau'_{2,0}(E_{\mathbf{Q}}) = E_{\mathbf{Q}}, \tag{24.15.6}$$

as in Section 23.6, where $E_{\mathbf{Q}}$ is the linear subspace of A'_0, as a vector space over $\mathbf{Q}$, spanned by Φ. As before, this leads to a one-to-one linear mapping from the corresponding real vector space $E_{\mathbf{R}}$ onto itself, which is an automorphism of Φ as a root system in $E_{\mathbf{R}}$.

Note that

$$\tau_2(B_\Delta) = B_\Delta, \tag{24.15.7}$$

by (24.15.1), and because $\sigma_2 \in \mathcal{E}(A, B_\Delta)$. Let Φ^+ be the set of positive roots with respect to Δ, as in Subsection 24.9.2. One can check that

$$\tau'_{2,0}(\Phi^+) = \Phi^+, \tag{24.15.8}$$

using (24.15.4) and (24.15.7).

Using (24.15.8), one can verify that

$$\tau'_{2,0}(\Delta) = \Delta. \tag{24.15.9}$$

More precisely, Δ consists of exactly the elements of Φ^+ that cannot be expressed as the sum of at least two other elements of Φ^+.

We shall see in Section 28.6 that every automorphism of Φ as a root system that sends Δ onto itself corresponds to an automorphism of A that maps A_0 onto itself. This also uses the remarks in Section 28.7.

The automorphisms of A that are equal to the identity mapping on A_0 are called *diagonal automorphisms*, and they will be discussed further in Sections 28.6 and 29.7.

This corresponds to some remarks on p87 of [14].

Part IV

Some related constructions

Chapter 25

Universal enveloping algebras

25.1 Polynomial algebras

Let I be a nonempty set, and let $\mathcal{M}_I$ be the set of functions α on I with values in the set $\mathbf{Z}_+ \cup \{0\}$ of nonnegative integers such that $\alpha(j) = 0$ for all but finitely many $j \in I$. The elements of $\mathcal{M}_I$ are considered as *multi-indices* with respect to I, which reduces to the usual notion when $I = \{1, \dots, n\}$ for some positive integer n. If $\alpha \in \mathcal{M}_I$, then we put

$$|\alpha| = \sum_{j \in I} \alpha(j), \tag{25.1.1}$$

which reduces to a finite sum. If $\beta \in \mathcal{M}_I$ too, then $\alpha + \beta \in \mathcal{M}_I$, and

$$|\alpha + \beta| = |\alpha| + |\beta|. \tag{25.1.2}$$

Let X_j, $j \in I$, be a commuting family of indeterminates. If $\alpha \in \mathcal{M}_I$, then X^α is considered as a formal monomial in the X_j's of degree $|\alpha|$. This may be identified with the formal product

$$X_{j_1}^{\alpha(j_1)} \cdots X_{j_n}^{\alpha(j_n)} \tag{25.1.3}$$

when $j_1, \dots, j_n$ are finitely many distinct elements of I, and $\alpha(j) = 0$ for every $j \in I \setminus \{j_1, \dots, j_n\}$. If $\beta \in \mathcal{M}_I$ as well, then the corresponding product of formal monomials can be defined as usual by

$$X^\alpha \cdot X^\beta = X^{\alpha + \beta}. \tag{25.1.4}$$

Let k be a commutative ring with a multiplicative identity element. A *formal polynomial* in the X_j's, $j \in I$, with coefficients in k can be expressed as

$$f(X) = \sum_{\alpha \in \mathcal{M}_I} f_\alpha \, X^\alpha, \tag{25.1.5}$$

where $f_\alpha \in k$ for every $\alpha \in \mathcal{M}_I$, and $f_\alpha = 0$ for all but finitely many $\alpha \in \mathcal{M}_I$. The space $k[\{X_j : j \in I\}]$ of these formal polynomials can be defined as the space $c_{00}(\mathcal{M}_I, k)$ of all k-valued functions on $\mathcal{M}_I$ with finite support, which is to say that are equal to 0 at all but finitely many elements of $\mathcal{M}_I$. This is a submodule of the space $c(\mathcal{M}_I, k)$ of all k-valued functions on $\mathcal{M}_I$, as a module over k with respect to pointwise addition and scalar multiplication of functions. Of course, this corresponds to termwise addition and scalar multiplication of formal polynomials as in (25.1.5).

Let

$$g(X) = \sum_{\beta \in \mathcal{M}_I} g_\beta \, X^\beta \tag{25.1.6}$$

be another formal polynomial in the X_j's, $j \in I$, with coefficients in k. If $\gamma \in \mathcal{M}_I$, then put

$$h_\gamma = \sum_{\alpha+\beta=\gamma} f_\alpha \, g_\beta, \tag{25.1.7}$$

where more precisely the sum is taken over all $\alpha, \beta \in \mathcal{M}_I$ such that $\alpha + \beta = \gamma$. It is easy to see that there are only finitely many such $\alpha, \beta \in \mathcal{M}_I$, so that the right side of (25.1.7) is a finite sum in k. We also have that (25.1.7) is equal to 0 for all but finitely many $\gamma \in \mathcal{M}_I$, because of the analogous conditions for f_α and g_β. Thus

$$h(X) = \sum_{\gamma \in \mathcal{M}_I} h_\gamma \, X^\gamma \tag{25.1.8}$$

is a formal polynomial in the X_j's, $j \in I$, with coefficients in k, and we put $f(X)\, g(X) = h(X)$. One can check that $k[X_j : j \in I\}]$ is a commutative associative algebra over k with respect to this definition of multiplication. Let us identify elements of k with the formal polynomials whose coefficients of X^α are equal to 0 when α is a nonzero element of $\mathcal{M}_I$, and are equal to the given element of k when $\alpha = 0$. This is a subalgebra of $k[\{X_j : j \in I\}]$, and $1 \in k$ corresponds to the multiplicative identity element in $k[\{X_j : j \in I\}]$.

Let B be an associative algebra over k with a multiplicative identity element e_B, and let b_j be an element of B for each $j \in I$. The Cartesian power B^I is the same as the Cartesian product of the family of copies of B indexed by I, and we let b be the element of B^I whose jth coordinate is equal to b_j for each $j \in I$. Suppose that the b_j's commute in B, which is to say that

$$b_j \, b_l = b_l \, b_j \tag{25.1.9}$$

for every $j, l \in I$. If $\alpha \in \mathcal{M}_I$, and $j_1, \ldots, j_n$ are finitely many distinct elements of I such that $\alpha(j) = 0$ when $j \in I \setminus \{j_1, \ldots, j_n\}$, then put

$$b^\alpha = b_{j_1}^{\alpha(j_1)} \cdots b_{j_n}^{\alpha(j_n)}. \tag{25.1.10}$$

As usual, $b_j^{\alpha(j)}$ is interpreted as being e_B when $\alpha(j) = 0$, so that the right side of (25.1.10) does not depend on the choice of $j_1, \ldots, j_n$. If $\beta \in \mathcal{M}_I$ too, then

$$b^{\alpha+\beta} = b^\alpha \, b^\beta, \tag{25.1.11}$$

because of (25.1.9). If $f(X)$ is as in (25.1.5), then put

$$f(b) = \sum_{\alpha \in \mathcal{M}_I} f_\alpha \, b^\alpha, \tag{25.1.12}$$

which reduces to a finite sum in B. It is easy to see that $f(X) \mapsto f(b)$ defines an algebra homomorphism from $k[\{X_j : j \in I\}]$ into B.

25.2 Tensor products of associative algebras

Let k be a commutative ring with a multiplicative identity element, and let B_1, B_2 be associative algebras over k. Thus B_1, B_2 are modules over k in particular, and we take $B = B_1 \bigotimes B_2$, as a module over k. If $b_1, b_1' \in B_1$ and $b_2, b_2' \in B_2$, then

$$(b_1 \, b_1') \otimes (b_2 \, b_2') \tag{25.2.1}$$

is an element of B, and this defines a multilinear mapping from $B_1 \times B_2 \times B_1 \times B_2$ into B. This multilinear mapping corresponds to a unique linear mapping from $B_1 \bigotimes B_2 \bigotimes B_1 \bigotimes B_2$ into B, as usual. Remember that $B_1 \bigotimes B_2 \bigotimes B_1 \bigotimes B_2$ can be identified with $B \bigotimes B$, as in Section 7.15. This leads to a bilinear mapping from $B \times B$ into B, by composing the standard bilinear mapping from $B \times B$ into $B \bigotimes B$ with the previous linear mapping from $B \bigotimes B$ into B. This bilinear mapping is used to define multiplication on B. By construction,

$$(b_1 \otimes b_2) \, (b_1' \otimes b_2') = (b_1 \, b_1') \otimes (b_2 \, b_2') \tag{25.2.2}$$

in B for every $b_1, b_1' \in B_1$ and $b_2, b_2' \in B_2$. One can check that multiplication on B is associative, because multiplication is associative on B_1 and B_2, by hypothesis. If multiplication is commutative on B_1 and B_2, then multiplication on B is commutative as well.

Suppose for the moment that B_1 and B_2 have multiplicative identity elements e_1 and e_2, respectively. In this case, $e_1 \otimes e_2$ is the multiplicative identity element in B. Observe that

$$b_1 \mapsto b_1 \otimes e_2 \tag{25.2.3}$$

and

$$b_2 \mapsto e_1 \otimes b_2 \tag{25.2.4}$$

are algebra homomorphisms from B_1 and B_2 into B. We also have that

$$(b_1 \otimes e_2) \, (e_1 \otimes b_2) = (e_1 \otimes b_2) \, (b_1 \otimes e_2) = b_1 \otimes b_2 \tag{25.2.5}$$

for every $b_1 \in B_1$ and $b_2 \in B_2$.

Let C be another associative algebra over k, and let ϕ_1, ϕ_2 be algebra homomorphisms from B_1, B_2 into C, respectively. Suppose that

$$\phi_1(b_1) \, \phi_2(b_2) = \phi_2(b_2) \, \phi_1(b_1) \tag{25.2.6}$$

for every $b_1 \in B_1$ and $b_2 \in B_2$. Of course, $(b_1, b_2) \mapsto \phi_1(b_1)\,\phi_2(b_2)$ is a bilinear mapping from $B_1 \times B_2$ into C. This leads to a unique linear mapping ϕ from B into C, with

$$\phi(b_1 \otimes b_2) = \phi_1(b_1)\,\phi_2(b_2) \tag{25.2.7}$$

for every $b_1 \in B_1$ and $b_2 \in B_2$. One can verify that ϕ is an algebra homomorphism from B into C under these conditions.

25.3 Tensor algebras

Let k be a commutative ring with a multiplicative identity element, and let V be a module over k. If n is a positive integer, then let V^n be the space of n-tuples of elements of V, which is the same as the Cartesian product of n copies of V. Remember that the nth tensor power $T^n V$ of V is defined as a module over k as in Section 7.15, as the tensor product of n copies of V. This is interpreted as being equal to V when $n = 1$, as before. In particular, the mapping from $(v_1, \ldots, v_n) \in V^n$ to $v_1 \otimes \cdots \otimes v_n \in T^n V$ is multilinear over k.

Let n_1 and n_2 be positive integers, and remember that there is a natural isomorphism between $(T^{n_1} V) \bigotimes (T^{n_2} V)$ and $T^{n_1 + n_2} V$, as modules over k, as in Section 7.15. There is also a natural bilinear mapping from $T^{n_1} V \times T^{n_2} V$ into $(T^{n_1} V) \bigotimes (T^{n_2} V)$, by the definition of the tensor product. This leads to a natural bilinear mapping from $(T^{n_1} V) \times (T^{n_2} V)$ into $T^{n_1 + n_2} V$. If $a_1 \in T^{n_1} V$ and $a_2 \in T^{n_2} V$, then let $a_1\, a_2$ be the image of (a_1, a_2) in $T^{n_1 + n_2} V$ under this mapping. If $a_1 = v_1 \otimes \cdots \otimes v_{n_1}$ and $a_2 = w_1 \otimes \cdots \otimes w_{n_2}$ for some $v_1, \ldots, v_{n_1}$ and $w_1, \ldots, w_{n_2}$ in V, then

$$(v_1 \otimes \cdots \otimes v_{n_1})\,(w_1 \otimes \cdots \otimes w_{n_2}) = v_1 \otimes \cdots \otimes v_{n_1} \otimes w_1 \otimes \cdots \otimes w_{n_2} \tag{25.3.1}$$

in $T^{n_1 + n_2} V$, by construction.

It is customary to define $T^n V$ when $n = 0$ to be k, as a module over itself. If W is any module over k, then scalar multiplication on W can be used to define bilinear mappings from $k \times W$ and from $W \times k$ into W. This leads to standard isomorphisms from $k \bigotimes W$ and from $W \bigotimes k$ onto W, as modules over k. In particular, we have a natural bilinear mapping from $T^{n_1} V \times T^{n_2} V$ into $T^{n_1 + n_2} V$ when $n_1 = 0$ or $n_2 = 0$ as well. If $a_1 \in T^{n_1} V$, $a_2 \in T^{n_2} V$, and $a_3 \in T^{n_3} V$ for some nonnegative integers n_1, n_2, n_3, then one can check that

$$(a_1 a_2)\, a_3 = a_1\, (a_2\, a_3) \tag{25.3.2}$$

in $T^{n_1 + n_2 + n_3} V$.

The *tensor algebra* on V is denoted TV, and defined initially as a module over k to be the direct sum of $T^n V$ over all nonnegative integers n,

$$TV = \bigoplus_{n=0}^{\infty} T^n V. \tag{25.3.3}$$

There is a natural bilinear mapping from $(TV) \times (TV)$ into TV, which is defined using the natural bilinear mapping from $(T^{n_1} V) \times (T^{n_2} V)$ into $T^{n_1 + n_2} V$ for

$n_1, n_2 \geq 0$ mentioned in the previous two paragraphs. If $a, b \in TV$, then let $a\, b$ be the image of (a, b) in TV under this mapping. It is easy to see this definition of multiplication on TV is associative, using (25.3.2). We may consider $k = T^0 V$ as a subalgebra of TV, and the multiplicative identity element 1 in k is the multiplicative identity element in TV too.

Let A be an associative algebra over k with a multiplicative identity element e, and let ϕ be a homomorphism from V into A, as modules over k. If n is a positive integer, then there is a natural multilinear mapping from V^n into A, which sends $(v_1, \ldots, v_n) \in V^n$ to $\phi(v_1) \cdots \phi(v_n)$. This leads to a unique linear mapping ψ_n from $T^n V$ into A, with

$$\psi_n(v_1 \otimes \cdots \otimes v_n) = \phi(v_1) \cdots \phi(v_n) \tag{25.3.4}$$

for every $(v_1, \ldots, v_n) \in V^n$. Put $\psi_0(t) = t\, e$ for every $t \in k = T^0 V$. If $a_1 \in T^{n_1} V$ and $a_2 \in T^{n_2} V$ for some $n_1, n_2 \geq 0$, then one can check that

$$\psi_{n_1+n_2}(a_1\, a_2) = \psi_{n_1}(a_1)\, \psi_{n_2}(a_2). \tag{25.3.5}$$

Let ψ be the mapping from TV into A which corresponds to ψ_n on $T^n V$ for every $n \geq 0$. This defines an algebra homomorphism from TV into A, because of (25.3.5). More precisely, this is the unique algebra homomorphism from TV into A that is equal to ϕ on $V = T^1 V$ and sends $1 \in k = T^0 V$ to e. Note that every algebra homomorphism ψ from TV into A with $\psi(1) = e$ occurs in this way, where ϕ corresponds to ψ on $V = T^1 V$. This corresponds to some of the remarks on p11 of [25], and on p89 of [14].

25.4 Defining universal enveloping algebras

Let k be a commutative ring with a multiplicative identity element, and let $(A, [\cdot, \cdot]_A)$ be a Lie algebra over k. A *universal enveloping algebra* of A is an associative algebra UA over k with a multiplicative identity element $e = e_{UA}$ and a mapping $i = i_{UA}$ from A into UA with the following two properties. First, i is a Lie algebra homomorphism from A into UA, considered as a Lie algebra over k with respect to the corresponding commutator bracket. This means that i is a homomorphism from A into UA as modules over k such that

$$i([x, y]_A) = i(x)\, i(y) - i(y)\, i(x) \tag{25.4.1}$$

for every $x, y \in A$.

Second, let B be an associative algebra over k with a multiplicative identity element e_B, and let ϕ be a Lie algebra homomorphism from A into B, as a Lie algebra over k with respect to the corresponding commutator bracket. As before, this means that ϕ is a homomorphism from A into B, as modules over k, such that

$$\phi([x, y]_A) = \phi(x)\, \phi(y) - \phi(y)\, \phi(x) \tag{25.4.2}$$

for every $x, y \in B$. Under these conditions, there should be a unique algebra homomorphism ψ from UA into B such that $\psi(e_{UA}) = e_B$ and

$$\psi \circ i = \phi \tag{25.4.3}$$

on A. This corresponds to Definition 1.1 on p11 of [25], and to the definition on p90 of [14].

In particular, we can apply the second condition to $B = UA$ and $\phi = i$. This implies that there is a unique algebra homomorphism ψ from UA into itself such that $\psi(e_{UA}) = e_{UA}$ and $\psi \circ i = i$. The identity mapping on UA satisfies these properties, which means that the identity mapping on UA is the only mapping on UA with these properties.

It is easy to see that the pair (UA, i) is unique when it exists, up to isomorphic equivalence. Indeed, let $\widetilde{U}A$ be another associative algebra over k with a multiplicative identity element $e_{\widetilde{U}A}$ and a Lie algebra homomorphism $i_{\widetilde{U}A}$ from A into $\widetilde{U}A$ that is a universal enveloping algebra over A. Because i_{UA} and $i_{\widetilde{U}A}$ are Lie algebra homomorphisms, there are unique algebra homomorphisms ψ from UA into $\widetilde{U}A$ and $\widetilde{\psi}$ from $\widetilde{U}A$ into UA such that $\psi(e_{UA}) = e_{\widetilde{U}A}$, $\widetilde{\psi}(e_{\widetilde{U}A}) = e_{UA}$, $\psi \circ i_{UA} = i_{\widetilde{U}A}$, and $\widetilde{\psi} \circ i_{\widetilde{U}A} = i_{UA}$. Observe that

$$(\widetilde{\psi} \circ \psi) \circ i_{UA} = \widetilde{\psi} \circ (\psi \circ i_{UA}) = \widetilde{\psi} \circ i_{\widetilde{UA}} = i_{UA}, \tag{25.4.4}$$

and similarly $(\psi \circ \widetilde{\psi}) \circ i_{\widetilde{U}A} = i_{\widetilde{U}A}$. Of course,

$$(\widetilde{\psi} \circ \psi)(e_{UA}) = \widetilde{\psi}(\psi(e_{UA})) = \widetilde{\psi}(e_{\widetilde{U}A}) = e_{UA}, \tag{25.4.5}$$

and similarly $(\psi \circ \widetilde{\psi})(e_{\widetilde{U}A}) = e_{\widetilde{U}A}$. Clearly $\widetilde{\psi} \circ \psi$ is an algebra homomorphism from UA into itself, and $\psi \circ \widetilde{\psi}$ is an algebra homomorphism from $\widetilde{U}A$ into itself. It follows that $\widetilde{\psi} \circ \psi$ is the identity mapping on UA, and that $\psi \circ \widetilde{\psi}$ is the identity mapping on $\widetilde{U}A$, as in the preceding paragraph. This corresponds to some remarks on p11 of [25], and on p90f of [14].

25.5 Constructing universal enveloping algebras

Let k be a commutative ring with a multiplicative identity element, and let $(A, [\cdot, \cdot]_A)$ be a Lie algebra over k. In particular, A is a module over k, so that the corresponding tensor algebra TA can be defined as in Section 25.3. Let $\mathcal{I}_A$ be the two-sided ideal in TA generated by elements of the form

$$[x, y]_A - x \otimes y - y \otimes x, \tag{25.5.1}$$

where $x, y \in A$. Of course, this uses the obvious embeddings of $A = T^1 A$ and $T^2 A$ in TA. Thus $\mathcal{I}_A$ consists of elements of TA that can be obtained by multiplying elements of the form (25.5.1) by other elements of TA on the left and right, and taking finite sums of such products.

The corresponding quotient

$$UA = (TA)/\mathcal{I}_A \tag{25.5.2}$$

is an associative algebra over k. Let q_A be the canonical quotient mapping from TA onto UA. Remember that $1 \in k = T^0 A$ is the multiplicative identity element in TA, so that $e_{UA} = q_A(1)$ is the multiplicative identity element in UA. Let $i = i_{UA}$ be the composition of the natural inclusion mapping of $A = T^1 A$ into TA with q_A. Let us check that (UA, i) is a universal enveloping algebra of A, as in Theorem 1.2 on p11 of [25], and as mentioned on p91 of [14].

It is easy to see that i is a Lie algebra homomorphism from A into UA, by construction. Let B be an associative algebra over k with a multiplicative identity element e_B, and let ϕ be a Lie algebra homomorphism from A into B. In particular, ϕ is a homomorphism from A into B as modules over k, and so there is a unique algebra homomorphism ρ from TA into B that is equal to ϕ on $A = T^1 A$ and sends $1 \in k = T^0 A$ to e_B, as in Section 25.3. If $x, y \in A$, then one can check that (25.5.1) is in the kernel of ρ, because ϕ is a Lie algebra homomorphism from A into B. This implies that $\mathcal{I}_A$ is contained in the kernel of ρ, so that ρ can be expressed as

$$\rho = \psi \circ q_A \tag{25.5.3}$$

on TA for some algebra homomorphism ψ from UA into B. Note that $\psi(e_{UA}) = \psi(q_A(1)) = \rho(1) = e_B$. We can compose both sides of (25.5.3) with the natural inclusion of $A = T^1 A$ into TA to get that

$$\phi = \psi \circ i \tag{25.5.4}$$

on A.

Suppose that $\widetilde{\psi}$ is another algebra homomorphism from UA into B such that $\widetilde{\psi}(e_{UA}) = e_B$ and $\phi = \widetilde{\psi} \circ i$. This implies that $\widetilde{\rho} = \widetilde{\psi} \circ q_A$ is an algebra homomorphism from TA into B such that $\widetilde{\rho}(1) = \widetilde{\psi}(q_A(1)) = \widetilde{\psi}(e_{UA}) = e_B$ and $\widetilde{\rho} = \phi$ on $A = T^1 A$. It follows that $\widetilde{\rho} = \rho$ on TA, as in Section 25.3. This means that $\widetilde{\psi} = \psi$ on UA, so that ψ is unique. This could also be obtained from the fact that UA is generated by e_{UA} and $i(A)$, as an algebra over k, because TA is generated by the images of $k = T^0 A$ and $A = T^1 A$ in TA, as an algebra over k.

25.6 Some properties of UA

Let k be a commutative ring with a multiplicative identity element, and let A be a module over k. Also let q_0 be the mapping from TA into k that sends each element of TA to its component in $T^0 A = k$. This is an algebra homomorphism from TA onto k. The kernel of q_0 is the two-sided ideal $\mathcal{I}_0$ in TA consisting of elements of TA whose component in $T^0 A$ is equal to 0, which corresponds to the direct sum of $T^n A$ over $n \geq 1$ in TA.

Suppose now that $(A, [\cdot,\cdot]_A)$ is a Lie algebra over k. Let $\mathcal{I}_A$ be the two-sided ideal in TA associated to A as in the previous section, and observe that

$$\mathcal{I}_A \subseteq \mathcal{I}_0. \tag{25.6.1}$$

Remember that q_A is the canonical quotient mapping from TA onto $UA = (TA)/\mathcal{I}_A$, as before. Using (25.6.1), we get that the restriction of q_A to $T^0 A = k$ is injective, as mentioned on p91 of [14]. We can also express q_0 as the composition of q_A with an algebra homomorphism from UA onto k. Alternatively, the map from A into k that sends every element of A to 0 is a Lie algebra homomorphism. This leads to an algebra homomorphism from UA into k that sends e to 1.

Let V be a module over k, and remember that the space $\mathrm{Hom}_k(V,V)$ of module homomorphisms from V into itself is an associative algebra over k with respect to composition of mappings, and with the identity mapping on V as the multiplicative identity element. A Lie algebra homomorphism from A into $\mathrm{Hom}_k(V,V)$ is the same as a representation of A, as a Lie algebra over k, on V. This leads to an algebra homomorphism from UA into $\mathrm{Hom}_k(V,V)$ that sends e_{UA} to the identity mapping on V, and whose composition with i_{UA} is the given representation of A on V. Thus, if V is a module over A as a Lie algebra, then V may be considered as a left module over UA as an associative algebra, as in the remark on p11f of [25].

There is an exercise on p12 of [25], which is attributed to Bergman, and which asks one to show that $UA = k$ if and only if $A = \{0\}$. More precisely, $UA = k$ means that $UA = q_A(k)$, which happens exactly when $\mathcal{I}_A = \mathcal{I}_0$. Of course, if $A = \{0\}$, then $\mathcal{I}_0 = \{0\}$, and $\mathcal{I}_A = \mathcal{I}_0$. Conversely, let us check that $A = \{0\}$ when $\mathcal{I}_A = \mathcal{I}_0$. The exercise comes with the hint that one should use the adjoint representation. Remember that A may be considered as a module over itself, as a Lie algebra over k, using the adjoint representation. Using this, we may consider A as a left module over UA, as an associative algebra over k, as in the preceding paragraph. If $\mathcal{I}_A = \mathcal{I}_0$, then it follows that the action of any element of A on A by the adjoint representation is equal to 0, so that A is commutative as a Lie algebra. In this case, the condition that $\mathcal{I}_A = \mathcal{I}_0$ implies that $A = T^1 A = \{0\}$, as desired.

Let A_0 be a Lie subalgebra of A, so that A_0 also has a universal enveloping algebra UA_0, with multiplicative identity element $e_0 = e_{UA_0}$ and corresponding Lie algebra homomorphism $i_0 = i_{UA_0}$ from A_0 into UA_0. Consider the restriction ϕ_0 of i_{UA} to A_0, which is a Lie algebra homomorphism from A_0 into UA. This leads to a unique algebra homomorphism ψ_0 from UA_0 into UA such that $\psi_0(e_0) = e_{UA}$ and $\psi_0 \circ i_0 = \phi_0$.

25.7 Commuting Lie subalgebras

Let k be a commutative ring with a multiplicative identity element, and let $(A, [\cdot,\cdot]_A)$ be a Lie algebra over k. Also let UA be a universal enveloping algebra of A, with multiplicative identity element $e = e_{UA}$ and corresponding Lie algebra homomorphism $i = i_{UA}$ from A into UA. Suppose that A_1 and A_2 are Lie subalgebras of A, and let UA_1, UA_2 be universal enveloping algebras of A_1, A_2, respectively, with multiplicative identity elements $e_j = e_{UA_j}$ and corresponding Lie algebra homomorphisms $i_j = i_{UA_j}$ from A_j into UA_j for $j = 1, 2$. As in the previous section, the restriction ϕ_j of i to A_j is a Lie algebra homomorphism from A_j into UA for $j = 1, 2$, which leads to a unique algebra homomorphism ψ_j from UA_j into UA such that $\psi_j(e_j) = e$ and $\psi_j \circ i_j = \phi_j$.

Suppose that A_1 and A_2 commute in A, in the sense that

$$[a_1, a_2]_A = 0 \tag{25.7.1}$$

for every $a_1 \in A_1$ and $a_2 \in A_2$. This implies that

$$i(a_1)\, i(a_2) = i(a_2)\, i(a_1) \tag{25.7.2}$$

in UA for every $a_1 \in A_1$ and $a_2 \in A_2$, because i is a Lie algebra homomorphism from A into UA. Using this, we get that

$$\psi_1(x_1)\, \psi_2(x_2) = \psi_2(x_2)\, \psi_1(x_1) \tag{25.7.3}$$

in UA for every $x_1 \in UA_1$ and $x_2 \in UA_2$. More precisely, this follows from (25.7.2) when $x_j \in i_j(A_j)$ for $j = 1, 2$. Of course, (25.7.3) holds automatically when $x_1 = e_1$ or $x_2 = e_2$. It follows that (25.7.3) holds for every $x_1 \in UA_1$ and $x_2 \in UA_2$, because UA_j is generated by e_j and $i_j(A_j)$ as an algebra over k for $j = 1, 2$. Let ψ be the unique linear mapping from $(UA_1) \bigotimes (UA_2)$ into UA such that

$$\psi(x_1 \otimes x_2) = \psi_1(x_1)\, \psi_2(x_2) \tag{25.7.4}$$

for every $x_1 \in UA_1$ and $x_2 \in UA_2$. This is an algebra homomorphism, as in Section 25.2, with $\psi(e_1 \otimes e_2) = \psi_1(e_1)\, \psi_2(e_2) = e$.

Suppose now that A corresponds to the direct sum of A_1 and A_2, so that every element of A can be expressed in a unique way as a sum of elements of A_1 and A_2. Observe that

$$a_1 \mapsto i_1(a_1) \otimes e_2 \tag{25.7.5}$$

is a Lie algebra homomorphism from A_1 into $(UA_1) \bigotimes (UA_2)$, and similarly that

$$a_2 \mapsto e_1 \otimes i_2(a_2) \tag{25.7.6}$$

is a Lie algebra homomorphism from A_2 into $(UA_1) \bigotimes (UA_2)$. If $a_1 \in A_1$ and $a_2 \in A_2$, then put

$$\rho(a_1 + a_2) = i_1(a_1) \otimes e_2 + e_1 \otimes i_2(a_2), \tag{25.7.7}$$

which defines a mapping from A into $(UA_1) \bigotimes (UA_2)$. It is easy to see that ρ is a Lie algebra homomorphism from A into $(UA_1) \bigotimes (UA_2)$, using (25.7.1). This implies that there is a unique algebra homomorphism θ from UA into $(UA_1) \bigotimes (UA_2)$ such that $\theta(e) = e_1 \otimes e_2$ and $\rho = \theta \circ i$.

Let us check that $\psi \circ \theta$ is the identity mapping on UA. Of course, $(\psi \circ \theta)(e) = \psi(\theta(e)) = \psi(e_1 \otimes e_2) = e$. If $a_1 \in A_1$ and $a_2 \in A_2$, then

$$\begin{aligned} (\psi \circ \theta)(i(a_1 + a_2)) &= \psi(\rho(a_1 + a_2)) \\ &= \psi(i_1(a_1) \otimes e_2) + \psi(e_1 \otimes i_2(a_2)) \\ &= \psi_1(i_1(a_1))\, \psi_2(e_2) + \psi_1(e_1)\, \psi_2(i_2(a_2)) \\ &= \phi_1(a_1) + \phi_2(a_2) = i(a_1 + a_2). \end{aligned} \tag{25.7.8}$$

This implies that $\psi \circ \theta$ is the identity mapping on UA, because UA is generated as an algebra over k by e and $i(A)$.

Similarly, we would like to verify that $\theta \circ \psi$ is the identity mapping on $(UA_1) \bigotimes (UA_2)$. It suffices to show that

$$(\theta \circ \psi)(x_1 \otimes x_2) = x_1 \otimes x_2 \tag{25.7.9}$$

for every $x_1 \in UA_1$ and $x_2 \in UA_2$. Observe that

$$\begin{aligned} (\theta \circ \psi)(x_1 \otimes x_2) &= \theta(\psi(x_1 \otimes x_2)) \\ &= \theta(\psi_1(x_1)\, \psi_2(x_2)) = \theta(\psi_1(x_1))\, \theta(\psi_2(x_2)) \end{aligned} \tag{25.7.10}$$

for every $x_1 \in UA_1$ and $x_2 \in UA_2$.

Let us check that

$$\theta(\psi_1(x_1)) = x_1 \otimes e_2 \tag{25.7.11}$$

for every $x_1 \in UA_1$. Of course, $\theta(\psi_1(e_1)) = \theta(e) = e_1 \otimes e_2$, so that (25.7.11) holds when $x_1 = e_1$. If $a_1 \in A_1$, then

$$\theta(\psi_1(i_1(a_1))) = \theta(i(a_1)) = \rho(a_1) = i_1(a_1) \otimes e_2. \tag{25.7.12}$$

This shows that (25.7.11) holds when $x_1 \in i_1(A_1)$. It follows that (25.7.11) holds for every $x_1 \in UA_1$, because UA_1 is generated by e_1 and $i_1(A_1)$, as an algebra over k.

If $x_2 \in UA_2$, then

$$\theta(\psi_2(x_2)) = e_1 \otimes x_2, \tag{25.7.13}$$

for the same reasons. If $x_1 \in UA_1$ as well, then we get that

$$\begin{aligned} (\theta \circ \psi)(x_1 \otimes x_2) &= \theta(\psi_1(x_1))\, \theta(\psi_2(x_2)) \\ &= (x_1 \otimes e_2)\, (e_1 \otimes x_2) = x_1 \otimes x_2, \end{aligned} \tag{25.7.14}$$

as desired. Thus UA is isomorphic to $(UA_1) \bigotimes (UA_2)$ in a natural way, as on p12 of [25].

25.8 Symmetric algebras

Let k be a commutative ring with a multiplicative identity element, and let A be a module over k. We may consider A as a commutative Lie algebra over k, by putting $[x, y]_A = 0$ for every $x, y \in A$. In this case, a universal enveloping algebra of A as a Lie algebra over k is called a *symmetric algebra* of A as a module over k, and is denoted SA, as on p12 of [25].

More precisely, a symmetric algebra SA of A comes with a multiplicative identity element $e = e_{SA}$, and a Lie algebra homomorphism $i = i_{SA}$ from A into SA. In this situation, the condition that i be a Lie algebra homomorphism means that i is a homomorphism from A into SA, as modules over k, and that

$$i(x)\, i(y) = i(y)\, i(x) \tag{25.8.1}$$

for every $x, y \in A$. This implies that SA is commutative as an algebra over k, because it is generated by $i(A)$ and e, as before.

The two-sided ideal $\mathcal{I}_A$ in the tensor algebra TA defined in Section 25.5 is generated by elements of the form

$$x \otimes y - y \otimes x \tag{25.8.2}$$

with $x, y \in A$ in this situation. This means that $\mathcal{I}_A$ consists of elements of TA that can be obtained by multiplying elements of the form (25.8.2) by other elements of TA on the left and right, and taking finite sums of such elements, as before. Thus a symmetric algebra of A can be obtained as the quotient

$$SA = (TA)/\mathcal{I}_A, \tag{25.8.3}$$

as in Section 25.5. This corresponds to the definition of the symmetric algebra on p89 of [14], and the characterization as a universal enveloping algebra of a commutative Lie algebra is mentioned in the example on p91 of [14].

Let us identify $T^n A$ with a submodule of TA, as a module over k, in the obvious way. It is easy to see that $\mathcal{I}_A$ corresponds to the direct sum of $\mathcal{I}_A \cap (T^n A)$ over $n \geq 2$ in TV. More precisely, $\mathcal{I}_A \cap (T^n A)$ consists of finite sums of elements that can be expressed as the product of the form (25.8.2) by an element of $T^j A$ on the left and $T^l A$ on the right, where j, l as nonnegative integers such that $j + l + 2 = n$. In particular, $\mathcal{I}_A \cap (T^n A) = \{0\}$ when $n = 0$ or 1. If n is any nonnegative integer, then $\mathcal{I}_A \cap (T^n A)$ is a submodule of T^n, as a module over k, so that the quotient

$$S^n A = (T^n A)/(\mathcal{I}_A \cap (T^n A)) \tag{25.8.4}$$

can be defined as a module over k. Thus (25.8.3) may be considered as the direct sum of $S^n A$ over $n \geq 0$, as a module over k. Note that $S^0 A = T^0 A = k$, and $S^1 A = T^1 A = A$.

Let SA be a symmetric algebra of A again, with $e = e_{SA}$ and $i = i_{SA}$ as before. The second property in the definition of a universal enveloping algebra says that if B is an associative algebra over k with a multiplicative identity element e_B, and ϕ is a Lie algebra homomorphism from A into B, then there is a unique algebra homomorphism ψ from SA into B such that $\psi(e) = e_B$ and $\psi \circ i = \phi$. In this situation, a mapping ϕ from A into B is a Lie algebra homomorphism if ϕ is a homomorphism from A into B, as modules over k, and

$$\phi(x)\, \phi(y) = \phi(y)\, \phi(x) \tag{25.8.5}$$

for every $x, y \in A$. Of course, (25.8.5) holds automatically when B is commutative, in which case this corresponds to a remark on p90 of [14]. Remember that SA is unique up to isomorphism, as in Section 25.4.

Suppose now that A is free as a module over k, so that A corresponds to the direct sum of a nonempty family of copies of k. Equivalently, there is a nonempty set I and an element e_j of A for each $j \in I$ so that every element of A can be expressed in a unique way as a finite linear combinations of e_j's, with coefficients in k. Let X_j, $j \in I$, be a commuting family of indeterminates, so that the corresponding polynomial algebra $k[\{X_j : j \in I\}]$ can be defined as in Section 25.1. There is a unique homomorphism i from A into $k[\{X_j : j \in I\}]$, as modules over k, such that

$$i(e_j) = X_j \tag{25.8.6}$$

for every $j \in I$. Let us check that this satisfies the requirements of a symmetric algebra of A.

Note that i is a Lie algebra homomorphism from A into $k[\{X_j : j \in I\}]$, because $k[\{X_j : j \in I\}]$ is a commutative algebra over k. Let B be an associative algebra over k with a multiplicative identity element e_B, and let ϕ be a Lie algebra homomorphism from A into B, where A is considered as a commutative Lie algebra over k. This means that ϕ is a homomorphism from A into B, as modules over k, that satisfies (25.8.5), as before. Put

$$b_j = \phi(e_j) \tag{25.8.7}$$

for each $j \in I$, so that $b_j\, b_l = b_l\, b_j$ for every $j, l \in I$. Let b be the element of the Cartesian power B^I whose jth coordinate is equal to b_j for each $j \in I$. If $f(X) \in k[\{X_j : j \in I\}]$, then put

$$\psi(f(X)) = f(b), \tag{25.8.8}$$

where the right side is as in Section 25.1. Thus ψ is an algebra homomorphism from $k[\{X_j : j \in I\}]$ into B, as before, and it is easy to see that $\psi \circ i = \phi$ on A. Of course, $\psi(1) = e_B$, by construction, and ψ is uniquely determined by these properties. This corresponds to some remarks on p12 of [25], and is mentioned on p90 of [14] as well.

25.9 A filtration on UA

Let k be a commutative ring with a multiplicative identity element, and let $(A, [\cdot,\cdot]_A)$ be a Lie algebra over k. Also let UA be a universal enveloping algebra of A, with multiplicative identity element e_{UA} and Lie algebra homomorphism i_{UA} from A into UA. If n is a nonnegative integer, then we let $U_n A$ be the submodule of UA, as a module over k, generated by products of the form

$$i_{UA}(x_1) \cdots i_{UA}(x_m), \tag{25.9.1}$$

where $x_1, \ldots, x_m \in A$ and $m \le n$. We interpret e_{UA} as being such a product with $m = 0$, so that multiples of e_{UA} by elements of k are in $U_n A$ for every

$n \geq 0$. More precisely, U_0A consists exactly of multiples of e_{UA} by elements of k, and

$$U_nA \subseteq U_{n+1}A \tag{25.9.2}$$

for every $n \geq 0$. Note that $\bigcup_{n=0}^{\infty} U_nA = UA$. This is the way that U_nA is defined on p13 of [25].

Alternatively, we can take UA to be obtained from the tensor algebra TA as in Section 25.5. If n is a nonnegative integer, then let T_nA be the submodule of TA that corresponds to the direct sum of T^mA over $m = 0, \ldots, n$. Thus T_0A corresponds to T^0A, as a submodule of TA, $T_nA \subseteq T_{n+1}A$ for every $n \geq 0$, and $TA = \bigcup_{n=0}^{\infty} T_nA$. If UA is the quotient of TA discussed before, then U_nA corresponds to the image of T_nA under the quotient mapping from TA onto UA. This is how U_nA is defined on p91 of [14].

If n is a positive integer, then put

$$\mathrm{gr}_n UA = (U_nA)/(U_{n-1}A), \tag{25.9.3}$$

where the quotient is defined as a module over k. Also put $\mathrm{gr}_0\, UA = U_0A$, and

$$\mathrm{gr}\, UA = \bigoplus_{n=0}^{\infty} \mathrm{gr}_n UA, \tag{25.9.4}$$

considered as a module over k for the moment. If n, r are nonnegative integers, then multiplication on UA defines a bilinear mapping from $(U_nA) \times (U_rA)$ into $U_{n+r}A$. It is easy to see that this determines a bilinear mapping from $(\mathrm{gr}_n\, UA) \times (\mathrm{gr}_r\, UA)$ into $\mathrm{gr}_{n+r}\, UA$ in a natural way. This defines a bilinear mapping of multiplication from $(\mathrm{gr}\, UA) \times (\mathrm{gr}\, UA)$ into $\mathrm{gr}\, UA$. One can check that multiplication on $\mathrm{gr}\, UA$ is associative, and that the element of $\mathrm{gr}\, UA$ corresponding to $e_{UA} \in U_0A = \mathrm{gr}_0\, UA$ is the multiplicative identity element. This is called the *graded algebra* associated to UA, as on p13 of [25].

Note that i_{UA} maps A into U_1A, which is mapped into $\mathrm{gr}_1\, UA$ by the quotient mapping. This gives a natural homomorphism from A into $\mathrm{gr}\, UA$, as modules over k. One can check that $\mathrm{gr}\, UA$ is generated, as an algebra over k, by the image of A under this mapping and the multiplicative identity element, as in Proposition 4.1 on p13 of [25].

Theorem 4.2 on p13 of [25] states that $\mathrm{gr}\, UA$ is commutative as an algebra over k. To see this, let $x, y \in A$ be given, and remember that

$$i_{UA}(x)\, i_{UA}(y) - i_{UA}(y)\, i_{UA}(x) = i_{UA}([x, y]_A) \tag{25.9.5}$$

in UA, because i_{UA} is a Lie algebra homomorphism from A into UA. Of course, $i_{UA}(x)\, i_{UA}(y)$ and $i_{UA}(y)\, i_{UA}(x)$ are elements of U_2A, which are mapped to the same element of $\mathrm{gr}_2\, UA$, by (25.9.5). This means that the images of x, y in $\mathrm{gr}\, UA$ commute. It follows that $\mathrm{gr}\, UA$ is commutative, because $\mathrm{gr}\, UA$ is generated as an algebra by the image of A and the multiplicative identity element, as in the preceding paragraph.

Let SA be a symmetric algebra of A, as a module over k, with multiplicative identity element e_{SA}, and homomorphism i_{SA} from A into SA, as modules over

k. Because $\operatorname{gr} UA$ is commutative, there is a unique algebra homomorphism ρ from SA into $\operatorname{gr} UA$ such that $\rho(e_{SA})$ is the multiplicative identity element in $\operatorname{gr} UA$, and $\rho \circ i_{SA}$ is the natural mapping from A into $\operatorname{gr} UA$. More precisely, ρ maps SA onto $\operatorname{gr} UA$, because $\operatorname{gr} UA$ is generated as an algebra by the image of A and the multiplicative identity element, as mentioned on p13 of [25].

This corresponds to the lemma on p91 of [14], which is formulated with UA given by the quotient of TA as in Section 25.5. If n is a nonnegative integer, then there is a natural module homomorphism from $T^n A$ into $U_n A$, using the quotient mapping from TA onto UA. More precisely, this mapping can be obtained by first mapping $T^n A$ into $T_n A$, and mapping $T_n A$ onto $U_n A$ using the quotient mapping from TA onto UA. This leads to a module homomorphism from $T^n A$ into $\operatorname{gr}_n UA$, by composition with the quotient mapping from $U_n A$ onto $\operatorname{gr}_n UA$. In fact, this module homomorphism maps $T^n A$ onto $\operatorname{gr}_n UA$. We can combine these module homomorphisms to get a module homomorphism from TA onto $\operatorname{gr} UA$. This maps the multiplicative identity element in TA to the multiplicative identity element in $\operatorname{gr} UA$. One can check that this is an algebra homomorphism from TA onto $\operatorname{gr} UA$.

Remember that a symmetric algebra SA of A can be obtained as a quotient of TA as well. One can verify that the ideal in TA used to get SA is contained in the kernel of the homomorphism from TA onto $\operatorname{gr} UA$ mentioned in the preceding paragraph, using (25.9.5). This leads to an algebra homomorphism from SA onto $\operatorname{gr} UA$, as before.

25.10 The Poincaré–Birkhoff–Witt theorem

Let us continue with the same notation and hyotheses as in the previous section, and suppose also that A is a free module over k. The Poincaré–Birkhoff–Witt theorem states that the homomorphism ρ from SA onto $\operatorname{gr} UA$ defined in the previous section is an isomorphism, as in Theorem 4.3 on p14 of [25]. Of course, if k is a field, so that A is a vector space over k, then A is automatically free as a module over k. This corresponds to the formulation of the theorem on p92 of [14].

To say that A is a free module over k means that there is a nonempty set I and a family $\{x_j\}_{j \in I}$ of elements of A indexed by I such that every element of A can be expressed in a unique way as a finite linear combination of the x_j's, with coefficients in k. We may refer to $\{x_j\}_{j \in I}$ as a *basis* for A, as a free module over k. Let $\preceq$ be a linear ordering on I.

Let n be a nonnegative integer, and let $j_1, \ldots, j_m$ be m elements of I for some $m \leq n$, with

$$j_1 \preceq \cdots \preceq j_m. \tag{25.10.1}$$

Thus the product

$$i_{UA}(x_{j_1}) \cdots i_{UA}(x_{j_m}) \tag{25.10.2}$$

is an element of $U_n A$. As before, we interpret (25.10.2) as being equal to e_{UA} when $m = 0$, in which case (25.10.1) is considered to hold vacuously. Lemma

4.4 on p14 of [25] states that $U_n A$ is generated, as a module over k, by products of the form (25.10.2).

The proof is by induction on n, with the base case $n = 0$ being trivial. Suppose that $n \geq 1$, and remember that $U_n A$ is generated as a module over k by products of the form (25.10.2) without the condition (25.10.1), by definition. Using (25.9.5), we can express an element of $U_n A$ as a linear combination of terms of the form (25.10.2), with coefficients in k, $m = n$, and the condition (25.10.1), plus an element of $U_{n-1} A$. This implies that $U_n A$ is generated as a module over k in the desired way, because of the corresponding property for $U_{n-1} A$, by the induction hypothesis.

Consider the following statement:

(25.10.3) the family of products of the form (25.10.2) with (25.10.1) and $m \geq 0$ is a basis for UA as a module over k.

Lemma 4.5 on p14 of [25] asserts that this is equivalent to the Poincaré–Birkhoff–Witt theorem. Lemma C on p92 of [14] corresponds to the fact that the theorem implies (25.10.3).

If $m \in \mathbf{Z}_+$, then let $\mathcal{M}_m(I)$ be the set of m-tuples $M = (j_1, \ldots, j_m)$ of elements of I that satisfy (25.10.1). We consider $M = \emptyset$ to be the unique element of $\mathcal{M}_0(I)$, and put

$$\mathcal{M}(I) = \bigcup_{m=0}^{\infty} \mathcal{M}_m(I). \tag{25.10.4}$$

If $M \in \mathcal{M}_m(I)$ for some $m \geq 0$, then m is called the *length* of M, and may be denoted length(M).

Remember that $\mathcal{M}_I$ is the set of all multi-indices with respect to I, as in Section 25.1. If $\alpha \in \mathcal{M}_I$, then let $M_\alpha \in \mathcal{M}(I)$ be the m-tuple with $m = |\alpha|$ obtained by taking the $j \in I$ with $\alpha(j) \neq 0$ in order and with multiplicity $\alpha(j)$, so that $M_0 = \emptyset$. Similarly, if $M \in \mathcal{M}_m(I)$ for some $m \geq 0$, then we can define $\alpha_M \in \mathcal{M}_I$ by taking $\alpha_M(j)$ to be the number of coordinates of M equal to j for each $j \in I$. This defines a one-to-one correspondence between $\mathcal{M}(I)$ and $\mathcal{M}_I$.

Let X_j, $j \in I$, be a commuting family of indeterminates, with the corresponding polynomial algebra $k[\{X_j : j \in I\}]$, as in Section 25.1. There is a unique homomorphism from A into $k[\{X_j : j \in I\}]$, as modules over k, that sends $x_j \in A$ to X_j for every $j \in I$. Using this module homomorphism, $k[\{X_j : j \in I\}]$ satisfies the requirements of a symmetric algebra of A, as in Section 25.8. Of course, the collection of monomials X^α, $\alpha \in \mathcal{M}_I$, is a basis for $k[\{X_j : j \in I\}]$ as a module over k.

If $M = (j_1, \ldots, j_n) \in \mathcal{M}_n(I)$ for some $n \geq 0$, then put

$$x_M = i_{UA}(x_{j_1}) \cdots i_{UA}(x_{j_n}), \tag{25.10.5}$$

which is interpreted as being e_{UA} when $M = \emptyset$, as before. This is an element of $U_n A$, and we let $\overline{x_M}$ be its image in $\operatorname{gr}_n UA$ under the corresponding quotient mapping. Using $k[\{X_j : j \in I\}]$ as the symmetric algebra of A, the mapping ρ from SA onto $\operatorname{gr} UA$ defined in the previous section corresponds exactly to the module homomorphism from $k[\{X_j : j \in I\}]$ into $\operatorname{gr} UA$ with

$$X^\alpha \mapsto \overline{x_{M_\alpha}} \tag{25.10.6}$$

for every $\alpha \in \mathcal{M}_I$.

The Poincaré–Birkhoff–Witt theorem is equivalent to the statement that ρ is injective, because we already know that it is a surjective algebra homomorphism. The injectivity of ρ is equivalent to saying that if $n \geq 0$, $c_M \in k$ for every $M \in \mathcal{M}_n(I)$, and

$$\sum_{M \in \mathcal{M}_n(I)} c_M \, \overline{x_M} = 0 \tag{25.10.7}$$

in $\operatorname{gr}_n UA$, then $c_M = 0$ for every $M \in \mathcal{M}_n(I)$. This holds trivially when $n = 0$, and so we may as well take $n \geq 1$. Note that (25.10.7) is the same as saying that

$$\sum_{M \in \mathcal{M}_n(I)} c_M \, x_M \equiv 0 \quad \text{modulo } U_{n-1}A \tag{25.10.8}$$

in U_nA when $n \geq 1$. This means that there are $c_M \in k$ for $M \in \mathcal{M}(I)$ with $\operatorname{length}(M) \leq n-1$ such that

$$\sum_{M \in \mathcal{M}_n(I)} c_M \, x_M = \sum_{\substack{M \in \mathcal{M}(I) \\ \operatorname{length}(M) < n}} c_M x_M \tag{25.10.9}$$

in U_nA, because $U_{n-1}A$ is generated as a module over k by the x_M with M in $\mathcal{M}(I)$ and $\operatorname{length}(M) \leq n-1$, as before.

Of course, (25.10.3) is the same as saying that the family of x_M, $M \in \mathcal{M}(I)$, is a basis for UA as a module over k. If this holds, then (25.10.9) implies that $c_M = 0$ for every $M \in \mathcal{M}(I)$ with $\operatorname{length}(M) \leq n$, and in particular when $\operatorname{length}(M) = n$, as desired. Conversely, if ρ is injective, then (25.10.9) implies that $c_M = 0$ for every $M \in \mathcal{M}(I)$ with $\operatorname{length}(M) = n$, as in the preceding paragraph. In this case, one can repeat the process to get that $c_M = 0$ for every $M \in \mathcal{M}(I)$ with $\operatorname{length}(M) \leq n$. This implies that the family of x_M, $M \in \mathcal{M}(I)$ is a basis for UA as a module over k, because UA is generated by the x_M's, $M \in \mathcal{M}(I)$, as a module over k.

25.11 The rest of the proof

Let us continue with the same notation and hypotheses as in the previous two sections. In order to prove the Poincaré–Birkhoff–Witt theorem, we take $\preceq$ to be a well-ordering on I. Let V be a free module over k with a basis consisting of elements Z_M for each $M \in \mathcal{M}(I)$, as on p14 of [25]. As a module over k, V is isomorphic to $k[\{X_j : j \in I\}]$, which is a symmetric algebra of A, and the argument on p93 of [14] uses this.

If $j \in I$ and $M = (j_1, \ldots, j_n) \in \mathcal{M}(I)$, then we put $j \preceq M$ when $j \preceq j_1$. In this case, we put

$$j\, M = (j, j_1, \ldots, j_n), \tag{25.11.1}$$

which is an element of $\mathcal{M}(I)$ too. If $M = \emptyset$, then $j \preceq M$ is interpreted as holding automatically, and $j\, M$ has only the one coordinate j. The main lemma on p14 of [25] states that V can be made a module over A, as a Lie algebra over k, in such a way that

$$x_j \cdot Z_M = Z_{j\, M} \tag{25.11.2}$$

for every $j \in I$ and $M \in \mathcal{M}(I)$ with $j \preceq M$. This corresponds to Lemma B on p94 of [14], part (a) in particular.

We first want to define $(x, v) \mapsto x \cdot v$ as a bilinear mapping from $A \times V$ into V. To do this, it suffices to define $x_j \cdot Z_M$ as an element of V for every $j \in I$ and $M \in \mathcal{M}(I)$. More precisely, we want to do this in such a way that

(25.11.3) $x_j \cdot Z_M$ is a finite linear combination of Z_L's with coefficients in k, $L \in \mathcal{M}(I)$, and $\operatorname{length}(L) \le \operatorname{length}(M) + 1$.

Note that (25.11.2) has this property.

Let $j \in I$ and $M \in \mathcal{M}(I)$ be given. Suppose that $x_{j_0} \cdot Z_N \in V$ has already been defined and satisfies (25.11.3) for $j_0 \in I$ and $N \in \mathcal{M}(I)$ such that either

$$\operatorname{length}(N) < \operatorname{length}(M), \tag{25.11.4}$$

or

$$\operatorname{length}(N) = \operatorname{length}(M),\ j_0 \preceq j, \text{ and } j_0 \ne j. \tag{25.11.5}$$

If $j \preceq M$, then $x_j \cdot Z_M$ can be defined as in (25.11.2). Otherwise, there are $j_1 \in I$ and $N \in \mathcal{M}(I)$ such that

$$j_1 \preceq N,\ M = j_1\, N,\ j_1 \preceq j, \text{ and } j_1 \ne j. \tag{25.11.6}$$

In this case, we would like to define $x_j \cdot Z_M \in V$ by

$$x_j \cdot Z_M = x_{j_1} \cdot (x_j \cdot Z_N) + ([x_j, x_{j_1}]_A) \cdot Z_N. \tag{25.11.7}$$

It is easy to see that the right side is defined as an element of V under these conditions, and that it satisfies (25.11.3) as well. One can use this to define $x_j \cdot Z_M$ for every $j \in I$ and $M \in \mathcal{M}(I)$, because I is well ordered by $\preceq$.

In order to show that V is a module over A as a Lie algebra over k, we need to check that

$$x \cdot (y \cdot v) - y \cdot (x \cdot v) = ([x, y]_A) \cdot v \tag{25.11.8}$$

for every $x, y \in A$ and $v \in V$. To do this, it suffices to verify that

$$x_j \cdot (x_l \cdot Z_N) - x_l \cdot (x_j \cdot Z_N) = ([x_j, x_l]_A) \cdot Z_N \tag{25.11.9}$$

for every $j, l \in I$ and $N \in \mathcal{M}(I)$. Arguing by induction on $\operatorname{length}(N)$ and $\min(j, l)$ as on p15 of [25], we may suppose that

$$x_{j_0} \cdot (x_{l_0} \cdot Z_{N_0}) - x_{l_0} \cdot (x_{j_0} \cdot Z_{N_0}) = ([x_{j_0}, x_{l_0}]_A) \cdot Z_{N_0} \tag{25.11.10}$$

holds for every $j_0, l_0 \in I$ and $N_0 \in \mathcal{M}(I)$ such that either

$$\text{length}\, N_0 < \text{length}\, N \tag{25.11.11}$$

or

$$\text{length}(N_0) = \text{length}(N),\ \min(j_0, l_0) \preceq \min(j, l), \text{ and } \min(j_0, l_0) \neq \min(j, l). \tag{25.11.12}$$

We may as well suppose that

$$l \preceq j \text{ and } l \neq j, \tag{25.11.13}$$

because both sides of (25.11.9) are antisymmetric in j and l, and are equal to 0 when $j = l$. Suppose first that $l \preceq N$, so that $x_l \cdot Z_N = Z_{l\,N}$. Thus (25.11.7) holds with $M = l\,N$ and $j_1 = l$. This implies (25.11.9), as desired.

Otherwise, there are $r \in I$ and $L \in \mathcal{M}(I)$ such that

$$r \preceq L,\ N = r\,L,\ r \preceq l, \text{ and } r \neq l. \tag{25.11.14}$$

This means that $Z_N = Z_{r\,L} = x_r \cdot Z_l$, as in (25.11.2). In this case, (25.11.9) is the same as saying that

$$x_j \cdot (x_l \cdot (x_r \cdot Z_L)) - x_l \cdot (x_j \cdot (x_r \cdot Z_L)) = ([x_j, x_l]_A) \cdot (x_r \cdot Z_L). \tag{25.11.15}$$

Consider the analogous equations

$$x_l \cdot (x_r \cdot (x_j \cdot Z_L)) - x_r \cdot (x_l \cdot (x_j \cdot Z_L)) = ([x_l, x_r]_A) \cdot (x_j \cdot Z_L) \tag{25.11.16}$$

and

$$x_r \cdot (x_j \cdot (x_l \cdot Z_L)) - x_j \cdot (x_r \cdot (x_l\, Z_L)) = ([x_r, x_j]_A) \cdot (x_l\, Z_L), \tag{25.11.17}$$

where the indices j, l, and r have been cyclically permuted. These two equations hold by induction, because $\min(l, r) = \min(r, j) = r$ is strictly less than $\min(j, l) = l$. This also uses the fact that $x_j \cdot Z_L$ and $x_l \cdot Z_L$ can be expressed as finite linear combinations of Z_{N_0}'s with $N_0 \in \mathcal{M}(I)$ and

$$\text{length}(N_0) \leq \text{length}(L) + 1 = \text{length}(N), \tag{25.11.18}$$

as in (25.11.3).

If $x, y \in A$, then

$$x \cdot (y \cdot Z_L) - y \cdot (x \cdot Z_L) = ([x, y]_A) \cdot Z_L, \tag{25.11.19}$$

by induction, because

$$\text{length}\, L = \text{length}(N) - 1 < \text{length}(N). \tag{25.11.20}$$

This implies that

$$\begin{aligned}([x_j, x_l]_A) \cdot (x_r \cdot Z_L) &= x_r \cdot ([x_j, x_l]_A \cdot Z_L) + ([[x_j, x_l]_A, x_r]_A) \cdot Z_L \\ &= x_r \cdot (x_j \cdot (x_l \cdot Z_L)) - x_r \cdot (x_l \cdot (x_j \cdot Z_L)) \\ &\quad +([[x_j, x_l]_A, x_r]_A) \cdot Z_L,\end{aligned} \tag{25.11.21}$$

using (25.11.19) in both steps. The left side of (25.11.21) is the same as the right side of (25.11.15), so that (25.11.15) is equivalent to

$$\begin{aligned}&x_j \cdot (x_l \cdot (x_r \cdot Z_L)) - x_l \cdot (x_j \cdot (x_r \cdot Z_L)) \\ &\quad = x_r \cdot (x_j \cdot (x_l \cdot Z_L)) - x_r \cdot (x_l \cdot (x_j \cdot Z_L)) \\ &\qquad +([[x_j, x_l]_A, x_r]_A) \cdot Z_L.\end{aligned} \tag{25.11.22}$$

Similarly, (25.11.16) and (25.11.17) imply that the equations analogous to (25.11.22) but with the indices j, l, and r permuted cyclically hold. Consider the equation obtained by adding the left and right sides of the three equations corresponding to (25.11.22) and the two analogous equations for (25.11.16) and (25.11.17). The terms on the left side of the new equation all cancel with terms on the right side of the new equation. There are also three terms on the right side of the new equation that correspond to the last term on the right side of (25.11.22), and the two analogous terms with the indices permuted cyclically. The sum of these three terms is equal to 0, by the Jacobi identity.

This means that the new equation holds automatically. Because the two equations analogous to (25.11.22) with the indices permuted cyclically hold, we get that (25.11.22) holds as well. It follows that (25.11.15) holds, so that (25.11.9) holds, as desired. This shows that V is a module over A as a Lie algebra over k.

We may consider V as a left module over UA too, as an associative algebra over k, as in Section 25.6. If $M \in \mathcal{M}(I)$, then $x_M \in UA$ can be defined as in (25.10.5). One can check that

$$x_M \cdot Z_\emptyset = Z_M, \tag{25.11.23}$$

using (25.11.2) and induction on the length of M. In particular, if $M = \emptyset$, then x_M is interpreted as being e_{UA}, which acts on V by the identity mapping.

Suppose that c_M is an element of k for every $M \in \mathcal{M}(I)$, with $c_M = 0$ for all but finitely many M, and

$$\sum_{M \in \mathcal{M}(I)} c_M\, x_M = 0 \tag{25.11.24}$$

in UA. This implies that

$$\sum_{M \in \mathcal{M}(I)} c_M\, Z_M = \sum_{M \in \mathcal{M}(I)} c_M\, x_M \cdot Z_\emptyset = 0 \tag{25.11.25}$$

in V. It follows that $c_M = 0$ for every $M \in \mathcal{M}(I)$, because the Z_M's form a basis for V as a free module over k, by construction. This means that the family of x_M, $M \in \mathcal{M}(I)$, is a basis for UA as a module over k, because UA is generated by the x_M's as a module over k, as in the previous section. This completes the proof of the Poincaré–Birkhoff–Witt theorem, as before.

25.12 Some corollaries

Let k be a commutative ring with a multiplicative identity element, and let $(A, [\cdot, \cdot]_A)$ be a Lie algebra over k. Also let UA be a universal enveloping algebra of A, with multiplicative identity element $e = e_{UA}$ and Lie algebra homomorphism $i = i_{UA}$ from A into UA. Remember that the submodule $U_n A$ of UA, as a module over k, is defined for nonnegative integers n as in Section 25.9. In particular, $U_0 A$ consists of multiples of e by elements of k, and $U_1 A$ consists of sums of elements of $U_0 A$ and $i(A)$.

More precisely, $U_1 A$ corresponds to the direct sum of $U_0 A$ and $i(A)$, as a module over k, as indicated on p13 of [25]. This can be seen using the natural algebra homomorphism from UA onto k mentioned in Section 25.6. This implies that the restriction of the quotient mapping from $U_1 A$ onto $\mathrm{gr}_1 UA = (U_1 A)/(U_0 A)$ to $i(A)$ is a one-to-one mapping from $i(A)$ onto $\mathrm{gr}_1 UA$.

If A is free as a module over k, then the Poincaré–Birkhoff–Witt theorem implies that i is an injective mapping from A into UA. This is Corollary 1 on p16 of [25], which corresponds to Corollary B on p92 of [14].

Let A_0 be a Lie subalgebra of A, and let UA_0 be a universal enveloping algebra of A_0, with multiplicative identity element $e_0 = e_{UA_0}$ and Lie algebra homomorphism $i_0 = i_{UA_0}$ from A_0 into UA_0. As in Section 25.6, the restriction ϕ_0 of i to A_0 is a Lie algebra homomorphism from A_0 into UA, which leads to a unique algebra homomorphism ϕ_0 from UA_0 into UA such that $\psi_0(e_0) = e$ and $\psi_0 \circ i_0 = \phi_0$. Suppose that A_0 is free as a module over k, with basis $\{x_j\}_{j \in I_0}$ for some nonempty set I_0. Suppose also that A is free as a module over k, and that $\{x_j\}_{j \in I_0}$ can be extended to a basis $\{x_j\}_{j \in I}$ of A, with $I_0 \subseteq I$. Let $\preceq$ be a linear ordering on I, with $j_0 \preceq l$ for every $j_0 \in I_0$ and $l \in I \setminus I_0$. Thus $\mathcal{M}(I)$ and $x_M \in UA$, $M \in \mathcal{M}(I)$, can be defined as in Section 25.10, and the family of x_M, $M \in \mathcal{I}$, is a basis for UA, as a module over k, by the Poincaré–Birkhoff–Witt theorem. This implies that ψ_0 is an injective mapping from UA_0 into UA, and more precisely that UA may be considered as a free module over UA_0, using x_M with $M \in \mathcal{M}(I \setminus I_0)$. This corresponds to Corollary D on p92 of [14].

Let A_1 and A_2 be Lie subalgebras of A, and let UA_1, UA_2 be universal enveloping algebras of A_1, A_2, respectively, with multiplicative identity elements $e_j = e_{UA_j}$ and Lie algebra homomorphisms $i_j = i_{UA_j}$ from A_j into UA_j for $j = 1, 2$. As before, the restriction ϕ_j of i to A_j is a Lie algebra homomorphism from A_j into UA for $j = 1, 2$, which leads to a unique algebra homomorphism ψ_j from UA_j into UA such that $\psi_j(e_j) = e$ and $\psi_j \circ i_j = \phi_j$. Observe that

$$(w_1, w_2) \mapsto \psi_1(w_1)\, \psi_2(w_2) \tag{25.12.1}$$

is a bilinear mapping from $(UA_1) \times (UA_2)$ into UA. Using this, we get a unique linear mapping from $(UA_1) \bigotimes (UA_2)$ into UA with

$$w_1 \otimes w_2 \mapsto \psi_1(w_1)\, \psi_2(w_2) \tag{25.12.2}$$

for every $w_1 \in UA_1$ and $w_2 \in UA_2$.

Suppose that A corresponds to the direct sum of A_1 and A_2, as a module over k, and that A_1 and A_2 are free as modules over k. Let $\{x_j\}_{j \in I_1}$ and $\{x_j\}_{j \in I_2}$ be bases for A_1 and A_2, respectively, where $I_1 \cap I_2 = \emptyset$. Of course, A is a free module over k as well, with basis $\{x_j\}_{j \in I}$, where $I = I_1 \cup I_2$. Let $\preceq$ be a linear ordering on I, with $j_1 \preceq j_2$ for every $j_1 \in I_1$ and $j_2 \in I_2$. Note that the restrictions of $\preceq$ to I_1 and I_2 define linear orderings on those sets.

Let $\mathcal{M}(I)$ and $x_M \in UA$, $M \in \mathcal{M}(I)$, be as in Section 25.10, so that the family of x_M, $M \in \mathcal{M}(I)$, is a basis for UA, as a module over k, by the Poincaré–Birkhoff–Witt theorem. Of course, we get analogous bases for UA_1 and UA_2, as modules over k, indexed by $\mathcal{M}(I_1)$ and $\mathcal{M}(I_2)$, respectively. This leads to a basis for $(UA_1) \bigotimes (UA_2)$, as a module over k, indexed by $\mathcal{M}(I_1) \times \mathcal{M}(I_2)$. Elements of $\mathcal{M}(I_1)$ and $\mathcal{M}(I_2)$ can be combined to get elements of $\mathcal{M}(I)$, and every element of $\mathcal{M}(I)$ can be obtained by combining unique elements of $\mathcal{M}(I_1)$ and $\mathcal{M}(I_2)$ in this way. This defines a one-to-one correspondence between $\mathcal{M}(I_1) \times \mathcal{M}(I_2)$ and $\mathcal{M}(I)$.

The linear mapping from $(UA_1) \bigotimes (UA_2)$ into UA determined by (25.12.2) defines a one-to-one correspondence between the bases for $(UA_1) \bigotimes (UA_2)$ and UA, as modules over k, defined in the preceding paragraph. In particular, this linear mapping is an isomorphism between $(UA_1) \bigotimes (UA_2)$ and UA, as modules over k, as in Corollary 2 on p16 of [25].

In this case, we also have an induced isomorphism from $(\operatorname{gr} UA_1) \bigotimes (\operatorname{gr} UA_2)$ onto $\operatorname{gr} UA$, as on p16 of [25]. More precisely, remember that $\operatorname{gr} UA$ is isomorphic to SA, as in the Poincaré–Birkhoff–Witt theorem, and similarly $\operatorname{gr} UA_1$, $\operatorname{gr} UA_2$ are isomorphic to SA_1, SA_2, respectively. The corresponding isomorphism from $(SA_1) \bigotimes (SA_2)$ onto SA can be seen in terms of bases here, or as in Section 25.7.

25.13 Some related filtrations

Let us look a bit more at the filtrations associated to the type of situation mentioned at the end of the previous section. Let k be a commutative ring with a multiplicative identity element again, let $(A, [\cdot,\cdot]_A)$ be a Lie algebra over k, and let A_1, A_2 be Lie subalgebras of A. Also let UA, UA_1, and UA_2 be universal enveloping algebras of A, A_1, and A_2, respectively, with multiplicative identity elements $e = e_{UA}$, $e_1 = e_{UA_1}$ and $e_2 = e_{UA_2}$, and Lie algebra homomorphisms $i = i_{UA}$, $i_1 = i_{UA_1}$, and $i_2 = i_{UA_2}$ from A, A_1, and A_2 into UA, UA_1, and UA_2, respectively. If n is a nonnegative integer, then the corresponding submodules U_nA, U_nA_1, and U_nA_2 of UA, UA_1, and UA_2, respectively, can be defined as in Section 25.9.

The restriction ϕ_j of i to A_j is a Lie algebra homomorphism from A_j into UA for $j = 1, 2$, which leads to a unique algebra homomorphism ψ_j from UA_j into UA such that $\psi_j(e_j) = e$ and $\psi_j \circ i = \phi_j$, as before. Using this, we get a bilinear mapping from $(UA_1) \times (UA_2)$ into UA as in (25.12.1), which leads to a unique linear mapping from $(UA_1) \bigotimes (UA_2)$ into UA that satisfies (25.12.2). If $w_1 \in U_{n_1} A_1$ and $w_2 \in U_{n_2} A_2$ for some $n_1, n_2 \geq 0$, then it is easy to see that

$$\psi_1(w_1)\, \psi_2(w_2) \in U_{n_1+n_2} A. \tag{25.13.1}$$

Let n be a nonnegative integer, and let $((UA_1) \bigotimes (UA_2))_n$ be the submodule of $(UA_1) \bigotimes (UA_2)$, as a module over k, generated by elements of the form $w_1 \otimes w_2$, with $w_1 \in U_{n_1} A_1$, $w_2 \in U_{n_2} A_2$, and $n_1 + n_2 \leq n$. Thus the linear mapping from $(UA_1) \bigotimes (UA_2)$ into UA mentioned before maps $((UA_1) \bigotimes (UA_2))_n$ into $U_n A$ for every $n \geq 0$, by (25.13.1).

Observe that

$$((UA_1) \bigotimes (UA_2))_n \subseteq ((UA_1) \bigotimes (UA_2))_{n+1} \tag{25.13.2}$$

for every $n \geq 0$, and that $\bigcup_{n=0}^{\infty} ((UA_1) \bigotimes (UA_2))_n = (UA_1) \bigotimes (UA_2)$. Remember that $gr_n UA$ is defined as in Section 25.9 for each nonnegative integer n, and similarly for $\mathrm{gr}_n\, UA_1$, $\mathrm{gr}_n\, UA_2$. Put

$$\mathrm{gr}_n((UA_1) \bigotimes (UA_2)) = ((UA_1) \bigotimes (UA_2))_n / ((UA_1) \bigotimes (UA_2))_{n-1} \tag{25.13.3}$$

for each positive integer n, where the quotient is defined as a module over k, and $\mathrm{gr}_0((UA_1) \bigotimes (UA_2))_0 = ((UA_1) \bigotimes (UA_2))_0$. Using the linear mapping from $(UA_1) \bigotimes (UA_2)$ into UA mentioned in the preceding paragraph, we get an induced linear mapping from $\mathrm{gr}_n((UA_1) \bigotimes (UA_2))_n$ into $\mathrm{gr}_n\, UA$ for every $n \geq 0$. If we put

$$\mathrm{gr}((UA_1) \bigotimes (UA_2)) = \bigoplus_{n=0}^{\infty} \mathrm{gr}_n((UA_1) \bigotimes (UA_2)), \tag{25.13.4}$$

then we get a homomorphism from $\mathrm{gr}((UA_1) \bigotimes (UA_2))$ into $\mathrm{gr}\, UA$, as modules over k.

Of course,

$$(w_1, w_2) \mapsto w_1 \otimes w_2 \tag{25.13.5}$$

defines a bilinear mapping from $(UA_1) \times (UA_2)$ into $((UA_1) \bigotimes (UA_2))$. If n_1, n_2 are nonnegative integers, then this bilinear mapping sends $(U_{n_1} A_1) \times (U_{n_2} A_2)$ into $((UA_1) \bigotimes (UA_2))_{n_1+n_2}$. This leads to a bilinear mapping

$$\text{from } (\mathrm{gr}_{n_1} UA_1) \times (\mathrm{gr}_{n_2} UA_2) \text{ into } \mathrm{gr}_{n_1+n_2}((UA_1) \bigotimes (UA_2)). \tag{25.13.6}$$

Using this, we get a bilinear mapping

$$\text{from } (\mathrm{gr}\, UA_1) \times (\mathrm{gr}\, UA_2) \text{ into } \mathrm{gr}((UA_1) \bigotimes (UA_2)). \tag{25.13.7}$$

This leads to a linear mapping

$$\text{from } (\mathrm{gr}\, UA_1) \bigotimes (\mathrm{gr}\, UA_2) \text{ into } \mathrm{gr}((UA_1) \bigotimes (UA_2)). \tag{25.13.8}$$

More precisely, if n is a nonnegative integer, then then $\mathrm{gr}_n((UA_1) \bigotimes (UA_2))$ is generated, as a module over k, by the images of $(\mathrm{gr}_{n_1} UA_1) \times (\mathrm{gr}_{n_2} UA_2)$, with $n_1 + n_2 = n$. This means that

$$(25.13.9) \qquad (\mathrm{gr}\, UA_1) \bigotimes (\mathrm{gr}\, UA_2) \text{ maps onto } \mathrm{gr}((UA_1) \bigotimes (UA_2)),$$

under the mapping just mentioned.

Suppose that A_1 and A_2 are free as modules over k, with bases $\{x_j\}_{j \in I_1}$ and $\{x_j\}_{j \in I_2}$, respectively. Suppose that I_1 and I_2 are also linearly ordered, so that $\mathcal{M}(I_1)$, $\mathcal{M}(I_2)$ can be defined as in Section 25.10. Using the Poincaré–Birkhoff–Witt theorem, we get bases for UA_1 and UA_2, as modules over k, indexed by $\mathcal{M}(I_1)$ and $\mathcal{M}(I_2)$, respectively. In particular, the mapping indicated in (25.13.8) is an isomorphism between modules over k in this situation. Using these bases for UA_1 and UA_2, we get a basis for $(UA_1) \bigotimes (UA_2)$ as well, as a module over k.

Suppose that A corresponds to the direct sum of A_1 and A_2, as a module over k. Thus A is free as a module over k too, with basis $\{x_j\}_{j \in I}$, where $I = I_1 \cup I_2$, and $I_1 \cap I_2 = \emptyset$. Let $\preceq$ be a linear ordering on I, with $j_1 \preceq j_2$ for every $j_1 \in I_1$ and $j_2 \in I_2$, and let us take I_1 and I_2 to be linearly ordered by the restrictions of $\preceq$ to the subsets of I. Using the Poincaré–Birkhoff–Witt theorem again, we get a basis for UA, as a module over k, indexed by the corresponding set $\mathcal{M}(I)$. As in the previous section, the linear mapping from $(UA_1) \bigotimes (UA_2)$ into UA determined by (25.12.2) is an isomorphism between these spaces, as modules over k, because it defines a one-to-one correspondence between their bases.

Similarly, the homomorphism from $\mathrm{gr}((UA_1) \bigotimes (UA_2))$ into $\mathrm{gr}\, UA$, as modules over k, mentioned earlier is an isomorphism under these conditions. This can be composed with the isomorphism indicated in (25.13.8), to get an isomorphism from $(\mathrm{gr}\, UA_1) \bigotimes (\mathrm{gr}\, UA_2)$ onto $\mathrm{gr}\, UA$, as modules over k, under these conditions.

25.14 The diagonal mapping

Let k be a commutative ring with a multiplicative identity element, and let $(A, [\cdot, \cdot]_A)$ be a Lie algebra over k. Also let UA be a universal enveloping algebra of A, with multiplicative identity element $e = e_{UA}$ and Lie algebra homomorphism $i = i_{UA}$ from A into UA, as before. Of course, $A \times A$ may be considered as a Lie algebra over k too, where addition, scalar multiplication, and the Lie bracket are defined coordinatewise. Note that $A_1 = A \times \{0\}$ and $A_2 = \{0\} \times A$ are Lie subalgebras of $A \times A$, and that $A \times A$ corresponds to the direct sum of A_1 and A_2, as a Lie algebra over k. We may consider UA to be a universal enveloping algebra of A_1 and A_2, using the obvious isomorphisms $a \mapsto (a, 0)$ and $a \mapsto (0, a)$ from A onto A_1 and A_2, respectively.

If $a_1, a_2 \in A$, then put

$$(25.14.1) \qquad \rho((a_1, a_2)) = i(a_1) \otimes e + e \otimes i(a_2),$$

which defines a mapping from $A \times A$ into $(UA) \bigotimes (UA)$. More precisely, ρ is a Lie algebra homomorphism from $A \times A$ into $(UA) \bigotimes (UA)$, as in Section 25.7. This leads to an algebra homomorphism θ from a universal enveloping algebra of $A \times A$ into $(UA) \bigotimes (UA)$, which is an algebra isomorphism in this situation, as before. One can use this to consider $(UA) \bigotimes (UA)$ as a universal enveloping algebra of $A \times A$.

Clearly $a \mapsto (a, a)$ is a Lie algebra homomorphism from A into $A \times A$. We can compose this with ρ to get a Lie algebra homomorphism

$$a \mapsto i(a) \otimes e + e \otimes i(a) \tag{25.14.2}$$

from A into $(UA) \bigotimes (UA)$. This leads to a unique algebra homomorphism Δ from UA into $(UA) \bigotimes (UA)$, where $\Delta(e) = e \otimes e$ and $\Delta \circ i$ is the same as (25.14.2). This is called the *diagonal map*, as in Definition 5.1 and Proposition 5.2 on p16 of [25].

An element α of UA is said to be *primitive* if

$$\Delta(\alpha) = \alpha \otimes e + e \otimes \alpha, \tag{25.14.3}$$

as in Definition 5.3 on p17 of [25]. Every element of $i(A)$ is primitive, as in the preceding paragraph.

If $t \in k$ and $n \in \mathbf{Z}_+$, then $n \cdot t$ denotes the sum of n t's in k, as usual. Suppose that k is torsion-free, so that $n \cdot t = 0$ implies $t = 0$. If A is free as a module over k, then Theorem 5.4 on p17 of [25] states that the only primitive elements of UA are in $i(A)$.

Suppose first that A is commutative as a Lie algebra over k, as in [25]. Let $\{x_j\}_{j \in I}$ be a basis for A, as a module over k, and let X_j, $j \in I$, be a commuting family of indeterminates. There is a unique module homomorphism from A into the polynomial algebra $k[\{X_j : j \in I\}]$ that sends x_j to X_j for every $j \in I$. Using this, $k[\{X_j : j \in I\}]$ may be considered as a symmetric algebra of A, as in Section 25.8. This means that $k[\{X_j : j \in I\}]$ is a universal enveloping algebra of A in this case.

Let X_j' and X_j'' be additional indeterminates for each $j \in I$, which commute with each other and with X_l', X_l'', $l \in I$. The tensor product of $k[\{X_j : j \in I\}]$ with itself can be identified with the polynomial algebra

$$k[\{X_j', X_j'' : j \in I\}], \tag{25.14.4}$$

where X_j' corresponds to $X_j \otimes 1$ and X_j'' corresponds to $1 \otimes X_j$ for every $j \in I$. In this situation, Δ corresponds to the mapping from $k[\{X_j : j \in I\}]$ to (25.14.4) that sends a formal polynomial $f(X)$ in the X_j's to the formal polynomial $f(X' + X'')$ in the X_j''s and X_j'''s, which replaces X_j with $X_j' + X_j''$ for every $j \in I$. The primitive elements correspond to $f(X) \in k[\{X_j : j \in I\}]$ such that

$$f(X' + X'') = f(X') + f(X''). \tag{25.14.5}$$

If $f(X)$ is homogeneous of degree n for some nonnegative integer n, then this would imply that

$$2^n \cdot f(X) = f(X + X) = f(X) + f(X) = 2 \cdot f(X), \tag{25.14.6}$$

which is to say that $(2^n - 2) \cdot f(X) = 0$. If $n \neq 1$, then this implies that $f(X) = 0$, because k is torsion-free, by hypothesis. Otherwise, one can apply this argument to the homogeneous components of $f(X)$, which satisfy the same condition.

Let us now consider the case where A is not necessarily commutative as a Lie algebra over k, as in [25] again. Remember that $a \mapsto (a, a)$ is a Lie algebra homomorphism from A into $A \times A$. If $U(A \times A)$ is a universal enveloping algebra of $A \times A$, then we can compose the previous Lie algebra homomorphism from A into $A \times A$ with the usual Lie algebra homomorphism from $A \times A$ into $U(A \times A)$ to get a Lie algebra homomorphism from A into $U(A \times A)$. This leads to a unique algebra homomorphism from UA into $U(A \times A)$, with the usual properties. It is easy to see that Δ is the same as the composition of this homomorphism with the algebra isomorphism θ from $U(A \times A)$ onto $(UA) \times (UA)$ mentioned earlier.

The algebra homomorphism from UA into $U(A \times A)$ mentioned in the preceding paragraph induces an algebra homomorphism from $\operatorname{gr} UA$ into $\operatorname{gr} U(A \times A)$. We also have that θ induces an algebra isomorphism from $\operatorname{gr} U(A \times A)$ onto $(\operatorname{gr} UA) \bigotimes (\operatorname{gr} UA)$, as in the previous sections. Using this, Δ induces an algebra homomorphism $\operatorname{gr} \Delta$ from $\operatorname{gr} UA$ into $(\operatorname{gr} UA) \bigotimes (\operatorname{gr} UA)$. Remember that $\operatorname{gr} UA$ is isomorphic to SA, by the Poincaré–Birkhoff–Witt theorem. Thus $\operatorname{gr} \Delta$ corresponds to an algebra homomorphism from SA into $(SA) \bigotimes (SA)$.

Of course, SA is the same as a universal enveloping algebra of A as a commutative Lie algebra over k. The algebra homomorphism from SA into $(SA) \bigotimes (SA)$ mentioned in the preceding paragraph corresponds exactly to the one considered in the first case. This can be seen by considering elements of $\operatorname{gr}_1 UA$ that come from elements of A in the usual way.

Let x be a primitive element of UA, and suppose that $x \in U_n A$ for some $n \geq 0$. This implies the analogous condition for the image of x in $\operatorname{gr}_n UA$ with respect to $\operatorname{gr} \Delta$. If $n > 1$, then it follows that the image of x in $\operatorname{gr}_n UA$ is equal to 0, as in the first case. This means that $x \in U_{n-1} A$, and we can repeat the process to get that $x \in U_1 A$.

Thus $x = t\, e + i(a)$ for some $t \in k$ and $a \in A$, which implies that

$$\Delta(x) = t\,(e \otimes e) + i(a) \otimes e + e \otimes i(a). \tag{25.14.7}$$

Observe that

$$x \otimes e + e \otimes x = t\,(e \otimes e) + i(a) \otimes e + t\,(e \otimes e) + e \otimes i(a). \tag{25.14.8}$$

The hypothesis that x be primitive means that (25.14.7) and (25.14.8) are the same, so that $t = 0$. This shows that $x = i(a) \in i(A)$, as desired.

25.15 More on primitive elements

Let us return to the situation considered at the beginning of the previous section. Thus we let k be a commutative ring with a multiplicative identity element again, and $(A, [\cdot, \cdot]_A)$ be a Lie algebra over k. Also let UA be a universal enveloping algebra of A, with multiplicative identity element $e = e_{UA}$ and Lie algebra homomorphism $i = i_{UA}$ from A into UA. Remember that the diagonal map Δ is an algebra homomorphism from UA into $(UA) \bigotimes (UA)$.

Let PUA be the set of primitive elements of UA. It is easy to see that PUA is a submodule of UA, as a module over k. Execise 1 on p17 of [25] asks one to show that if $x, y \in PUA$, then $[x, y] = x\,y - y\,x \in PUA$. This means that

$$\Delta([x, y]) = ([x, y]) \otimes e + e \otimes ([x, y]). \tag{25.15.1}$$

Of course, $\Delta([x, y]) = [\Delta(x), \Delta(y)]$, because Δ is an algebra homomorphism. It follows that

$$\Delta([x, y]) = [x \otimes e + e \otimes x, y \otimes e + e \otimes y], \tag{25.15.2}$$

because x, y are primitive by hypothesis. It is easy to obtain (25.15.1) from (25.15.2), because of the way multiplication is defined in $(UA) \otimes (UA)$, as in Section 25.2.

Of course, we may as well suppose that $k \neq \{0\}$, so that $1 \neq 0$ in k. Let us suppose from now on in this section that there is a prime number p such that $p \cdot 1 = 0$ in k, as in Exercise 2 on p17 of [25]. Of course, this means that $p \cdot t = 0$ for every $t \in k$.

Let n be a positive integer that is not a multiple of p, so that there is a positive integer m such that $m\,n - 1$ is a multiple of p. If $t \in k$, then

$$m \cdot (n \cdot t) = (m\,n) \cdot t = t. \tag{25.15.3}$$

In particular, if $n \cdot t = 0$, then $t = 0$.

If $y \in PUA$, then part (a) of Exercise 2 on p17 of [25] asks us to show that

$$y^p \in PUA. \tag{25.15.4}$$

Observe that

$$\Delta(y^p) = (\Delta(y))^p = (y \otimes e + e \otimes y)^p, \tag{25.15.5}$$

because Δ is an algebra homomorphism. The right side can be expanded into a sum, using the binomial theorem, because $y \otimes e$ commutes with $e \otimes y$ in $(UA) \bigotimes (UA)$. It is well known and easy to see that the binomial coefficient $\binom{p}{j}$ is a multiple of p when $j = 1, \ldots, p - 1$. It follows that

$$\Delta(y^p) = (y \otimes e)^p + (e \otimes y)^p = y^p \otimes e + e \otimes y^p, \tag{25.15.6}$$

as desired.

Let us suppose for the rest of the section that A is free as a module over k, and let $\{x_j\}_{j \in I}$ be a basis for A, as a module over k. If $j \in I$, then $i(x_j) \in PUA$, as in the previous section. This implies that

$$i(x_j)^{p^\nu} \in PUA \tag{25.15.7}$$

for every positive integer ν, by (25.15.4). Part (b) of Exercise 2 on p17 of [25] asks us to show that the family of elements of PUA of the form

$$i(x_j)^{p^\nu}, \text{ with } j \in I \text{ and } \nu \in \mathbf{Z}_+ \cup \{0\}, \tag{25.15.8}$$

is a basis for PUA, as a module over k. It suffices to show that every element of PUA can be expressed as a finite linear combination of these elements, because of the Poincaré–Birkhoff–Witt theorem.

Suppose first that A is commutative as a Lie algebra over k, as in the previous section, and let X_j, $j \in I$, be a commuting family of indeterminates again. As before, the polynomial algebra $k[\{X_j : j \in I\}]$ may be considered as a symmetric algebra of A, using the unique module homomorphism from A into this algebra that sends x_j to X_j for every $j \in I$. This is the same as a universal enveloping algebra of A in this case. Let X'_j and X''_j be additional indeterminates for each $j \in I$ again, which commute with each other and X'_l, X''_l, $l \in I$, so that the tensor product of $k[\{X_j : j \in I\}]$ with itself can be identified with

$$k[\{X'_j, X''_j : j \in I\}], \tag{25.15.9}$$

as before. Remember that Δ corresponds in this situation to the mapping from $k[\{X_j : j \in I\}]$ to (25.15.9) that sends a formal polynomial $f(X)$ in the X_j's to the formal polynomial $f(X' + X'')$ in the X'_j and X''_j's. The primitive elements correspond to the formal polynomials $f(X)$ such that

$$f(X' + X'') = f(X') + f(X''), \tag{25.15.10}$$

as before. In particular, this implies that the constant term in $f(X)$ is equal to 0.

If $f(X)$ satisfies (25.14.5, 2), then we would like to show that $f(X)$ can be expressed as a finite linear combination of the monomials $X_j^{p^\nu}$, with $j \in I$ and $\nu \in \mathbf{Z}_+ \cup \{0\}$. We may as well suppose that the linear terms in $f(X)$ are equal to 0, which would correspond to $\nu = 0$. Under these conditions, one can check that the formal partial derivative of $f(X)$ in the jth variable is equal to 0 for every $j \in I$. To see this, consider the sum of the terms in $f(X' + X'')$ with exactly one factor of X''_j and no factors of X''_l when $j \neq l$, and any number of factors of X'_l for $l \in I$. This sum is equal to the formal partial derivative of $f(X')$ in the jth variable times X''_j. This would have to be a scalar multiple of X''_j, by (25.15.10), which would be a term in $f(X'')$. In fact, this has to be equal to 0, because the linear terms in $f(X)$ are supposed to be equal to 0.

If $j \in I$, then $f(X)$ can be identified with a formal polynomial in X_j whose coefficients are formal polynomials in X_l, $j \neq l$. The formal partial derivative of $f(X)$ in the jth variable corresponds to the usual formal derivative of $f(X)$ as a formal polynomial in this way. In this situation, the condition that the derivative be equal to 0 implies that this formal polynomial in X_j can be expressed as a formal polynomial in X_j^p. This means that $f(X)$ can be expressed as a formal polynomial in X_j^p, $j \in I$, with coefficients in k. Let us express this formally as

$$f(X) = g(X^p). \tag{25.15.11}$$

Using the binomial theorem again, we get that $(X'_j + X''_j)^p = (X'_j)^p + (X''_j)^p$ for every $j \in I$. This implies that g corresponds to a primitive element in the polynomial algebra as well. Note that the linear terms in g correspond to terms in $f(X)$ of the form X_j^p, $j \in I$. We can subtract the linear terms from g, and repeat the previous argument. After a finite number of steps, we can express $f(X)$ as a linear combination of monomials $X_j^{p^\nu}$, with $j \in I$, $\nu \geq 0$, as desired.

If A is not necessarily commutative as a Lie algebra over k, then one can reduce to the previous case, as in the preceding section. Let $x \in PUA$ be given, and suppose that $x \in U_n A$ for some $n \geq 0$. This implies that the image of x in $\operatorname{gr}_n UA$ satisfies the analogous primitivity condition with respect to $\operatorname{gr} \Delta$, as before. Using the previous case, we can express the image of x in $\operatorname{gr}_n UA$ in the analogous way. This means that x can be expressed as the sum of a finite linear combination of elements of PUA of the form (25.15.8) and an element of $U_{n-1}A$. This element of $U_{n-1}A$ is primitive as well, because PUA is a submodule of UA, as a module over k. Thus we can repeat the process, to get that x is a finite linear combination of elements of PUA of the form (25.15.8), as desired.

If $x, y \in i(A)$, then part (c) of Exercise 2 on p17 of [25] asks us to show that

$$(x + y)^p - x^p - y^p \in i(A). \tag{25.15.12}$$

Note that $x^p, y^p, (x + y)^p \in PUA$, as in (25.15.7), and because $i(A) \subseteq PUA$. This implies that

$$(x + y)^p - x^p - y^p \in PUA, \tag{25.15.13}$$

because PAU is a submodule of UA, as a module over k.

We also have that

$$(x + y)^p - x^p - y^p \in U_{p-1}A. \tag{25.15.14}$$

More precisely, $(x + y)^p - x^p - y^p \in U_p A$, and (25.15.14) is the same as saying that its image in $\operatorname{gr}_p UA$ is equal to 0. This can be obtained from the binomial theorem, because $\binom{p}{l}$ is a multiple of p when $l = 1, \ldots, p - 1$. It is easy to see that (25.15.12) follows from (25.15.13) and (25.15.14), using the basis (25.15.8) for PUA.

Chapter 26

Free Lie algebras

26.1 Magmas and their homomorphisms

A *magma* is a set M together with a mapping from $M \times M$ into M, which may be expressed as

$$(x, y) \mapsto x\,y. \tag{26.1.1}$$

This is Definition 1.1 on p18 of [25]. A mapping ϕ from M into another magma N is said to be a *magma homomorphism* if

$$\phi(x\,y) = \phi(x)\,\phi(y) \tag{26.1.2}$$

for every $x, y \in M$.

Let X be a set, and put $X_1 = X$. If $n \geq 2$ is an integer, then X_n can be defined recursively as the disjoint union of $X_j \times X_l$, where $j, l \in \mathbf{Z}_+$ and $j + l = n$. Let M_X be the disjoint union of the X_n's, $n \in \mathbf{Z}_+$. There is a natural binary operation on M_X, defined using the embedding of $X_j \times X_l$ into X_{j+l} for every $j, l \geq 1$, by construction. This makes M_X into a magma, which is the *free magma on* X, as on p18 of [25]. The elements of M_X may be described as non-associative words on X. If $n \in \mathbf{Z}_+$, then the elements of X_n are said to have length n.

If f is any mapping from X into a magma N, then there is a unique extension of f to a magma homomorphism F from M_X into N. This is Theorem 1.2 on p18 of [25]. More precisely, if $j, l \in \mathbf{Z}_+$, $x \in X_j$, and $y \in X_l$, then $(x, y) \in X_{j+l}$, and F should satisfy

$$F((x, y)) = F(x)\,F(y). \tag{26.1.3}$$

This can be used to define F recursively on M_X.

Of course, M_X is generated by elements of X in the obvious way. Every element of $M_X \setminus X$ can be expressed in a unique way as a product of elements of M_x, as mentioned on p18 of [25].

26.2 Magmas and algebras

Let k be a commutative (associative) ring with a multiplicative identity element, and let M be a nonempty magma. We can define an algebra A over k in the strict sense using M in the usual way, whose elements are formal sums

$$\sum_{m \in M} c_m \, m \tag{26.2.1}$$

with $c_m \in k$ for every $m \in M$, and $c_m = 0$ for all but finitely many $m \in M$. More precisely, this can be defined as the space of k-valued functions on M with finite support, and it is convenient to express the elements of A as formal sums in this way. Of course, A is a module over k with respect to pointwise addition and scalar multiplication of functions on M, which corresponds to termwise addition and scalar multiplication of these formal sums. Multiplication on M extends to a bilinear mapping from $A \times A$ into A, which defines multiplication on A.

Let X be a nonempty set, and let M_X be the free magma on X, as in the previous section. Using M_X, we get an algebra $A_X(k) = A_X$ over k in the strict sense, as in the preceding paragraph. This is called the *free algebra on* X over k, as in Definition 2.1 on p18 of [25].

Let B be another algebra over k in the strict sense, and let f be a mapping from X into B. Under these conditions, there is a unique extension of f to an algebra homomorphism F from A_X into B, as in Theorem 2.2 on p19 of [25]. Note that B may be considered as a magma with respect to multiplication. Thus f can first be extended to a magma homomorphism from M_X into B, as in the previous section. This can be extended to a mapping F from A_X into B that is linear over k. It is easy to see that F is an algebra homomorphism on A_X, because it is a magma homomorphism on M_X. The uniqueness of F follows from the fact that A_X is generated by X, as an algebra over k.

Remember that the length of an element of M_X is defined as in the previous section. Let us say that an element

$$a = \sum_{m \in M_X} c_m \, m \tag{26.2.2}$$

of A_X is homogeneous of degree n for some positive integer n if $c_m = 0$ for every $m \in M_X$ such that the length of m is not equal to n. The set $A_X^n(k) = A_X^n$ of elements of A_X that are homogeneous of degree n is a submodule of A_X, as a module over k, and A_X corresponds to the direct sum of these submodules, as a module over k. If $a_1, a_2 \in A_X$ are homogeneous of degrees $n_1, n_2 \geq 1$, respectively, then $a_1 \, a_2$ is homogeneous of degree $n_1 + n_2$. Thus A_X is graded as an algebra over k in the strict sense in this way, as mentioned on p19 of [25].

26.3 Constructing free Lie algebras

Let k be a commutative ring with a multiplicative identity element again, and let X be a nonempty set. Also let A_X be the free algebra on X over k, as in the previous section. Consider the two-sided ideal $\mathcal{I}_X$ of A_X generated by elements of the form

$$a\,a, \tag{26.3.1}$$

with $a \in A_X$, and

$$J(a,b,c) = (a\,b)\,c + (b\,c)\,a + (c\,a)\,b, \tag{26.3.2}$$

with $a, b, c \in A_X$. Thus an element of $\mathcal{I}_X$ is a finite sum of elements of A_X, each of which can be obtained by starting with an element of the form (26.3.1) or (26.3.2), and multiplying it on the left and right by elements of A_X. More precisely, one can multiply elements of the form (26.3.1) or (26.3.2) by elements of A_X on the left or right by elements of A_X repeatedly, and in any order.

Thus the quotient

$$A_X/\mathcal{I}_X \tag{26.3.3}$$

is defined as an algebra over k in the strict sense. It is easy to see that (26.3.3) is a Lie algebra over k, because elements of A_X of the form (26.3.1) and (26.3.2) are mapped to 0 in (26.3.3). More precisely, the Lie bracket on (26.3.3) is the binary operation that corresponds to multiplication on A_X. This is called the *free Lie algebra on* X over k, as in Definition 3.1 on p19 of [25]. This may be denoted $L_X(k)$, or L_X when the choice of k is clear.

Of course, there is a natural mapping from X into L_X, obtained by restricting the quotient mapping from A_X onto L_X to X, as a subset of A_X. Note that L_X is generated as an algebra over k by the image of X in L_X, because A_X is generated as an algebra over k by X, by construction.

Let B be a Lie algebra over k, and let f be a mapping from X into B. As in the previous section, there is a unique extension of f to an algebra homomorphism F from A_X into B. This extension maps elements of A_X of the form (26.3.1) and (26.3.2) to 0 in B, because B is a Lie algebra over k. This implies that $\mathcal{I}_X$ is contained in the kernel of F. This leads to an algebra homomorphism from L_X into B. By construction, the composition of this algebra homomorphism with the natural mapping from X into L_X is f. This algebra homomorphism from L_X into B is uniquely determined by this property, because L_X is generated as an algebra by the image of X, as in the preceding paragraph.

This property is essentially used to define free Lie algebras on X on p94f of [14]. It is easy to see that the free Lie algebra on X is uniquely determined by this property, up to a unique isomorphism, as on p95 of [14]. The existence of a free Lie algebra on X is obtained another way on p95 of [14], and we shall return to this later.

Let Y be another nonempty set, and let L_Y be the corresponding free algebra on Y over k. If f is a mapping from X into Y, then we get a mapping from X into L_Y, by composing f with the natural mapping from Y into L_Y. This leads to a unique Lie algebra homomorphism from L_X into L_Y, whose composition with the natural mapping from X into L_X is the mapping from X into L_Y just mentioned, as before. This is one of the properties of free Lie algebras mentioned on p19 of [25].

Remember that A_X is graded as an algebra over k in the strict sense, as in the previous section. Let $\mathcal{I}_X^\#$ be the collection of elements of A_X whose homogeneous components are elements of $\mathcal{I}_X$. Thus $\mathcal{I}_X^\# \subseteq \mathcal{I}_X$ automatically, and we would like to verify that

$$\mathcal{I}_X^\# = \mathcal{I}_X, \tag{26.3.4}$$

as on p19 of [25]. It suffices to check that $\mathcal{I}_X$ is generated by homogeneous elements of A_X, as a two-sided ideal in A_X.

Let $a \in A_X$ be given, and let a_n be the homogeneous component of a_n for each positive integer n, so that $a_n = 0$ for all but finitely many $n \geq 1$, and $a = \sum_{n=1}^\infty a_n$. Observe that

$$a\,a = \sum_{n=1}^\infty a_n\,a_n + \sum_{n=2}^\infty \sum_{l=1}^{n-1} (a_l\,a_n + a_n\,a_l). \tag{26.3.5}$$

Clearly $a_n\,a_n \in \mathcal{I}_X$ for every $n \geq 1$, and

$$a_l\,a_n + a_n\,a_l = (a_l + a_n)\,(a_l + a_n) - a_l\,a_l - a_n\,a_n \tag{26.3.6}$$

is an element of $\mathcal{I}_X$ when $l < n$. This implies that $a\,a$ can be expressed as a finite sum of homogeneous elements of $\mathcal{I}_X$.

Similarly, let $b, c \in A_X$ be given, with homogeneous components b_n, c_n for every $n \geq 1$, respectively. It is easy to see that

$$J(a, b, c) = \sum_{j=1}^\infty \sum_{l=1}^\infty \sum_{n=1}^\infty J(a_j, b_l, c_n). \tag{26.3.7}$$

Thus $J(a, b, c)$ can be expressed as a finite sum of homogeneous elements of $\mathcal{I}_X$ too. It follows that (26.3.4) holds, as before.

Let us say that an element of L_X is homogeneous of degree $n \in \mathbf{Z}_+$ if it is the image of an element of A_X that is homogeneous of degree n under the natural quotient mapping. This makes L_X a graded algebra over k as well, because of (26.3.4), as on p19 of [25].

In particular, 0 is the only element of $\mathcal{I}_X$ that is homogeneous of degree 1. Thus the quotient mapping from A_X onto L_X is injective on the submodule of A_X consisting of elements that are homogeneous of degree 1. This corresponds to part of the statement at the top of p20 of [25].

26.4 Degree 2 in L_X

Let k be a commutative ring with a multiplicative identity element, and let A be a module over k. Thus $A \bigotimes A$ can be defined as a module over k in the usual way. Let B be the submodule of $A \bigotimes A$ generated by elements of $A \bigotimes A$ of the form $a \otimes a$, with $a \in A$. Equivalently, B consists of finite linear combinations of elements of this form, with coefficients in k. In particular, if $x, y \in A$, then

$$x \otimes y + y \otimes x = (x + y) \otimes (x + y) - x \otimes x - y \otimes y \tag{26.4.1}$$

is an element of B. We can define $\bigwedge^2 A$ to be the quotient

$$(A \bigotimes A)/B, \tag{26.4.2}$$

as a module over k. If $x, y \in A$, then let $x \wedge y$ be the image of $x \otimes y$ under the quotient mapping from $A \bigotimes A$ onto (26.4.2). By construction, $a \wedge a = 0$ for every $a \in A$, and $x \wedge y = -y \wedge x$ for every $x, y \in A$.

Consider $A \times (\bigwedge^2 A)$, as a module over k with respect to coordinatewise addition and scalar multiplication. Of course, this is the same as the direct sum of A and $\bigwedge^2 A$, as a module over k. If $x, y \in A$ and $u, v \in \bigwedge^2 A$, then put

$$[(x, u), (y, v)] = (0, x \wedge y). \tag{26.4.3}$$

One can check that $A \times (\bigwedge^2 A)$ is a Lie algebra over k with respect to this definition of Lie bracket, as on p2 of [25].

Let X be a nonempty set, and let A_X be as in Section 26.2. Remember that A_X is a graded as an algebra over k in the strict sense, and let A be the submodule of A consisting of elements that are homogeneous of degree 1. The elements of A correspond to formal sums of elements of X with coefficients in k, where all but finitely many of the coefficients are equal to 0. This can be identified with the space of all k-valued functions on X with finite support, and is free as a module over k.

Similarly, the elements of A_X that are homogeneous of degree 2 correspond to formal sums of elements of $X \times X$ with coefficients in k, where all but finitely many of the coefficients are equal to 0. The submodule of A_X consisting of elements that are homogeneous of degree 2 is free as a module over k, and can be identified with $A \bigotimes A$. The intersection of this submodule with the ideal $\mathcal{I}_X$ in A_X defined in the previous section corresponds in this way exactly to the submodule B of $A \bigotimes A$ mentioned earlier. Remember that the free Lie algebra L_X on X over k is graded as an algebra over k, as in the previous section. The submodule of L_X consisting of homogeneous elements of degree 2 corresponds to $\bigwedge^2 A$, as on p20 of [25].

Of course, we can identify A and $\bigwedge^2 A$ with submodules of $A \times (\bigwedge^2 A)$, as a module over k, in the obvious way. Thus the natural mapping from X into A can be identified with a mapping from X into $A \times (\bigwedge^2 A)$. This leads to a Lie algebra homomorphism from L_X into $A \times (\bigwedge^2 A)$, as in the previous section. This homomorphism sends homogeneous elements of L_X of degree 1 and 2 to their counterparts in A and $\bigwedge^2 A$, as on p20 of [25]. Homogeneous elements of L_X of larger degree are sent to 0 by this homomorphism.

If $a_1, a_2 \in A$, then a_1, a_2 can be identified with homogeneous elements of L_X of degree 1, whose Lie bracket $[a_1, a_2]$ is homogeneous of degree 2 in L_X. This corresponds to $a_1 \wedge a_2$ in $\bigwedge^2 A$, as before. In particular, if $x, y \in X$, then x, y can be identified with elements of A, and $[x, y]$ defined as a homogeneous element of L_X of degree 2.

Let $\preceq$ be a linear ordering on X. The collection of elements of L_X of the form $[x, y]$, where $x, y \in X$, $x \preceq y$, and $x \neq y$, is a basis for the set of homogeneous elements of L_X of degree 2, as a module over k, as on p20 of [25].

26.5 Free associative algebras

Let k be a commutative ring with a multiplicative identity element, and let X be a nonempty set. Also let $E = E_X$ be the free module over k with the elements of X as a basis, so that the elements of E can be given as formal sums

$$\sum_{x \in X} c_x \, x, \tag{26.5.1}$$

with $c_x \in k$ for every $x \in X$, and $c_x = 0$ for all but finitely many $x \in X$. This can be defined as the space of k-valued functions on X with finite support, which can be expressed as formal sums in this way for convenience. This is a module over k with respect to termwise addition and scalar multiplication of formal sums, which corresponds to pointwise addition and scalar multiplication of functions on X.

The *free associative algebra on X over k*, $\mathrm{Assoc}_X(k) = \mathrm{Assoc}_X$, is defined to be the tensor algebra TE on E, as in Definition 4.1 on p20 of [25]. If f is any mapping from X into a module A over k, then f has a natural unique extension to a module homomorphism ϕ from E into A. If A is an associative algebra over k with a multiplicative identity element e, then there is a unique algebra homomorphism ψ from TE into A that is equal to ϕ on $E = T^1 E$ and sends $1 \in k = T^0 E$ to e, as in Section 25.3.

Of course, Assoc_X may be considered as a Lie algebra over k, using the commutator bracket corresponding to multiplication on Assoc_X. The natural inclusion mapping from X into $E = T^1 E$ may be considered as a mapping from X into $\mathrm{Assoc}_X = TE$, which leads to a unique Lie algebra homomorphism ϕ from the free Lie algebra L_X on X over k into Assoc_X, as in Section 26.3. More precisely,

(26.5.2) the composition of ϕ with natural mapping from X into L_X is the same as the natural mapping from X into Assoc_X.

Let UL_X be a universal enveloping algebra of L_X, with corresponding multiplicative identity element e_{UL_X} and mapping i_{UL_X} from L_X into UL_X. The Lie algebra homomorphism ϕ from L_X into Assoc_X mentioned in the preceding paragraph leads to a unique algebra homomorphism Φ from UL_X into Assoc_X such that $\Phi(e_{UL_X}) = 1 \in k \in T^0 E$ and

$$\Phi \circ i_{UL_X} = \phi, \tag{26.5.3}$$

as in Section 25.4.

Similarly,

(26.5.4) there is a natural mapping from X into UL_X, which is obtained by composing the natural mapping from X into L_X with i_{UL_X}.

This leads to a unique algebra homomorphism Ψ from Assoc_X into UL_X, such that

(26.5.5) the composition of Ψ with the natural mapping from X

into Assoc_X is the same as the mapping in (26.5.4),

and which sends $1 \in k = T^0 E$ to e_{UL_X}.

Thus $\Phi \circ \Psi$ is an algebra homomorphism from Assoc_X to itself, which sends $1 \in k = T^0 E$ to itself. By construction, the composition of $\Phi \circ \Psi$ with the natural mapping from X into Assoc_X is that mapping. More precisely, the composition of $\Phi \circ \Psi$ with the natural mapping from X into Assoc_X is the same as the composition of (26.5.3) with the natural mapping from X into L_X. This is the same as the natural mapping from X into Assoc_X, as in (26.5.2). It follows that $\Phi \circ \Psi$ is the identity mapping on Assoc_X.

We also have that $\Psi \circ \Phi$ is an algebra homomorphism from UL_X to itself that sends e_{UL_X} to itself. In order to show that $\Psi \circ \Phi$ is the identity mapping on UL_X, it suffices to verify that

(26.5.6) $$(\Psi \circ \Phi) \circ i_{UL_X} = i_{UL_X}.$$

Observe that

(26.5.7) $$(\Psi \circ \Phi) \circ i_{UL_X} = \Psi \circ (\Phi \circ i_{UL_X}) = \Psi \circ \phi,$$

by (26.5.3). The composition of this mapping with the natural mapping from X into L_X is the same as the composition of Ψ with the natural mapping from X into Assoc_X, by (26.5.2). This is the same as (26.5.4), as in (26.5.5). This means that the compositions of both sides of (26.5.6) with the natural mapping from X into L_X are the same. Of course, both sides of (26.5.6) are Lie algebra homomorphisms from L_X into UL_X. This implies (26.5.6), because L_X is generated as a Lie algebra over k by the image of the natural mapping from X into L_X.

Thus Φ is an algebra isomorphism from UL_X onto Assoc_X, and Ψ is its inverse. This is the first part of Theorem 4.2 on p20 of [25], which corresponds to Exercise 4 on p95 of [14].

Note that

(26.5.8) ϕ maps L_X onto the Lie subalgebra of Assoc_X generated by the image of the natural mapping from X into Assoc_X,

because ϕ is a Lie algebra homomorphism from L_X into Assoc_X, and L_X is generated as a Lie algebra over k by the image of the natural mapping from X into L_X. This is the easy part of the second part of Theorem 4.2 on p20 of [25].

26.6 Injectivity and free modules

Let us continue with the same notation and hypotheses as in the previous section. Under these conditions, we have that

(26.6.1) ϕ is injective as a mapping from L_X into Assoc_X.

This means that ϕ is a Lie algebra isomorphism from L_X onto the Lie subalgebra of Assoc_X generated by the image of the natural mapping from X into Assoc_X, because of (26.5.8). This is the second part of Theorem 4.2 on p20 of [25]. The Lie subalgebra of Assoc_X generated by the image of the natural mapping from X into Assoc_X is used to construct free Lie algebras on p95 of [14].

Part of the third part of Theorem 4.2 on p20 of [25] states that

$$L_X \text{ is free as a module over } k. \tag{26.6.2}$$

Of course, this holds automatically when k is a field. Note that i_{UL_X} is injective as a mapping from L_X into UL_X when (26.6.2) holds, by the Poincaré–Birkhoff–Witt theorem. In this case, (26.6.1) follows from (26.5.3) and the fact that Φ is an isomorphism from UL_X onto Assoc_X, as mentioned on p21 of [25]. Exercise 6 on p95 of [14] asks how the Poincaré–Birkhoff–Witt theorem is used there, perhaps more precisely in the verification of the requirements of free Lie algebras.

Remember that L_X is graded as an algebra over k, as in Section 26.3. If $n \in \mathbf{Z}_+$, then let $L_X^n = L_X^n(k)$ be the submodule of L_X, as a module over k, consisting of elements of L_X that are homogeneous of degree n. The other part of the third part of Theorem 4.2 on p20 of [25] states that

$$L_X^n \text{ is free as a module over } k \text{ for each } n \geq 1. \tag{26.6.3}$$

This implies (26.6.2), because L_X corresponds to the direct sum of L_X^n, $n \geq 1$, as a module over k. As before, (26.6.3) holds automatically when k is a field.

If X has only finitely many elements, then L_X^n is finitely generated as a module over k for each $n \geq 1$. More precisely, this follows from the analogous statement for the free algebra A_X on X over k. The fourth part of Theorem 4.2 concerns the rank of L_X^n, as a free module over k, in this case.

Of course, $\mathrm{Assoc}_X = TE$ is graded as an associative algebra over k, where T^nE corresponds to the submodule of TE of elements that are homogeneous of degree $n \geq 0$. Let $\mathrm{Assoc}_X^n = \mathrm{Assoc}_X^n(k)$ be the submodule of $\mathrm{Assoc}_X = TE$, as a module over k, that corresponds to T^nE for each nonnegative integer n. Similarly, Assoc_X is graded as a Lie algebra over k in this way, with respect to the commutator bracket corresponding to multiplication. Let us check that

$$\phi(L_X^n) \subseteq \mathrm{Assoc}_X^n \tag{26.6.4}$$

for every $n \geq 1$.

Let f be the natural mapping from X into Assoc_X, which corresponds to the natural inclusion mapping of X into $E = T^1E$. Also let A_X be the free algebra on X over k, and let A_X^n be the submodule of A_X consisting of elements that are homogeneous of degree $n \in \mathbf{Z}_+$, as in Section 26.2. There is a unique extension of f to an algebra homomorphism F from A_X into Assoc_X, considered as a Lie algebra over k with respect to the commutator bracket corresponding to multiplication, as before. It is easy to see that

$$F(A_X^n) \subseteq \mathrm{Assoc}_X^n \tag{26.6.5}$$

for every $n \geq 1$. Remember that L_X is a quotient of A_X, and that L_X^n is the image of A_X^n under the quotient mapping. By construction, F is the same as the quotient mapping composed with ϕ. Thus (26.6.4) follows from (26.6.5).

Suppose that k is a field, and that X has only finitely many elements, as in the first step on p21 of [25]. Let $\{\gamma_j\}_{j \in I}$ be a homogeneous basis for L_X, as a graded vector space over k. This means that for each $j \in I$, $\gamma_j \in L_X^{n(j)}$ for some $n(j) \in \mathbf{Z}_+$, and for each $n \in \mathbf{Z}_+$, the collection of γ_j with $n(j) = n$ is a basis for L_X^n, as a vector space over k. Also let $\preceq$ be a linear ordering on I.

The Poincaré–Birkhoff–Witt theorem implies that the family of products of the form

$$i_{UL_X}(\gamma_{j_1}) \cdots i_{UL_X}(\gamma_{j_m}), \tag{26.6.6}$$

where $j_1, \ldots, j_m \in I$ satisfy $j_1 \preceq \cdots \preceq j_m$ and m is a nonnegative integer, form a basis for UL_X. This implies that the corresponding family of products

$$\phi(\gamma_{j_1}) \cdots \phi(\gamma_{j_m}) \tag{26.6.7}$$

is a basis for Assoc_X as a vector space over k. More precisely, this uses (26.5.3) and the fact that Φ is an algebra isomorphism from UL_X onto Assoc_X. We also have that $\phi(\gamma_j) \in \mathrm{Assoc}_X^{n(j)}$ for every $j \in I$, by (26.6.4). This means that (26.6.7) is homogeneous of degree

$$n(j_1) + \cdots + n(j_m) \tag{26.6.8}$$

in Assoc_X, which is interpreted as being equal to 0 when $m = 0$.

This can be used to express the dimension of Assoc_X^n in terms of the dimensions of L_X^r with $r \leq n$, as in [25]. This means that the dimension of L_X^n can be expressed in terms of the dimension of Assoc_X^n and the dimensions of L_X^r with $r < n$, as in the remark on p20 of [25]. In particular, the dimension of L_X^n does not depend on k.

26.7 Finite sets X, $k = \mathbf{Z}$

Let k be a commutative ring with a multiplicative identity element, and let X be a nonempty set. Also let M_X be the free magma on X, and let $A_X(k)$ be the free algebra on X over k, as in Sections 26.1 and 26.2. Remember that $\mathcal{I}_X = \mathcal{I}_X(k)$ is the two sided ideal in $A_X(k)$ generated by elements of the form $a\,a$ and $J(a, b, c)$, where $a, b, c \in A_X(k)$ and $J(a, b, c)$ is as in (26.3.2). Equivalently, $\mathcal{I}_X(k)$ is generated as a two-sided ideal in $A_X(k)$ by elements of the form

$$m\,m, \tag{26.7.1}$$

with $m \in M_X$,

$$m_1\,m_2 + m_2\,m_1 = (m_1 + m_2)\,(m_1 + m_2) - m_1\,m_1 - m_2\,m_2, \tag{26.7.2}$$

with $m_1, m_2 \in M_X$, and

$$J(m_1, m_2, m_3), \tag{26.7.3}$$

with $m_1, m_2, m_3 \in M_X$. This can be seen by expressing $a, b, c \in A_X(k)$ as linear combinations of elements of M_X with coefficients in k.

Let us now consider the cases where k is $\mathbf{Z}$ or $\mathbf{Z}/p\,\mathbf{Z}$ for some prime number p. There is a natural mapping from $A_X(\mathbf{Z})$ onto $A_X(\mathbf{Z}/p\,\mathbf{Z})$, defined by applying the quotient mapping from $\mathbf{Z}$ onto $\mathbf{Z}/p\,\mathbf{Z}$ to the coefficients of elements of $A_X(\mathbf{Z})$. One can check that this mapping also sends $\mathcal{I}_X(\mathbf{Z})$ onto $\mathcal{I}_X(\mathbf{Z}/p\,\mathbf{Z})$. This leads to a mapping from $L_X(\mathbf{Z})$ onto $L_X(\mathbf{Z}/p\,\mathbf{Z})$.

More precisely, the mapping from $A_X(\mathbf{Z})$ onto $A_X(\mathbf{Z}/p\,\mathbf{Z})$ mentioned in the preceding paragraph sends $A_X^n(\mathbf{Z})$ onto $A_X^n(\mathbf{Z}/p\,\mathbf{Z})$ for every $n \in \mathbf{Z}_+$, where $A_X^n(k)$ consists of the elements of $A_X(k)$ that are homogeneous of degree n, as in Section 26.2. Similarly, the induced mapping from $L_X(\mathbf{Z})$ onto $L_X(\mathbf{Z}/p\,\mathbf{Z})$ sends $L_X^n(\mathbf{Z})$ onto $L_X^n(\mathbf{Z}/p\,\mathbf{Z})$ for every $n \in \mathbf{Z}_+$, where $L_X^n(k)$ consists of elements of $L_X(k)$ that are homogeneous of degree n, as in Section 26.3.

Of course, p times any element of $L_X(\mathbf{Z})$ is mapped to 0 in $L_X(\mathbf{Z}/p\,\mathbf{Z})$. Conversely, one can check that any element of $L_X(\mathbf{Z})$ that is mapped to 0 in $L_X(\mathbf{Z}/p\,\mathbf{Z})$ can be expressed as p times an element of $L_X(\mathbf{Z})$.

Suppose now that X has only finitely many elements. Remember that $L_X^n(\mathbf{Z})$ is finitely generated as a module over $\mathbf{Z}$ for every $n \geq 1$ in this case, as in the previous section, which means that $L_X^n(\mathbf{Z})$ is finitely generated as a commutative group. It follows that $L_X^n(\mathbf{Z})$ is isomorphic to a direct sum of finitely many cyclic groups for each $n \geq 1$.

The dimension of $L_X^n(\mathbf{Z}/p\mathbf{Z})$, as a vector space over $\mathbf{Z}/p\,\mathbf{Z}$, can be determined as in the previous section, and does not depend on p. Using this, one can check that $L_X^n(\mathbf{Z})$ is isomorphic to the direct sum of finitely many infinite cyclic groups for each $n \geq 1$. More precisely, the number of factors is the same as the common value of the dimension of $L_X^n(\mathbf{Z}/p\,\mathbf{Z})$ as a vector space over $\mathbf{Z}/p\,\mathbf{Z}$.

In particular, $L_X(\mathbf{Z})$ is free as a module over $\mathbf{Z}$ for every $n \geq 1$, which implies that $L_X(\mathbf{Z})$ is free as a module over $\mathbf{Z}$ too. It follows that the mapping ϕ from $L_X(\mathbf{Z})$ into $\mathrm{Assoc}_X(\mathbf{Z})$ defined in Section 26.5 is injective, as in the previous section. This corresponds to the second step on p22 of [25].

26.8 Arbitrary sets X, $k = \mathbf{Z}$

Let k be a commutative ring with a multiplicative identity element, and let X be a nonempty set. Also let L_X be the free Lie algebra on X over k, let E_X be the free module on X over k, and let $\mathrm{Assoc}_X = TE_X$ be the free associative algebra on X over k, as in Sections 26.3 and 26.5. Remember that the natural inclusion of X in $E_X = T^1 E_X$ leads to a unique Lie algebra homomorphism $\phi = \phi_X$ from L_X into Assoc_X, as before.

Let Y be a nonempty subset of X. The free Lie algebra L_Y on Y over k, the free module E_Y on Y over k, and the free associative algebra $\mathrm{Assoc}_Y = TE_Y$ on Y over k can be defined in the same way as before. Of course, there is a natural inclusion of E_Y into E_X, which leads to a natural inclusion of Assoc_Y into Assoc_X. There is a natural Lie algebra homomorphism from L_Y into L_X as well, as in Section 26.3.

Let ϕ_Y be the unique Lie algebra homomorphism from L_Y into Assoc_Y obtained from the natural inclusion of Y in E_Y, as in Section 26.5. One can check that the composition of the natural Lie algebra homomorphism from L_Y into L_X with ϕ_X is the same as the composition of ϕ_Y with the natural inclusion from Assoc_Y into Assoc_X.

Suppose now that $k = \mathbf{Z}$. If Y has only finitely many elements, then ϕ_Y is injective, as in the previous section. This implies that ϕ_X is injective on the image of L_Y in L_X under the natural Lie algebra homomorphism.

It is easy to see that every element of L_X is in the image of L_Y for some nonempty finite subset Y of X. It follows that ϕ_X is injective as a mapping from L_X into Assoc_X.

Note that Assoc_X is free as a module over $\mathbf{Z}$, which is to say as a commutative group. It is well known that subgroups of free abelian groups are free abelian groups too.

Using the injectivity of ϕ_X, we get that L_X^n is a free abelian group for every $n \geq 1$, and that L_X is a free abelian group. Equivalently, these are free as modules over $\mathbf{Z}$. This corresponds to the third step on p22 of [25].

26.9 Arbitrary X, k

Let k be a commutative ring with a multiplicative identity element, and let X be a nonempty set. Also let M_X be the free magma on X, let $A_X(k)$ be the free algebra on X over k, and let $L_X(k)$ be the free Lie algebra on X over k, as in Sections 26.1, 26.2, and 26.3. Remember that $L_X(k)$ is the quotient of $A_X(k)$ by the two-sided ideal $\mathcal{I}_X(k)$ discussed in Sections 26.3 and 26.7. Of course, $A_X(\mathbf{Z})$, $L_X(\mathbf{Z})$, and $\mathcal{I}_X(\mathbf{Z})$ can be defined in the same way. If $n \in \mathbf{Z}_+$, then let $L_X^n(k)$, $L_X^n(\mathbf{Z})$ be the subsets of $L_X(k)$, $L_X(\mathbf{Z})$ consisting of elements that are homogeneous of degree n, as before.

One can identify $L_X(k)$ with the tensor product of $L_X(\mathbf{Z})$ with k over $\mathbf{Z}$. This is stated more broadly on p19 of [25]. Of course, $A_X(k)$ corresponds to the tensor product of $A_X(\mathbf{Z})$ with k over $\mathbf{Z}$, because $A_X(\mathbf{Z})$ is a free module over $\mathbf{Z}$ with basis M_X. We also have that $\mathcal{I}_X(k)$ is the image of the tensor product of $\mathcal{I}_X(\mathbf{Z})$ with k over $\mathbf{Z}$. Similarly, $L_X^n(k)$ can be identified with the tensor product of $L_X^n(\mathbf{Z})$ with k over $\mathbf{Z}$ for each $n \geq 1$.

Remember that $L_X(\mathbf{Z})$ is a free module over $\mathbf{Z}$ for every $n \geq 1$, and that $L_X(\mathbf{Z})$ is a free module over $\mathbf{Z}$, as in the previous section. It follows that $L^n(k)$ is a free module over k for every $n \geq 1$, and that $L_X(k)$ is a free module over k. This implies that the Lie algebra homomorphism ϕ from $L_X(k)$ into $\mathrm{Assoc}_X(k)$ defined in Section 26.5 is injective, as in Section 26.6. If X has only finitely many elements, then the rank of $L_X^n(k)$ as a free module over k is the same as the rank of $L_X^n(\mathbf{Z})$ as a free module over $\mathbf{Z}$, which is the same as the dimension in the case of fields. This corresponds to the fourth step on p22 of [25].

26.10 Bases from P. Hall families

Let X be a nonempty set, and let M_X be the free magma on X, as in Section 26.1. A *P. Hall family* in M_X is a subset H of M_X equipped with a linear ordering $\preceq$ that satisfies the following three properties. First,

(26.10.1) $$X \subseteq H.$$

Second, if $u, v \in H$, then

(26.10.2) $u \preceq v$ when the length of u is strictly less than the length of v.

Third, suppose that $u \in M_X \setminus X$, so that u can be expressed in a unique way as

(26.10.3) $$u = v\,w,$$

with $v, w \in M_X$. In this case, $u \in H$ if and only if v, w satisfy the following two conditions. The first condition is that

(26.10.4) $$v, w \in H,\ v \preceq w,\ v \neq w.$$

The second condition is that either $w \in X$, or

(26.10.5) $$w = w'\,w'',\ \text{with } w', w'' \in H,\ w' \preceq v.$$

This is Definition 5.1 on p22f of [25]. Of course, in (26.10.5), w should satisfy the requirements of the third property of a P. Hall family as well.

Lemma 5.2 on p23 of [25] states that there is always a P. Hall family in M_X. Remember that for each positive integer n, X_n is the set of elements of M_X of length n, as in Section 26.1. We would like to define $H^n \subseteq X_n$ recursively, which will be the set of elements in the Hall family that are in X_n. More precisely, we should also choose a linear ordering on H^n for each n, which leads to a linear ordering on their union that satisfies (26.10.2). Put $H^1 = X = X_1$, which we can take to be equipped with any linear ordering.

Suppose that $H^1, \ldots, H^{n-1}$ have been chosen for some $n \geq 2$, as well as linear orderings on them. This leads to a linear ordering on their union that satisfies (26.10.2), as before. Suppose also that their union satisfies the three properties of a P. Hall family for elements of length less than or equal to $n - 1$. Using the third property of a P. Hall family, H^n is uniquely determined as a subset of X_n. In order to continue the process, we can choose any linear ordering on H^n. Thus we can repeat the process, to choose H^n and a linear ordering on it for every $n \geq 1$. It is easy to see that $H = \bigcup_{n=1}^{\infty} H^n$ is a P. Hall family in M_X, as desired.

Let k be a commutative ring with a multiplicative identity element, so that the free algebra $A_X(k)$ on X over k can be defined as in Section 26.2. Let $L_X(k)$ be the corresponding free Lie algebra on X over k, as in Section 26.3. If H is a P. Hall family in M_X, then the elements of H may be considered as elements of $A_X(k)$, which are mapped into $L_X(k)$ by the quotient mapping from $A_X(k)$ onto $L_X(k)$. Theorem 5.3 on p23 of [25] states that the images of the elements of H in $L_X(k)$ form a basis for $L_X(k)$, as a module over k.

26.11 More on L_X^n

Let k be a commutative ring with a multiplicative identity element, and let X be a nonempty set. Thus the free algebra A_X on X over k can be defined as in Section 26.2. Remember that A_X is graded as an algebra over k in the strict sense, and let A_X^n be the submodule of A_X, as a module over k, of elements that are homogeneous of degree $n \in \mathbf{Z}_+$, as before. If $n_1, n_2 \in \mathbf{Z}_+$, then

$$A_X^{n_1} \cdot A_X^{n_2} \subseteq A_X^{n_1+n_2}, \tag{26.11.1}$$

where the left side is defined as in Section 9.2. If $n \geq 2$, then it is easy to see that every element of A_X^n can be expressed as a finite sum of elements of $A_X^{n_1} \cdot A_X^{n_2}$, where $n_1 + n_2 = n$.

Similarly, the free Lie algebra L_X on X over k is a graded algebra over k, as in Section 26.3. Let L_X^n be the submodule of L_X, as a module over k, consisting of elements that are homogeneous of degree $n \in \mathbf{Z}_+$, as before. If $n_1, n_2 \in \mathbf{Z}_+$, then

$$[L_X^{n_1}, L_X^{n_2}] \subseteq L_X^{n_1+n_2}, \tag{26.11.2}$$

where the left side is as defined in Section 9.2. If $n \geq 2$, then every element of L_X^n can be expressed as a finite sum of elements of $[L_X^{n_1}, L_X^{n_2}]$, where $n_1 + n_2 = n$. This follows from the analogous statement for A_X^n, in the preceding paragraph.

If $n \geq 2$, then

$$[L_X^1, L_X^{n-1}] = L_X^n, \tag{26.11.3}$$

as in Exercise 2 on p29 of [25]. To see this, let n_1, n_2 be positive integers with $n_1 + n_2 = n$, and let $u_1 \in L_X^{n_1}$ and $u_2 \in L_X^{n_2}$ be given. We would like to show that $[u_1, u_2] \in [L_X^1, L_X^{n-1}]$, which is obvious when n_1 or n_2 is equal to 1. Otherwise, we may as well suppose that $n_2 \geq n_1 > 1$. Thus u_1 can be expressed as a finite sum of terms of the form $[u_{1,1}, u_{1,2}]$, where $u_{1,1} \in L_X^{n_{1,1}}$ and $u_{1,2} \in L_X^{n_{1,2}}$ for some positive integers $n_{1,1}$ and $n_{1,2}$ with $n_{1,1} + n_{1,2} = n_1$. This means that $[u_1, u_2]$ can be expressed as a finite sum of terms of the form

$$[[u_{1,1}, u_{1,2}], u_2] = [[u_{1,1}, u_2], u_{1,2}] + [u_{1,1}, [u_{1,2}, u_2]]. \tag{26.11.4}$$

The terms on the right side are elements of $[L_X^{n_{1,1}+n_2}, L_X^{n_{1,2}}]$ and $[L_X^{n_{1,1}}, L_X^{n_{1,2}+n_2}]$, respectively. Of course, $n_{1,1}, n_{1,2} < n_1$, and so one can repeat the process as needed to get that $[u_1, u_2] \in [L_X^1, L_X^{n-1}]$, as desired. Equivalently, if $n \geq 2$, then L_X^n is generated, as a module over k, by elements of the form

$$[x_1, [x_2, \ldots [x_{n-1}, x_n] \cdots]], \tag{26.11.5}$$

where $x_1, \ldots, x_n \in X$.

Let L be any Lie algebra over k, and suppose that L is generated, as a Lie algebra over k, by a nonempty subset X. Under these conditions, L is generated as a module over k by the elements of X and elements of the form (26.11.5), where $x_1, \ldots, x_n \in X$ for some $n \geq 2$. This could be obtained from the previous remarks for free Lie algebras, or verified directly using the same type of arguments.

Chapter 27

Some more Lie algebras

27.1 Generators and relations

Let k be a commutative ring with a mutliplicative identity element, and let X be a nonempty set. Thus the free Lie algebra $L_X = L_X(k)$ on X over k may be defined as in Section 26.3. If $E \subseteq L_X$, then let $\mathcal{R}(E)$ be the ideal in L_X generated by E. Equivalently, $\mathcal{R}(E)$ consists of finite linear combinations of the elements of E and other elements of L_X obtained by taking brackets of elements of E with elements of L_X any number of times. The quotient $L_X/\mathcal{R}(E)$ may be described as the Lie algebra over k generated by the images of the elements of X in the quotient, and with relations given by condition that the images of the elements of E in the quotient be equal to 0, as on p95 of [14].

If B is any Lie algebra over k, then any mapping from X into B leads to a unique Lie algebra homomorphism from L_X into B, as before. If this Lie algebra homomorphism maps the elements of E to 0, then it maps the elements of $\mathcal{R}(E)$ to 0 as well. This leads to an induced Lie algebra homomorphism from $L_X/\mathcal{R}(E)$ into B. If B is generated as a Lie algebra over k by the images of the elements of X, then the Lie algebra homomorphism from L_X into B just mentioned is surjective. Of course, this implies that the corresponding Lie algebra homomorphism from $L_X/\mathcal{R}(E)$ into B is surjective as well.

Let V be a vector space over the real numbers of positive finite dimension, and let Φ be a reduced root system in V. If $\alpha \in \Phi$, then let σ_α be the symmetry on V with vector α that maps Φ onto itself, as usual. Remember that σ_α can be expressed as $\sigma_\alpha(v) = v - \lambda_\alpha(v)\,\alpha$, where λ_α is a linear functional on V such that $\lambda_\alpha(\alpha) = 2$. Let $(\cdot,\cdot)$ be an inner product on V that is invariant under the Weyl group of Φ. If $\alpha \in \Phi$, then σ_α is the reflection on V with respect to $(\cdot,\cdot)$ associated to α, so that $\lambda_\alpha(v) = 2\,(v,\alpha)\,(\alpha,\alpha)^{-1}$ for every $v \in V$. Put

$$n(\alpha,\beta) = \lambda_\beta(\alpha) = 2\,(\alpha,\beta)\,(\beta,\beta)^{-1} \tag{27.1.1}$$

for every $\alpha, \beta \in \Phi$, as before. Remember that this is an integer, by the definition of a root system. Let Δ be a base for Φ, so that the restriction of (27.1.1) to

$\alpha, \beta \in \Delta$ is the Cartan matrix of Φ with respect to Δ. If $\alpha, \beta \in \Delta$ and $\alpha \neq \beta$, then

$$-3 \leq n(\alpha, \beta) \leq 0, \tag{27.1.2}$$

as in Section 20.2. We have also seen that the Cartan matrix is invertible, as in Section 21.15.

Let k be a field of characteristic 0, and let X_Δ, Y_Δ, and H_Δ be disjoint sets, with distinct elements $\widehat{x}_\alpha$, $\widehat{y}_\alpha$, and $\widehat{h}_\alpha$ indexed by $\alpha \in \Delta$, respectively. Also let $\widehat{L} = \widehat{L}(k)$ be the free Lie algebra on

$$X_\Delta \cup Y_\Delta \cup H_\Delta \tag{27.1.3}$$

over k. If $\alpha, \beta \in \Delta$, then put $\delta_{\alpha,\beta} = 1$ when $\alpha = \beta$, and equal to 0 when $\alpha \neq \beta$. Let $\widehat{E}_0$ be the subset of $\widehat{L}$ consisting of the following elements, for $\alpha, \beta \in \Delta$:

$$[\widehat{h}_\alpha, \widehat{h}_\beta], \tag{27.1.4}$$

$$[\widehat{x}_\alpha, \widehat{y}_\beta] - \delta_{\alpha,\beta}\,\widehat{h}_\alpha, \tag{27.1.5}$$

$$[\widehat{h}_\alpha, \widehat{x}_\beta] - n(\beta, \alpha)\,\widehat{x}_\beta, \tag{27.1.6}$$

$$[\widehat{h}_\alpha, \widehat{y}_\beta] + n(\beta, \alpha)\,\widehat{y}_\beta. \tag{27.1.7}$$

This leads to an ideal $\mathcal{R}(\widehat{E}_0)$ in $\widehat{L}$, as before.

Let

$$\widetilde{L} = \widetilde{L}(k) = \widehat{L}/\mathcal{R}(\widehat{E}_0) \tag{27.1.8}$$

be the corresponding quotient Lie algebra, and let $\widetilde{x}_\alpha$, $\widetilde{y}_\alpha$, and $\widetilde{h}_\alpha$ be the images of $\widehat{x}_\alpha$, $\widehat{y}_\alpha$, and $\widehat{h}_\alpha$, respectively, under the quotient mapping for each $\alpha \in \Delta$. Note that $\widetilde{L}$ is generated by the $\widetilde{x}_\alpha$'s, $\widetilde{y}_\alpha$'s, and $\widetilde{h}_\alpha$'s, $\alpha \in \Delta$, as a Lie algebra over k. If $\alpha, \beta \in \Delta$, then we have that

$$[\widetilde{h}_\alpha, \widetilde{h}_\beta] = 0, \tag{27.1.9}$$

$$[\widetilde{x}_\alpha, \widetilde{y}_\beta] = \delta_{\alpha,\beta}\,\widetilde{h}_\alpha, \tag{27.1.10}$$

$$[\widetilde{h}_\alpha, \widetilde{x}_\beta] = n(\beta, \alpha)\,\widetilde{x}_\beta, \tag{27.1.11}$$

$$[\widetilde{h}_\alpha, \widetilde{y}_\beta] = -n(\beta, \alpha)\,\widetilde{y}_\beta \tag{27.1.12}$$

in $\widetilde{L}$, by construction. This Lie algebra has been analyzed by Chevalley, Harish-Chandra, and Jacobson. Here we are largely following the discussion that begins on p96 of [14].

27.2 A module over $\widehat{L}$

Let us continue with the same notation and hypotheses as in the previous section, and let Z_Δ be a vector space over k with a basis given by distinct elements z_α, $\alpha \in \Delta$. If m is a positive integer, then the mth tensor power $T^m Z_\Delta$ is a vector space over k, and we can get a basis for $T^m Z_\Delta$ using elements of the form $z_{\alpha_1} \otimes \cdots \otimes z_{\alpha_m}$, where $\alpha_1, \ldots, \alpha_m \in \Delta$. Remember that the tensor algebra $T Z_\Delta$

is obtained by taking the direct sum of $T^m Z_\Delta$ over all nonnegative integers m, with $T^0 Z_\Delta = k$, as in Section 25.3. We would like to make TZ_Δ into a module over $\widehat{L}$ in a certain way, as on p97 of [14]. To do this, we need to define the action of the generators of $\widehat{L}$ on TZ_Δ.

Of course, we can get a basis for TZ_Δ, as a vector space over k, using the bases for $T^m Z_\Delta$ mentioned in the preceding paragraph for each $m \geq 1$, and $1 \in k$. In order to define the action of the generators of $\widehat{L}$ on TZ_Δ, it suffices to define the action on the basis elements of TZ_Δ. If $\alpha \in \Delta$, then we put

$$\widehat{h}_\alpha \cdot 1 = 0, \tag{27.2.1}$$

and

$$\begin{aligned} \widehat{h}_\alpha \cdot (z_{\gamma_1} \otimes \cdots \otimes z_{\gamma_m}) \\ = \ -(n(\gamma_1, \alpha) + \cdots + n(\gamma_m, \alpha))\,(z_{\gamma_1} \otimes \cdots \otimes z_{\gamma_m}) \end{aligned} \tag{27.2.2}$$

for every $m \geq 1$ and $\gamma_1, \ldots, \gamma_m \in \Delta$. Similarly, we put

$$\widehat{y}_\alpha \cdot 1 = z_\alpha, \tag{27.2.3}$$

and

$$\widehat{y}_\alpha \cdot (z_{\gamma_1} \otimes \cdots \otimes z_{\gamma_m}) = z_\alpha \otimes z_{\gamma_1} \otimes \cdots \otimes z_{\gamma_m} \tag{27.2.4}$$

for every $m \geq 1$ and $\gamma_1, \ldots, \gamma_m \in \Delta$. We also put

$$\widehat{x}_\alpha \cdot 1 = 0, \tag{27.2.5}$$

and

$$\widehat{x}_\alpha \cdot z_\gamma = 0 \tag{27.2.6}$$

for every $\gamma \in \Delta$. If $m \geq 2$ and $\gamma_1, \ldots, \gamma_m \in \Delta$, then we put

$$\begin{aligned} \widehat{x}_\alpha \cdot (z_{\gamma_1} \otimes \cdots \otimes z_{\gamma_m}) \\ = \ z_{\gamma_1} \otimes (\widehat{x}_\alpha \cdot (z_{\gamma_2} \otimes \cdots \otimes z_{\gamma_m})) \\ -\delta_{\gamma_1, \alpha}\,(n(\gamma_2, \alpha) + \cdots + n(\gamma_m, \alpha))\,(z_{\gamma_2} \otimes \cdots \otimes z_{\gamma_m}). \end{aligned} \tag{27.2.7}$$

More precisely, this can be used to define the left side recursively.

Let $gl(TZ_\Delta)$ be the space of linear mappings from TZ_Δ into itself, as a Lie algebra over k with respect to the corresponding commutator bracket, as usual. If $\alpha \in \Delta$, then we get elements of $gl(TZ_\Delta)$ associated to $\widehat{h}_\alpha$, $\widehat{y}_\alpha$, and $\widehat{x}_\alpha$, as in the previous paragraph. This leads to a Lie algebra homomorphism $\widehat{\phi}$ from $\widehat{L}$ into $gl(TZ_\Delta)$, so that TZ_Δ becomes a module over $\widehat{L}$, as a Lie algebra over k. We would like to show that

$$\mathcal{R}(\widehat{E}_0) \subseteq \ker \widehat{\phi}, \tag{27.2.8}$$

where $\mathcal{R}(\widehat{E}_0)$ is as in the previous section. This corresponds to the proposition on p97 of [14].

Of course, it suffices to show that

$$\widehat{E}_0 \subseteq \ker \widehat{\phi}, \tag{27.2.9}$$

where $\widehat{E}_0$ is as in the previous section, because $\mathcal{R}(\widehat{E}_0)$ is the ideal in $\widehat{L}$ generated by $\widehat{E}_0$. If $\alpha, \beta \in \Delta$, then it is easy to see that

$$\widehat{\phi}([\widehat{h}_\alpha, \widehat{h}_\beta]) = [\widehat{\phi}(\widehat{h}_\alpha), \widehat{\phi}(\widehat{h}_\beta)] = 0, \tag{27.2.10}$$

which is to say that the actions of $\widehat{h}_\alpha$ and $\widehat{h}_\beta$ on TZ_Δ commute. Note that the action of $\widehat{y}_\alpha$ on TZ_Δ is the same as multiplication by z_α on the left, with respect to multiplication on the tensor algebra TZ_Δ.

Let $\alpha, \beta \in \Delta$ be given, and let us check that

$$\widehat{\phi}([\widehat{x}_\alpha, \widehat{y}_\beta]) = [\widehat{\phi}(\widehat{x}_\alpha), \widehat{\phi}(\widehat{y}_\beta)] = \delta_{\alpha,\beta}\, \widehat{\phi}(\widehat{h}_\alpha). \tag{27.2.11}$$

Observe that $\widehat{x}_\alpha \cdot (\widehat{y}_\beta \cdot 1) = \widehat{x}_\alpha \cdot z_\beta = 0$, so that

$$\widehat{x}_\alpha \cdot (\widehat{y}_\beta \cdot 1) - \widehat{y}_\beta \cdot (\widehat{x}_\alpha \cdot 1) = 0, \tag{27.2.12}$$

which is the same as $\delta_{\alpha,\beta}\, \widehat{h}_\alpha \cdot 1$. If $m \geq 2$ and $\gamma_2, \ldots, \gamma_m \in \Delta$, then

$$\begin{aligned} & \widehat{x}_\alpha \cdot (\widehat{y}_\beta \cdot (z_{\gamma_2} \otimes \cdots \otimes z_{\gamma_m})) - \widehat{y}_\beta \cdot (\widehat{x}_\alpha \cdot (z_{\gamma_2} \otimes \cdots \otimes z_{\gamma_m})) \\ = {} & \widehat{x}_\alpha \cdot (z_\beta \otimes z_{\gamma_2} \otimes \cdots \otimes z_{\gamma_m}) - z_\beta \otimes (\widehat{x}_\alpha \cdot (z_{\gamma_2} \otimes \cdots \otimes z_{\gamma_m})) \\ = {} & -\delta_{\beta,\alpha}\, (n(\gamma_2, \alpha) + \cdots + n(\gamma_m, \alpha))\, (z_{\gamma_2} \otimes \cdots \otimes z_{\gamma_m}) \\ = {} & \delta_{\beta,\alpha}\, \widehat{h}_\alpha \cdot (z_{\gamma_2} \otimes \cdots \otimes z_{\gamma_m}). \end{aligned} \tag{27.2.13}$$

More precisely, this uses (27.2.7) in the second step. This shows that (27.2.11) holds.

Similarly, let us verify that

$$\widehat{\phi}([\widehat{h}_\alpha, \widehat{y}_\beta]) = [\widehat{\phi}(\widehat{h}_\alpha), \widehat{\phi}(\widehat{y}_\beta)] = -n(\beta, \alpha)\, \widehat{\phi}(\widehat{y}_\beta). \tag{27.2.14}$$

Observe that

$$\begin{aligned} \widehat{h}_\alpha \cdot (\widehat{y}_\beta \cdot 1) - \widehat{y}_\beta \cdot (\widehat{h}_\alpha \cdot 1) & = \widehat{h}_\alpha \cdot z_\beta \\ & = -n(\beta, \alpha)\, z_\beta = -n(\beta, \alpha)\, \widehat{y}_\beta \cdot 1. \end{aligned} \tag{27.2.15}$$

If $\gamma_1, \ldots, \gamma_m \in \Delta$ for some $m \geq 1$, then

$$\begin{aligned} & \widehat{h}_\alpha \cdot (\widehat{y}_\beta \cdot (z_{\gamma_1} \otimes \cdots \otimes z_{\gamma_m})) - \widehat{y}_\beta \cdot (\widehat{h}_\alpha \cdot (z_{\gamma_1} \otimes \cdots \otimes z_{\gamma_m})) \\ = {} & \widehat{h}_\alpha \cdot (z_\beta \otimes \cdot z_{\gamma_1} \otimes \cdots \otimes z_{\gamma_m}) - z_\beta \otimes (\widehat{h}_\alpha \cdot (z_{\gamma_1} \otimes \cdots \otimes z_{\gamma_m})) \\ = {} & -n(\beta, \alpha)\, (z_\beta \otimes z_{\gamma_1} \otimes \cdots \otimes z_{\gamma_m}) \\ = {} & -n(\beta, \alpha)\, \widehat{y}_\beta \cdot (z_{\gamma_1} \otimes \cdots \otimes z_{\gamma_m}). \end{aligned} \tag{27.2.16}$$

This implies (27.2.14).

Note that

$$\widehat{h}_\alpha \cdot (\widehat{x}_\beta \cdot 1) = n(\beta, \alpha)\, \widehat{x}_\beta \cdot 1 = 0. \tag{27.2.17}$$

We would like to check that

$$\begin{aligned} &\widehat{h}_\alpha \cdot (\widehat{x}_\beta \cdot (z_{\gamma_1} \otimes \cdots \otimes z_{\gamma_m})) \\ &\quad = -(n(\gamma_1, \alpha) + \cdots + n(\gamma_m, \alpha) - n(\beta, \alpha))\, \widehat{x}_\beta \cdot (z_{\gamma_1} \otimes \cdots \otimes z_{\gamma_m}) \end{aligned} \tag{27.2.18}$$

for every $m \geq 1$ and $\gamma_1, \ldots, \gamma_m \in \Delta$. If $m = 1$, then both sides of the equation are equal to 0. Suppose that $m \geq 2$, and that the analogous statement holds when $m - 1$, by induction, so that

$$\begin{aligned} &\widehat{h}_\alpha \cdot (\widehat{x}_\beta \cdot (z_{\gamma_2} \otimes \cdots \otimes z_{\gamma_m})) \\ &\quad = -(n(\gamma_2, \alpha) + \cdots n(\gamma_m, \alpha) - n(\beta, \alpha))\, \widehat{x}_\beta \cdot (z_{\gamma_2} \otimes \cdots \otimes z_{\gamma_m}). \end{aligned} \tag{27.2.19}$$

Using this, one can verify that

$$\begin{aligned} &\widehat{h}_\alpha \cdot (z_{\gamma_1} \otimes (\widehat{x}_\beta \cdot (z_{\gamma_2} \otimes \cdots \otimes z_{\gamma_m}))) \\ &\quad = -(n(\gamma_1, \alpha) + \cdots + n(\gamma_m, \alpha) - n(\beta, \alpha))\, (z_{\gamma_1} \otimes (\widehat{x}_\beta \cdot (z_{\gamma_2} \otimes \cdots \otimes z_{\gamma_m}))). \end{aligned} \tag{27.2.20}$$

One can obtain (27.2.18) from this and (27.2.7). More precisely, this also uses the fact that

$$\begin{aligned} &\widehat{h}_\alpha \cdot (\delta_{\gamma_1, \beta}\, (z_{\gamma_2} \otimes \cdots \otimes z_{\gamma_m})) \\ &\quad = -\delta_{\gamma_1, \beta}\, (n(\gamma_2, \alpha) + \cdots + n(\gamma_m, \alpha))\, (z_{\gamma_2} \otimes \cdots \otimes z_{\gamma_m}) \\ &\quad = -\delta_{\gamma_1, \beta}\, (n(\gamma_1, \alpha) + n(\gamma_2, \alpha) + \cdots + n(\gamma_m, \alpha) - n(\beta, \alpha))\, (z_{\gamma_2} \otimes \cdots \otimes z_{\gamma_m}). \end{aligned} \tag{27.2.21}$$

Let us check that

$$\widehat{\phi}([\widehat{h}_\alpha, \widehat{x}_\beta]) = [\widehat{\phi}(\widehat{h}_\alpha), \widehat{\phi}(\widehat{x}_\beta)] = n(\beta, \alpha)\, \widehat{\phi}(\widehat{x}_\beta). \tag{27.2.22}$$

Observe that

$$\widehat{h}_\alpha \cdot (\widehat{x}_\beta \cdot 1) - \widehat{x}_\beta \cdot (\widehat{h}_\alpha \cdot 1) = 0, \tag{27.2.23}$$

which is the same as $n(\beta, \alpha)\, \widehat{x}_\beta \cdot 1$. Let $\gamma_1, \ldots, \gamma_m \in \Delta$ be given for some $m \geq 1$, and note that

$$\begin{aligned} &\widehat{x}_\beta \cdot (\widehat{h}_\alpha \cdot (z_{\gamma_1} \otimes \cdots \otimes z_{\gamma_m})) \\ &\quad = -(n(\gamma_1, \alpha) + \cdots + n(\gamma_m, \alpha))\, \widehat{x}_\beta \cdot (z_{\gamma_1} \otimes \cdots \otimes z_{\gamma_m}). \end{aligned} \tag{27.2.24}$$

Combining this with (27.2.18), we obtain that

$$\begin{aligned} &\widehat{h}_\alpha \cdot (\widehat{x}_\beta \cdot (z_{\gamma_1} \otimes \cdots \otimes z_{\gamma_m})) - \widehat{x}_\beta \cdot (\widehat{h}_\alpha \cdot (z_{\gamma_1} \otimes \cdots \otimes z_{\gamma_m})) \\ &\quad = (-(n(\gamma_1, \alpha) + \cdots + n(\gamma_m, \alpha) - n(\beta, \alpha)) + (n(\gamma_1, \alpha) + \cdots + n(\gamma_m, \alpha))) \\ &\qquad \widehat{x}_\beta \cdot (z_{\gamma_1} \otimes \cdots \otimes z_{\gamma_m}) \\ &\quad = n(\beta, \alpha)\, \widehat{x}_\beta \cdot (z_{\gamma_1} \otimes \cdots \otimes z_{\gamma_m}). \end{aligned} \tag{27.2.25}$$

This implies (27.2.22), using (27.2.23) as well.

It follows that (27.2.9) holds, because of (27.2.10), (27.2.11), (27.2.14), and (27.2.22). This implies (27.2.8), as before.

27.3 Some properties of $\widetilde{L}$

We continue with the same notation and hypotheses as in the previous two sections. In particular, remember that $\widetilde{L} = \widehat{L}/\mathcal{R}(\widehat{E}_0)$, and that $\widetilde{x}_\alpha$, $\widetilde{y}_\alpha$, $\widetilde{h}_\alpha$ are the images of $\widehat{x}_\alpha, \widehat{y}_\alpha, \widehat{h}_\alpha \in \widehat{L}$ in $\widetilde{L}$, respectively, under the natural quotient mapping for each $\alpha \in \Delta$. In the previous section, a Lie algebra homomorphism $\widehat{\phi}$ from $\widehat{L}$ into $gl(TZ_\Delta)$ was defined, whose kernel contains $\mathcal{R}(\widehat{E}_0)$. This leads to a Lie algebra homomorphism $\widetilde{\phi}$ from $\widetilde{L}$ into $gl(TZ_\Delta)$, whose composition with the natural quotient mapping from $\widehat{L}$ onto $\widetilde{L}$ is equal to $\widehat{\phi}$, as in the proposition on p97 of [14]. Thus TZ_Δ may be considered as a module over $\widetilde{L}$, as a Lie algebra over k.

Of course, $\widetilde{\phi}(\widetilde{x}_\alpha) = \widehat{\phi}(\widehat{x}_\alpha)$, $\widetilde{\phi}(\widetilde{y}_\alpha) = \widehat{\phi}(\widehat{y}_\alpha)$, and $\widetilde{\phi}(\widetilde{h}_\alpha) = \widehat{\phi}(\widehat{h}_\alpha)$ for every $\alpha \in \Delta$, by construction. This means that the actions of $\widetilde{x}_\alpha$, $\widetilde{y}_\alpha$, and $\widetilde{h}_\alpha$ on TZ_Δ are the same as for $\widehat{x}_\alpha$, $\widehat{y}_\alpha$, and $\widehat{h}_\alpha$, respectively, for each $\alpha \in \Delta$.

Let $\widetilde{\mathcal{H}}$ be the linear span of the $\widetilde{h}_\alpha$'s, $\alpha \in \Delta$, in $\widetilde{L}$. This is a Lie subalgebra of $\widetilde{L}$, that is commutative as a Lie algebra, because the $\widetilde{h}_\alpha$'s commute with each other, as in (27.1.9). Let $\widetilde{\mathcal{X}}$ be the Lie subalgebra of $\widetilde{L}$ generated by the $\widetilde{x}_\alpha$'s, $\alpha \in \Delta$, and let $\widetilde{\mathcal{Y}}$ be the Lie subalgebra of $\widetilde{L}$ generated by the $\widetilde{y}_\alpha$'s, $\alpha \in \Delta$. The theorem on p97f of [14] states that

(27.3.1) the $\widetilde{h}_\alpha$'s, $\alpha \in \Delta$, form a basis for $\widetilde{\mathcal{H}}$ as a vector space over k,

and that

(27.3.2) $\widetilde{L}$ corresponds to the direct sum of $\widetilde{\mathcal{X}}$, $\widetilde{\mathcal{H}}$, and $\widetilde{\mathcal{Y}}$, as a vector space over k.

Step (1) on p98 of [14] states that the intersection of the linear span of the $\widehat{h}_\alpha$'s, $\alpha \in \Delta$, in $\widehat{L}$ with the kernel of $\widehat{\phi}$ is trivial. To see this, let $a_\alpha \in k$ be given for each $\alpha \in \Delta$, and put

$$\widehat{h} = \sum_{\alpha \in \Delta} a_\alpha \, \widehat{h}_\alpha. \tag{27.3.3}$$

Thus $\widehat{h} \in \widehat{L}$, and

$$\widehat{h} \cdot z_\gamma = -\sum_{\alpha \in \Delta} a_\alpha \, n(\gamma, \alpha) \, z_\gamma \tag{27.3.4}$$

for every $\gamma \in \Delta$, by (27.2.2). If $\widehat{\phi}(\widehat{h}) = 0$, then (27.3.4) is equal to 0 for each $\gamma \in \Delta$, so that

$$\sum_{\alpha \in \Delta} a_\alpha \, n(\gamma, \alpha) = 0 \tag{27.3.5}$$

for every $\gamma \in \Delta$. We would like to use this to get that $a_\alpha = 0$ for every $\alpha \in \Delta$.

Remember that the Cartan matrix is invertible, as a matrix of real numbers, as in Section 21.15. The entries of the Cartan matrix are integers, so that its determinant is a nonzero integer. If we consider the Cartan matrix as having entries in k, then its determinant is still nonzero, because k has characteristic 0, by hypothesis. This means that the Cartan matrix is also invertible as a matrix with entries in k. Thus (27.3.5) implies that $a_\alpha = 0$ for every $\alpha \in \Delta$, as desired.

Of course,

$$\widetilde{h} = \sum_{\alpha \in \Delta} a_\alpha \, \widetilde{h}_\alpha \tag{27.3.6}$$

is the image of (27.3.3) under the natural quotient mapping from $\widehat{L}$ onto $\widetilde{L}$. If $\widetilde{h} = 0$, then $\widehat{\phi}(\widehat{h}) = \widetilde{\phi}(\widetilde{h}) = 0$, so that $a_\alpha = 0$ for every $\alpha \in \Delta$, as before. It follows that the restriction of the natural quotient mapping from $\widehat{L}$ onto $\widetilde{L}$ to the linear span of the $\widehat{h}_\alpha$'s, $\alpha \in \Delta$, in $\widehat{L}$ is injective, as in Step (2) on p98 of [14]. This implies that the dimension of $\widetilde{\mathcal{H}}$, as a vector space over k, is the same as the number of elements in Δ, as in Step (4) on p98 of [14]. Equivalently, this means that (27.3.1) holds.

In particular,

$$\widetilde{h}_\alpha \neq 0 \text{ for each } \alpha \in \Delta. \tag{27.3.7}$$

This implies that

$$\widetilde{x}_\alpha,\ \widetilde{y}_\alpha \neq 0 \text{ for each } \alpha \in \Delta, \tag{27.3.8}$$

because $[\widetilde{x}_\alpha, \widetilde{y}_\alpha] = \widetilde{h}_\alpha$, as in (27.1.10).

If $\beta \in \Delta$, then put

$$f_\beta(\alpha) = n(\beta, \alpha) \tag{27.3.9}$$

for every $\alpha \in \Delta$, which may be considered as a k-valued function on Δ. In fact, the f_β's form a basis for the space of k-valued functions on Δ, as a vector space over k. This follows from the invertibility of the Cartan matrix, as a matrix with entries in k, as before. In particular, for each $\beta \in \Delta$, $f_\beta \not\equiv 0$ on Δ. Similarly, if $\beta, \beta' \in \Delta$ and $\beta \neq \beta'$, then $f_\beta \neq f_{\beta'}$, as functions on Δ. We also have that $f_\beta \neq -f_{\beta'}$, even when $\beta = \beta'$. This uses the hypothesis that k has characteristic 0, so that $1 \neq -1$ in k.

One can use this to check that

$$\begin{aligned}&\text{the set of } \widetilde{x}_\beta\text{'s, } \widetilde{y}_\beta\text{'s, and } \widetilde{h}_\beta\text{'s, } \beta \in \Delta, \\ &\text{is linearly independent in } \widetilde{L},\end{aligned} \tag{27.3.10}$$

as in Step (3) on p98 of [14]. This also uses the fact that the $\widetilde{x}_\beta$', $\widetilde{y}_\beta$'s, and $\widetilde{h}_\beta$'s are simultaneous eigenvectors for $\mathrm{ad}_{\widetilde{h}_\alpha}$, $\alpha \in \Delta$, as in (27.1.9), (27.1.11), and (27.1.12), with the corresponding eigenvalues given by $f_\beta(\alpha)$, $-f_\beta(\alpha)$, and 0, respectively. Note that the $\mathrm{ad}_{\widetilde{h}_\alpha}$'s, $\alpha \in \Delta$, commute with each other, as linear mappings on $\widetilde{L}$, because the $\widetilde{h}_\alpha$'s commute in $\widetilde{L}$, as in Section 2.4.

More precisely, suppose that we have a linear combination of the $\widetilde{x}_\beta$'s, $\widetilde{y}_\beta$'s, and $\widetilde{h}_\beta$'s, $\beta \in \Delta$, in $\widetilde{L}$ that is equal to 0. One can show that the coefficients of the $\widetilde{x}_\beta$'s and $\widetilde{y}_\beta$'s are all equal to 0, and that the corresponding linear combination of the $\widetilde{h}_\beta$'s is equal to 0, using the earlier remarks about the f_β's. It follows that the coefficients of the $\widetilde{h}_\beta$'s have to be equal to 0 too, by (27.3.1).

Equivalently, consider the linear subspace of $\widehat{L}$ spanned by the $\widehat{x}_\beta$'s, $\widehat{y}_\beta$'s, and $\widehat{h}_\beta$'s, $\beta \in \Delta$. The restriction of the natural quotient mapping from $\widehat{L}$ onto $\widetilde{L}$ to this linear subspace is injective, as in Step (3) on p98 of [14].

27.4 Some brackets in $\widetilde{L}$

Let us continue with the discussion in the previous section. In particular, we would like to prove (27.3.2).

If $\widetilde{u}_1, \ldots, \widetilde{u}_r \in \widetilde{L}$ for some $r \geq 2$, then put

$$[\widetilde{u}_1, \ldots, \widetilde{u}_r] = [\widetilde{u}_1, [\widetilde{u}_2, \ldots [\widetilde{u}_{r-1}, \widetilde{u}_r] \cdots]]. \tag{27.4.1}$$

If $\alpha, \beta_1, \ldots, \beta_r \in \Delta$, then

$$[\widetilde{h}_\alpha, [\widetilde{x}_{\beta_1}, \ldots, \widetilde{x}_{\beta_r}]] = (n(\beta_1, \alpha) + \cdots + n(\beta_r, \alpha))\,[\widetilde{x}_{\beta_1}, \ldots, \widetilde{x}_{\beta_r}], \tag{27.4.2}$$

as in Step (5) on p98 of [14]. This follows from (27.1.11) and the Jacobi identity when $r = 2$, and one can use induction to get the analogous conclusion for every $r \geq 2$. Similarly,

$$[\widetilde{h}_\alpha, [\widetilde{y}_{\beta_1}, \ldots, \widetilde{y}_{\beta_r}]] = -(n(\beta_1, \alpha) + \cdots + n(\beta_r, \alpha))\,[\widetilde{y}_{\beta_1}, \ldots, \widetilde{y}_{\beta_r}], \tag{27.4.3}$$

by (27.1.12).

If $\alpha, \beta_1, \ldots, \beta_r \in \Delta$ for some $r \geq 2$ again, then

$$[\widetilde{y}_\alpha, [\widetilde{x}_{\beta_1}, \ldots, \widetilde{x}_{\beta_r}]] \tag{27.4.4}$$

can be expressed as a linear combination of $\widetilde{x}_{\beta_1}$ and $\widetilde{x}_{\beta_2}$ when $r = 2$, and as a linear combination of terms of the form

$$[\widetilde{x}_{\gamma_1}, \ldots, \widetilde{x}_{\gamma_{r-1}}] \tag{27.4.5}$$

when $r \geq 3$, where $\gamma_1, \ldots, \gamma_{r-1} \in \{\beta_1, \ldots, \beta_r\}$. In particular, this means that (27.4.4) is an element of $\widetilde{\mathcal{X}}$, as in Step 6 on p98 of [14]. If $r = 2$, then the previous statement can be obtained from (27.1.10), (27.1.11), and the Jacobi identity. If $r \geq 3$, then one can use induction and (27.4.2). Similarly,

$$[\widetilde{x}_\alpha, [\widetilde{y}_{\beta_1}, \ldots, \widetilde{y}_{\beta_r}]] \tag{27.4.6}$$

can be expressed as a linear combination of $\widetilde{y}_{\beta_1}$ and $\widetilde{y}_{\beta_2}$ when $r = 2$, and as a linear combination of terms of the form

$$[\widetilde{y}_{\gamma_1}, \ldots, \widetilde{y}_{\gamma_{r-1}}] \tag{27.4.7}$$

when $r \geq 3$, where $\gamma_1, \ldots, \gamma_{r-1} \in \{\beta_1, \ldots, \beta_r\}$, as before.

Remember that $\widetilde{\mathcal{X}}$ and $\widetilde{\mathcal{Y}}$ are the Lie subalgebras of $\widetilde{L}$ generated by the $\widetilde{x}_\alpha$'s and $\widetilde{y}_\alpha$'s, respectively, with $\alpha \in \Delta$. Note that $\widetilde{\mathcal{X}}$ is spanned by the $\widetilde{x}_\alpha$'s, $\alpha \in \Delta$, and elements of the form $[\widetilde{x}_{\alpha_1}, \ldots, \widetilde{x}_{\alpha_r}]$, where $\alpha_1, \ldots, \alpha_r \in \Delta$ for some $r \geq 2$, as in Section 26.11. Similarly, $\widetilde{\mathcal{Y}}$ is spanned by the $\widetilde{y}_\alpha$'s, $\alpha \in \Delta$, and elements of the form $[\widetilde{y}_{\alpha_1}, \ldots, \widetilde{y}_{\alpha_r}]$, with $\alpha_1, \ldots, \alpha_r \in \Delta$ for some $r \geq 2$.

One can check that the linear subspace $\widetilde{\mathcal{X}} + \widetilde{\mathcal{H}} + \widetilde{\mathcal{Y}}$ of $\widetilde{L}$ spanned by elements of $\widetilde{\mathcal{X}}$, $\widetilde{\mathcal{H}}$, and $\widetilde{\mathcal{Y}}$ is a Lie subalgebra of $\widetilde{L}$, as in Step (7) on p98 of [14]. More precisely, this uses the fact that $\widetilde{\mathcal{H}}$ is a Lie subalgebra of $\widetilde{L}$, (27.4.2), and (27.4.3), as well as (27.1.10) and the earlier remarks about (27.4.4) and (27.4.6).

It follows that $\widetilde{\mathcal{X}} + \widetilde{\mathcal{H}} + \widetilde{\mathcal{Y}}$ is equal to $\widetilde{L}$, because $\widetilde{L}$ is generated as a Lie algebra by the $\widetilde{x}_\alpha$'s, $\widetilde{y}_\alpha$'s, and $\widetilde{h}_\alpha$'s, $\alpha \in \Delta$.

In order to verify (27.3.2), we need to show that if a sum of elements of $\widetilde{\mathcal{X}}$, $\widetilde{\mathcal{H}}$, and $\widetilde{\mathcal{Y}}$ is equal to 0, then each term is 0. Note that $\widetilde{\mathcal{X}}$ is spanned by simultaneous eigenvectors for $\mathrm{ad}_{\widetilde{h}_\alpha}$, $\alpha \in \Delta$, by (27.4.2). The corresponding eigenvalues for the simultaneous eigenvectors are given by nontrivial sums of f_β's, $\beta \in \Delta$. Similarly, $\widetilde{\mathcal{Y}}$ is spanned by simultaneous eigenvectors for $\mathrm{ad}_{\widetilde{h}_\alpha}$, $\alpha \in \Delta$, by (27.4.3), with the corresponding eigenvalues given by nontrivial sums of $-f_\beta$'s, $\beta \in \Delta$. Of course, $\widetilde{\mathcal{H}}$ is contained in the kernel of $\mathrm{ad}_{\widetilde{h}_\alpha}$ for each $\alpha \in \Delta$, by (27.1.9). Because k has characteristic 0, nontrivial sums of f_β's or of $-f_\beta$'s cannot be equal to 0 on all of Δ, or equal to each other on all of Δ. This can be used to get that if a sum of elements of $\widetilde{\mathcal{X}}$, $\widetilde{\mathcal{H}}$, and $\widetilde{\mathcal{Y}}$ is equal to 0, then each term is 0, as in Step (8) on p98 of [14].

27.5 Eigenvectors in $\widetilde{L}$

Let us look a bit more at the simultaneous eigenvectors for $\mathrm{ad}_{\widetilde{h}_\alpha}$, $\alpha \in \Delta$, in $\widetilde{L}$, as in the previous two sections. Remember that $\widetilde{\mathcal{H}}$ is the linear span of the $\widetilde{h}_\alpha$'s, $\alpha \in \Delta$. Let $\widetilde{\mathcal{H}}'$ be the dual of $\widetilde{\mathcal{H}}$, as a vector space over k, as usual. If $\widetilde{\mu} \in \widetilde{\mathcal{H}}'$, then put

$$\widetilde{L}_{\widetilde{\mu}} = \{\widetilde{u} \in L : [\widetilde{h}, \widetilde{u}] = \widetilde{\mu}(\widetilde{h})\, \widetilde{u} \text{ for every } \widetilde{h} \in \widetilde{\mathcal{H}}\}, \tag{27.5.1}$$

which is a linear subspace of $\widetilde{L}$. Of course, the $\mathrm{ad}_{\widetilde{h}}$'s, $\widetilde{h} \in \widetilde{\mathcal{H}}$, commute as linear mappings on $\widetilde{L}$, because of the same property of the $\mathrm{ad}_{\widetilde{h}_\alpha}$'s, $\alpha \in \Delta$.

Suppose for the moment that $\widetilde{\mu}_1, \ldots, \widetilde{\mu}_n$ are distinct elements of $\widetilde{\mathcal{H}}'$, and that $\widetilde{u}_j \in \widetilde{L}_{\widetilde{\mu}_j}$ for $j = 1, \ldots, n$. If $\sum_{j=1}^n \widetilde{u}_j = 0$, then $\widetilde{u}_j = 0$ for every $j = 1, \ldots, n$, by standard arguments.

Remember that the $\widetilde{h}_\alpha$'s, $\alpha \in \Delta$, form a basis for $\widetilde{\mathcal{H}}$. If $\beta \in \Delta$, then there is a unique $\widetilde{\nu}_\beta \in \widetilde{\mathcal{H}}'$ such that

$$\widetilde{\nu}_\beta(\widetilde{h}_\alpha) = n(\beta, \alpha) \tag{27.5.2}$$

for every $\alpha \in \Delta$. The $\widetilde{\nu}_\beta$'s, $\beta \in \Delta$, form a basis for $\widetilde{\mathcal{H}}'$, as a vector space over k. This is essentially the same as the fact that the f_β's in (27.3.9) form a basis for the space of k-valued functions on Δ, as before.

Every element of $\widetilde{\mathcal{X}}$ can be expressed as the sum of elements of finitely many of the subspaces $\widetilde{L}_{\widetilde{\mu}}$, where $\widetilde{\mu} \in \widetilde{\mathcal{H}}'$ can be expressed as a nontrivial sum of $\widetilde{\nu}_\beta$'s, as in the previous section. Similarly, every element of $\widetilde{\mathcal{Y}}$ can be expressed as the sum of finitely many elements of $\widetilde{L}_{\widetilde{\mu}}$'s, where $\widetilde{\mu} \in \widetilde{\mathcal{H}}'$ can be expressed as a nontrivial sum of $-\widetilde{\nu}_\beta$'s. It follows that $\widetilde{\mathcal{X}}$ and $\widetilde{\mathcal{Y}}$ correspond to direct sums of their intersections with the appropriate subspaces $\widetilde{L}_{\widetilde{\mu}}$, as vector spaces over k.

Clearly $\widetilde{\mathcal{H}} \subseteq \widetilde{L}_0$, by (27.1.9). Remember that $\widetilde{L}$ corresponds to the direct sum of $\widetilde{\mathcal{X}}$, $\widetilde{\mathcal{H}}$, and $\widetilde{\mathcal{Y}}$, as a vector space over k, as in (27.3.2). Using this, one can check that

(27.5.3) $$\widetilde{\mathcal{H}} = \widetilde{L}_0.$$

This also uses the hypothesis that k have characteristic 0, so that nontrivial sums of $\widetilde{\nu}_\beta$'s cannot be equal to 0.

Similarly, $\widetilde{L}_{\widetilde{\mu}} \subseteq \widetilde{\mathcal{X}}$ when $\widetilde{\mu} \in \widetilde{\mathcal{H}}$ is a nontrivial sum of $\widetilde{\nu}_\beta$'s, and $\widetilde{L}_{\widetilde{\mu}} \subseteq \widetilde{\mathcal{Y}}$ when $\widetilde{\mu}$ is a nontrivial sum of $-\widetilde{\nu}_\beta$'s. This uses the hypothesis that k have characteristic 0, to get that nontrivial sums of $\widetilde{\nu}_\beta$'s cannot be equal to nontrivial sums of $-\widetilde{\nu}_\beta$'s. This implies that $\widetilde{\mathcal{X}}$ corresponds to the direct sum of the subspaces $\widetilde{L}_{\widetilde{\mu}}$, where $\widetilde{\mu} \in \widetilde{\mathcal{H}}'$ can be expressed as a nontrivial sum of $\widetilde{\nu}_\beta$'s, and that $\widetilde{\mathcal{Y}}$ corresponds to the direct sum of the suspaces $\widetilde{L}_{\widetilde{\mu}}$, where $\widetilde{\mu} \in \widetilde{\mathcal{H}}'$ can be expressed as a nontrivial sum of $-\widetilde{\nu}_\beta$'s, as vector spaces over k.

Let $\widetilde{\mu} \in \widetilde{\mathcal{H}}'$ be given, and suppose that $\widetilde{L}_{\widetilde{\mu}} \neq \{0\}$. Under these conditions, one can verify that either $\widetilde{\mu} = 0$, or $\widetilde{\mu}$ is a nontrivial sum of $\widetilde{\nu}_\beta$'s, or $\widetilde{\mu}$ is a nontrivial sum of $-\widetilde{\nu}_\beta$'s.

If $\widetilde{\mu} \in \widetilde{\mathcal{H}}'$, then $\widetilde{L}_{\widetilde{\mu}}$ is finite-dimensional, as a vector space over k. This follows from (27.5.3) when $\widetilde{\mu} = 0$, and otherwise we may suppose that $\widetilde{\mu}$ is a nontrivial sum of ν_β's, or that $\widetilde{\mu}$ is a nontrivial sum of $-\nu_\beta$'s, as in the preceding paragraph. In both cases, the elements of $\widetilde{L}_{\widetilde{\mu}}$ considered in the previous section are contained in finite-dimensional subspaces of $\widetilde{L}$. One can check that all of the elements of $\widetilde{L}_{\widetilde{\mu}}$ can be obtained as linear combinations of those considered before, because $\widetilde{L}$ is spanned by elements of this type and the $\widetilde{h}_\alpha$'s, as in the previous section.

This corresponds to some remarks on p98 of [14], after the proof of the theorem, and on p53 of [24]. In particular, the elements of $\widetilde{L}_{\widetilde{\mu}}$ are said to have *weight* $\widetilde{\mu}$.

27.6 Some more properties of $\widetilde{L}$

Let us continue with the same notation and hypotheses as in the previous five sections. Thus the tensor algebra TZ_Δ from Section 27.2 is an associative algebra over k, which may be considered as a Lie algebra over k with respect to the corresponding commutator bracket. Let L_{Y_Δ} be the free Lie algebra on $Y_\Delta = \{\widehat{y}_\alpha : \alpha \in \Delta\}$ over k, and let ψ_1 be the Lie algebra homomorphism from L_{Y_Δ} into TZ_Δ that sends $\widehat{y}_\alpha$ to $z_\alpha \in Z_\Delta$ for every $\alpha \in \Delta$. Note that

(27.6.1) ψ_1 is injective as a mapping from L_{Y_Δ} into TZ_Δ, as in Section 26.6. More precisely, this corresponds to identifying TZ_Δ with the free associative algebra $\mathrm{Assoc}_{Y_\Delta}$ on Y_Δ over k, by identifying $\widehat{y}_\alpha$ with z_α for each $\alpha \in \Delta$.

Of course, each element of TZ_Δ determines a linear mapping from TZ_Δ into itself, defined by multiplication on the left by the given element of TZ_Δ. In particular, this defines a Lie algebra homomorphism from TZ_Δ into $gl(TZ_\Delta)$. Note that this mapping is injective, because TZ_Δ has a multiplicative identity element. Let ψ_1' be the mapping from L_{Y_Δ} into $gl(TZ_\Delta)$ which is the composition of ψ_1 with the Lie algebra homomorphism from TZ_Δ into $gl(TZ_\Delta)$ just mentioned. Thus ψ_1' is an injective Lie algebra homomorphism from L_{Y_Δ} into $gl(TZ_\Delta)$.

Let $\widehat{\phi}$ be the Lie algebra homomorphism from $\widehat{L}$ into $gl(TZ_\Delta)$ defined in Section 27.2. Remember that $\widehat{\phi}(\widehat{y}_\alpha)$ is the linear mapping from TZ_Δ to itself corresponding to left multiplication by z_α for each $\alpha \in \Delta$. There is a natural Lie algebra homomorphism from L_{Y_Δ} into $\widehat{L}$, which sends $\widehat{y}_\alpha$ to itself as an element of $\widehat{L}$ for every $\alpha \in \Delta$. Let $\widehat{\phi}_1$ be the composition of this homomorphism with $\widehat{\phi}$, so that $\widehat{\phi}_1$ is a Lie algebra homomorphism from L_{Y_Δ} into $gl(TZ_\Delta)$. Observe that

(27.6.2) $$\widehat{\phi}_1 = \psi_1'$$

on L_{Y_Δ}, because both mappings send $\widehat{y}_\alpha$ to the linear mapping from TZ_Δ into itself that corresponds to left multiplication by z_α for each $\alpha \in \Delta$.

Remember from Section 27.3 that $\widehat{\phi}$ is the same as the composition of the natural quotient mapping from $\widehat{L}$ onto $\widetilde{L}$ with the Lie algebra homomorphism $\widetilde{\phi}$ from $\widetilde{L}$ into $gl(TZ_\Delta)$. Let ρ_1 be the composition of the natural mapping from L_{Y_Δ} into $\widehat{L}$ with the quotient mapping from $\widehat{L}$ onto $\widetilde{L}$. Thus ρ_1 is a Lie algebra homomorphism from L_{Y_Δ} into $\widetilde{L}$, and

(27.6.3) $$\widehat{\phi}_1 = \widetilde{\phi} \circ \rho_1$$

on L_{Y_Δ}, by construction. It follows that

(27.6.4) ρ_1 is injective as a mapping from L_{Y_Δ} into $\widetilde{L}$,

because of (27.6.2) and the fact that ψ_1' is injective on L_{Y_Δ}, as before.

Note that $\rho_1(\widehat{y}_\alpha) = \widetilde{y}_\alpha$ for each $\alpha \in \Delta$, by construction. Let $\widetilde{\mathcal{Y}}$ be the Lie subalgebra of $\widetilde{L}$ generated by the $\widetilde{y}_\alpha$'s, $\alpha \in \Delta$, as in Section 27.3. Thus

(27.6.5) $$\rho_1(L_{Y_\Delta}) = \widetilde{\mathcal{Y}},$$

because L_{Y_Δ} is generated by Y_Δ as a Lie algebra over k. This shows that $\widetilde{\mathcal{Y}}$ is isomorphic to L_{Y_Δ} as a Lie algebra over k, as in Exercise 1 on p101 of [14].

Let $\widehat{\sigma}$ be the Lie algebra homomorphism from $\widehat{L}$ into itself such that

(27.6.6) $$\widehat{\sigma}(\widehat{x}_\alpha) = -\widehat{y}_\alpha,\ \widehat{\sigma}(\widehat{y}_\alpha) = -\widehat{x}_\alpha, \text{ and } \widehat{\sigma}(\widehat{h}_\alpha) = -\widehat{h}_\alpha$$

for every $\alpha \in \Delta$. The composition of $\widehat{\sigma}$ with itself sends $\widehat{x}_\alpha$, $\widehat{y}_\alpha$, and $\widehat{h}_\alpha$ to themselves, respectively, for every $\alpha \in \Delta$. Thus $\widehat{\sigma} \circ \widehat{\sigma}$ is the identity mapping on $\widehat{L}$, and in particular $\widehat{\sigma}$ is a Lie algebra automorphism of $\widehat{L}$. It is easy to see that

$$\widehat{\sigma}(\mathcal{R}(\widehat{E}_0)) = \mathcal{R}(\widehat{E}_0), \tag{27.6.7}$$

where $\widehat{E}_0 \subseteq \widehat{L}$ is as in Section 27.1, and $\mathcal{R}(\widehat{E}_0)$ is the ideal in $\widehat{L}$ generated by $\widehat{E}_0$. This implies that there is a Lie algebra automorphism $\widetilde{\sigma}$ of $\widetilde{L}$, whose composition with the quotient mapping from $\widehat{L}$ onto $\widetilde{L}$ is the same as the composition of the quotient mapping with $\widehat{\sigma}$.

Of course,

$$\widetilde{\sigma}(\widetilde{x}_\alpha) = -\widetilde{y}_\alpha,\ \widetilde{\sigma}(\widetilde{y}_\alpha) = -\widetilde{x}_\alpha, \text{ and } \widetilde{\sigma}(\widetilde{h}_\alpha) = -\widetilde{h}_\alpha \tag{27.6.8}$$

for every $\alpha \in \Delta$. This implies that

$$\widetilde{\sigma}(\widetilde{\mathcal{Y}}) = \widetilde{\mathcal{X}}, \tag{27.6.9}$$

which is the Lie subalgebra of $\widetilde{L}$ generated by the $\widetilde{x}_\alpha$'s, $\alpha \in \Delta$, as before. In particular, $\widetilde{\mathcal{X}}$ and $\widetilde{\mathcal{Y}}$ are isomorphic as Lie algebras over k, as in Exercise 1 on p101 of [14].

27.7 Some more relations in $\widetilde{L}$

Let us continue with the same notation and hypotheses as in the previous sections. Remember that $n(\alpha, \beta) \in \mathbf{Z}$ for every $\alpha, \beta \in \Delta$, with $-3 \leq n(\alpha, \beta) \leq 0$ when $\alpha \neq \beta$. Put

$$\widetilde{x}_{\alpha,\beta} = (\mathrm{ad}_{\widetilde{x}_\alpha})^{-n(\beta,\alpha)+1}(\widetilde{x}_\beta), \quad \widetilde{y}_{\alpha,\beta} = (\mathrm{ad}_{\widetilde{y}_\alpha})^{-n(\beta,\alpha)+1}(\widetilde{y}_\beta) \tag{27.7.1}$$

for every $\alpha, \beta \in \Delta$ with $\alpha \neq \beta$, which are elements of $\widetilde{L}$. We would like to show that

$$\mathrm{ad}_{\widetilde{x}_\gamma}(\widetilde{y}_{\alpha,\beta}) = 0 \tag{27.7.2}$$

for every $\alpha, \beta, \gamma \in \Delta$ with $\alpha \neq \beta$, as in the lemma on p99 of [14]. We also have that

$$\mathrm{ad}_{\widetilde{y}_\gamma}(\widetilde{x}_{\alpha,\beta}) = 0 \tag{27.7.3}$$

when $\alpha \neq \beta$, using a similar argument, or the automorphism $\widetilde{\sigma}$ on $\widetilde{L}$ discussed in the previous section.

Suppose first that $\alpha \neq \gamma$, so that $[\widetilde{x}_\gamma, \widetilde{y}_\alpha] = 0$, as in (27.1.10). This implies that $\mathrm{ad}_{\widetilde{x}_\gamma}$ and $\mathrm{ad}_{\widetilde{y}_\alpha}$ commute as linear mappings on $\widetilde{L}$, as in Section 2.4. It follows that

$$\mathrm{ad}_{\widetilde{x}_\gamma}(\widetilde{y}_{\alpha,\beta}) = (\mathrm{ad}_{\widetilde{y}_\alpha})^{-n(\beta,\alpha)+1}(\mathrm{ad}_{\widetilde{x}_\gamma}(\widetilde{y}_\beta)) \tag{27.7.4}$$

in this case. If $\beta \neq \gamma$, then $\mathrm{ad}_{\widetilde{x}_\gamma}(\widetilde{y}_\beta) = 0$, by (27.1.10) again, so that (27.7.2) holds. If $\beta = \gamma$, then (27.7.4) reduces to

$$\mathrm{ad}_{\widetilde{x}_\beta}(\widetilde{y}_{\alpha,\beta}) = (\mathrm{ad}_{\widetilde{y}_\alpha})^{-n(\beta,\alpha)+1}(\widetilde{h}_\beta), \tag{27.7.5}$$

by (27.1.10).

Note that

$$\mathrm{ad}_{\widetilde{y}_\alpha}(\widetilde{h}_\beta) = n(\alpha,\beta)\,\widetilde{y}_\alpha, \tag{27.7.6}$$

by (27.1.12). If $n(\alpha,\beta) = 0$, then it follows that (27.7.2) holds, by (27.7.5). Otherwise, if $n(\alpha,\beta) \neq 0$, then $n(\beta,\alpha) \neq 0$, by (27.1.1). More precisely, $n(\beta,\alpha) < 0$, because $\alpha \neq \beta$, so that

$$-n(\beta,\alpha) + 1 \geq 2. \tag{27.7.7}$$

This means that (27.7.2) follows from (27.7.5), because $\mathrm{ad}_{\widetilde{y}_\alpha}(\widetilde{y}_\alpha) = 0$.

Suppose now that $\alpha = \gamma$, so that we would like to show that

$$\mathrm{ad}_{\widetilde{x}_\alpha}(\widetilde{y}_{\alpha,\beta}) = 0 \tag{27.7.8}$$

when $\alpha \neq \beta$. Remember that $\widetilde{x}_\alpha, \widetilde{y}_\alpha, \widetilde{h}_\alpha \neq 0$, as in (27.3.7) and (27.3.8). The linear span of $\widetilde{x}_\alpha$, $\widetilde{y}_\alpha$, and $\widetilde{h}_\alpha$ in $\widetilde{L}$ is a Lie subalgebra of $\widetilde{L}$, because of (27.1.10), (27.1.11), and (27.1.12). This subalgebra is isomorphic to $sl(2,k)$ as a Lie algebra over k, because $n(\alpha,\alpha) = 2$. Thus we may consider $\widetilde{L}$ as a module over $sl(2,k)$, as a Lie algebra over k, using ad_w when w is in the linear span of $\widetilde{x}_\alpha$, $\widetilde{y}_\alpha$, and $\widetilde{h}_\alpha$.

Note that $\mathrm{ad}_{\widetilde{x}_\alpha}(\widetilde{y}_\beta) = 0$, as in (27.1.10), because $\alpha \neq \beta$. We also have that $\mathrm{ad}_{\widetilde{h}_\alpha}(\widetilde{y}_\beta) = -n(\beta,\alpha)\,\widetilde{y}_\beta$, as in (27.1.12). This means that $\widetilde{y}_\beta$ is a maximal or primitive vector of weight $\lambda = -n(\beta,\alpha)$ in $\widetilde{L}$ as a module over the linear span of $\widetilde{x}_\alpha$, $\widetilde{y}_\alpha$, and $\widetilde{h}_\alpha$, as in Section 15.2. If j is a positive integer, then

$$\mathrm{ad}_{\widetilde{x}_\alpha}((\mathrm{ad}_{\widetilde{y}_\alpha})^j(\widetilde{y}_\beta)) = j\,(\lambda - j + 1)\,(\mathrm{ad}_{\widetilde{y}_\alpha})^{j-1}(\widetilde{y}_\beta), \tag{27.7.9}$$

as in (15.3.4). The right side is equal to 0 when $j = \lambda + 1 = -n(\beta,\alpha) + 1$, which implies (27.7.8), as desired.

27.8 Serre's theorem

Let us continue with the same notation and hypotheses as in the previous sections, Section 27.1 in particular. If $\alpha, \beta \in \Delta$ and $\alpha \neq \beta$, then put

$$\widehat{x}_{\alpha,\beta} = (\mathrm{ad}_{\widehat{x}_\alpha})^{-n(\beta,\alpha)+1}(\widehat{x}_\beta), \quad \widehat{y}_{\alpha,\beta} = (\mathrm{ad}_{\widehat{y}_\alpha})^{-n(\beta,\alpha)+1}(\widehat{y}_\beta), \tag{27.8.1}$$

which are elements of $\widehat{L}$. Of course, $\mathrm{ad}_{\widehat{x}_\alpha}$ and $\mathrm{ad}_{\widehat{y}_\alpha}$ refer to the adjoint representation on $\widehat{L}$ here. Remember that $n(\beta,\alpha) \leq 0$ when $\alpha \neq \beta$, so that $-n(\beta,\alpha) + 1 \in \mathbf{Z}_+$. Clearly the images of $\widehat{x}_{\alpha,\beta}$ and $\widehat{y}_{\alpha,\beta}$ in $\widetilde{L}$ under the natural quotient mapping are the same as $\widetilde{x}_{\alpha,\beta}$ and $\widetilde{y}_{\alpha,\beta}$ in (27.7.1), respectively.

Let $\widehat{E}_1$ be the subset of $\widehat{L}$ consisting of $\widehat{x}_{\alpha,\beta}$ and $\widehat{y}_{\alpha,\beta}$ for $\alpha, \beta \in \Delta$ with $\alpha \neq \beta$. Remember that $\widehat{E}_0 \subseteq \widehat{L}$ was defined in Section 27.1, and let $\mathcal{R}(\widehat{E}_0 \cup \widehat{E}_1)$ be the ideal in $\widehat{L}$ generated by $\widehat{E}_0 \cup \widehat{E}_1$. Thus the quotient

$$\widehat{L}/\mathcal{R}(\widehat{E}_0 \cup \widehat{E}_1) \tag{27.8.2}$$

is a Lie algebra over k. A famous theorem of Serre states that this is a finite-dimensional semisimple Lie algebra, as on p52 of [24], and p99 of [14]. More precisely, the linear span of the images of the $\widehat{h}_\alpha$'s, $\alpha \in \Delta$, in (27.8.2) is a Cartan subalgebra of this Lie algebra, which corresponds to the given root system Φ.

Let $\widetilde{E}_1$ be the subset of $\widetilde{L}$ consisting of $\widetilde{x}_{\alpha,\beta}$ and $\widetilde{y}_{\alpha,\beta}$ for $\alpha, \beta \in \Delta$ with $\alpha \neq \beta$, which is the same as the image of $\widehat{E}_1$ under the natural quotient mapping from $\widehat{L}$ onto $\widetilde{L}$. Also let $\mathcal{R}(\widetilde{E}_1) = \mathcal{R}_{\widetilde{L}}(\widetilde{E}_1)$ be the ideal in $\widetilde{L}$ generated by $\widetilde{E}_1$. Consider the quotient

$$L = L(k) = \widetilde{L}/\mathcal{R}(\widetilde{E}_1), \tag{27.8.3}$$

which is a Lie algebra over k. There is a natural Lie algebra homomorphism from $\widehat{L}$ onto L, which is the composition of the quotient mappings from $\widehat{L}$ onto $\widetilde{L}$ and from $\widetilde{L}$ onto L. The kernel of this homomorphism is $\mathcal{R}(\widehat{E}_0 \cup \widehat{E}_1)$, which leads to a natural Lie algebra isomorphism from (27.8.2) onto L.

Let x_α, y_α, and h_α be the images of $\widetilde{x}_\alpha$, $\widetilde{y}_\alpha$, and $\widetilde{h}_\alpha$, respectively, under the natural quotient mapping from $\widetilde{L}$ onto L for each $\alpha \in \Delta$. Of course, these correspond to the images of $\widehat{x}_\alpha$, $\widehat{y}_\alpha$, and $\widehat{h}_\alpha$, respectively, in (27.8.2) for every $\alpha \in \Delta$. If $\alpha, \beta \in \Delta$, then

$$[h_\alpha, h_\beta] = 0, \tag{27.8.4}$$
$$[x_\alpha, y_\beta] = \delta_{\alpha,\beta}\, h_\alpha, \tag{27.8.5}$$
$$[h_\alpha, x_\beta] = n(\beta, \alpha)\, x_\beta, \tag{27.8.6}$$
$$[h_\alpha, y_\beta] = -n(\beta, \alpha)\, y_\beta \tag{27.8.7}$$

in L, because of the analogous properties of $\widetilde{x}_\alpha$, $\widetilde{y}_\alpha$, and $\widetilde{h}_\alpha$ in $\widetilde{L}$, as in Section 27.1. If $\alpha \neq \beta$, then we also have that

$$(\mathrm{ad}_{x_\alpha})^{-n(\beta,\alpha)+1}(x_\beta) = (\mathrm{ad}_{y_\alpha})^{-n(\beta,\alpha)+1}(y_\beta) = 0 \tag{27.8.8}$$

in L, by definition of $\widetilde{E}_1$.

The proof of Serre's theorem will be discussed in the next sections, and continuing in the next chapter.

27.9 Ideals $\mathcal{I}$, $\mathcal{J}$

We continue with the discussion of Serre's theorem, from the previous section.

Remember that $\widetilde{\mathcal{X}}$, $\widetilde{\mathcal{Y}}$ are the Lie subalgebras of $\widetilde{L}$ generated by the $\widetilde{x}_\alpha$'s, $\widetilde{y}_\alpha$'s, respectively, with $\alpha \in \Delta$, as in Section 27.3. Let $\widetilde{E}_{1,1}$ be the subset of $\widetilde{L}$ consisting of $\widetilde{x}_{\alpha,\beta}$ for $\alpha, \beta \in \Delta$ with $\alpha \neq \beta$, and let $\widetilde{E}_{1,2}$ be the set of $\widetilde{y}_{\alpha,\beta}$ for $\alpha, \beta \in \Delta$ with $\alpha \neq \beta$. Thus

$$\widetilde{E}_1 = \widetilde{E}_{1,1} \cup \widetilde{E}_{1,2}, \ \widetilde{E}_{1,1} \subseteq \widetilde{\mathcal{X}}, \text{ and } \widetilde{E}_{1,2} \subseteq \widetilde{\mathcal{Y}}. \tag{27.9.1}$$

Let $\mathcal{I}$ be the ideal in $\widetilde{\mathcal{X}}$ generated by $\widetilde{E}_{1,1}$, and let $\mathcal{J}$ be the ideal in $\widetilde{\mathcal{Y}}$ generated by $\widetilde{E}_{1,2}$. Note that

$$\mathcal{I}, \mathcal{J} \subseteq \mathcal{R}(\widetilde{E}_1). \tag{27.9.2}$$

We would like to show that

$$\mathcal{I}, \mathcal{J} \text{ are ideals in } \widetilde{L}, \tag{27.9.3}$$

as in Step (1) on p99 of [14], and (a) on p53 of [24]. We shall do this for $\mathcal{J}$, since the argument for $\mathcal{I}$ is analogous, as in [14]. Observe that

$$[\widetilde{h}_\gamma, \widetilde{y}_{\alpha,\beta}] = (-n(\beta,\gamma) + (n(\beta,\alpha) - 1)\, n(\alpha,\gamma))\, \widetilde{y}_{\alpha,\beta} \tag{27.9.4}$$

for every $\alpha, \beta, \gamma \in \Delta$ with $\alpha \neq \beta$, by (27.4.3) and the definition (27.7.1) of $\widetilde{y}_{\alpha,\beta}$. It is easy to see that

$$\mathrm{ad}_{\widetilde{h}_\gamma}(\widetilde{\mathcal{Y}}) \subseteq \widetilde{\mathcal{Y}} \tag{27.9.5}$$

for every $\gamma \in \Delta$, using (27.1.12) and the Jacobi identity; a more precise version of this is given by (27.4.3). It follows from (27.9.4) and (27.9.5) that

$$\mathrm{ad}_{\widetilde{h}_\gamma}(\mathcal{J}) \subseteq \mathcal{J} \tag{27.9.6}$$

for every $\gamma \in \Delta$, using the Jacobi identity again.

Remember that $\widetilde{\mathcal{H}}$ is the linear span of the $\widetilde{h}_\alpha$'s, $\alpha \in \Delta$, in $\widetilde{L}$, as in Section 27.3. Observe that

$$\mathrm{ad}_{\widetilde{x}_\gamma}(\widetilde{\mathcal{Y}}) \subseteq \widetilde{\mathcal{Y}} + \widetilde{\mathcal{H}} \tag{27.9.7}$$

for every $\gamma \in \Delta$, by (27.1.10) and the earlier remarks about (27.4.6). One can check that

$$\mathrm{ad}_{\widetilde{x}_\gamma}(\mathcal{J}) \subseteq \mathcal{J} \tag{27.9.8}$$

for every $\gamma \in \Delta$, using (27.7.2), (27.9.6), (27.9.7), and the Jacobi identity. This implies that $\mathcal{J}$ is an ideal in $\widetilde{L}$, because $\widetilde{L}$ is generated as a Lie algebra over k by the $\widetilde{x}_\gamma$'s and $\widetilde{y}_\gamma$'s, $\gamma \in \Delta$. More precisely, this is the same as saying that the normalizer of $\mathcal{J}$ in $\widetilde{L}$ is $\widetilde{L}$, and the normalizer of $\mathcal{J}$ in $\widetilde{L}$ is automatically a Lie subalgebra of $\widetilde{L}$, by the Jacobi identity.

Step (2) on p99 of [14] states that

$$\mathcal{I} + \mathcal{J} = \mathcal{R}(\widetilde{E}_1), \tag{27.9.9}$$

which corresponds to a remark just after (a) on p53 of [24]. Of course,

$$\mathcal{I} + \mathcal{J} \subseteq \mathcal{R}(\widetilde{E}_1), \tag{27.9.10}$$

by (27.9.2). We also have that $\widetilde{E}_1 \subseteq \mathcal{I} + \mathcal{J}$, by construction. Note that $\mathcal{I} + \mathcal{J}$ is an ideal in $\widetilde{L}$, by (27.9.3). This implies that $\mathcal{R}(\widetilde{E}_1) \subseteq \mathcal{I} + \mathcal{J}$, as desired.

27.10 Subalgebras $\mathcal{X}$, $\mathcal{H}$, and $\mathcal{Y}$ of L

Let us continue with the same notation and hypotheses as in the previous sections. Let $\mathcal{X}$, $\mathcal{H}$, and $\mathcal{Y}$ be the images of $\widetilde{\mathcal{X}}$, $\widetilde{\mathcal{H}}$, and $\widetilde{\mathcal{Y}}$, respectively, under the natural quotient mapping from $\widetilde{L}$ onto L. Thus $\mathcal{X}$, $\mathcal{H}$, and $\mathcal{Y}$ are Lie subalgebras of L, and $\mathcal{H}$ is commutative as a Lie algebra over k, because of the analogous properties of $\widetilde{\mathcal{X}}$, $\widetilde{\mathcal{H}}$, and $\widetilde{\mathcal{Y}}$ in $\widetilde{L}$. More precisely, $\mathcal{X}$ is the Lie subalgebra of L generated by the x_α's, $\alpha \in \Delta$, and $\mathcal{Y}$ is the Lie subalgebra of L generated by the y_α's, $\alpha \in \Delta$. Similarly, $\mathcal{H}$ is the same as the linear span of the h_α's, $\alpha \in \Delta$, in L.

Remember that $\widetilde{L}$ corresponds to the direct sum of $\widetilde{\mathcal{X}}$, $\widetilde{\mathcal{H}}$, and $\widetilde{\mathcal{Y}}$ as a vector space over k, as in (27.3.2). Similarly,

(27.10.1) L corresponds to the direct sum of $\mathcal{X}$, $\mathcal{H}$, and $\mathcal{Y}$, as a vector space over k.

This follows from (27.9.9), and the analogous statement for $\widetilde{L}$. This is part of Step (3) on p100 of [14], and of (b) on p53 of [24].

The kernels of the restrictions of the natural quotient mapping from $\widetilde{L}$ onto L to $\widetilde{\mathcal{X}}$ and $\widetilde{\mathcal{Y}}$ are $\mathcal{I}$ and $\mathcal{J}$, respectively, because of (27.9.9). Thus we can identify $\mathcal{X}$, $\mathcal{Y}$ with the quotients

$$\widetilde{\mathcal{X}}/\mathcal{I}, \quad \widetilde{\mathcal{Y}}/\mathcal{J}, \tag{27.10.2}$$

respectively. Similarly, the restriction of the natural quotient mapping from $\widetilde{L}$ onto L to $\widetilde{\mathcal{H}}$ is injective, by (27.9.9). This permits us to identify $\widetilde{\mathcal{H}}$ with $\mathcal{H}$. This is also part of Step (3) on p100 of [14], and (b) on p53 of [24].

Remember that the $\widetilde{h}_\alpha$'s, $\alpha \in \Delta$, form a basis for $\widetilde{\mathcal{H}}$ as a vector space over k, as in (27.3.1). This means that the h_α's, $\alpha \in \Delta$, form a basis for $\mathcal{H}$ as a vector space over k. In particular, $\widetilde{h}_\alpha \neq 0$ for each $\alpha \in \Delta$, as in (27.3.7), so that $h_\alpha \neq 0$ for every $\alpha \in \Delta$ too. This implies that $x_\alpha, y_\alpha \neq 0$ for every $\alpha \in \Delta$, because $[x_\alpha, y_\alpha] = h_\alpha$, as in (27.8.5).

Using this, one can verify that

(27.10.3) the set of x_β's, y_β's, and h_β's, $\beta \in \Delta$, is linearly independent in L,

as in (27.3.10). More precisely, the x_β's, y_β's, and h_β's are simultaneous eigenvectors for ad_{h_α} on L, $\alpha \in \Delta$, by (27.8.4), (27.8.6), and (27.8.7). To get linear independence, one also uses the fact that the eigenvalues for the x_β's and y_β's correspond to distinct functions of α on Δ that are not identically 0, as before. This permits one to reduce to the linear independence of the h_β's, $\beta \in \Delta$. Equivalently, the restriction of the natural quotient mapping from $\widetilde{L}$ onto L to the linear subspace of $\widetilde{L}$ spanned by the $\widetilde{x}_\beta$'s, $\widetilde{y}_\beta$'s, and $\widetilde{h}_\beta$'s, $\beta \in \Delta$, is injective, as in Step (4) on p100 of [14].

27.11 Eigenvectors in L

We continue with the same notation and hypotheses as in the previous sections.

Let $\mathcal{H}'$ be the dual of $\mathcal{H}$, as a vector space over k, as usual, and put

$$L_\mu = \{u \in L : [h, u] = \mu(h)\, u \text{ for every } h \in \mathcal{H}\} \tag{27.11.1}$$

for each $\mu \in \mathcal{H}'$. The elements of L_μ are said to have *weight* μ. If $\mu \in \mathcal{H}'$, then let $\widetilde{\mu}$ be the corresponding linear functional on $\widetilde{\mathcal{H}}$, which is the composition of μ with the restriction to $\widetilde{\mathcal{H}}$ of the natural quotient mapping from $\widetilde{L}$ onto L. Observe that

(27.11.2) the natural quotient mapping from $\widetilde{L}$ onto L maps $\widetilde{L}_{\widetilde{\mu}}$ into L_μ,

where $\widetilde{L}_{\widetilde{\mu}}$ is as in (27.5.1). Of course, $\mathcal{H} \subseteq L_0$, by (27.8.4).

If $\beta \in \Delta$, then there is a unique $\nu_\beta \in \mathcal{H}'$ such that

$$\nu_\beta(h_\alpha) = n(\beta, \alpha) \tag{27.11.3}$$

for every $\alpha \in \Delta$, because the h_α's form a basis for $\mathcal{H}$. The composition of ν_β with the restriction of the natural quotient mapping from $\widetilde{L}$ onto L to $\widetilde{\mathcal{H}}$ is the same as $\widetilde{\nu}_\beta \in \widetilde{\mathcal{H}}'$, defined in (27.5.2). It is easy to see that the ν_β's, $\beta \in \Delta$, form a basis for $\mathcal{H}'$, as a vector space over k, because of the analogous statement for the $\widetilde{\nu}_\beta$'s in Section 27.5.

Every element of $\mathcal{X}$ can be expressed as the sum of finitely elements of the subspaces L_μ, where $\mu \in \mathcal{H}'$ can be expressed as a nontrivial sum of ν_β's. This follows from (27.11.2) and the analogous statement for $\widetilde{\mathcal{X}}$ in Section 27.5. We also have that every element of $\mathcal{Y}$ can be expressed as the sum of finitely many elements of L_μ's, where $\mu \in \mathcal{H}'$ can be expressed as a nontrivial sum of $-\nu_\beta$'s. This implies that $\mathcal{X}$ and $\mathcal{Y}$ correspond to the direct sums of their intersections with the appropriate subspaces L_μ, as vector spaces over k, as in Section 27.5.

As before, one can use this to check that

$$\mathcal{H} = L_0. \tag{27.11.4}$$

Similarly, $\mathcal{X}$ corresponds to the direct sum of the subspaces L_μ, where $\mu \in \mathcal{H}'$ can be expressed as a nontrivial sum of ν_β's, and $\mathcal{Y}$ corresponds to the direct sum of the subspaces L_μ, where $\mu \in \mathcal{H}'$ can be expressed as a nontrivial sum of $-\nu_\beta$'s, as vector spaces over k. This uses the hypothesis that k have characteristic 0, so that nontrivial sums of ν_β's or of $-\nu_\beta$'s cannot be equal to 0, or to each other. If $\mu \in \mathcal{H}'$ and $L_\mu \neq \{0\}$, then one can verify that $\mu = 0$, or μ is a nontrivial sum of ν_β's, or μ is a nontrivial sum of $-\nu_\beta$'s.

More precisely, every element of $\mathcal{X}$ can be expressed as the sum of the images under the natural quotient mapping from $\widetilde{L}$ onto L of finitely many elements of $\widetilde{L}_{\widetilde{\mu}}$, where $\widetilde{\mu}$ is a nontrivial sum of $\widetilde{\nu}_\beta$'s, and every element of $\mathcal{Y}$ can be expressed as the sum of the images of finitely many elements of $\widetilde{L}_{\widetilde{\mu}}$, where $\widetilde{\mu}$ is a nontrivial sum of $-\widetilde{\nu}_\beta$'s. Let $\mu \in \mathcal{H}'$ be given, and let $\widetilde{\mu}$ be the corresponding linear functional on $\widetilde{\mathcal{H}}'$ again, as in (27.11.2). One can check that

(27.11.5) the natural quotient mapping from $\widetilde{L}$ onto L maps $\widetilde{L}_{\widetilde{\mu}}$ onto L_μ.

This follows from (27.11.4) when $\mu = 0$. Otherwise, one can use the previous remarks about $\mathcal{X}$, $\mathcal{Y}$.

Using (27.11.5), we get that L_μ is finite-dimensional as a vector space over k for every $\mu \in \mathcal{H}'$, because of the analogous statement for $\widetilde{L}_{\widetilde{\mu}}$ in Section 27.5. This corresponds to Step (5) on p100 of [14], and some remarks on p53 of [24].

27.12 Locally nilpotent linear mappings

Let k be a field, and let V be a vector space over k. A linear mapping T from V into itself is said to be *locally nilpotent* if for each $v \in V$ there is a positive integer l such that $T^l(v) = 0$. If W is a finite-dimensional linear subspace of V, then it follows that there is a positive integer r such that $T^r(W) = \{0\}$. In this case, the linear subspace W_1 of V spanned by $W, T(W), \ldots, T^r(W)$ is finite-dimensional and satisfies

$$T(W_1) \subseteq W_1. \tag{27.12.1}$$

If T_1, T_2 are commuting locally nilpotent linear mappings from V into itself, then it is easy to see that $T_1 + T_2$ is locally nilpotent on V as well.

Suppose now that k has characteristic 0, and let T be a locally nilpotent linear mapping from V into itself. If $v \in V$, then put

$$(\exp T)(v) = \sum_{j=0}^{\infty} (1/j!)\, T^j(v), \tag{27.12.2}$$

where the sum on the right reduces to a finite sum in V. It is easy to see that this defines a linear mapping from V into itself.

Let T_1, T_2 be commuting locally nilpotent linear mappings from V into itself again. If $v \in V$, then

$$T_1^j(T_2^l(v)) = T_2^l(T_1^j(v)) = 0 \tag{27.12.3}$$

when j or l is sufficiently large. One can check that

$$(\exp(T_1 + T_2))(v) = (\exp T_1)((\exp T_2)(v)), \tag{27.12.4}$$

using the binomial theorem in the usual way. If T is a locally nilpotent linear mapping from V into itself, then one can apply the previous statement to T, $-T$ to get that $\exp T$ is invertible on V, with inverse equal to $\exp(-T)$. This is related to some remarks just before the theorem on p99 of [14].

Let $\mathcal{A}$ be an algebra over k in the strict sense, and let δ be a derivation on $\mathcal{A}$. If δ is locally nilpotent on $\mathcal{A}$, then $\exp \delta$ is an algebra automorphism of $\mathcal{A}$, as in Section 14.11.

Let us now return to the discussion of Serre's theorem, as in the previous sections. We would like to show that for each $\alpha \in \Delta$, ad_{x_α} and ad_{y_α} are locally nilpotent as linear mappings from L into itself, as in Step (6) on p100 of [14], and (c) on p53 of [24]. Put

$$V_\alpha = \{u \in L : \mathrm{ad}_{x_\alpha}^l(u) = 0 \text{ for some } l \in \mathbf{Z}_+\}, \tag{27.12.5}$$

which is a linear subspace of L. One can check that V_α is a Lie subalgebra of L, using the fact that ad_{x_α} is a derivation on L. Observe that $x_\beta \in V_\alpha$ for every $\beta \in \Delta$, by (27.8.8). One can verify that $y_\beta \in V_\alpha$ for every $\beta \in \Delta$, using (27.8.5) and (27.8.6). It follows that $L \subseteq V_\alpha$, because L is generated as a Lie algebra over k by the x_β's and y_β's, $\beta \in \Delta$. This means that ad_{x_α} is locally nilpotent on L, and the argument for ad_{y_α} is analogous.

Let $\alpha \in \Delta$ be given, and note that $-\mathrm{ad}_{y_\alpha}$ is locally nilpotent on L. Thus $\exp \mathrm{ad}_{x_\alpha}$ and $\exp(-\mathrm{ad}_{y_\alpha})$ are Lie algebra automorphisms of L, because ad_{x_α}, $-\mathrm{ad}_{y_\alpha}$ are derivations on L, as before. It follows that

$$\theta_\alpha = (\exp \mathrm{ad}_{x_\alpha}) \circ (\exp -\mathrm{ad}_{y_\alpha}) \circ (\exp \mathrm{ad}_{x_\alpha}) \tag{27.12.6}$$

is a Lie algebra automorphism of L too. This corresponds to Step (7) on p100 of [14], and to part of (d) on p54 of [24].

If $u \in L$ satisfies $[x_\alpha, u] = [y_\alpha, u] = 0$, then

$$(\exp \mathrm{ad}_{x_\alpha})(u) = (\exp -\mathrm{ad}_{y_\alpha})(u) = u, \tag{27.12.7}$$

and hence

$$\theta_\alpha(u) = u. \tag{27.12.8}$$

Remember that $n(\alpha, \alpha) = 2$, as in Section 27.1. Using the same type of argument as in Section 23.7, we get that

$$\theta_\alpha(x_\alpha) = -y_\alpha, \quad \theta_\alpha(y_\alpha) = -x_\alpha, \quad \theta_\alpha(h_\alpha) = -h_\alpha. \tag{27.12.9}$$

27.13 Some properties of θ_α

Let us continue with the same notation and hypotheses as in the previous sections. In particular, let $\alpha \in \Delta$ be given again, and let θ_α be the Lie algebra automorphism of L defined in (27.12.6). If $h \in \mathcal{H}$, then h can be expressed in a unique way as

$$h = \sum_{\beta \in \Delta} c_\beta \, h_\beta, \tag{27.13.1}$$

with $c_\beta \in k$ for each $\beta \in \Delta$. In this case,

$$[h, x_\alpha] = \sum_{\beta \in \Delta} c_\beta \, [h_\beta, x_\alpha] = \sum_{\beta \in \Delta} c_\beta \, n(\alpha, \beta) \, x_\alpha, \tag{27.13.2}$$

$$[h, y_\alpha] = \sum_{\beta \in \Delta} c_\beta \, [h_\beta, y_\alpha] = -\sum_{\beta \in \Delta} c_\beta \, n(\alpha, \beta) \, y_\alpha, \tag{27.13.3}$$

by (27.8.6) and (27.8.7). If

$$\sum_{\beta \in \Delta} c_\beta \, n(\alpha, \beta) = 0, \tag{27.13.4}$$

then it follows that $[h, x_\alpha] = [h, y_\alpha] = 0$, so that

$$\theta_\alpha(h) = h, \tag{27.13.5}$$

as in (27.12.8).

If $h = h_\alpha$, then (27.13.4) does not hold, because k has characteristic 0, so that $n(\alpha, \alpha) = 2$ is not zero in k. It follows that

(27.13.6) $\mathcal{H}$ is spanned by h_α and the $h \in \mathcal{H}$ that satisfy (27.13.4),

as a vector space over k. This implies that

$$\theta_\alpha(\mathcal{H}) = \mathcal{H}, \tag{27.13.7}$$

by (27.12.9) and (27.13.5). Note that

$$\theta_\alpha(\theta_\alpha(h)) = h \tag{27.13.8}$$

for every $h \in \mathcal{H}$.

If $h \in \mathcal{H}$ is as in (27.13.1), then put

$$\nu_\alpha(h) = \sum_{\beta \in \Delta} c_\beta \, n(\alpha, \beta). \tag{27.13.9}$$

This defines a linear functional on $\mathcal{H}$, which is the same as the one in (27.11.3), with α and β interchanged. Observe that $\nu_\alpha(h_\alpha) = n(\alpha, \alpha) = 2$, and that

$$\theta_\alpha(h) = h - \nu_\alpha(h) \, h_\alpha \tag{27.13.10}$$

for every $h \in \mathcal{H}$, because of (27.12.9) and (27.13.5).

Let $\mu \in \mathcal{H}'$ be given, and put

$$\zeta_{\mu,\alpha}(h) = \mu(\theta_\alpha(h)) \tag{27.13.11}$$

for every $h \in \mathcal{H}$, which defines a linear functional on $\mathcal{H}$ too. Clearly $h \in \mathcal{H}$ and $u \in L$ satisfy

$$[h, u] = \zeta_{\mu,\alpha}(h) \, u \tag{27.13.12}$$

if and only if

$$[\theta_\alpha(h), \theta_\alpha(u)] = \mu(\theta_\alpha(h)) \, \theta_\alpha(u), \tag{27.13.13}$$

because θ_α is a Lie algebra automorphism of L. This implies that

$$\theta_\alpha(L_{\zeta_{\mu,\alpha}}) = L_\mu, \tag{27.13.14}$$

where L_μ, $L_{\zeta_{\mu,\alpha}}$ are as in (27.11.1). This corresponds to part of Step (8) on p100 of [14], and of (d) on p54 of [24].

Equivalently,

$$\zeta_{\mu,\alpha}(h) = \mu(h) - \nu_\alpha(h) \, \mu(h_\alpha) \tag{27.13.15}$$

for every $h \in \mathcal{H}$, by (27.13.10). This means that

$$\zeta_{\mu,\alpha} = \mu - \mu(h_\alpha)\,\nu_\alpha, \tag{27.13.16}$$

as elements of $\mathcal{H}'$. Let $\gamma \in \Delta$ be given, and let $\nu_\gamma \in \mathcal{H}'$ be as in (27.11.3) and (27.13.9), so that

$$\nu_\gamma(h_\beta) = n(\gamma, \beta) \tag{27.13.17}$$

for every $\beta \in \Delta$. If we take $\mu = \nu_\gamma$ in (27.13.16), then we get that

$$\zeta_{\nu_\gamma,\alpha} = \nu_\gamma - \nu_\gamma(h_\alpha)\,\nu_\alpha = \nu_\gamma - n(\gamma, \alpha)\,\nu_\alpha. \tag{27.13.18}$$

This means that

$$\zeta_{\nu_\gamma,\alpha} = \nu_\gamma - \lambda_\alpha(\gamma)\,\nu_\alpha, \tag{27.13.19}$$

where $\lambda_\alpha(\gamma) \in \mathbf{Z}$ is as in Section 27.1.

27.14 Roots and $\mathcal{H}'$

We continue with the discussion of Serre's theorem, as in the previous sections. Remember from Section 27.1 that V is a vector space over the real numbers of positive finite dimension, Φ is a reduced root system in V, and that Δ is a base for Φ. Let Θ_Φ be the subgroup of V, as a commutative group with respect to addition, generated by Φ. This is the same as the subgroup of V generated by Δ, which consists of linear combinations of elements of Δ with coefficients in $\mathbf{Z}$.

If $\alpha \in \Phi$, then σ_α is the symmetry on V with vector α that maps Φ onto itself, as before. This can be expressed as $\sigma_\alpha(v) = v - \lambda_\alpha(v)\,\alpha$, where λ_α is a linear functional on V such that $\lambda_\alpha(\alpha) = 2$ and $\lambda_\alpha(\beta) \in \mathbf{Z}$ for every $\beta \in \Phi$. Observe that σ_α maps Θ_Φ onto itself, and that λ_α maps Θ_Φ into $\mathbf{Z}$. If σ is in the Weyl group W of Φ, then it follows that

$$\sigma(\Theta_\Phi) = \Theta_\Phi. \tag{27.14.1}$$

If $\gamma \in \Theta_\Phi$, then let ν_γ be the linear functional on $\mathcal{H}$ such that

$$\nu_\gamma(h_\beta) = \lambda_\beta(\gamma) \tag{27.14.2}$$

for every $\beta \in \Delta$. This is equivalent to (27.13.17) when $\gamma \in \Delta$, by (27.1.1). Note that

$$\gamma \mapsto \nu_\gamma \tag{27.14.3}$$

is a homomorphism from Θ_Φ into $\mathcal{H}'$, as commutative groups with respect to addition. Remember that the ν_γ's, $\gamma \in \Delta$, form a basis for $\mathcal{H}'$ as a vector space over k, as in Section 27.11. This implies that (27.14.3) is injective on Θ_Φ, because k has characteristic 0.

Let $\alpha \in \Delta$ be given, and let θ_α be the Lie algebra automorphism of L defined in Section 27.12. If $\gamma \in \Theta_\Phi$, then $\zeta_{\nu_\gamma,\alpha} \in \mathcal{H}'$ can be defined as in (27.13.11). Using (27.13.16), we get that

$$\zeta_{\nu_\gamma,\alpha} = \nu_\gamma - \nu_\gamma(h_\alpha)\,\nu_\alpha = \nu_\gamma - \lambda_\alpha(\gamma)\,\nu_\alpha. \tag{27.14.4}$$

Equivalently, this means that

$$\zeta_{\nu_\gamma, \alpha} = \nu_{\sigma_\alpha(\gamma)}. \tag{27.14.5}$$

It follows that

$$\theta_\alpha(L_{\nu_{\sigma_\alpha(\gamma)}}) = L_{\nu_\gamma}, \tag{27.14.6}$$

by taking $\mu = \nu_\gamma$ in (27.13.14).

Remember that L_μ is finite-dimensional as a vector space over k for every $\mu \in \mathcal{H}'$, as in Section 27.11. Using (27.14.6), we get that

$$\dim L_{\nu_\gamma} = \dim L_{\nu_{\sigma_\alpha(\gamma)}} \tag{27.14.7}$$

for every $\alpha \in \Delta$ and $\gamma \in \Theta_\Phi$. This implies that

$$\dim L_{\nu_\gamma} = \dim L_{\nu_{\sigma(\gamma)}} \tag{27.14.8}$$

for every $\sigma \in W$ and $\gamma \in \Theta_\Phi$. More precisely, this uses the fact that W is generated by σ_α with $\alpha \in \Delta$, as in Section 19.14. This corresponds to Step (8) on p100 of [14], and (d) on p54 of [24].

27.15 Some dimensions of eigenspaces

We continue with the same notation and hypotheses as in the previous sections. Let $\beta \in \Delta$ be given, and let $\widetilde{\nu}_\beta$ be the linear functional on $\widetilde{\mathcal{H}}$ such that $\widetilde{\nu}_\beta(\widetilde{h}_\alpha) = n(\beta, \alpha)$ for every $\alpha \in \Delta$, as in (27.5.2). Remember that $\widetilde{L}_{\widetilde{\nu}_\beta}$ consists of the $\widetilde{u} \in \widetilde{L}$ such that $[\widetilde{h}, \widetilde{u}] = \widetilde{\nu}_\beta(\widetilde{h})\, \widetilde{u}$ for every $\widetilde{h} \in \widetilde{\mathcal{H}}$, as in (27.5.1). Equivalently, this means that $[\widetilde{h}_\alpha, \widetilde{u}] = n(\beta, \alpha)\, \widetilde{u}$ for every $\alpha \in \Delta$. In particular, $\widetilde{x}_\beta \in \widetilde{L}_{\widetilde{\nu}_\beta}$, by (27.1.11).

In fact, $\widetilde{L}_{\widetilde{\nu}_\beta}$ is spanned by $\widetilde{x}_\beta$. Remember that $\widetilde{L}$ is spanned by $\widetilde{\mathcal{X}}$, $\widetilde{\mathcal{H}}$, and $\widetilde{\mathcal{Y}}$, and more precisely by elements of $\widetilde{L}_{\widetilde{\mu}}$ for suitable $\widetilde{\mu} \in \widetilde{\mathcal{H}}'$. Only multiples of $\widetilde{x}_\beta$ by elements of k were needed when $\widetilde{\mu} = \widetilde{\nu}_\beta$. This implies that $\widetilde{L}_{\widetilde{\nu}_\beta}$ consists of only multiples of $\widetilde{x}_\beta$.

Similarly, if $r \in \mathbf{Z}$ and $r \neq 0, \pm 1$, then $\widetilde{L}_{r\,\widetilde{\nu}_\beta} = \{0\}$. Indeed, If $|r| \geq 2$, then the only elements of $\widetilde{L}_{r\,\widetilde{\nu}_\beta}$ that would have been needed before were multiples of $[\widetilde{x}_{\beta_1}, \ldots, \widetilde{x}_{\beta_{|r|}}]$ or $[\widetilde{y}_{\beta_1}, \ldots, \widetilde{y}_{\beta_{|r|}}]$ with $\beta_l = \beta$ for $l = 1, \ldots, |r|$, as in Section 27.4. Of course, $[\widetilde{x}_{\beta_1}, \ldots, \widetilde{x}_{\beta_{|r|}}]$ and $[\widetilde{y}_{\beta_1}, \ldots, \widetilde{y}_{\beta_{|r|}}]$ are equal to 0 in this case. It follows that 0 is the only element of $\widetilde{L}_{r\,\widetilde{\nu}_\beta}$ when $|r| \geq 2$.

Let ν_β be the linear functional on $\mathcal{H}$ such that $\nu_\beta(h_\alpha) = n(\beta, \alpha)$ for every $\alpha \in \Delta$, as in (27.11.3). Note that $\widetilde{\nu}_\beta$ is the same as the composition of ν_β with the restriction to $\widetilde{\mathcal{H}}$ of the natural quotient mapping from $\widetilde{L}$ onto L. If $r \in \mathbf{Z}$, then the natural quotient mapping from $\widetilde{L}$ onto L maps $\widetilde{L}_{r\,\widetilde{\nu}_\beta}$ onto $L_{r\,\nu_\beta}$, as in (27.11.5). This implies that

$$L_{r\,\nu_\beta} = \{0\} \text{ when } |r| \geq 2, \tag{27.15.1}$$

by the remarks in the preceding paragraph.

If we take $r = 1$, then we get that L_{ν_β} is spanned by x_β, because of the analogous statement for $\widetilde{L}_{\widetilde{\nu}_\beta}$. Remember that $x_\beta \neq 0$, as in Section 27.10. Thus

$$\dim L_{\nu_\beta} = 1. \tag{27.15.2}$$

This corresponds to Step (9) on p100 of [14], and (e) on p54 of [24].

Let Θ_Φ be as in the previous section, and if $\gamma \in \Theta_\Phi$, then let $\nu_\gamma \in \mathcal{H}'$ be as in (27.14.2). Remember that this is equivalent to the previous definition when $\gamma \in \Delta$. If $\gamma \in \Phi$, then there is an element σ of the Weyl group of Φ such that $\sigma(\gamma) \in \Delta$, as in Section 19.14. It follows that

$$\dim L_{\nu_\gamma} = 1, \tag{27.15.3}$$

by (27.14.8) and (27.15.2).

If $r \in \mathbf{Z}$, then $r\,\gamma \in \Theta_\Phi$, and $r\,\nu_\gamma = \nu_{r\,\gamma}$. Similarly, $\nu_{\sigma(r\,\gamma)} = \nu_{r\,\sigma(\gamma)} = r\,\nu_{\sigma(\gamma)}$. If $|r| \geq 2$, then we get that

$$\dim L_{r\,\nu_\gamma} = 0, \tag{27.15.4}$$

using (27.14.8) and (27.15.1). This corresponds to Step (10) on p100 of [14], and (f) on p54 of [24].

Chapter 28

Some more Lie algebras, 2

28.1 Linear combinations of roots

Let us continue with the discussion of Serre's theorem, as in the previous chapter. We first need an auxiliary result about root systems. Remember that $(\cdot, \cdot)$ is an inner product on V that is invariant under the Weyl group of Φ, as in Section 27.1. If $w \in V$, then let V'_w be the linear subspace of the dual V' of V consisting of linear functionals on V that are equal to 0 at w, which is a hyperplane in V' when $w \neq 0$. Of course, one can use $(\cdot, \cdot)$ to identify V' with V, and V'_w with the set of vectors in V that are orthogonal to w.

Suppose that

(28.1.1) $\gamma \in V$ is not a multiple of any element of Φ by a real number.

This implies that $\gamma \neq 0$, and that $V'_\gamma \neq V'_\alpha$ for each $\alpha \in \Phi$. More precisely, $V'_\gamma \not\subseteq V'_\alpha$ for each $\alpha \in \Phi$, so that $V'_\gamma \cap V'_\alpha$ is a hyperplane in V'_γ for every $\alpha \in \Phi$. It follows that the union of $V'_\gamma \cap V'_\alpha$ over $\alpha \in \Phi$ is a proper subset of V'_γ, as in Section 18.12. Equivalently, this means that V'_γ is not contained in the union of V'_α, $\alpha \in \Phi$. Let τ be an element of V'_γ that is not in V'_α for any $\alpha \in \Phi$. Thus $\tau \in V'$ satisfies

(28.1.2) $$\tau(\gamma) = 0 \text{ and } \tau(\alpha) \neq 0 \text{ for every } \alpha \in \Phi.$$

As in Section 19.14, there is an element σ of the Weyl group of Φ such that $\tau(\sigma(\beta)) \geq 0$ for every $\beta \in \Delta$. This means that

(28.1.3) $$\tau(\sigma(\beta)) > 0 \text{ for every } \beta \in \Delta,$$

because $\sigma(\beta) \in \Phi$, so that $\tau(\sigma(\beta)) \neq 0$, by (28.1.2). Note that $\sigma(\Delta)$ is a basis for V, because Δ is a basis for V. Thus we can express γ as

(28.1.4) $$\gamma = \sum_{\beta \in \Delta} c_\beta \, \sigma(\beta)$$

for some real numbers c_β, $\beta \in \Delta$. It follows that

$$0 = \tau(\gamma) = \sum_{\beta \in \Delta} c_\beta \, \tau(\sigma(\beta)). \tag{28.1.5}$$

Of course, $c_\beta \neq 0$ for some $\beta \in \Delta$, because $\gamma \neq 0$. In fact, (28.1.5) implies that

$$c_\beta > 0 \text{ for some } \beta \in \Delta, \text{ and } c_\beta < 0 \text{ for some } \beta \in \Delta, \tag{28.1.6}$$

because of (28.1.3). This corresponds to Exercise 10 on p54 of [14], and (g) on p54 of [24].

Suppose now that γ is also an element of the subgroup Θ_Φ of V generated by Φ, as a commutative group with respect to addition. This implies that

$$\sigma^{-1}(\gamma) = \sum_{\beta \in \Delta} c_\beta \, \beta \tag{28.1.7}$$

is an element of Θ_Φ too, as in (27.14.1), so that $c_\beta \in \mathbf{Z}$ for every $\beta \in \Delta$. Let $\nu_\gamma \in \mathcal{H}'$ be as in (27.14.2), and similarly for $\nu_{\sigma^{-1}(\gamma)}$. Remember that $L_\mu \subseteq L$ is defined for $\mu \in \mathcal{H}'$ as in (27.11.1). It follows that

$$\dim L_{\nu_\gamma} = \dim L_{\nu_{\sigma^{-1}(\gamma)}}, \tag{28.1.8}$$

as in (27.14.8).

As in Section 27.11, $L_\mu = \{0\}$ unless $\mu = 0$, or μ can be expressed as a sum of ν_β's, $\beta \in \Delta$, or μ can be expressed as a sum of $-\nu_\beta$'s, $\beta \in \Delta$. This implies that

$$L_{\nu_{\sigma^{-1}(\gamma)}} = \{0\} \tag{28.1.9}$$

under the conditions described in the previous paragraphs, because of (28.1.6). This means that

$$L_{\nu_\gamma} = \{0\}, \tag{28.1.10}$$

by (28.1.8). More precisely, this holds when $\gamma \in \Theta_\Phi$ satisfies (28.1.1). This corresponds to part of Step (11) on p100 of [14], and of (h) on p54 of [24].

28.2 The dimension of L

Let us continue with the same notation and hypotheses as in the previous sections. If $\alpha \in \Phi$, $\gamma \in \Theta_\Phi$, and

$$\gamma = t \, \alpha \tag{28.2.1}$$

for some $t \in \mathbf{R}$, then

$$t \in \mathbf{Z}. \tag{28.2.2}$$

This is easy to see when α is an element of a base for Φ, because γ can be expressed in a unique way as a linear combination of elements of the base, with coefficients in $\mathbf{Z}$. Remember that Φ is supposed to be reduced as a root system in V, as in Section 27.1. This implies that every element of Φ is an element of a base for Φ, as in Section 19.14.

If (28.2.1) and (28.2.2) hold, then (28.1.10) holds when

$$|t| \geq 2, \tag{28.2.3}$$

as in (27.15.4). Combining this with the remarks in the previous section, we get that (28.1.10) holds for every $\gamma \in \Theta_\Phi$ such that $\gamma \neq 0$ and $\gamma \notin \Phi$.

Remember that $L_\mu = \{0\}$ unless $\mu \in \mathcal{H}'$ satisfies $\mu = 0$, or μ is a sum of ν_β's, $\beta \in \Delta$, or μ is a sum of $-\nu_\beta$'s, $\beta \in \Delta$. In particular, this means that $L_\mu = \{0\}$ unless $\mu = \nu_\gamma$ for some $\gamma \in \Theta_\Phi$. It follows from this and the remarks in the preceding paragraph that $L_\mu = \{0\}$ unless $\mu = 0$, or $\mu = \nu_\alpha$ for some $\alpha \in \Phi$.

Remember that $\mathcal{X}$ corresponds to the direct sum of the subspaces L_μ, where $\mu \in \mathcal{H}'$ can be expressed as a nontrivial sum of ν_β's, $\beta \in \Delta$, as a vector space over k, as in Section 27.11. Similarly, $\mathcal{Y}$ corresponds to the direct sum of the subspaces L_μ, where μ can be expressed as a nontrivial sum of ν_β's, $\beta \in \Delta$, as a vector space over k. Let $\Phi^+ = \Phi^+_\Delta$ be the set of $\alpha \in \Phi$ that can be expressed as a linear combination of $\beta \in \Delta$ with nonnegative coefficients, so that $\Phi = \Phi^+ \cup (-\Phi^+)$. Note that $\nu_{-\alpha} = -\nu_\alpha$ for every $\alpha \in \Phi$, by the definition (27.14.2) of ν_α. Thus $\mathcal{X}$ corresponds to the direct sum of the subspaces L_{ν_α}, $\alpha \in \Phi^+$, as a vector space over k, and $\mathcal{Y}$ corresponds to the direct sum of the subspaces $L_{-\nu_\alpha}$, $\alpha \in \Phi^+$, as a vector space over k. These subspaces have dimension equal to 1, as in (27.15.3). This means that $\mathcal{X}$ and $\mathcal{Y}$ are finite-dimensional as vector spaces over k, with dimension equal to the number of elements of Φ^+.

Remember that L corresponds to the direct sum of $\mathcal{X}$, $\mathcal{H}$, and $\mathcal{Y}$ as a vector space over k, as in (27.10.1). We also have that the h_α's, $\alpha \in \Delta$, form a basis for $\mathcal{H}$ as a vector space over k, as in Section 27.10. Thus the dimension of $\mathcal{H}$ as a vector space over k is equal to the number of elements of Δ, which is the same as the dimension of V as a vector space over $\mathbf{R}$. It follows that the dimension of L, as a vector space over k, is equal to the sum of the number of elements of Φ and the number of elements of Δ. This corresponds to Step (12) on p100 of [14], and to (i) on p54 of [24].

28.3 Automorphisms and the Weyl group

We continue with the same notation and hypotheses as in the previous sections. If $\alpha \in \Phi$, then σ_α is the symmetry on V with vector α that maps Φ onto itself, as usual. Suppose that $\alpha \in \Delta$, and let θ_α be the automorphism of L associated to α as in Section 27.12. Remember that θ_α maps $\mathcal{H}$ onto itself, as in (27.13.7). If $\mu \in \mathcal{H}'$, then let $\zeta_{\mu,\alpha} \in \mathcal{H}'$ be as in (27.13.11), so that $\zeta_{\mu,\alpha}(h) = \mu(\theta_\alpha(h))$ for every $h \in \mathcal{H}$.

Suppose that γ is an element of the subgroup Θ_Φ of V, as a commutative group with respect to addition, generated by Φ. Thus $\nu_\gamma \in \mathcal{H}'$ can be defined as in (27.14.2), so that $\zeta_{\nu_\gamma,\alpha}$ can be defined as before. Remember that $\zeta_{\nu_\gamma,\alpha} = \nu_{\sigma_\alpha(\gamma)}$, as in (27.14.5).

Let $\alpha_1, \ldots, \alpha_r$ be a finite sequence of elements of Δ, possibly with repetitions. Thus

$$\sigma = \sigma_{\alpha_1} \circ \cdots \circ \sigma_{\alpha_r} \tag{28.3.1}$$

is an element of the Weyl group of Φ, and

$$\theta = \theta_{\alpha_r} \circ \cdots \circ \theta_{\alpha_1} \tag{28.3.2}$$

is a Lie algebra automorphism of L. If $\mu \in \mathcal{H}'$, then put

$$\zeta_{\mu,\theta}(h) = \mu(\theta(h)) \tag{28.3.3}$$

for every $h \in \mathcal{H}$, which defines a linear functional on $\mathcal{H}'$. Observe that

$$\zeta_{\nu_\gamma,\theta} = \nu_{\sigma(\gamma)}, \tag{28.3.4}$$

because of the analogous statement for σ_α mentioned in the preceding paragraph.

If $\mu \in \mathcal{H}'$, then let L_μ be as in (27.11.1). Observe that $h \in \mathcal{H}$ and $u \in L$ satisfy

$$[h, u] = \zeta_{\mu,\theta}(h)\, u \tag{28.3.5}$$

if and only if

$$[\theta(h), \theta(u)] = \mu(\theta(h))\, \theta(u). \tag{28.3.6}$$

This means that

$$\theta(L_{\zeta_{\mu,\theta}}) = L_\mu, \tag{28.3.7}$$

which could also be obtained from (27.13.14). It follows that

$$\theta(L_{\nu_{\sigma(\gamma)}}) = L_{\nu_\gamma}, \tag{28.3.8}$$

by (28.3.4).

If $\beta \in \Delta$, then L_{ν_β} is spanned by x_β, as in Section 27.15. Similarly, one can check that $L_{-\nu_\beta}$ is spanned by y_β. This implies that $[L_{\nu_\beta}, L_{-\nu_\beta}]$ is spanned by h_β, because of (27.8.5). Remember that $x_\beta, y_\beta, h_\beta \neq 0$, as in Section 27.10. The linear subspace of L spanned by L_{ν_β}, $L_{-\nu_\beta}$, and $[L_{\nu_\beta}, L_{-\nu_\beta}]$ is a Lie subalgebra of L isomorphic to $sl_2(k)$, because of (27.8.5), (27.8.6), (27.8.7) and the fact that $n(\beta, \beta) = 2$, as in Section 27.1.

If $\gamma \in \Phi$, then there is an element σ of the Weyl group of Φ such that $\sigma(\gamma)$ is contained in Δ, as in Section 19.14. Remember that σ can be expressed as in (28.3.1), with $\alpha_1, \ldots, \alpha_r \in \Delta$, as in Section 19.14, so that we get a Lie algebra automorphism θ of L as in (28.3.2). This means that (28.3.8) holds, and similarly

$$\theta(L_{-\nu_{\sigma(\gamma)}}) = L_{-\nu_\gamma}. \tag{28.3.9}$$

It follows that

$$\theta([L_{\nu_{\sigma(\gamma)}}, L_{-\nu_{\sigma(\gamma)}}]) = [\theta(L_{\nu_{\sigma(\gamma)}}), \theta(L_{-\nu_{\sigma(\gamma)}})] = [L_{\nu_\gamma}, L_{-\nu_\gamma}]. \tag{28.3.10}$$

In particular,

$$\dim[L_{\nu_\gamma}, L_{-\nu_\gamma}] = 1, \tag{28.3.11}$$

because $[L_{\nu_{\sigma(\gamma)}}, L_{-\nu_{\sigma(\gamma)}}]$ is one-dimensional as a linear subspace of L, as in the preceding paragraph.

We also get that the linear subspace of L spanned by L_{ν_γ}, $L_{-\nu_\gamma}$, and $[L_{\nu_\gamma}, L_{-\nu_\gamma}]$ is a Lie subalgebra of L isomorphic to $sl_2(k)$. More precisely, this subspace is the image under θ of the linear subspace of L spanned by $L_{\nu_{\sigma(\gamma)}}$, $L_{-\nu_{\sigma(\gamma)}}$, and $[L_{\nu_{\sigma(\gamma)}}, L_{-\nu_{\sigma(\gamma)}}]$. The latter subspace of L is a Lie subalgebra isomorphic to $sl_2(k)$, because $\sigma(\gamma) \in \Delta$, as before. This corresponds to (j) on p55 of [24].

28.4 Semisimplicity of L

Let us continue with the same notation and hypotheses as in the previous sections. We would like to show that L is semisimple as a Lie algebra over k. It suffices to show that if C is an ideal in L that is commutative as a Lie algebra, then $C = \{0\}$, as in Section 9.4.

Remember that L corresponds to the direct sum of the linear subspaces L_μ, $\mu \in \mathcal{H}'$, defined in (27.11.1), as a vector space over k. More precisely, L corresponds to the direct sum of $\mathcal{H} = L_0$ and the linear subspaces L_{ν_α}, $\alpha \in \Phi$, as in Section 28.2. If $h \in \mathcal{H}$, then ad_h maps C into itself, because C is an ideal in L. This implies that C corresponds to the direct sum of $C \cap \mathcal{H}$ and the subspaces $C \cap L_{\nu_\alpha}$, $\alpha \in \Phi$, as a vector space over k.

If $\alpha \in \Phi$, then the linear subspace of L spanned by

$$L_{\nu_\alpha},\ L_{-\nu_\alpha},\ \text{and } [L_{\nu_\alpha}, L_{-\nu_\alpha}] \tag{28.4.1}$$

is a Lie subalgebra of L isomorphic to $sl_2(k)$ as a Lie algebra over k, as in the previous section. The intersection of C with this Lie subalgebra is an ideal in this Lie subalgebra, and hence the intersection is trivial, because $sl_2(k)$ is simple. In particular, $C \cap L_{\nu_\alpha} = \{0\}$ for every $\alpha \in \Phi$. It follows that $C \subseteq \mathcal{H}$.

If $\beta \in \Delta$, then $x_\beta \in L_{\nu_\beta}$, as in Section 27.15. Equivalently, $[h, x_\beta] = \nu_\beta(h)\, x_\beta$ for every $h \in \mathcal{H}$. If $h \in C$, then $[h, x_\beta] \in C$, because C is an ideal in L. This implies that $[h, x_\beta] = 0$ for every $h \in C$, by (27.10.3). Thus $\nu_\beta(h) = 0$ for every $h \in C$. Remember that the ν_β's, $\beta \in \Delta$, form a basis for the dual of $\mathcal{H}$, as a vector space over k, as in Section 27.11. This implies that $C = \{0\}$, as desired. This corresponds to Step (13) on p100 of [14], and (k) on p55 of [24].

Of course, $\mathcal{H}$ is commutative as a Lie subalgebra of L, and in particular $\mathcal{H}$ is nilpotent as a Lie algebra. Let us check that $\mathcal{H}$ is self-normalizing in L, which means that $\mathcal{H}$ is a Cartan subalgebra of L. Suppose that $u \in L$ is in the normalizer $N_L(\mathcal{H})$ of $\mathcal{H}$ in L, so that ad_u maps $\mathcal{H}$ into itself. As before, u can be expressed as the sum of an element of $\mathcal{H}$ and elements of L_{ν_α}, $\alpha \in \Phi$. If the component of u in L_{ν_α} is not equal to 0 for some $\alpha \in \Phi$, then the component of $[h_\alpha, u]$ in L_{ν_α} is nonzero, and $[h_\alpha, u]$ is not contained in $\mathcal{H}$. Thus the component of u in L_{ν_α} is equal to 0 for every $\alpha \in \Phi$ when $u \in N_L(\mathcal{H})$. This means that $N_L(\mathcal{H})$ is contained in $\mathcal{H}$, as desired.

Remember that V is the vector space over the real numbers of positive finite dimension in which Φ is a root system. Consider the linear subspace of V, as a vector space over $\mathbf{Q}$, generated by Φ. It is easy to see that the mapping $\gamma \mapsto \nu_\gamma$ defined in Section 27.14 extends to an injective linear mapping from the subspace of V just mentioned into $\mathcal{H}'$, as a vector space over $\mathbf{Q}$.

Remember that $L_\mu \neq \{0\}$ when $\mu \in \mathcal{H}'$ and $\mu \neq \{0\}$ exactly when $\mu = \nu_\alpha$ for some $\alpha \in \Phi$, as in Section 28.2. Thus we get the usual relationship between Φ and the set of $\mu \in \mathcal{H}'$ such that $\mu \neq 0$ and $L_\mu \neq \{0\}$. This corresponds to Step (14) on p100 of [14], and (l) on p55 of [24].

28.5 An isomorphism theorem

Let V_1, V_2 be vector spaces over the real numbers of equal positive finite dimension, and let Φ_1, Φ_2 be reduced root systems in V_1, V_2, respectively. If $i = 1, 2$ and $\alpha, \beta \in \Phi_i$, then let

(28.5.1) $$n_i(\alpha, \beta) \in \mathbf{Z}$$

be as in (27.1.1), as usual. Let Δ_i be a base for Φ_i for $i = 1, 2$, and remember that

(28.5.2) $$-3 \le n_i(\alpha, \beta) \le 0$$

for every $\alpha, \beta \in \Delta_i$ with $\alpha \neq \beta$, as in (27.1.2).

Let k be a field of characteristice 0, and suppose that $(A_i, [\cdot,\cdot]_{A_i})$ is a finite-dimensional Lie algebra over k for $i = 1, 2$ with the following properties. If $i = 1, 2$ and $\alpha \in \Delta_i$, then $x_{i,\alpha}$, $y_{i,\alpha}$, and $h_{i,\alpha}$ are elements of A_i. If $\alpha, \beta \in \Delta_i$, then

(28.5.3) $$[h_{i,\alpha}, h_{i,\beta}]_{A_i} = 0,$$

(28.5.4) $$[x_{i,\alpha}, y_{i,\beta}]_{A_i} = \delta_{\alpha,\beta}\, h_{i,\alpha},$$

(28.5.5) $$[h_{i,\alpha}, x_{i,\beta}]_{A_i} = n_i(\beta,\alpha)\, x_{i,\beta},$$

(28.5.6) $$[h_{i,\alpha}, y_{i,\beta}]_{A_i} = -n_i(\beta,\alpha)\, y_{i,\beta},$$

where $\delta_{\alpha,\beta} \in k$ is equal to 1 when $\alpha = \beta$, and is equal to 0 when $\alpha \neq \beta$, as usual. If $\alpha \neq \beta$, then

(28.5.7) $$(\mathrm{ad}_{A_i, x_{i,\alpha}})^{-n_i(\beta,\alpha)+1}(x_{i,\beta}) = (\mathrm{ad}_{A_i, y_{i,\alpha}})^{-n_i(\beta,\alpha)+1}(y_{i,\beta}) = 0.$$

We also ask that A_i be generated as a Lie algebra over k by

(28.5.8) $$x_{i,\alpha},\ y_{i,\alpha},\ \text{and } h_{i,\alpha},\ \alpha \in \Delta_i,$$

and that the dimension of A_i as a vector space over k be equal to the sum of the number of elements of Φ_i and the number of elements of Δ_i.

Of course, the number of elements of Δ_i is the same as the dimension of V_i. Suppose that ϕ is a one-to-one mapping from Δ_1 onto Δ_2 such that

(28.5.9) $$n_2(\phi(\alpha), \phi(\beta)) = n_1(\alpha, \beta)$$

for every $\alpha, \beta \in \Delta_1$. Thus ϕ has a unique extension to a one-to-one linear mapping from V_1 onto V_2 that maps Φ_1 onto Φ_2, as in Section 20.2. Conversely, if a one-to-one linear mapping from V_1 onto V_2 maps Φ_1 onto Φ_2 and Δ_1 onto Δ_2, then its restriction to Δ_1 satisfies (28.5.9), as before.

Under these conditions, there is a unique Lie algebra isomorphism from A_1 onto A_2 with

(28.5.10) $$x_{1,\alpha} \mapsto x_{2,\phi(\alpha)}, \quad y_{1,\alpha} \mapsto y_{2,\phi(\alpha)}, \quad h_{1,\alpha} \mapsto h_{2,\phi(\alpha)},$$

for every $\alpha \in \Delta_1$. This corresponds to Theorem 8' on p50 of [24], and to part (b) of the theorem on p101 of [14]. This is also related to Theorem 7 on p49 of [24], whose proof is discussed on p55 of [24]. Another approach to isomorphisms like these is discussed in Section 14.2 of [14].

Note that Serre's theorem shows that there are Lie algebras with these properties, as in Sections 27.8 and 28.2. This permits us to reduce to the case where A_1 is as in Serre's theorem. It follows from the proof of Serre's theorem that there is a unique Lie algebra homomorphism from A_1 into A_2 that satisfies (28.5.10). This homomorphism is surjective, because A_2 is generated by (28.5.8) with $i = 2$, as a Lie algebra over k. This homomorphism is injective as well, because A_1 and A_2 have the same dimension, as vector spaces over k.

28.6 Some automorphisms

Let V_1 be a vector space over the real numbers of positive finite dimension, and let Φ_1 be a reduced root system in V_1. Also let $n_1(\alpha, \beta)$ be as before for $\alpha, \beta \in \Phi_1$, and let Δ_1 be a base for Φ_1. Suppose that $(A_1, [\cdot, \cdot]_{A_1})$ is a finite-dimensional Lie algebra over a field k of characteristic 0 with the properties mentioned in the previous section. In particular, A_1 should be generated as a Lie algebra over k by (28.5.8), with $i = 1$.

In this section, we take $V_2 = V_1$, $\Phi_2 = \Phi_1$, and $A_2 = A_1$. Thus $n_2(\cdot, \cdot)$ is the same as $n_1(\cdot, \cdot)$. Let Δ_2 be another base for Φ_1, and suppose that we have generators for $A_1 = A_2$ as in (28.5.8), with $i = 2$, and which satisfy the same conditions as before.

Let ϕ be a one-to-one mapping from Δ_1 onto Δ_2 such that

(28.6.1) $$n_1(\phi(\alpha), \phi(\beta)) = n_1(\alpha, \beta)$$

for every $\alpha, \beta \in \Delta_1$, which is the same as (28.5.9) in this case. As before, ϕ has a unique extension to an automorphism of Φ_1. Conversely, if T is any automorphism of Φ_1, then $\Delta_2 = T(\Delta_1)$ is a base for Φ_1, and the restriction of T to Δ_1 satisfies (28.6.1).

The isomorphism theorem described in the previous section implies that there is a unique Lie algebra automorphism of A_1 that satisfies (28.5.10). This is related to the remarks at the beginning of Section 14.3 on p76 of [14].

Remember that the mapping T from V_1 onto itself defined by

(28.6.2) $$T(v_1) = -v_1$$

defines an automorphism of Φ_1. In particular,

$$n_1(-\alpha, -\beta) = n_1(\alpha, \beta) \tag{28.6.3}$$

for every $\alpha, \beta \in \Phi_1$. If $\alpha \in \Delta_1$, then $-\alpha \in T(\Delta_1)$, and we put

$$x_{2,-\alpha} = -y_{1,\alpha}, \quad y_{2,-\alpha} = -x_{1,\alpha}, \quad h_{2,-\alpha} = -h_{1,\alpha}. \tag{28.6.4}$$

One can check that $x_{2,-\alpha}$, $y_{2,-\alpha}$, and $h_{2,-\alpha}$, $\alpha \in \Delta_1$, satisfy the requirements in the previous section for $A_1 = A_2$, using (28.6.3) and the analogous properties of $x_{1,\alpha}$, $y_{1,\alpha}$, and $h_{1,\alpha}$.

It follows that there is a unique Lie algebra automorphism σ of A_1 with

$$x_{1,\alpha} \mapsto -y_{1,\alpha}, \quad y_{1,\alpha} \mapsto -x_{1,\alpha}, \quad h_{1,\alpha} \mapsto -h_{1,\alpha} \tag{28.6.5}$$

for every $\alpha \in \Delta_1$. Observe that $\sigma \circ \sigma$ is the identity mapping on A_1, because it sends the generators $x_{1,\alpha}$, $y_{1,\alpha}$, and $h_{1,\alpha}$ to themselves for every $\alpha \in \Delta_1$. This corresponds to the corollary to Theorem 7 on p49 of [24], and to the remark after Theorem 8' on p50 of [24]. This also corresponds to the proposition on p77 of [14].

Of course, the identity mapping on V_1 is an automorphism of Φ_1. Let t_α be a nonzero element of k for every $\alpha \in \Delta_1$, and put $\Delta_2 = \Delta_1$ and

$$x_{2,\alpha} = t_\alpha \, x_{1,\alpha}, \quad y_{2,\alpha} = (1/t_\alpha) \, y_{1,\alpha}, \quad h_{2,\alpha} = h_{1,\alpha} \tag{28.6.6}$$

for every $\alpha \in \Delta_1$. It is easy to see that $x_{2,\alpha}$, $y_{2,\alpha}$, and $h_{2,\alpha}$, $\alpha \in \Delta_1$, satisfy the requirements in the previous section for $A_1 = A_2$, using the analogous properties of $x_{1,\alpha}$, $y_{1,\alpha}$, and $h_{1,\alpha}$. This implies that there is a unique Lie algebra automorphism of A_1 with

$$x_{1,\alpha} \mapsto t_\alpha \, x_{1,\alpha}, \quad y_{1,\alpha} \mapsto (1/t_\alpha) \, y_{1,\alpha}, \quad h_{1,\alpha} \mapsto h_{1,\alpha} \tag{28.6.7}$$

for every $\alpha \in \Delta_1$. This corresponds to the *diagonal automorphisms* mentioned on p87 of [14].

Let T be an automorphism of Φ_1 such that

$$T(\Delta_1) = \Delta_1. \tag{28.6.8}$$

Put $\Delta_2 = \Delta_1$, and let ϕ be the restriction of T to Δ_1. Equivalently, one can take ϕ to be any one-to-one mapping from Δ_1 onto itself that satisfies (28.6.1). Of course,

$$x_{2,\alpha} = x_{1,\alpha}, \quad y_{2,\alpha} = y_{1,\alpha}, \quad h_{2,\alpha} = h_{1,\alpha} \tag{28.6.9}$$

automatically satisfy the requirements in the previous section for $A_1 = A_2$, by hypothesis. Thus there is a unique Lie algebra automorphism of A_1 with

$$x_{1,\alpha} \mapsto x_{1,\phi(\alpha)}, \quad y_{1,\alpha} \mapsto y_{1,\phi(\alpha)}, \quad h_{1,\alpha} \mapsto h_{1,\phi(\alpha)} \tag{28.6.10}$$

for every $\alpha \in \Delta_1$. More precisely, the collection of automorphisms of Φ_1 that satisfy (28.6.8) is a group with respect to composition of mappings, and we get an injective homomorphism from this group into the automorphism group of A_1. This corresponds to Exercise 6 on p77 of [14].

28.7 Roots and diagonalizability

Let V be a vector space over the real numbers of positive finite dimension, and let Φ be a reduced root system in V. As usual, if $\alpha \in \Phi$, then we let σ_α be the symmetry on V with vector α that maps Φ onto itself. Thus σ_α can be expressed as $\sigma_\alpha(v) = v - \lambda_\alpha(v)\,\alpha$, where λ_α is a linear functional on V with $\lambda_\alpha(\alpha) = 2$. Remember that $\lambda_\alpha(\beta) \in \mathbf{Z}$ for every $\beta \in \Phi$, by the definition of a root system.

Let Θ be the subgroup of V, as a commutative group with respect to addition, generated by Φ. We would like to consider a Lie algebra $(A, [\cdot,\cdot]_A)$ over a field k with properties like those mentioned in Sections 22.11, 23.3, 23.4, and 23.5. In particular, these conditions will hold in the situation described in Section 22.1, as before.

If $\alpha \in \Phi \cup \{0\}$, then we ask that A_α be a linear subspace of A, and that A correspond to the direct sum of A_α, $\alpha \in \Phi \cup \{0\}$, as a vector space over k. More precisely, if $\alpha \in \Phi$, then we ask that A_α have dimension one. As before, it is convenient to put $A_\alpha = \{0\}$ when $\alpha \in \Theta \setminus (\Phi \cup \{0\})$, and we ask that $[A_\alpha, A_\beta] \subseteq A_{\alpha+\beta}$ for every $\alpha, \beta \in \Theta$.

Let A_0' be the dual space of linear functionals on A_0, as a vector space over k, as usual. Suppose that ϕ is a group homomorphism from Θ into A_0', as a commutative group with respect to addition, such that $\mathrm{ad}_w(x) = \phi_\alpha(w)\,x$ for every $w \in A_0$ and $x \in A_\alpha$, $\alpha \in \Phi \cup \{0\}$, where $\phi_\alpha = \phi(\alpha)$. In particular, this implies that A_0 is a Lie subalgebra of A that is commutative as a Lie algebra.

Let Δ be a base for Φ, and let $\Phi^+ = \Phi^{\Delta,+}$ be the corresponding set of positive roots in Φ. If $\alpha \in \Delta$, $\beta \in \Phi^+$, and $\alpha + \beta \in \Phi$, then we ask that

$$[A_\alpha, A_\beta] = A_{\alpha+\beta}, \quad [A_{-\alpha}, A_{-\beta}] = A_{-\alpha-\beta}. \tag{28.7.1}$$

Suppose that $x_{A,\alpha}$, $y_{A,\alpha}$ are nonzero elements of A_α, $A_{-\alpha}$, respectively, for each $\alpha \in \Delta$, and put

$$h_{A,\alpha} = [x_{A,\alpha}, y_{A,\alpha}]_A, \tag{28.7.2}$$

which is an element of A_0. We ask that $\phi_\beta(h_{A,\alpha}) = \lambda_\alpha(\beta) \cdot 1$ in k for every $\alpha \in \Delta$ and $\beta \in \Phi$, and that the $h_{A,\alpha}$'s, $\alpha \in \Delta$, form a basis for A_0.

Under these conditions, A is generated by $x_{A,\alpha}$, $y_{A,\alpha}$, $h_{A,\alpha}$, $\alpha \in \Delta$, as a Lie algebra over k, as in Section 23.4. These generators satisfy the same relations as in Section 28.5, as discussed in Section 23.5. We also have that the dimension of A as a vector space over k is equal to the sum of the numbers of elements of Φ and Δ.

If k has characteristic 0, then all of the conditions mentioned in Section 28.5 are satisfied. It follows that there is a unique Lie algebra isomorphism from the Lie algebra L obtained from Serre's theorem in Section 27.8 onto A, with

$$x_\alpha \mapsto x_{A,\alpha}, \quad y_\alpha \mapsto y_{A,\alpha}, \quad h_\alpha \mapsto h_{A,\alpha} \tag{28.7.3}$$

for every $\alpha \in \Delta$. This corresponds to Theorem 7 on p49 of [24]. This is also related to Theorems 8 and 8' on p50 of [24], and part (b) of the theorem on p101 of [14]. Note that the remarks in the previous section can be used as well in this case.

28.8 Quotients of $\widetilde{L}$

Let V be a vector space over the real numbers of positive finite dimension again, and let Φ be a reduced root system in V. Also let σ_α, λ_α be as before for every $\alpha \in \Phi$, and put $n(\alpha, \beta) = \lambda_\beta(\alpha)$ for every $\alpha, \beta \in \Phi$, as in (27.1.1). Let Δ be a base for Φ as well, and let k be a field of characteristic 0. Under these conditions, the Lie algebra $\widetilde{L} = \widetilde{L}(k)$ can be defined as in Section 27.1.

Let $(B, [\cdot,\cdot]_B)$ be a Lie algebra over k with the following properties. If $\alpha \in \Delta$, then there are elements $x_{B,\alpha}$, $y_{B,\alpha}$, and $h_{B,\alpha}$ that satisfy the Weyl relations. This means that for every $\alpha, \beta \in \Delta$, we have that

$$[h_{B,\alpha}, b_{B,\beta}]_B = 0, \tag{28.8.1}$$

$$[x_{B,\alpha}, y_{B,\beta}]_B = \delta_{\alpha,\beta}\, h_{B,\alpha}, \tag{28.8.2}$$

$$[h_{B,\alpha}, x_{B,\beta}]_B = n(\beta, \alpha)\, x_{B,\beta}, \tag{28.8.3}$$

$$[h_{B,\alpha}, y_{B,\beta}]_B = -n(\beta, \alpha)\, y_{B,\beta}. \tag{28.8.4}$$

Let us also ask that B be generated by $x_{B,\alpha}$, $y_{B,\alpha}$, $h_{B,\alpha}$, $\alpha \in \Delta$, as a Lie algebra over k. Of course, this can be arranged by replacing B with the subalgebra generated by these elements.

Remember that $\widetilde{L}$ is generated by elements $\widetilde{x}_\alpha$, $\widetilde{y}_\alpha$, and $\widetilde{h}_\alpha$, $\alpha \in \Delta$, that satisfy the Weyl relations. More precisely, $\widetilde{L}$ was defined to be the quotient of a suitable free Lie algebra by the ideal corresponding to the Weyl relations. It follows that there is a unique Lie algebra homomorphism from $\widetilde{L}$ onto B with

$$\widetilde{x}_\alpha \mapsto x_{B,\alpha}, \quad \widetilde{y}_\alpha \mapsto y_{B,\alpha}, \quad \widetilde{h}_\alpha \mapsto h_{B,\alpha} \tag{28.8.5}$$

for every $\alpha \in \Delta$.

Let $\alpha, \beta \in \Delta$ and a nonnegative integer l be given. Observe that

$$\mathrm{ad}_{\widetilde{L},\widetilde{h}_\alpha}((\mathrm{ad}_{\widetilde{L},\widetilde{x}_\alpha})^l(\widetilde{x}_\beta)) = (l \cdot n(\alpha, \alpha) + n(\beta, \alpha))\,(\mathrm{ad}_{\widetilde{L},\widetilde{x}_\alpha})^l(\widetilde{x}_\beta) \tag{28.8.6}$$

and

$$\mathrm{ad}_{\widetilde{L},\widetilde{h}_\alpha}((\mathrm{ad}_{\widetilde{L},\widetilde{y}_\alpha})^l(\widetilde{y}_\beta)) = -(l \cdot n(\alpha, \alpha) + n(\beta, \alpha))\,(\mathrm{ad}_{\widetilde{L},\widetilde{y}_\alpha})^l(\widetilde{y}_\beta), \tag{28.8.7}$$

by (27.4.2) and (27.4.3), respectively. This implies that

$$\begin{aligned} &\mathrm{ad}_{B,h_{B,\alpha}}((\mathrm{ad}_{B,x_{B,\alpha}})^l(x_{B,\beta})) \\ &\quad = (l \cdot n(\alpha, \alpha) + n(\beta, \alpha))\,(\mathrm{ad}_{B,x_{B,\alpha}})^l(x_{B,\beta}) \end{aligned} \tag{28.8.8}$$

and

$$\begin{aligned} &\mathrm{ad}_{B,h_{B,\alpha}}((\mathrm{ad}_{B,y_{B,\alpha}})^l)(y_{B,\beta}) \\ &\quad = -(l \cdot n(\alpha, \alpha) + n(\beta, \alpha))\,(\mathrm{ad}_{B,y_{B,\alpha}})^l(y_{B,\beta}). \end{aligned} \tag{28.8.9}$$

Of course, these identities could also be obtained more directly, using the same type of argument.

Remember that $n(\alpha,\alpha) = \lambda_\alpha(\alpha) = 2$. If, for each $l \geq 0$,

$$(\mathrm{ad}_{B,x_{B,\alpha}})^l(x_{B,\beta}) \neq 0, \tag{28.8.10}$$

then it follows that B has infinite dimension as a vector space over k, because these elements of B are eigenvectors of $\mathrm{ad}_{B,h_{B,\alpha}}$ with distinct eigenvalues. Equivalently, if B has finite dimension as a vector space over k, then

$$(\mathrm{ad}_{B,x_{B,\alpha}})^l(x_{B,\beta}) = 0 \tag{28.8.11}$$

for some $l \geq 0$. Similarly,

$$(\mathrm{ad}_{B,y_{B,\alpha}})^l(y_{B,\beta}) = 0 \tag{28.8.12}$$

for some $l \geq 0$ in this case. This corresponds to the fact that (ii) implies (iii) in the exercise on p55 of [24], which is related to Execise 3 on p101 of [14].

28.9 Additional identities in B

Let us continue with the same notation and hypotheses as in the previous section. Let $\alpha, \beta \in \Delta$ be given again, and suppose that $\alpha \neq \beta$. Remember that

$$\mathrm{ad}_{\widetilde{L},\widetilde{x}_\alpha}((\mathrm{ad}_{\widetilde{L},\widetilde{y}_\alpha})^j(\widetilde{y}_\beta)) = j\,(-n(\beta,\alpha) - j + 1)\,(\mathrm{ad}_{\widetilde{L},\widetilde{y}_\alpha})^{j-1}(\widetilde{y}_\beta) \tag{28.9.1}$$

for every positive integer j, as in (27.7.9). Similarly,

$$\mathrm{ad}_{\widetilde{L},\widetilde{y}_\alpha}((\mathrm{ad}_{\widetilde{L},\widetilde{x}_\alpha})^j(\widetilde{x}_\beta)) = j\,(-n(\beta,\alpha) - j + 1)\,(\mathrm{ad}_{\widetilde{L},\widetilde{x}_\alpha})^{j-1}(\widetilde{x}_\beta) \tag{28.9.2}$$

for every positive integer j. This can be obtained from (28.9.1) using the automorphism $\widetilde{\sigma}$ of $\widetilde{L}$ discussed in Section 27.6, which sends $\widetilde{x}_\gamma$, $\widetilde{y}_\gamma$ to $-\widetilde{y}_\gamma$, $-\widetilde{x}_\gamma$, respectively, for each $\gamma \in \Delta$.

It follows that

$$\begin{aligned} &\mathrm{ad}_{B,x_{B,\alpha}}((\mathrm{ad}_{B,y_{B,\alpha}})^j(y_{B,\beta})) \\ &\quad = j\,(-n(\beta,\alpha) - j + 1)\,(\mathrm{ad}_{B,y_{B,\alpha}})^{j-1}(y_{B,\beta}) \end{aligned} \tag{28.9.3}$$

for every positive integer j, using the Lie algebra homomorphism from $\widetilde{L}$ onto B mentioned in the previous section. Similarly,

$$\begin{aligned} &\mathrm{ad}_{B,y_{B,\alpha}}((\mathrm{ad}_{B,x_{B,\alpha}})^j(x_{B,\beta})) \\ &\quad = j\,(-n(\beta,\alpha) - j + 1)\,(\mathrm{ad}_{B,x_{B,\alpha}})^{j-1}(x_{B,\beta}) \end{aligned} \tag{28.9.4}$$

for every positive integer j.

Remember that $-3 \leq n(\beta,\alpha) \leq 0$, as in (27.1.2). If (28.8.11) holds for some $l \geq 0$, then

$$(\mathrm{ad}_{B,x_{B,\alpha}})^{-n(\beta,\alpha)+1}(x_{B,\beta}) = 0. \tag{28.9.5}$$

More precisely, this is trivial when

$$l \le -n(\beta, \alpha) + 1, \tag{28.9.6}$$

and otherwise one can use (28.9.4). Similarly, if (28.8.12) holds for some $l \ge 0$, then

$$(\mathrm{ad}_{B, y_{B,\alpha}})^{-n(\beta,\alpha)+1}(y_{B,\beta}) = 0, \tag{28.9.7}$$

because of (28.9.3). This corresponds to the fact that (iii) implies (i) in the exercise on p55 of [24]. In particular, (28.9.5) and (28.9.7) hold when B has finite dimension as a vector space over k, by the remarks in the previous section. This corresponds to Exercise 3 on p101 of [14].

Let $L = L(k)$ be the Lie algebra defined as in Serre's theorem, in Section 27.8. Remember that L is a quotient of $\widetilde{L}$, and that the natural quotient mapping sends $\widetilde{x}_\gamma$, $\widetilde{y}_\gamma$, and $\widetilde{h}_\gamma$ to x_γ, y_γ, and h_γ, respectively, for each $\gamma \in \Delta$. If (28.9.5) and (28.9.7) hold for every $\alpha, \beta \in \Delta$ with $\alpha \ne \beta$, then there is a unique Lie algebra homomorphism from L onto B with

$$x_\gamma \mapsto x_{B,\gamma}, \quad y_\gamma \mapsto y_{B,\gamma}, \quad h_\gamma \mapsto h_{B,\gamma} \tag{28.9.8}$$

for every $\gamma \in \Delta$. More precisely, the Lie algebra homomorphism from $\widetilde{L}$ onto B mentioned in the previous section is the same as the composition of the natural quotient mapping from $\widetilde{L}$ onto L with this homomorphism from L onto B. This shows that any finite-dimensional quotient of $\widetilde{L}$ is in fact a quotient of L.

28.10 Eigenspaces in L

Let V be a vector space over the real numbers of positive finite dimension, and let Φ be a reduced root system in V again. If $\alpha, \beta \in \Phi$, then we let $n(\alpha, \beta) \in \mathbf{Z}$ be as in (27.1.1), and we let Δ be a base for Φ. Let k be a field of characteristic 0, and let $L = L(k)$ be the Lie algebra over k defined as in Serre's theorem, in Section 27.8. Remember that L is generated by the elements x_α, y_α, and h_α with $\alpha \in \Delta$.

Let $\mathcal{H}$ be the linear subspace of L spanned by the h_α's, $\alpha \in \Delta$, as in Section 27.10. Also let $\mathcal{H}'$ be the dual of $\mathcal{H}$, as a vector space over k. If $\mu \in \mathcal{H}'$, then let L_μ be the set of $u \in L$ such that

$$[h, u] = \mu(h)\, u \tag{28.10.1}$$

for every $h \in \mathcal{H}$, as in (27.11.1). If $\mu_1, \mu_2 \in \mathcal{H}'$, then it is easy to see that

$$[L_{\mu_1}, L_{\mu_2}] \subseteq L_{\mu_1 + \mu_2}, \tag{28.10.2}$$

using the Jacobi identity. Remember that $\mathcal{H} = L_0$, as in (27.11.4).

Let Θ_Φ be the subgroup of V, as a commutative group with respect to addition, generated by Φ, which is the same as the subgroup generated by Δ.

If $\gamma \in \Theta_\Phi$, then let ν_γ be the linear functional defined on $\mathcal{H}$ as in (27.14.2). If $\gamma \in \Phi$, then

$$\nu_\gamma(h_\beta) = n(\gamma, \beta) \tag{28.10.3}$$

for every $\beta \in \Delta$, because of (27.1.1). Remember that $\gamma \mapsto \nu_\gamma$ is a homomorphism from Θ_Φ into $\mathcal{H}'$, as commutative groups with respect to addition.

If $\gamma \in \Phi$, then L_{ν_γ} has dimension one as a vector space over k, as in Section 27.15. Let $\gamma \in \Phi$ be given, and let σ be an element of the Weyl group of Φ such that $\sigma(\gamma) \in \Delta$, as in Section 19.14. This leads to an automorphism θ of L, as in Section 28.3. By construction, θ maps $L_{\nu_{\sigma(\gamma)}}$, $L_{-\nu_{\sigma(\gamma)}}$ onto L_{ν_γ}, $L_{-\nu_\gamma}$, respectively, and thus $[L_{\nu_{\sigma(\gamma)}}, L_{-\nu_{\sigma(\gamma)}}]$ onto $[L_{\nu_\gamma}, L_{-\nu_\gamma}]$, as before.

Remember that $[L_{\nu_{\sigma(\gamma)}}, L_{-\nu_{\sigma(\gamma)}}]$ is spanned by $h_{\sigma(\gamma)}$, because $\sigma(\gamma) \in \Delta$. Put

$$h_\gamma = \theta(h_{\sigma(\gamma)}), \tag{28.10.4}$$

which is an element of $[L_{\nu_\gamma}, L_{-\nu_\gamma}]$. In fact, $[L_{\nu_\gamma}, L_{-\nu_\gamma}]$ is spanned by h_γ, because $[L_{\nu_{\sigma(\gamma)}}, L_{-\nu_{\sigma(\gamma)}}]$ is spanned by $h_{\sigma(\gamma)}$.

If $\alpha \in \Theta_\Phi$, then

$$\nu_\alpha(h_\gamma) = \nu_\alpha(\theta(h_{\sigma(\gamma)})) = \nu_{\sigma(\alpha)}(h_{\sigma(\gamma)}), \tag{28.10.5}$$

using (28.3.4) in the second step. If $\alpha \in \Phi$, then $\sigma(\alpha) \in \Phi$, then we get that

$$\nu_\alpha(h_\gamma) = n(\sigma(\alpha), \sigma(\gamma)), \tag{28.10.6}$$

by (28.10.3), and because $\sigma(\gamma) \in \Delta$. This implies that

$$\nu_\alpha(h_\gamma) = n(\alpha, \gamma), \tag{28.10.7}$$

because σ is an automorphism of Φ, as in Section 20.2.

In particular,

$$\nu_\gamma(h_\gamma) = 2, \tag{28.10.8}$$

by the definition of $n(\gamma, \gamma)$, as in (27.1.1). It follows that h_γ does not depend on the choice of σ. More precisely, this also uses the fact that $[L_{\nu_\gamma}, L_{-\nu_\gamma}]$ is spanned by h_γ, as before.

If $\gamma_1, \gamma_2 \in \Phi$ and $\gamma_1 + \gamma_2 \in \Phi$, then

$$[L_{\nu_{\gamma_1}}, L_{\nu_{\gamma_2}}] = L_{\nu_{\gamma_1+\gamma_2}}. \tag{28.10.9}$$

Remember that L is semisimple, as in Section 28.4. This permits us to use many of the remarks in Chapter 17, although a number of these properties have already been established. In particular, (28.10.9) was discussed in Section 17.9. Remember that if $\gamma \in \Phi$, then the linear subspace of L spanned by L_{ν_γ}, $L_{-\nu_\gamma}$, and $[L_{\nu_\gamma}, L_{-\nu_\gamma}]$ is a Lie subalgebra of L that is isomorphic to $sl_2(k)$, as in Section 28.3.

Let $\alpha \in \Delta$ be given, and remember that $x_\alpha \in L_{\nu_\alpha}$, $y_\alpha \in L_{-\nu_\alpha}$, by construction. If $\gamma \in \Phi$ and $\alpha + \gamma \in \Phi$, then the restriction of ad_{x_α} to L_{ν_γ} is a one-to-one mapping onto $L_{\nu_{\alpha+\gamma}}$. Similarly, the restriction of ad_{y_α} to $L_{-\nu_\gamma}$ is a one-to-one mapping onto $L_{-\nu_{\alpha+\gamma}}$. This is the same as (28.10.9) with $\gamma_1 = \alpha$, $\gamma_2 = \gamma$ and $\gamma_1 = -\alpha$, $\gamma_2 = -\gamma$, respectively, as in Section 17.9. Note that the fact that the linear subspace of L spanned by x_α, y_α, and h_α is a Lie subalgebra of L isomorphic to $sl_2(k)$ can be verified more directly, as in Section 28.3.

If $u_1, \ldots, u_r \in L$ for some $r \geq 2$, then put

$$[u_1, \ldots, u_r] = [u_1, [u_2, \ldots [u_{r-1}, u_r] \ldots]], \tag{28.10.10}$$

as before. Let $\alpha_1, \ldots, \alpha_r$ be a finite sequence of elements of Δ, possible with repetitions, such that

$$\sum_{j=1}^{l} \alpha_j \in \Phi \tag{28.10.11}$$

for every $l = 1, \ldots, r$. If $r \geq 2$, then we get that

$$[x_{\alpha_1}, \ldots, x_{\alpha_r}] \neq 0 \tag{28.10.12}$$

and

$$[y_{\alpha_1}, \ldots, y_{\alpha_r}] \neq 0, \tag{28.10.13}$$

as in the preceding paragraph.

28.11 Subsets of Δ

Let us continue with the same notation and hypotheses as in the previous section. Let Δ_0 be a nonempty subset of Δ, and let V_0 be the linear subspace of V spanned by Δ_0. Remember that

$$\Phi_0 = \Phi \cap V_0 \tag{28.11.1}$$

is a root system in V_0, as in Section 20.6. If $\alpha, \beta \in \Phi_0$, then the analogue $n_0(\alpha, \beta)$ of (27.1.1) for Φ_0 is the same as $n(\alpha, \beta)$, as in Section 20.15. Note that Δ_0 is a base for Φ_0, as before.

Let $L^0 = L^0(k)$ be the Lie algebra over k defined as in Serre's theorem in Section 27.8, using Φ_0 and Δ_0. More precisely, if $\alpha \in \Delta_0$, then let $x_{0,\alpha}$, $y_{0,\alpha}$, and $h_{0,\alpha}$ be the corresponding generators in L^0, as before. These generators satisfy the same relations in L^0 as their analogues in L, because $n_0(\alpha, \beta) = n(\alpha, \beta)$ for every $\alpha, \beta \in \Delta_0$.

The construction used in Serre's theorem implies that there is a unique Lie algebra homomorphism from L^0 into L with

$$x_{0,\alpha} \mapsto x_\alpha, \quad y_{0,\alpha} \mapsto y_\alpha, \quad h_{0,\alpha} \mapsto h_\alpha, \tag{28.11.2}$$

for every $\alpha \in \Delta_0$. This homomorphism maps L^0 onto the Lie subalgebra of L generated by x_α, y_α, h_α, with $\alpha \in \Delta_0$. We would like to check that this homomorphism is injective. This corresponds to Exercise 8 on p101 of [14].

It suffices to show that the dimension of the Lie subalgebra of L generated by x_α, y_α, h_α, $\alpha \in \Delta_0$, is at least the dimension of L^0. To do this, it is enough to verify that if $\gamma \in \Phi_0$, then L_{ν_γ} is contained in this subalgebra of L. This is clear when $\gamma \in \Delta_0$ or $-\gamma \in \Delta_0$.

Let $\gamma \in \Phi_0$ be a positive root with respect to Δ_0, so that γ can be expressed as a linear combination of elements of Δ_0 with nonnegative coefficients. Remember that γ can be expressed as $\sum_{j=1}^r \alpha_j$, where $\alpha_j \in \Delta_0$ for every $j = 1, \ldots, r$, and

$$\sum_{j=1}^{l} \alpha_j \in \Phi_0 \tag{28.11.3}$$

for every $l = 1, \ldots, r$, as in Section 19.12. Suppose that $\gamma \notin \Delta_0$, so that $r \geq 2$.

Observe that

$$[x_{\alpha_1}, \ldots, x_{\alpha_r}] \tag{28.11.4}$$

and

$$[y_{\alpha_1}, \ldots, y_{\alpha_r}] \tag{28.11.5}$$

are elements of this subalgebra of L. These are also elements of L_{ν_γ} and $L_{-\nu_\gamma}$, respectively.

Remember that (28.11.4) and (28.11.5) are nonzero under these conditions, as in the previous section. It follows that L_{ν_γ} and $L_{-\nu_\gamma}$ are spanned by (28.11.4) and (28.11.5), respectively, because L_{ν_γ} and $L_{-\nu_\gamma}$ are one-dimensional linear subspaces of L, as in Section 27.15. This implies that L_{ν_γ} and $L_{-\nu_\gamma}$ are contained in this subalgebra of L, as desired.

Chapter 29

Chevalley's normalization

29.1 Linearly independent roots

Let V be a vector space over the real numbers of positive finite dimension, and let Φ be a reduced root system in V. As usual, if $\alpha \in \Phi$, then we let σ_α be the symmetry on V with vector α that maps Φ onto itself. Let $(\cdot, \cdot)$ be an inner product on V that is invariant under the Weyl group of Φ, so that σ_α is the reflection on V with respect to $(\cdot, \cdot)$ associated to α for every $\alpha \in \Phi$. If $\alpha, \beta \in \Phi$, then

(29.1.1) $$n(\beta, \alpha) = 2\,(\beta, \alpha)\,(\alpha, \alpha)^{-1} \in \mathbf{Z},$$

as before.

Suppose that $\alpha, \beta \in \Phi$ are linearly independent in V, which is to say that they are not proportional in V. Let r, q be the largest nonnegative integers such that

(29.1.2) $$\beta - r\,\alpha,\ \beta + q\,\alpha \in \Phi,$$

as in Section 20.5. Remember that

(29.1.3) $$2\,(\beta, \alpha)\,(\alpha, \alpha)^{-1} = r - q,$$

as in (20.5.10). This corresponds to part (a) of the proposition on p145 of [14], and was also mentioned on p45 of [14].

Let V_1 be the linear subspace of V spanned by α and β, and let Φ_1 be the set of elements of Φ that can be expressed as a linear combination of α and β with integer coefficients. Note that if the sum of two elements of Φ_1 is an element of Φ, then the sum is also an element of Φ_1. It follows that Φ_1 is a root system in V_1, as in Section 20.6. More precisely, Φ_1 is reduced, because Φ is reduced, by hypothesis. This corresponds to Exercise 7 on p46 of [14], as before.

Under these conditions, there are at most two possible values for the norms of elements of Φ_1 with respect to $(\cdot, \cdot)$, as in part (b) of the proposition on p145 of [14], and its proof. More precisely, this follows from the remarks in Section 20.7 when Φ_1 is irreducible in V_1. Otherwise, if Φ_1 is reducible, then it consists of only $\pm\alpha$, $\pm\beta$, because Φ_1 is reduced. In this case, it is clear that there are at most two possible values for the norms of elements of Φ_1.

If $\alpha + \beta \in \Phi$, then part (c) of the proposition on p145 of [14] states that

$$r + 1 = q\,(\alpha + \beta, \alpha + \beta)\,(\beta, \beta)^{-1}. \tag{29.1.4}$$

To see this, we first use (29.1.3) to get that

$$\begin{aligned} & r + 1 - q\,(\alpha + \beta, \alpha + \beta)\,(\beta, \beta)^{-1} \\ = {} & q + 2\,(\beta, \alpha)\,(\alpha, \alpha)^{-1} + 1 - q\,(\alpha + \beta, \alpha + \beta)\,(\beta, \beta)^{-1} \\ = {} & 2\,(\beta, \alpha)\,(\alpha, \alpha)^{-1} + 1 - q\,(\alpha, \alpha)\,(\beta, \beta)^{-1} - 2\,q\,(\alpha, \beta)\,(\beta, \beta)^{-1}. \end{aligned} \tag{29.1.5}$$

If we put

$$A = 2\,(\beta, \alpha)\,(\alpha, \alpha)^{-1} + 1, \tag{29.1.6}$$

$$B = 1 - q\,(\alpha, \alpha)\,(\beta, \beta)^{-1}, \tag{29.1.7}$$

then the right side of (29.1.5) is the same as $A\,B$. Thus it suffices to show that $A = 0$ or $B = 0$.

Remember that

$$n(\beta, \alpha)\,n(\alpha, \beta) = 0, 1, 2, \text{ or } 3, \tag{29.1.8}$$

because α and β are not proportional in V, as in Section 19.9. Suppose for the moment that

$$(\alpha, \alpha) \geq (\beta, \beta), \tag{29.1.9}$$

so that

$$|n(\beta, \alpha)| \leq |n(\alpha, \beta)|. \tag{29.1.10}$$

This implies that

$$|n(\beta, \alpha)| = 0 \text{ or } 1, \tag{29.1.11}$$

by (29.1.8). If $n(\beta, \alpha) = -1$, then $A = 0$, as desired.

Otherwise, if $n(\beta, \alpha) = 0$ or 1, then $(\beta, \alpha) \geq 0$. This implies that

$$(\beta + \alpha, \beta + \alpha) > (\alpha, \alpha),\ (\beta, \beta). \tag{29.1.12}$$

Note that $\alpha + \beta \in \Phi_1$, because $\alpha + \beta \in \Phi$, by hypothesis. It follows that

$$(\alpha, \alpha) = (\beta, \beta) \tag{29.1.13}$$

in this case, because there are at most two possible values for the norms of elements of Φ_1, as before.

Similarly,

$$(\beta + 2\,\alpha, \beta + 2\,\alpha) > (\beta + \alpha, \beta + \alpha), \tag{29.1.14}$$

because $(\beta, \alpha) \geq 0$. This implies that $\beta + 2\,\alpha \not\in \Phi_1$, because there are at most two possible values of the norms of elements of Φ_1. This means that $\beta + 2\,\alpha \not\in \Phi$. Remember that $\beta + j\,\alpha \in \Phi$ when $j \in \mathbf{Z}$ and $-r < j < q$, as in Section 20.5. It follows that $q \leq 1$, by the definition q. Thus $q = 1$, because $\alpha + \beta \in \Phi$. This implies that $B = 0$, because of (29.1.13).

Suppose now that

(29.1.15) $$(\alpha, \alpha) < (\beta, \beta).$$

Observe that

(29.1.16) $$(\alpha + \beta, \alpha + \beta) = (\alpha, \alpha) \text{ or } (\beta, \beta),$$

because $\alpha + \beta \in \Phi_1$, and there are at most two possible values for the norms of elements of Φ_1. This implies that $(\alpha, \beta) < 0$, so that

(29.1.17) $$n(\alpha, \beta) < 0.$$

We also get that

(29.1.18) $$(\beta - \alpha, \beta - \alpha) > (\beta, \beta).$$

It follows that $\beta - \alpha \not\in \Phi$, because otherwise $\beta - \alpha$ would be an element of Φ_1, and have the same norm as α or β.

This shows that $r = 0$, because $\beta + j\,\alpha \in \Phi$ when $j \in \mathbf{Z}$ and $-r < j < q$, as before. Using (29.1.15) and the fact that $(\alpha, \beta) \neq 0$, we obtain that

(29.1.19) $$|n(\alpha, \beta)| < |n(\beta, \alpha)|.$$

Combining this with (29.1.8), we get that $n(\alpha, \beta) = -1, 0$, or 1. This means that

(29.1.20) $$n(\alpha, \beta) = -1,$$

because of (29.1.17).

Because $r = 0$, (29.1.3) reduces to saying that $q = -n(\beta, \alpha)$. Equivalently,

(29.1.21) $$q = \frac{n(\beta, \alpha)}{n(\alpha, \beta)},$$

by (29.1.20). This implies that

(29.1.22) $$q = \frac{(\beta, \beta)}{(\alpha, \alpha),}$$

by the definition of $n(\cdot, \cdot)$. It follows that $B = 0$ in this case as well.

29.2 An identity for root strings

Let V be a vector space over the real numbers of positive finite dimension, and let Φ be a root system in V. Also let $(\cdot, \cdot)$ be an inner product on V that is invariant under the Weyl group of Φ, and suppose that $\alpha, \beta \in \Phi$ are not proportional in V. As before, we take r, q to be the largest nonnegative integers such that $\beta - r\,\alpha, \beta + q\,\alpha \in \Phi$. Similarly, let r', q' be the largest nonnegative integers such that

(29.2.1) $$\alpha - r'\,\beta,\ \alpha + q'\,\beta \in \Phi.$$

Thus

(29.2.2) $$2\,(\alpha,\beta)\,(\beta,\beta)^{-1} = r' - q',$$

as in (29.1.3) and Section 20.5. We would like to check that

(29.2.3) $$q\,(r+1)\,(\beta,\beta)^{-1} = q'\,(r'+1)\,(\alpha,\alpha)^{-1},$$

as in Exercise 10 on p47 of [14]. This is mentioned in Exercise 3 on p150 of [14] as well.

Remember that $\beta + j\,\alpha \in \Phi$ for every integer j with $-r \le j \le q$, as in Section 20.5. Similarly, if $l \in \mathbf{Z}$ and $-r' \le l \le q'$, then $\alpha + l\,\beta \in \Phi$.

It follows that $q = 0$ if and only if $\alpha + \beta \notin \Phi$. Of course, $q' = 0$ if and only if $\alpha+\beta \notin \Phi$ too, for the same reason. Thus $q = 0$ if and only if $q' = 0$, in which case (29.2.3) holds trivially.

Similarly, $r = 0$ if and only if $\beta - \alpha \notin \Phi$. The same argument shows that $r' = 0$ if and only if $\alpha - \beta \notin \Phi$. Of course, $\alpha - \beta \in \Phi$ if and only if $\beta - \alpha \in \Phi$. This means that $r = 0$ if and only if $r' = 0$. In this case, (29.2.3) follows from (29.1.3) and (29.2.2).

Thus we may suppose from now on that $q, q', r, r' \ge 1$. Remember that

(29.2.4) $$q + r,\ q' + r' \le 3,$$

as in Section 20.5.

Observe that $q = r$ if and only if $(\alpha,\beta) = 0$, by (29.1.3). Similarly, $q' = r'$ if and only if $(\alpha,\beta) = 0$. Under these conditions, we get that $q = r = q' = r' = 1$, because of (29.2.4). Thus it suffices to verify that $(\alpha,\alpha) = (\beta,\beta)$, to get (29.2.3).

Remember that $\alpha + \beta \in \Phi$, because $q, q' \ge 1$. We also have that

(29.2.5) $$(\alpha, \alpha+\beta) = (\alpha,\alpha), \quad (\beta, \alpha+\beta) = (\beta,\beta)$$

and

(29.2.6) $$(\alpha+\beta, \alpha+\beta) = (\alpha,\alpha) + (\beta,\beta),$$

because $(\alpha,\beta) = 0$. In particular,

(29.2.7) $$\max((\alpha,\alpha),(\beta,\beta)) < (\alpha+\beta,\alpha+\beta) \le 2\,\max((\alpha,\alpha),(\beta,\beta)).$$

Note that $\alpha + \beta$ is not proportional to either α or β in V.

Using the remarks in Section 19.9, we obtain that $(\alpha+\beta,\alpha+\beta)$ is either 1, 2, or 3 times (α,α), and similarly for (β,β). In fact, $(\alpha+\beta,\alpha+\beta)$ has to be 2 times (α,α) or (β,β), because of (29.2.7). In either case, we get that $(\alpha,\alpha) = (\beta,\beta)$, as desired.

Suppose now that $(\alpha,\beta) \ne 0$, so that $q \ne r$ and $q' \ne r'$. It follows that

(29.2.8) $$|q - r| = |q' - r'| = 1,$$

because of (29.2.4). This implies that $(\alpha,\alpha) = (\beta,\beta)$, because of (29.1.3) and (29.2.2). Using this and (29.1.3), (29.2.2) again, we get that

(29.2.9) $$r - q = r' - q'.$$

One can use this and (29.2.4) to verify that $q = q'$ and $r = r'$. More precisely, either $q = q'$ is equal to 1 and $r = r'$ is equal to 2, or the other way around. This implies (29.2.3), because $(\alpha,\alpha) = (\beta,\beta)$.

29.3 Related properties of λ_α's

Let V be a vector space over the real numbers of positive finite dimension again, and let Φ be a root system in V. If $\alpha \in \Phi$, then the symmetry σ_α on V with vector α that maps Φ onto itself can be expressed as $\sigma_\alpha(v) = v - \lambda_\alpha(v)\,\alpha$, where λ_α is a linear functional on V such that $\lambda_\alpha(\alpha) = 2$, as usual. Let $(\cdot,\cdot)$ be an inner product on V that is invariant under the Weyl group of Φ, so that σ_α is the reflection on V with respect to $(\cdot,\cdot)$ associated to α for every $\alpha \in \Phi$. This means that $\lambda_\alpha(v) = 2\,(v,\alpha)\,(\alpha,\alpha)^{-1}$ for every $\alpha \in \Phi$ and $v \in V$, as before.

Suppose that $\alpha, \beta \in \Phi$ are not proportional in V, and let $r, q, r', q' \geq 0$ be as in the previous section. If we multiply both sides of (29.2.3) by $2\,(\alpha,\beta)$, then we get that

$$q\,(r+1)\,\lambda_\beta(\alpha) = q'\,(r'+1)\,\lambda_\alpha(\beta). \tag{29.3.1}$$

If $(\alpha,\beta) = 0$, then $\lambda_\alpha(\beta) = \lambda_\beta(\alpha) = 0$, $q = q'$, and $r = r'$, as in the previous section.

Suppose now that Φ is a reduced root system, and that $\alpha + \beta \in \Phi$ too. If $v \in V$, then

$$\begin{aligned} \lambda_{\alpha+\beta}(v) &= 2\,(\alpha+\beta,\alpha+\beta)^{-1}\,(v,\alpha+\beta) \\ &= (\alpha+\beta,\alpha+\beta)^{-1}\,(\alpha,\alpha)\,\lambda_\alpha(v) + (\alpha+\beta,\alpha+\beta)^{-1}\,(\beta,\beta)\,\lambda_\beta(v). \end{aligned} \tag{29.3.2}$$

It follows that

$$\lambda_{\alpha+\beta}(v) = q'\,(r'+1)^{-1}\,\lambda_\alpha(v) + q\,(r+1)^{-1}\,\lambda_\beta(v) \tag{29.3.3}$$

for every $v \in V$, using (29.1.4) and its analogue for q', r'. Note that λ_α and λ_β are not proportional as linear functionals on V, because α and β are not proportional in V. Thus the coefficients of λ_α and λ_β on the right side of (29.3.3) are uniquely determined by this condition.

29.4 Associated Lie algebras

Let V be a vector space over the real numbers of positive finite dimension again, and let Φ be a reduced root system in V. If $\alpha \in \Phi$, then the symmetry σ_α on V with vector α that maps Φ onto itself can be expressed as $\sigma_\alpha(v) = v - \lambda_\alpha(v)\,\alpha$, where λ_α is a linear functional on V with $\lambda_\alpha(\alpha) = 2$. If $\alpha, \beta \in \Phi$, then

$$n(\beta,\alpha) = \lambda_\alpha(\beta) \in \mathbf{Z}, \tag{29.4.1}$$

by the definition of a root system. Of course, this is the same as (29.1.1), where $(\cdot,\cdot)$ is an inner product on V that is invariant under the Weyl group. Let Θ be the subgroup of V, as a commutative group with respect to addition, that is generated by Φ.

Let k be a field of characteristic 0. We would like to consider a Lie algebra $(A, [\cdot,\cdot]_A)$ over k as in Serre's theorem in Section 27.8, or equivalently as in Section 28.7. Thus, if $\alpha \in \Phi \cup \{0\}$, then we ask that A_α be a linear subspace of A, and that A correspond to the direct sum of A_α, $\alpha \in \Phi \cup \{0\}$, as a vector space over k. Put $A_\alpha = \{0\}$ when $\alpha \in \Theta \setminus (\Phi \cup \{0\})$, so that we may ask that $[A_\alpha, A_\beta] \subseteq A_{\alpha+\beta}$ for every $\alpha, \beta \in \Theta$. We also ask that A_α have dimension one as a vector space over k when $\alpha \in \Phi$.

As usual, A_0' denotes the dual space of linear functionals on A_0, as a vector space over k. We ask that there be a group homomorphism ϕ from Θ into A_0', as a commutative group with respect to addition, such that $\mathrm{ad}_w(x) = \phi_\alpha(w)\,x$ for every $w \in A_0$, $x \in A_\alpha$, and $\alpha \in \Phi \cup \{0\}$, where $\phi_\alpha = \phi(\alpha)$. Of course, this implies that A_0 is a Lie subalgebra of A that is commutative as a Lie algebra.

If $\alpha, \beta \in \Phi$ and $\alpha + \beta \in \Phi$, then we ask that

$$[A_\alpha, A_\beta] = A_{\alpha+\beta}. \tag{29.4.2}$$

We also ask that for each $\alpha \in \Phi$ there be an element h_α of $[A_\alpha, A_{-\alpha}] \subseteq A_0$ such that

$$\phi_\beta(h_\alpha) = \lambda_\alpha(\beta) \tag{29.4.3}$$

for every $\beta \in \Phi$. In particular, this means that $\phi_\alpha(h_\alpha) = 2 \cdot 1 = 1 + 1$ in k, which is not zero, because k has characteristic zero. Of course, $[A_\alpha, A_{-\alpha}]$ has dimension at most one as a vector space over k, because A_α, $A_{-\alpha}$ are one-dimensional. It follows that $[A_\alpha, A_{-\alpha}]$ is the one-dimensional linear subspace of A spanned by h_α, and that h_α is uniquely determined by (29.4.3), with $\beta = \alpha$.

Let Δ be a base for Φ. We ask that h_α, $\alpha \in \Delta$, be a basis for A_0, as a vector space over k. If A is as in Section 22.1, then conditions like these were discussed in Section 22.11. We also have that A is isomorphic to the Lie algebra obtained as in Serre's theorem in Section 27.8, as discussed in Section 28.7. If A is obtained as in Serre's theorem, then conditions like these follow from properties discussed in Sections 27.11, 27.15, 28.2, and 28.10.

If $\beta \in \Phi$, then (29.4.3) defines a k-valued function of $\alpha \in \Delta$, which is the same as (27.3.9) when $\beta \in \Delta$. The collection of these functions with $\beta \in \Delta$ is a basis for the space of k-valued functions on Δ, as a vector space over k, as in Section 27.3. This means that ϕ_β, $\beta \in \Delta$, is a basis for A_0' as a vector space over k. If A is as in Section 22.1, then this can be obtained from the facts that A_0' is spanned by ϕ_β, $\beta \in \Delta$, as a vector space over k, and the dimension of A_0' is the same as the number of elements of Δ, which is the dimension of V. If $h \in A_0$, then it follows that h is uniquely determined by $\phi_\beta(h)$, $\beta \in \Delta$.

Remember that Θ is the same as the subgroup of V, as a commutative group with respect to addition, generated by Δ. The remark in the preceding paragraph implies that ϕ is injective as a mapping from Θ into A_0'. This also uses the hypothesis that k have characteristic 0. If $\alpha \in \Phi \cup \{0\}$, then one can use the previous statement to get that A_α consists of all $x \in A$ such that $\mathrm{ad}_w(x) = \phi_\alpha(w)\,x$ for every $w \in A_0$.

If $\alpha \in \Phi$, then λ_α is an element of the dual V' of V, as a vector space over $\mathbf{R}$. The set Φ' of λ_α, $\alpha \in \Phi$, is a root system in V', as in Section 19.8. The set Δ' of λ_α, $\alpha \in \Delta$, is a base for Φ', as in Section 19.13, and because Φ is reduced, by hypothesis. Thus, if $\gamma \in \Phi$, then λ_γ can be expressed as a linear combination of λ_α, $\alpha \in \Delta$, with coefficients in $\mathbf{Z}$.

If $\gamma \in \Phi$, then it follows that h_γ can be expressed as a linear combination of h_α, $\alpha \in \Delta$, with the same coefficients in $\mathbf{Z}$ as in the preceding paragraph. This uses (29.4.3), and the fact that h_γ is uniquely determined by $\phi_\beta(h_\gamma)$, $\beta \in \Delta$, as before.

29.5 A lemma about brackets

Let us continue with the same notation and hypotheses as in the previous section. Also let $\alpha, \beta \in \Phi$ be given, and suppose that α, β are not proportional in V. Let r, q be the largest nonnegative integers such that $\beta - r\,\alpha$ and $\beta + q\,\alpha$ are elements of Φ, as before. It follows that

$$\beta + j\,\alpha \in \Phi \tag{29.5.1}$$

for every $j \in \mathbf{Z}$ with $-r \leq j \leq q$, as in Section 20.5.

Suppose that $x_\alpha \in A_\alpha$ and $x_{-\alpha} \in A_{-\alpha}$ satisfy

$$[x_\alpha, x_{-\alpha}]_A = h_\alpha. \tag{29.5.2}$$

Of course, this implies that $x_\alpha, x_{-\alpha} \neq 0$, and (29.5.2) can always be arranged by multiplying x_α or $x_{-\alpha}$ by a suitable element of k. If $x_\beta \in A_\beta$, then

$$[x_{-\alpha}, [x_\alpha, x_\beta]_A]_A = q\,(r+1)\,x_\beta. \tag{29.5.3}$$

This corresponds to the lemma on p146 of [14].

Note that $[x_\alpha, x_\beta]_A \in A_{\alpha+\beta}$, so that the left side of (29.5.3) is an element of A_β. If $\alpha + \beta \notin \Phi$, then $A_{\alpha+\beta} = \{0\}$, which means that $[x_\alpha, x_\beta]_A = 0$. We also have that $q = 0$ in this case, so that (29.5.3) holds.

Let E be the linear subspace of A spanned by $A_{\beta+j\,\alpha}$, $j \in \mathbf{Z}$. More precisely, we may as well restrict our attention to $-r \leq j \leq q$, because otherwise $\beta + j\,\alpha$ is not in Φ, and $A_{\beta+j\,\alpha} = \{0\}$. We also have that E corresponds to the direct sum of $A_{\beta+j\,\alpha}$, $-r \leq j \leq q$, because A corresponds to the direct sum of A_γ, $\gamma \in \Phi \cup \{0\}$, as a vector space over k. It follows that

$$\dim E = q + r + 1 \tag{29.5.4}$$

as a vector space over k, because A_γ is one-dimensional for every $\gamma \in \Phi$.

The linear span of x_α, $x_{-\alpha}$, and h_α in A is a Lie subalgebra of A that is isomorphic to $sl_2(k)$. If we consider A as a module over this subalgebra, then E is a submodule of A. This is basically the same as in Section 17.9, with $y_\alpha = x_{-\alpha}$.

The weights of h_α on E are given by

$$\phi_{\beta+j\,\alpha}(h_\alpha) = \phi_\beta(h_\alpha) + j\,\phi_\alpha(h_\alpha) = \phi_\beta(h_\alpha) + 2\,j, \tag{29.5.5}$$

with $-r \leq j \leq q$. One can verify that E is irreducible as a module over $sl_2(k)$, as in Section 17.9.

Under these conditions, E is as in Section 15.3 as a module over $sl_2(k)$, with $m = q + r$, as in Section 17.9. To get (29.5.3), one can consider v_q in Section 15.3, as on p146 of [14].

29.6 Some remarks about automorphisms

Let us continue with the same notation and hypotheses as in Section 29.4. Suppose that σ is a Lie algebra automorphism of A such that

$$\sigma(w) = -w \tag{29.6.1}$$

for every $w \in A_0$. Let $w \in A_0$ and $x \in A$ be given, and observe that

$$[w, \sigma(x)]_A = -[\sigma(w), \sigma(x)]_A = -\sigma([w, x]_A). \tag{29.6.2}$$

Also let $\alpha \in \Phi$ be given, and note that $\phi_{-\alpha}(w) = -\phi_\alpha(w)$. It follows that $[w, x]_A = \phi_\alpha(w)\, x$ if and only if

$$[w, \sigma(x)]_A = \phi_{-\alpha}(w)\, \sigma(x). \tag{29.6.3}$$

This implies that

$$\sigma(A_\alpha) = A_{-\alpha}, \tag{29.6.4}$$

because A_α consists of all $x \in A$ such that $\mathrm{ad}_w(x) = \phi_\alpha(w)\, x$ for every $w \in A_0$, as in Section 29.4, and similarly for $-\alpha$. Of course, (29.6.4) holds for $\alpha = 0$ too, by hypothesis.

Let $x_\alpha \in A_\alpha$ and $y_\alpha \in A_{-\alpha}$ be given, with $x_\alpha, y_\alpha \neq 0$. Observe that there are $\xi_\alpha, \eta_\alpha \in k$ such that

$$\sigma(x_\alpha) = \xi_\alpha\, y_\alpha, \quad \sigma(y_\alpha) = \eta_\alpha\, x_\alpha, \tag{29.6.5}$$

because of (29.6.4) and the analogous statement for $-\alpha$. This also uses the fact that A_α, $A_{-\alpha}$ are one-dimensional linear subspaces of A, and we have that $\xi_\alpha, \eta_\alpha \neq 0$, because σ is injective on A. It follows that

$$\sigma([x_\alpha, y_\alpha]_A) = [\sigma(x_\alpha), \sigma(y_\alpha)]_A = -\xi_\alpha\, \eta_\alpha\, [x_\alpha, y_\alpha]_A. \tag{29.6.6}$$

Remember that $[x_\alpha, y_\alpha]_A \in A_0$, so that

$$\sigma([x_\alpha, y_\alpha]_A) = -[x_\alpha, y_\alpha]_A, \tag{29.6.7}$$

by (29.6.1).

Note that $[x_\alpha, y_\alpha]_A \neq 0$, because $[A_\alpha, A_{-\alpha}]_A$ is one-dimensional as a linear subspace of A. Thus we get that

$$\xi_\alpha\, \eta_\alpha = 1 \tag{29.6.8}$$

in k. This implies that

$$\sigma(\sigma(x_\alpha)) = x_\alpha, \quad \sigma(\sigma(y_\alpha)) = y_\alpha. \tag{29.6.9}$$

It follows that $\sigma \circ \sigma$ is the identity mapping on A, because $\alpha \in \Phi$ is arbitrary, and using (29.6.1) on A_0. Remember that an automorphism on A with these properties was discussed in Section 28.6.

Let $\alpha \in \Phi$ be given again, and let x_α be a nonzero element of A_α. Also let ζ_α be a nonzero element of k, and put

$$z_\alpha = \zeta_\alpha \, x_\alpha, \quad z_{-\alpha} = -\sigma(z_\alpha) = -\zeta_\alpha \, \sigma(x_\alpha). \tag{29.6.10}$$

Thus

$$[z_\alpha, z_{-\alpha}]_A = -\zeta_\alpha^2 \, [x_\alpha, \sigma(x_\alpha)]_A, \tag{29.6.11}$$

and $[x_\alpha, \sigma(x_\alpha)]_A \neq 0$, as before. If k is algebraically closed, then we can choose ζ_α so that

$$[z_\alpha, z_{-\alpha}]_A = h_\alpha. \tag{29.6.12}$$

Note that $-\zeta_\alpha$ would also work, and that only these two elements of k would have this property.

29.7 Diagonal automorphisms

We continue with the same notation and hypotheses as in Section 29.4. Suppose now that τ is a Lie algebra automorphism of A such that

$$\tau(w) = w \tag{29.7.1}$$

for every $w \in A_0$. If $w \in A_0$ and $x \in A$, then

$$[w, \tau(x)]_A = [\tau(w), \tau(x)]_A = \tau([w, x]_A). \tag{29.7.2}$$

If $\alpha \in \Phi$, then it follows that $[w, x]_A = \phi_\alpha(w) \, x$ if and only if

$$[w, \tau(x)]_A = \phi_\alpha(w) \, \tau(x). \tag{29.7.3}$$

This means that

$$\tau(A_\alpha) = A_\alpha \tag{29.7.4}$$

for every $\alpha \in \Phi$, as before.

In this case, τ is said to be a *diagonal automorphism* of A, as on p87 of [14]. If $\alpha \in \Phi$, then there are nonzero elements τ_α, $\tau_{-\alpha}$ such that τ corresponds to multiplication by τ_α, $\tau_{-\alpha}$ on A_α, $A_{-\alpha}$, respectively, because A_α, $A_{-\alpha}$ are one-dimensional linear subspaces of A. It is easy to see that

$$\tau_\alpha \, \tau_{-\alpha} = 1, \tag{29.7.5}$$

because $[A_\alpha, A_{-\alpha}]$ is a nontrivial linear subspace of A_0.

Of course, any Lie algebra automorphism of A is uniquely determined by its values on a set of generators of A as a Lie algebra over k. If A is as in Serre's theorem in Section 27.8, then the diagonal automorphisms of A can be obtained as in Section 28.6.

Let σ be a Lie algebra automorphism of A that satisfies (29.6.1), and thus (29.6.4) for every $\alpha \in \Phi$. If τ is a diagonal automorphism of A, then one can check that

$$\sigma \circ \tau = \tau^{-1} \circ \sigma. \tag{29.7.6}$$

Observe that $\sigma \circ \tau$ is a Lie algebra automorphism of A that sends every $w \in A_0$ to $-w$. If $\widetilde{\sigma}$ is any Lie algebra automorphism of A that sends every $w \in A_0$ to $-w$, then

$$\sigma^{-1} \circ \widetilde{\sigma} \tag{29.7.7}$$

is a diagonal automorphism on A.

Let τ be a diagonal automorphism on A again, and for each $\alpha \in \Phi$, let τ_α be the nonzero element of k such that τ corresponds to multiplication by τ_α on A_α, as before. Similarly, we may as well put $\tau_0 = 1$. If $\alpha, \beta \in \Phi$ and $\alpha + \beta \in \Phi$, then it is easy to see that

$$\tau_{\alpha+\beta} = \tau_\alpha \, \tau_\beta, \tag{29.7.8}$$

because $[A_\alpha, A_\beta] = A_{\alpha+\beta} \neq \{0\}$.

Let Δ be a base for Φ, and let $\beta \in \Phi$ be given. We would like to check that τ_β is uniquely determined by the values of τ_α with $\alpha \in \Delta$. Suppose first that β is a positive root with respect to Δ, so that β can be expressed as a linear combination of elements of Δ with nonnegative coefficients. Remember that β can be expressed $\sum_{j=1}^r \alpha_j$, where $\alpha_j \in \Delta$ for every $j = 1, \ldots, r$, and $\sum_{j=1}^l \alpha_j \in \Phi$ for every $l = 1, \ldots, r$, as in Section 19.12. This implies that

$$\tau_\beta = \tau_{\alpha_1} \cdots \tau_{\alpha_r}, \tag{29.7.9}$$

by (29.7.8). Otherwise, if $-\beta$ is a positive root, then one can reduce to the previous case, using (29.7.5).

Let Θ be the subgroup of V, as a commutative group with respect to addition, generated by Φ, which is the same as the subgroup of V generated by Δ. Every mapping from Δ into $k \setminus \{0\}$ has a unique extension to a group homomorphism from Θ into the multiplicative group of nonzero elements of k. In particular, $\alpha \mapsto \tau_\alpha$, $\alpha \in \Delta$, has a unique extension to a group homomorphism from Θ into $k \setminus \{0\}$. If $\beta \in \Phi$, then τ_β is the same as the value of this extension at β, by the remarks in the preceding paragraph. Conversely, every group homomorphism from Θ into $k \setminus \{0\}$ corresponds to a diagonal automorphism on A in this way.

29.8 Basis vectors in A

Let us continue with the same notation and hypotheses as in Section 29.4. As before, we let Δ be a base for Φ, and ask that h_α, $\alpha \in \Delta$, be a basis for A_0, as a vector space over k. Let z_α be a nonzero element of A_α for each $\alpha \in \Phi$. Note that the collection of z_α's, $\alpha \in \Phi$, together with h_α, $\alpha \in \Delta$, is a basis for A as a vector space over k.

If $\alpha, \beta \in \Phi$ and $\alpha + \beta \in \Phi$, then there is a unique element $c_{\alpha,\beta}$ of k such that

$$[z_\alpha, z_\beta]_A = c_{\alpha,\beta} \, z_{\alpha+\beta}, \tag{29.8.1}$$

because $[z_\alpha, z_\beta]_A$ is an element of $A_{\alpha+\beta}$, which is spanned by $z_{\alpha+\beta}$. Of course, if $\alpha, \beta \in \Phi$ and $\alpha + \beta \notin \Phi \cup \{0\}$, then $[z_\alpha, z_\beta]_A = 0$, because $[z_\alpha, z_\beta] \in A_{\alpha+\beta} = \{0\}$.

Observe that

$$[h_\alpha, z_\beta]_A = \phi_\beta(h_\alpha)\, z_\beta = \lambda_\alpha(\beta)\, z_\beta \tag{29.8.2}$$

for every $\alpha, \beta \in \Phi$, as in Section 29.4. If $\gamma \in \Phi$, then h_γ can be expressed as a linear combination of h_α, $\alpha \in \Delta$, with coefficients in $\mathbf{Z}$ obtained from the dual root system Φ', as in Section 29.4.

As in Section 28.6, there is a Lie algebra automorphism σ on A such that $\sigma(w) = -w$ for every $w \in A_0$, and $\sigma \circ \sigma$ is the identity mapping on A. It follows that $\sigma(A_\alpha) = A_{-\alpha}$ for every $\alpha \in \Phi$, as in Section 29.6. Let Φ^+ be the set of positive roots with respect to Δ, which is to say the set of $\alpha \in \Phi$ that can be expressed as linear combinations of elements of Δ with nonnegative coefficients.

Suppose for the moment that k is algebraically closed. If $\alpha \in \Phi^+$, then there is a nonzero element z_α of A_α such that

$$z_{-\alpha} = -\sigma(z_\alpha) \tag{29.8.3}$$

satisfies

$$[z_\alpha, z_{-\alpha}]_A = h_\alpha, \tag{29.8.4}$$

as in Section 29.6. Note that $z_{-\alpha}$ is a nonzero element of $A_{-\alpha}$. By doing this for every $\alpha \in \Phi^+$, we get a nonzero element z_α of A_α for every $\alpha \in \Phi$. We also have that the analogues of (29.8.3) and (29.8.4) hold with α replaced with $-\alpha$, because $\sigma \circ \sigma$ is the identity mapping on A, and $h_{-\alpha} = -h_\alpha$.

Let z_α be a nonzero element of A_α for each $\alpha \in \Phi$ again, and suppose that (29.8.4) holds for every $\alpha \in \Phi$. Also let $c_{\alpha,\beta} \in k$ be defined for $\alpha, \beta \in \Phi$ with $\alpha + \beta \in \Phi$ as in (29.8.1), as before. Note that $[\cdot,\cdot]_A$ is uniquely determined on A by the $c_{\alpha,\beta}$'s under these conditions.

Suppose that (29.8.3) holds for every $\alpha \in \Phi$. If $\alpha, \beta \in \Phi$ and $\alpha + \beta \in \Phi$, then

$$\begin{aligned}[z_{-\alpha}, z_{-\beta}]_A = [-\sigma(z_\alpha), -\sigma(z_\beta)]_A &= \sigma([z_\alpha, z_\beta]_A) \\ &= c_{\alpha,\beta}\, \sigma(z_{\alpha+\beta}) = -c_{\alpha,\beta}\, z_{-\alpha-\beta}.\end{aligned} \tag{29.8.5}$$

Of course, $-\alpha, -\beta, -\alpha - \beta \in \Phi$ in this case, so that

$$[z_{-\alpha}, z_{-\beta}]_A = c_{-\alpha,-\beta}\, z_{-\alpha-\beta}, \tag{29.8.6}$$

as in (29.8.1). It follows that

$$c_{-\alpha,-\beta} = -c_{\alpha,\beta} \tag{29.8.7}$$

for every $\alpha, \beta \in \Phi$ with $\alpha + \beta \in \Phi$. This corresponds to Theorem 10 on p51 of [24], and to parts (a) and (b) of the proposition on p146 of [14].

Let z_α be a nonzero element of A_α for each $\alpha \in \Phi$ again, and suppose that (29.8.4) holds for every $\alpha \in \Phi$. If $\alpha, \beta \in \Phi$ and $\alpha + \beta \in \Phi$, then let $c_{\alpha,\beta} \in k$ be as in (29.8.1), and suppose that (29.8.7) holds. Under these conditions, the the collection of z_α's, $\alpha \in \Phi$, together with the h_α's, $\alpha \in \Delta$, is said to be a *Chevalley basis* for A, as on p147 of [14].

29.9 Some properties of the $c_{\alpha,\beta}$'s

We continue with the same notation and hypotheses as in Section 29.4. Let z_α be a nonzero element of A_α for every $\alpha \in \Phi$ again, and suppose that (29.8.4) holds for every $\alpha \in \Phi$. If $\alpha, \beta \in \Phi$ and $\alpha + \beta \in \Phi$, then let $c_{\alpha,\beta} \in k$ be as in (29.8.1).

Let $\alpha, \beta \in \Phi$ with $\alpha + \beta \in \Phi$ be given, so that $-\alpha, -\beta, -\alpha - \beta \in \Phi$ too. Observe that

$$(29.9.1) \qquad \begin{aligned} [[z_\alpha, z_\beta]_A, [z_{-\alpha}, z_{-\beta}]_A]_A &= [c_{\alpha,\beta}\, z_{\alpha+\beta}, c_{-\alpha,-\beta}\, z_{-\alpha-\beta}]_A \\ &= c_{\alpha,\beta}\, c_{-\alpha,-\beta}\, h_{\alpha+\beta}. \end{aligned}$$

We can also use the Jacobi identity to get that

$$(29.9.2) \qquad \begin{aligned} &[[z_\alpha, z_\beta]_A, [z_{-\alpha}, z_{-\beta}]_A]_A \\ &\quad = [z_\alpha, [z_\beta, [z_{-\alpha}, z_{-\beta}]_A]_A]_A - [z_\beta, [z_\alpha, [z_{-\alpha}, z_{-\beta}]_A]_A]_A \\ &\quad = -[z_\alpha, [z_\beta, [z_{-\beta}, z_{-\alpha}]_A]_A]_A - [z_\beta, [z_\alpha, [z_{-\alpha}, z_{-\beta}]_A]_A]_A. \end{aligned}$$

Note that α and β are not proportional in V, because $\alpha + \beta \in \Phi$, and Φ is reduced. Let r, q be the largest nonnegative integers such that $\beta - r\,\alpha$ and $\beta + q\,\alpha$ are elements of Φ again. Similarly, let r', q' be the largest nonnegative integers such that $\alpha - r'\,\beta$ and $\alpha + q'\,\beta$ are elements of Φ. Equivalently, r, q are the largest nonnegative integers such that

$$(29.9.3) \qquad (-\beta) - r\,(-\alpha),\ (-\beta) + q\,(-\alpha) \in \Phi,$$

and r', q' are the largest nonnegative integers such that

$$(29.9.4) \qquad (-\alpha) - r'\,(-\beta),\ (-\alpha) + q'\,(-\beta) \in \Phi.$$

Of course,

$$(29.9.5) \qquad q, q' \ge 1,$$

because $\alpha + \beta \in \Phi$.

Note that

$$(29.9.6) \qquad [z_\alpha, [z_{-\alpha}, z_{-\beta}]_A]_A = q\,(r+1)\, z_{-\beta},$$

as in (29.5.3). Similarly,

$$(29.9.7) \qquad [z_\beta, [z_{-\beta}, z_{-\alpha}]_A]_A = q'\,(r'+1)\, z_{-\alpha}.$$

Combining these identites with (29.9.2), we get that

$$(29.9.8) \qquad \begin{aligned} [[z_\alpha, z_\beta]_A, [z_{-\alpha}, z_{-\beta}]_A]_A &= -q'\,(r'+1)\,[z_\alpha, z_{-\alpha}]_A - q\,(r+1)\,[z_\beta, z_{-\beta}]_A \\ &= -q'\,(r'+1)\, h_\alpha - q\,(r+1)\, h_\beta. \end{aligned}$$

It follows that

$$(29.9.9) \qquad c_{\alpha,\beta}\, c_{-\alpha,-\beta}\, h_{\alpha+\beta} = -q'\,(r'+1)\, h_\alpha - q\,(r+1)\, h_\beta,$$

by (29.9.1).

If $\gamma \in \Phi$, then we can evaluate ϕ_γ at both sides of (29.9.9), using (29.4.3), to get that

$$c_{\alpha,\beta}\, c_{-\alpha,-\beta}\, \lambda_{\alpha+\beta}(\gamma) = -q'\,(r'+1)\,\lambda_\alpha(\gamma) - q\,(r+1)\,\lambda_\beta(\gamma). \tag{29.9.10}$$

In particular, we can take $\gamma = \alpha + \beta$, to get that $2\, c_{\alpha,\beta}\, c_{-\alpha,-\beta}$ corresponds to an integer under the natural embedding of $\mathbf{Q}$ into k. This means that

$$c_{\alpha,\beta}\, c_{-\alpha,-\beta}\, \lambda_{\alpha+\beta} = -q'\,(r'+1)\,\lambda_\alpha - q\,(r+1)\,\lambda_\beta \tag{29.9.11}$$

as linear functionals on V, because V is spanned by Φ. Comparing this with (29.3.3), we obtain that

$$c_{\alpha,\beta}\, c_{-\alpha,-\beta} = -(r+1)^2 = -(r'+1)^2. \tag{29.9.12}$$

This also uses (29.9.5), and corresponds to a remark on p148 of [14].

If (29.8.7) holds, then we get that

$$c_{\alpha,\beta}^2 = (r+1)^2 = (r'+1)^2. \tag{29.9.13}$$

This means that

$$c_{\alpha,\beta} = \pm(r+1) = \pm(r'+1), \tag{29.9.14}$$

which is part of a famous theorem of Chevalley, as in part (d) of the theorem on p147 of [14], and Theorem 11 on p51 of [24]. More precisely, some of the previous arguments correspond to the proof of part (c) of the proposition on p146f of [14].

Remember Δ is a base for Φ, and that the z_α's, $\alpha \in \Phi$, together with the h_α's, $\alpha \in \Delta$, form a basis for A as a vector space over k, which is a Chevalley basis, as in the previous section. Observe that the brackets of any two elements of this basis can be expressed as a linear combination of elements of the basis with integer coefficients, because of (29.9.14). This corresponds to the theorem on p147 of [14].

Let $A(\mathbf{Z})$ be the collection of elements of A that can be expressed as linear combinations of the z_α's, $\alpha \in \Phi$, and the h_α's, $\alpha \in \Delta$, with integer coefficients. This is a subgroup of A, as a commutative group with respect to addition, and in fact a Lie subalgebra of A, as a Lie algebra over $\mathbf{Z}$. This is part of Remark (1) on p51 of [24], and is also mentioned on p149 of [14].

Note that $h_\gamma \in A(\mathbf{Z})$ for every $\gamma \in \Phi$, as in Section 29.4. This implies that $A(\mathbf{Z})$ does not depend on the base Δ for Φ, as mentioned on p149 of [14].

29.10 Uniqueness of Chevalley bases

Let us continue with the same notation and hypotheses as in Section 29.4. Let z_α, $\widetilde{z}_\alpha$ be nonzero elements of A_α for every $\alpha \in \Phi$. Thus, for each $\alpha \in \Phi$, there is a nonzero element η_α of k such that

$$\widetilde{z}_\alpha = \eta_\alpha\, z_\alpha. \tag{29.10.1}$$

Suppose that $[z_\alpha, z_{-\alpha}]_A = h_\alpha$ for every $\alpha \in \Phi$, as before. Observe that

$$[\widetilde{z}_\alpha, \widetilde{z}_{-\alpha}]_A = h_\alpha \tag{29.10.2}$$

for every $\alpha \in \Phi$ if and only if

$$\eta_\alpha\, \eta_{-\alpha} = 1 \tag{29.10.3}$$

for every $\alpha \in \Phi$, as on p148 of [14].

If $\alpha, \beta \in \Phi$ and $\alpha + \beta \in \Phi$, then there is a unique $c_{\alpha,\beta} \in k$ such that $[z_\alpha, z_\beta]_A = c_{\alpha,\beta}\, z_{\alpha+\beta}$, as before. Similarly, there is a unique $\widetilde{c}_{\alpha,\beta} \in k$ such that

$$[\widetilde{z}_\alpha, \widetilde{z}_\beta]_A = \widetilde{c}_{\alpha,\beta}\, \widetilde{z}_{\alpha+\beta}. \tag{29.10.4}$$

More precisely, $c_{\alpha,\beta}, \widetilde{c}_{\alpha,\beta} \neq 0$, because of (29.4.2). Using (29.10.1), we get that

$$\widetilde{c}_{\alpha,\beta}\, \eta_{\alpha+\beta} = \eta_\alpha\, \eta_\beta\, c_{\alpha,\beta}. \tag{29.10.5}$$

Suppose that $c_{-\alpha,-\beta} = -c_{\alpha,\beta}$ for every $\alpha, \beta \in \Phi$ with $\alpha + \beta \in \Phi$, as before. Suppose also that (29.10.3) holds for every $\alpha \in \Phi$. Under these conditions, one can check that

$$\widetilde{c}_{-\alpha,-\beta} = -\widetilde{c}_{\alpha,\beta} \tag{29.10.6}$$

for every $\alpha, \beta \in \Phi$ with $\alpha + \beta \in \Phi$ if and only if

$$\eta_{\alpha+\beta} = \pm \eta_\alpha\, \eta_\beta \tag{29.10.7}$$

for every $\alpha, \beta \in \Phi$ with $\alpha + \beta \in \Phi$, as on p148 of [14].

Let Δ be a base for Φ, and remember that Θ is the subgroup of V, as a commutative group with respect to addition, generated by Φ. This is the same as the subgroup of V generated by Δ, and every mapping from Δ into $k \setminus \{0\}$ has a unique extension to a group homomorphism from Θ into the multiplicative group of nonzero elements of k.

Suppose now that η_α is a nonzero element of k for each $\alpha \in \Phi$ that satisfies (29.10.3) for every $\alpha \in \Phi$, and (29.10.7) for every $\alpha, \beta \in \Phi$ with $\alpha + \beta \in \Phi$. Let $\alpha \mapsto \tau_\alpha$ be the unique group homomorphism from Θ into the multiplicative group of nonzero elements of k such that

$$\tau_\alpha = \eta_\alpha \quad \text{for every } \alpha \in \Delta. \tag{29.10.8}$$

If $\alpha \in \Phi$, then let ρ_α be the nonzero element of k determined by

$$\eta_\alpha = \rho_\alpha\, \tau_\alpha. \tag{29.10.9}$$

Observe that

$$\rho_\alpha\, \rho_{-\alpha} = 1 \tag{29.10.10}$$

for every $\alpha \in \Phi$, and that

$$\rho_{\alpha+\beta} = \pm \rho_\alpha\, \rho_\beta \tag{29.10.11}$$

for every $\alpha, \beta \in \Phi$ with $\alpha + \beta \in \Phi$, because of the analogous properties of the η_α's and τ_α's. We would like to verify that

$$\rho_\beta = \pm 1 \tag{29.10.12}$$

for every $\beta \in \Phi$.

Of course, $\rho_\alpha = 1$ for every $\alpha \in \Delta$, by construction. Suppose that $\beta \in \Phi$ is a positive root with respect to Δ, so that β can be expressed as a linear combination of elements of Δ with nonnegative coefficients. In this case, β can be expressed as $\sum_{j=1}^{r} \alpha_j$, where $\alpha_j \in \Delta$ for every $j = 1, \ldots, r$, and $\sum_{j=1}^{l} \alpha_j \in \Phi$ for every $l = 1, \ldots, r$, as in Section 19.12. This permits one to obtain (29.10.12) using (29.10.11). If $-\beta$ is a positive root, then (29.10.12) can be obtained from (29.10.10) and the previous case.

Let the z_α's and $\widetilde{z}_\alpha$'s be as before, so that the z_α's, $\alpha \in \Phi$, together with the h_α's, $\alpha \in \Delta$, is a Chevalley basis for A, and similarly for the $\widetilde{z}_\alpha$'s. The corresponding η_α's can be defined for $\alpha \in \Phi$ as in (29.10.1), and satisfy (29.10.3) and (29.10.7). Thus we can define τ_α and ρ_α as in (29.10.8) and (29.10.9), respectively. Using the τ_α's, we get a diagonal automorphism τ of A, as in Section 29.7. Note that $\tau(h) = h$ for every $h \in A_0$, and $\tau(z_\alpha) = \tau_\alpha\, z_\alpha$ for every $\alpha \in \Phi$, as before.

If $\alpha \in \Phi$, then we get that

$$\widetilde{z}_\alpha = \rho_\alpha\, \tau(z_\alpha). \tag{29.10.13}$$

Let $A(\mathbf{Z})$ be the collection of elements of A that can be expressed as linear combinations of the z_α's, $\alpha \in \Phi$, and h_α's, $\alpha \in \Delta$, with coefficients in $\mathbf{Z}$, as in the previous section. Similarly, let $\widetilde{A}(\mathbf{Z})$ be the collection of elements of A that can be expressed as linear combinations of the $\widetilde{z}_\alpha$'s, $\alpha \in \Phi$, and h_α's, $\alpha \in \Delta$, with coefficients in $\mathbf{Z}$. It is easy to see that

$$\widetilde{A}(\mathbf{Z}) = \tau(A(\mathbf{Z})), \tag{29.10.14}$$

using (29.10.12) and (29.10.13). In particular, the restriction of τ to $A(\mathbf{Z})$ defines an isomorphism from $A(\mathbf{Z})$ onto $\widetilde{A}(\mathbf{Z})$ as Lie algebras over $\mathbf{Z}$, as in Exercise 5 on p150 of [14].

29.11 The complex case

Let us continue with the same notation and hypotheses as in Section 29.4, with $k = \mathbf{C}$. As before, we let Δ be a base for Φ, so that h_α, $\alpha \in \Delta$, forms a basis for A_0, as a vector space over $\mathbf{C}$. If $\alpha \in \Phi$, then we let z_α be a nonzero element of A_α, and ask that z_α, $\alpha \in \Phi$, together with h_α, $\alpha \in \Delta$, be a Chevalley basis for A. Let $\Phi^+ = \Phi^{\Delta,+}$ be the set of positive roots with respect to Δ, which is to say the set of elements of Φ that can be expressed as linear combinations of elements of Δ with nonnegative coefficients.

If $\alpha \in \Phi^+$, then put

$$u_\alpha = z_\alpha - z_{-\alpha}, \quad v_\alpha = i\,(z_\alpha + z_{-\alpha}). \tag{29.11.1}$$

This corresponds to Remark (3) on p52 of [24], and Exercise 7 on p151 of [14]. It is easy to see that

$$\{u_\alpha, v_\alpha : \alpha \in \Phi^+\} \cup \{i\, h_\alpha : \alpha \in \Delta\} \tag{29.11.2}$$

is a basis for A, as a vector space over $\mathbf{C}$. In particular, the elements of (29.11.2) are linearly independent in A, as a vector space over $\mathbf{R}$. Let B be the linear span of (29.11.2) in A, as a vector space over $\mathbf{R}$.

Let $i\,B$ be the set of elements of A that can be expressed as i times an element of B, as usual. Observe that

$$B + (i\,B) = A, \tag{29.11.3}$$

because (29.11.2) is a basis for A as a vector space over $\mathbf{C}$. Similarly,

$$B \cap (i\,B) = \{0\}. \tag{29.11.4}$$

This means that A may be considered as the complexification of B, as a vector space over $\mathbf{R}$.

Let $\alpha \in \Delta$ and $\beta \in \Phi^+$ be given, and observe that

$$\begin{aligned} [i\,h_\alpha, u_\beta]_A &= i\,[h_\alpha, z_\beta]_A - i\,[h_\alpha, z_{-\beta}]_A \\ &= i\,\lambda_\alpha(\beta)\, z_\beta - i\,\lambda_\alpha(-\beta)\, z_{-\beta} = \lambda_\alpha(\beta)\, v_\beta. \end{aligned} \tag{29.11.5}$$

Similarly,

$$\begin{aligned} [i\,h_\alpha, v_\beta]_A &= -[h_\alpha, z_\beta]_A - [h_\alpha, z_{-\beta}]_A \\ &= -\lambda_\alpha(\beta)\, z_\beta - \lambda_\alpha(-\beta)\, z_{-\beta} = -\lambda_\alpha(\beta)\, u_\beta. \end{aligned} \tag{29.11.6}$$

Note that the right sides of (29.11.5) and (29.11.6) are elements of B.

If $\alpha \in \Phi^+$, then

$$[u_\alpha, v_\alpha]_A = 2\,i\,[z_\alpha, z_{-\alpha}]_A = 2\,i\,h_\alpha. \tag{29.11.7}$$

This is an element of B, because h_α can be expressed as a linear combination of h_β, $\beta \in \Delta$, with integer coefficients, as in Section 29.4.

If $\alpha, \beta \in \Phi$ and $\alpha + \beta \in \Phi$, then there is a unique $c_{\alpha,\beta} \in \mathbf{C}$ such that $[z_\alpha, z_\beta]_A = c_{\alpha,\beta}\, z_{\alpha+\beta}$, as before. More precisely, $c_{\alpha,\beta} \in \mathbf{R}$, by (29.9.14).

Let $\alpha, \beta \in \Phi^+$ be given, with $\alpha \neq \beta$. Note that $\alpha + \beta \neq 0$ in this case. If $\alpha + \beta \notin \Phi$, then $-\alpha - \beta \notin \Phi$, and

$$[z_\alpha, z_\beta]_A = [z_{-\alpha}, z_{-\beta}]_A = 0. \tag{29.11.8}$$

Similarly, if $\alpha - \beta \notin \Phi$, then $\beta - \alpha \notin \Phi$, and

$$[z_{-\alpha}, z_\beta]_A = [z_\alpha, z_{-\beta}]_A = 0. \tag{29.11.9}$$

If $\alpha + \beta \in \Phi$, then

$$\begin{aligned} [z_\alpha, z_\beta]_A + [z_{-\alpha}, z_{-\beta}]_A &= c_{\alpha,\beta}\, z_{\alpha+\beta} + c_{-\alpha,-\beta}\, z_{-\alpha-\beta} \\ &= c_{\alpha,\beta} z_{\alpha+\beta} - c_{\alpha,\beta}\, z_{-\alpha-\beta} = c_{\alpha,\beta}\, u_{\alpha+\beta}, \end{aligned} \tag{29.11.10}$$

using (29.8.7) in the second step. Similarly, if $\alpha - \beta \in \Phi$, then

$$(29.11.11)\quad \begin{aligned} [z_{-\alpha}, z_\beta]_A + [z_\alpha, z_{-\beta}]_A &= c_{-\alpha,\beta}\, z_{-\alpha+\beta} + c_{\alpha,-\beta}\, z_{\alpha-\beta} \\ &= c_{\alpha,-\beta}\, (z_{\alpha-\beta} - z_{\beta-\alpha}). \end{aligned}$$

This is the same as $c_{\alpha,-\beta}\, u_{\alpha-\beta}$ when $\alpha - \beta \in \Phi^+$, and $-c_{\alpha,-\beta}\, u_{\beta-\alpha}$ when $\beta - \alpha \in \Phi^+$.

If $\alpha + \beta \in \Phi$, then we also have that

$$(29.11.12)\quad \begin{aligned} i\,[z_\alpha, z_\beta]_A - i\,[z_{-\alpha}, z_{-\beta}]_A &= i\, c_{\alpha,\beta}\, z_{\alpha+\beta} - i\, c_{-\alpha,-\beta}\, z_{-\alpha-\beta} \\ &= i\, c_{\alpha,\beta}\, z_{\alpha+\beta} + i\, c_{\alpha,\beta}\, z_{-\alpha-\beta} = c_{\alpha,\beta}\, v_{\alpha+\beta}. \end{aligned}$$

If $\alpha - \beta \in \Phi$, then

$$(29.11.13)\quad \begin{aligned} i\,[z_{-\alpha}, z_\beta]_A - i\,[z_\alpha, z_{-\beta}]_A &= i\, c_{-\alpha,\beta}\, z_{-\alpha+\beta} \\ -i\, c_{\alpha,-\beta}\, z_{\alpha-\beta} &= -i\, c_{\alpha,-\beta}\, (z_{\alpha-\beta} + z_{\beta-\alpha}). \end{aligned}$$

This is the same as $-c_{\alpha,-\beta}\, v_{\alpha-\beta}$ when $\alpha - \beta \in \Phi^+$, and $-c_{\alpha,-\beta}\, v_{\beta-\alpha}$ when $\beta - \alpha \in \Phi^+$.

Using these remarks, one can check that

$$(29.11.14)\qquad [u_\alpha, u_\beta]_A,\ [u_\alpha, v_\beta]_A,\ [v_\alpha, v_\beta]_A \in A$$

for every $\alpha, \beta \in \Phi^+$. It follows that B is a Lie subalgebra of A, as a Lie algebra over $\mathbf{R}$, as in Remark (3) on p52 of [24], and Exercise 7 on p151 if [14]. Thus A may be considered as the complexification of B as a Lie algebra over $\mathbf{R}$.

29.12 The corresponding Killing forms

Let us continue with the same notation and hypotheses as in the previous section. If $x \in A$, then $\mathrm{ad}_{A,x}$ defines a linear mapping from A into itself, as a vector space over $\mathbf{C}$, as in Section 2.4. Similarly, if $x \in B$, then $\mathrm{ad}_{B,x}$ defines a linear mapping from B into itself, as a vector space over $\mathbf{R}$. Of course, $\mathrm{ad}_{B,x}$ is the same as the restriction of $\mathrm{ad}_{A,x}$ to B in this case.

Remember that the Killing form on A is defined by

$$(29.12.1)\qquad b_A(x,y) = \mathrm{tr}_A(\mathrm{ad}_{A,x} \circ \mathrm{ad}_{A,y})$$

for every $x, y \in A$, where the right side is the trace of $\mathrm{ad}_{A,x} \circ \mathrm{ad}_{A,y}$ as a linear mapping from A into itself, as a complex vector space. Similarly, the Killing form on B is defined by

$$(29.12.2)\qquad b_B(x,y) = \mathrm{tr}_B(\mathrm{ad}_{B,x} \circ \mathrm{ad}_{B,y})$$

for every $x, y \in B$, where the right side is the trace of $\mathrm{ad}_{B,x} \circ \mathrm{ad}_{B,y}$ as a linear mapping from B into itself, as a real vector space. If $x, y \in B$, then

$$(29.12.3)\qquad b_A(x,y) = b_B(x,y),$$

as in Exercise 7 on p151 of [14]. This uses the fact that a basis for B as a real vector space is also a basis for A as a complex vector space, as in the previous section.

If $\alpha, \beta \in \Phi$ and $\alpha + \beta \neq 0$, then

$$b_A(z_\alpha, z_\beta) = 0, \tag{29.12.4}$$

as in Section 17.3. Note that the Lie subalgebra of A that is denoted B in Section 17.3 may be taken to be A_0 here. Similarly, if $\alpha \in \Phi$ and $w \in A_0$, then

$$b_A(z_\alpha, w) = 0, \tag{29.12.5}$$

as before.

If $\alpha, \beta \in \Phi^+$ and $\alpha \neq \beta$, then it is easy to see that

$$b_A(u_\alpha, u_\beta) = b_A(u_\alpha, v_\beta) = b_A(v_\alpha, v_\beta) = 0, \tag{29.12.6}$$

using (29.12.4). This implies that

$$b_B(u_\alpha, u_\beta) = b_B(u_\alpha, v_\beta) = b_B(v_\alpha, v_\beta) = 0, \tag{29.12.7}$$

by (29.12.3). Similarly, if $\alpha \in \Phi^+$ and $\beta \in \Delta$, then

$$b_A(u_\alpha, i\, h_\beta) = b_A(v_\alpha, i\, h_\beta) = 0, \tag{29.12.8}$$

by (29.12.5). This implies that

$$b_B(u_\alpha, i\, h_\beta) = b_B(v_\alpha, i\, h_\beta) = 0, \tag{29.12.9}$$

by (29.12.3).

If $\alpha \in \Phi^+$, then

$$b_A(u_\alpha, v_\alpha) = i\, b_A(z_\alpha - z_{-\alpha}, z_\alpha + z_{-\alpha}), \tag{29.12.10}$$

by the definition (29.11.1) of u_α, v_α. Of course,

$$b_A(z_\alpha, z_\alpha) = b_A(z_{-\alpha}, z_{-\alpha}) = 0, \tag{29.12.11}$$

by (29.12.4). This implies that

$$b_A(u_\alpha, v_\alpha) = 0, \tag{29.12.12}$$

because $b_A(\cdot, \cdot)$ is symmetric on A. It follows that

$$b_B(u_\alpha, v_\alpha) = 0, \tag{29.12.13}$$

by (29.12.3).

Remember that for each $\alpha \in \Phi$ there is a linear functional ϕ_α on A_0 such that $\mathrm{ad}_{A,w}(z_\alpha) = \phi_\alpha(w)$ for every $w \in A_0$. We also have that $\phi_\alpha(h_\beta) = \lambda_\beta(\alpha) \in \mathbf{R}$ for every $\beta \in \Phi$, as in (29.4.3). If $w \in A_0 \cap B$, then w can be expressed as a linear combination of $i\,h_\beta$, $\beta \in \Delta$, with coefficients in $\mathbf{R}$, by construction. This implies that

$$\phi_\alpha(w) \in i\,\mathbf{R} \tag{29.12.14}$$

for every $\alpha \in \Phi$ and $w \in A_0 \cap B$.

If $w, w' \in A_0$, then

$$b_A(w, w') = \sum_{\alpha \in \Phi} \phi_\alpha(w)\,\phi_\alpha(w'). \tag{29.12.15}$$

This follows from the fact that the z_α's, $\alpha \in \Phi$, together with the h_β's, $\beta \in \Delta$, form a basis for A as a vector space over $\mathbf{C}$. If $w, w' \in A_0 \cap B$, then

$$b_B(w, w') = \sum_{\alpha \in \Phi} \phi_\alpha(w)\,\phi_\alpha(w'), \tag{29.12.16}$$

by (29.12.3). In particular,

$$b_B(w, w) = \sum_{\alpha \in \Phi} \phi_\alpha(w)^2 \tag{29.12.17}$$

for every $w \in A_0 \cap B$.

If $w \in A_0 \cap B$, then every term in the sum on the right side of (29.12.17) is less than or equal to 0, by (29.12.14). If each of these terms is equal to 0, then $w = 0$, as in Section 29.4. This implies that $b_B(\cdot, \cdot)$ is negative-definite on $A_0 \cap B$.

Let $\alpha \in \Phi^+$ be given, and observe that

$$b_B([u_\alpha, v_\alpha]_A, i\,h_\alpha) = 2\,b_B(i\,h_\alpha, i\,h_\alpha), \tag{29.12.18}$$

by (29.11.7). Remember that $h_\alpha \neq 0$, as in Section 29.4, and that $i\,h_\alpha \in B$, as in the previous section. Thus

$$b_B([u_\alpha, v_\alpha]_A, i\,h_\alpha) < 0, \tag{29.12.19}$$

as in the preceding paragraph.

Of course,

$$b_B([u_\alpha, v_\alpha]_A, i\,h_\alpha) = -b_B(v_\alpha, [u_\alpha, i\,h_\alpha]_A), \tag{29.12.20}$$

as in Section 7.9. We also have that

$$b_B(v_\alpha, [u_\alpha, i\,h_\alpha]_A) = -\lambda_\alpha(\alpha)\,b_B(v_\alpha, v_\alpha) = -2\,b_B(v_\alpha, v_\alpha), \tag{29.12.21}$$

by (29.11.5). This implies that

$$b_B(v_\alpha, v_\alpha) < 0, \tag{29.12.22}$$

by (29.12.19).

Similarly,

$$b_B([u_\alpha, v_\alpha]_A, i\,h_\alpha) = -b_B([v_\alpha, u_\alpha]_A, i\,h_\alpha) = b_B(u_\alpha, [v_\alpha, i\,h_\alpha]_A), \tag{29.12.23}$$

as in Section 7.9. Note that

$$b_B(u_\alpha, [v_\alpha, i\,h_\alpha]_A) = \lambda_\alpha(\alpha)\,b_B(u_\alpha, u_\alpha) = 2\,b_B(u_\alpha, u_\alpha), \tag{29.12.24}$$

by (29.11.6). This means that

$$b_B(u_\alpha, u_\alpha) < 0, \tag{29.12.25}$$

because of (29.12.19). One can check more directly that $b_B(u_\alpha, u_\alpha) = b_B(v_\alpha, v_\alpha)$ too.

It follows that $b_B(\cdot,\cdot)$ is negative-definite on B, as in Remark (3) on p52 of [24], and Exercise 7 on p151 of [14].

29.13 Using other commutative rings

Let us return to the same notation and hypotheses as in Section 29.4. Thus Δ is a base for Φ, and we let z_α be a nonzero element of A_α for every $\alpha \in \Phi$. Suppose that z_α, $\alpha \in \Phi$, together with h_α, $\alpha \in \Delta$, is a Chevalley basis for A, as in Section 29.8. Let $A(\mathbf{Z})$ be the collection of elements of A that can be expressed as a linear combination of the z_α's, $\alpha \in \Phi$, and h_α's, $\alpha \in \Delta$, with integer coefficients. This is a Lie subalgebra of A, as a Lie algebra over $\mathbf{Z}$, as in Section 29.9.

Let k_1 be a commutative ring with a multiplicative identity element. Let us define $A(k_1)$ initially as a free module over k_1 with basis consisting of z_α, $\alpha \in \Phi$, and h_α, $\alpha \in \Delta$. These basis elements may also be denoted z_{α,k_1}, $\alpha \in \Phi$, and h_{α,k_1}, $\alpha \in \Delta$, to be more precise. One may consider $A(k_1)$ to be the same as the tensor product of $A(\mathbf{Z})$ and k_1, as modules over $\mathbf{Z}$. One can use multiplication on k_1 to define scalar multiplication by elements of k_1 on this tensor product over $\mathbf{Z}$, to get a module over k_1.

If n is a positive integer, then we can consider the sum of n 1's in k_1, where 1 is the multiplicative identity element in k_1. This leads to a natural ring homomorphism from $\mathbf{Z}$ into k_1, as usual. Using this, we get a mapping from $A(\mathbf{Z})$ into $A(k_1)$ that is linear over $\mathbf{Z}$.

It is easy to define the Lie bracket $[\cdot,\cdot]_{A(k_1)}$ initially as a mapping from $A(k_1) \times A(k_1)$ into $A(k_1)$ that is bilinear over k_1. The brackets of basis elements can be defined using the corresponding brackets in $A(\mathbf{Z})$, and the natural mapping from $A(\mathbf{Z})$ into $A(k_1)$ described in the preceding paragraph. This can be extended in a unique way to a mapping from $A(k_1) \times A(k_1)$ into $A(k_1)$ that is bilinear over k.

Clearly $[\cdot,\cdot]_{A(k_1)}$ is antisymmetric on $A(k_1)$, because $[\cdot,\cdot]_A$ is antisymmetric on A. One can check that $[a,a]_{A(k_1)} = 0$ for every $a \in A(k_1)$, using the antisymmetry of $[\cdot,\cdot]_{A(k_1)}$ on $A(k_1)$, and the fact that this property holds when a is a basis element, because of the corresponding property of $[\cdot,\cdot]_A$ on A. Similarly, $[\cdot,\cdot]_{A(k_1)}$ satisfies the Jacobi identity on $A(k_1)$, because $[\cdot,\cdot]_A$ satisfies the Jacobi identity on A. Thus $A(k_1)$ is a Lie algebra over k_1 with respect to $[\cdot,\cdot]_{A(k_1)}$. This may be called a *Chevalley algebra*, as on p149 of [14]. This is also related to Remark (1) on p51 of [24].

Of course, $A(k_1)$ may be considered as a Lie algebra over $\mathbf{Z}$ as well. The natural mapping from $A(\mathbf{Z})$ into $A(k_1)$ mentioned earlier is a homomorphism as a mapping between Lie algebras over $\mathbf{Z}$.

Remember that $A(\mathbf{Z})$ does not depend on the base Δ for Φ, as in Section 29.9. This used the fact that for each $\gamma \in \Phi$, h_γ can be expressed as a linear combination of h_α, $\alpha \in \Delta$, with integer coefficients, as in Section 29.4. Similarly, if $\alpha \in \Delta$, then h_α can be expressed as a linear combination of h_β, with β in any other base for Φ, and with integer coefficients. One can use this to check that $A(k_1)$ does not depend on Δ, up to isomorphism, as a Lie algebra over k_1. Another base for Φ essentially only leads to another basis for $A(k_1)$ as a free module over k_1. If $A(k_1)$ is considered as the tensor product of $A(\mathbf{Z})$ and k_1 over $\mathbf{Z}$, then this clearly does not depend on Δ, because $A(\mathbf{Z})$ does not depend on Δ.

Let $\widetilde{z}_\alpha$ be another nonzero element of A_α for each $\alpha \in \Phi$, and suppose that $\widetilde{z}_\alpha$, $\alpha \in \Phi$, together with h_α, $\alpha \in \Delta$, is another Chevalley basis for A. Under these conditions, there is a diagonal automorphism τ of A such that for every $\alpha \in \Phi$, $\widetilde{z}_\alpha = \rho_\alpha\,\tau(z_\alpha)$ with $\rho_\alpha = \pm 1$, as in Section 29.10. If $\widetilde{A}(\mathbf{Z})$ is the collection of elements of A that can be expressed as linear combinations of the $\widetilde{z}_\alpha$'s, $\alpha \in \Phi$, and h_α's, $\alpha \in \Delta$, then $\widetilde{A}(\mathbf{Z}) = \tau(A(\mathbf{Z}))$, as before. Let $\widetilde{A}(k_1)$ be the Lie algebra over k_1 defined using the $\widetilde{z}_\alpha$'s in the same way as before. One can check that τ leads to an isomorphism from $A(k_1)$ onto $\widetilde{A}(k_1)$, as Lie algebras over k_1. If $A(k_1)$, $\widetilde{A}(k_1)$ are considered as tensor products of $A(\mathbf{Z})$, $\widetilde{A}(\mathbf{Z})$, respectively, and k_1 over $\mathbf{Z}$, then this follows from the fact that the restriction of τ to $A(\mathbf{Z})$ defines an isomorphism from $A(\mathbf{Z})$ onto $\widetilde{A}(\mathbf{Z})$, as Lie algebras over $\mathbf{Z}$. This corresponds to a remark on p149 of [14].

29.14 Some mappings on $A(\mathbf{Z})$

Let us continue with the same notation and hypotheses as in Section 29.4 again. Remember that Δ is a base for Φ, and let z_α be a nonzero element of A_α for every $\alpha \in \Phi$. Suppose that z_α, $\alpha \in \Phi$, together with h_α, $\alpha \in \Delta$, is a Chevalley basis for A, as in Section 29.8, and let $A(\mathbf{Z})$ be the collection of elements of A that can be expressed as a linear combination of the z_α's, $\alpha \in \Phi$, and h_α's, $\alpha \in \Delta$, with integer coefficients. This is a Lie subalgebra of A, as a Lie algebra over $\mathbf{Z}$, as in Section 29.9.

Let $\alpha \in \Phi$ and a positive integer m be given. We would like to check that $(1/m!)\,(\mathrm{ad}_{z_\alpha})^m$ maps $A(\mathbf{Z})$ into itself, as in the proposition on p149 of [14]. It suffices to show that

$$(1/m!)\,(\mathrm{ad}_{z_\alpha})^m(h_\beta) \in A(\mathbf{Z}) \tag{29.14.1}$$

for every $\beta \in \Delta$, and that

$$(1/m!)\,(\mathrm{ad}_{z_\alpha})^m(z_\beta) \in A(\mathbf{Z}) \tag{29.14.2}$$

for every $\beta \in \Phi$.

If $\beta \in \Delta$, then

$$\mathrm{ad}_{z_\alpha}(h_\beta) = [z_\alpha, h_\beta]_A = -\lambda_\beta(\alpha)\, z_\alpha, \tag{29.14.3}$$

which is an element of $A(\mathbf{Z})$. It follows that $(\mathrm{ad}_{z_\alpha})^m(h_\beta) = 0$ when $m \geq 2$, so that (29.14.1) holds for every $m \geq 1$.

Note that $(\mathrm{ad}_{z_\alpha})^m(z_\alpha) = 0$ for every $m \geq 1$, so that (29.14.2) holds trivially when $\alpha = \beta$. Remember that $\mathrm{ad}_{z_\alpha}(z_{-\alpha}) = [z_\alpha, z_{-\alpha}]_A = h_\alpha$, as in Section 29.8. This implies that (29.14.2) holds when $m = 1$ and $\beta = -\alpha$, because $h_\alpha \in A(\mathbf{Z})$, as in Section 29.9. It follows that

$$(1/2!)\,(\mathrm{ad}_{z_\alpha})^2(z_{-\alpha}) = (1/2)\,[z_\alpha, h_\alpha]_A = -(\lambda_\alpha(\alpha)/2)\, z_\alpha = -z_\alpha, \tag{29.14.4}$$

so that (29.14.2) holds when $m = 2$ and $\beta = -\alpha$. If $m \geq 3$, then we get that $(\mathrm{ad}_{z_\alpha})^m(z_{-\alpha}) = 0$, so that (29.14.2) holds when $\beta = -\alpha$.

Suppose now that $\beta \in \Phi$, $\beta \neq \pm\alpha$. Thus α, β are linearly independent in V, because Φ is reduced, by hypothesis. If $\gamma \in \Phi$ is not proportional to α, then let $r(\gamma)$, $q(\gamma)$ be the largest nonnegative integers such that

$$\gamma - r(\gamma)\,\alpha,\ \gamma + q(\gamma)\,\alpha \in \Phi, \tag{29.14.5}$$

as in Section 20.5. Remember that $\gamma + j\,\alpha \in \Phi$ when j is an integer that satisfies $-r(\gamma) \leq j \leq q(\gamma)$, as before. If $\alpha + \gamma \in \Phi$, then

$$[z_\alpha, z_\gamma]_A = c_{\alpha,\gamma}\, z_{\alpha+\gamma} = \pm(r(\gamma) + 1)\, z_{\alpha+\gamma}, \tag{29.14.6}$$

as in Sections 29.8 and 29.9.

Let j be a nonnegative integer less than or equal to $q(\beta)$, and observe that

$$r(\beta + j\,\alpha) = r(\beta) + j. \tag{29.14.7}$$

If $0 \leq j < q(\beta)$, then $\beta + j\,\alpha$ and $\beta + (j+1)\,\alpha$ are elements of Φ, and

$$\begin{aligned}[z_\alpha, z_{\beta+j\,\alpha}]_A &= \pm(r(\beta + j\,\alpha) + 1)\, z_{\beta+(j+1)\,\alpha} \\ &= \pm(r(\beta) + j + 1)\, z_{\beta+(j+1)\,\alpha}.\end{aligned} \tag{29.14.8}$$

If m is a positive integer less than or equal to $q(\beta)$, then we get that

$$(\mathrm{ad}_{z_\alpha})^m(z_\beta) = \pm\Big(\prod_{j=0}^{m-1}(r(\beta) + j + 1)\Big)\, z_{\beta+m\,\alpha}. \tag{29.14.9}$$

This means that

$$(1/m!)\,(\mathrm{ad}_{z_\alpha})^m(z_\beta) = \pm\binom{r(\beta) + m}{m}\, z_{\beta+m\,\alpha}, \tag{29.14.10}$$

where $\binom{r(\beta)+m}{m}$ is the usual binomial coefficient. It follows that (29.14.2) holds in this case, because the binomial coefficient is an integer.

Note that $(\mathrm{ad}_{z_\alpha})^{q(\beta)+1}(z_\beta) = 0$, because $\beta + (q(\beta) + 1)\,\alpha \not\in \Phi$. This implies that $(\mathrm{ad}_{z_\alpha})^m(z_\beta) = 0$ when $m \ge q(\beta) + 1$, so that (29.14.2) holds for every $m \ge 1$, as desired.

If $c \in \mathbf{Z}$, then

$$\exp(c\,\mathrm{ad}_{z_\alpha}) = \sum_{m=0}^{\infty} (c^m/m!)\,(\mathrm{ad}_{z_\alpha})^m \tag{29.14.11}$$

defines a Lie algebra automorphism of A, as in Section 14.11, because ad_{z_α} is nilpotent on A. We also have that

$$(\exp(c\,\mathrm{ad}_{z_\alpha}))(A(\mathbf{Z})) \subseteq A(\mathbf{Z}), \tag{29.14.12}$$

because $(1/m!)\,(\mathrm{ad}_{z_\alpha})^m$ maps $A(\mathbf{Z})$ into itself for every m, as before. This implies that

$$(\exp(c\,\mathrm{ad}_{z_\alpha}))(A(\mathbf{Z})) = A(\mathbf{Z}), \tag{29.14.13}$$

by applying the previous statement to $-c$. This corresponds to some remarks on p150 of [14], and is related to Remark (1) on p51 of [24].

29.15 Some related mappings on $A(k_1)$

We continue with the same notation and hypotheses as in the previous section. Let $\alpha \in \Phi$ be given again, and for each positive integer m, put

$$Z_{\alpha,m} = (1/m!)\,(\mathrm{ad}_{z_\alpha})^m. \tag{29.15.1}$$

This defines a linear mapping from A into itself, as a vector space over k, which may be interpreted as the identity mapping on A when $m = 0$. Remember that

$$Z_{\alpha,m}(A(\mathbf{Z})) \subseteq A(\mathbf{Z}) \tag{29.15.2}$$

for every $m \ge 0$, as before.

If l, m are nonnegative integers, then

$$\binom{l+m}{l} Z_{\alpha,l+m} = Z_{\alpha,l} \circ Z_{\alpha,m}, \tag{29.15.3}$$

by construction. If n is a nonnegative integer and $a, b \in A$, then

$$(\mathrm{ad}_{z_\alpha})^n([a,b]_A) = \sum_{j=0}^{n} \binom{n}{j} [(\mathrm{ad}_{z_\alpha})^j(a), (\mathrm{ad}_{z_\alpha})^{n-j}(b)]_A, \tag{29.15.4}$$

because ad_{z_α} is a derivation on A, as in Section 14.10. Equivalently, this means that

$$Z_{\alpha,n}([a,b]_A) = \sum_{j=0}^{n} [Z_{\alpha,j}(a), Z_{\alpha,n-j}(b)]_A. \tag{29.15.5}$$

Let k_1 be a commutative ring with a multiplicative identity element, and let $A(k_1)$ be as in Section 29.13. Note that every mapping from $A(\mathbf{Z})$ into itself that is linear over $\mathbf{Z}$ leads to a linear mapping from $A(k_1)$ into itself that is linear over k_1. This can be seen in terms of the bases for $A(\mathbf{Z})$, $A(k_1)$ as free modules over $\mathbf{Z}$, k_1, respectively, described earlier, or by considering $A(k_1)$ as the tensor product of $A(\mathbf{Z})$ and k_1, as modules over $\mathbf{Z}$. This correspondence between mappings on $A(\mathbf{Z})$ and on $A(k_1)$ is linear over $\mathbf{Z}$, and preserves compositions.

If m is a nonnegative integer, then let Z_{α,m,k_1} be the mapping on $A(k_1)$ that corresponds to the restriction of $Z_{\alpha,m}$ to $A(\mathbf{Z})$ in this way. If l is another nonnegative integer, then

(29.15.6) $$\binom{l+m}{l} Z_{\alpha,l+m,k_1} = Z_{\alpha,l,k_1} \circ Z_{\alpha,m,k_1},$$

by (29.15.3). Similarly, if n is a nonnegative integer and $a, b \in A(k_1)$, then

(29.15.7) $$Z_{\alpha,n,k_1}([a,b]_{A(k_1)}) = \sum_{j=0}^{n} [Z_{\alpha,j,k_1}(a), Z_{\alpha,n-j,k_1}(b)]_{A(k_1)},$$

by (29.15.5). More precisely, it suffices to verify this when a, b are basis elements of $A(k_1)$, which can be obtained from the previous case.

If $t \in k_1$, then put

(29.15.8) $$E_{\alpha,k_1}(t) = \sum_{l=0}^{\infty} t^l \, Z_{\alpha,l,k_1}.$$

Of course, $Z_{\alpha,l} = 0$ for all but finitely many $l \geq 0$, because z_α is ad-nilpotent in A. This implies that $Z_{\alpha,l,k_1} = 0$ for the same $l \geq 0$, so that the right side of (29.15.8) reduces to a finite sum. Thus (29.15.8) defines $E_{\alpha,k_1}(t)$ as a linear mapping from $A(k_1)$ into itself.

If $r \in k_1$ too, then

(29.15.9) $$E_{\alpha,k_1}(r+t) = \sum_{n=0}^{\infty} (r+t)^n \, Z_{\alpha,n,k_1} = \sum_{n=0}^{\infty} \sum_{l=0}^{n} \binom{n}{l} r^l \, t^{n-l} \, Z_{\alpha,n,k_1},$$

by the binomial theorem. This implies that

(29.15.10) $$E_{\alpha,k_1}(r+t) = \sum_{n=0}^{\infty} \sum_{l=0}^{n} r^l \, t^{n-l} \, Z_{\alpha,l,k_1} \circ Z_{\alpha,n-l,k_1},$$

by (29.15.6). It follows that

(29.15.11) $$E_{\alpha,k_1}(r+t) = E_{\alpha,k_1}(r) \circ E_{\alpha,k_1}(t),$$

because the right side of (29.15.10) corresponds to the Cauchy product of the series that defined $E_{\alpha,k_1}(r)$ and $E_{\alpha,k_1}(t)$. In particular, $E_{\alpha,k_1}(t)$ is invertible on $A(k_1)$, with

(29.15.12) $$E_{\alpha,k_1}(t)^{-1} = E_{\alpha,k_1}(-t),$$

because $E_{\alpha,k_1}(0)$ is the identity mapping on $A(k_1)$.

If $a, b \in A(k_1)$, then

$$\begin{aligned}(E_{\alpha,k_1}(t))([a,b]_{A(k_1)}) &= \sum_{n=0}^{\infty} t^n\, Z_{\alpha,n,k_1}([a,b]_{A(k_1)}) \\ &= \sum_{n=0}^{\infty} t^n \sum_{l=0}^{n} [Z_{\alpha,l,k_1}(a), Z_{\alpha,n-l,k_1}]_{A(k_1)}, \end{aligned} \tag{29.15.13}$$

using (29.15.7) in the second step. This implies that

$$\begin{aligned}(E_{\alpha,k_1}(t))([a,b]_{A(k_1)}) &= \sum_{n=0}^{\infty} \sum_{l=0}^{n} [t^l\, Z_{\alpha,l,k_1}(a), t^{n-l}\, Z_{\alpha,n-l,k_1}(b)]_{A(k_1)} \\ &= [(E_{\alpha,k_1}(t))(a), (E_{\alpha,k_1}(t))(b)]_{A(k_1)}, \end{aligned} \tag{29.15.14}$$

because the right side is equal to the Cauchy product with respect to $[\cdot,\cdot]_{A(k_1)}$ of the series that define $(E_{\alpha,k_1}(t))(a)$ and $(E_{\alpha,k_1}(t))(b)$. Thus $E_{\alpha,k_1}(t)$ is an automorphism of $A(k_1)$, as a Lie algebra over k_1.

This corresponds to some remarks on p150 of [14], and to Exercise 11 on p151 of [14]. This is also related to Remark (1) on p51 of [24].

Chapter 30

Roots and abstract weights

30.1 Abstract weights

Let V be a vector space over the real numbers of positive finite dimension, and let Φ be a root system in V. If $\alpha \in \Phi$, then let σ_α be the unique symmetry on V with vector α that maps Φ onto itself, as usual. Thus σ_α can be expressed as $\sigma_\alpha(v) = v - \lambda_\alpha(v)\,\alpha$, where λ_α is a linear functional on V with $\lambda_\alpha(\alpha) = 2$.

As before, we let $\Theta = \Theta_\Phi$ be the subgroup of V, as a commutative group with respect to addition, generated by Φ. Equivalently, this is the subgroup of V generated by any base for Φ. This may be called the *root lattice* in V associated to Φ, as on p67 of [14].

Put

(30.1.1) $$\Upsilon = \Upsilon_\Phi = \{v \in V : \lambda_\alpha(v) \in \mathbf{Z} \text{ for every } \alpha \in \Phi\}.$$

The elements of Υ may be called *(abstract) weights* with respect to Φ, as on p67 of [14]. This corresponds to P on p63 of [24], where the root system is associated to a finite-dimensional semisimple Lie algebra. Note that Υ is a subgroup of V, as a commutative group with respect to addition. We also have that

(30.1.2) $$\Theta \subseteq \Upsilon,$$

by the definition of a root system.

Let V' be the dual space of linear functionals on V, and remember that

(30.1.3) $$\Phi' = \{\lambda_\alpha : \alpha \in \Phi\}$$

is a root system in V', as in Section 19.8. If $\alpha \in \Phi$ and $2\,\alpha \in \Phi$, then $\sigma_{2\,\alpha} = \sigma_\alpha$, and $\lambda_{2\,\alpha} = \lambda_\alpha/2$, as in Section 19.13. Let Δ be a base for Φ, and put

(30.1.4) $$\Delta_1 = \{\beta \in \Delta : 2\,\beta \notin \Phi\}, \quad \Delta_2 = \{\beta \in \Delta : 2\,\beta \in \Phi\}.$$

Note that $\Delta_2 = \emptyset$ when Φ is reduced, and put

(30.1.5) $$\Delta_1' = \{\lambda_\beta : \beta \in \Delta_1\}, \quad \Delta_2^* = \{\lambda_\beta/2 : \beta \in \Delta_2\}.$$

Remember that $\Delta_1' \cup \Delta_2^*$ is a base for Φ', as in Section 19.13.

It follows that

$$\text{(30.1.6)} \qquad \Upsilon = \{v \in V : \lambda_\beta(v) \in \mathbf{Z} \text{ for every } \beta \in \Delta_1, \text{ and } \lambda_\beta(v)/2 \in \mathbf{Z} \text{ for every } \beta \in \Delta_2\}.$$

Equivalently,

$$\text{(30.1.7)} \qquad \Upsilon = \{v \in V : \lambda(v) \in \mathbf{Z} \text{ for every } \lambda \in \Delta_1' \cup \Delta_2^*\}.$$

In particular, $\Delta_1' \cup \Delta_2^*$ is a basis for V', as a vector space over $\mathbf{R}$. If $v \in V$, then

$$\text{(30.1.8)} \qquad \lambda \mapsto \lambda(v)$$

defines a real-valued function on $\Delta_1' \cup \Delta_2^*$. The mapping from $v \in V$ to (30.1.8) defines a one-to-one linear mapping from V onto the space of real-valued functions on $\Delta_1' \cup \Delta_2^*$. Thus, for each $\mu \in \Delta_1' \cup \Delta_2^*$, there is a unique $v_\mu \in V$ such that

$$\text{(30.1.9)} \qquad \begin{aligned} \lambda(v_\mu) &= 1 \quad \text{when } \lambda = \mu \\ &= 0 \quad \text{for every } \lambda \in \Delta_1' \cup \Delta_2^* \text{ with } \lambda \neq \mu. \end{aligned}$$

The v_μ's, $\mu \in \Delta_1' \cup \Delta_2^*$, form a basis for V, which is dual to $\Delta_1' \cup \Delta_2^*$.

Using (30.1.7), we get that

$$\text{(30.1.10)} \qquad v_\lambda \in \Upsilon$$

for every $\lambda \in \Delta_1' \cup \Delta_2'$. The v_λ's, $\lambda \in \Delta_1' \cup \Delta_2^*$, are called the *fundamental (dominant) weights* with respect to Δ, as on p67 of [14], and Remark (2) on p62 of [24]. Note that Υ consists exactly of linear combinations of the v_λ's, $\lambda \in \Delta_1' \cup \Delta_2^*$, with integer coefficients.

30.2 Some remarks about lattices

Let V be a vector space over the real numbers of positive finite dimension n, and let $u_1, \ldots, u_n$ and $w_1, \ldots, w_n$ be bases for V. Also let A and B be the subgroups of V, as a commutative group with respect to addition, generated by the u_j's and w_j's, respectively. Equivalently, A and B consist of the elements of V that can be expressed as linear combinations of the u_j's and w_j's, respectively, with integer coefficients.

Suppose that

$$\text{(30.2.1)} \qquad B \subseteq A.$$

This means that for each $l = 1, \ldots, n$, w_l can be expressed as a linear combination of the u_j's with integer coefficients. Let T be the linear mapping from V onto itself with

$$\text{(30.2.2)} \qquad T(u_l) = w_l$$

for every $l = 1, \ldots, n$. Note that T is invertible, so that $\det T \neq 0$. We also have that

$$T(A) = B, \tag{30.2.3}$$

by construction.

Of course, T corresponds to an $n \times n$ matrix, with respect to the basis $u_1, \ldots, u_n$ of V. The entries of this matrix are obtained by expressing w_l as a linear combination of the u_j's for each $l = 1, \ldots, n$. In particular, the entries of the matrix associated to T are integers in this case. This implies that

$$\det T \in \mathbf{Z}. \tag{30.2.4}$$

Using Cramer's rule, we get that $(\det T)\, T^{-1}$ corresponds to a matrix with integer entries as well. This means that

$$(\det T)\, T^{-1}(A) \subseteq A. \tag{30.2.5}$$

It follows that

$$(\det T)\, A \subseteq T(A) = B. \tag{30.2.6}$$

This implies that the quotient group A/B has only finitely many elements.

Because V is isomorphic to $\mathbf{R}^n$ as a vector space over $\mathbf{R}$, one can define n-dimensional volumes on V as on $\mathbf{R}^n$. These volumes are determined up to multiplication by a positive real number, depending on the isomorphism with $\mathbf{R}^n$. These volumes are invariant under translations on V, and are changed by T by a factor of $|\det T|$, because of the analogous properties on $\mathbf{R}^n$.

It is well known that

$$\#(A/B) = |\det T|, \tag{30.2.7}$$

where the left side is the number of elements of A/B. To see this, one can consider the quotients V/A and V/B of V by A and B, respectively. There is a natural quotient mapping from V/B onto V/A, because of (30.2.1). The natural quotient mapping from V onto V/A is the same as the composition of the natural quotient mapping from V onto V/B with the quotient mapping from V/B onto V/A. One can define n-dimensional volumes on V/A and V/B that correspond locally to volumes on V under the quotient mappings. In particular, volumes on V/A correspond locally to volumes on V/B under the natural quotient mapping. This implies that the ratio of the volumes of V/B and V/A is equal to $\#(A/B)$.

There is also a natural one-to-one mapping from V/A onto V/B induced by T. Because volumes on V are changed by T by a factor of $|\det T|$, volumes on the quotients are changed in the same way by the mapping induced by T, where the volumes on the quotients correspond locally to volumes on V as before. This means that the ratio of the volumes of V/B and V/A is equal to $|\det T|$, which implies (30.2.7).

Let us return now to the situation considered in the previous section. Note that Θ is generated, as a subgroup of V, by Δ, which is a basis for V. We also have that Υ is generated, as a subgroup of V, by the v_λ's, $\lambda \in \Delta_1' \cup \Delta_2^*$, which form a basis for V too. Remember that $\Theta \subseteq \Upsilon$, so that the quotient Υ/Θ is defined as a commutative group, and has only finitely many elements, as before. This is known as the *fundamental group* of Φ, as on p68 of [14].

Suppose that Φ is reduced, as a root system in V. This means that $\Delta_1 = \Delta$ and $\Delta_2 = \emptyset$, and we put

$$\Delta' = \{\lambda_\beta : \beta \in \Delta\}, \tag{30.2.8}$$

which is the same as Δ_1' in this case. If $\beta \in \Delta$, then there is a unique $v_\beta = v_{\lambda_\beta} \in V$ such that

$$\begin{aligned} \lambda_\alpha(v_\beta) &= 1 \quad \text{when } \alpha = \beta \\ &= 0 \quad \text{for every } \alpha \in \Delta \text{ with } \alpha \neq \beta, \end{aligned} \tag{30.2.9}$$

as in (30.1.9). The v_β's, $\beta \in \Delta$, form a basis for V, which is dual to Δ', as a basis for V', as before. If $v \in V$, then

$$v = \sum_{\beta \in \Delta} \lambda_\beta(v)\, v_\beta. \tag{30.2.10}$$

In particular, if $\alpha \in \Delta$, then

$$\alpha = \sum_{\beta \in \Delta} \lambda_\beta(\alpha)\, v_\beta. \tag{30.2.11}$$

Remember that $n(\alpha, \beta) = \lambda_\beta(\alpha)$, $\alpha, \beta \in \Delta$, is the Cartan matrix of Φ with respect to Δ, as in Section 20.2. The determinant of the Cartan matrix is a positive integer, as in Section 21.15. In fact,

$$\#(\Upsilon/\Theta) = \det(n(\alpha, \beta))_{\alpha, \beta \in \Delta}, \tag{30.2.12}$$

as in (30.2.7). This corresponds to some remarks on p68 of [14].

30.3 Related positivity conditions

Let us go back to the notation and hypotheses in Section 30.1. In particular, Δ is a base for Φ, and we put

$$\Upsilon^+ = \Upsilon^+_{\Phi,\Delta} = \{v \in \Upsilon : \lambda_\alpha(v) \geq 0 \text{ for every } \alpha \in \Delta\}. \tag{30.3.1}$$

The elements of Υ^+ are said to be *dominant weights* with respect to Δ, as on p67 of [14]. If $v \in \Upsilon$ satisfies

$$\lambda_\alpha(v) > 0 \quad \text{for every } \alpha \in \Delta, \tag{30.3.2}$$

then v is said to be *strongly dominant.*

Equivalently, it is easy to see that

$$\Upsilon^+ = \{v \in \Upsilon : \lambda(v) \geq 0 \text{ for every } \lambda \in \Delta_1' \cup \Delta_2^*\}. \tag{30.3.3}$$

Similarly, (30.3.2) holds if and only if

$$\lambda(v) > 0 \quad \text{for every } \lambda \in \Delta_1' \cup \Delta_2^*. \tag{30.3.4}$$

If $\mu \in \Delta_1' \cup \Delta_2^*$ and $v_\mu \in \Upsilon$ is as in (30.1.9), then we get that

$$v_\mu \in \Upsilon^+, \tag{30.3.5}$$

by (30.3.3).

Let $\Phi^+ = \Phi^{\Delta,+}$ be the set of $\alpha \in \Phi$ that can be expressed as linear combinations of elements of Δ with nonnegative coefficients, as usual. Put

$$(\Phi')^+ = \{\lambda_\alpha : \alpha \in \Phi^+\}. \tag{30.3.6}$$

Remember that $\Delta_1' \cup \Delta_2^*$ is a base for Φ', as a root system in V'. One can check directly that

$$\Delta_1' \cup \Delta_2^* \subseteq (\Phi')^+, \tag{30.3.7}$$

because $\Delta \subseteq \Phi^+$.

In fact, $(\Phi')^+$ consists exactly of the elements of Φ' that can be expressed as linear combinations of elements of $\Delta_1' \cup \Delta_2^*$ with nonnegative coefficients. This is basically implicit in the proof of the fact that $\Delta_1' \cup \Delta_2^*$ is a base for Φ', as in Section 19.13. More precisely, in the proof an inner product on V that is invariant under the Weyl group of Φ was used to identify V and V'. Using this identification, $\Delta_1' \cup \Delta_2^*$ was shown to correspond to the construction of a base for a root system in Section 19.11. The set of positive roots with respect to this base is also determined in this construction, as before. In this case, the set of positive roots corresponds exactly to $(\Phi')^+$. This is because of the way that the linear functional τ is defined in the proof in Section 19.13.

If $v \in \Upsilon^+$, then it follows that

$$\lambda_\alpha(v) \geq 0 \quad \text{for every } \alpha \in \Phi^+. \tag{30.3.8}$$

This corresponds to the statement following Theorem 3 on p60 of [24]. Similarly, if $v \in \Upsilon$ is strongly dominant, then

$$\lambda_\alpha(v) > 0 \quad \text{for every } \alpha \in \Phi^+. \tag{30.3.9}$$

Let $(\cdot,\cdot)$ be an inner product on V that is invariant under the Weyl group of Φ. If $\alpha \in \Phi$, then σ_α is the reflection on V associated to α with respect to $(\cdot,\cdot)$, so that $\lambda_\alpha(v) = 2\,(v,\alpha)\,(\alpha,\alpha)^{-1}$, as before. Under these conditions,

$$\Upsilon^+ = \{v \in \Upsilon : (v,\alpha) \geq 0 \text{ for every } \alpha \in \Delta\}. \tag{30.3.10}$$

Similarly, $v \in \Upsilon$ is strongly dominant if and only if

$$(v,\alpha) > 0 \quad \text{for every } \alpha \in \Delta. \tag{30.3.11}$$

This corresponds to some remarks about Weyl chambers on p67 of [14].

If $v \in V$, then (30.3.8) holds if and only if

$$(v, \alpha) \geq 0 \quad \text{for every } \alpha \in \Phi^+. \tag{30.3.12}$$

In particular, this holds when $v \in \Upsilon^+$, as before. Alternatively, (30.3.12) holds when $v \in V$ satisfies $(v, \alpha) \geq 0$ for every $\alpha \in \Delta$, by definition of Φ^+.

Similarly, $v \in V$ satisfies (30.3.9) if and only if

$$(v, \alpha) > 0 \quad \text{for every } \alpha \in \Phi^+. \tag{30.3.13}$$

This holds when $v \in \Upsilon$ is strongly dominant, as before. Alternatively, (30.3.11) implies (30.3.13), by definition of Φ^+.

30.4 Automorphisms and Υ

Let us continue with the notation and hypotheses in Section 30.1 again. Remember that a one-to-one linear mapping T from V onto itself is an automorphism of Φ when $T(\Phi) = \Phi$, and that $\mathrm{Aut}(\Phi)$ denotes the group of these automorphisms. If $T \in \mathrm{Aut}(\Phi)$, then

$$T(\Theta) = \Theta. \tag{30.4.1}$$

In this case,

$$\lambda_{T(\alpha)}(T(v)) = \lambda_\alpha(v) \tag{30.4.2}$$

for every $\alpha \in \Phi$ and $v \in V$, as in Section 19.5. One can use this to check that

$$T(\Upsilon) = \Upsilon. \tag{30.4.3}$$

Remember that the quotient group Υ/Θ has only finitely many elements, as in Section 30.2. If $T \in \mathrm{Aut}(\Phi)$, then T induces an automorphism $\widehat{T}$ of Υ/Θ, by (30.4.1) and (30.4.3).

If $\alpha \in \Phi$ and $v \in \Upsilon$, then

$$\sigma_\alpha(v) - v = -\lambda_\alpha(v)\, \alpha \in \Theta. \tag{30.4.4}$$

Of course, $\sigma_\alpha \in \mathrm{Aut}(\Phi)$, so that σ_α induces an automorphism $\widehat{\sigma_\alpha}$ on Υ/Θ, as in the preceding paragraph. It follows from (30.4.4) that $\widehat{\sigma_\alpha}$ is the identity mapping on Υ/Θ. If σ is any element of the Weyl group of Φ, then $\sigma \in \mathrm{Aut}(\Phi)$, and we get that $\widehat{\sigma}$ is the identity mapping on Υ/Θ. Equivalently, this means that

$$\sigma(v) - v \in \Theta \tag{30.4.5}$$

for every $v \in \Upsilon$.

Let $(\cdot, \cdot)$ be an inner product on V that is invariant under the Weyl group of Φ. Remember that Δ is a base for Φ, and suppose for the rest of the section that Φ is reduced, as a root system in V. If $v \in V$, then there is an element σ of the Weyl group of Φ such that

$$(\sigma(v), \alpha) \geq 0 \quad \text{for every } \alpha \in \Delta, \tag{30.4.6}$$

as in Section 20.9. If $v \in \Upsilon$, then $\sigma(v) \in \Upsilon$, and it follows that

$$\sigma(v) \in \Upsilon^+, \tag{30.4.7}$$

as in(30.3.10). This corresponds to part of Lemma A on p68 of [14].

As in Section 21.12, a linear functional μ on V is said to be nonnegative with respect to Δ if

$$\mu(\alpha) \geq 0 \quad \text{for every } \alpha \in \Delta. \tag{30.4.8}$$

If $v \in V$, then put

$$\mu_v(w) = (v, w) \tag{30.4.9}$$

for every $w \in V$, which defines a linear functional on V. If σ is in the Weyl group of Φ, then

$$\mu_{\sigma(v)}(w) = (\sigma(v), w) = (v, \sigma^{-1}(w)) \tag{30.4.10}$$

for every $w \in V$, which is to say that

$$\mu_{\sigma(v)} = \mu \circ \sigma^{-1}. \tag{30.4.11}$$

Suppose that μ_v is nonnegative with respect to Δ, and that $\mu_{\sigma(v)}$ is nonnegative with respect to Δ for some σ in the Weyl group of Φ. Under these conditions,

$$\mu_{\sigma(v)} = \mu_v, \tag{30.4.12}$$

as in Section 21.12. Equivalently, this means that

$$\sigma(v) = v. \tag{30.4.13}$$

In particular, this holds when $v \in \Upsilon^+$ and $\sigma(v) \in \Upsilon^+$ for some σ in the Weyl group of Φ. This is another part of Lemma A on p68 of [14].

Suppose again that μ_v is nonnegative with respect to Δ for some $v \in V$, and that $\mu_{\sigma(v)}$ is nonnegative with respect to Δ for some σ in the Weyl group of Φ. As in Section 21.12, this implies that σ can be expressed as the composition of finitely many reflections σ_α with $\alpha \in \Delta$ and

$$\mu_v = \mu_v \circ \sigma_\alpha. \tag{30.4.14}$$

Observe that (30.4.14) implies that

$$\mu_v(\alpha) = -\mu_v(\alpha), \tag{30.4.15}$$

so that $\mu_v(\alpha) = 0$. This is not possible when μ_v is strictly positive with respect to Δ, in the sense that

$$\mu_v(\alpha) = (v, \alpha) > 0 \quad \text{for every } \alpha \in \Delta. \tag{30.4.16}$$

In this case, we get that σ is the identity mapping on V.

If $v \in \Upsilon$ is strongly dominant and $\sigma(v) \in \Upsilon^+$ for some σ in the Weyl group of Φ, then it follows that σ is the identity mapping on V. This is another part of Lemma A on p68 of [14].

30.5 Some partial orderings on V

Let us continue with the usual notation and hypotheses in Section 30.1. Thus Δ is a base for Φ, and a basis for V in particular. Consider the binary relation $\preceq = \preceq_\Delta$ defined on V by putting $v \preceq w$ when $v, w \in V$ and either $v = w$, or $w - v$ can be expressed as a finite sum of elements of Δ. This defines a partial ordering on V, as on p47 of [14].

Similarly, consider the binary relation $\preceq^{\mathbf{R}} = \preceq^{\mathbf{R}}_\Delta$ defined on V by putting $v \preceq^{\mathbf{R}} w$ when $v, w \in V$ and $w - v$ can be expressed as a linear combination of elements of Δ with nonnegative coefficients. This defines a partial ordering on V too, as mentioned in Exercise 14 on p55 of [14]. Of course,

$$v \preceq w \quad \text{implies} \quad v \preceq^{\mathbf{R}} w \tag{30.5.1}$$

for every $v, w \in V$. Conversely, if $v, w \in V$, $v \preceq^{\mathbf{R}} w$, and $w - v \in \Theta$, then $v \preceq w$.

Let $v \in V$ and $\alpha \in \Delta$ be given, and note that

$$v - \sigma_\alpha(v) = \lambda_\alpha(v)\, \alpha. \tag{30.5.2}$$

In this case, $\sigma_\alpha(v) \preceq^{\mathbf{R}} v$ when $\lambda_\alpha(v) \geq 0$, and $v \preceq^{\mathbf{R}} \sigma_\alpha(v)$ when $\lambda_\alpha(v) \leq 0$. If $v \in \Upsilon$, then we get that $\sigma_\alpha(v) \preceq v$ when $\lambda_\alpha(v) \geq 0$, and $v \preceq \sigma_\alpha(v)$ when $\lambda_\alpha(v) \leq 0$.

Let $v \in V$ be given again, and suppose that σ is an element of the Weyl group of Φ such that $\sigma(v)$ is maximal with respect to $\preceq^{\mathbf{R}}$ among the images of v under elements of the Weyl group. If $\alpha \in \Delta$ and $\sigma(v) \preceq^{\mathbf{R}} \sigma_\alpha(\sigma(v))$, then it follows that $\sigma_\alpha(\sigma(v)) = \sigma(v)$. This means that

$$\lambda_\alpha(\sigma(v)) \geq 0 \quad \text{for every } \alpha \in \Delta, \tag{30.5.3}$$

as in the preceding paragraph.

Let $(\cdot, \cdot)$ be an inner product on V that is invariant under the Weyl group of Φ. Observe that (30.5.3) is the same as saying that (30.4.6) holds.

Of course, there are only finitely many images of v in V under elements of the Weyl group of Φ, because the Weyl group has only finitely many elements. This implies that there is an element σ of the Weyl group such that $\sigma(v)$ is maximal with respect to $\preceq^{\mathbf{R}}$, because every nonempty finite partially-ordered set has a maximal element. This gives another way to get the existence of an element σ of the Weyl group such that (30.4.6) holds, as in Exercise 14 on p55 of [14].

Let σ^0 be any element of the Weyl group of Φ. Consider the set of elements σ^1 of the Weyl group such that

$$\sigma^0(v) \preceq^{\mathbf{R}} \sigma^1(v). \tag{30.5.4}$$

Let σ be an element of this set such that $\sigma(v)$ is maximal with respect to $\preceq^{\mathbf{R}}$ among the images of v under the elements of this set, which exists as before. Thus

$$\sigma^0(v) \preceq^{\mathbf{R}} \sigma(v), \tag{30.5.5}$$

and it is easy to see that $\sigma(v)$ is maximal among all images of v under elements of the Weyl group with respect to $\preceq^{\mathbf{R}}$. This implies that (30.4.6) holds, as before.

Suppose from now on in this section that Φ is reduced, as a root system in V. Suppose also that $v \in V$ satisfies

$$(v, \alpha) \geq 0 \quad \text{for every } \alpha \in \Delta. \tag{30.5.6}$$

This is the same as saying that the linear functional μ_v on V associated to v as in (30.4.9) is nonnegative with respect to Δ. If σ is an element of the Weyl group that satisfies (30.4.6), then $\mu_{\sigma(v)}$ is nonnegative with respect to Δ too. This implies that $\sigma(v) = v$, as before.

If σ^0 is any element of the Weyl group, then there is an element σ of the Weyl group that satisfies (30.4.6) and (30.5.5). Under these conditions, we get that

$$\sigma^0(v) \preceq^{\mathbf{R}} v, \tag{30.5.7}$$

because $\sigma(v) = v$, as in the preceding paragraph.

Suppose that v is a dominant weight, so that $v \in \Upsilon$ and (30.5.6) holds, as in (30.3.10). Note that $v - \sigma^0(v) \in \Theta$, as in (30.4.5). In this case, (30.5.7) implies that

$$\sigma^0(v) \preceq v. \tag{30.5.8}$$

This corresponds to another part of Lemma A on p68 of [14].

30.6 Some more properties of Υ

Let us continue with the usual notation and hypotheses in Section 30.1 again. In particular, Δ is a base for Φ, so that Υ^+ can be defined as in Section 30.3. Let $\preceq$ be defined on V as in the previous section, and let $(\cdot, \cdot)$ be an inner product on V that is invariant under the Weyl group of Φ.

Let $v \in \Upsilon^+$ be given, and suppose that

$$w \in \Upsilon^+ \text{ satisfies } w \preceq v. \tag{30.6.1}$$

This implies that $v + w \in \Upsilon^+$, and that $v - w$ can be expressed as a sum of elements of Δ. It follows that

$$(v + w, v - w) \geq 0, \tag{30.6.2}$$

because $(v + w, \alpha) \geq 0$ for every $\alpha \in \Delta$. This means that

$$(v, v) - (w, w) \geq 0, \tag{30.6.3}$$

which is to say that $(w, w) \leq (v, v)$. Using this, one can check that there are only finitely many w as in (30.6.1), which is Lemma B at the top of p70 of [14].

Let Φ^+ be the set of elements of Φ that can be expressed as linear combinations of elements of Δ with nonnegative coefficients, as before. Suppose from now on in this section that Φ is reduced as a root system in V, and put

$$\rho = \frac{1}{2} \sum_{\gamma \in \Phi^+} \gamma, \tag{30.6.4}$$

as in Section 19.12. If $\alpha \in \Delta$, then

$$\sigma_\alpha(\rho) = \rho - \alpha, \tag{30.6.5}$$

as before. Equivalently, this means that

$$\lambda_\alpha(\rho) = 1 \tag{30.6.6}$$

for every $\alpha \in \Delta$. This shows that

$$\rho \in \Upsilon^+, \tag{30.6.7}$$

and more precisely that ρ is strongly dominant with respect to Δ, as in Lemma A around the middle of p70 of [14].

Because Φ is reduced, we have that $\Delta_1 = \Delta$ and $\Delta_2 = \emptyset$, in the notation of Section 30.1. If $\beta \in \Delta$, then let $v_\beta = v_{\lambda_\beta} \in \Upsilon$ be as in Sections 30.1 and 30.2. Using (30.2.10) and (30.6.6), we get that

$$\rho = \sum_{\beta \in \Delta} v_\beta. \tag{30.6.8}$$

This is another part of Lemma A around the middle of p70 of [14].

Let $u \in \Upsilon^+$ be given, and suppose that $w = \sigma^{-1}(u)$ for some σ in the Weyl group of Φ. Under these conditions, Lemma B around the middle of p70 of [14] states that

$$(w + \rho, w + \rho) \le (u + \rho, u + \rho), \tag{30.6.9}$$

with equality only when $u = w$. To see this, observe first that

$$(w + \rho, w + \rho) = (\sigma(w + \rho), \sigma(w + \rho)) = (u + \sigma(\rho), u + \sigma(\rho)). \tag{30.6.10}$$

This implies that

$$(w + \rho, w + \rho) = (u + \rho, u + \rho) - 2\,(u, \rho - \sigma(\rho)), \tag{30.6.11}$$

because $(\sigma(\rho), \sigma(\rho)) = (\rho, \rho)$.

Note that

$$\sigma(\rho) \preceq \rho, \tag{30.6.12}$$

by (30.5.8) and (30.6.7). Thus $\rho - \sigma(\rho)$ is either equal to 0, or a sum of elements of Δ. It follows that

$$(u, \rho - \sigma(\rho)) \ge 0, \tag{30.6.13}$$

because $u \in \Upsilon^+$. This implies (30.6.9), using (30.6.11). We also get that equality holds in (30.6.9) if and only if

$$(u, \rho - \sigma(\rho)) = 0. \tag{30.6.14}$$

Clearly

$$\begin{aligned}(u, \rho - \sigma(\rho)) &= (u, \rho) - (u, \sigma(\rho)) \\ &= (u, \rho) - (\sigma^{-1}(u), \rho) = (u - w, \rho).\end{aligned} \tag{30.6.15}$$

We also have that

$$w \preceq u, \tag{30.6.16}$$

as in (30.5.8), because $u \in \Upsilon^+$. This means that either $u = w$, or $u - w$ is a sum of elements of Δ. In the second case, we would get that

$$(u, \rho - \sigma(\rho)) = (u - w, \rho) > 0, \tag{30.6.17}$$

because ρ is strongly dominant with respect to Δ, as before. Thus (30.6.14) holds only when $u = w$, as desired.

30.7 Saturated subsets of Υ

Let us continue with the same notation and hypotheses as in Sections 30.1 and 30.3, and let $\preceq$ be defined on V as in Section 30.5. A subset Π of Υ is said to be *saturated* if for every $v \in \Pi$ and $\alpha \in \Phi$ we have that

$$v - j\,\alpha \in \Pi \tag{30.7.1}$$

for every integer j between 0 and $\lambda_\alpha(v)$, as on p70 of [14]. Of course, this holds trivially when $j = 0$, and it is also supposed to hold when $j = \lambda_\alpha(v)$.

If $\alpha \in \Phi$, then it follows that $\sigma_\alpha(\Pi) \subseteq \Pi$. This implies that $\sigma_\alpha(\Pi) = \Pi$, because σ_α is its own inverse on V. Thus

$$\sigma(\Pi) = \Pi \tag{30.7.2}$$

for every σ in the Weyl group of Φ when Π is saturated, as on p70 of [14].

A saturated set $\Pi \subseteq \Upsilon$ is said to have *highest weight* $v \in \Upsilon^+$ if $v \in \Pi$ and

$$w \preceq v \quad \text{for every } w \in \Pi, \tag{30.7.3}$$

as on p70 of [14]. It is easy to see that $\Pi = \{0\}$ is saturated, with highest weight 0, as in Example (1) on p70 of [14].

Let us check that $\Pi = \Phi \cup \{0\}$ is saturated, as in Example (2) on p70 of [14]. If $v = 0$, then $\lambda_\alpha(v) = 0$ for every $\alpha \in \Phi$, and (30.7.1) holds trivially. Otherwise, let $v, \alpha \in \Phi$ be given, and note that (30.7.1) holds when $j = \lambda_\alpha(v)$, because $\sigma_\alpha(v) \in \Phi$, by the definition of a root system. If v and α are not proportional in V, then it follows that (30.7.1) holds when j is between 0 and $\lambda_\alpha(v)$, as in Section 20.5. If v and α are proportional in V, then this can be verified directly.

Let us say that an element of Φ is maximal with respect to Δ if it is maximal with respect to $\preceq$. This is equivalent to the definition of a maximal root in Section 20.8. If $\alpha \in \Phi$, then the set of $\beta \in \Phi$ such that $\alpha \preceq \beta$ is a nonempty finite set. It follows that this set has a maximal element β_0 with respect to $\preceq$, and it is easy to see that β_0 is also maximal in Φ.

Suppose for the moment that Φ is irreducible as a root system in V. This implies that Φ has a unique maximal element α_0, as in Section 20.8. If $\alpha \in \Phi$, then

(30.7.4) $$\alpha \preceq \alpha_0,$$

by the remarks in the preceding paragraph, and which was also mentioned in Section 20.8. It is easy to see that (30.7.4) holds with $\alpha = 0$ too.

Let $(\cdot, \cdot)$ be an inner product on V that is invariant under the Weyl group of Φ. If $\gamma \in \Delta$, then

(30.7.5) $$(\alpha_0, \gamma) \geq 0,$$

as in Section 20.8. This means that

(30.7.6) $$\alpha_0 \in \Upsilon^+,$$

as in Section 30.3. It follows that $\Pi = \Phi \cup \{0\}$ has highest weight α_0 under these conditions, as on p70 of [14].

Suppose that $\Pi \subseteq \Upsilon$ is saturated, and has highest weight $v \in \Upsilon^+$. Using the remarks near the beginning of the previous section, we get that $\Pi \cap \Upsilon^+$ has only finitely many elements. Suppose also that Φ is reduced, as a root system in V. If $w \in \Pi$, then there is an element σ in the Weyl group of Φ such that $\sigma(w) \in \Upsilon^+$, as in Section 30.4. We also have that $\sigma(w) \in \Pi$, as in (30.7.2). It follows that Π has only finitely many elements under these conditions, because $\Pi \cap \Upsilon^+$ and the Weyl group of Φ have only finitely many elements. This is Lemma A near the bottom of p70 of [14].

30.8 More on highest weights

We continue with the same notation and hypotheses as in Sections 30.1 and 30.3, and to let $\preceq$ be defined on V as in Section 30.5. We also ask that Φ be reduced as a root system in V in this section. Let $(\cdot, \cdot)$ be an inner product on V that is invariant under the Weyl group of Φ.

Suppose that $\Pi \subseteq \Upsilon$ is saturated, with highest weight $v \in \Upsilon^+$. If $u \in \Upsilon^+$ and $u \preceq v$, then Lemma B at the bottom of p70 of [14] states that

(30.8.1) $$u \in \Pi.$$

To see this, we shall consider elements w of Π of the form

(30.8.2) $$w = u + \sum_{\alpha \in \Delta} c_\alpha \, \alpha,$$

where c_α is a nonnegative integer for each $\alpha \in \Delta$. Of course, if this happens with $c_\alpha = 0$ for each $\alpha \in \Delta$, then (30.8.1) holds, as desired. Note that $w = v$ can be expressed as in (30.8.2), by hypothesis.

Suppose that $w \in \Pi$ is of the form (30.8.2), and that $c_\alpha > 0$ for some $\alpha \in \Delta$. Thus $\sum_{\alpha \in \Delta} c_\alpha \, \alpha \neq 0$, which implies that

$$\Big(\sum_{\alpha \in \Delta} c_\alpha \, v_\alpha, \sum_{\beta \in \Delta} c_\beta \, \beta \Big) > 0. \tag{30.8.3}$$

It follows that there is a $\beta_0 \in \Delta$ such that $c_{\beta_0} > 0$ and

$$\Big(\sum_{\alpha \in \Delta} c_\alpha \, \alpha, \beta_0 \Big) > 0. \tag{30.8.4}$$

Equivalently,

$$\lambda_{\beta_0} \Big(\sum_{\alpha \in \Delta} c_\alpha \, \alpha \Big) > 0. \tag{30.8.5}$$

We also have that

$$\lambda_{\beta_0}(u) \geq 0, \tag{30.8.6}$$

because $u \in \Upsilon^+$, by hypothesis. Combining this with (30.8.5), we obtain that

$$\lambda_{\beta_0}(w) > 0. \tag{30.8.7}$$

This means that $\lambda_{\beta_0}(w) \geq 1$, because $w \in \Pi \subseteq \Upsilon$, so that $\lambda_{\beta_0}(w) \in \mathbf{Z}$. It follows that

$$w - \beta \in \Pi, \tag{30.8.8}$$

because $w \in \Pi$ and Π is saturated.

Note that $c_{\beta_0} \geq 1$, because $c_{\beta_0} > 0$ and $c_{\beta_0} \in \mathbf{Z}$. This means that $w - \beta$ can be expressed as in (30.8.2) as well. Thus we can start with $w = v$ and repeat the process, as needed, to get that (30.8.1) holds.

If $u \in \Upsilon^+$ and $u \preceq v$, then

$$\sigma(u) \in \Pi \tag{30.8.9}$$

for every element σ of the Weyl group of Φ, because of (30.8.1) and (30.7.2). Conversely, if $u_1 \in \Pi$, then there is an element σ_1 of the Weyl group of Φ such that

$$\sigma_1^{-1}(u_1) \in \Upsilon^+, \tag{30.8.10}$$

as in Section 30.4. We also have that $\sigma_1^{-1}(u_1) \in \Pi$, by (30.7.2), and that $\sigma_1^{-1}(u_1) \preceq v$, because Π has highest weight v, by hypothesis.

It follows that

$$\Pi = \{\sigma(u) : u \in \Upsilon^+, \, u \preceq v, \text{ and } \sigma \text{ is an element of the Weyl group of } \Phi\}, \tag{30.8.11}$$

as on p71 of [14]. In particular, this means that Π is uniquely determined by v.

30.9 More on saturated sets

We continue with the same notations and hypotheses as in Sections 30.1 and 30.3 again, and to let $\preceq$ be defined on V as in Section 30.5. We ask that Φ be reduced as a root system in V in this section too.

Let Π be a subset of Υ that is invariant under the Weyl group of Φ, so that $\sigma(\Pi) = \Pi$ for every element σ of the Weyl group. Suppose that for every $w \in \Pi \cap \Upsilon^+$ and $\alpha \in \Phi$ we have that

$$w - j\,\alpha \in \Pi \tag{30.9.1}$$

for every integer j between 0 and $\lambda_\alpha(w)$. We would like to check that Π is saturated as a subset of Υ under these conditions. This is related to a remark on p71 of [14].

To do this, let $v \in \Pi$ be given. Remember that there is an element σ of the Weyl group such that $\sigma(v) \in \Upsilon^+$, as in Section 30.4. Note that $\sigma(v) \in \Pi$, by hypothesis. Let $\alpha \in \Phi$ be given, and remember that

$$\lambda_{\sigma(\alpha)}(\sigma(v)) = \lambda_\alpha(v), \tag{30.9.2}$$

as in (30.4.2).

If j is an integer between 0 and $\lambda_{\sigma(\alpha)}(\sigma(v))$, then

$$\sigma(v) - j\,\sigma(\alpha) \in \Pi, \tag{30.9.3}$$

by hypothesis, and because $\sigma(\alpha) \in \Phi$. This implies that $v - j\,\alpha \in \Pi$, because $\sigma(\Pi) = \Pi$. Equivalently, this holds for every integer j between 0 and $\lambda_\alpha(v)$, by (30.9.2), as desired.

Let $v \in \Upsilon^+$ be given, and let $\Pi = \Pi_v$ be as in (30.8.11). We would like to verify that Π is saturated as a subset of Υ, as in Exercise 10 on p72 of [14]. Of course, Π is invariant under the Weyl group of Φ, by construction. Let $w \in \Pi \cap \Upsilon^+$ and $\alpha \in \Phi$ be given. It suffices to show that (30.9.1) holds for every integer j between 0 and $\lambda_\alpha(w)$, as before.

By definition of Π, there is a $u \in \Upsilon^+$ and an element σ of the Weyl group such that $w = \sigma(u)$ and $u \preceq v$. Under these conditions, we have that $u = w$, as in Section 30.4. Thus $w \preceq v$.

If $j \in \mathbf{Z}$, then $w - j\,\alpha \in \Upsilon$, and so there is an element σ_j of the Weyl group such that

$$\sigma_j(w - j\,\alpha) \in \Upsilon^+, \tag{30.9.4}$$

as in Section 30.4. We would like to check that

$$\sigma_j(w - j\,\alpha) \preceq v \tag{30.9.5}$$

when j is between 0 and $\lambda_\alpha(w)$.

Remember that $\sigma_j(w) \preceq w$, because $w \in \Upsilon^+$, as in Section 30.5. If

$$j\,\sigma_j(\alpha) \succeq 0, \tag{30.9.6}$$

then we get that

$$\sigma_j(w - j\,\alpha) = \sigma_j(w) - j\,\sigma_j(\alpha) \preceq \sigma_j(w) \preceq w \preceq v. \tag{30.9.7}$$

Observe that

$$w - j\,\alpha = \sigma_\alpha(w) - (j - \lambda_\alpha(w))\,\alpha, \tag{30.9.8}$$

so that

$$\sigma_j(w - j\,\alpha) = \sigma_j(\sigma_\alpha(w)) - (j - \lambda_\alpha(w))\,\sigma_j(\alpha). \tag{30.9.9}$$

As before, $\sigma_j(\sigma_\alpha(w)) \preceq w$, because $w \in \Upsilon^+$, as in Section 30.5. If

$$(j - \lambda_\alpha(w))\,\sigma_j(\alpha) \succeq 0, \tag{30.9.10}$$

then it follows that

$$\sigma_j(w - j\,\alpha) \preceq \sigma_j(\sigma_\alpha(w)) \preceq w \preceq v. \tag{30.9.11}$$

Because $\sigma_j(\alpha) \in \Phi$, we automatically have that $\sigma_j(\alpha) \succeq 0$ or $\sigma_j(\alpha) \preceq 0$. If j is between 0 and $\lambda_\alpha(w)$, then it is easy to see that one of j and $j - \lambda_\alpha(w)$ is greater than or equal to 0, and the other is less than or equal to 0. This implies that (30.9.6) or (30.9.10) holds. It follows that (30.9.5) holds in either case, by (30.9.7) and (30.9.11). This shows that Π is saturated in Υ, as desired.

It is easy to see that Π has highest weight v, as on p71 of [14]. More precisely, $v \in \Pi$ by construction, because $v \in \Upsilon^+$, by hypothesis. Let $u \in \Upsilon^+$ with $u \preceq v$ be given, and let σ be an element of the Weyl group of Φ. Note that $\sigma(u) \preceq u$, as in Section 30.5. This implies that $\sigma(u) \preceq v$, as desired.

30.10 Another look at saturated sets

Let us continue with the same notation and hypotheses as in the previous section. Also let $v \in \Upsilon^+$ be given, and put

$$\Pi^v = \{u \in \Upsilon : \sigma(u) \preceq v \text{ for every element } \sigma \text{ of the Weyl group of } \Phi\}. \tag{30.10.1}$$

Observe that

$$v \in \Pi^v, \tag{30.10.2}$$

because $v \in \Upsilon^+$, as in Section 30.5. Of course, Π^v is automatically invariant under every element of the Weyl group of Φ.

Let $\Pi_v = \Pi$ be the subset of Υ defined as in (30.8.11) again, and let us check that

$$\Pi^v = \Pi_v. \tag{30.10.3}$$

By construction, every element of Π_v is of the form $\tau(u)$, where $u \in \Upsilon^+$, $u \preceq v$, and τ is an element of the Weyl group of Φ. Let σ be any element of the Weyl group of Φ, so that $\sigma \circ \tau$ is an element of the Weyl group too. This implies that

$$\sigma(\tau(u)) \preceq u, \tag{30.10.4}$$

because $u \in \Upsilon^+$, as in Section 30.5. It follows that

$$\sigma(\tau(u)) \preceq v, \tag{30.10.5}$$

so that $\tau(u) \in \Pi^v$.

Now let u be any element of Π^v, and let σ be an element of the Weyl group of Φ such that $\sigma(u) \in \Upsilon^+$, as in Section 30.4. We also have that $\sigma(u) \preceq v$, by definition of Π^v. This implies that $u \in \Pi_v$, because the inverse of σ is in the Weyl group of Φ.

Let us verify directly that Π^v is saturated as a subset of Υ, as a variant of the argument in the previous section. Let $u \in \Pi^v$ and $\alpha \in \Phi$ be given, and let us check that

$$u - j\,\alpha \in \Pi^v \tag{30.10.6}$$

for every integer j between 0 and $\lambda_\alpha(u)$. To do this, let an element σ of the Weyl group of Φ be given, and let us show that

$$\sigma(u - j\,\alpha) \preceq v. \tag{30.10.7}$$

Of course, $\sigma(u) \preceq v$, because $u \in \Pi^v$. If

$$j\,\sigma(\alpha) \succeq 0, \tag{30.10.8}$$

then

$$\sigma(u - j\,\alpha) = \sigma(u) - j\,\sigma(\alpha) \preceq \sigma(u) \preceq v. \tag{30.10.9}$$

We also have that

$$u - j\,\alpha = \sigma_\alpha(u) - (j - \lambda_\alpha(u))\,\alpha, \tag{30.10.10}$$

so that

$$\sigma(u - j\,\alpha) = \sigma(\sigma_\alpha(u)) - (j - \lambda_\alpha(u))\,\sigma(\alpha). \tag{30.10.11}$$

Note that $\sigma(\sigma_\alpha(u)) \preceq v$, because $u \in \Pi^v$ and $\sigma \circ \sigma_\alpha$ is in the Weyl group of Φ. If

$$(j - \lambda_\alpha(u))\,\sigma(\alpha) \succeq 0, \tag{30.10.12}$$

then we get that

$$\sigma(u - j\,\alpha) \preceq \sigma(\sigma_\alpha(u)) \preceq v. \tag{30.10.13}$$

As before, we automatically have that $\sigma(\alpha) \succeq 0$ or $\sigma(\alpha) \preceq 0$, because $\sigma(\alpha)$ is in Φ. We also have that one of j and $j - \lambda_\alpha(u)$ is greater than or equal to 0, and the other is less than or equal to 0, because j is between 0 and $\lambda_\alpha(u)$, by hypothesis. Using this, it is easy to see that (30.10.8) or (30.10.12) holds. In either case, we get that (30.10.7) holds, as desired. Note that Π^v has highest weight v, by construction.

30.11 A property of saturated sets

Let us continue with the same notations and hypotheses as in Section 30.1 and 30.3, and let $\preceq$ be defined on V as in Section 30.5. In this section, we continue to suppose that Φ is reduced as a root system in V. Let $(\cdot, \cdot)$ be an inner product on V that is invariant under the Weyl group of Φ.

Let Π be a saturated subset of Υ, with highest weight $v \in \Upsilon^+$. If $w \in \Pi$ and ρ is as in Section 30.6, then Lemma C on p71 of [14] states that

$$(w + \rho, w + \rho) \le (v + \rho, v + \rho), \tag{30.11.1}$$

with equality only when $w = v$. To see this, let σ be an element of the Weyl group of Φ such that $u = \sigma(w) \in \Upsilon^+$, as in Section 30.4. Remember that

$$(w + \rho, w + \rho) \le (u + \rho, u + \rho), \tag{30.11.2}$$

with equality only when $u = w$, as in Section 30.6. Thus it suffices to show that

$$(u + \rho, u + \rho) \le (v + \rho, v + \rho), \tag{30.11.3}$$

with equality only when $u = v$.

Note that $u \in \Pi$, because $\sigma(\Pi) = \Pi$, as in Section 30.7. This means that $u \preceq v$, because Π has highest weight v. Observe that

$$\begin{aligned} &(v + \rho, v + \rho) - (u + \rho, u + \rho) \\ &\quad = ((v + \rho, v + \rho) - (v + \rho, u + \rho)) + ((v + \rho, u + \rho) - (u + \rho, u + \rho)) \\ &\quad = (v + \rho, v - u) + (v - u, u + \rho). \end{aligned} \tag{30.11.4}$$

Remember that $\rho \in \Upsilon^+$, and in fact ρ is strongly dominant, as in Section 30.6. This implies that $u + \rho$ and $v + \rho$ are strongly dominant too, because $u, v \in \Upsilon^+$.

It follows that each of the terms on the right side of (30.11.4) is greater than or equal to 0, with equality only when $u = v$, because $u \preceq v$. Combining this with (30.11.4), we get that (30.11.3) holds, with equality only when $u = v$, as desired.

Chapter 31

Regular elements and polynomials

31.1 Integral domains and polynomials

As usual, a commutative ring A with a nonzero multiplicative identity element is said to be an *integral domain* if it has no nontrivial zero-divisors. This means that if $a, b \in A$ and $a, b \neq 0$, then $a\,b \neq 0$.

Let A be an integral domain, and let T be an indeterminate. It is well known and easy to see that the ring $A[T]$ of formal polynomials in T with coefficients in A is an integral domain too.

Similarly, let $T_1, \ldots, T_n$ be n commuting indeterminates, for some positive integer n. It is well known that the ring $A[T_1, \ldots, T_n]$ of formal polynomials in $T_1, \ldots, T_n$ with coefficients in A is an integral domain. To see this, remember that $A[T_1, \ldots, T_n]$ is isomorphic to the ring

$$(A[T_1, \ldots, T_{n-1}])[T_n] \tag{31.1.1}$$

of formal polynomials in T_n with coefficients in $A[T_1, \ldots, T_{n-1}]$, as in Section 5.8. This permits one to reduce to the $n = 1$ case, using induction.

Let T be an indeterminate again, and let $f(T)$ be a nonzero element of $A[T]$. This leads to a polynomial function $f(a)$ on A with values in A, as in Section 5.7. It is well known and not difficult to show that $f(a) = 0$ for only finitely many $a \in A$. More precisely, the number of such elements a of A is less than or equal to the degree of $f(T)$.

Let $T_1, \ldots, T_n$ be n commuting indeterminates again, and let $f(T_1, \ldots, T_n)$ be a nonzero element of $A[T_1, \ldots, T_n]$. This leads to a polynomial function $f(a_1, \ldots, a_n)$ on the space A^n of n-tuples of elements of A with values in A, as in Section 5.9.

Suppose that $E_1, \ldots, E_n$ are infinite subsets of A, and put

$$E = \prod_{j=1}^{n} E_j. \tag{31.1.2}$$

Under these conditions, there is an $(a_1, \ldots, a_n) \in E$ such that $f(a_1, \ldots, a_n) \neq 0$. In particular, if A has infinitely many elements, then $f(a_1, \ldots, a_n) \neq 0$ for some $(a_1, \ldots, a_n) \in A^n$.

To see this, it is helpful to consider $f(T_1, \ldots, T_n)$ as an element of (31.1.1), as before. More precisely, we can express $f(T_1, \ldots, T_n)$ as

$$f(T_1, \ldots, T_n) = \sum_{j=1}^{l} f_j(T_1, \ldots, T_{n-1})\, T_n^j, \tag{31.1.3}$$

where l is a nonnegative integer and $f_j(T_1, \ldots, T_{n-1})$ is an element of

$$A[T_1, \ldots, T_{n-1}] \tag{31.1.4}$$

for each $j = 0, 1, \ldots, l$. The hypothesis that $f(T_1, \ldots, T_n) \neq 0$ means that $f_j(T_1, \ldots, T_{n-1}) \neq 0$ for some j, and one may as well suppose that this holds with $j = l$.

If $a_n \in A$, then

$$f(T_1, \ldots, T_{n-1}, a_n) = \sum_{j=0}^{l} f_j(T_1, \ldots, T_{n-1})\, a_n^j \tag{31.1.5}$$

defines an element of (31.1.4). Equivalently, if we consider (31.1.3) as a formal polynomial in T_n with coefficients in (31.1.4), then we can evaluate the corresponding polynomial function at a_n to get an element of (31.1.4).

Of course, (31.1.3) is nonzero as an element of (31.1.1), by hypothesis. This implies that (31.1.5) can be equal to 0 as an element of (31.1.4) for only finitely many $a_n \in A$, as before. In particular, there is an $a_n \in E_n$ such that (31.1.5) is nonzero as an element of (31.1.4), because E_n has infinitely many elements, by hypothesis.

If $n \geq 2$, then we may as well suppose that the polynomial function on A^{n-1} associated to (31.1.5) is nonzero at some element $(a_1, \ldots, a_{n-1})$ of $\prod_{j=1}^{n-1} E_j$, by induction. The value of this function at $(a_1, \ldots, a_{n-1})$ is the same as the value of the polynomial function on A^n associated to $f(T_1, \ldots, T_{n-1}, T_n)$ at $(a_1, \ldots, a_{n-1}, a_n)$. Thus $f(a_1, \ldots, a_n) \neq 0$, as desired.

31.2 The Zariski topology

Let k be an integral domain, let n be a positive integer, and let $T_1, \ldots, T_n$ be n commuting indeterminates. Also let k^n be the set of n-tuples of elements of k, as usual, so that every element of $k[T_1, \ldots, T_n]$ determines a polynomial function on k^n, as in Section 5.9. If C is a nonempty subset of $k[T_1, \ldots, T_n]$, then let

$$\mathcal{V}(C) = \mathcal{V}_{k^n}(C) = \{(x_1, \ldots, x_n) \in k^n : f(x_1, \ldots, x_n) = 0 \text{ for every } f(T_1, \ldots, T_n) \in C\} \tag{31.2.1}$$

be the set of points in k^n at which all of the polynomial functions associated to elements of C vanish.

It is easy to see that (31.2.1) is the same as for the ideal in $k[T_1, \ldots, T_n]$ generated by C. If k is Noetherian, then it is well known that $k[T_1, \ldots, T_n]$ is Noetherian, so that every ideal in $k[T_1, \ldots, T_n]$ is finitely generated.

If C_1, C_2 are nonempty subsets of $k[T_1, \ldots, T_n]$, then the collection $C_1 \cdot C_2$ of all products of elements of C_1 and C_2 is a nonempty subset of $k[T_1, \ldots, T_n]$ as well. One can check that

$$\mathcal{V}(C_1 \cdot C_2) = \mathcal{V}(C_1) \cup \mathcal{V}(C_2), \tag{31.2.2}$$

because k is an integral domain.

Similarly, let I be a nonempty set, and let C_j be a nonempty subset of $k[T_1, \ldots, T_n]$ for each $j \in I$. Observe that

$$\mathcal{V}\Big(\bigcup_{j \in I} C_j\Big) = \bigcap_{j \in I} \mathcal{V}(C_j). \tag{31.2.3}$$

A subset of k^n of the form (31.2.1) is said to be *Zariski closed.* Note that the empty set and k^n are Zariski-closed sets. Thus the collection of Zariski-closed subsets of k^n is the collection of closed sets with respect to a topology on k^n, which is the *Zariski topology.*

It is easy to see that a subset of k^n with only one element is Zariski closed, so that k^n satisfies the first separation condition with respect to the Zariski topology. If k has only finitely many elements, then the Zariski topology on k^n is the same as the discrete topology.

Of course, the Zariski topology can be defined on k, by taking $n = 1$ in the previous definition. The Zariski-closed subsets of k are the finite subsets of k, as well as k itself. Note that polynomial functions on k^n are continuous with respect to the Zariski topologies on k and k^n.

A subset of k^n is said to be *irreducible* if it is not contained in the union of two Zariski-closed sets, neither of which contains the given set. If k has infinitely many elements, then it is well known that

$$k^n \text{ is irreducible,} \tag{31.2.4}$$

as in Lemma A on p133 of [14].

Indeed, suppose that C_1, C_2 are nonempty subsets of $k[T_1, \ldots, T_n]$ such that

$$k^n \subseteq \mathcal{V}(C_1) \cup \mathcal{V}(C_2), \tag{31.2.5}$$

and that k^n is not contained in either $\mathcal{V}(C_1)$ or $\mathcal{V}(C_2)$. This implies that there are elements $f(T_1, \ldots, T_n)$, $g(T_1, \ldots, T_n)$ of C_1, C_2, respectively, such that the corresponding polynomial functions are nonzero at some elements of k^n. Of course, this means that the corresponding formal polynomials are nonzero, so that their product

$$f(T_1, \ldots, T_n)\, g(T_1, \ldots, T_n) \tag{31.2.6}$$

is nonzero as an element of $k[T_1, \ldots, T_n]$ too, as in the previous section. It follows that the polynomial function on k^n corresponding to (31.2.6) is nonzero at an element of k^n, because k has infinitely many elements, as in the previous section. This contradicts (31.2.5), which implies that the product of the polynomial functions corresponding to $f(T_1, \ldots, T_n)$ and $g(T_1, \ldots, T_n)$ vanishes everywhere on k^n.

If U, V are two nonempty Zariski-open subsets of k^n, then (31.2.4) implies that

$$U \cap V \neq \emptyset \tag{31.2.7}$$

when k has infinitely many elements. This means that nonempty Zariski-open subsets of k^n are dense in k^n with respect to the Zariski topology when k has infinitely many elements, as in the corollary on p133 of [14].

31.3 Polynomial mappings

Let us continue with the same notation and hypotheses as in the previous section, and let m be another positive integer. Also let $Z_1, \ldots, Z_m$ be m commuting indeterminates, so that elements of $k[Z_1, \ldots, Z_m]$ determine polynomial functions on k^m, as before.

Suppose that

$$\phi_1(Z_1, \ldots, Z_m), \ldots, \phi_n(Z_1, \ldots, Z_m) \tag{31.3.1}$$

are n elements of $k[Z_1, \ldots, Z_m]$. These determine n polynomial functions on k^m, which can be used to define a mapping ϕ from k^m into k^n. More precisely, if $x \in k^m$, then $\phi(x)$ is the element of k^n whose jth coordinate is $\phi_j(x_1, \ldots, x_m)$ for every $j = 1, \ldots, n$.

It is easy to see that the composition of a polynomial function on k^n with ϕ is a polynomial function on k^m. Indeed, if $f(T_1, \ldots, T_n) \in k[T_1, \ldots, T_n]$, then one can get an element of $k[Z_1, \ldots, Z_m]$ by replacing T_j with $\phi_j(Z_1, \ldots, Z_m)$ for every $j = 1, \ldots, n$. This defines a homomorphism from $k[T_1, \ldots, T_n]$ into $k[Z_1, \ldots, Z_m]$, as algebras over k, with

$$T_j \mapsto \phi_j(Z_1, \ldots, Z_m) \tag{31.3.2}$$

for each $j = 1, \ldots, n$. Of course, this homomorphism takes elements of k to themselves, as formal polynomials in $T_1, \ldots, T_n$ or $Z_1, \ldots, Z_m$. The composition of the polynomial function on k^n associated to $f(T_1, \ldots, T_n)$ with ϕ is the same as the polynomial function on k^m associated to the corresponding element of $k[Z_1, \ldots, Z_m]$.

Let C be a nonempty subset of $k[T_1, \ldots, T_n]$, and let C_0 be the corresponding collection of elements of $k[Z_1, \ldots, Z_m]$, as in the preceding paragraph. Observe that

$$\phi^{-1}(\mathcal{V}_{k^n}(C)) = \mathcal{V}_{k^m}(C_0), \tag{31.3.3}$$

where $\mathcal{V}_{k^n}(C)$, $\mathcal{V}_{k^m}(C_0)$ are as in (31.2.1). This implies that ϕ is continuous with respect to the Zariski topologies on k^m, k^n.

Remember that k^m, k^n may be considered as modules over k, with respect to coordinatewise addition and scalar multiplication. Let $a = (a_{j,l})$ be an $n \times m$ matrix with entries in k, and consider

$$\phi_j(Z_1, \ldots, Z_m) = \sum_{l=1}^{m} a_{j,l}\, Z_l \tag{31.3.4}$$

for each $j = 1, \ldots, n$. The corresponding mapping ϕ from k^m into k^n is a module homomorphism in this case.

Suppose that $m = n$, and that a is invertible as an $n \times n$ matrix with entries in k. This implies that ϕ is a one-to-one mapping from k^n onto itself, whose inverse corresponds to the inverse of a. It follows that ϕ is a homeomorphism from k^n onto itself, with respect to the Zariski topology.

If V is any module over k that is free of rank n, then V is isomorphic to k^n, as a module over k. In particular, we can use this to define the Zariski topology on V. Using the remarks in the preceding paragraph, we get that this topology does not depend on the particular isomorphism between V and k^n.

Suppose now that $m = 1$, so that we can use a single indeterminate Z. If $a_1, \ldots, a_n$ and $b_1, \ldots, b_n$ are elements of k, then we can take

$$\phi_j(Z) = a_j\, Z + b_j \tag{31.3.5}$$

for $j = 1, \ldots, n$. The corresponding mapping ϕ from k into k^n maps k onto an affine line in k^n, at least if $a_j \neq 0$ for some j.

31.4 More on the Zariski topology

Let X be a topological space, and let E be a subset of X. As in Section 31.2, we may say that E is *irreducible* if E is not contained in the union of two closed subsets of X, neither of which contains E. Let us check that this implies that E is connected, as mentioned on p133 of [14].

If E is not connected, then E can be expressed as the union of two nonempty separated subsets E_1, E_2 of X. This means that

$$\overline{E_1} \cap E_2 = E_1 \cap \overline{E_2} = \emptyset, \tag{31.4.1}$$

where $\overline{E_1}$, $\overline{E_2}$ are the closures of E_1, E_2 in X, respectively. It follows that

$$E \subseteq \overline{E_1} \cup \overline{E_2}, \tag{31.4.2}$$

and that E is not contained in either $\overline{E_1}$ or $\overline{E_2}$. This contradicts irreducibility, as desired.

Note that X is irreducible as a subset of itself if and only if X cannot be expressed as the union of two proper closed subsets of itself. This is the same as saying that the intersection of any two nonempty open subsets of X is nonempty. Equivalently, this means that any nonempty open subset of X is dense in X.

Suppose that X is irreducible, as a subset of itself. If U is any open subset of X, then one can verify that U is irreducible in X.

Let us continue now with the same notation and hypotheses as in Section 31.2. Suppose for the moment that k has infinitely many elements, so that k^n is irreducible, as before. If U is a Zariski-open subset of k^n, then U is irreducible, as in the preceding paragraph. This implies that U is connected with respect to the Zariski topology.

Let k be a field equipped with an absolue value function $|\cdot|$. Note that polynomial functions on k^n are continuous, with respect to the topology determined on k by the metric associated to $|\cdot|$, and the corresponding product topology on k^n. This implies that Zariski-closed subsets of k^n are closed sets with respect to this product topology.

Suppose that $|\cdot|$ is not the trivial absolute value function on k. This means that open balls in k with respect to the metric associated to $|\cdot|$ have infinitely many elements. It follows that any nonempty open subset of k^n with respect to the corresponding product topology contains the Cartesian product of n infinite subsets of k. If a polynomial on k^n vanishes on a nonempty open subset W of k^n with respect to this product topology, then the polynomial vanishes on all of k^n, as in Section 31.1. Thus W is dense in k^n with respect to the Zariski topology under these conditions.

Equivalently, a proper Zarski-closed subset of k^n has empty interior with respect to this product topology. This implies that a nonempty Zariski-open subset of k^n is dense in k^n with respect to this product topology in this case.

Of course, any two distinct elements of k^n are contained in a unique affine line in k^n. Let U be a Zariski-open subset of k^n. The intersection of U with any affine line in k^n is either empty, or contains all but finitely many elements of the line. One can use this to check that any Zariski-open subset of $\mathbf{C}^n$ is path connected, with respect to the product topology on $\mathbf{C}^n$ corresponding to the standard topology on $\mathbf{C}$.

31.5 Regular elements of Lie algebras

Let k be a field, and let $(A, [\cdot,\cdot]_A)$ be a Lie algebra over k of positive finite dimension n, as a vector space over k. Also let T be an indeterminate, and let $I = I_A$ be the identity mapping on A. If $x \in A$, then let

$$Q_x(T) = \det(\mathrm{ad}_x - T\,I) \tag{31.5.1}$$

be the characteristic polynomial of ad_x, as a linear mapping from A into itself, as in Section 18.3.

Of course, we can use a basis for A to identify A with k^n, as a vector space over k. This permits us to express (31.5.1) as

$$Q_x(T) = \sum_{j=0}^{n} q_j(x)\, T^j, \tag{31.5.2}$$

where $q_j(x)$ corresponds to a homogeneous polynomial of degree $n - j$ in the coordinates of x for every $j = 0, 1, \ldots, n$, as in Section 18.3 again.

Let us suppose from now on in this section that k has infinitely many elements. This implies that formal polynomials in n commuting indeterminates with coefficients in k are uniquely determined by the corresponding polynomial functions on k^n, as in Section 31.1.

Remember that $q_n(x)$ corresponds to the constant polynomial $(-1)^n$, by construction. Let n_0 be the smallest integer $j = 0, 1, \ldots, n$ such that $q_j(x)$ is not identically zero on A. This may be called the *rank* of A, as in Definition 2 on p11 of [24], or the *ρ-rank* of A, as on p133 of [14].

Of course, $\mathrm{ad}_x(x) = 0$ for every $x \in A$, which implies that $q_0(x) = 0$, because $n \geq 1$, by hypothesis. This means that

$$n_0 \geq 1, \tag{31.5.3}$$

as on p11 of [24].

If $x \in A$, then let $n_0(x)$ be the smallest integer $j = 0, 1, \ldots, n$ such that $q_j(x) \neq 0$. This was initially defined another way in Section 18.3, and the equivalence with this formulation was mentioned just afterwards. Note that

$$n_0(x) \leq n, \tag{31.5.4}$$

because $q_n(x) = (-1)^n$, and that

$$n_0 = \min\{n_0(x) : x \in A\}, \tag{31.5.5}$$

by construction.

Thus $n_0 = n$ if and only if $n_0(x) = n$ for every $x \in A$. This happens exactly when A is nilpotent as a Lie algebra, as on p11 of [24], and mentioned in Section 18.3.

Observe that $x \in A$ satisfies

$$n_0(x) = n_0 \tag{31.5.6}$$

if and only if

$$q_{n_0}(x) \neq 0, \tag{31.5.7}$$

because $q_j(x) = 0$ when $j < n_0$, by definition of n_0. In this case, x is said to be *regular*, as in Definition 2 on p11 of [24], or *ρ-regular*, as on p133 of [14]. The set $\mathcal{R}(A)$ of regular elements of A is nonempty, by (31.5.5).

31.6 The set of regular elements

Let us continue with the same notation and hypotheses as in the previous section. As before, we can use a basis for A to identify A with k^n, as a vector space over k. Using this, we can define the Zariski topology on A as in Section 31.2. The Zariski topology on A does not depend on the choice of basis, as in Section 31.3.

The set $\mathcal{R}(A)$ of regular elements of A is an open set with respect to the Zariski topology on A, because of the characterization (31.5.7) of its elements. We also have that $\mathcal{R}(A) \neq \emptyset$, by definition of n_0, as in the previous section. It follows that $\mathcal{R}(A)$ is dense in A with respect to the Zariski topology, as in Section 31.2, because k has infinitely many elements. This corresponds to some remarks on p133 of [14].

Let $|\cdot|$ be an absolute value function on k. As usual, the metric on k associated to $|\cdot|$ determines a topology on k, which leads to the corresponding product topology on k^n. This defines a topology on A, that we shall call the topology associated to $|\cdot|$, because A is identified with k^n. It is easy to see that this topology does not depend on the choice of basis for A, because linear mappings from k^n into itself are continuous with respect to this product topology.

The topology on A associated to $|\cdot|$ is at least as strong as the Zariski topology, as in Section 31.4. This means that $\mathcal{R}(A)$ is an open set in A with respect to the topology associated to $|\cdot|$. If $|\cdot|$ is not the trivial absolute value function on k, then $\mathcal{R}(A)$ is dense in A with respect to the topology associated to $|\cdot|$, as in Section 31.4 again.

Note that $\mathcal{R}(A)$ is connected with respect to the Zariski topology on A, because k has infinitely many elements, as in Section 31.4. If $k = \mathbf{C}$ with the standard absolute value function, then $\mathcal{R}(A)$ is path connected with respect to the topology on A associated to $|\cdot|$, as before. These properties of $\mathcal{R}(A)$ correspond to Proposition 1 on p11 of [24].

If $x \in A$, then let $A_{x,0}$ be the set of $y \in A$ such that $(\mathrm{ad}_x)^l(y) = 0$ for some positive integer l, as in Section 18.1. Remember that this is a Lie subalgebra of A, which is called an Engel subalgebra, as in Section 18.4. We also have that

$$n_0(x) = \dim A_{x,0}, \tag{31.6.1}$$

as in Section 18.3.

Thus

$$n_0 = \min\{\dim A_{x,0} : x \in A\}, \tag{31.6.2}$$

by (31.5.5). Similarly,

$$\mathcal{R}(A) = \{x \in A : \dim A_{x,0} = n_0\}. \tag{31.6.3}$$

If $x \in \mathcal{R}(A)$, then $A_{x,0}$ is minimal with respect to inclusion among Engel subalgebras of A, because the dimension of $A_{x,0}$ is minimal among the dimensions of Engel subalgebras of A. This implies that

$$A_{x,0} \text{ is a Cartan subalgebra of } A, \tag{31.6.4}$$

as in the theorem on p80 of [14], and as mentioned in Section 18.8. This corresponds to Theorem 1 on p12 of [24].

31.7 Regularity and automorphisms

Let us continue with the same notation and hypotheses as in the previous two sections. Suppose for the moment that ϕ is an automorphism of A, as a Lie algebra over k. If $x, y \in A$, then

$$\phi(\mathrm{ad}_x(y)) = \phi([x, y]_A) = [\phi(x), \phi(y)]_A = \mathrm{ad}_{\phi(x)}(\phi(y)). \tag{31.7.1}$$

This means that $\phi \circ \mathrm{ad}_x = \mathrm{ad}_{\phi(x)} \circ \phi$, so that

$$\mathrm{ad}_{\phi(x)} = \phi \circ \mathrm{ad}_x \circ \phi^{-1}. \tag{31.7.2}$$

It follows that ad_x and $\mathrm{ad}_{\phi(x)}$ have the same characteristic polynomials, which is to say that

$$Q_{\phi(x)}(T) = Q_x(T). \tag{31.7.3}$$

This implies that

$$q_j(\phi(x)) = q_j(x) \tag{31.7.4}$$

for every $j = 0, 1, \ldots, n$. One can also verify that

$$\phi(A_{x,0}) = A_{\phi(x),0}. \tag{31.7.5}$$

Note that

$$n_0(\phi(x)) = n_0(x), \tag{31.7.6}$$

using either the characterization of $n_0(x)$ in Section 31.5, or (31.6.1). Similarly,

$$\phi(\mathcal{R}(A)) = \mathcal{R}(A). \tag{31.7.7}$$

Let x be an element of $\mathcal{R}(A)$, so that $A_{x,0}$ is a Cartan subalgebra of A. Note that $x \in A_{x,0}$, so that every element of $\mathcal{R}(A)$ is contained in a Cartan subalgebra of A.

Suppose for the moment that k is an algebraically closed field of characteristic 0. If C is any Cartan subalgebra of A, then there is a Lie algebra automorphism ϕ of A such that

$$C = \phi(A_{x,0}), \tag{31.7.8}$$

as in Section 24.9. Of course, this means that

$$C = A_{\phi(x),0}, \tag{31.7.9}$$

by (31.7.5). We also have that $\phi(x) \in \mathcal{R}(A)$, by (31.7.7). This corresponds to Corollary 2 on p13 of [24].

Observe that

$$\dim C = \dim A_{x,0} = n_0 \tag{31.7.10}$$

under these conditions. This corresponds to Corollary 1 on p13 of [24]. It follows that the definition of the rank of A in Section 24.13 is equivalent to the one in Section 31.5 when k is an algebraically closed field of characteristic 0.

31.8 Regular semisimple elements

Let us continue with the same notation and hypotheses as in the previous three sections. If $x \in A$ is ad-diagonalizable, then $A_{x,0}$ is the same as the kernel of ad_x on A. This is the same as the centralizer $C_A(x) = C_A(\{x\})$ of x in A, so that

$$A_{x,0} = C_A(x), \tag{31.8.1}$$

as in Section 18.9.

Of course, if x is any element of A, then $C_A(x)$ contains any commutative Lie subalgebra of A that contains x. If $C_A(x)$ is commutative as a Lie subalgebra of A, then $C_A(x)$ is maximal among commutative Lie subalgebras of A.

Suppose that $C_A(x)$ is a toral subalgebra of A, as in Section 17.1. Remember that toral subalgebras of A are commutative as Lie subalgebras of A. This implies that $C_A(x)$ is maximal among toral subalgebras of A, as in the preceding paragraph.

If $C_A(x)$ is a toral subalgebra of A, then x is ad-diagonalizable in A, because $x \in C_A(x)$. This means that (31.8.1) holds, so that

$$n_0(x) = \dim C_A(x), \tag{31.8.2}$$

by (31.6.1).

Suppose from now on in this section that k is an algebraically closed field of characteristic 0, and that A is semisimple as a Lie algebra over k. If $x \in A$ has the property that $C_A(x)$ is a toral subalgebra of A, and thus a maximal toral subalgebra of A, then x may be called *regular semisimple* in A, as on p80 of [14].

If B is any maximal toral subalgebra of A, then

$$B = C_A(x) \tag{31.8.3}$$

for some $x \in A$, which is therefore regular semisimple in A, as on p80 of [14]. Indeed, B is a Cartan subalgebra of A, as in Section 18.10. This implies that

$$B = A_{x,0} \tag{31.8.4}$$

for some $x \in A$, as in Section 18.8. Of course, $x \in A_{x,0}$, so that $x \in B$, and thus x is ad-diagonalizable in A. This means that (31.8.3) follows from (31.8.1) and (31.8.4), as desired.

Alternatively, one can get $x \in A$ such that (31.8.3) holds as in Section 18.13, as mentioned on p80 of [14]. This uses the fact that B is equal to its centralizer $C_A(B)$ in A, as in Section 17.4.

Suppose that $x \in A$ and that $A_{x,0}$ is a Cartan subalgebra of A. Every Cartan subalgebra of A is of this form, as in Section 18.8 again. Under these conditions, $A_{x,0}$ is a maximal toral subalgebra of A, as in Section 18.10. This implies that x is ad-diagonalizable in A, because $x \in A_{x,0}$, so that (31.8.1) holds. It follows that x is regular semisimple in A.

If $x \in \mathcal{R}(A)$, then $A_{x,0}$ is a Cartan subalgebra of A, as before. In particular, this implies that x is ad-diagonalizable in A, as in Corollary 2 on p15 of [24]. This is also mentioned on p134 of [14], using another argument. More precisely, x is regular semisimple in A, as in the preceding paragraph.

31.9 Regularity and semisimplicity

We continue with the same notation and hypotheses as in the previous four sections. Let us also continue to ask that k be an algebraically closed field of characteristic 0, and that A be semisimple as a Lie algebra over k.

Let $x \in A$ be given, and let $x = x_1 + x_2$ be the abstract Jordan decomposition of x in A, as in Section 14.3. Thus $x_1, x_2 \in A$, x_1 is ad-diagonalizable in A, x_2 is ad-nilpotent in A, and $[x_1, x_2]_A = 0$. This means that $\mathrm{ad}_x = \mathrm{ad}_{x_1} + \mathrm{ad}_{x_2}$ is the usual Jordan decomposition of ad_x, as a linear mapping from A into itself.

It follows that ad_x and ad_{x_1} have the same characteristic polynomials, as linear mappings from A into itself. This means that

$$Q_x(T) = Q_{x_1}(T), \tag{31.9.1}$$

in the notation of Section 31.5. It follows that

$$q_j(x) = q_j(x_1) \tag{31.9.2}$$

for every $j = 0, 1, \ldots, n$. This is related to some remarks on p133 of [14]. Similarly,

$$n_0(x) = n_0(x_1), \tag{31.9.3}$$

using the characterization of $n_0(\cdot)$ in Section 31.5.

Alternatively, one can check directly that

$$A_{x,0} = A_{x_1,0}, \tag{31.9.4}$$

as in Section 18.9. This implies (31.9.3), because of (31.6.1).

This gives another way to see that there are elements of $\mathcal{R}(A)$ that are ad-diagonalizable in A, as on p133 of [14]. More precisely, $x \in \mathcal{R}(A)$ if and only if $x_1 \in \mathcal{R}(A)$, by (31.9.3).

If $y \in A$ is ad-diagonalizable, then y is contained in a maximal toral subalgebra B of A. If z is any element of B, then z is ad-diagonalizable in A, so that $A_{z,0} = C_A(z)$, as in (31.8.1). We also have that $B \subseteq C_A(z)$, because B is commutative as a Lie subalgebra of A, as in Section 17.1. This implies that

$$n_0(z) = \dim A_{z,0} = \dim C_A(z) \geq \dim B. \tag{31.9.5}$$

Note that there are $z \in B$ such that $B = C_A(z)$, so that equality holds in (31.9.5), as in the previous section.

Of course, we can take $z = y$ in (31.9.5), to get that

$$n_0(y) = \dim A_{y,0} \geq \dim B. \tag{31.9.6}$$

If $y \in \mathcal{R}(A)$ too, then we get that

(31.9.7) $$n_0 = n_0(y) = \dim B,$$

because there are $z \in B$ for which equality holds in (31.9.5). This implies that $A_{y,0} = C_A(y) = B$, so that y is regular semisimple in A, in the sense described in the previous section. If $z \in B$ and $C_A(z) = B$, so that equality holds in (31.9.5), then we obtain that $n_0(z) = n_0$, which means that $z \in \mathcal{R}(A)$. This corresponds to some remarks on p133 of [14].

Suppose that $x \in \mathcal{R}(A)$, so that the ad-diagonalizable part x_1 of x is in $\mathcal{R}(A)$ too, as before. This implies that x_1 is regular semisimple in A, as in the preceding paragraph. Thus $C_A(x_1)$ is a toral subalgebra of A that contains the ad-nilpotent part x_2 of x. This means that x_2 is also ad-diagonalizable, so that $\mathrm{ad}_{x_2} = 0$. It follows that $x_2 = 0$, because A is semisimple, by hypothesis. Equivalently, $x = x_1$, so that x is ad-diagonalizable. This gives another way to see that every element of $\mathcal{R}(A)$ is ad-diagonalizable in A, as on p133f of [14]. More precisely, this gives another way to see that every element of $\mathcal{R}(A)$ is regular semisimple in A.

If w is any regular semisimple element of A, then $n_0(w) = \dim C_A(w)$, as in (31.8.2). In this case, $C_A(w)$ is a maximal toral subalgebra of A, and thus a Cartan subalgebra of A, as in Section 18.10. This implies that $\dim C_A(w) = n_0$, by (31.7.10). It follows that

(31.9.8) $$n_0(w) = n_0,$$

so that $w \in \mathcal{R}(A)$. This shows that $\mathcal{R}(A)$ is the same as the set of all regular semisimple elements of A, as on p134 of [14].

31.10 Symmetric algebras and homomorphisms

Let k be a commutative ring with a multiplicative identity element, and let V be a module over k. Also let SV be a symmetric algebra of V, as in Section 25.8. Thus SV is a commutative associative algebra over k with a multiplicative identity element e_{SV}, and SV comes with a homomorphism i_{SV} from V into SV, as modules over k.

Let B be a commutative associative algebra over k with a multiplicative identity element e_B. If ϕ is a homomorphism from V into B, as modules over k, then there is a unique algebra homomorphism ψ from SV into B such that $\psi(e_{SV}) = e_B$ and

(31.10.1) $$\psi \circ i_{SV} = \phi,$$

as in Section 25.8. Note that SV is uniquely determined, up to isomorphic equivalence, by this property.

Let W be another module over k, and let SW be a symmetric algebra of W, with multiplicative identity element e_{SW}, and module homomorphism i_{SW} from W into SW. If ξ_1 is a homomorphism from V into W, as modules over k, then

(31.10.2) $$i_{SW} \circ \xi_1$$

is a homomorphism from V into SW, as modules over k. This leads to a unique algebra homomorphism η_1 from SV into SW such that $\eta_1(e_{SV}) = e_{SW}$ and

$$\eta_1 \circ i_{SV} = i_{SW} \circ \xi_1, \tag{31.10.3}$$

as before.

Similarly, let Z be a third module over k, and let SZ be a symmetric algebra of Z, with multiplicative identity element e_{SZ}, and module homomorphism i_{SZ} from Z into SZ. Also let ξ_2 be a module homomorphism from W into Z, so that

$$i_{SZ} \circ \xi_2 \tag{31.10.4}$$

is a module homomorphism from W into SZ. Using this, we get a unique algebra homomorphism η_2 from SW into SZ such that $\eta_2(e_{SW}) = e_{SZ}$ and

$$\eta_2 \circ i_{SW} = i_{SZ} \circ \xi_2, \tag{31.10.5}$$

as usual.

Under these conditions, $\xi_2 \circ \xi_1$ is a homomorphism from V into Z, as modules over k, and

$$i_{SZ} \circ \xi_2 \circ \xi_1 \tag{31.10.6}$$

is a module homomorphism from V into SZ. Of course, $\eta_2 \circ \eta_1$ is an algebra homomorphism from SV into SZ that maps e_{SV} to e_{SZ}, and

$$\eta_2 \circ \eta_1 \circ i_{SV} = \eta_2 \circ i_{SW} \circ \xi_1 = i_{SZ} \circ \xi_2 \circ \xi_1, \tag{31.10.7}$$

by (31.10.3) and (31.10.5). In fact, $\eta_2 \circ \eta_1$ is uniquely determined by these properties, as before.

In particular, we can take $V = Z$, $SV = SZ$, and $i_{SV} = i_{SZ}$. If $\xi_2 \circ \xi_1$ is the identity mapping on V, then we get that $\eta_2 \circ \eta_1$ is the identity mapping on SV.

Similarly, if $\xi_1 \circ \xi_2$ is the identity mapping on W, then $\eta_1 \circ \eta_2$ is the identity mapping on SW. If ξ_1 is a module isomorphism from V onto W, then it follows that η_1 is an algebra isomorphism from SV onto SW.

31.11 Some polynomial functions on V'

Let k be a commutative ring with a multiplicative identity element again, and let V be a module over k. Put

$$V' = \mathrm{Hom}_k(V, k), \tag{31.11.1}$$

which is the space of module homomorphisms from V into k, considered as a module over itself. Remember that V' is a module over k too, with respect to pointwise addition and scalar multiplication of functions on V.

Let SV be a symmetric algebra of V, with multiplicative identity element e_{SV}, and module homomorphism i_{SV} from V into SV. If $\phi_0 \in V'$, then there is a unique algebra homomorphism ψ_0 from SV into k such that $\psi_0(e_{SV}) = 1$ and

$$\psi_0 \circ i_{SV} = \phi_0. \tag{31.11.2}$$

This corresponds to taking $B = k$ in the previous section.

Let $c(V', k)$ be the set of all functions on V' with values in k. This is a module over k with respect to pointwise addition and scalar multiplication of functions on V', and a commutative algebra over k with respect to pointwise multiplication of functions on V'. The multiplicative identity element in $c(V', k)$ is the constant function on V' equal to $1 \in k$.

Note that $V'' = \mathrm{Hom}_k(V', k)$ may be considered as a submodule of $c(V', k)$, as a module over k. If $v \in V$, then let $\Phi(v)$ be the k-valued function on V' defined by

$$\Phi(v)(\phi_0) = \phi_0(v) \tag{31.11.3}$$

for every $\phi_0 \in V'$. This defines Φ as a module homomorphism from V into $c(V', k)$. More precisely, Φ maps V into V''.

It follows that there is a unique algebra homomorphism Ψ from SV into $c(V', k)$ such that $\Psi(e_{SV})$ is the constant function equal to 1 on V' and

$$\Psi \circ i_{SV} = \Phi. \tag{31.11.4}$$

This corresponds to taking $B = c(V', k)$ in the previous section. Note that Ψ maps SV onto the subalgebra of $c(V', k)$ generated by $\Phi(V)$ and the constant functions.

Let $\phi_0 \in V'$ be given, and put

$$E_{\phi_0}(f) = f(\phi_0) \tag{31.11.5}$$

for every $f \in c(V', k)$. This defines an algebra homomorphism from $c(V', k)$ into k. Observe that

$$E_{\phi_0} \circ \Phi = \phi_0, \tag{31.11.6}$$

as a mapping from V into k, by construction.

Clearly $E_{\phi_0} \circ \Psi$ is an algebra homomorphism from SV into k that sends e_{SV} to 1. We also have that

$$E_{\phi_0} \circ \Psi \circ i_{SV} = E_{\phi_0} \circ \Phi = \phi_0, \tag{31.11.7}$$

by (31.11.4) and (31.11.6). This implies that

$$E_{\phi_0} \circ \Psi = \psi_0, \tag{31.11.8}$$

where ψ_0 is as in (31.11.2).

Suppose now that V is free as a module over k, with positive finite rank n, so that V can be identified with k^n, as a module over k. In this case, every element of V' can be expressed in a unique way as a linear combination of the coordinates of an element of k^n with coefficients in k, so that V' can be identified with k^n too, as a module over k.

Similarly, the elements of V'' can be expressed in a unique way as a linear combination of the coordinates of an element of V' with coefficients in k. This means that the mapping Φ defined earlier is an isomorphism from V onto V'', as modules over k. Thus Ψ maps SV onto the subalgebra of $c(V', k)$ generated by V'' and the constant functions.

Under these conditions, SV can be identified with the algebra of formal polynomials in n commuting indeterminates with coefficients in k, as in Section 25.8. With these identifications, Ψ corresponds to the usual mapping from formal polynomials to polynomial functions on k^n.

31.12 Polynomials and symmetric algebras

Let k be a commutative ring with a multiplicative identity element, let V be a module over k, and let $c(V, k)$ be the set of all functions on V with values in k. Thus $c(V, k)$ is a module over k with respect to pointwise addition and scalar multiplication, and a commutatitive associative algebra over k with respect to pointwise multiplication of functions. Put $V' = \mathrm{Hom}_k(V, k)$ again, which may be considered as a submodule of $c(V, k)$, as a module over k.

Let SV' be the symmetric algebra associated to V', as in Section 25.8. This is a commutative associative algebra over k, with a multiplicative identity element $e_{SV'}$. This also comes with a homomorphism $i_{SV'}$ from V' into SV', as modules over k, as before.

Let B be a commutative associative algebra over k, with a multiplicative identity element e_B, and let ϕ be a homomorphism from V' into B, as modules over k. Under these conditions, there is a unique algebra homomorphism ψ from SV' into B such that $\psi(e_{SV'}) = e_B$ and

(31.12.1) $$\psi \circ i_{SV'} = \phi,$$

as in Section 25.8.

Let us take $B = c(V, k)$, whose multiplicative identity element is the constant function equal to $1 \in k$ on V. The natural inclusion mapping from V' into $c(V, k)$ leads to an algebra homomorphism from SV' into $c(V, k)$, as in the preceding pargraph.

One may consider SV' as the algebra of polynomials associated to V, as on p126 of [14]. The algebra homomorphism from SV' into $c(V, k)$ mentioned in the previous paragraph maps SV' onto the subalgebra of $c(V, k)$ generated by V' and the constant functions.

Suppose for the moment that V is a free module over k of positive finite rank n, so that V can be identified with k^n, as a module over k. In this case, V' can be identified with k^n too, as a module over k, as in the previous section. Equivalently, V' is freely generated by the n coordinate functions on k^n, as a module over k.

Using this, one can identify SV' with the algebra of formal polynomials in n commuting indeterminates with coefficients in k, as in Section 25.8. With these identifications, the algebra homomorphism from SV' into $c(V, k)$ corresponds to the usual mapping from formal polynomials to polynomial functions on k^n.

Let V be any module over k again, let W be another module over k, and put $W' = \mathrm{Hom}_k(W, k)$, as before. If ξ is a module homomorphism from W into V, then there is a natural dual homomorphism ξ' from V' into W'. This is defined by composing a module homomorphism from V into k with ξ, to get a module homomorphism from W into k.

Let SW' be the symmetric algebra associated to W', with multiplicative identity element $e_{SW'}$ and module homomorphism $i_{SW'}$ from W' into SW'. Note that

$$i_{SW'} \circ \xi' \tag{31.12.2}$$

is a homomorphism from V' into SW', as modules over k. This leads to a unique algebra homomorphism η from SV' into SW' such that $\eta(e_{SV'}) = e_{SW'}$ and

$$\eta \circ i_{SV'} = i_{SW'} \circ \xi', \tag{31.12.3}$$

as before.

If ξ is a module isomorphism from W onto V, then ξ' is a module isomorphism from W' onto V'. This implies that η is an algebra isomorphism from SV' onto SW', as in Section 31.10.

Suppose that V, W are free as modules over k, with positive finite ranks n, m, respectively. Thus V, V' and W, W' can be identified with k^n and k^m, respectively, as modules over k, as before.

In this case, a module homomorphism ξ from W into V corresponds exactly to an $n \times m$ matrix with entries in k in the usual way. The corresponding dual homomorphism ξ' corresponds to the transpose of this matrix in the same way. The algebra homomorphism η from SV' into SW' obtained from ξ as in (31.12.3) corresponds to the analogous algebra homomorphism obtained from an $n \times m$ matrix with entries in k in Section 31.3.

31.13 Polynomials on Lie algebras

Let k be a field with infinitely many elements, and let $(A, [\cdot, \cdot]_A)$ be a Lie algebra over k of positive finite dimension n. Remember that the set $\mathcal{R}(A)$ of regular elements of A is dense in A with respect to the Zariski topology, as in Section 31.6. Of course, this uses the identification of A with k^n, as a vector space over k, as before.

Let $\mathcal{C}(A)$ be the union of all of the Cartan subalgebras of A. Observe that

$$\mathcal{R}(A) \subseteq \mathcal{C}(A), \tag{31.13.1}$$

because every element of $\mathcal{R}(A)$ is contained in a Cartan subalgebra of A, as mentioned in Section 31.7. It follows that $\mathcal{C}(A)$ is dense in A with respect to the Zariski topology.

Suppose from now on in this section that k is an algebraically closed field of characteristic 0. Let $\mathcal{E}(A)$ be the subgroup of the group of all Lie algebra automorphisms of A generated by exponentials of strongly ad-nilpotent elements of A, as in Section 24.3. Also let f be a polynomial function on A that is invariant under $\mathcal{E}(A)$.

If C is a Cartan subalgebra of A and

$$f(x) = 0 \quad \text{for every } x \in C, \tag{31.13.2}$$

then

$$f(x) = 0 \quad \text{for every } x \in A. \tag{31.13.3}$$

Indeed, remember that every Cartan subalgebra of A is conjugate to C by an element of $\mathcal{E}(A)$, as in Section 24.9. Thus (31.13.2) implies that

$$f(x) = 0 \quad \text{for every } x \in \mathcal{C}(A), \tag{31.13.4}$$

because f is invariant under $\mathcal{E}(A)$, by hypothesis. This implies (31.13.3), because $\mathcal{C}(A)$ is Zariski dense in A, as before. This corresponds to some remarks on p132, 134 of [14].

Chapter 32

Some remarks and helpful facts

32.1 Roots and vector spaces

Let k be a field of characteristic 0, and let A_0 be a vector space over k of positive finite dimension n. Also let A_0' be the dual space of linear functionals on A_0, as usual, and let Φ be a finite set of nonzero elements of A_0' whose linear span is A_0'. We would like to consider conditions on A_0 and Φ like those in Sections 22.11, 28.7, 29.4, and 33.1, without the larger Lie algebra.

Of course, we may consider A_0 and A_0' as vector spaces over $\mathbf{Q}$, using the natural embedding of $\mathbf{Q}$ into k. Let $E_{\mathbf{Q}}$ be the linear subspace of A_0', as a vector space over $\mathbf{Q}$, spanned by Φ. We can use $E_{\mathbf{Q}}$ to get a vector space $E_{\mathbf{R}}$ over $\mathbf{R}$, as in Section 17.13. Thus $E_{\mathbf{Q}}$ corresponds to a linear subspace of $E_{\mathbf{R}}$, as a vector space over $\mathbf{Q}$, and any basis for $E_{\mathbf{Q}}$, as a vector space over $\mathbf{Q}$, is a basis for $E_{\mathbf{R}}$, as a vector space over $\mathbf{R}$, by construction.

We ask that Φ be a root system in $E_{\mathbf{R}}$. If $\alpha \in \Phi$, then let σ_α be the symmetry on $E_{\mathbf{R}}$ with vector α that maps Φ onto itself, as usual. Note that

$$\sigma_\alpha(E_{\mathbf{Q}}) = E_{\mathbf{Q}}. \tag{32.1.1}$$

Let λ_α be the linear functional on $E_{\mathbf{R}}$ corresponding to σ_α, so that σ_α is the identity mapping on $E_{\mathbf{R}}$ minus λ_α times α. Remember that λ_α takes integer values on Φ, by definition of a root system, which means that λ_α takes values in $\mathbf{Q}$ on $E_{\mathbf{Q}}$.

Let Δ be a base for Φ as a root system in $E_{\mathbf{R}}$. The elements of Δ are automatically linearly independent in $E_{\mathbf{Q}}$, as a vector space over $\mathbf{Q}$, because they are linearly independent in $E_{\mathbf{R}}$, as a vector space over $\mathbf{R}$. Observe that $E_{\mathbf{Q}}$ is spanned by Δ, as a vector space over $\mathbf{Q}$, because $E_{\mathbf{Q}}$ is spanned by Φ, and every element of Φ can be expressed as a linear combination of elements of Δ with integer coefficients. This means that

$$\Delta \text{ is a basis for } E_{\mathbf{Q}}, \tag{32.1.2}$$

as a vector space over $\mathbf{Q}$.

Similarly, A_0' is spanned by Δ, as a vector space over k, because A_0' is spanned by Φ, by hypothesis. We ask that

$$\Delta \text{ be a basis for } A_0', \tag{32.1.3}$$

as a vector space over k. Equivalently, this means that

$$\dim_k A_0' = \dim_{\mathbf{Q}} E_{\mathbf{Q}}, \tag{32.1.4}$$

where the subscripts indicate the fields over which the dimensions of the corresponding vector spaces are taken. This is the same as saying that

$$\dim_{\mathbf{Q}} E_{\mathbf{Q}} = n, \tag{32.1.5}$$

because

$$\dim_k A_0' = \dim_k A_0 = n, \tag{32.1.6}$$

by hypothesis.

Let T be an automorphism of Φ in $E_{\mathbf{R}}$, so that T is a one-to-one linear mapping from $E_{\mathbf{R}}$ onto itself such that $T(\Phi) = \Phi$. This implies that

$$T(E_{\mathbf{Q}}) = E_{\mathbf{Q}}. \tag{32.1.7}$$

The restriction of T to $E_{\mathbf{Q}}$ is a one-to-one linear mapping from $E_{\mathbf{Q}}$ onto itself, as a vector space over $\mathbf{Q}$. Every linear mapping from $E_{\mathbf{Q}}$ into itself, as a vector space over $\mathbf{Q}$, has a unique extension to a linear mapping from $E_{\mathbf{R}}$ into itself, as a vector space over $\mathbf{R}$. A one-to-one linear mapping from $E_{\mathbf{Q}}$ onto itself extends to a one-to-one linear mapping from $E_{\mathbf{R}}$ onto itself.

Similarly, every linear mapping from $E_{\mathbf{Q}}$ into itself, as a vector space over $\mathbf{Q}$, has a unique extension to a linear mapping from A_0' into itself, as a vector space over k, because of (32.1.3). The extension of a one-to-one linear mapping from $E_{\mathbf{Q}}$ onto itself is a one-to-one linear mapping from A_0' onto itself. If R is a one-to-one linear mapping from A_0' onto itself, as a vector space over k, and $R(\Phi) = \Phi$, then

$$R(E_{\mathbf{Q}}) = E_{\mathbf{Q}}. \tag{32.1.8}$$

The restriction of R to $E_{\mathbf{Q}}$ is a one-to-one linear mapping from $E_{\mathbf{Q}}$ onto itself, as a vector space over $\mathbf{Q}$.

It follows that the group $\mathrm{Aut}(\Phi)$ of automorphisms of Φ in $E_{\mathbf{R}}$ can be identified with the group of one-to-one linear mappings from $E_{\mathbf{Q}}$ onto itself, as a vector space over $\mathbf{Q}$, that send Φ onto itself. This can also be identified with the group of one-to-one linear mappings from A_0' onto itself, as a vector space over k, that send Φ onto itself. Similarly, the Weyl group of Φ can be identified with a group of one-to-one linear mappings from $E_{\mathbf{Q}}$ onto itself, or a group of one-to-one linear mappings from A_0' onto itself.

32.2 Roots and dual spaces

Let us continue with the same notation and hypotheses as in the previous section. If $\alpha \in \Phi$, then λ_α is an element of the dual $E'_{\mathbf{R}}$ of $E_{\mathbf{R}}$, as a vector space over **R**. Put

$$\Phi' = \{\lambda_\alpha : \alpha \in \Phi\}, \tag{32.2.1}$$

which is a root system in $E'_{\mathbf{R}}$, as in Section 19.8.

Similarly, let $E'_{\mathbf{Q}}$ be the dual of $E_{\mathbf{Q}}$, as a vector space over **Q**. Every element of $E'_{\mathbf{Q}}$ has a unique extension to an element of $E'_{\mathbf{R}}$, so that $E'_{\mathbf{Q}}$ may be identified with a subset of $E'_{\mathbf{R}}$. Equivalently, the elements of $E'_{\mathbf{Q}}$ correspond to the elements of $E'_{\mathbf{R}}$ that take values in **Q** on $E_{\mathbf{Q}}$. Thus

(32.2.2) $E'_{\mathbf{Q}}$ corresponds to a linear subspace of $E'_{\mathbf{R}}$,
as a vector space over **Q**.

If $\alpha \in \Phi$, then λ_α takes values in **Q** on $E_{\mathbf{Q}}$, as in the previous section, so that Φ' corresponds to a subset of $E'_{\mathbf{Q}}$. Let Δ be a base of Φ, and put

$$\Delta' = \{\lambda_\beta : \beta \in \Delta\}. \tag{32.2.3}$$

If Φ is reduced as a root system in $E_{\mathbf{R}}$, then Δ' is a base for Φ', as in Section 19.13. Otherwise, one can get a base for Φ by replacing λ_β with $\lambda_\beta/2$ when $\beta \in \Delta$ and $2\,\beta \in \Phi$, as before. In either case,

(32.2.4) Δ' is a basis for $E'_{\mathbf{R}}$,

as a vector space over **R**.

In particular, the elements of Δ' are linearly independent in $E'_{\mathbf{R}}$, as a vector space over **R**. Of course, this means that the elements of Δ' are linearly independent in $E'_{\mathbf{R}}$ as a vector space over **Q**. This implies that Δ' corresponds to a linearly independent set in $E'_{\mathbf{Q}}$, as a vector space over **Q**. More precisely, this uses the fact that if a linear combination of elements of Δ' is equal to 0 on $E_{\mathbf{Q}}$, then it is equal to 0 on $E_{\mathbf{R}}$ too.

Remember that

$$\dim_{\mathbf{Q}} E_{\mathbf{Q}} = \dim_{\mathbf{R}} E_{\mathbf{R}}, \tag{32.2.5}$$

by construction. This implies that

$$\dim_{\mathbf{Q}} E'_{\mathbf{Q}} = \dim_{\mathbf{R}} E'_{\mathbf{R}}. \tag{32.2.6}$$

It follows that

(32.2.7) Δ' corresponds to a basis for $E'_{\mathbf{Q}}$,

as a vector space over **Q**.

Let A''_0 be the dual of A'_0, as a vector space over k. Every element of $E'_{\mathbf{Q}}$ has a unique extension to an element of A''_0, because Δ is a basis for A'_0, as a vector space over k. Thus $E'_{\mathbf{Q}}$ corresponds to a subset of A''_0, whose elements are the linear functionals on A_0' that take values in $\mathbf{Q}$ on $E_{\mathbf{Q}}$, with respect to the natural embedding of $\mathbf{Q}$ into k. More precisely,

(32.2.8) $E'_{\mathbf{Q}}$ corresponds to a linear subspace of A_0'', as a vector space over $\mathbf{Q}$.

Remember that there is a natural isomorphism from A_0 onto A_0'', as vector spaces over k. This isomorphism sends $w \in A_0$ to the linear functional on A_0' defined by evaluating an element of A_0' at w.

If $\alpha \in \Phi$, then there is a unique element h_α of A_0 such that

$$\beta(h_\alpha) = \lambda_\alpha(\beta) \tag{32.2.9}$$

for every $\beta \in \Phi$. The right side is an integer, by definition of a root system, which may be considered as an element of k, using the natural embedding of $\mathbf{Q}$ into k. The uniqueness of h_α follows from the fact that A_0' is spanned by Φ, as a vector space over k.

To get the existence of h_α, we consider λ_α as an element of $E'_{\mathbf{Q}}$, which can be extended to a unique element of A_0'', as before. This element of A_0'' can be expressed in terms of evaluation at an element of A_0, which is h_α. More precisely, (32.2.9) holds for every $\beta \in E_{\mathbf{Q}}$. By construction,

$$\beta \mapsto \beta(h_\alpha) \tag{32.2.10}$$

is the linear functional on A_0' whose restriction to $E_{\mathbf{Q}}$ is the same as λ_α.

Remember that σ_α sends $E_{\mathbf{Q}}$ onto itself, as in the previous section. The restriction of σ_α to $E_{\mathbf{Q}}$ has a unique extension to a one-to-one linear mapping from A_0' onto itself, as a vector space over k, as before. This extension is given by

$$\beta \mapsto \beta - \beta(h_\alpha)\,\alpha, \tag{32.2.11}$$

by the remarks in the previous two paragraphs.

32.3 Dual spaces and abstract weights

Let us continue with the same notation and hypotheses as in the previous two sections. Remember that $E_{\mathbf{Q}}$ is the linear span of Φ in A_0', as a vector space over $\mathbf{Q}$. We may also consider $E_{\mathbf{Q}}$ to be the linear span of Φ in $E_{\mathbf{R}}$, as a vector space over $\mathbf{Q}$.

Remember that the restrictions of the λ_α's, $\alpha \in \Delta$, to $E_{\mathbf{Q}}$ form a basis for $E'_{\mathbf{Q}}$, as a vector space over $\mathbf{Q}$. This implies that

(32.3.1) any function of $\alpha \in \Delta$ with values in $\mathbf{Q}$ can be obtained by evaluating λ_α at an element of $E_{\mathbf{Q}}$.

If $z \in E_{\mathbf{R}}$, then z is uniquely determined by $\lambda_\alpha(z)$, $\alpha \in \Delta$, because the λ_α's, $\alpha \in \Delta$, form a basis for $E'_{\mathbf{R}}$. If $\lambda_\alpha(z) \in \mathbf{Q}$ for every $\alpha \in \Delta$, then there is an element of $E_{\mathbf{Q}}$ for which the values of λ_α, $\alpha \in \Delta$, are the same, as in the preceding paragraph. This means that $z \in E_{\mathbf{Q}}$, because z is determined by $\lambda_\alpha(z)$, $\alpha \in \Delta$. Thus

$$E_{\mathbf{Q}} = \{z \in E_{\mathbf{R}} : \lambda_\alpha(z) \in \mathbf{Q} \text{ for every } \alpha \in \Delta\}, \tag{32.3.2}$$

because λ_α maps $E_{\mathbf{Q}}$ into $\mathbf{Q}$ for every $\alpha \in \Phi$, as before. Of course, it follows that

$$E_{\mathbf{Q}} = \{z \in E_{\mathbf{R}} : \lambda_\alpha(z) \in \mathbf{Q} \text{ for every } \alpha \in \Phi\}. \tag{32.3.3}$$

If $\beta \in A_0'$, then put

$$f_\beta(\alpha) = \beta(h_\alpha) \tag{32.3.4}$$

for every $\alpha \in \Delta$, so that f_β defines a k-valued function on Δ. Of course, the set of k-valued functions on Δ is a vector space over k, with respect to pointwise addition and scalar multiplication. Clearly

$$\{f_\beta : \beta \in A_0'\} \tag{32.3.5}$$

is a linear subspace of the space of all k-valued functions on Δ, because A_0' is a vector space over k, and f_β is linear in β over k.

If $\beta \in E_{\mathbf{Q}}$, then

$$f_\beta(\alpha) = \lambda_\alpha(\beta) \tag{32.3.6}$$

for every $\alpha \in \Delta$, as in (32.2.9), where the right side is considered as an element of k, using the natural embedding of $\mathbf{Q}$ into k. Every $\mathbf{Q}$-valued function on Δ corresponds to some $\beta \in E_{\mathbf{Q}}$ in this way, as in (32.3.1). This implies that every k-valued function on Δ can be expressed as f_β for some $\beta \in A_0'$, because (32.3.5) is a linear subspace of the space of all k-valued functions on Δ, as in the preceding paragraph.

It follows that

$$\text{the } h_\alpha\text{'s, } \alpha \in \Delta, \text{ are linearly independent in } A_0, \tag{32.3.7}$$

because otherwise the values of the f_β's, $\beta \in A_0'$, on Δ would satisfy a nontrivial linear relation. Note that the dimension of A_0, as a vector space over k, is equal to the number of elements of Δ, by the remarks in Section 32.1. This means that

$$\{h_\alpha : \alpha \in \Delta\} \text{ is a basis for } A_0, \tag{32.3.8}$$

as a vector space over k.

In particular, every element of A_0' is uniquely determined by its values on the h_α's, $\alpha \in \Delta$. If $\nu \in A_0'$ and $\nu(h_\alpha)$ corresponds to an element of $\mathbf{Q}$ for every $\alpha \in \Delta$, under the natural embedding of $\mathbf{Q}$ into k, then it follows that $\nu \in E_{\mathbf{Q}}$, because of (32.3.1). This shows that

$$E_{\mathbf{Q}} = \{\nu \in A_0' : \nu(h_\alpha) \in \mathbf{Q} \text{ for every } \alpha \in \Delta\}. \tag{32.3.9}$$

We also have that

$$E_{\mathbf{Q}} = \{\nu \in A_0' : \nu(h_\alpha) \in \mathbf{Q} \text{ for every } \alpha \in \Phi\}, \tag{32.3.10}$$

because $\nu(h_\alpha) = \lambda_\alpha(\nu) \in \mathbf{Q}$ for every $\alpha \in \Phi$ when $\nu \in E_{\mathbf{Q}}$, as in (32.2.9).

Put

$$\Upsilon = \Upsilon_\Phi = \{z \in E_{\mathbf{R}} : \lambda_\alpha(z) \in \mathbf{Z} \text{ for every } \alpha \in \Phi\}, \tag{32.3.11}$$

as in Section 30.1. If Φ is reduced as a root system in $E_{\mathbf{R}}$, then

$$\Upsilon = \{z \in E_{\mathbf{R}} : \lambda_\alpha(z) \in \mathbf{Z} \text{ for every } \alpha \in \Delta\}, \tag{32.3.12}$$

because the collection Δ' of λ_α, $\alpha \in \Delta$, is a base for Φ', as before. Note that

$$\Upsilon \subseteq E_{\mathbf{Q}}, \tag{32.3.13}$$

by (32.3.3). Thus

$$\Upsilon = \{z \in E_{\mathbf{Q}} : \lambda_\alpha(z) \in \mathbf{Z} \text{ for every } \alpha \in \Phi\}, \tag{32.3.14}$$

and

$$\Upsilon = \{z \in E_{\mathbf{Q}} : \lambda_\alpha(z) \in \mathbf{Z} \text{ for every } \alpha \in \Delta\} \tag{32.3.15}$$

when Φ is reduced.

Let us check that

$$\Upsilon = \{\nu \in A_0' : \nu(h_\alpha) \in \mathbf{Z} \text{ for every } \alpha \in \Phi\}. \tag{32.3.16}$$

If $\nu \in A_0'$ satisfies $\nu(h_\alpha) \in \mathbf{Z}$ for every $\alpha \in \Phi$, then $\nu \in E_{\mathbf{Q}}$, by (32.3.10). This means that $\nu(h_\alpha) = \lambda_\alpha(\nu)$ for every $\alpha \in \Phi$, as in (32.2.9). It follows that $\nu \in \Upsilon$, by (32.3.14). It is easy to see that Υ is contained in the right side of (32.3.16), using (32.3.14) and the fact that $E_{\mathbf{Q}} \subseteq A_0'$, by construction. Similarly,

$$\Upsilon = \{\nu \in A_0' : \nu(h_\alpha) \in \mathbf{Z} \text{ for every } \alpha \in \Delta\} \tag{32.3.17}$$

when Φ is reduced as a root system in $E_{\mathbf{R}}$. This uses (32.3.9) and (32.3.15), to get that the right side is contained in Υ.

As in Section 30.3, we put

$$\Upsilon^+ = \Upsilon^+_{\Phi,\Delta} = \{z \in \Upsilon : \lambda_\alpha(z) \geq 0 \text{ for every } \alpha \in \Delta\}. \tag{32.3.18}$$

This is the same as

$$\Upsilon^+ = \{z \in \Upsilon : \lambda_\alpha(z) \geq 0 \text{ for every } \alpha \in \Phi^+\}, \tag{32.3.19}$$

where Φ^+ is the set of positive roots with respect to Δ, as usual. Equivalently,

$$\begin{aligned} \Upsilon^+ &= \{\nu \in \Upsilon : \nu(h_\alpha) \geq 0 \text{ for every } \alpha \in \Delta\} \\ &= \{\nu \in \Upsilon : \nu(h_\alpha) \geq 0 \text{ for every } \alpha \in \Phi^+\}, \end{aligned} \tag{32.3.20}$$

by (32.2.9) and (32.3.13). An element of A_0' may be called *integral* if it is in Υ, and *dominant integral* if it is in Υ^+, as on p112 of [14].

32.4 Abstract weights and group rings

We continue with the same notation and hypotheses as in the previous three sections. More precisely, in this section it is enough to have Φ as a root system in $E_{\mathbf{R}}$, and to let Υ be as in (32.3.11). However, it will be helpful later on to consider Φ and Υ as being contained in A_0'.

Remember that Υ is a commutative group with respect to addition, which may be considered as a subgroup of $E_{\mathbf{Q}}$, $E_{\mathbf{R}}$, or A_0'. We would like to consider the group ring $\mathbf{Z}[\Upsilon]$ of Υ with coefficients in $\mathbf{Z}$, which may also be considered as the group algebra of Υ over $\mathbf{Z}$. Normally the elements of $\mathbf{Z}[\Upsilon]$ might be defined as formal linear combinations of elements of Υ with integer coefficients, where multiplication in $\mathbf{Z}[\Upsilon]$ is defined using the group operation on Υ. Because the group operation on Υ is addition, it is better to express the embedding of Υ into $\mathbf{Z}[\Upsilon]$ another way.

Thus we take $\mathbf{Z}[\Upsilon]$ to be the free module over $\mathbf{Z}$ with distinct basis elements denoted e_α, $\alpha \in \Upsilon$. If $\alpha, \beta \in \Upsilon$, then we put

$$e_\alpha \, e_\beta = e_{\alpha+\beta}, \tag{32.4.1}$$

using addition in Υ on the right. This can be used to define multiplication in $\mathbf{Z}[\Upsilon]$, which is bilinear over $\mathbf{Z}$. Note that e_0 is the multiplicative identity element in $\mathbf{Z}[\Upsilon]$. This corresponds to some remarks on p124 of [14], and on p63 of [24].

Alternatively, consider the set $c_{00}(\Upsilon, \mathbf{Z})$ of all $\mathbf{Z}$-valued functions on Υ with finite support, which is to say that they are equal to 0 at all but finitely many elements of Υ. This is a commutative group with respect to pointwise addition of functions. If $f, g \in c_{00}(\Upsilon, \mathbf{Z})$, then their convolution product is the $\mathbf{Z}$-valued function on Υ defined by

$$(f * g)(\gamma) = \sum_{\alpha+\beta=\gamma} f(\alpha) \, g(\beta) \tag{32.4.2}$$

for every $\gamma \in \Upsilon$. More precisely, the sum on the right is taken over all $\alpha, \beta \in \Upsilon$ with $\alpha + \beta = \gamma$. This reduces to a finite sum when either f or g has finite support in Υ. If f and g both have finite support in Υ, then $f * g$ has finite support in Υ too, and is thus an element of $c_{00}(\Upsilon, \mathbf{Z})$. One can check that $c_{00}(\Upsilon, \mathbf{Z})$ is a commutative ring with respect to convolution.

If $\alpha \in \Upsilon$, then one can take e_α to be the k-valued function on Υ equal to 1 at α, and to 0 at all other elements of Υ. This is an element of $c_{00}(\Upsilon, \mathbf{Z})$, and $c_{00}(\Upsilon, \mathbf{Z})$ is a free module over $\mathbf{Z}$ with basis e_α, $\alpha \in \Upsilon$. It is easy to see that (32.4.1) holds for every $\alpha, \beta \in \Upsilon$, using the convolution product on the left side. Note that automorphisms of Υ as a commutative group lead to ring automorphisms of $\mathbf{Z}[\Upsilon]$.

32.5 Homomorphisms and Lie algebras

Let k be a commutative ring with a multiplicative identity element, and let $(A_1, [\cdot,\cdot]_{A_1})$, $(A_2, [\cdot,\cdot]_{A_2})$ be Lie algebras over k. Also let UA_1, UA_2 be universal enveloping algebras of A_1, A_2, respectively, as in Section 25.4. Thus UA_1, UA_2 are associative algebras over k with multiplicative identity elements e_{UA_1}, e_{UA_2}, respectively. We have Lie algebra homomorphisms i_{UA_1}, i_{UA_2} from A_1, A_2 into UA_1, UA_2, respectively, as well.

Suppose that ξ_1 is a Lie algebra homomorphism from A_1 into A_2. Of course, this implies that

$$i_{UA_2} \circ \xi_1 \tag{32.5.1}$$

is a Lie algebra homomorphism from A_1 into UA_2. It follows that there is a unique algebra homomorphism η_1 from UA_1 into UA_2 such that $\eta_1(e_{UA_1}) = e_{UA_2}$ and

$$\eta_1 \circ i_{UA_1} = i_{UA_2} \circ \xi_1, \tag{32.5.2}$$

as in Section 25.4.

Let $(A_3, [\cdot,\cdot]_{A_3})$ be another Lie algebra over k, and let UA_3 be a universal enveloping algebra of A_3, with multiplicative identity element e_{UA_3} and Lie algebra homomorphism i_{UA_3} from A_3 into UA_3. If ξ_2 is a Lie algebra homomorphism from A_2 into A_3, then

$$i_{UA_3} \circ \xi_2 \tag{32.5.3}$$

is a Lie algebra homomorphism from A_2 into UA_3. This leads to a unique algebra homomorphism η_2 from UA_2 into UA_3 such that $\eta_2(e_{UA_2}) = e_{UA_3}$ and

$$\eta_2 \circ i_{UA_2} = i_{UA_3} \circ \xi_2, \tag{32.5.4}$$

as before.

It follows that $\xi_2 \circ \xi_1$ is a Lie algebra homomorphism from A_1 into A_3, so that

$$i_{UA_3} \circ \xi_2 \circ \xi_1 \tag{32.5.5}$$

is a Lie algebra homomorphism from A_1 into UA_3. Observe that $\eta_2 \circ \eta_1$ is an algebra homomorphism from UA_1 into UA_3 with

$$(\eta_2 \circ \eta_1)(e_{UA_1}) = \eta_2(\eta_1(e_{UA_1})) = \eta_2(e_{UA_2}) = e_{UA_3} \tag{32.5.6}$$

and

$$\eta_2 \circ \eta_1 \circ i_{UA_1} = \eta_2 \circ i_{UA_2} \circ \xi_1 = i_{UA_3} \circ \xi_2 \circ \xi_1. \tag{32.5.7}$$

More precisely, $\eta_2 \circ \eta_1$ is uniquely determined by these properties, because UA_1 is a universal enveloping algebra of A_1.

Suppose that $A_1 = A_3$, $UA_1 = UA_3$, and $i_{UA_1} = i_{UA_3}$. If $\xi_2 \circ \xi_1$ is the identity mapping on A_1, then it follows that $\eta_2 \circ \eta_1$ is the identity mapping on UA_1, by uniqueness.

If $\xi_1 \circ \xi_2$ is the identity mapping on A_2, then $\eta_1 \circ \eta_2$ is the identity mapping on UA_2, for the same reasons. If ξ_1 is a Lie algebra isomorphism from A_1 onto A_2, then we get that η_1 is an algebra isomorphism from UA_1 onto UA_2. Of course, these remarks reduce to those in Section 31.10 when the Lie algebras are commutative.

Let us now take $A_1 = A_2$, $UA_1 = UA_2$, and $i_{UA_1} = i_{UA_2}$. If ξ_1 is a Lie algebra automorphism of A_1, then η_1 is an algebra automorphism of UA_1.

32.6 Submodules of UA

Let k be a commutative ring with a multiplicative identity element again, and let $(A, [\cdot, \cdot]_A)$ be a Lie algebra over k. Also let UA be a universal enveloping algebra of A, as in Section 25.4. As usual, UA is an associative algebra over k with a multiplicative identity element $e = e_{UA}$, and we have a Lie algebra homomorphism $i = i_{UA}$ from A into UA.

If $a \in A$ and $w \in UA$, then put

$$\delta_a(w) = [i(a), w] = i(a)\, w - w\, i(a). \tag{32.6.1}$$

This defines a derivation on UA, as an associative algebra over k, as in Section 2.5. Of course,

$$\delta_a(i(x)) = [i(a), i(x)] = i([a, x]_A) \tag{32.6.2}$$

for every $a, x \in A$, because i is a Lie algebra homomorphism from A into UA.

In fact, UA is a module over A, as a Lie algebra over k, with respect to (32.6.1). Remember that UA is a Lie algebra over k, with respect to the commutator bracket defined using multiplication in UA, because UA is an associative algebra over k. Thus UA may be considered as a module over itself, as a Lie algebra over k, with respect to the adjoint representation. Equivalently, the adjoint representation on UA is a Lie algebra homomorphism from UA into the Lie algebra of homomorphisms from UA into itself, as a module over k. By construction, $a \mapsto \delta_a$ is the same as the composition of i with the Lie algebra homomorphism just mentioned, and thus defines a Lie algebra homomorphism from A into the the Lie algebra of module homomorphisms from UA into itself, as a module over k.

If n is a nonnegative integer, then let U_nA be the submodule of UA, as a module over k, generated by products of at most n elements of $i(A)$, as in Section 25.9. We interpret e as being a product of 0 elements of $i(A)$, so that $e \in U_nA$ for every $n \geq 0$, as before. If $x_1, \ldots, x_m \in A$, then

$$\begin{aligned} &\delta_a(i(x_1) \cdots i(x_m)) \\ &\quad = \sum_{j=1}^{m} i(x_1) \cdots i(x_{j-1})\, \delta_a(i(x_j))\, i(x_{j+1}) \cdots i(x_m), \end{aligned} \tag{32.6.3}$$

because δ_a is a derivation on UA. This implies that

$$\begin{aligned} &\delta_a(i(x_1) \cdots i(x_m)) \\ &\quad = \sum_{j=1}^{m} i(x_1) \cdots i(x_{j-1})\, i([a, x_j]_A)\, i(x_{j+1}) \cdots i(x_m), \end{aligned} \tag{32.6.4}$$

by (32.6.2). It follows that

$$U_nA \text{ is a submodule of } UA, \text{ as a module over } A, \tag{32.6.5}$$

for every $n \geq 0$.

Remember that $\bigcup_{n=0}^{\infty} U_n A = UA$, as in Section 25.9. If A is finitely-generated as a module over k, then it is easy to see that $U_n A$ is finitely-generated as a module over k for every $n \geq 0$. In particular, if k is a field, and A has finite dimension as a vector space over k, then $U_n A$ has finite dimension as a vector space over k for every $n \geq 0$. This corresponds to Exercise 3 on p95 of [14].

32.7 Some automorphisms of UA

Let k be a field of characteristic 0, and let $(A, [\cdot, \cdot]_A)$ be a Lie algebra over k. Suppose that $a \in A$ is ad-nilpotent, so that $\mathrm{ad}_{A,a}$ is nilpotent as a linear mapping on A. Thus $\exp \mathrm{ad}_{A,a}$ defines a Lie algebra automorphism of A, as in Section 14.11.

Let UA be a universal enveloping algebra of A, with multiplicative identity element $e = e_{UA}$, and Lie algebra homomorphism $i = i_{UA}$ from A into UA, as in Section 25.4 again. There is a unique algebra automorphism η of UA such that $\eta(e) = e$ and

$$\eta \circ i = i \circ (\exp \mathrm{ad}_{A,a}), \tag{32.7.1}$$

as in Section 32.5.

Let δ_a be defined on UA as in the previous section. If $x_1, \ldots, x_m \in A$, then it is easy to see that

$$(\delta_a)^l (i(x_1) \cdots i(x_m)) = 0 \tag{32.7.2}$$

when l is sufficiently large, depending on m. This implies that for each nonnegative integer n, the restriction of δ_a to $U_n A$ is nilpotent, where $U_n A$ is as in the previous section.

In particular, δ_a is locally nilpotent on UA, as in Section 27.12. It follows thst $\exp \delta_a$ can be defined as a linear mapping from UA into itself, as before. More precisely, $\exp \delta_a$ is invertible as a linear mapping on UA, with inverse equal to $\exp(-\delta_a)$. In fact, $\exp \delta_a$ is an algebra automorphism of UA, because δ_a is a derivation on UA, as in the previous section. Note that $\exp \delta_a$ maps e to itself.

Clearly $\delta_a \circ i = i \circ \mathrm{ad}_{A,a}$, by construction. Using this, one can check that

$$(\exp \delta_a) \circ i = i \circ (\exp \mathrm{ad}_{A,a}). \tag{32.7.3}$$

Thus $\eta = \exp \delta_a$, by uniqueness.

32.8 Polarization

Let k be a commutative ring with a multiplicative identity element, and let n be a positive integer. If $a \in k$, then let $v(a)$ be the element of k^n defined by

$$v(a) = (1, a, a^2, \ldots, a^{n-1}). \tag{32.8.1}$$

If $a_1, \ldots, a_n$ are n elements of k, then $v(a_1), \ldots, v(a_n)$ make up an $n \times n$ matrix with entries in k. The determinant of this matrix is the well-known *Vandermonde determinant*

$$\prod_{1 \le j < l \le n} (a_l - a_j). \tag{32.8.2}$$

Suppose now that k is a field, so that k^n is a vector space over k, with respect to coordinatewise addition and scalar multiplication. If $a_1, \ldots, a_n$ are distinct elements of k, then (32.8.2) is not equal to 0. This implies that $v(a_1), \ldots, v(a_n)$ form a basis for k^n, as a vector space over k.

Let X, Y be commuting indeterminates, and remember that

$$(a\,X + Y)^n = \sum_{j=0}^{n} \binom{n}{j} a^j\, X^j\, Y^{n-j} \tag{32.8.3}$$

for every $a \in k$, by the binomial theorem. If k has characteristic 0 and $a_1, \ldots, a_n, a_{n+1}$ are $n+1$ distinct elements of k, then every homogeneous formal polynomial in X, Y with coefficients in k and of degree n can be expressed as a linear combination of $(a_j\,X + Y)^n$, $1 \le j \le n+1$. This can be obtained from the remarks in the preceding paragraph, with n replaced by $n+1$, and using the fact that $\binom{n}{j}$ is nonzero for every $j = 0, \ldots, n$.

Let r be a positive integer, and let $T_1, \ldots, T_r$ be r commuting indeterminates. If k has characteristic 0, then it is well known that every formal polynomial in $T_1, \ldots, T_r$ with coefficients in k can be expressed as a linear combination of powers of linear polynomials. This is known as *polarization*, and can be seen using induction on r and the remarks in the previous paragraph, as in Exercise 5 on p134 of [14].

More precisely, if $E_1, \ldots, E_r$ are infinite subsets of k, then it suffices to use powers of linear polynomials for which the coefficient of T_j is an element of E_j for each $j = 1, \ldots, r$. In particular, it is enough to use powers of linear polynomials for which the coefficient of T_j corresponds to an integer for each j, under the natural embedding of $\mathbf{Q}$ into k.

Suppose that k has characteristic 0, and let V be a vector space over k of dimension r. Thus the dual space V' of linear functionals on V has dimension r as well, as a vector space over k. Polynomial functions on V can be obtained using a basis for V, and formal polynomials in r commuting indeterminates with coefficients in k. Equivalently, the algebra of polynomial functions on V is generated by V' and the constant functions on V.

Every polynomial function on V can be expressed as a linear combination of powers of elements of V'. This follows from the previous remarks about formal polynomials.

Let $\lambda_1, \ldots, \lambda_r$ be a basis for V', as a vector space over k. Of course, polynomial functions on V can be expressed as polynomials in $\lambda_1, \ldots, \lambda_r$, with coefficients in k.

Let Λ be the subgroup of V', as a group with respect to addition, generated by $\lambda_1, \ldots, \lambda_r$. This consists of the linear combinations of $\lambda_1, \ldots, \lambda_r$ whose coefficients correspond to integers, with respect to the natural embedding of $\mathbf{Q}$ into k.

Every polynomial function on V can be expressed as a linear combination of powers of elements of Λ, by the analogous statement for formal polynomials mentioned earlier. This corresponds to a remark on p126 of [14].

32.9 The center of UA

Let k be a field of characteristic 0, and let $(A, [\cdot, \cdot]_A)$ be a Lie algebra over k. Also let UA be a universal enveloping algebra of A, with multiplicative identity element $e = e_{UA}$, and Lie algebra homomorphism $i = i_{UA}$ from A into UA, as in Section 25.4. Consider the center $\mathcal{Z}$ of UA, as an associative algebra over k. Of course, $\mathcal{Z}$ is a subalgebra of UA that contains e.

If $a \in A$, then let δ_a be as in Section 32.6. Note that

$$\delta_a(z) = 0 \tag{32.9.1}$$

for every $a \in A$ and $z \in \mathcal{Z}$. More precisely, $\mathcal{Z}$ consists exactly of the $z \in UA$ such that (32.9.1) holds for every $a \in A$, because UA is generated as an associative algebra over k by e and $i(A)$.

Suppose that a is ad-nilpotent in A, so that δ_a is locally nilpotent on UA, as in Section 32.7. If $z \in \mathcal{Z}$, then

$$(\exp \delta_a)(z) = z, \tag{32.9.2}$$

by (32.9.1).

Remember that $\operatorname{Int} A$ is the subgroup of the group of Lie algebra automorphisms of A generated by automorphisms of the form $\exp \operatorname{ad}_{A,a}$, where $a \in A$ is ad-nilpotent, as in Section 14.11. We have also seen that every Lie algebra automorphism of A leads to an algebra automorphism of UA, as in Section 32.5. If $a \in A$ is ad-nilpotent, then the algebra automorphism of UA corresponding to $\exp \operatorname{ad}_{A,a}$ is $\exp \delta_a$, as in Section 32.7. If $z \in \mathcal{Z}$, then z is fixed by these automorphisms on UA, as in (32.9.2). This means that z is fixed by all of the automorphisms of UA corresponding to elements of $\operatorname{Int} A$, as on p128 of [14].

Suppose that $a \in A$ is ad-nilpotent again, so that $t\, a$ is ad-nilpotent in A for every $t \in k$. Similarly, $\delta_{t\, a} = t\, \delta_a$ is locally nilpotent on UA for every $t \in k$. If $w \in UA$ satisfies

$$(\exp t\, \delta_a)(w) = w \tag{32.9.3}$$

for every $t \in k$, then we would like to show that

$$\delta_a(w) = 0. \tag{32.9.4}$$

This corresponds to some remarks on p128f of [14].

Let $U_n A$ be as in Section 32.6 for each nonnegative integer n, and let n_0 be a nonnegative integer such that $w \in U_{n_0} A$. Remember that the restriction of

δ_a to $U_{n_0} A$ is nilpotent, as in Section 32.7. Thus there is a positive integer l_0 such that $(\delta_a)^{l_0} = 0$ on $U_{n_0} A$. If $t \in k$, then we get that

$$\exp t\, \delta_a = \sum_{j=0}^{l_0 - 1} (t^j / j!)\, (\delta_a)^j \tag{32.9.5}$$

on $U_{n_0} A$.

Let $t_1, \ldots, t_{l_0}$ be l_0 distinct elements of k. Under these conditions, there are l_0 elements $c_1, \ldots, c_{l_0}$ of k such that

$$\sum_{r=1}^{l_0} c_r\, (\exp t_r\, \delta_a) = \delta_a \tag{32.9.6}$$

on $U_{n_0} A$. This uses (32.9.5) and the remarks at the beginning of the previous section.

It follows that

$$\delta_a(w) = \Big(\sum_{r=1}^{l_0} c_r\Big)\, w, \tag{32.9.7}$$

by (32.9.3), and because $w \in U_{n_0} A$. This implies (32.9.4), because $(\delta_a)^{l_0}(w) = 0$.

Suppose that $w \in UA$ is invariant under all of the automorphisms of UA that correspond to elements of $\operatorname{Int} A$, as before. This implies that (32.9.3) holds for every $a \in A$ that is ad-nilpotent, and every $t \in k$. This means that (32.9.4) holds for every $a \in A$ that is ad-nilpotent.

Remember that UA is a module over A, as a Lie algebra over k, with respect to the action of $a \in A$ defined by δ_a, as in Section 32.6. If (32.9.4) holds for some collection of $a \in A$, then it holds for every a in the Lie subalgebra of A generated by this collection.

Suppose that A is generated, as a Lie algebra over k, by ad-nilpotent elements. If $w \in UA$ is invariant under all of the automorphisms of UA that correspond to elements of $\operatorname{Int} A$, then we get that (32.9.4) holds for every $a \in A$. This means that $w \in \mathcal{Z}$, as in the lemma on p128 of [14].

32.10 Constant-coefficient differential operators

Let k be a commutative ring with a multiplicative identity element, and let n be a positive integer. Also let $\partial_1, \ldots, \partial_n$ be commuting formal symbols, which may be used to represent partial derivatives in some related commuting indeterminates, as in Section 5.11. A *formal differential operator* in $\partial_1, \ldots, \partial_n$ with coefficients in k can be expressed as

$$\sum_{|\alpha| \le N} a^\alpha\, \partial^\alpha, \tag{32.10.1}$$

where N is a nonnegative integer, the sum is taken over all multi-indices α of length n with $|\alpha| \le N$, and $a^\alpha \in k$ for each such α. This is basically the same as a formal polynomial in $\partial_1, \ldots, \partial_n$, considered as n commuting indeterminates, with coefficients in k. The usual way of multiplying formal differential operators corresponds to multiplication of formal polynomials in $\partial_1, \ldots, \partial_n$ with coefficients in k in this case.

Let $T_1, \ldots, T_n$ be n commuting indeterminates, so that formal differential operators in $\partial_1, \ldots, \partial_n$ with coefficients in $k[[T_1, \ldots, T_n]]$ may be defined as in Section 5.11. Now $\partial_1, \ldots, \partial_n$ may be used to represent partial derivatives in $T_1, \ldots, T_n$, as before, so that multiplication on $k[[T_1, \ldots, T_n]]$ may be extended to

(32.10.2) the space of formal differential operators in $\partial_1, \ldots, \partial_n$ with coefficients in $k[[T_1, \ldots, T_n]]$,

as before. Note that

(32.10.3) the space of formal differential operators in $\partial_1, \ldots, \partial_n$ with coefficients in k

corresponds to a commutative subalgebra of (32.10.2), with respect to multiplication of formal differential operators. Multiplication of formal differential operators in $\partial_1, \ldots, \partial_n$ with coefficients in k, as formal differential operators with coefficients in $k[[T_1, \ldots, T_n]]$, corresponds exactly to multiplication of formal polynomials in $\partial_1, \ldots, \partial_n$ with coefficients in k, as in the preceding paragraph.

If $\partial_1, \ldots, \partial_n$ are simply considered as n commuting indeterminates, then (32.10.2) may be defined as a module over k as the space

$$(k[[T_1, \ldots, T_n]])[\partial_1, \ldots, \partial_n] \tag{32.10.4}$$

of formal polynomials in $\partial_1, \ldots, \partial_n$ with coefficients in $k[[T_1, \ldots, T_n]]$, as a module over k, as in Section 5.8. This is essentially the same as in Section 5.11, with some additional notation. Using this identification, (32.10.3) corresponds to

$$k[\partial_1, \ldots, \partial_n], \tag{32.10.5}$$

as a submodule of (32.10.4), as a module over k. One may consider (32.10.4) as a module over $k[[T_1, \ldots, T_n]]$ too, as a commutative algebra over k, with respect to multiplication on the left by elements of $k[[T_1, \ldots, T_n]]$. This corresponds to multiplication of an element of $k[[T_1, \ldots, T_n]]$, considered as an element of (32.10.2) of order 0, with another element of (32.10.2), as in Section 5.11.

We can also use multiplication on $k[[T_1, \ldots, T_n]]$ to define multiplication on (32.10.4) as in Section 5.8, so that $\partial_1, \ldots, \partial_n$ are not considered as being related to differentiation in $T_1, \ldots, T_n$. This defines a commutative algebra over k, which is a commutative algebra over $k[[T_1, \ldots, T_n]]$ as well. If $\partial_1, \ldots, \partial_n$ may be used to represent partial derivatives in some related commuting indeterminates, then this would basically correspond to the derivatives of $T_1, \ldots, T_n$

being equal to 0. Of course, (32.10.5) is a subalgebra of (32.10.4) with respect to this definition of multiplication on (32.10.4). This definition of multiplication on (32.10.5) corresponds to multiplication of formal differential operators in $\partial_1, \ldots, \partial_n$ with coefficients in k, as before.

Let L_1, L_2 be formal differential operators in $\partial_1, \ldots, \partial_n$ with coefficients in $k[[T_1, \ldots, T_n]]$ of order

$$N_1, N_2 \geq 0, \tag{32.10.6}$$

respectively. This means that the coefficients of ∂^α in L_1, L_2 are equal to zero when α is a multi-index of length n with $|\alpha|$ strictly larger than N_1, N_2, respectively. If $N_1 = N_2 = 0$, then L_1, L_2 correspond to elements of $k[[T_1, \ldots, T_n]]$, and the product of L_1 and L_2 as formal differential operators corresponds to their product as formal polynomials in $\partial_1, \ldots, \partial_n$ with coefficients in $k[[T_1, \ldots, T_n]]$. Otherwise, the product of L_1 and L_2 as formal differential operators corresponds to their product as formal polynomials in $\partial_1, \ldots, \partial_n$ with coefficients in $k[[T_1, \ldots, T_n]]$, plus a formal differential operator in $\partial_1, \ldots, \partial_n$ with coefficients in $k[[T_1, \ldots, T_n]]$ of order

$$N_1 + N_2 - 1. \tag{32.10.7}$$

In particular, the commutator of L_1 and L_2 with respect to multiplication of formal differential operators is a formal differential operator in $\partial_1, \ldots, \partial_n$ with coefficients in $k[[T_1, \ldots, T_n]]$ of order (32.10.7).

Part V

Some representation theory

Chapter 33

Representations and semisimplicity

33.1 Diagonalizability and roots

Let k be a field of characteristic 0, and let $(A, [\cdot,\cdot]_A)$ be a Lie algebra over k of positive finite dimension. We would like to consider conditions on A like those in Section 29.4. More precisely, we shall start here with conditions related to diagonalizability, and consider additional conditions related to roots. In particular, these conditions hold when k is algebraically closed, and A is semisimple.

Suppose that A_0 is a Lie subalgebra of A, and that every element of A_0 is ad-diagonalizable as an element of A. This implies that A_0 is commutative as a Lie algebra, as in Section 17.1. Thus A_0 is contained in its centralizer $C_A(A_0)$ in A, and we ask that

$$C_A(A_0) = A_0. \tag{33.1.1}$$

Remember that this holds when k is algebraically closed, A is semisimple, and A_0 is a maximal toral subalgebra of A, as in Section 17.4. Note that (33.1.1) implies that $A_0 \neq \{0\}$, because $A \neq \{0\}$.

Let A_0' be the dual space of linear functionals on A_0, as a vector space over k, as usual. If $\alpha \in A_0'$, then let A_α be the set of $x \in A$ such that $\mathrm{ad}_w(x) = \alpha(w)\, x$ for every $w \in A_0$, which is a linear subspace of A. The condition (33.1.1) says exactly that A_α is equal to A_0 when $\alpha = 0$.

Let $\Phi = \Phi_{A_0}$ be the set of $\alpha \in A_0'$ such that $\alpha \neq 0$ and $A_\alpha \neq \{0\}$. Thus A corresponds to the direct sum of A_α, $\alpha \in \Phi \cup \{0\}$, as a vector space over k, as in Section 17.2. Remember that $[A_\alpha, A_\beta] \subseteq A_{\alpha+\beta}$ for every $\alpha, \beta \in A_0'$, as before.

Under the conditions mentioned so far, the center $Z(A)$ of A as a Lie algebra is contained in A_0, and in fact is the intersection of the kernels of the elements of Φ. We ask that $Z(A) = \{0\}$, which means that A_0' is spanned by Φ, as a vector space over k. This implies that $\Phi \neq \emptyset$, because $A_0 \neq \{0\}$.

We ask that for each $\alpha \in \Phi$, A_α have dimension one, as a vector space over k. We also ask that for every $\alpha \in \Phi$ there be an element h_α of $[A_\alpha, A_{-\alpha}] \subseteq A_0$

such that $\alpha(h_\alpha) = 2 = 1 + 1$ in k. This determines h_α uniquely, because k has characteristic 0, and $[A_\alpha, A_{-\alpha}]$ has dimension at most one as a vector space over k. Note that A is semisimple under these conditions, as in Section 17.15. If $\alpha, \beta \in \Phi$ and $\alpha + \beta \in \Phi$, then we ask that $[A_\alpha, A_\beta] = A_{\alpha+\beta}$.

Let $E_{\mathbf{Q}}$ be the linear subspace of A_0', as a vector space over $\mathbf{Q}$, spanned by Φ. This leads to a vector space $E_{\mathbf{R}}$ over $\mathbf{R}$, as in Section 17.13. More precisely, $E_{\mathbf{Q}}$ corresponds to a linear subspace of $E_{\mathbf{R}}$, as a vector space over $\mathbf{Q}$, and any basis for $E_{\mathbf{Q}}$, as a vector space over $\mathbf{Q}$, is a basis for $E_{\mathbf{R}}$, as a vector space over $\mathbf{R}$.

We ask that Φ be a reduced root system in $E_{\mathbf{R}}$, and we let Δ be a base for Φ. In particular, this means that Δ is a basis for $E_{\mathbf{R}}$, as a vector space over $\mathbf{R}$. This implies that Δ is a basis for $E_{\mathbf{Q}}$, as a vector space over $\mathbf{Q}$, because $E_{\mathbf{Q}}$ is spanned by Δ, as a vector space over $\mathbf{Q}$.

Note that A_0' is spanned by Δ, as a vector space over k, because A_0' is spanned by Φ, as before. We ask that Δ be a basis for A_0', as a vector space over k, which means that Δ is linearly independent in A_0', as a vector space over k. We also ask that h_α, $\alpha \in \Delta$, form a basis for A_0, as a vector space over k.

Let $\alpha \in \Phi$ be given, and let σ_α be the symmetry on $E_{\mathbf{R}}$ with vector α that maps Φ onto itself. Thus there is a linear functional λ_α on $E_{\mathbf{R}}$ so that σ_α minus the identity mapping on $E_{\mathbf{R}}$ is equal to $-\lambda_\alpha$ times α. We ask that

$$\beta(h_\alpha) = \lambda_\alpha(\beta) \tag{33.1.2}$$

for every $\beta \in \Phi$, where the right side is an integer by the definition of a root system, which may be considered as an element of k.

If $\Psi_0 \subseteq \Phi \cup \{0\}$, then $A(\Psi_0)$ denotes the linear subspace of A spanned by A_α, $\alpha \in \Psi_0$, as in Section 22.4. Let $\Phi^+ = \Phi^{\Delta,+}$ be the set of positive roots in Φ with respect to Δ, which is to say the elements of Φ that can be expressed as linear combinations of elements of Δ with nonnegative coefficients. Put

$$B_\Delta = A(\Phi^+ \cup \{0\}), \tag{33.1.3}$$

which is the standard Borel subalgebra of A associated to A_0 and Δ, as in Section 22.12.

In particular, the conditions considered in Section 32.1 hold here. Thus the remarks in Sections 32.2 and 32.3 can be used here too.

33.2 Using a larger field

Let k, k_1 be fields, with $k \subseteq k_1$. If V is a vector space over k, then we can get a vector space $\widetilde{V}$ over k_1 from V in a well-known way. Of course, $\widetilde{V}$ may also be considered as a vector space over k, and V may be considered as a linear subspace of $\widetilde{V}$, as a vector space over k. If $\{v_j\}_{j\in I}$ is a basis for V as a vector space over k, then $\{v_j\}_{j\in I}$ corresponds to a basis for $\widetilde{V}$ as a vector space over k_1 too. In particular, the dimension of $\widetilde{V}$, as a vector space over k_1, is the same as the dimension of V, as a vector space over k.

One can use a basis for V to obtain $\widetilde{V}$ in this way, and verify that $\widetilde{V}$ does not depend on the choice of basis for V, up to isomorphic equivalence. In particular, every element of $\widetilde{V}$ can be expressed as a finite linear combination of elements of V, with coefficients in k_1. Any collection of linearly independent vectors in V, as a vector space over k, is linearly independent in $\widetilde{V}$ as well, as a vector space over k_1.

If W_1 is a vector space over k_1, then W_1 may be considered as a vector space over k. Every linear mapping from V into W_1 as a vector space over k has a unique extension to a linear mapping from $\widetilde{V}$ into W_1, as vector spaces over k_1. Of course, the restriction of any linear mapping from $\widetilde{V}$ into W_1, as vector spaces over k_1, to V is linear as a mapping into W_1, as a vector space over k.

If Z is a linear subspace of V, then one can get a vector space $\widetilde{Z}$ over k_1 in the same way. More precisely, $\widetilde{Z}$ corresponds to a linear subspace of $\widetilde{V}$, whose intersection with V is Z. If V is the direct sum of some family of vector spaces over k, then $\widetilde{V}$ is the direct sum of the corresponding family of vector spaces over k_1.

Let Z be any vector space over k, and let $\widetilde{Z}$ be the corresponding vector space over k_1. If W_1 is a vector space over k_1 again, then any mapping from $V \times Z$ into W_1 that is bilinear over k has a unique extension to a mapping from $\widetilde{V} \times \widetilde{Z}$ into W_1 that is bilinear over k_1.

Let $(A, [\cdot,\cdot]_A)$ be a Lie algebra over k, so that A is a vector space over k in particular. Thus we can get a corresponding vector space $\widetilde{A}$ over k_1 as before. The Lie bracket $[\cdot,\cdot]_A$ has a unique extension to a mapping $[\cdot,\cdot]_{\widetilde{A}}$ from $\widetilde{A} \times \widetilde{A}$ into $\widetilde{A}$ that is bilinear over k_1, as in the previous paragraph. One can check that $\widetilde{A}$ is a Lie algebra over k_1 with respect to $[\cdot,\cdot]_{\widetilde{A}}$. Note that $\widetilde{A}$ may be considered as a Lie algebra over k, and that A is a Lie subalgebra of $\widetilde{A}$, as a Lie algebra over k.

If B is a Lie subalgebra of A, then B is a linear subspace of A in particular, and $\widetilde{B}$ corresponds to a linear subspace of $\widetilde{A}$, as a vector space over k_1. It is easy to see that $\widetilde{B}$ is a Lie subalgebra of $\widetilde{A}$, as a Lie algebra over k_1.

Let V be a vector space over k again, and suppose that V is a module over A, as a Lie algebra over k. If $\widetilde{A}$, $\widetilde{V}$ are as before, then the action of A on V has a unique extension to a mapping from $\widetilde{A} \times \widetilde{V}$ into $\widetilde{V}$ that is bilinear over k_1, as before. One can verify that this makes $\widetilde{V}$ into a module over $\widetilde{A}$, as a Lie algebra over k_1.

33.3 Related spaces of linear mappings

Let k, k_1 be fields with $k \subseteq k_1$ again, let V be a vector space over k, and let W_1 be a vector space over k_1. Thus W_1 may also be considered as a vector space over k, and we let $\mathcal{L}_k(V, W_1)$ be the space of linear mappings from V into W_1, as a vector space over k. Of course, the space of all mappings from any nonempty set into W_1 may be considered as a vector space over k_1, with respect to pointwise addition and scalar multiplication. It is easy to see that $\mathcal{L}_k(V, W_1)$

is a linear subspace of the space of all mappings from V into W_1, as a vector space over k_1. This means that $\mathcal{L}_k(V, W_1)$ may be considered as a vector space over k_1.

There is a natural mapping from $\mathcal{L}_k(V, W_1)$ into the space $\mathcal{L}_{k_1}(\widetilde{V}, W_1)$ of all linear mappings from $\widetilde{V}$ into W_1, as vector spaces over k_1. This mapping sends an element of $\mathcal{L}_k(V, W_1)$ to its unique extension to an element of $\mathcal{L}_{k_1}(\widetilde{V}, W_1)$, as before. Similarly, there is a natural mapping from $\mathcal{L}_{k_1}(\widetilde{V}, W_1)$ into $\mathcal{L}_k(V, W_1)$, which sends an element of $\mathcal{L}_{k_1}(\widetilde{V}, W_1)$ to its restriction to V. Of course, these two mappings are inverses of each other. These mappings are also linear over k_1, so that we get

(33.3.1) a natural isomorphism from $\mathcal{L}_k(V, W_1)$ onto $\mathcal{L}_{k_1}(\widetilde{V}, W_1)$, as vector spaces over k_1.

Let W be another vector space over k, and let $\widetilde{W}$ be the corresponding vector space over k_1. As before, $\widetilde{W}$ may be considered as a vector space over k that contains W as a linear subspace. A linear mapping from V into W, as vector spaces over k, may be considered as a linear mapping from V into $\widetilde{W}$, as vector spaces over k. This may be extended to a unique linear mapping from $\widetilde{V}$ into $\widetilde{W}$, as vector spaces over k_1.

We can take $W_1 = \widetilde{W}$ in (33.3.1), to get

(33.3.2) a natural isomorphism from $\mathcal{L}_k(V, \widetilde{W})$ onto $\mathcal{L}_{k_1}(\widetilde{V}, \widetilde{W})$, as vector spaces over k_1.

We may also consider $\widetilde{W}$ and $\mathcal{L}_k(V, \widetilde{W})$ as vector spaces over k, and the space $\mathcal{L}_k(V, W)$ of all linear mappings from V into W, as vector spaces over k, is a linear subspace of $\mathcal{L}_k(V, \widetilde{W})$, as a vector space over k. Thus

(33.3.3) $\mathcal{L}_k(V, W)$ corresponds to a linear subspace of $\mathcal{L}_{k_1}(\widetilde{V}, \widetilde{W})$, as a vector space over k,

using the natural isomorphism mentioned in (33.3.2).

Suppose that $\{v_j\}_{j \in I}$ is a basis for V as a vector space over k, which may also be considered as a basis for $\widetilde{V}$ as a vector space over k_1. We may as well suppose that $I \neq \emptyset$, which is to say that $V \neq \{0\}$. Let $c(I, W)$, $c(I, \widetilde{W})$ be the spaces of functions on I with values in W, $\widetilde{W}$, respectively. These are vector spaces over k, k_1, respectively, with respect to pointwise addition and scalar multiplication.

A linear mapping from V into W is determined by its values on the basis vectors, and any element of $c(I, W)$ determines such a linear mapping in this way. This defines

(33.3.4) an isomorphism from $\mathcal{L}_k(V, W)$ onto $c(I, W)$, as vector spaces over k.

Similarly, we get

(33.3.5) an isomorphism from $\mathcal{L}_k(V, \widetilde{W})$ onto $c(I, \widetilde{W})$, as vector spaces over k_1.

In the same way, we obtain

(33.3.6) an isomorphism from $\mathcal{L}_{k_1}(\widetilde{V}, \widetilde{W})$ onto $c(I, \widetilde{W})$, as vector spaces over k_1.

Of course, (33.3.5) and (33.3.6) correspond to each other as in (33.3.2). Note that $c(I, \widetilde{W})$ may be considered as a vector space over k, by considering $\widetilde{W}$ as a vector space over k. Clearly

(33.3.7) $c(I, W)$ is a linear subspace of $c(I, \widetilde{W})$, as a vector space over k,

because W is a linear subspace of $\widetilde{W}$, as a vector space over k. This corresponds to the fact that $\mathcal{L}_k(V, W)$ may be considered as a linear subspace of $\mathcal{L}_k(V, \widetilde{W})$, as a vector space over k, using (33.3.4) and (33.3.5). Similarly, (33.3.3) corresponds to (33.3.7), using (33.3.4) and (33.3.6).

Let V', $\widetilde{V}'$ be the duals of V, $\widetilde{V}$, as vector spaces over k, k_1, respectively. Thus V' consists of the linear functionals on V, which are linear mappings from V into k, and $\widetilde{V}$ consists of mappings from $\widetilde{V}$ into k_1 that are linear over k_1. Of course, $W = k$ may be considered as a one-dimensional vector space over k, for which we get $\widetilde{W} = k_1$, as a one-dimensional vector space over k_1.

The space $\mathcal{L}_k(V, k_1)$ of linear mappings from V into k_1, as a vector space over k, may be considered as a vector space over k_1, as before. There is a natural isomorphism between this space and $\widetilde{V}'$, as vector spaces over k_1, as in (33.3.2). As a vector space over k, $\mathcal{L}_k(V, k_1)$ contains V' as a linear subspace. This means that

(33.3.8) V' corresponds to a linear subspace of $\widetilde{V}'$, as a vector space over k,

in a natural way, as in (33.3.3).

Suppose that V has positive finite dimension n, and let $v_1, \ldots, v_n$ be a basis for V. This may also be considered as a basis for $\widetilde{V}$, as a vector space over k_1, as before. Using this basis, we can identify V' with k^n, and $\widetilde{V}'$ with k_1^n. One can use this to see that the vector space $\widetilde{(V')}$ over k_1 associated to V' can be identified with $\widetilde{V}'$.

33.4 Larger fields and toral subalgebras

Let k, k_1 be fields with $k \subseteq k_1$ again, and let $(A, [\cdot,\cdot]_A)$ be a Lie algebra over k of positive finite dimension. This leads to a vector space $\widetilde{A}$ over k_1 of the same dimension, with A a linear subapce of $\widetilde{A}$ as a vector space over k, as in Section 33.2. As before, $[\cdot,\cdot]_A$ has a unique extension to a mapping $[\cdot,\cdot]_{\widetilde{A}}$ from $\widetilde{A} \times \widetilde{A}$

into $\widetilde{A}$ that is bilinear over k_1, and which makes $(\widetilde{A}, [\cdot,\cdot]_{\widetilde{A}})$ into a Lie algebra over k_1.

Suppose that A_0 is a Lie subalgebra of A such that every element of A_0 is ad-diagonalizable as an element of A, so that A_0 is commutative as a Lie algebra, as in Section 17.1. If α is an element of the dual A_0' of A_0, as a vector space over k, then let A_α be the set of $x \in A$ such that $\mathrm{ad}_{A,w}(x) = \alpha(w)\, x$ for every $w \in A_0$, as before. Suppose that A_0 is its own centralizer in A, as in (33.1.1), so that A_0 is the same as A_α with $\alpha = 0$.

Let $\Phi = \Phi_{A_0}$ be the set of $\alpha \in A_0'$ such that $\alpha \neq 0$ and $A_\alpha \neq \{0\}$, as before. Remember that A corresponds to the direct sum of the linear subspaces A_α, $\alpha \in \Phi \cup \{0\}$, as a vector space over k, as in Section 17.2. If $\alpha \in A_0'$, so that A_α is a linear subspace of A, then let $\widetilde{(A_\alpha)}$ be the linear subspace of $\widetilde{A}$ as a vector space over k_1 obtained from A_α as before. Observe that $\widetilde{A}$ corresponds to the direct sum of $\widetilde{(A_\alpha)}$, $\alpha \in \Phi \cup \{0\}$, as a vector space over k_1, as in Section 33.2.

More precisely, $\widetilde{(A_0)}$ is a Lie subalgebra of $\widetilde{A}$, as a Lie algebra over k_1. If $\alpha \in A_0'$, then let $\widetilde{\alpha}$ be the unique extension of α to a mapping from $\widetilde{(A_0)}$ into k_1 that is linear over k_1, so that $\widetilde{\alpha}$ is an element of the dual $\widetilde{(A_0)}'$ of $\widetilde{(A_0)}$, as a vector space over k_1. It is easy to see that

$$\mathrm{ad}_{\widetilde{A},w}(x) = [w,x]_{\widetilde{A}} = \widetilde{\alpha}(w)\, x \tag{33.4.1}$$

for every $w \in \widetilde{(A_0)}$ and $x \in \widetilde{(A_\alpha)}$, because this holds when $w \in A_0$ and $x \in A_\alpha$, by construction.

In particular, the elements of $\widetilde{(A_0)}$ are ad-diagonalizable in $\widetilde{A}$. If $\beta \in \widetilde{(A_0)}'$, then we can take $\widetilde{A}_\beta$ to be the set of $x \in \widetilde{A}$ such that $\mathrm{ad}_{\widetilde{A},w}(x) = \beta(w)\, x$ for every $w \in \widetilde{(A_0)}$, as usual. If $\alpha \in A_0'$ and $\widetilde{\alpha}$ is the corresponding element of $\widetilde{(A_0)}'$, then

$$\widetilde{(A_\alpha)} \subseteq \widetilde{A}_{\widetilde{\alpha}}, \tag{33.4.2}$$

by (33.4.1). Let $\widetilde{\Phi} = \widetilde{\Phi}_{\widetilde{(A_0)}}$ be the set of $\beta \in \widetilde{(A_0)}'$ such that $\beta \neq 0$ and $\widetilde{A}_\beta \neq \{0\}$, as usual. Thus

$$\{\widetilde{\alpha} : \alpha \in \Phi\} \subseteq \widetilde{\Phi}, \tag{33.4.3}$$

by (33.4.2).

In fact,

$$\widetilde{\Phi} = \{\widetilde{\alpha} : \alpha \in \Phi\}, \tag{33.4.4}$$

and

$$\widetilde{A}_{\widetilde{\alpha}} = \widetilde{(A_\alpha)} \tag{33.4.5}$$

for every $\alpha \in A_0'$. This follows from (33.4.1) and the fact that $\widetilde{A}$ corresponds to the direct sum of $\widetilde{(A_\alpha)}$, $\alpha \in \Phi \cup \{0\}$, as a vector space over k_1. In particular, if $\alpha = 0$, then $\widetilde{\alpha} = 0$ as an element of $\widetilde{(A_0)}'$, and we get that

$$\widetilde{A}_0 = \widetilde{(A_0)}. \tag{33.4.6}$$

Note that $\widetilde{(A_0)}$ is commutative as a Lie algebra over k_1, and that it is its own centralizer in $\widetilde{A}$, by (33.4.6).

If $\alpha, \beta \in A_0'$, then $[A_\alpha, A_\beta] \subseteq A_{\alpha+\beta}$ in A, as in Section 17.2. This implies that $[\widetilde{(A_0)}, \widetilde{(A_\beta)}] \subseteq \widetilde{(A_{\alpha+\beta})}$ in $\widetilde{A}$. If $[A_\alpha, A_\beta] = A_{\alpha+\beta}$ in A, then we get that

$$[\widetilde{(A_\alpha)}, \widetilde{(A_\beta)}] = \widetilde{(A_{\alpha+\beta})} \tag{33.4.7}$$

in $\widetilde{A}$.

Every element of $\widetilde{(A_0)}'$ can be expressed as a linear combination of elements of the form $\widetilde{\alpha}$, $\alpha \in A_0'$. Suppose that A_0' is spanned by Φ, as a vector space over k. This means that the center $Z(A)$ of A as a Lie algebra over k is trivial, as in Section 33.1. Under these conditions, we get that $\widetilde{(A_0)}'$ is spanned by $\widetilde{\Phi}$, as a vector space over k_1. This means that $Z(\widetilde{A}) = \{0\}$, as before.

Suppose that for each $\alpha \in \Phi$, A_α has dimension one, as a vector space over k. This implies that $\widetilde{(A_\alpha)}$ has dimension one, as a vector space over k_1. Suppose also that for every $\alpha \in \Phi$ there is an element h_α of $[A_\alpha, A_{-\alpha}] \subseteq A_0$ such that $\alpha(h_\alpha) = 2$. Of course, h_α may also be considered as an element of $[\widetilde{(A_\alpha)}, \widetilde{(A_{-\alpha})}]$ in $\widetilde{A}$.

Suppose that k has characteristic 0, so that k_1 has characteristic 0 as well. The linear subspace $E_{\mathbf{Q}}$ of A_0', as a vector space over $\mathbf{Q}$, corresponds exactly to the linear subspace of $\widetilde{(A_0)}'$ spanned by $\widetilde{\Phi}$, as a vector space over $\mathbf{Q}$, because of (33.4.4). This means that the associated vector space $E_{\mathbf{R}}$ over $\mathbf{R}$ corresponds exactly to the analogous vector space over $\mathbf{R}$ for $\widetilde{(A_0)}'$.

Suppose that Φ is a reduced root system in $E_{\mathbf{R}}$, so that $\widetilde{\Phi}$ is a reduced root system in the analogous vector space over $\mathbf{R}$ for $\widetilde{(A_0)}'$. Let Δ be a base for Φ, which means that $\widetilde{\Delta} = \{\widetilde{\alpha} : \alpha \in \Delta\}$ is a base for $\widetilde{\Phi}$. If h_α, $\alpha \in \Delta$, is a basis for A_0, as a vector space over k, then this is also a basis for $\widetilde{(A_0)}$, as a vector space over k_1.

If $Z(A) = \{0\}$, then A_0' is spanned by Φ as a vector space over k, and $\widetilde{(A_0)}'$ is spanned by $\widetilde{\Phi}$ as a vector space over k_1, as before. In this case, we get that A_0' is spanned by Δ as a vector space over k, and that $\widetilde{(A_0)}'$ is spanned by $\widetilde{\Delta}$ as a vector space over k_1. If Δ is a basis for A_0' as a vector space over k, then $\widetilde{\Delta}$ is a basis for $\widetilde{(A_0)}'$, as a vector space over k_1.

If $\alpha, \beta \in \Phi$, then one may ask that $\beta(h_\alpha)$ can be expressed in terms of Φ as a root system as in (33.1.2). This implies the analogous condition for $\widetilde{\Phi}$.

If $\Psi_0 \subseteq \Phi \cup \{0\}$, then $A(\Psi_0)$ is the linear subspace of A spanned by A_α, $\alpha \in \Psi_0$, as in Section 33.1. Similarly, if $\Psi_1 \subseteq \widetilde{\Phi} \cup \{0\}$, then let $\widetilde{A}(\Psi_1)$ be the linear subspace of $\widetilde{A}$, as a vector space over k_1, spanned by $\widetilde{A}_\gamma$, $\gamma \in \Psi_1$, as before. If $\Psi_0 \subseteq \Phi \cup \{0\}$, then

$$\Psi_1 = \{\widetilde{\alpha} : \alpha \in \Psi_0\} \tag{33.4.8}$$

is contained in $\widetilde{\Phi} \cup \{0\}$, and

$$\widetilde{A}(\Psi_1) = (\widetilde{A(\Psi_0)}), \tag{33.4.9}$$

by (33.4.5).

Let $\Phi^+ = \Phi^{\Delta,+}$ be the set of positive roots in Φ with respect to Δ, and let $\widetilde{\Phi}^+ = \widetilde{\Phi}^{\widetilde{\Delta},+}$ be the set of positive roots in $\widetilde{\Phi}$ with respect to $\widetilde{\Delta}$. Observe that

$$\widetilde{\Phi}^+ = \{\widetilde{\beta} : \beta \in \Phi^+\}. \tag{33.4.10}$$

Remember that, under the conditions on A and A_0 considered in Section 33.1, $B_\Delta = A(\Phi^+ \cup \{0\})$ is the standard Borel subalgebra of A associated to A_0 and Δ, as in Section 22.12. In this case, $\widetilde{A}$ and $(\widetilde{A_0})$ satisfy the analogous conditions over k_1, and

$$\widetilde{B}_{\widetilde{\Delta}} = \widetilde{A}(\widetilde{\Phi}^+ \cup \{0\}) \tag{33.4.11}$$

is the standard Borel subalgebra of $\widetilde{A}$, as a Lie algebra over k_1, associated to $(\widetilde{A_0})$ and $\widetilde{\Delta}$. We also have that

$$\widetilde{B}_{\widetilde{\Delta}} = (\widetilde{B_\Delta}), \tag{33.4.12}$$

by (33.4.9) and (33.4.10).

33.5 Weights and modules

Let us return to the same notation and hypotheses as in Section 33.1. Let V be a vector space over k which is a module over A, as a Lie algebra over k. If $\mu \in A_0'$, then put

$$V_\mu = \{v \in V : w \cdot v = \mu(w)\, v \text{ for every } w \in A_0\}, \tag{33.5.1}$$

which is a linear subspace of V. An element of V_μ is said to have *weight* μ with respect to A_0, as on p56 of [24].

The elements of V_μ may also be called *eigenvectors* of A_0 in V with weight μ, as on p57 of [25]. More precisely, Chapter VII of [25] deals with representations of $sl_n(k)$, $n \geq 2$. However, all but one of the results discussed there extend to arbitrary semisimple Lie algebras, as in Remark 1 on p61 of [25].

The dimension of V_μ is called the *multiplicity* of μ in V, as on p56 of [24], and Definition 2.3 on p58 of [25]. In particular, μ is said to be a *weight* of V with respect to A_0 when $V_\mu \neq \{0\}$, as on p107 of [14], p56 of [24], and Definition 2.3 on p58 of [25]. In this case, V_μ may be called a *weight space* of V with respect to μ, as on p107 of [14].

Let $\alpha, \mu \in A_0'$ be given, and suppose that $x \in A_\alpha$, $v \in V_\mu$. If $w \in A_0$, then

$$w \cdot (x \cdot v) = x \cdot (w \cdot v) + ([w, x]_A) \cdot v = \mu(w)\,(x \cdot v) + \alpha(w)\,(x \cdot v). \tag{33.5.2}$$

This shows that

$$x \cdot v \in V_{\mu+\alpha}, \tag{33.5.3}$$

as in part (a) of the lemma on p107 of [14], part (a) of Proposition 1 on p56 of [24], and Proposition 2.1 on p57 of [25]. Of course, this can be seen more directly when $\alpha = 0$, and it is trivial when $\alpha \not\in \Phi \cup \{0\}$, in which case $A_\alpha = \{0\}$.

Let $\widehat{V}$ be the linear subspace of V spanned by V_μ, $\mu \in A_0'$. In fact,

$$\widehat{V} \text{ corresponds to the direct sum of } V_\mu,\ \mu \in A_0', \text{ as a vector space over } k. \tag{33.5.4}$$

This means that if $\mu_1, \ldots, \mu_r$ are finitely many distinct elements of A_0', $v_j \in V_{\mu_j}$ for each $j = 1, \ldots, r$, and

$$\sum_{j=1}^{r} v_j = 0, \tag{33.5.5}$$

then $v_j = 0$ for every $j = 1, \ldots, r$. This can be obtained from the fact that eigenvectors of a linear mapping with distinct eigenvalues are linearly independent. This corresponds to the first part of part (b) of the lemma on p107 of [14], the first part of part (b) of Proposition 1 on p56 of [24], and part of Proposition 2.2 on p57 of [25].

It is easy to see that $\widehat{V}$ is a submodule of V, as a module over A, using (33.5.3). This corresponds to the second part of part (b) of the lemma on p107 of [14], the second part of part (b) of Proposition 1 on p56 of [24], and a remark in the proof of Proposition 2.2 on p57 of [25].

As an example, consider A as a module over itself, with respect to the adjoint representation. In this case, the weights are the roots $\alpha \in \Phi$, with the corresponding weight spaces A_α of dimension 1, and 0. This is Example (1) on p107 of [14], and Example 2.4 of p58 of [25].

33.6 Primitive or maximal vectors

Let us continue to use the same notation and hypotheses as in Section 33.1. In particular, Δ is a base for Φ as a root system, and Φ^+ is the set of positive roots in Φ with respect to Δ. Let V be a vector space over k that is a module over A as a Lie algebra over k again.

If $v \in V$ and $E \subseteq A$, then put

$$E \cdot v = \{x \cdot v : x \in E\}, \tag{33.6.1}$$

which is a linear subspace of V when E is a linear subspace of A. Suppose that

$$E_1 \cdot v = E_2 \cdot v = \{0\} \tag{33.6.2}$$

for some linear subspaces E_1, E_2 of A. If $x_1 \in E_1$ and $x_2 \in E_2$, then we get that

$$([x_1, x_2]_A) \cdot v = x_1 \cdot (x_2 \cdot v) - x_2 \cdot (x_1 \cdot v) = 0. \tag{33.6.3}$$

This means that

$$([E_1, E_2]) \cdot v = \{0\} \tag{33.6.4}$$

when (33.6.2) holds. If $\alpha, \beta \in \Phi$ satisfy $A_\alpha \cdot v = A_\beta \cdot v = \{0\}$ and $\alpha + \beta \in \Phi$, then it follows that

$$\Big(A_{\alpha+\beta}\Big) \cdot v = \{0\}, \tag{33.6.5}$$

because $[A_\alpha, A_\beta] = A_{\alpha+\beta}$.

If

$$A_\alpha \cdot v = \{0\} \quad \text{for every } \alpha \in \Delta, \tag{33.6.6}$$

then

$$A_\gamma \cdot v = \{0\} \quad \text{for every } \gamma \in \Phi^+. \tag{33.6.7}$$

This is implicit in a remark on p108 of [14], and on p57 of [24]. To see this, let $\gamma \in \Phi^+$ be given, and remember that γ can be expressed as $\sum_{j=1}^r \alpha_j$, where $\alpha_j \in \Delta$ for each $j = 1, \ldots, r$, and $\sum_{j=1}^l \alpha_j \in \Phi$ for every $l = 1, \ldots, r$, as in Section 19.12. Under these conditions, one can check that

$$\Big(A_{\big(\sum_{j=1}^l \alpha_j\big)}\Big) \cdot v = \{0\} \tag{33.6.8}$$

for every $l = 1, \ldots, r$, using (33.6.5).

Let μ be a linear functional on A_0. We say that $v \in V_\mu$ is a *primitive* or *maximal vector of weight* μ in V if $v \neq 0$ and (33.6.6) or equivalently (33.6.7) holds, as on p108 of [14], and p57 of [24]. We may simply say that $v \in V$ is a *primitive* or *maximal vector* in V if v is primitive or maximal of weight μ for some $\mu \in A_0'$.

Remember that B_Δ is the standard Borel subalgebra of A associated to A_0 and Δ, as in Section 33.1. Remember also that $N_\Delta = A(\Phi^+)$ is a Lie subalgebra of A that is nilpotent as a Lie algebra over k and whose elements are ad-nilpotent in A, and that $[B_\Delta, B_\Delta] = N_\Delta$, as in Sections 22.6 and 24.10. By construction, B_Δ corresponds to the direct sum of A_0 and N_Δ, as a vector space over k.

Let us say that $v \in V$ is an *eigenvector* of $x \in A$ if $x \cdot v$ is the multiple of v by an element of k, which is the corresponding *eigenvalue*. Of course, this is the same as saying that v is an eigenvector for the linear mapping corresponding to x on V, as a module over A. If $E \subseteq A$ and v is an eigenvector of every $x \in E$, then v is said to be an *eigenvector* of E. If v is an eigenvector of $x_1, x_2 \in A$ with eigenvalues $c_1, c_2 \in k$, then

$$\begin{aligned} ([x_1, x_2]_A) \cdot v &= x_1 \cdot (x_2 \cdot v) - x_2 \cdot (x_1 \cdot v) \\ &= c_2\,(x_1 \cdot v) - c_1\,(x_2 \cdot v) = c_1\,c_2\,v - c_1\,c_2\,v = 0. \end{aligned} \tag{33.6.9}$$

This means that v is an eigenvector of $[x_1, x_2]_A$, with eigenvalue 0.

If $v \in V$ is an eigenvector of B_Δ, then v is an eigenvector of every element of N_Δ with eigenvalue 0, because $[B_\Delta, B_\Delta] = N_\Delta$. This is the same as saying that (33.6.7) holds. More precisely, $v \in V$ is an eigenvector of B_Δ if and only if v is an eigenvector of A_0 and (33.6.7) holds, as in Proposition 2.5 on p58 of [25].

Note that a nonzero $v \in V$ is an eigenvector of A_0 if and only if $v \in V_\mu$ for some $\mu \in A_0'$, and that μ is unique. Thus a nonzero $v \in V$ is primitive or maximal if and only if it is an eigenvector of A_0 and satisfies (33.6.7), or equivalently v is an eigenvector of B_Δ. This corresponds to Definition 2.6 on p58 of [25], and is also mentioned on p57 of [24].

33.7 Representations and UA

Let k be a commutative ring with a multiplicative identity element, and let $(A, [\cdot,\cdot]_A)$ be a Lie algebra over k. Also let V be a module over k, which is a module over A, as a Lie algebra over k. Suppose that UA is a universal enveloping algebra of A with multiplicative identity element $e = e_{UA}$ and associated mapping $i = i_{UA}$ from A into UA, as in Section 25.4.

Remember that the space $\mathrm{Hom}_k(V, V)$ of homomorphisms from V into itself, as a module over k, is an associative algebra over k with respect to composition of mappings. In particular, $\mathrm{Hom}_k(V, V)$ is a Lie algebra over k, with respect to the commutator bracket. To say that V is a module over A as a Lie algebra over k means that we have a Lie algebra homomorphism from A into $\mathrm{Hom}_k(V, V)$.

Because UA is a universal enveloping algebra of A, there is a corresponding homomorphism from UA into $\mathrm{Hom}_k(V, V)$, as associative algebras over k, that sends e to the identity mapping on V. This defines a representation of UA, as an associative algebra over k, on V. Equivalently, V may be considered as a (left) module over UA, as an associative algebra over k.

If $x \in A$ and $v \in V$, then the action of x on v may be denoted $x \cdot v$, as usual. Similarly, if $u \in UA$ and $v \in V$, then let the action of u on v be denoted $u \cdot v$. It should be clear in practice which is intended, and the two are compatible in the sense that $x \cdot v$ is the same as $i(x) \cdot v$ for every $x \in A$.

Let $v \in V$ be given, and define $E \cdot v \subseteq V$ as in (33.6.1) when $E \subseteq A$. This is a submodule of V, as a module over k, when E is a submodule of A, as a module over k. If $E \subseteq UA$, then $E \cdot v$ can be defined as a subset of V analogously, and is a submodule of V as a module over k when E is a submodule of UA as a module over k. Note that $v \in E \cdot v$ when $e \in E \subseteq UA$.

Clearly every submodule of V, as a module over UA, is a submodule of V, as a module over A. Conversely, any submodule of V as a module over A is a submodule of V as a module over UA, because UA is generated by e and $i(A)$, as an associative algebra over k.

If $v \in V$, then it is easy to see that $(UA) \cdot v$ is a submodule of V, as a module over UA, that contains v, and in fact it is the smallest such submodule of V. Equivalently, $(UA) \cdot v$ is a submodule of V, as a module over A, that contains v, and is the smallest such submodule.

Remember that i is injective as a mapping from A into UA when A is free as a module over k, as in Section 25.12. In this case, we may identify A with $i(A) \subseteq UA$. In particular, this condition holds when k is a field.

33.8 Spanning standard cyclic modules

Let us return now to the notation and hypotheses in Section 33.1, so that in particular k is a field of characteristic 0, and $(A, [\cdot, \cdot]_A)$ is a Lie algebra over k of positive finite dimension. Let V be a module over A again, as a Lie algebra over k, and let UA be a universal enveloping algebra of A, so that V may also be considered as a module over UA, as an associative algebra over k. Suppose that $v \in V$ is a primitive or maximal vector of weight $\mu \in A_0'$, as in Section 33.6, and that

(33.8.1) $$V = (UA) \cdot v.$$

In this case, V is said to be *standard cyclic* of weight μ, as on p108 of [14]. Of course, if (33.8.1) does not hold, $(UA) \cdot v$ is a submodule of V, as a module over A, which is standard cyclic of weight μ as a module over A.

If $\alpha \in \Phi^+$, then let x_α be a nonzero element of A_α, so that A_α consists of multiples of x_α by elements of k. Also let y_α be the unique element of $A_{-\alpha}$ such that $[x_\alpha, y_\alpha]_A = h_\alpha$. Thus $y_\alpha \neq 0$, because $h_\alpha \neq 0$, so that $A_{-\alpha}$ consists exactly of multiples of y_α by elements of k.

Remember that $A(-\Phi^+)$ is the linear subspace of A spanned by $A_{-\alpha}$, with $\alpha \in \Phi^+$, as in Sections 22.4 and 33.1. More precisely, $A(-\Phi^+)$ is a Lie subalgebra of A, as in Section 22.6. Because $A(-\Phi^+)$ and B_Δ are Lie subalgebras of A, there are natural injective homomorphisms from universal enveloping algebras $UA(-\Phi^+)$ and UB_Δ of $A(-\Phi^+)$ and B_Δ, respectively, into UA, as associative algebras over k, as in Section 25.12. Thus we may identify $UA(-\Phi^+)$ and UB_Δ with subalgebras of UA in this way.

By construction, A corresponds to the direct sum of $A(-\Phi^+)$ and B_Δ, as a vector space over k. This leads to an isomorphism between UA and $(UA(-\Phi^+)) \bigotimes (UB_\Delta)$, as vector spaces over k, as in Section 25.12. In particular,

(33.8.2) every element of UA can be expressed as a finite sum, where each term corresponds to the product of an element of $UA(-\Phi^+)$ and an element of UB_Δ.

Observe that

(33.8.3) $$(UB_\Delta) \cdot v = \{t\, v : t \in k\},$$

because v is an eigenvector of B_Δ, by hypothesis. This also uses the fact that UB_Δ is generated as an associative algebra over k by its multiplicative identity element and the image of B_Δ in UB_Δ. It follows that

(33.8.4) $$V = (UA(-\Phi^+)) \cdot v,$$

by (33.8.1) and (33.8.2).

Let $\beta_1, \ldots, \beta_r$ be a list of the elements of Φ^+, so that $y_{\beta_1}, \ldots, y_{\beta_r}$ is a basis for $A(-\Phi^+)$, as a vector space over k. If $m_1, \ldots, m_r$ are nonnegative integers, then

(33.8.5) $$y_{\beta_1}^{m_1} \cdots y_{\beta_r}^{m_r}$$

corresponds to an element of $UA(-\Phi^+) \subseteq UA$. More precisely, y_{β_j} is identified with an element of $UA(-\Phi^+)$ for each $j = 1, \ldots, r$, so that $y_{\beta_j}^{m_j}$ corresponds to an element of $UA(-\Phi^+)$ as well. Of course, this is interpreted as being the multiplicative identity element when $m_j = 0$. Thus the product of $y_{\beta_j}^{m_j}$ over $j = 1, \ldots, r$ corresponds to an element of $UA(-\Phi^+)$ too.

The elements of $UA(-\Phi^+)$ of the form (33.8.5), where m_j is a nonnegative integer for each $j = 1, \ldots, r$, form a basis for $UA(-\Phi^+)$ as a vector space over k, by the Poincaré–Birkhoff–Witt theorem. In particular,

(33.8.6) $UA(-\Phi^+)$ is spanned by elements of the form (33.8.5), as a vector space over k.

If m_j is a nonnegative integer for each $j = 1, \ldots, r$, then (33.8.5) acts on v to get an element

$$(y_{\beta_1}^{m_1} \cdots y_{\beta_r}^{m_r}) \cdot v \tag{33.8.7}$$

of V. In fact,

(33.8.8) V is spanned by elements of the form (33.8.7), as a vector space over k.

This follows from (33.8.4) and (33.8.6). This corresponds to the first part of part (a) of the theorem on p108 of [14], part (1) of Proposition 2 on p57 of [24], and part of the proof of Theorem 3.1 on p58 of [25].

If m_j is a nonnegative integer for each $j = 1, \ldots, r$, then

$$\text{(33.8.7) has weight } \mu - \sum_{j=1}^{r} m_j\, \beta_j \tag{33.8.9}$$

as an element of V, in the sense of Section 33.5. This follows from (33.5.3), because $v \in V_\mu$, by hypothesis. This implies that (33.8.7) has weight of the form

$$\mu - \sum_{\alpha \in \Delta} c_\alpha\, \alpha, \tag{33.8.10}$$

where c_α is a nonnegative integer for each $\alpha \in \Delta$, because $\beta_j \in \Phi^+$ for every $j = 1, \ldots, r$.

In particular, V is spanned by its weight spaces, by (33.8.8). This means that

(33.8.11) V corresponds to the direct sum of its weight spaces, as a vector space over k,

as in Section 33.5. We also get that

(33.8.12) all of the weights of V are of the form mentioned in (33.8.9), and thus (33.8.10).

This corresponds to the second part of part (a) and part (b) of the theorem on p108 of [14], the first part of part (2) of Proposition 2 on p57 of [24], and part (b) of Theorem 3.1 on p58 of [25].

Remember that Δ is supposed to be a basis for A_0', as a vector space over k, as in Section 33.1. In particular, the elements of Δ are linearly independent in A_0', as a vector space over k. If c_α is a nonnegative integer for each $\alpha \in \Delta$, then there are only finitely many nonnegative integers $m_1, \ldots, m_r$ such that

$$\sum_{j=1}^{r} m_j\, \beta_j = \sum_{\alpha \in \Delta} c_\alpha\, \alpha. \tag{33.8.13}$$

This uses the facts that $\beta_j \in \Phi^+$ for every $j = 1, \ldots, r$, and k has characteristic 0, by hypothesis. Similarly, if $c_\alpha = 0$ for every $\alpha \in \Delta$, and $m_1, \ldots, m_r$ are nonnegative integers, then (33.8.13) holds only when $m_j = 0$ for every $j = 1, \ldots, r$.

It follows that

(33.8.14) the weight spaces in V have finite dimension,

as in the first part of part (c) of the theorem on p108 of [14], and the second part of part (2) of Proposition 2 on p57 of [24]. We also get that

$$\dim V_\mu = 1, \tag{33.8.15}$$

as in the second part of part (c) of the theorem on p108 of [14], part (3) of Proposition 2 on p57 of [24], and part (c) of Theorem 3.1 on p58 of [25]. Note that μ may be called the *highest weight* of V, because all of the weights of V are of the form (33.8.10), with $c_\alpha \geq 0$ for every $\alpha \in \Delta$.

33.9 Indecomposability

Let us continue with the same notation and hypotheses as in the previous section. We would like to show that V is *indecomposable* as a module over A, which is to say that it cannot be expressed is the direct sum of two nontrivial submodules of V. This corresponds to the first part of part (e) of the theorem on p108 of [14], and to part (4) of Proposition 2 on p57 of [24].

Suppose that V corresponds to the direct sum of two linear subspaces Y and Z, and that Y and Z are submodules of V, as a module over A. Thus we get linear projection mappings from V onto Y and Z whose kernels are Z and Y, respectively, and these projections commute with the action of A on V. If $\nu \in A_0'$, then one can use this to check that these projection mappings send V_ν into Y_ν and Z_ν, respectively, where V_ν, Y_ν and Z_ν are as in Section 33.5. This means that V_ν corresponds to the direct sum of Y_ν and Z_ν, as a vector space over k.

In particular, if we take $\nu = \mu$, then we get that one of Y_μ or Z_μ has dimension one, by (33.8.15). This implies that v is an element of Y or Z, so that Y or Z is all of V, because V is generated by v as a module over A, as in (33.8.1). Of course, this means that the other of Y or Z is $\{0\}$, so that V is indecomposable, as desired. This is the argument near the top of p58 of [24].

If V has finite dimension as a vector space over k, then it follows that V is irreducible as a module over A, by Weyl's theorem. This uses the hypothesis that k have characteristic 0, as well as the semisimplicity of A, as in Section 33.1. This corresponds to part (d) of Proposition 3 on p60 of [24], and part (a) of Theorem 3.1 on p58 of [25].

Let Z be any submodule of V as a module over A, so that Z is a linear subspace of V, and the action of A on V maps Z into itself. Part (d) of the theorem on p108 of [14] states that

(33.9.1) Z corresponds to the direct sum of its weight spaces, as a vector space over k.

Of course, it suffices to check that Z is spanned by its weight spaces, as in Section 33.5.

Suppose for the sake of a contradiction that there is an element of Z that is not in the linear span of the weight spaces of Z. Because V is spanned by its weight spaces, every element of Z can be expressed as

$$z = \sum_{j=1}^{n} z_j, \tag{33.9.2}$$

where for each $j = 1, \ldots, n$, $z_j \in V_{\nu_j}$ for some $\nu_j \in A_0'$. Let n be the smallest positive integer for which there is a $z \in Z$ that is not in the linear span of the weight spaces of Z, and which can be expressed as in (33.9.2). Of course, this means that $n \geq 2$, and that the ν_j's are distinct elements of A_0'. We also have that $z_j \notin Z$ for each $j = 1, \ldots, n$.

Because $\nu_1 \neq \nu_2$, there is a $w \in A_0$ such that $\nu_1(w) \neq \nu_2(w)$. Observe that

$$w \cdot z = \sum_{j=1}^{n} w \cdot z_j = \sum_{j=1}^{n} \nu_j(w)\, z_j, \tag{33.9.3}$$

so that

$$w \cdot z - \nu_1(w)\, z = \sum_{j=2}^{n} (\nu_j(w) - \nu_1(w))\, z_j. \tag{33.9.4}$$

The left side is an element of Z, and the minimality of n implies that it is in the linear span of the weight spaces of Z. Remember that the linear span of the weight spaces in V corresponds to the direct sum of the weight spaces in V, as a vector space over k, as in Section 33.5. It follows that the terms in the sum on the right side of (33.9.4) are elements of Z. This implies that $z_2 \in Z$, because $\nu_2(w) \neq \nu_1(w)$, by construction. This is a contradiction, as in the preceding paragraph.

Let Z be a submodule of V as a module over A again, and suppose that $Z \neq V$. This implies that $v \notin Z$, by (33.8.1), and thus

$$Z \cap V_\mu = \{0\}, \tag{33.9.5}$$

by (33.8.15). Let V^0 be the linear subspace of V spanned by the weight spaces V_ν with $\nu \in A_0'$ and $\nu \neq \mu$. This is a proper linear subspace of V, because V corresponds to the direct sum of its weight spaces, and $V_\mu \neq \{0\}$, by hypothesis. Using (33.9.5), we get that

$$Z \subseteq V^0, \tag{33.9.6}$$

because Z is spanned by its weight spaces, as before.

Let V^1 be the linear subspace of V spanned by all of the proper submodules of V, as a module over A. Thus

$$V^1 \subseteq V^0, \tag{33.9.7}$$

by (33.9.6). In particular, this implies that V is indecomposable as a module over A, as on p109 of [14]. More precisely, V is not spanned by proper submodules, as a module over A.

It is easy to see that V^1 is a submodule of V, as a module over A. In fact, V^1 is the unique maximal proper submodule of V, as a module over A, as in part (e) of the theorem on p108 of [14]. The quotient V/V^1 is a module over A in a natural way, because V^1 is a submodule of V. Observe that

$$V/V^1 \text{ is irreducible, as a module over } A, \tag{33.9.8}$$

as in part (e) of the theorem on p108 of [14], because V^1 is a maximal proper submodule of V. Of course, $V/V^1 \neq \{0\}$, because $V^1 \neq V$.

If the quotient of V by a proper submodule is irreducible as a module over A, then that submodule of V is maximal. This means that V/V^1 is the only nontrivial irreducible quotient of V, as a module over A, as in part (e) of the theorem on p108 of [14].

33.10 Irreducible standard cyclic modules

Let us use the same notation and hypotheses as in Section 33.1 again, and let V be a module over A, as a Lie algebra over k. Suppose that $v \in V$ is a primitive or maximal vector of weight $\mu \in A_0'$, and that V is irreducible as a module over A. Let UA be a universal enveloping algebra of A, so that $(UA) \cdot v$ is a submodule of V that contains v. Because V is irreducible, we get that $V = (UA) \cdot v$, so that V is standard cyclic of weight μ. This corresponds to the first step in the proof of Theorem 1 on p58 of [24].

Thus V satisfies the hypotheses in Section 33.8, and so has the same properties as before. This corresponds to part (b) of Theorem 1 on p58 of [24].

Suppose that $v_1 \in V$ is another primitive or maximal vector, with weight $\mu_1 \in A_0'$. It follows that

$$V = (UA) \cdot v_1, \tag{33.10.1}$$

because V is irreducible, as before. This means that the analogues of the statements in Section 33.8 for v_1 and μ_1 hold as well.

Because μ_1 is a weight of V, there are nonnegative integers c_α, $\alpha \in \Delta$, such that

$$\mu_1 = \mu - \sum_{\alpha \in \Delta} c_\alpha \, \alpha, \tag{33.10.2}$$

as in (33.8.12). Similarly, there are nonnegative integers $c_{1,\alpha}$, $\alpha \in \Delta$, such that

$$\mu = \mu_1 - \sum_{\alpha \in \Delta} c_{1,\alpha} \, \alpha, \tag{33.10.3}$$

by the analogue of (33.8.12) for μ_1, and the fact that μ is a weight of V. It follows that $c_{1,\alpha} = -c_\alpha$ for every $\alpha \in \Delta$, because Δ is a basis for A_0', and k has characteristic 0, as in Section 33.1. This implies that $c_\alpha = c_{1,\alpha} = 0$ for every $\alpha \in \Delta$, so that

$$\mu_1 = \mu. \tag{33.10.4}$$

We also get that

$$v_1 = t_1 \, v \text{ for some } t_1 \in k \setminus \{0\}, \tag{33.10.5}$$

by (33.8.15).

This corresponds to the corollary on p109 of [14], part (a) of Theorem 1 on p58 of [24], and part (1) of Theorem 3.2 on p59 of [25]. Note that μ may be called the *highest weight* of V, as in [24, 25]. This terminology may also be used for any standard cyclic module of weight μ, as in [14]. Of course, this refers to the expression of other weights as in (33.8.10).

Let Z be another irreducible module over A with a primitive or maximal vector z. If Z is isomorphic to V as a module over A, then Z has highest weight μ too, because of (33.10.4). Conversely, suppose that Z has highest weight μ, and let us show that Z is isomorphic to V, as modules over A. This corresponds to Theorem A on p109 of [14], part (c) of Theorem 1 on p58 of [24], and part (2) of Theorem 3.2 on p59 of [25].

Let Y be the direct sum of V and Z, which is the same as the Cartesian product of V and Z, where addition and scalar multiplication are defined coordinatewise. More precisely, Y is a module over A, where the action of A is defined coordinatewise as well. Observe that

$$y = (v, z) \tag{33.10.6}$$

is a primitive or maximal vector of weight μ in Y. Put

$$E = (UA) \cdot y, \tag{33.10.7}$$

which is the submodule of Y, as a module over A, generated by y. Thus E is a standard cyclic module of weight μ, by construction.

Let p_V, p_Z be the obvious projections from Y onto V, Z, respectively, and let ϕ_V, ϕ_Z be their restrictions to E. Of course, these mappings are module homomorphisms, and

$$\phi_V(y) = v, \ \phi_Z(y) = z. \tag{33.10.8}$$

This implies that

(33.10.9) $$\phi_V(E) = V,\ \phi_Z(E) = Z,$$

because V, Z are standard cyclic with respect to v, z, respectively, as before. The kernels of ϕ_V, ϕ_Z are

(33.10.10) $$\ker \phi_V = (\{0\} \times Z) \cap E,\ \ker \phi_Z = (V \times \{0\}) \cap E.$$

Of course, $V \times \{0\}$ and $\{0\} \times Z$ may be identified with V and Z, respectively, as modules over A.

Note that the only elements of E of weight μ are multiples of y by elements of k, as in (33.8.15). Thus there are no nonzero elements of the kernels of ϕ_V or ϕ_Z of weight μ. It follows that $(0, z) \not\in \ker \phi_V$, $(v, 0) \not\in \ker \phi_Z$, so that

(33.10.11) $$\ker \phi_V \ne \{0\} \times Z,\ \ker \phi_Z \ne V \times \{0\}.$$

We can identify $\ker \phi_V$, $\ker \phi_Z$ with submodules of Z, V, respectively, as modules over A. These submodules are proper, by (33.10.11).

This implies that these submodules are trivial, because V and Z are irreducible, by hypothesis. This means that the kernels of ϕ_V and ϕ_Z are trivial, so that ϕ_V, ϕ_Z are isomorphisms from E onto V, Z, respectively, as modules over A. Of course, this leads to an isomorphism from V onto Z. This is the argument on p58f of [24].

The argument on p109 of [14] uses the fact that V and Z are isomorphic to irreducible quotients of E, while there is only one irreducible quotient of E, as in Section 33.9.

If V and Z have finite dimension as vector spaces over k, then E has finite dimension too. This implies that E is irreducible as a module over A, because E is indecomposable, as in the previous section. In this case, one can get that the kenrels of ϕ_V and ϕ_Z are trivial because they are proper submodules of E. This is the argument used on p59 of [25], where the modules are taken to be finite-dimensional.

33.11 Representations and left ideals

Let k be a commutative ring with a multiplicative identity element, and let $(A, [\cdot, \cdot]_A)$ be a Lie algebra over A. Also let UA be a universal enveloping algebra of A with multiplicative identity element $e = e_{UA}$ and associated mapping $i = i_{UA}$ from A into UA, as in Section 25.4.

Suppose that $\mathcal{I}$ is a left ideal in UA, as an associative algebra over k. The quotient $(UA)/\mathcal{I}$ can be defined as a module over k, and in fact as a left module over UA. Let $q_{\mathcal{I}}$ be the natural quotient mapping from UA onto $(UA)/\mathcal{I}$, so that $q_{\mathcal{I}}(e)$ is an element of the quotient. Of course,

(33.11.1) $$(UA) \cdot q_{\mathcal{I}}(e) = (UA)/\mathcal{I},$$

by construction. Note that $(UA)/\mathcal{I}$ may be considered as a module over A too, as a Lie algebra over k.

Suppose that V is a module over k that is a module over A as a Lie algebra over k. Thus V may be considered as a (left) module over UA, as an associative algebra over UA, as before. If $v \in V$, then

$$\mathcal{I}_v = \{x \in UA : x \cdot v = 0\} \tag{33.11.2}$$

is a left ideal in UA. This means that the quotient $(UA)/\mathcal{I}_v$ is defined as a left module over UA. The mapping

$$x \mapsto x \cdot v \tag{33.11.3}$$

from UA into V leads to an injective homomorphism from $(UA)/\mathcal{I}_v$ into V, as left modules over UA. More precisely, this mapping sends $(UA)/\mathcal{I}_v$ onto $(UA) \cdot v$, which is a submodule of V, as a module over UA. If $V = (UA) \cdot v$, then we get an isomorphism from $(UA)/\mathcal{I}_v$ onto V, as left modules over UA.

Note that quotients of $(UA)/\mathcal{I}$, as a left module over UA, or as a module over A as a Lie algebra over k, correspond to quotients of UA by left ideals in UA that contain $\mathcal{I}$. Thus $(UA)/\mathcal{I}$ is nontrivial and irreducible as a left module over UA, or as a module over A as a Lie algebra over k, exactly when $\mathcal{I} \neq UA$ is maximal as a proper left ideal in UA.

33.12 Tensor products over algebras

Let k be a commutative ring with a multiplicative identity element, and let $\mathcal{A}$ be an associative algebra over k, with a multiplicative identity element $e = e_{\mathcal{A}}$. Also let V, W be modules over k, where V is a right module over $\mathcal{A}$, and W is a left module over $\mathcal{A}$. The *tensor product* of V and W over $\mathcal{A}$ is a module $V \bigotimes_{\mathcal{A}} W$ over k with the following two properties.

First, the tensor product is equipped with a mapping from $V \times W$ into $V \bigotimes_{\mathcal{A}} W$ that is bilinear over k. If $v \in V$ and $w \in W$, then the image of (v, w) under this mapping is denoted $v \otimes w$, as usual. This mapping should also satisfy

$$(v \cdot a) \otimes w = v \otimes (a \cdot w) \tag{33.12.1}$$

for every $a \in \mathcal{A}$, $v \in V$, and $w \in W$.

Second, let Z be any module over k, and let b be a mapping from $V \times W$ into Z that is bilinear over k. Suppose that

$$b(v \cdot a, w) = b(v, a \cdot w) \tag{33.12.2}$$

for every $a \in \mathcal{A}$, $v \in V$, and $w \in W$. Under these conditions, there should be a unique homomorphism c from $V \bigotimes_{\mathcal{A}} W$ into Z, as modules over k, such that

$$b(v, w) = c(v \otimes w) \tag{33.12.3}$$

for every $v \in V$ and $w \in W$.

The tensor product can be obtained using a standard construction, and it is unique up to a suitable isomorphic equivalence. Note that $V \bigotimes_{\mathcal{A}} W$ is generated as a module over k by elements of the form $v \otimes w$, $v \in V$, $w \in W$.

Let I be a nonempty set, and let V_j be a right module over $\mathcal{A}$ for every $j \in I$. Thus $\bigoplus_{j \in I} V_j$ is a right module over $\mathcal{A}$ too, and one can check that

$$\Big(\bigoplus_{j \in I} V_j\Big) \bigotimes_{\mathcal{A}} W = \bigoplus_{j \in I} (V_j \bigotimes_{\mathcal{A}} W). \tag{33.12.4}$$

Similarly, if W_j is a left module over $\mathcal{A}$ for every $j \in I$, then $\bigoplus_{j \in I} W_j$ is a left module over $\mathcal{A}$, and one can verify that

$$V \bigotimes_{\mathcal{A}} \Big(\bigoplus_{j \in I} W_j\Big) = \bigoplus_{j \in I} (V \bigotimes_{\mathcal{A}} W_j). \tag{33.12.5}$$

Let V_1, V_2 be right modules over $\mathcal{A}$, and let W_1, W_2 be left modules over $\mathcal{A}$. Suppose that ϕ_{V_1} is a homomorphism from V_1 into V_2, as right modules over $\mathcal{A}$, and that ϕ_{W_1} is a homomorphism from W_1 into W_2, as left modules over $\mathcal{A}$. Consider the mapping from $V_1 \times W_1$ into $V_2 \bigotimes_{\mathcal{A}} W_2$ defined by

$$(v_1, w_1) \mapsto \phi_{V_1}(v_1) \otimes \phi_{W_1}(w_1). \tag{33.12.6}$$

This mapping is bilinear over k, and satisfies

$$\begin{aligned} \phi_{V_1}(v_1 \cdot a) \otimes \phi_{W_1}(w_1) &= (\phi_{V_1}(v_1) \cdot a) \otimes \phi_{W_1}(w_1) \\ &= \phi_{V_1}(v) \otimes (a \cdot \phi_{W_1}(w_1)) = \phi_{V_1}(v_1) \otimes \phi_{W_1}(a \cdot w_1) \end{aligned} \tag{33.12.7}$$

for every $a \in \mathcal{A}$, $v_1 \in V_1$, and $w_1 \in W_1$. This leads to a unique homomorphism ϕ from $V_1 \bigotimes_{\mathcal{A}} W_1$ into $V_2 \bigotimes_{\mathcal{A}} W_2$, as modules over k, such that

$$\phi(v_1 \otimes w_1) = \phi_{V_1}(v_1) \otimes \phi_{W_1}(w_1) \tag{33.12.8}$$

for every $v_1 \in V_1$ and $w_1 \in W_1$.

Let V_3 be another right module over $\mathcal{A}$, and let W_3 be another left module over $\mathcal{A}$. Suppose that ψ_{V_2} is a homomorphism from V_2 into V_3, as right modules over $\mathcal{A}$, and that ψ_{W_2} is a homomorphism from W_2 into W_3, as left modules over $\mathcal{A}$. This leads to a homomorphism ψ from $V_2 \bigotimes_{\mathcal{A}} W_2$ into $V_3 \bigotimes_{\mathcal{A}} W_3$, as modules over k, as in the previous paragraph. Of course, $\psi_{V_2} \circ \phi_{V_1}$ is a homomorphism from V_1 into V_3, as right modules over $\mathcal{A}$, and $\psi_{W_2} \circ \phi_{W_1}$ is a homomorphism from W_1 into W_3, as left modules over $\mathcal{A}$. One can verify that $\psi \circ \phi$ is the same as the homomorphism from $V_1 \bigotimes_{\mathcal{A}} W_1$ into $V_3 \bigotimes_{\mathcal{A}} W_3$, as modules over k, obtained from $\psi_{V_2} \circ \phi_{V_1}$, $\psi_{W_2} \circ \phi_{W_1}$ as before.

33.13 Using modules over other algebras

Let us continue with the same notation and hypotheses as in the previous section. Suppose now that $\mathcal{A}_1$ is another associative algebra over k with a multiplicative identity element $e_1 = e_{\mathcal{A}_1}$. Let V, W be modules over k, where V is a left module over $\mathcal{A}_1$, V is a right module over $\mathcal{A}$, and W is a left module over $\mathcal{A}$. More precisely, we suppose that the left and right actions on V commute with each other, so that

$$(a_1 \cdot v) \cdot a = a_1 \cdot (v \cdot a) \tag{33.13.1}$$

for every $a \in \mathcal{A}$, $a_1 \in \mathcal{A}_1$, and $v \in V$. Of course, $V \bigotimes_{\mathcal{A}} W$ can be defined as a module over k, as in the previous section.

If $a_1 \in \mathcal{A}_1$, then

$$v \mapsto a_1 \cdot v \tag{33.13.2}$$

defines a mapping from V into itself that is linear over k. In fact, this is a homomorphism from V into itself, as a right module over $\mathcal{A}$, because of (33.13.1). Using this and the identity mapping on W, we get a homomorphism from $V \bigotimes_{\mathcal{A}} W$ into itself, as a module over k, as in the previous section. This homomorphism defines an action of a_1 on the left on $V \bigotimes_{\mathcal{A}} W$, which is characterized by the property that

$$a_1 \cdot (v \otimes w) = (a_1 \cdot v) \otimes w \tag{33.13.3}$$

for every $a_1 \in \mathcal{A}_1$, $v \in V$, and $w \in W$. One can check that

$$V \bigotimes_{\mathcal{A}} W \text{ becomes a left module over } \mathcal{A}_1 \tag{33.13.4}$$

in this way.

Let Z be a module over k that is a left module over $\mathcal{A}_1$, and let b be a mapping from $V \times W$ into Z that is bilinear over k and satisfies (33.12.2). Thus there is a unique homomorphism c from $V \bigotimes_{\mathcal{A}} W$ into Z, as modules over k, that satisfies (33.12.3), as in the previous section. Suppose now in addition that

$$a_1 \cdot b(v, w) = b(a_1 \cdot v, w) \tag{33.13.5}$$

for every $a_1 \in \mathcal{A}_1$, $v \in V$, and $w \in W$. This means that

$$a_1 \cdot c(v \otimes w) = c(a_1 \cdot (v \otimes w)) \tag{33.13.6}$$

for every $a_1 \in \mathcal{A}_1$, $v \in V$, and $w \in W$. One can use this to check that c is a homomorphism from $V \bigotimes_{\mathcal{A}} W$ into Z, as left modules over $\mathcal{A}_1$.

Of course, there are analogous statements when W is also a right module over an associative algebra $\mathcal{A}_2$ over k, where the left action on W by elements of $\mathcal{A}$ commutes with the right action by elements of $\mathcal{A}_2$.

Note that $\mathcal{A}_1$ may be considered as a left and right module over itself. The left and right actions of $\mathcal{A}_1$ on itself commute, by associativity.

Suppose that $\mathcal{A}_1$ contains $\mathcal{A}$ as a subalgebra, with $e_1 = e$. We may consider $\mathcal{A}_1$ as a left and right module over itself, and over $\mathcal{A}$. Let us consider $\mathcal{A}_1$ as a left module over itself and as a right module over $\mathcal{A}$, and let W be a left module over $\mathcal{A}$ again. Under these conditions,

$$\mathcal{A}_1 \bigotimes_{\mathcal{A}} W \tag{33.13.7}$$

becomes a left module over $\mathcal{A}_1$, as before.

In particular, we can take $\mathcal{A}_1 = \mathcal{A}$ here, so that $\mathcal{A} \bigotimes_{\mathcal{A}} W$ may be considered as a left module over $\mathcal{A}$. Of course, we already have a mapping from $\mathcal{A} \times W$ into W that is bilinear over k, given by the action of $\mathcal{A}$ on W as a left module over $\mathcal{A}$. It is easy to see that W satisfies the requirements of the tensor product $\mathcal{A} \bigotimes_{\mathcal{A}} W$, as a module over k, with respect to this mapping from $\mathcal{A} \times W$ into W. One can verify that the action of $\mathcal{A}$ on $\mathcal{A} \bigotimes_{\mathcal{A}} W$ on the left just mentioned corresponds exactly to the given action of $\mathcal{A}$ on W on the left.

33.14 Existence of standard cyclic modules

Let us return to the notation and hypotheses in Section 33.1. Let $\mu \in A_0'$ be given. We would like to show that there is a standard cyclic module over A with weight μ.

Remember that Δ is a base for the root system Φ, and that B_Δ is the standard Borel subalgebra of A associated to A_0 and Δ. We also have that B_Δ corresponds to the direct sum of A_0 and $N_\Delta = A(\Phi^+)$ as a vector space over k, and that $[B_\Delta, B_\Delta] = N_\Delta$, as before.

Let $L(\mu)$ be a one-dimensional vector space over k. We can define an action of B_Δ on $L(\mu)$ by putting

$$(w + x) \cdot u = \mu(w)\, u \tag{33.14.1}$$

for every $w \in A_0$, $x \in N_\Delta$, and $u \in L(\mu)$. It is easy to see that this makes $L(\mu)$ into a module over B_Δ, as a Lie algebra over k.

Let UA be a universal enveloping algebra of A, with multiplicative identity element $e = e_{UA}$ and associated mapping $i = i_{UA}$ from A into UA, as in Section 25.4. We may as well take the universal enveloping algebra UB_Δ of B_Δ to be the subalgebra of UA generated by e and $i(B_\Delta)$, as in Section 25.12. We may also consider $L(\mu)$ as a left module over UB_Δ, as an associative algebra over k. Remember that i is injective, as in Section 25.12, so that we may as well identify A with its image in UA.

Of course, UA may be considered as a right module over itself, and thus a right module over UB_Δ. Let us take

$$Z(\mu) = (UA) \bigotimes_{UB_\Delta} L(\mu), \tag{33.14.2}$$

where the right side is as in the previous two sections. More precisely, this is a module over k, and in fact a left module over UA. This means that $Z(\mu)$ may be considered as a module over A, as a Lie algebra over k.

Let u_0 be a nonzero element of $L(\mu)$, and put

$$v = e \otimes u_0 \in Z(\mu). \tag{33.14.3}$$

One can check that

$$(UA) \cdot v = Z(\mu), \tag{33.14.4}$$

because $L(\mu)$ has dimension one, as a vector space over k. If $w \in A_0$, then

$$(33.14.5)\quad \begin{aligned} w \cdot v = w \cdot (e \otimes u_0) = w \otimes u_0 &= e \otimes (w \cdot u_0) \\ &= \mu(w)\,(e \otimes u_0) = \mu(w)\,v. \end{aligned}$$

Similarly, if $x \in N_\Delta$, then

$$(33.14.6)\qquad x \cdot v = x \cdot (e \otimes u_0) = x \otimes u_0 = e \otimes (x \cdot u_0) = 0.$$

Remember that $A(-\Phi^+)$ is a Lie subalgebra of A, and that A corresponds to the direct sum of $A(-\Phi^+)$ and B_Δ, as linear subspaces of A. This leads to an isomorphism between UA and $(UA(-\Phi^+)) \bigotimes (UB_\Delta)$, as vector spaces over k, as in Section 25.12. One can use this to get that UA is free as a right module over UB_Δ. This corresponds to part of Corollary D on p92 of [14], aside from using right modules here.

More precisely, let $x_\alpha \in A_\alpha$ and $y_\alpha \in A_{-\alpha}$ be as in Section 33.8 for each α in Φ^+, and let $\beta_1, \ldots, \beta_r$ be a list of the elements of Φ^+ again. Thus $y_{\beta_1}, \ldots, y_{\beta_r}$ form a basis for $A(-\Phi^+)$, as a vector space over k, and

$$(33.14.7)\qquad \{y_{\beta_1}^{m_1} \cdots y_{\beta_r}^{m_r} : m_1, \ldots, m_r \in \mathbf{Z}_+ \cup \{0\}\}$$

is a basis for $UA(-\Phi^+)$, as a vector space over k, by the Poincaré–Birkhoff–Witt theorem, as before. One can use the Poincaré–Birkhoff–Witt theorem again to get that UA is free as a right module over UB_Δ, with basis (33.14.7).

Indeed, the Poincaré–Birkhoff–Witt theorem implies that UA corresponds to the direct sum of the linear subspaces

$$(33.14.8)\qquad y_{\beta_1}^{m_1} \cdots y_{\beta_r}^{m_r}\,(UB_\Delta)$$

as a vector space over k, where $m_1, \ldots, m_r$ are nonnegative integers. The Poincaré–Birkoff–Witt theorem also ensures that

$$(33.14.9)\qquad z \mapsto y_{\beta_1}^{m_1} \cdots y_{\beta_r}^{m_r}\, z$$

is a one-to-one linear mapping from UB_Δ onto (33.14.8) for all $m_1, \ldots, m_r \ge 0$. This can be seen by combining $y_{\beta_1}, \ldots, y_{\beta_r}$ with a basis for B_Δ, as a vector space over k, to get a basis for A, as a vector space over k.

Clearly (33.14.8) is a submodule of UA, as a right module over UB_Δ, for every $m_1, \ldots, m_r \ge 0$. In fact, (33.14.9) is an isomorphism from UB_Δ onto (33.14.8), as right modules over UB_Δ, for every $m_1, \ldots, m_r \ge 0$. This means that UA corresponds to the direct sum of the submodules (33.14.8) as a right module over UB_Δ, and that UA is free as a right module over UB_Δ.

It follows that $Z(\mu)$ corresponds to the direct sum of

$$(33.14.10)\qquad (y_{\beta_1}^{m_1} \cdots y_{\beta_r}^{m_r}(UB_\Delta)) \bigotimes_{UB_\Delta} L(\mu)$$

as a vector space over k, where $m_1, \ldots, m_r$ are nonnegative integers. Note that (33.14.10) is isomorphic to $L(\mu)$ as a vector space over k for every $m_1, \ldots, m_r \ge$

0, as in the previous section. This means that (33.14.10) is a one-dimensional vector space over k spanned by

$$(y_{\beta_1}^{m_1} \cdots y_{\beta_r}^{m_r}) \cdot (e \otimes u_0) = (y_{\beta_1}^{m_1} \cdots y_{\beta_r}^{m_r}) \cdot v \tag{33.14.11}$$

for every $m_1, \ldots, m_r \geq 0$, where v is as in (33.14.3).

In particular, (33.14.11) is nonzero for all nonnegative integers $m_1, \ldots, m_r$. It follows that $v \neq 0$, by taking $m_1 = \cdots = m_r = 0$. This shows that v is a primitive or maximal vector in $Z(\mu)$ with weight μ. Thus $Z(\mu)$ is standard cyclic of weight μ, as a module over A. We also get that the elements (33.14.11) of $Z(\mu)$, with $m_1, \ldots, m_r \geq 0$, form a basis for $Z(\mu)$, as a vector space over k. This corresponds to some of the remarks on p110 of [14], and on p59 of [24]. This corresponds to part of Exercise 6 on p62 of [25] as well.

Observe that

$$z \mapsto z \cdot (e \otimes u_0) \tag{33.14.12}$$

is a one-to-one linear mapping from $UA(-\Phi^+)$ onto $Z(\mu)$, because (33.14.7) is a basis for $UA(-\Phi^+)$, as a vector space over k. Note that $Z(\mu)$ may be considered as a left module over $UA(-\Phi^+)$, where $UA(-\Phi^+)$ is identitifed with a subalgebra of UA in the usual way. In fact, (33.14.12) is an isomorphism from $UA(-\Phi^+)$ onto $Z(\mu)$, as left modules over $UA(-\Phi^+)$, as mentioned on p110 of [14].

As in Section 33.9, $Z(\mu)$ has a unique nontrivial irreducible quotient, as a module over A. It is easy to see that the quotient is also standard cyclic of weight μ, using the image of v in the quotient. This corresponds to Theorem B on p110 of [14], Theorem 2 on p59 of [24], and part of Exercise 6 on p62 of [25].

More precisely, $Z(\mu)$ is universal as a standard cyclic module of weight μ over A, as in the next section. These modules are known as *Verma modules*, as mentioned on p167 of [14].

33.15 Homomorphisms into other modules

Let us continue with the same notation and hypotheses as in the previous section, including those from Section 33.1. Let V be a vector space over k that is a module over A, as a Lie algebra over k, and suppose that $v_0 \in V$ is a primitive or maximal vector of weight μ. Of course, V may also be considered as a module over B_Δ, as a Lie algebra over k. The linear span V_0 of v_0 in V is a submodule of V, as a module over B_Δ.

There is a unique linear mapping from $L(\mu)$ onto V_0 that sends u_0 to v_0. This mapping is a homomorphism from $L(\mu)$ into V_0, as modules over B_Δ.

We may consider V_0 as a left module over UB_Δ, and V as a left module over UA, as associative algebras over k. If $z \in UA$ and $t \in k$, then put

$$b(z, t\, u_0) = z \cdot (t\, v_0), \tag{33.15.1}$$

which is an element of V. This defines b as a mapping from $(UA) \times L(\mu)$ into V that is bilinear over k.

If $a \in UB_\Delta$ and $t \in k$, then $a \cdot (t\, u_0) \in L(\mu)$, because $L(\mu)$ is a left module over UB_Δ. If $z \in UA$, then we get that

$$b(z\, a, t\, u_0) = (z\, a) \cdot (t\, v_0) = z \cdot (a \cdot (t\, v_0)) = b(z, a \cdot (t\, u_0)). \tag{33.15.2}$$

This implies that there is a unique mapping c from $Z(\mu) = (UA) \bigotimes_{UB_\Delta} L(\mu)$ into V that is linear over k and satisfies

$$b(z, t\, u_0) = c(z \otimes (t\, u_0)) \tag{33.15.3}$$

for every $t \in k$ and $z \in UA$, as in Section 33.12.

If $a, z \in UA$ and $t \in k$, then

$$a \cdot b(z, t\, u_0) = a \cdot (z \cdot (t\, v_0)) = (a\, z) \cdot (t\, v_0) = b(a\, z, t\, u_0). \tag{33.15.4}$$

It follows that c is a homomorphism from $Z(\mu)$ into V as left modules over UA, as in Section 33.13. This means that c is a homomorphism from $Z(\mu)$ into V as modules over A, as a Lie algebra over k.

Remember that $v = e \otimes u_0$, as in (33.14.3). Thus

$$c(v) = b(e, u_0) = e \cdot v_0 = v_0. \tag{33.15.5}$$

This implies that

$$c(Z(\mu)) = c((UA) \cdot v) = (UA) \cdot v_0, \tag{33.15.6}$$

using (33.14.4) in the first step. It follows that c maps $Z(\mu)$ onto V exactly when

$$(UA) \cdot v_0 = V, \tag{33.15.7}$$

which means that V is standard cyclic of weight μ, as in Section 33.8.

If $m_1, \ldots, m_r$ are nonnegative integers, then

$$c((y_{\beta_1}^{m_1} \cdots y_{\beta_r}^{m_r}) \cdot v) = (y_{\beta_1}^{m_1} \cdots y_{\beta_r}^{m_r}) \cdot c(v) = (y_{\beta_1}^{m_1} \cdots y_{\beta_r}^{m_r}) \cdot v_0. \tag{33.15.8}$$

Note that c is injective if and only if these vectors are linearly independent in V, as a vector space over k, because the vectors (33.14.11) form a basis for $Z(\mu)$ as a vector space over k, as in the previous section.

One can also obtain $Z(\mu)$ as the quotient of UA by a suitable left ideal, as on p110 of [14]. This gives another way to get the module homomorphism c from $Z(\mu)$ into V.

Chapter 34

Some related examples and properties

34.1 Some remarks about $sl_2(k)$

Let k be a commutative ring with a multiplicative identity element, and let us take $A = sl_2(k)$, as a Lie algebra over k with respect to the usual commutator bracket. As usual, we put $x = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}$, $y = \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix}$, and $h = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$, so that $sl_2(k)$ is freely generated as a module over k by x, y, and h. Remember that $[x, y] = h$, $[h, x] = 2 \cdot x$, and $[h, y] = -2 \cdot y$.

Let A_0 be the subset of $sl_2(k)$ consisting of multiples of h by elements of k, which is a commutative Lie subalgebra of $sl_2(k)$. Suppose now that k is a field of characteristic 0, and let us consider the conditions discussed in Section 33.1 in this case. Of course, the elements of A_0 are ad-diagonalizable in A, and it is easy to see that the centralizer of A_0 in A is equal to A_0. Similarly, the center of A is trivial.

Let A_0' be the dual space of linear functionals on A_0, which correspond to multiplication by an element of k, because A_0 is one-dimensional as a vector space over k. If $\alpha \in A_0'$, then

$$A_\alpha = \{z \in A : [h, z] = \alpha(h)\, z\} \tag{34.1.1}$$

here, which is the same as A_0 when $\alpha = 0$. If $\alpha_x, \alpha_y \in A_0'$ are determined by $\alpha_x(h) = 2$, $\alpha_y(h) = -2$, then A_{α_x}, A_{α_y} are the linear subspaces of A spanned by x, y, respectively. Note that $\alpha_y = -\alpha_x$, and that A corresponds to the direct sum of A_0, A_{α_x}, and A_{α_y}, as a vector space over k. Thus

$$\Phi = \Phi_{A_0} = \{\alpha_x, \alpha_y\} \tag{34.1.2}$$

is the set of nonzero $\alpha \in A_0'$ such that $A_\alpha \neq \{0\}$.

The linear subspace $E_{\mathbf{Q}}$ of A_0', as a vector space over $\mathbf{Q}$, spanned by Φ consists of linear functionals on A_0 defined by multiplication by an element of $\mathbf{Q}$, with respect to the natural embedding of $\mathbf{Q}$ into k. This can be identified with $\mathbf{Q}$, as a vector space over itself, in the obvious way, so that the corresponding vector space $E_{\mathbf{R}}$ over $\mathbf{R}$ can be identified with $\mathbf{R}$. Of course, Φ is a reduced root system in $E_{\mathbf{R}}$, and

$$\Delta = \{\alpha_x\} \tag{34.1.3}$$

is a base for Φ.

Using this base, we have that $\Phi^+ = \Phi^{\Delta,+} = \{\alpha_x\}$ is the set of positive roots in Φ. The standard Borel subalgebra $B_\Delta = A(\Phi^+ \cup \{0\})$ of A associated to A_0 and Δ is the same as the linear span of x and h in A.

With this notation, we have that $h_{\alpha_x} = h$ and $h_{\alpha_y} = -h$. The symmetry $\sigma_{\alpha_x} = \sigma_{\alpha_y}$ on $E_{\mathbf{R}}$ corresponds to multiplication by -1. The associated linear functionals λ_{α_x}, λ_{α_y} on $E_{\mathbf{R}}$ are determined by $\lambda_{\alpha_x}(\alpha_x) = \lambda_{\alpha_y}(\alpha_y) = 2$.

The other conditions mentioned in Section 33.1 can be verified directly here. If V is a module over A, then the basic notions concerning weights and primitive or maximal vectors in Sections 33.5, 33.6 correspond to those discussed in Sections 15.1, 15.2, respectively.

34.2 Some modules over $sl_2(k)$

Let k be a commutative ring with a multiplicative identity element, and let $\mu_0 \in k$ be given. Also let $Z_0(\mu_0)$ be a free module over k with generators $v_0, v_1, v_2, v_3, \ldots$, and put $v_{-1} = 0$, for convenience. Of course, this does not depend on μ_0, as a module over k.

Put

$$H(v_j) = (\mu_0 - 2\,j) \cdot v_j, \tag{34.2.1}$$
$$Y(v_j) = (j+1) \cdot v_{j+1}, \tag{34.2.2}$$
$$X(v_j) = (\mu_0 - j + 1) \cdot v_{j-1} \tag{34.2.3}$$

for each $j \geq 0$. More precisely, one can use the natural ring homomorphism from $\mathbf{Z}$ into k here, or interpret multiplication of elements of $Z_0(\mu_0)$ by integers in the usual way. Let H, Y, and X be the unique homomorphisms from $Z_0(\mu_0)$ into itself, as a module over k, that satisfy these conditions. We may use H_{μ_0}, Y_{μ_0}, and X_{μ_0} to indicate the dependence on μ_0, and that these are considered as mappings on $Z_0(\mu_0)$. Note that (34.2.1) and (34.2.2) hold trivially when $j = -1$.

The definitions of H, Y, and X are analogous to those in Section 15.4, and we shall say more about that later. As before, we have that

$$\begin{aligned} H(X(v_j)) - X(H(v_j)) &= (\mu_0 - j + 1) \cdot H(v_{j-1}) - (\mu_0 - 2\,j) \cdot X(v_j) \\ &= (\mu_0 - j + 1)\,(\mu_0 - 2\,(j-1)) \cdot v_{j-1} \\ &\quad -(\mu_0 - 2\,j) X(v_j) \\ &= ((\mu_0 - 2\,(j-1)) - (\mu_0 - 2\,j)) \cdot X(v_j) = 2 \cdot X(v_j) \end{aligned} \tag{34.2.4}$$

for every $j \geq 0$. In the same way,

$$\begin{aligned} H(Y(v_j)) - Y(H(v_j)) &= (j+1) \cdot H(v_{j+1}) - (\mu_0 - 2\,j) \cdot Y(v_j) \\ &= (j+1)\,(\mu_0 - 2\,(j+1)) \cdot v_{j+1} - (\mu_0 - 2\,j) \cdot Y(v_j) \\ &= ((\mu_0 - 2\,(j+1)) - (\mu_0 - 2\,j)) \cdot Y(v_j) = -2 \cdot Y(v_j) \end{aligned} \tag{34.2.5}$$

for each $j \geq 0$. Similarly,

$$\begin{aligned} X(Y(v_j)) - Y(X(v_j)) &= (j+1) \cdot X(v_{j+1}) - (\mu_0 - j + 1) \cdot Y(v_{j-1}) \\ &= (j+1)\,(\mu_0 - (j+1) + 1) \cdot v_j \\ &\quad -(\mu_0 - j + 1)\,((j-1)+1) \cdot v_j \\ &= ((j+1)\,(\mu_0 - j) - (\mu_0 - j + 1)\,j) \cdot v_j \\ &= ((\mu_0 - j) - j) \cdot v_j = H(v_j) \end{aligned} \tag{34.2.6}$$

for each $j \geq 0$. Thus

$$[H, X] = 2 \cdot X, \quad [H, Y] = -2 \cdot Y, \quad \text{and} \quad [X, Y] = H, \tag{34.2.7}$$

as mappings from $Z_0(\mu_0)$ into itself.

Using this, we may consider $Z_0(\mu_0)$ as a module over $sl_2(k)$, as a Lie algebra over k. More precisely, if $x, y, h \in sl_2(k)$ are as in the previous section, then their actions on $Z_0(\mu_0)$ are defined by X, Y, and H, respectively. This defines a representation of $sl_2(k)$ on $Z_0(\mu_0)$, by (34.2.7). This corresponds to the first part of part (a) of Exercise 7 on p34 of [14].

Let m be a nonnegative integer, and let $Z_{0,m}(\mu_0)$ be the set of $z \in Z_0(\mu_0)$ such that for each $j = 0, \ldots, m$, the coefficient of v_j in z is equal to 0. This is a submodule of $Z_0(\mu_0)$, as a module over k. Thus the quotient $Z_0(\mu_0)/Z_{0,m}(\mu_0)$ is defined as a module over k too. Let q_m be the natural quotient mapping from $Z_0(\mu_0)$ onto $Z_0(\mu_0)/Z_{0,m}(\mu_0)$. It is easy to see that $Z_0(\mu_0)/Z_{0,m}(\mu_0)$ is free as a module over k, with generators $q_m(v_j)$, $j = 0, \ldots, m$.

Suppose that

$$\mu_0 = m \cdot 1, \tag{34.2.8}$$

as an element of k. This implies that

$$x \cdot v_{m+1} = X(v_{m+1}) = 0, \tag{34.2.9}$$

by (34.2.3). In this case, one can check that $Z_{0,m}(\mu_0)$ is a submodule of $Z_0(\mu_0)$, as a module over $sl_2(k)$.

It follows that $Z_0(\mu_0)/Z_{0,m}(\mu_0)$ is defined as a module over $sl_2(k)$ under these conditions. Observe that

$$y \cdot q_m(v_m) = q_m(y \cdot v_m) = q_m(Y(v_m)) = 0 \tag{34.2.10}$$

in $Z_0(\mu_0)/Z_{0,m}(\mu_0)$, by (34.2.2). One can use this to get that $Z_0(\mu_0)/Z_{0,m}(\mu_0)$ is isomorphic to the module $W(m)$ discussed in Section 15.4, as modules over $sl_2(k)$. More precisely, $q_m(v_j)$, $j = 0, \ldots, m$, correspond to the generators of $W(m)$, as a module over k, in Section 15.4. This is related to part (b) of Exercise 7 on p34 of [14].

34.3 Some module homomorphisms

Let k be a field of characteristic 0, and let V be a vector space over k that is a module over $A = sl_2(k)$, as a Lie algebra over k. Also let A_0 be the linear span of h in A, as in Section 34.1. If $\mu_0 \in k$, then there is a unique linear functional μ on A_0 such that

$$\mu(h) = \mu_0, \tag{34.3.1}$$

and every linear functional on A_0 is of this form.

Let $\rho = \rho^V$ be the given representation of $sl_2(k)$ on V. An eigenvector of ρ_h in V with eigenvalue $\mu_0 \in k$ is the same as an eigenvector of A_0 in V with weight $\mu \in A_0'$ as in (34.3.1), as defined in Section 33.5. A nonzero eigenvector v of this type is primitive or maximal of weight μ_0 in the sense of Section 15.2 if $x \cdot v = 0$, which is the same as saying that v is primitive or maximal of weight μ in the sense of Section 33.6. Of course, this uses Δ as in (34.1.3).

Let $\mu_0 \in k$ be given, and let $Z_0(\mu_0)$ be as in the previous section, as a vector space over k, and a module over $sl_2(k)$. Note that v_0 is a primitive or maximal vector of weight μ_0 in $Z_0(\mu_0)$, as in Section 15.2. It is easy to see that $Z_0(\mu_0)$ is standard cyclic with respect to v_0, as in Section 33.8.

Suppose that $v \in V$ is primitive or maximal of weight μ_0 in the sense of Section 15.2. Observe that there is a unique linear mapping ϕ from $Z_0(\mu_0)$ into V such that

$$\phi(v_j) = (1/j!)\,(\rho_y)^j(v) \tag{34.3.2}$$

for every nonnegative integer j. In fact, ϕ is a homomorphism from $Z_0(\mu_0)$ into V, as modules over $sl_2(k)$. This follows from the remarks in Section 15.3, with $\lambda = \mu_0$.

Of course, $\phi(Z_0(\mu_0))$ is the same as the linear subspace of V spanned by the vectors (34.3.2). This is the same as the submodule of V, as a module over $sl_2(k)$, generated by v. Thus $\phi(Z_0(\mu_0)) = V$ exactly when V is standard cyclic with respect to v, as in Section 33.8.

If ϕ is injective as a mapping from $Z_0(\mu_0)$ into V, then (34.3.2) is nonzero for every $j \geq 0$. Conversely, if (34.3.2) is nonzero for every $j \geq 0$, then these vectors are linearly independent in V. This is because these vectors are eigenvectors for ρ_h with distinct eigenvalues, as in Section 15.3. In this case, ϕ is injective on $Z_0(\mu_0)$.

If $j = 0$, then (34.3.2) is equal to v, which is nonzero by hypothesis. Suppose now that (34.3.2) is equal to 0 for some $j \geq 1$, and thus all larger j. Let m be the largest nonnegative integer such that (34.3.2) is nonzero when $j = m$, which implies that (34.3.2) is nonzero when $j \leq m$, and equal to 0 when $j > m$. Under these conditions,

$$\mu_0 = m, \tag{34.3.3}$$

with respect to the natural embedding of $\mathbf{Q}$ into k, as in Section 15.3.

The vectors (34.3.2) with $j = 0, \ldots, m$ are linearly independent in V, because they are nonzero eigenvectors of ρ_h with distinct eigenvalues, as before. This implies that the kernel of ϕ is equal to the linear subspace $Z_{0,m}(\mu_0)$ of $Z_0(\mu_0)$

defined in the previous section. Remember that $Z_{0,m}(\mu_0)$ is a submodule of $Z_0(\mu_0)$, as a module over $sl_2(k)$, in this case, which also follows from the fact that ϕ is a module homomorphism.

Using (34.3.3), we get that (34.2.9) holds, as before. This means that v_{m+1} is primitive or maximal of weight

$$\mu_0 - 2\,(m+1) = -m-2 \tag{34.3.4}$$

in $Z_0(\mu_0)$. Note that $v_{m+1} \in Z_{0,m}(\mu_0)$, so that v_{m+1} may be considered as primitive or maximal in $Z_{0,m}(\mu_0)$, as a module over $sl_2(k)$.

If j is a nonnegative integer, then $Y^j(v_{m+1})$ is a nonzero multiple of v_{m+1+j}, by (34.2.2). Thus $Z_{0,m}(\mu_0)$ is spanned by $Y^j(v_{m+1})$, $j \ge 0$, as a vector space over k. This means that $Z_{0,m}(\mu_0)$ is standard cyclic with respect to v_{m+1}, as a module over $sl_2(k)$.

Let $Z_0(-m-2)$ be as in the previous section, using the natural embedding of $\mathbf{Q}$ into k to identify $-m-2$ with an element of k. The same argument as before leads to an isomorphism from $Z_0(-m-2)$ onto $Z_{0,m}(\mu_0)$, as modules over $sl_2(k)$. This corresponds to part of part (b) of Exercise 7 on p34 of [14].

34.4 Some properties of $Z_0(\mu_0)$

Let k be a field of characteristic 0 again, let $\mu_0 \in k$ be given, and let $Z_0(\mu_0)$ be as in Section 34.2. If z is any element of $Z_0(\mu_0)$, then $X^j(x) = 0$ when j is large enough. Suppose that $z \ne 0$, and let j_1 be the largest nonnegative integer such that

$$z_1 = X^{j_1}(z) \ne 0. \tag{34.4.1}$$

Thus

$$X(z_1) = X^{j_1+1}(z) = 0. \tag{34.4.2}$$

Let Z_1 be a submodule of $Z_0(\mu_0)$, as a module over $sl_2(k)$. If $Z_1 \ne \{0\}$, then there is a $z_1 \in Z_1$ such that $z_1 \ne 0$ and $X(z_1) = 0$, by the remarks in the preceding paragraph.

Suppose for the moment that μ_0 does not correspond to a nonnegative integer, with respect to the natural embedding of $\mathbf{Q}$ into k. If $z \in Z_0(\mu_0)$ satisfies

$$x \cdot z = X(z) = 0, \tag{34.4.3}$$

then it is easy to see that z is a multiple of v_0, using (34.2.3).

If Z_1 is a nontrivial submodule of $Z_0(\mu_0)$, as a module over $sl_2(k)$, then it follows that Z_1 contains a nonzero multiple of v_0. It is easy to see that $Z_1 = Z_0(\mu_0)$ in this case, using the action of y on Z_1. This means that $Z_0(\mu_0)$ is irreducible, as a module over $sl_2(k)$. This corresponds to part (c) of Exercise 7 on p34 of [14], and is related to the second part of part (a) of Exercise 7.

Let m be a nonnegative integer, and suppose now that μ_0 corresponds to m, under the natural embedding of $\mathbf{Q}$ into k. If $z \in Z_0(\mu_0)$ satisfies (34.4.3), then one can check that z is a linear combination of v_0 and v_{m+1}, using (34.2.3).

Let Z_1 be a submodule of $Z_0(\mu_0)$ again, as a module over $sl_2(k)$. Suppose that $Z_1 \neq \{0\}$, and let z_1 be a nonzero element of Z_1 such that $X(z_1) = 0$, as before. Thus z_1 is a linear combination of v_0 and v_{m+1}, as in the previous paragraph. Remember that v_0 and v_{m+1} are eigenvectors of H with distinct eigenvalues, by (34.2.1). One can use this to get that both the v_0 and v_{m+1} components of z_1 are in Z_1, because Z_1 is a submodule of $Z_0(\mu_0)$.

If Z_1 contains a nonzero multiple of v_0, then $Z_1 = Z_0(\mu_0)$, as before. If $Z_1 \neq Z_0(\mu_0)$, then it follows that Z_1 contains a nonzero multiple of v_{m+1}. This is related to the second part of part (a) of Exercise 7 on p34 of [14].

Let $Z_{0,m}(\mu_0)$ be the linear subspace of $Z_0(\mu_0)$ defined in Section 34.2, which is a submodule of $Z_0(\mu_0)$, as a module over $sl_2(k)$, in this case. If Z_1 is a submodule of $Z_0(\mu_0)$, as a module over $sl_2(k)$, that contains a nonzero multiple of v_{m+1}, then one can check that

$$Z_{0,m}(\mu_0) \subseteq Z_1, \tag{34.4.4}$$

using the action of y on Z_1.

In particular, one can use this to get that $Z_{0,m}(\mu_0)$ is irreducible as a module over $sl_2(k)$, which corresponds to part of part (b) of Exercise 7 on p34 of [14]. This could also be obtained from the fact that $Z_{0,m}(\mu_0)$ is isomorphic to $Z_0(-m-2)$, as modules over $sl_2(k)$, as in the previous section.

Let Z_1 be a nontrivial submodule of $Z_0(\mu_0)$ again, as a module over $sl_2(k)$, so that (34.4.4) holds, as before. If $Z_1 \neq Z_{0,m}(\mu_0)$, then $Z_1 = Z_0(\mu_0)$. Equivalently, this means that $Z_0(\mu_0)/Z_{0,m}(\mu_0)$ is irreducible as a module over $sl_2(k)$. As in Section 34.2, the quotient is isomorphic to the module $W(m)$ in Section 15.4, whose irreducibility was discussed in Section 15.5. This corresponds to another part of part (b) of Exercise 7 on p34 of [14].

Alternatively, if $Z_1 \neq Z_{0,m}(\mu_0)$, then Z_1 contains a nonzero element for which the coefficient of v_j is equal to 0 when $j \geq m+1$. One can apply X to this element repeatedly, if necessary, to get that Z_1 contains a nonzero multiple of v_0. This implies that $Z_1 = Z_0(\mu_0)$, as before. One could also start with any $z \in Z_1 \setminus Z_{0,m}(\mu_0)$, and apply X to it repeatedly, as needed, to get $z_1 \in Z_1 \setminus Z_{0,m}(\mu_0)$ such that $X(z_1) = 0$. This implies that the v_0 component of z_1 is nonzero, and that it is contained in Z_1, as before.

Note that $Z_0(\mu_0)$ does not correspond to the direct sum of $Z_{0,m}(\mu_0)$ and some other submodule, as a module over $sl_2(k)$. This is mentioned in part (b) of Exercise 7 on p34 of [14] as well.

34.5 Comparison with $Z(\mu)$

Let k be a field of characteristic 0, and let us return to the same notation and hypotheses as in Section 34.1. Also let $\mu_0 \in k$ be given, and let μ be the linear functional on the linear span A_0 of h in $A = sl_2(k)$ with $\mu(h) = h_0$, as before. We would like to review the construction of $Z(\mu)$ in Section 33.14 in this case, and to compare it with $Z_0(\mu_0)$ in Section 34.2.

As in Section 34.1, $\alpha_x \in A_0'$ is defined by $\alpha_x(h) = 2$, $\Delta = \{\alpha_x\}$ is a base for Φ, $\Phi^+ = \Phi^{\Delta,+} = \{\alpha_x\}$, and the standard Borel subalgebra $B_\Delta = A(\Phi^+ \cup \{0\})$ of A associated to A_0 and Δ is the same as the linear span of x and h in A. Observe that $N_\Delta = A(\Phi^+)$ is the linear span of x in A, B_Δ corresponds to the direct sum of A_0 and N_Δ as a vector space over k, and that $[B_\Delta, B_\Delta] = N_\Delta$.

As in Section 33.14, we let $L(\mu)$ be a one-dimensional vector space over k, and we can define an action of B_Δ on $L(\mu)$ by putting

$$(w + t\,x) \cdot u = \mu(w)\,u \tag{34.5.1}$$

for every $w \in A_0$, $t \in k$, and $u \in L(\mu)$. Of course, this means that $h \cdot u = \mu_0\,u$ and $x \cdot u = 0$. This makes $L(\mu)$ into a module over B_Δ, as a Lie algebra over k, as before.

Let UA be a universal enveloping algebra of A, with multiplicative identity element $e = e_{UA}$ and associated mapping $i = i_{UA}$ from A into UA, as before. The subalgebra of UA generated by e and $i(B_\Delta)$ is a universal enveloping algebra of B_Δ, and we denote it UB_Δ. Remember that i is injective, and let us identify A with its image $i(A)$ in UA, as usual. Thus UB_Δ is the same as the subalgebra of UA generated by e, x, and h in this case. We may consider $L(\mu)$ as a left module over UB_Δ, as an associative algebra over k, as before.

As in Section 33.14, we take

$$Z(\mu) = (UA) \bigotimes_{UB_\Delta} L(\mu), \tag{34.5.2}$$

where UA is considered as a right module over UB_Δ, and the tensor product is as in Sections 33.12 and 33.13. This is a vector space over k, a left module over UA, and thus a module over A, as a Lie algebra over k.

Let u_0 be a nonzero element of $L(\mu)$, and put $v = e \otimes u_0 \in Z(\mu)$, as before. Remember that $Z(\mu)$ is generated by v, as a left module over UA. If $w \in A_0$, then

$$w \cdot v = \mu(w)\,v, \tag{34.5.3}$$

as in Section 33.14. This means that that $h \cdot v = \mu_0\,v$, and we also have that $x \cdot v = 0$, as before.

Remember from Section 34.1 that $\alpha_y = -\alpha_x$, so that $-\Phi^+ = \{\alpha_y\}$. Thus $A(-\Phi^+)$ is spanned by y, and is a Lie subalgebra of A. The elements of $Z(\mu)$ of the form

$$y^m \cdot v, \tag{34.5.4}$$

where m is a nonnegative integer, form a basis for $Z(\mu)$ as a vector space over k, as in Section 33.14.

It follows that v is a primitive or maximal vector in $Z(\mu)$ with weight μ, and that $Z(\mu)$ is standard cyclic of weight μ, as a module over A, as before. This leads to an isomorphism ϕ from $Z_0(\mu_0)$ onto $Z(\mu)$, as modules over A, as in Section 34.3. Alternatively, one can get a module isomorphism from $Z(\mu)$ onto $Z_0(\mu_0)$ as in Section 33.15. This corresponds to Exercise 4 on p111 of [14].

34.6 Looking at x in UA

Let k be a commutative ring with a multiplicative identity element and $k \neq \{0\}$, and take $A = sl_2(k)$, as in Section 34.1. Also let UA be a universal enveloping algebra of A, with multiplicative identity element $e = e_{UA}$ and associated mapping $i = i_{UA}$, as in Section 25.4.

Remember that $sl_2(k)$ is freely generated, as a module over k, by the usual elements x, y, and h. As in Section 25.12, the Poincaré–Birkhoff–Witt theorem implies that i is an injective mapping from A into UA. Thus we may identify A with $i(A)$, as before.

In particular, we may consider x, y, and h as elements of UA. If $w \in UA$, then we would like to check that

$$w\,(e - x) \neq e, \tag{34.6.1}$$

so that $e - x$ does not have a left inverse in UA. This corresponds to part of part (c) of Exercise 2 on p111 of [14].

Let us use the ordering y, h, x, for the basis elements of A. The Poincaré–Birkhoff–Witt theorem implies that the collection of products of the form

$$y^{j_1}\, h^{j_2}\, x^{j_3}, \tag{34.6.2}$$

where j_1, j_2, j_3 are nonnegative integers, is a basis for UA as a module over k, as in Section 25.10. If $w \in UA$ is expressed as a linear combination of these basis elements, then $w\,x$ can be expressed as a linear combination of these basis elements in a simple way. One can use this to get (34.6.1), as desired.

Let $\mathcal{I}$ be a left ideal in UA, as an associative algebra over k. Thus the quotient $(UA)/\mathcal{I}$ can be defined as a module over k, and as a left module over UA. Let $q = q_{\mathcal{I}}$ be the natural quotient mapping from UA onto $(UA)/\mathcal{I}$, so that

$$(UA) \cdot q(e) = (UA)/\mathcal{I}, \tag{34.6.3}$$

by construction, as in Section 33.11. Of course, we may also consider $(UA)/\mathcal{I}$ as a module over A, as a Lie algebra over k, as before.

Suppose that

$$e - x \in \mathcal{I}. \tag{34.6.4}$$

Equivalently, this means that

$$q(x) = q(e). \tag{34.6.5}$$

Note that

$$q(x) = q(x\,e) = x \cdot q(e), \tag{34.6.6}$$

using the fact that $(UA)/\mathcal{I}$ is a left module over UA in the second step. Thus (34.6.5) is the same as saying that

$$x \cdot q(e) = q(e) \tag{34.6.7}$$

in $(UA)/\mathcal{I}$.

Observe that

$$q(e) \neq 0 \tag{34.6.8}$$

if and only if

$$\mathcal{I} \neq UA, \tag{34.6.9}$$

because $e \in \mathcal{I}$ if and only if $\mathcal{I} = UA$. Clearly

$$\mathcal{I}_0 = \{w\,(e - x) : w \in UA\} \tag{34.6.10}$$

is a left ideal in UA, which does not contain e, by (34.6.1).

34.7 Some related properties of x and h

Let us continue with the same notation and hypotheses as in the previous section. Observe that

$$\begin{aligned}(x - e)\,h &= h\,(x - e) - (h\,x - x\,h) \\ &= h\,(x - e) - 2 \cdot x = h\,(x - e) - 2 \cdot (x - e) - 2 \cdot e,\end{aligned} \tag{34.7.1}$$

using the fact that $[h, x] = 2 \cdot x$ in the second step. If r is a positive integer, then we get that

$$(x - e)^r\,h = (x - e)^{r-1}\,h\,(x - e) - 2 \cdot (x - e)^r - 2 \cdot (x - e)^{r-1}. \tag{34.7.2}$$

It follows that

$$(x - e)^r\,h = h\,(x - e)^r - (2\,r) \cdot (x - e)^r - (2\,r) \cdot (x - e)^{r-1} \tag{34.7.3}$$

for every $r \geq 1$, by using (34.7.2) repeatedly, or induction.

If r, m are positive integers with $r > m$, then one can use (34.7.3) to check that

$$(x - e)^r\,h^m \in \mathcal{I}_0, \tag{34.7.4}$$

where $\mathcal{I}_0$ is as in (34.6.10). Similarly, one can use (34.7.3) to verify that

$$(x - e)^r\,h^r - ((-2)^r\,r!) \cdot e \in \mathcal{I}_0 \tag{34.7.5}$$

for every $r \geq 1$. This corresponds to part of part (c) of Exercise 2 on p111 of [14].

Let V be a module over k that is a module over $A = sl_2(k)$, as a Lie algebra over k. Thus V may be considered as a left module over UA, as an associative algebra over k. Let v_0 be an element of V, and suppose that

$$x \cdot v_0 = v_0. \tag{34.7.6}$$

Equivalently, this means that

$$(e - x) \cdot v_0 = 0. \tag{34.7.7}$$

It follows that

$$\mathcal{I}_0 \cdot v_0 = \{0\}. \tag{34.7.8}$$

If r and m are positive integers with $r > m$, then we get that

$$((x - e)^r\, h^m) \cdot v_0 = 0, \tag{34.7.9}$$

by (34.7.4). We also have that

$$((x - e)^r\, h^r) \cdot v_0 = ((-2)^r\, r!) \cdot v_0 \tag{34.7.10}$$

for every $r \geq 1$, by (34.7.5).

Suppose now that k is a field of characteristic 0, and that $v_0 \neq 0$. Under these conditions, one can check that the elements of V of the form $h^r \cdot v_0$, where r is a nonnegative integer, are linearly independent, using (34.7.10). This corresponds to another part of part (c) of Exercise 2 on p111 of [14].

If $\mathcal{I}$ is a proper left ideal in UA that satisfies (34.6.4), then we can take $V = (UA)/\mathcal{I}$, as in the previous section, with $v_0 = q(e)$. If $\mathcal{I}$ is also maximal as a proper left ideal in UA, then $(UA)/\mathcal{I}$ is irreducible as a left module over UA, or a module over A as a Lie algebra over k, as in Section 33.11.

34.8 Irreducibility and weights

Let us return to the notation and hypotheses in Section 33.1, so that k is a field of characteristic 0, and $(A, [\cdot,\cdot]_A)$ is a Lie algebra over k with the properties mentioned before. Remember that A_0 is a Lie subalgebra of A that is commutative as a Lie algebra. Let V be a vector space over k that is a module over A, as a Lie algebra over k.

Let $\widehat{V}$ be the linear subspace of V spanned by the weight spaces of V with respect to A_0, as in Section 33.5. Thus $\widehat{V}$ is a submodule of V, as a module over A, as before. If $\widehat{V} \neq \{0\}$, and V is irreducible as a module over A, then we get that

$$\widehat{V} = V. \tag{34.8.1}$$

This corresponds to part (a) of Exercise 2 on p110 of [14].

If $v \in V$ is an eigenvector of A_0 of some weight, then the linear span of v in V is mapped into itself by every element of A_0. If $v \in \widehat{V}$, then v can be expressed as the sum of finitely many eigenvectors of A_0. This implies that

(34.8.2) there is a finite-dimensional linear subspace of V that contains v and is mapped into itself by every element of A_0.

If (34.8.1) holds, then it follows that (34.8.2) holds for every $v \in V$. This corresponds to part of part (b) of Exercise 2 on p111 of [14].

Suppose for the moment that $A = sl_2(k)$, as in Section 34.1, and that V is as in the previous section. If $v_0 \neq 0$, then we have seen that (34.8.2) does not hold with $v = v_0$. This means that

$$\widehat{V} = \{0\} \tag{34.8.3}$$

when V is irreducible, as before. This corresponds to part of part (c) of Exercise 2 on p111 of [14].

Remember that the actions of the elements of A_0 on V commute with each other, because A_0 is commutative as a Lie algebra, and V is a module over A, as a Lie algebra over k. Suppose that U is a linear subspace of V of positive finite dimension that is mapped into itself by every element of A_0. If k is algebraically closed, then the action of any element of A_0 on U has a nontrival eigenspace. One can use this to get a nontrivial linear subspace of U consisting of eigenvectors for the actions of all of the elements of A_0, because the actions of the elements of A_0 on V commute, as before. This means that

$$U \cap \widehat{V} \neq \{0\}, \tag{34.8.4}$$

which corresponds to part of part (b) of Exercise 2 on p111 of [14].

Suppose that $v \in V$ has the property that

(34.8.5) for every $w \in A_0$ there is a finite-dimensional linear subspace of V that contains v and is mapped into itself by the action of w on V.

Under these conditions, one can check that (34.8.2) holds. This uses the fact that A_0 has finite dimension, as a vector space over k, and that the actions of the elements of A_0 on V commute. This corresponds to another part of part (b) of Exercise 2 on p111 of [14].

Of course, (34.8.2) implies (34.8.5) automatically.

34.9 Weight spaces in $Z(\mu)$

Let us go back to the notation and hypotheses in Section 33.1 again. More precisely, let $\mu \in A_0'$ be given, and let $Z(\mu)$ be the universal standard cyclic module of weight μ over A constructed in Section 33.14.

Remember that $v = e \otimes u_0 \in Z(\mu)$ is a primitive or maximal vector in $Z(\mu)$ of weight μ, and that $(UA) \cdot v = Z(\mu)$. Let $\beta_1, \ldots, \beta_r$ be a list of the elements of Φ^+, so that $y_{\beta_1}, \ldots, y_{\beta_r}$ is a basis for $A(-\Phi^+)$, as a vector space over k, as in Section 33.14. We have seen that

$$\{(y_{\beta_1}^{m_1} \cdots y_{\beta_r}^{m_r}) \cdot v : m_1, \ldots, m_r \in \mathbf{Z}_+ \cup \{0\}\} \tag{34.9.1}$$

form a basis for $Z(\mu)$, as a vector space over k.

If $m_1, \ldots, m_r$ are nonnegative integers, then

$$(y_{\beta_1}^{m_1} \cdots y_{\beta_r}^{m_r}) \cdot v \text{ has weight } \mu - \sum_{j=1}^{r} m_j\, \beta_j \tag{34.9.2}$$

as an element of $Z(\mu)$ in the sense of Section 33.5, as in Section 33.8. All of the weights of $Z(\mu)$ are of this form, as before.

Remember that Δ is a base for the root system Φ, and that Δ is a basis for A_0', as a vector space over k, as in Section 33.1. If $m_1, \ldots, m_r$ are nonnegative integers, then there are nonnegative integers c_α, $\alpha \in \Delta$, such that

$$\sum_{j=1}^{r} m_j \, \beta_j = \sum_{\alpha \in \Delta} c_\alpha \, \alpha, \tag{34.9.3}$$

because $\beta_j \in \Phi^+$ for each $j = 1, \ldots, r$, by hypothesis.

If c_α is a nonnegative integer for each $\alpha \in \Delta$, then there are only finitely many families of nonnegative integers $m_1, \ldots, m_r$ such that (34.9.3) holds, as in Section 33.8. More precisely, this is considered as an equality in A_0', and uses the fact that k is a field of characteristic 0.

If $\nu \in A_0'$, then let $\mathcal{P}(\nu)$ be the number of families of nonnegative integers $m_1, \ldots, m_r$ such that

$$\nu = \sum_{j=1}^{r} m_j \, \beta_j. \tag{34.9.4}$$

Of course, this number may be 0, but it is finite, as in the preceding paragraph.

Thus $\mathcal{P}(\mu - \nu)$ is the same as the number of families of nonnegative integers $m_1, \ldots, m_r$ such that

$$\nu = \mu - \sum_{j=1}^{r} m_j \, \beta_j. \tag{34.9.5}$$

Equivalently, this is the number of families of nonnegative integers $m_1, \ldots, m_r$ such that

$$(y_{\beta_1}^{m_1} \cdots y_{\beta_r}^{m_r}) \cdot v \text{ has weight } \nu, \tag{34.9.6}$$

by (34.9.2).

Let $Z(\mu)_\nu$ be the linear subspace of $Z(\mu)$ consisting of vectors of weight ν, as in Section 33.5. Under these conditions, we get that

$$\dim Z(\mu)_\nu = \mathcal{P}(\mu - \nu), \tag{34.9.7}$$

as a vector space over k. More precisely, $Z(\mu)_\nu \neq \{0\}$ exactly when $\mathcal{P}(\mu - \nu) > 0$, in which case we get a basis for $Z(\mu)_\nu$ using the vectors mentioned in (34.9.6). This corresponds to Exercise 5 on p111 of [14].

Chapter 35

Formal Laurent series

35.1 Formal Laurent polynomials and series

Let k be a commutative ring with a multiplicative identity element, let A be a module over k, let n be a positive integer, and let $T_1, \ldots, T_n$ be n commuting indeterminates. If $\alpha = (\alpha_1, \ldots, \alpha_n)$ is an n-tuple of integers, then the *degree* of α is defined by

$$\deg(\alpha) = \sum_{j=1}^{n} \alpha_j. \tag{35.1.1}$$

This is the same as the degree of the corresponding formal Laurent monomial

$$T^\alpha = T_1^{\alpha_1} \cdots T_n^{\alpha_n}. \tag{35.1.2}$$

A *formal Laurent series* in $T_1, \ldots, T_n$ with coefficients in A can be expressed as

$$f(T) = f(T_1, \ldots, T_n) = \sum_{\alpha \in \mathbf{Z}^n} f_\alpha \, T^\alpha, \tag{35.1.3}$$

where $f_\alpha \in A$ for every $\alpha \in \mathbf{Z}^n$. A formal power series in $T_1, \ldots, T_n$ with coefficients in A may be considered as a formal Laurent series as in (35.1.3), with $f_\alpha \neq 0$ only when $\alpha_j \geq 0$ for each $j = 1, \ldots, n$.

The space

$$LS_A(T_1, \ldots, T_n) = LS(A)(T_1, \ldots, T_n) \tag{35.1.4}$$

of all formal Laurent series in $T_1, \ldots, T_n$ with coefficients in A can be defined as the set of all A-valued functions on $\mathbf{Z}^n$. This is a module over k with respect to pointwise addition and scalar multiplication of A-valued functions on $\mathbf{Z}^n$, which corresponds to termwise addition and scalar multiplication of formal Laurent series as in (35.1.3). Of course, this is the same as the direct product of copies of A indexed by $\mathbf{Z}^n$, as a module over k. The space $A[[T_1, \ldots, T_n]]$ of formal power series in $T_1, \ldots, T_n$ with coefficients in A corresponds to a submodule of $LS_A(T_1, \ldots, T_n)$, as a module over k.

A *formal Laurent polynomial* in $T_1, \ldots, T_n$ with coefficients in A may be defined as a formal Laurent series as in (35.1.3) such that $f_\alpha = 0$ for all but finitely many $\alpha \in \mathbf{Z}^n$. The space

$$LP_A(T_1, \ldots, T_n) = LP(A)(T_1, \ldots, T_n) \tag{35.1.5}$$

of formal Laurent polynomials in $T_1, \ldots, T_n$ with coefficients in k may be defined as the space of A-valued functions on $\mathbf{Z}^n$ with finite support. This is a submodule of $LS_A(T_1, \ldots, T_n)$, as a module over k, which corresponds to the direct sum of copies of A indexed by $\mathbf{Z}^n$. A formal polynomial in $T_1, \ldots, T_n$ with coefficients in A may be considered as a formal Laurent polynomial as in (35.1.3), with $f_\alpha \neq 0$ only when $\alpha_j \geq 0$ for each $j = 1, \ldots, n$, and for only finitely many such α. The space $A[T_1, \ldots, T_n]$ of formal polynomials in $T_1, \ldots, T_n$ with coefficients in A corresponds to a submodule of $LP_A(T_1, \ldots, T_n)$, as a module over k.

Let l, m be positive integers, and let $X_1, \ldots, X_l$, $Y_1, \ldots, Y_m$ be commuting indeterminates. Let us identify $\mathbf{Z}^l \times \mathbf{Z}^m$ with $\mathbf{Z}^{l+m}$ in the obvious way. Thus if $\beta \in \mathbf{Z}^l$ and $\gamma \in \mathbf{Z}^m$, then (β, γ) is identified with an element of $\mathbf{Z}^{l+m}$. The degrees of β, γ, and (β, γ) can be defined as before, so that

$$\deg(\beta, \gamma) = \deg(\beta) + \deg(\gamma). \tag{35.1.6}$$

In this case, we may consider

$$X^\beta \, Y^\gamma = X_1^{\beta_1} \cdots X_l^{\beta_l} \, Y_1^{\gamma_1} \cdots Y_m^{\gamma_m} \tag{35.1.7}$$

as a formal Laurent monomial in $X_1, \ldots X_l$, $Y_1, \ldots, Y_m$ with degree (35.1.6).

We can define $LS_A(X_1, \ldots, X_l)$ as a module over k as before, so that

$$LS(LS_A(X_1, \ldots, X_l))(Y_1, \ldots, Y_m) \tag{35.1.8}$$

may be defined as a module over k in the same way. There is an obvious one-to-one correspondence between (35.1.8) and

$$LS_A(X_1, \ldots, X_l, Y_1, \ldots, Y_m), \tag{35.1.9}$$

which associates an A-valued function on $\mathbf{Z}^{l+m}$ with a function on $\mathbf{Z}^m$ that takes values in the space of A-valued functions on $\mathbf{Z}^l$. This defines an isomorphism between (35.1.8) and (35.1.9), as modules over k. Similarly, we can define $LP_A(X_1, \ldots, X_l)$ as a module over k as before, so that

$$LP(LP_A(X_1, \ldots, X_l))(Y_1, \ldots, Y_m) \tag{35.1.10}$$

may be defined as a module over k too. The one-to-one correspondence between (35.1.8) and (35.1.9) just mentioned sends (35.1.10) onto

$$LP_A(X_1, \ldots, X_l, Y_1, \ldots, Y_m). \tag{35.1.11}$$

35.2 Multiplication and Laurent series

Let us continue with the same notation and hypotheses as in the previous section. If $\alpha, \beta \in \mathbf{Z}^n$, then $\alpha + \beta \in \mathbf{Z}^n$ is defined as usual by coordinatewise addition, and

(35.2.1) $$\deg(\alpha + \beta) = \deg(\alpha) + \deg(\beta).$$

Similarly, multiplication of the corresponding formal Laurent monomials is defined by

(35.2.2) $$T^\alpha \, T^\beta = T^{\alpha+\beta}.$$

Let A be an algebra over k in the strict sense, where multiplication of $a, b \in A$ is expressed as $a\,b$. Suppose that $f(T) \in LS_A(T_1, \ldots, T_n)$ is as in (35.1.3), and that

(35.2.3) $$g(T) = \sum_{\beta \in \mathbf{Z}^n} g_\beta \, T^\beta$$

is another element of $LS_A(T_1, \ldots, T_n)$. If $\gamma \in \mathbf{Z}^n$, then we would like to put

(35.2.4) $$h_\gamma = \sum_{\alpha+\beta=\gamma} f_\alpha \, g_\beta,$$

where more precisely the sum is taken over all $\alpha, \beta \in \mathbf{Z}^n$ with $\alpha + \beta = \gamma$. This defines an element of A when all but finitely many terms in the sum on the right are equal to 0. In particular, this happens for every $\gamma \in \mathbf{Z}^n$ when $f(T)$ and $g(T)$ are formal power series in $T_1, \ldots, T_n$, as in Section 5.8, and when at least one of $f(T)$ and $g(T)$ is a formal Laurent polynomial in $T_1, \ldots, T_n$.

If (35.2.4) is defined as an element of A for every $\gamma \in \mathbf{Z}^n$, then

(35.2.5) $$h(T) = \sum_{\gamma \in \mathbf{Z}^n} h_\gamma \, T^\gamma$$

defines an element of $LS_A(T_1, \ldots, T_n)$. In this case, we put

(35.2.6) $$f(T)\, g(T) = h(T).$$

Of course, this agrees with the definition of the product in Section 5.8 when $f(T), g(T) \in A[[T_1, \ldots, T_n]]$. If $f(T)$ and $g(T)$ are both formal Laurent polynomials in $T_1, \ldots, T_n$, then we also get that (35.2.4) is equal to 0 for all but finitely many $\gamma \in \mathbf{Z}^n$, so that

(35.2.7) $$h(T) \in LP_A(T_1, \ldots, T_n).$$

This makes $LP_A(T_1, \ldots, T_n)$ an algebra over k in the strict sense, which contains $A[T_1, \ldots, T_n]$ as a subalgebra.

If A is an associative algebra over k, then one can check that

(35.2.8) $LP_A(T_1, \ldots, T_n)$ is an associative algebra over k

too. Similarly,

(35.2.9) $\quad LS_A(T_1, \ldots, T_n)$ is a left and right module over $LP_A(T_1, \ldots, T_n)$

under these conditions. If A has a multiplicative identity element e, then the corresponding formal Laurent polynomial in $T_1, \ldots, T_n$ is the multiplicative identity element in $LP_A(T_1, \ldots, T_n)$. If A is commutative, then multiplication of formal Laurent series in $T_1, \ldots, T_n$ with coefficients in A is commutative when it is defined. In particular,

(35.2.10) $\quad LP_k(T_1, \ldots, T_n)$ is a commutative associative algebra over k.

Suppose that A is a module over k again, let $f(T) \in LS_k(T_1, \ldots, T_n)$ be as in (35.1.3), and let $g(T) \in LS_A(T_1, \ldots, T_n)$ be as in (35.2.3). Note that $f_\alpha\, g_\beta$ is defined as an element of A for every $\alpha, \beta \in \mathbf{Z}^n$, using scalar multiplication on A. If $\gamma \in \mathbf{Z}^n$, then we would like to define h_γ as an element of A as in (35.2.4). As before, this make sense when all but finitely many terms in the sum on the right side of (35.2.4) are equal to 0. This happens for every $\gamma \in \mathbf{Z}^n$ when $f(T)$ and $g(T)$ are formal power series in $T_1, \ldots, T_n$, and when at least one of $f(T)$ and $g(T)$ is a formal Laurent polynomial in $T_1, \ldots, T_n$.

If (35.2.4) is defined as an element of A for every $\gamma \in \mathbf{Z}^n$, then (35.2.5) defines an element of $LS_A(T_1, \ldots, T_n)$, which we use to define $f(T)\, g(T)$ as in (35.2.6). In particular, one can check that

(35.2.11) $\quad LS_A(T_1, \ldots, T_n)$ is a module over $LP_k(T_1, \ldots, T_n)$

in this way. If $f(T)$ and $g(T)$ are both formal Laurent polynomials in $T_1, \ldots, T_n$, then (35.2.4) is equal to 0 for all but finitely many $\gamma \in \mathbf{Z}^n$, so that (35.2.7) holds. This means that

(35.2.12) $\quad LP_A(T_1, \ldots, T_n)$ is a submodule of $LS_A(T_1, \ldots, T_n)$, as a module over $LP_k(T_1, \ldots, T_n)$.

Let $l, m \in \mathbf{Z}_+$ and $X_1, \ldots, X_l$, $Y_1, \ldots, Y_m$ be as in the previous section. If A is an algebra over k in the strict sense, then $LP_A(X_1, \ldots, X_l)$ is an algebra over k in the strict sense with respect to multiplication of formal Laurent polynomials, as before. One can use this to define multiplication on (35.1.10), to get an algebra over k in the strict sense. Of course, (35.1.11) is an agebra over k in the strict sense with respect to multiplication of formal Laurent polynomials as well. One can check that the bijection between (35.1.10) and (35.1.11) mentioned in the previous section is an algebra isomorphism under these conditions. In particular,

(35.2.13)
$$LP(LP_k(X_1, \ldots, X_l))(Y_1, \ldots, Y_m)$$

is a commutative associative algebra over k. This algebra is isomorphic to

(35.2.14)
$$LP_k(X_1, \ldots, X_l, Y_1, \ldots, Y_m),$$

using the bijection just mentioned.

Similarly, if A is a module over k, then $LS_A(X_1, \ldots, X_l)$ may be considered as a module over $LP_k(X_1, \ldots, X_l)$. This permits (35.1.8) to be considered as a module over (35.2.13). We may also consider (35.1.9) as a module over (35.2.14). One can check that scalar multiplication on (35.1.8) by elements of (35.2.13) corresponds to scalar multiplication on (35.1.9) by elements of (35.2.14). More precisely, this uses the bijection between (35.1.8) and (35.1.9) mentioned in the previous section, and the analogous bijection between (35.2.13) and (35.2.14).

35.3 Laurent polynomial functions

Let k be a commutative ring with a multiplicative identity element, and let n be a positive integer. Also let $t = (t_1, \ldots, t_n)$ be an n-tuple of elements of k, and suppose that t_j has a multiplicative inverse in k for each $j = 1, \ldots, n$. If $\alpha \in \mathbf{Z}^n$, then

(35.3.1) $$t^\alpha = t_1^{\alpha_1} \cdots t_n^{\alpha_n}$$

is defined as an element of k. Note that

(35.3.2) $$t^{\alpha+\beta} = t^\alpha \, t^\beta$$

for every $\alpha, \beta \in \mathbf{Z}^n$.

Let A be a module over k, and let $T_1, \ldots, T_n$ be commuting indeterminates. Suppose that $f(T) \in LP_A(T_1, \ldots, T_n)$ is as in (35.1.3). If $t \in k^n$ is as in the preceding paragraph, then

(35.3.3) $$f(t) = \sum_{\alpha \in \mathbf{Z}^n} f_\alpha \, t^\alpha$$

defines an element of A. More precisely, $f_\alpha \, t^\alpha$ is defined as an element of A for each $\alpha \in \mathbf{Z}^n$, using scalar multiplication on A. We also have that $f_\alpha \, t^\alpha = 0$ for all but finitely many $\alpha \in \mathbf{Z}^n$, by hypothesis. The mapping from $LP_A(T_1, \ldots, T_n)$ into k defined by $f(T) \mapsto f(t)$ is clearly linear over k. If $f(T) \in k[T_1, \ldots, T_n]$, then this is the same as the definition of $f(t)$ in Section 5.9.

Suppose for the moment that A is an algebra over k in the strict sense, where multiplication of $a \, b \in A$ is expressed as $a \, b$. If $f(T), g(T) \in LP_A(T_1, \ldots, T_n)$, then $h(T) = f(T) \, g(T)$ is defined as an element of $LP_A(T_1, \ldots, T_n)$, as in the previous section. If $t \in k^n$ is as before, then $f(t)$, $g(t)$, and $h(t)$ are defined as elements of A, as in the preceding paragraph. Under these conditions, one can verify that

(35.3.4) $$h(t) = f(t) \, g(t)$$

Thus $f(T) \mapsto f(t)$ is a homomorphism from $LP_A(T_1, \ldots, T_n)$ into A, as algebras over k.

Let A be a module over k again, and let $f(T) \in LP_k(T_1, \ldots, T_n)$ and $g(T)$ in $LP_A(T_1, \ldots, T_n)$ be given. Remember that $h(T) = f(T) \, g(T)$ is defined as an element of $LP_A(T_1, \ldots, T_n)$, as in the previous section. If $t \in k^n$ is as before, then $f(t) \in k$, and $g(t)$, $h(t)$ are defined as elements of A. One can verify that (35.3.4) holds in this case too.

Now let A be an associative algebra over k with a multiplicative identity element e, and let A^n be the space of n-tuples of elements of A, as usual. Suppose that $a = (a_1, \ldots, a_n) \in A^n$ has commuting coordinates, so that $a_j\, a_l = a_l\, a_j$ for every $j, l = 1, \ldots, n$. Of course, this holds trivially when $n = 1$. Suppose also that a_j is invertible in A for each $j = 1, \ldots, n$. It follows that a_j^{-1} commutes with a_l and with a_l^{-1} for every $j, l = 1, \ldots, n$. If $\alpha \in \mathbf{Z}^n$, then

(35.3.5) $$a^\alpha = a_1^{\alpha_1} \cdots a_n^{\alpha_n}$$

defines an element of A. Observe that

(35.3.6) $$a^{\alpha+\beta} = a^\alpha\, a^\beta$$

for every $\alpha, \beta \in \mathbf{Z}^n$. Let $f(T) \in LP_k(T_1, \ldots, T_n)$ be as in (35.1.3) again. One can define $f(a)$ as an element of A by

(35.3.7) $$f(a) = \sum_{\alpha \in \mathbf{Z}^n} f_\alpha\, a^\alpha,$$

as before. One can check that $f(T) \mapsto f(a)$ defines a homomorphism from $LP_k(T_1, \ldots, T_n)$ into A, as algebras over k.

35.4 Differentiating Laurent series

Let n be a positive integer, let $\alpha \in \mathbf{Z}^n$ be given, and let l be a positive integer with $l \le n$. As in Section 5.10, we define $\alpha^+(l) \in \mathbf{Z}^n$ by

(35.4.1) $$\begin{aligned} \alpha_j^+(l) &= \alpha_j && \text{when } j \ne l \\ &= \alpha_l + 1 && \text{when } j = l. \end{aligned}$$

Similarly, let us define $\alpha^-(l) \in \mathbf{Z}^n$ by

(35.4.2) $$\begin{aligned} \alpha_j^-(l) &= \alpha_j && \text{when } j \ne l \\ &= \alpha_l - 1 && \text{when } j = l. \end{aligned}$$

This is a bit different from the way that $\alpha(l)$ was defined before, because we are using n-tuples of arbitrary integers here.

Let k be a commutative ring with a multiplicative identity element, let A be a module over k, and let $T_1, \ldots, T_n$ be commuting indeterminates. Also let $f(T)$ be a formal Laurent series in $T_1, \ldots, T_n$ with coefficients in A, as in (35.1.3). The formal *partial derivative* of $f(T)$ in T_l can be defined as a formal Laurent series in $T_1, \ldots, T_n$ with coefficients in A by

(35.4.3) $$\partial_l f(T) = \frac{\partial}{\partial T_l} f(T) = \sum_{\alpha \in \mathbf{Z}^n} (\alpha_l + 1) \cdot f_{\alpha^+(l)}\, T^\alpha.$$

This is essentially the same as

(35.4.4) $$\sum_{\alpha \in \mathbf{Z}^n} \alpha_l \cdot f_\alpha\, T^{\alpha^-(l)}.$$

This agrees with the analogous definition for partial derivatives of formal power series in $T_1, \ldots, T_n$, in Section 5.10. If $f(T) \in LP_A(T_1, \ldots, T_n)$, then these sums reduce to finite sums, and $\partial_l f(T) \in LP_A(T_1, \ldots, T_n)$ too. Note that the mapping

$$f(T) \mapsto \partial_l f(T) \tag{35.4.5}$$

is a homomorphism from $LS_A(T_1, \ldots, T_n)$ into itself, as a module over k. One can verify that

$$\partial_l(\partial_m f(T)) = \partial_m(\partial_l f(T)) \tag{35.4.6}$$

for every $l, m = 1, \ldots, n$ and $f(T) \in LS_A(T_1, \ldots, T_n)$.

Suppose for the moment that A is an algebra in the strict sense, where multiplication of $a, b \in A$ is expressed as $a\,b$. Let $f(T)$ and $g(T)$ be formal Laurent series in $T_1, \ldots, T_n$ with coefficients in A, where at least one of $f(T)$ and $g(T)$ is a formal Laurent polynomial in $T_1, \ldots, T_n$. Thus $f(T)\,g(T)$ is defined as an element of $LS_A(T_1, \ldots, T_n)$, as in Section 35.1. Under these conditions, one can check that

$$\partial_l(f(T)\,g(T)) = (\partial_l f(T))\,g(T) + f(T)\,(\partial_l g(T)). \tag{35.4.7}$$

Note that both terms on the right are defined as elements of $LS_A(T_1, \ldots, T_n)$. Of course, one can reduce to the case where one of $f(T)$ and $g(T)$ is a multiple of a single Laurent monomial, by linearity. In particular, the partial derivative defines a derivation on $LP_A(T_1, \ldots, T_n)$, as an algebra over k.

Let A be a module over k again, and let $f(T) \in LS_k(T_1, \ldots, T_n)$ and $g(T)$ in $LS_A(T_1, \ldots, T_n)$ be given, where at least one of $f(T)$ and $g(T)$ is a formal Laurent polynomial in $T_1, \ldots, T_n$. This implies that $f(T)\,g(T)$ is defined as an element of $LS_A(T_1, \ldots, T_n)$, as in Section 35.1. One can verify that (35.4.7) holds in this case too. As before, both terms on the right side of (35.4.7) are defined as elements of $LS_A(T_1, \ldots, T_n)$, and one may as well suppose that one of $f(T)$ and $g(T)$ is a multiple of a single Laurent monomial.

35.5 Derivatives and functions

Let k be a commutative ring with a multiplicative identity element, and let A be an associative algebra over k with a multiplicative identity element e. Also let a be an invertible element of A, and let u be another element of A that commutes with a and satisfies

$$u^2 = 0. \tag{35.5.1}$$

Of course, u commutes with a^{-1} too. One can check that $a + u$ is invertible in A as well, with

$$(a + u)^{-1} = a^{-1} - a^{-2}\,u. \tag{35.5.2}$$

If j is any integer, then

$$(a + u)^j = a^j + j \cdot a^{j-1}\,u. \tag{35.5.3}$$

More precisely, this can be verified directly when $j \ge 0$, as in Section 5.7. Similarly,

$$(35.5.4) \qquad (a+u)^{-j} = (a^{-1} - a^{-2}\,u)^j = a^{-j} - j \cdot (a^{-1})^{j-1}\,a^{-2}\,u = a^{-j} - j \cdot a^{-j-1}\,u$$

for every $j \ge 1$.

Now let n be a positive integer, and let $a = (a_1, \ldots, a_n)$ be an n-tuple of commuting invertible elements of A. Let $u = (u_1, \ldots, u_n)$ be another n-tuple of elements of A, with

$$(35.5.5) \qquad a_j\,u_l = u_l\,a_j$$

and

$$(35.5.6) \qquad u_j\,u_l = 0$$

for every $j, l = 1, \ldots, n$. It follows that a_j^{-1} commutes with u_l for every $j, l = 1, \ldots, n$, as before. Note that $a_l + u_l$ is invertible in A for each $l = 1, \ldots, n$, with inverse as in (35.5.2). If α_l is any integer, then

$$(35.5.7) \qquad (a_l + u_l)^{\alpha_l} = a_l^{\alpha_l} + \alpha_l \cdot a_l^{\alpha_l - 1}\,u_l,$$

as in (35.5.3).

Observe that $a_j + u_j$ commutes with $a_l + u_l$ for each $j, l = 1, \ldots, n$. If $\alpha \in \mathbf{Z}^n$, then a^α and $(a+u)^\alpha$ can be defined as elements of A as in Section 35.3. One can check that

$$(35.5.8) \qquad (a+u)^\alpha = a^\alpha + \sum_{l=1}^n \alpha_l \cdot a^{\alpha^-(l)}\,u_l,$$

where $\alpha^-(l) \in \mathbf{Z}^n$ is as in the previous section, using (35.5.7). Let $T_1, \ldots, T_n$ be n commuting indeterminates, and let $f(T) \in LP_k(T_1, \ldots, T_n)$ be given, so that $\partial_l f(T) \in LP_k(T_1, \ldots, T_n)$ is defined as in the previous section. One can verify that

$$(35.5.9) \qquad f(a+u) = f(a) + \sum_{l=1}^n (\partial_l f)(a)\,u_l,$$

using (35.5.8), where $f(a+u)$, $f(a)$, and $(\partial_l f)(a)$ are defined as elements of A as in Section 35.3.

Let $t = (t_1, \ldots, t_n)$ be an n-tuple of invertible elements of k, and let $u = (u_1, \ldots, u_n)$ be an n-tuple of elements of k such that (35.5.6) holds for every $j, l = 1, \ldots, n$. Thus $t_l + u_l$ is invertible in k for each $l = 1, \ldots, n$, with inverse as in (35.5.2). If $\alpha \in \mathbf{Z}^n$, then t^α and $(t+u)^\alpha$ can be defined as elements of k as in Section 35.3, and $(t+u)^\alpha$ can be expressed as in (35.5.8). Let A be a module over k, and let $f(T) \in LP_A(T_1, \ldots, T_n)$ be given, so that $\partial_l f(T)$ can be defined as an element of $LP_A(T_1, \ldots, T_n)$ as in the previous section. As before, one can check that

$$(35.5.10) \qquad f(t+u) = f(t) + \sum_{l=1}^n (\partial_l f)(t)\,u_l,$$

where $f(t+u)$, $f(t)$, and $(\partial_l f)(t)$ are defined as elements of A as in Section 35.3.

35.6 Differential operators and Laurent series

Let k be a commutative ring with a multiplicative identity element, let n be a positive integer, and let $\partial_1, \ldots, \partial_n$ be commuting formal symbols, which may be used to represent partial derivatives. Also let $\alpha = (\alpha_1, \ldots, \alpha_n)$ be a multi-index of length n, which is to say an n-tuple of nonnegative integers, and let

$$\partial^\alpha = \partial_1^{\alpha_1} \cdots \partial_n^{\alpha_n} \tag{35.6.1}$$

be the corresponding formal product of ∂_l's. Remember that $|\alpha|$ is the same as the degree of α, as an n-tuple of integers, as in Section 35.1. A *formal differential operator* in $\partial_1, \ldots, \partial_n$ with coefficients in $LP_k(T_1, \ldots, T_n)$ can be expressed as

$$\sum_{|\alpha| \le N} a^\alpha(T)\, \partial^\alpha, \tag{35.6.2}$$

where N is a nonnegative integer, the sum is taken over all multi-indices α of length n with $|\alpha| \le N$, and $a^\alpha(T) \in LP_k(T_1, \ldots, T_n)$ for each such α. Remember that the analogous notions with coefficients in $k[T_1, \ldots, T_n]$ or $k[[T_1, \ldots, T_n]]$ were discussed in Section 5.11.

As before, we can take $a^\alpha(T) = 0$ when $|\alpha| > N$, so that $a^\alpha(T)$ is defined for every multi-index α. The space of these formal differential operators can be defined as the space of functions $\alpha \mapsto a^\alpha(T)$ from $(\mathbf{Z}_+ \cup \{0\})^n$ into $LP_k(T_1, \ldots, T_n)$ with $a^\alpha(T) = 0$ for all but finitely many α. This is a module over k with respect to pointwise addition and scalar multiplication, which corresponds to termwise addition and scalar multiplication of sums as in (35.6.2). The space of these formal differential operators corresponds to the direct sum of copies of $LP_k(T_1, \ldots, T_n)$ indexed by $(\mathbf{Z}_+ \cup \{0\})^n$, as a module over k.

We can identify elements of $LP_k(T_1, \ldots, T_n)$ with sums of the form (35.6.2), with $N = 0$. Multiplication on $LP_k(T_1, \ldots, T_n)$ can be extended to formal differential operators, with

$$\partial_l(b^\beta(T)\partial^\beta) = (\partial_l b^\beta(T))\, \partial^\beta + b^\beta(T)\, \partial_l\, \partial^\beta \tag{35.6.3}$$

for every $l = 1, \ldots, n$, multi-index β, and $b^\beta(T) \in LP_k(T_1, \ldots, T_n)$, as before. Of course,

$$\partial_l\, \partial^\beta = \partial^{\beta^+(l)}, \tag{35.6.4}$$

in the notation of Section 35.4. The space of these formal partial differential operators is an associative algebra over k, which contains $LP_k(T_1, \ldots, T_n)$ as a subalgebra. The multiplicative identity element in k corresponds to an element of $LP_k(T_1, \ldots, T_n)$, and thus a formal differential operator, and this is the identity element in the space of these formal differential operators.

Let A be a module over k. If α is a multi-index of length n and $f(T)$ is a formal Laurent series in $T_1, \ldots, T_n$ with coefficients in A, then

$$\partial^\alpha f(T) = \partial_1^{\alpha_1} \cdots \partial_n^{\alpha_n} f(T) \tag{35.6.5}$$

defines an element of $LS_A(T_1, \ldots, T_n)$ too, using the definition of partial derivatives on $LS_A(T_1, \ldots, T_n)$ in Section 35.4. This is interpreted as being $f(T)$ when $\alpha = 0$. If (35.6.2) is a formal differential operator in the symbols $\partial_1, \ldots, \partial_n$ with coefficients in $LP_k(T_1, \ldots, T_n)$, then

$$\Big(\sum_{|\alpha| \le N} a^\alpha(T)\, \partial^\alpha\Big) f(T) = \sum_{|\alpha| \le N} a^\alpha(T)\, \partial^\alpha f(T) \tag{35.6.6}$$

defines an element of $LS_A(T_1, \ldots, T_n)$, where the products on the right are as in Section 35.1. Similarly, if f is a formal Laurent polynomial in $T_1, \ldots, T_n$ with coefficients in A, then (35.6.5) is in $LP_A(T_1, \ldots, T_n)$ for each α, so that (35.6.6) is in $LP_A(T_1, \ldots, T_n)$ as well.

Thus (35.6.2) determines a mapping from $LS_A(T_1, \ldots, T_n)$ into itself that is linear over k. Of course, the space

$$\mathrm{Hom}_k(LS_A(T_1, \ldots, T_n), LS_A(T_1, \ldots, T_n)) \tag{35.6.7}$$

of homomorphisms from $LS_A(T_1, \ldots, T_n)$ into itself, as a module over k, is an associative algebra over k with respect to composition of mappings. One can verify that the mapping from the space of formal differential operators in the symbols $\partial_1, \ldots, \partial_n$ with coefficients in $LP_k(T_1, \ldots, T_n)$ into (35.6.7) just defined is an algebra homomorphism, with respect to multiplication of formal differential operators, as described before.

The space of formal differential operators in the symbols $\partial_1, \ldots, \partial_n$ with coefficients in $k[T_1, \ldots, T_n]$ may be considered as a subalgebra of the space of formal differential operators in $\partial_1, \ldots, \partial_n$ with coefficients in $LP_k(T_1, \ldots, T_n)$. In particular, formal differential operators in $\partial_1, \ldots, \partial_n$ with coefficients in $k[T_1, \ldots, T_n]$ determine mappings on $LS_A(T_1, \ldots, T_n)$ as before. The restrictions of these mappings to $A[[T_1, \ldots, T_n]]$ are the same as the analogous mappings discussed in Section 5.11.

Let us now take $A = k$, as a module over itself, and suppose that for every $m \in \mathbf{Z}_+$ and $t \in k$ with $m \cdot t = 0$ in k, we have that $t = 0$. Of course, this holds when $k = \mathbf{Z}$, or k is a field of characteristic 0, or at least an algebra over $\mathbf{Q}$. Under these conditions, one can check that a formal differential operator (35.6.2) in $\partial_1, \ldots, \partial_n$ with coefficients in $LP_k(T_1, \ldots, T_n)$ is uniquely determined by the corresponding mapping on $LS_k(T_1, \ldots, T_n)$. In fact, (35.6.2) is uniquely determined by the restriction of this mapping to $k[T_1, \ldots, T_n]$, as in Section 5.11.

As in Section 32.10, the space of formal differential operators in $\partial_1, \ldots, \partial_n$ with coefficients in $LP_k(T_1, \ldots, T_n)$ is essentially the same, as a module over k, as the space

$$(LP_k(T_1, \ldots, T_n))[\partial_1, \ldots, \partial_n] \tag{35.6.8}$$

of formal polynomials in $\partial_1, \ldots, \partial_n$, as n commuting indeterminates, with coefficients in $LP_k(T_1, \ldots, T_n)$, as a module over k. We can also use multiplication on $LP_k(T_1, \ldots, T_n)$ to define multiplication on (35.6.8) as in Section 5.8, in which case $\partial_1, \ldots, \partial_n$ are not considered as being related to differentiation in $T_1, \ldots, T_n$. This makes (35.6.8) a commutative algebra over k, and over $LP_k(T_1, \ldots, T_n)$, as before. If L_1, L_2 are formal differential operators in $\partial_1, \ldots, \partial_n$ with coefficients in $LP_k(T_1, \ldots, T_n)$ of order $N_1, N_2 \geq 0$, respectively, then their product as formal differential operators corresponds to their product as formal polynomials in $\partial_1, \ldots, \partial_n$ with coefficients in $LP_k(T_1, \ldots, T_n)$, plus a formal differential operator in $\partial_1, \ldots, \partial_n$ with coefficients in $LP_k(T_1, \ldots, T_n)$ of order $N_1 + N_2 - 1$, at least when $N_1 + N_2 \geq 1$. In particular, the commutator of L_1 and L_2 with respect to multiplication of formal differential operators is a formal differential operator in $\partial_1, \ldots, \partial_n$ with coefficients in $LP_k(T_1, \ldots, T_n)$ of order $N_1 + N_2 - 1$, as before.

35.7 First-order operators

Let k be a commutative ring with a multiplicative identity element, let n be a positive integer, and let $T_1, \ldots, T_n$ be n commuting indeterminates. Also let $\partial_1, \ldots, \partial_n$ be n commuting formal symbols, as in the previous section, and let

$$a(T) = (a^1(T), \ldots, a^n(T)) \tag{35.7.1}$$

be an n-tuple of formal Laurent polynomials in $T_1, \ldots, T_n$ with coefficients in k. Thus

$$D_{a(T)} = \sum_{j=1}^{n} a^j(T)\, \partial_j \tag{35.7.2}$$

defines a formal differential operator in the symbols $\partial_1, \ldots, \partial_n$ with coefficients in $LP_k(T_1, \ldots, T_n)$, as in the previous section.

Let $b(T) = (b^1(T), \ldots, b^n(T))$ be another n-tuple of formal Laurent polynomials in $T_1, \ldots, T_n$ with coefficients in k, so that $D_{b(T)}$ can be defined as in the preceding paragraph. Under these conditions, $D_{a(T)}\, D_{b(T)}$ and $D_{b(T)}\, D_{a(T)}$ can be defined as formal differential operators in $\partial_1, \ldots, \partial_n$ with coefficients in $LP_k(T_1, \ldots, T_n)$ too, as before. One can check that

$$\begin{aligned} & D_{a(T)}\, D_{b(T)} - D_{b(T)}\, D_{a(T)} \\ &= \sum_{j=1}^{n} \sum_{l=1}^{n} (a^j(T)\, \partial_j b^l(T) - b^j(T)\, \partial_j a^l(T))\, \partial_l, \end{aligned} \tag{35.7.3}$$

as in Section 5.12. Put

$$c^l(T) = \sum_{j=1}^{n} (a^j(T) \partial_j b^l(T) - b^j(T)\, \partial_j a^l(T)) \tag{35.7.4}$$

for each $l = 1, \ldots, n$, which is a formal Laurent polynomial in $T_1, \ldots, T_n$ with coefficients in k. It follows that

$$D_{a(T)}\, D_{b(T)} - D_{b(T)}\, D_{a(T)} = D_{c(T)}, \tag{35.7.5}$$

where $c(T) = (c^1(T), \ldots, c^n(T))$.

If $f(T) \in LS_k(T_1, \ldots, T_n)$, then

$$D_{a(T)} f(T) = \sum_{j=1}^{n} a^j(T)\, \partial_j f(T) \tag{35.7.6}$$

defines an element of $LS_k(T_1, \ldots, T_n)$ as well, as in the previous section. Similarly, if $f(T) \in LP_k(T_1, \ldots, T_n)$, then this is an element of $LP_k(T_1, \ldots, T_n)$, as before. If $f(T), g(T) \in LS_k(T_1, \ldots, T_n)$, and at least one of $f(T)$ and $g(T)$ is in $LP_k(T_1, \ldots, T_n)$, then $f(T)\, g(T)$ is defined as an element of $LS_k(T_1, \ldots, T_n)$, and we have that

$$D_{a(T)}(f(T)\, g(T)) = (D_{a(T)} f(T))\, g(T) + f(T)\, (D_{a(T)} g(T)). \tag{35.7.7}$$

In particular, $D_{a(T)}$ defines a derivation on $LP_k(T_1, \ldots, T_n)$.

Now let δ be any derivation on $LP_k(T_1, \ldots, T_n)$, as an algebra over k. Observe that

$$\delta(1) = 0, \tag{35.7.8}$$

because $\delta(1) = \delta(1 \cdot 1) = \delta(1)\, 1 + 1\, \delta(1) = \delta(1) + \delta(1)$. It follows that

$$\delta(T_j^{-1}) = -T_j^{-2}\, \delta(T_j) \tag{35.7.9}$$

for every $j = 1, \ldots, n$, because $0 = \delta(T_j\, T_j^{-1}) = \delta(T_j)\, T_j^{-1} + T_j\, \delta(T_j^{-1})$. Put

$$a^j(T) = \delta(T_j) \tag{35.7.10}$$

for every $j = 1, \ldots, n$, which is an element of $LP_k(T_1, \ldots, T_n)$, and let $a(T)$ be as in (35.7.1). One can check that

$$\delta(f(T)) = D_{a(T)} f(T) \tag{35.7.11}$$

for every $f(T) \in LP_k(T_1, \ldots, T_n)$ under these conditions.

Put $e^j(T) = T_j$ for each $j = 1, \ldots, n$, so that

$$e(T) = (e^1(T), \ldots, e^n(T)) = (T_1, \ldots, T_n). \tag{35.7.12}$$

The corresponding formal differential operator

$$D_{e(T)} = \sum_{j=1}^{n} e^j(T)\, \partial_j = \sum_{j=1}^{n} T_j\, \partial_j \tag{35.7.13}$$

is the analogue of the classical *Euler operator*. It is easy to see that

$$D_{e(T)}(T^\alpha) = (\deg(\alpha) \cdot 1)\, T^\alpha \tag{35.7.14}$$

for every $\alpha \in \mathbf{Z}^n$. Let A be a module over k, and let $f(T) = \sum_{\alpha \in \mathbf{Z}^n} f_\alpha\, T^\alpha$ be a formal Laurent series in $T_1, \ldots, T_n$ with coefficients in A. Observe that

$$D_{e(T)} f(T) = \sum_{\alpha \in \mathbf{Z}^n} \deg(\alpha) \cdot f_\alpha\, T^\alpha. \tag{35.7.15}$$

35.8 Homogeneous Laurent series

Let k be a commutative ring with a multiplicative identity element, let A be a module over k, and let n be a positive integer. Also let $T_1, \ldots, T_n$ be n commuting indeterminates for some positive integer n, and let $f(T) = \sum_{\alpha \in \mathbf{Z}^n} f_\alpha \, T^\alpha$ be a formal Laurent series in $T_1, \ldots, T_n$ with coefficients in A. We say that $f(T)$ is *homogeneous of degree* d for some integer d if

$$f_\alpha = 0 \text{ for every } \alpha \in \mathbf{Z}^n \text{ with } \deg(\alpha) \neq d. \tag{35.8.1}$$

If $f(T)$ is a formal polynomial in $T_1, \ldots, T_n$, and $d \geq 0$, then this is equivalent to the definition of homogeneity of degree d in Section 5.13.

The space $LS_{A,d}(T_1, \ldots, T_n)$ of formal Laurent series in $T_1, \ldots, T_n$ with coefficients in A that are homogeneous of degree $d \in \mathbf{Z}$ is a submodule of the space $LS_A(T_1, \ldots, T_n)$ of all formal Laurent series in $T_1, \ldots, T_n$ with coefficients in A, as a module over k. Observe that $LS_{A,d}(T_1, \ldots, T_n)$ corresponds to the direct product of copies of A indexed by $\alpha \in \mathbf{Z}^n$ with $\deg(\alpha) = d$, and that $LS_A(T_1, \ldots, T_n)$ corresponds to the direct product of $LS_{A,d}(T_1, \ldots, T_n)$ over $d \in \mathbf{Z}$, as modules over k.

Similarly, let

$$LP_{A,d}(T_1, \ldots, T_n) = LP_A(T_1, \ldots, T_n) \cap LS_{A,d}(T_1, \ldots, T_n) \tag{35.8.2}$$

be the space of formal Laurent polynomials in $T_1, \ldots, T_n$ with coefficients in A that are homogeneous of degree $d \in \mathbf{Z}$, as formal Laurent series in $T_1, \ldots, T_n$. This corresponds to the direct sum of copies of A indexed by $\alpha \in \mathbf{Z}^n$ with $\deg(\alpha) = d$ as a module over k, and $LP_A(T_1, \ldots, T_n)$ corresponds to the direct sum of $LP_{A,d}(T_1, \ldots, T_n)$ over $d \in \mathbf{Z}$.

Let A be an algebra over k in the strict sense, where multiplication of $a, b \in A$ is expressed as $a\,b$. Suppose that $f(T) \in LS_{A,d_1}(T_1, \ldots, T_n)$ and $g(T)$ is in $LS_{A,d_2}(T_1, \ldots, T_n)$ for some $d_1, d_2 \in \mathbf{Z}$. If $f(T)$ or $g(T)$ is a formal Laurent polynomial in $T_1, \ldots, T_n$, then $f(T)\,g(T)$ can be defined as a formal Laurent series in $T_1, \ldots, T_n$ with coefficients in A, as in Section 35.1. Under these conditions, it is easy to see that

$$f(T)\,g(T) \in LS_{A,d_1+d_2}(T_1, \ldots, T_n). \tag{35.8.3}$$

If $f(T)$ and $g(T)$ are both formal Laurent polynomials in $T_1, \ldots, T_n$, then

$$f(T)\,g(T) \in LP_{A,d_1+d_2}(T_1, \ldots, T_n). \tag{35.8.4}$$

Suppose that A is an associative algebra over k, so that $LP_A(T_1, \ldots, T_n)$ is an associative algebra over k as well, as in Section 35.1. Under these conditions, $LS_A(T_1, \ldots, T_n)$ may be considered as a left and right module over $LP_A(T_1, \ldots, T_n)$, as before. Note that

$$LP_{A,0}(T_1, \ldots, T_n) \text{ is a subalgebra of } LP_A(T_1, \ldots, T_n), \tag{35.8.5}$$

by (35.8.4). Thus $LS_A(T_1, \ldots, T_n)$ may be considered as a left and right module over $LP_{A,0}(T_1, \ldots, T_n)$ too. If d is any integer, then

(35.8.6) $$LS_{A,d}(T_1, \ldots, T_n) \text{ is a submodule of } LS_A(T_1, \ldots, T_n), \text{ as a left or right module over } LP_{A,0}(T_1, \ldots, T_n),$$

by (35.8.3).

Let A be a module over k again, and suppose that $f(T) \in LS_{k,d_1}(T_1, \ldots, T_n)$ and $g(T) \in LS_{A,d_2}(T_1, \ldots, T_n)$ for some $d_1, d_2 \in \mathbf{Z}$. If $f(T)$ or $g(T)$ is a formal Laurent polynomial in $T_1, \ldots, T_n$, then $f(T)\, g(T)$ can be defined as a formal Laurent series in $T_1, \ldots, T_n$ with coefficients in A, as in Section 35.1. It is easy to see that (35.8.3) holds in this case. If $f(T)$ and $g(T)$ are both formal Laurent polynomials in $T_1, \ldots, T_n$, then (35.8.4) holds.

Remember that $LS_A(T_1, \ldots, T_n)$ is a module over $LP_k(T_1, \ldots, T_n)$, as in Section 35.1. We may also consider $LS_A(T_1, \ldots, T_n)$ as a module over the subalgebra $LP_{k,0}(T_1, \ldots, T_n)$ of $LP_k(T_1, \ldots, T_n)$. If $d \in \mathbf{Z}$, then

(35.8.7) $$LS_{A,d}(T_1, \ldots, T_n) \text{ is a submodule of } LS_A(T_1, \ldots, T_n), \text{ as a module over } LP_{k,0}(T_1, \ldots, T_n).$$

Similarly, $LP_A(T_1, \ldots, T_n)$ is a submodule of $LS_A(T_1, \ldots, T_n)$, as a module over $LP_k(T_1, \ldots, T_n)$, and thus as a module over $LP_{k,0}(T_1, \ldots, T_n)$ too. If $d \in \mathbf{Z}$, then

(35.8.8) $$LP_{A,d}(T_1, \ldots, T_n) \text{ is a submodule of } LP_A(T_1, \ldots, T_n), \text{ as a module over } LP_{k,0}(T_1, \ldots, T_n).$$

If $f(T) \in LS_{A,d}(T_1, \ldots, T_n)$ for some $d \in \mathbf{Z}$, then it is easy to see that

(35.8.9) $$\partial_l f(T) \in LS_{A,d-1}(T_1, \ldots, T_n)$$

for every $l = 1, \ldots, n$, where the partial derivative $\partial_l f(T)$ is as in Section 35.4. Put $e(T) = (T_1, \ldots, T_n)$, and let $D_{e(T)} = \sum_{j=1}^n T_j\, \partial_j$ be the corresponding first-order differential operator, as in Section 35.7. If $f(T) \in LS_{A,d}(T_1, \ldots, T_n)$, then

(35.8.10) $$D_{e(T)} f(T) = d \cdot f(T),$$

by (35.7.15).

35.9 Homogeneity and differential operators

Let k be a commutative ring with a multiplicative identity element, let n be a positive integer, and let $T_1, \ldots, T_n$ be n commuting indeterminates. Also let $\partial_1, \ldots, \partial_n$ be n commuting formal symbols, which may be used to represent partial derivatives, as in Section 35.6. Consider a formal differential operator

(35.9.1) $$L = \sum_{|\alpha| \le N} a^\alpha(T)\, \partial^\alpha$$

in $\partial_1, \ldots, \partial_n$ with coefficients in $LP_k(T_1, \ldots, T_n)$. We say that L is *homogeneous of degree* d for some integer d if

$$a^\alpha(T) \in LP_{k,d+|\alpha|}(T_1, \ldots, T_n) \tag{35.9.2}$$

for each multi-index α. This agrees with the definition in Section 5.14 when $a^\alpha(T)$ is a formal polynomial in $T_1, \ldots, T_n$ for each α.

Let L_1, L_2 be formal differential operators in $\partial_1, \ldots, \partial_n$ with coefficients in $LP_k(T_1, \ldots, T_n)$, and suppose that L_1, L_2 are homogeneous of degree $d_1, d_2 \in \mathbf{Z}$, respectively. Under these conditions, one can check that their product

$$L_1\, L_2 \text{ is homogeneous of degree } d_1 + d_2. \tag{35.9.3}$$

More precisely, one can first verify this when L_1 is of the form ∂_j for some $j = 1, \ldots, n$, as in Section 5.14. One can use this to get that (35.9.3) holds when $L_1 = \partial^\alpha$ for some multi-index α, as before. The analogous statement for arbitrary L_1 can be obtained from this and (35.8.4).

Let L_1 be a formal differential operator in $\partial_1, \ldots, \partial_n$ with coefficients in $LP_k(T_1, \ldots, T_n)$ that is homogeneous of degree $d_1 \in \mathbf{Z}$ again, and let A be a module over k. If $f(T)$ is a formal Laurent series in $T_1, \ldots, T_n$ with coefficients in A that is homogeneous of degree $d \in \mathbf{Z}$, then

$$L_1 f(T) \in LS_{A,d_1+d}(T_1, \ldots, T_n). \tag{35.9.4}$$

This is the same as (35.8.9) when $L_1 = \partial_l$ for some $l = 1, \ldots, n$. This implies that (35.9.4) holds when $L_1 = \partial^\alpha$ for some multi-index α. One can use this and (35.8.3) to get that (35.9.4) holds for any L_1.

Remember that

$$\text{the space of formal differential operators in } \partial_1, \ldots, \partial_n \text{ with coefficients in } LP_k(T_1, \ldots, T_n) \tag{35.9.5}$$

is an associative algebra over k, as in Section 35.6. The space of formal differential operators in $\partial_1, \ldots, \partial_n$ with coefficients in $k[T_1, \ldots, T_n]$ is a subalgebra of (35.9.5), as before.

The space of formal differential operators in $\partial_1, \ldots, \partial_n$ with coefficients in $LP_k(T_1, \ldots, T_n)$ that are homogeneous of degree $d \in \mathbf{Z}$ is a submodule of (35.9.5), as a module over k. In fact,

$$\text{the space of formal differential operators in } \partial_1, \ldots, \partial_n \text{ with coefficients in } LP_k(T_1, \ldots, T_n) \text{ that are homogeneous of degree } 0 \tag{35.9.6}$$

is a subalgebra of (35.9.5). Of course, the space of formal differential operators in $\partial_1, \ldots, \partial_n$ with coefficients in $k[T_1, \ldots, T_n]$ that are homogeneous of degree 0 is a subalgebra of (35.9.6).

If $a(T) = (a^1(T), \ldots, a^n(T))$ is an n-tuple of formal Laurent polynomials in $T_1, \ldots, T_n$ with coefficients in k, then put $D_{a(T)} = \sum_{j=1}^n a^j(T)\, \partial_j$, as in Section 35.7. Observe that

$$\{D_{a(T)} : a(T) \in (LP_k(T_1, \ldots, T_n))^n\} \tag{35.9.7}$$

is a submodule of (35.9.5), as a module over k. More precisely, (35.9.7) is a Lie subalgebra of (35.9.5), with respect to the commutator bracket, as in Section 35.7. The space of $D_{a(T)}$ with $a(T) \in (k[T_1, \ldots, T_n])^n$ is a Lie subalgebra of (35.9.7).

Similarly,

$$\{D_{a(T)} : a(T) \in (LP_{k,1}(T_1, \ldots, T_n))^n\} \tag{35.9.8}$$

is a Lie subalgebra of (35.9.6), with respect to the commutator bracket. This is also a subalgebra of (35.9.7), as a Lie algebra over k. Remember that $g_n(k)$ is the space of $D_{a(T)}$, where $a^j(T)$ is in the space $k_1[T_1, \ldots, T_n]$ of formal polynomials in $T_1, \ldots, T_n$ with coefficients in k that are homogeneous of degree one for each $j = 1, \ldots, n$, as in Section 5.15. This is a subalgebra of (35.9.8), as a Lie algebra over k.

If $a(T) \in (k_1[T_1, \ldots, T_n])^n$, then $a^j(T)$ can be expressed as $\sum_{l=1}^n a_l^j\, T_l$ for each $j = 1, \ldots, n$, where $a_l^j \in k$ for every $j, l = 1, \ldots, n$. Remember that $s_n(k)$ is the space of $D_{a(T)}$ with $a(T) \in (k_1[T_1, \ldots, T_n])^n$ and $\sum_{j=1}^n a_j^j = 0$, as in Section 5.15. This is a subalgebra of $g_n(k)$, as a Lie algebra over k, as before. In particular, $s_n(k)$ may be considered as a subalgebra of (35.9.8), as a Lie algebra over k.

35.10 Representations and Laurent series

Let k be a commutative ring with a multiplicative identity element, let A be a module over k, and let n be a positive integer. Also let $T_1, \ldots, T_n$ be n commuting indeterminates, and let $\partial_1, \ldots, \partial_n$ be n commuting formal symbols, which may be used to represent partial derivatives, as before. Remember that the space $LS_A(T_1, \ldots, T_n)$ of formal Laurent series in $T_1, \ldots, T_n$ with coefficients in A is a module over k, with respect to termwise addition and scalar multiplication, as in Section 35.1.

The space of formal differential operators in $\partial_1, \ldots, \partial_n$ with coefficients in $LP_k(T_1, \ldots, T_n)$ is an associative algebra over k, as in Section 35.6. These formal differential operators determine homomorphisms from $LS_A(T_1, \ldots, T_n)$ into itself, as a module over k, as before. This defines a representation of (35.9.5), as an associative algebra over k, on $LS_A(T_1, \ldots, T_n)$.

Remember that the mappings from $LS_A(T_1, \ldots, T_n)$ into itself associated to formal differential operators in $\partial_1, \ldots, \partial_n$ with coefficients in $LP_k(T_1, \ldots, T_n)$ send $LP_A(T_1, \ldots, T_n)$ into itself, as in Section 35.6. Thus

$$LP_A(T_1, \ldots, T_n) \text{ is a submodule of } LS_A(T_1, \ldots, T_n), \tag{35.10.1}$$

as a left module over (35.9.5).

In particular, $LS_A(T_1, \ldots, T_n)$ may be considered as a left module over (35.9.6), as an associative algebra over k. Similarly, $LP_A(T_1, \ldots, T_n)$ is a submodule of $LS_A(T_1, \ldots, T_n)$, as a left module over (35.9.6).

If $d \in \mathbf{Z}$, then

(35.10.2) $\quad LS_{A,d}(T_1, \ldots, T_n)$ is a submodule of $LS_A(T_1, \ldots, T_n)$,

as a left module over (35.9.6), as in the previous section. We also have that

(35.10.3) $\quad LP_{A,d}(T_1, \ldots, T_n)$ is a submodule of $LP_A(T_1, \ldots, T_n)$,

as a left module over (35.9.6).

Remember that (35.9.7) is a Lie algebra over k, with respect to the commutator bracket. We may consider $LS_A(T_1, \ldots, T_n)$ as a module over (35.9.7), as a Lie algebra over k. Similarly, we may consider $LP_A(T_1, \ldots, T_n)$ as a submodule of $LS_A(T_1, \ldots, T_n)$, as a module over (35.9.7).

Remember too that (35.9.8) is a subalgebra of (35.9.7), as a Lie algebra over k. This permits us to consider $LS_A(T_1, \ldots, T_n)$ as a module over (35.9.8), as a Lie algebra over k. We may consider $LP_A(T_1, \ldots, T_n)$ as a submodule of $LS_A(T_1, \ldots, T_n)$, as a module over (35.9.8) as well.

Similarly, $g_n(k)$ is a subalgebra of (35.9.8), as a Lie algebra over k, and $s_n(k)$ is a subalgebra of $g_n(k)$. Thus

(35.10.4) we may consider $LS_A(T_1, \ldots, T_n)$ as a module over $g_n(k)$ or $s_n(k)$,

as Lie algebras over k. As usual, $LP_A(T_1, \ldots, T_n)$ may be considered as a submodule of $LS_A(T_1, \ldots, T_n)$, as a module over $g_n(k)$ or $s_n(k)$.

If $d \in \mathbf{Z}$, then (35.10.2) holds, with $LS_A(T_1, \ldots, T_n)$ considered as a module over (35.9.8), $g_n(k)$, or $s_n(k)$. Similarly, (35.10.3) holds, with $LP_A(T_1, \ldots, T_n)$ considered as a module over (35.9.8), $g_n(k)$, or $s_n(k)$.

Note that

(35.10.5) $\quad A[[T_1, \ldots, T_n]]$ is a submodule of $LS_A(T_1, \ldots, T_n)$,

as a module over $g_n(k)$ or $s_n(k)$. Similarly,

(35.10.6) $\quad A[T_1, \ldots, T_n]$ is a submodule of $LP_A(T_1, \ldots, T_n)$,

as a module over $g_n(k)$ or $s_n(k)$. If d is a nonnegative integer, then the space $A_d[T_1, \ldots, T_n]$ of formal polynomials in $T_1, \ldots, T_n$ with coefficients in A that are homogeneous of degree d is a submodule of $A[T_1, \ldots, T_n]$, as a module over $g_n(k)$ or $s_n(k)$, as in Section 6.15. In this case,

(35.10.7) $\quad A_d[T_1, \ldots, T_n]$ is a submodule of $LP_{A,d}(T_1, \ldots, T_n)$,

as a module over $g_n(k)$ or $s_n(k)$.

35.11 A linear mapping onto A

Let k be a commutative ring with a multiplicative identity element, and let A be a module over k. Also let n be a positive integer, and let $T_1, \ldots, T_n$ be n commuting indeterminates, as before. If $f(T) = \sum_{\alpha \in \mathbf{Z}^n} f_\alpha \, T^\alpha$ is a formal Laurent series in $T_1, \ldots, T_n$ with coefficients in A, then put

(35.11.1) $$I_0(f(T)) = f_0.$$

This defines a homomorphism from $LS_A(T_1, \ldots, T_n)$ onto A, as modules over k.

If $\beta \in \mathbf{Z}^n$, then $f(T)\, T^\beta \in LS_A(T_1, \ldots, T_n)$, and

(35.11.2) $$I_0(f(T)\, T^\beta) = f_{-\beta}.$$

Note that

(35.11.3) $$I_0(f) = 0$$

when $f(T)$ is homogeneous of degree $d \neq 0$.

Suppose for the moment that A is an algebra over k in the strict sense. In this case, it is easy to see that the restriction of I_0 to $A[[T_1, \ldots, T_n]]$ defines an algebra homomorphism from $A[[T_1, \ldots, T_n]]$ onto A.

If l is a positive integer with $l \le n$, then

(35.11.4) $$T_l \, \partial_l f(T) = \sum_{\alpha \in \mathbf{Z}^n} \alpha_l \cdot f_\alpha \, T^\alpha.$$

This implies that

(35.11.5) $$I_0(T_l \partial_l f(T)) = 0.$$

Let $\partial_1, \ldots, \partial_n$ be n commuting formal symbols, which may be used to represent partial derivatives, as usual. Put $e(T) = (T_1, \ldots, T_n)$, so that the corresponding formal differential operator $D_{e(T)} = \sum_{j=1}^n T_j \, \partial_j$ is the analogue of the classical Euler operator, as in Section 35.7. Thus

(35.11.6) $$I_0(D_{e(T)} f(T)) = 0,$$

by (35.11.5). If k is a field of characteristic 0, then it is easy to see that

(35.11.7) $D_{e(T)}$ maps $LS_A(T_1, \ldots, T_n)$ onto the kernel of I_0.

Similarly, $D_{e(T)}$ maps $LP(T_1, \ldots, T_n)$ onto the kernel of the restriction of I_0 to $LP_A(T_1, \ldots, T_n)$ under these conditions.

35.12 Some related bilinear functionals

Let k be a commutative ring with a multiplicative identity element, let n be a positive integer, and let $T_1, \ldots, T_n$ be n commuting indeterminates. Thus I_0 may be defined as a homomorphism from $LS_k(T_1, \ldots, T_n)$ onto k, as modules over k, as in the previous section. If $f(T) = \sum_{\alpha \in \mathbf{Z}^n} f_\alpha \, T^\alpha$ and $g(T) =$

$\sum_{\beta \in \mathbf{Z}^n} g_\beta \, T^\beta$ are formal Laurent series in $T_1, \ldots, T_n$ with coefficients in k, then we would like to put

$$B_0(f(T), g(T)) = I_0(f(T)\, g(T)), \tag{35.12.1}$$

when $f(T)\, g(T)$ is defined as an element of $LS_k(T_1, \ldots, T_n)$. In particular, we can do this when at least one of $f(T)$ and $g(T)$ is a Laurent polynomial.

Equivalently,

$$B_0(f(T), g(T)) = \sum_{\alpha \in \mathbf{Z}^n} f_\alpha \, g_{-\alpha}, \tag{35.12.2}$$

which is defined as an element of k when $f_\alpha \, g_{-\alpha} = 0$ for all but finitely many $\alpha \in \mathbf{Z}^n$. This holds when at least one of $f(T)$ and $g(T)$ is a Laurent polynomial, as before. We may consider B_0 as a k-valued function on

$$LP_k(T_1, \ldots, T_n) \times LS_k(T_1, \ldots, T_n) \tag{35.12.3}$$

or

$$LS_k(T_1, \ldots, T_n) \times LP_k(T_1, \ldots, T_n). \tag{35.12.4}$$

We may also simply consider B_0 as a k-valued function on

$$LP_k(T_1, \ldots, T_n) \times LP_k(T_1, \ldots, T_n). \tag{35.12.5}$$

It is easy to see that B_0 is bilinear over k in each case.

If at least one of $f(T)$ and $g(T)$ is a Laurent polynomial, then

$$B_0(f(T), g(T)) = B_0(g(T), f(T)). \tag{35.12.6}$$

This can be obtained from the fact that $f(T)\, g(T) = g(T)\, f(T)$, as in Section 35.2, or from (35.12.2). Similarly, if $a(T)$ is a Laurent polynomial in $T_1, \ldots, T_n$ with coefficients in k, then

$$B_0(a(T)\, f(T), g(T)) = B_0(f(T), a(T)\, g(T)). \tag{35.12.7}$$

If l is a positive integer with $l \le n$, then

$$I_0(T_l \, \partial_l(f(T)\, g(T))) = 0, \tag{35.12.8}$$

as in (35.11.5). This implies that

$$B_0(T_l \, \partial_l f(T), g(T)) = -B_0(f(T), T_l \, \partial_l g(T)). \tag{35.12.9}$$

Observe that

$$B_0(f(T), T^\beta) = f_{-\beta} \tag{35.12.10}$$

for every $\beta \in \mathbf{Z}^n$. If $f(T)$, $g(T)$ are homogeneous of degrees d_1, d_2, respectively, and $d_1 + d_2 \ne 0$, then

$$B_0(f(T), g(T)) = 0, \tag{35.12.11}$$

when the left side is defined.

35.13 Adjoints of differential operators

Let k be a commutative ring with a multiplicative identity element, and suppose that for every $m \in \mathbf{Z}_+$ and $t \in k$ with $m \cdot t = 0$, we have that $t = 0$. In particular, this holds when $k = \mathbf{Z}$, or k is a field of characteristic 0, or at least an algebra over $\mathbf{Q}$. Also let n be a positive integer, let $T_1, \ldots, T_n$ be n commuting indeterminates, and let $\partial_1, \ldots, \partial_n$ be n commuting formal symbols, which may be used to represent partial derivatives, as before. Suppose that L is a formal differential operator in $\partial_1, \ldots, \partial_n$ with coefficients in $LP_k(T_1, \ldots, T_n)$. Let us say that a formal differential operator L^* in $\partial_1, \ldots, \partial_n$ with coefficients in $LP_k(T_1, \ldots, T_n)$ is the *adjoint* of L if

$$B_0(L(f(T)), g(T)) = B_0(f(T), L^*(g(T))) \tag{35.13.1}$$

for every $f(T), g(T) \in LS_k(T_1, \ldots, T_n)$ with at least one of $f(T)$, $g(T)$ in $LP_k(T_1, \ldots, T_n)$.

If (35.13.1) holds for every $f(T), g(T) \in LP_k(T_1, \ldots, T_n)$, then $L^*(g(T))$ is uniquely determined by L and $g(T)$ for every $g(T) \in LP_k(T_1, \ldots, T_n)$. This means that the mapping on $LP_k(T_1, \ldots, T_n)$ corresponding to L^* is uniquely determined by L. It follows that L^* is uniquely determined by L under these conditions, as in Section 35.6.

If L is of order 0, then L corresponds to multiplication by an element of $LP_k(T_1, \ldots, T_n)$, and one can take $L^* = L$, as in (35.12.7). If $L = T_l\, \partial_l$ for some $l = 1, \ldots, n$, then one can take $L^* = -T_l\, \partial_l$, as in (35.12.9).

Let L_1, L_2 be formal differential operators in $\partial_1, \ldots, \partial_n$ with coefficients in $LP_k(T_1, \ldots, T_n)$, and suppose that L_1^*, L_2^* are formal differential operators in $\partial_1, \ldots, \partial_n$ with coefficients in $LP_k(T_1, \ldots, T_n)$ that are adjoints of L_1, L_2, respectively. It is easy to see that $L_1^* + L_2^*$ is the adjoint of $L_1 + L_2$ in this case. Similarly, if $a \in k$, then $a\, L_1^*$ is the adjoint of $a\, L_1$. If $f(T)$, $g(T)$ are elements of $LS_k(T_1, \ldots, T_n)$, at least one of which is in $LP_k(T_1, \ldots, T_n)$, then

$$\begin{aligned} B_0(L_2(L_1(f(T))), g(T)) &= B_0(L_1(f(T)), L_2^*(g(T))) \\ &= B_0(f(T), L_1^*(L_2^*(g(T)))). \end{aligned} \tag{35.13.2}$$

This means that the product of L_1^* and L_2^* is the adjoint of the product of L_1 and L_2.

If L is any formal differential operator in $\partial_1, \ldots, \partial_n$ with coefficients in $LP_k(T_1, \ldots, T_n)$, then one can use the remarks in the previous two paragraphs to get that there is a formal differential operator L^* in $\partial_1, \ldots, \partial_n$ with coefficients in $LP_k(T_1, \ldots, T_n)$ that is the adjoint of L. More precisely, L can be expressed as a sum of products of formal differential operators of order 0, and formal differential operators of the form $T_l\, \partial_l$, $1 \le l \le n$. The adjoints of each of these can be obtained as before, which can be used to get the adjoint of L. Note that

$$(L^*)^* = L, \tag{35.13.3}$$

so that $L \mapsto L^*$ is an involution on the algebra of formal differential operators in $\partial_1, \ldots, \partial_n$ with coefficients in $LP_k(T_1, \ldots, T_n)$. If L is homogeneous of degree d, then one can verify that L^* is homogeneous of degree d as well.

Chapter 36

Formal Laurent series, 2

36.1 Laurent series and $sl_2(k)$

Let k be a commutative ring with a multiplicative identity element, and let A be a module over k. We would like to consider formal Laurent polynomials and series with coefficients in A, as in the previous chapter, with $n = 2$. Thus we let T_1, T_2 be commuting indeterminates, and we let ∂_1, ∂_2 be commuting formal symbols, which may be used to represent partial derivatives, as before.

Put

$$H = T_1\,\partial_1 - T_2\,\partial_2, \tag{36.1.1}$$

$$X = T_1\,\partial_2, \tag{36.1.2}$$

$$Y = T_2\,\partial_1, \tag{36.1.3}$$

which are formal differential operators in ∂_1, ∂_2 with coefficients in $k_1[T_1, T_2]$. Note that H, X, and Y are homogeneous of degree 0, as in Sections 5.14 and 35.9. In fact,

$$H, X, Y \in s_2(k), \tag{36.1.4}$$

where $s_2(k)$ is as in Sections 5.15 and 35.9. More precisely, $s_2(k)$ is freely generated by H, X, and Y, as a module over k.

Remember that $s_2(k)$ is a Lie algebra over k, with respect to the commutator bracket corresponding to products of formal differential operators. It is easy to see that

$$[X, Y] = H, \tag{36.1.5}$$

$$[H, X] = 2 \cdot X, \tag{36.1.6}$$

$$[H, Y] = -2 \cdot Y. \tag{36.1.7}$$

Thus $s_2(k)$ is isomorphic to $sl_2(k)$, as a Lie algebra over k, where the usual elements h, x, and y of $sl_2(k)$ as in Section 34.1 correspond to H, X, and Y, repsectively. This is related to some of the remarks in Section 5.15.

We may consider the space $LS_A(T_1, T_2)$ of formal Laurent series in T_1, T_2 with coefficients in A as a module over $s_2(k)$, as a Lie algebra over k, as in Section 35.10. This may be considered as a representation of $sl_2(k)$, as a Lie algebra over k, on $LS_A(T_1, T_2)$, using the isomorphism mentioned in the preceding paragraph. That is to say, the actions of h, x, and y on $LS_A(T_1, T_2)$ under this representation are given by H, X, and Y, respectively.

The space $LP_A(T_1, T_2)$ of formal Laurent polynomials in T_1, T_2 with coefficients in A is a submodule of $LS_A(T_1, T_2)$, as a module over $sl_2(k)$. Similarly, $A[[T_1, T_2]]$ is a submodule of $LS_A(T_1, T_2)$, and $A[T_1, T_2]$ is a submodule of each of $A[[T_1, T_2]]$ and $LP_A(T_1, T_2)$, as modules over $sl_2(k)$.

If $d \in \mathbf{Z}$, then $LS_{A,d}(T_1, T_2)$, $LP_{A,d}(T_1, T_2)$ are submodules of $LS_A(T_1, T_2)$, $LP_A(T_1, T_2)$, respectively, as modules over $s_2(k)$, as in Section 35.10. If $d \geq 0$, then $A_d[T_1, T_2]$ is a submodule of $A[T_1, T_2]$ and $LP_{A,d}(T_1, T_2)$, as modules over $s_2(k)$, as before.

Let $d \in \mathbf{Z}$ and $f(T) \in LS_{A,d}(T_1, T_2)$ be given. Thus

$$f(T) = \sum_{j=-\infty}^{\infty} f_j \, T_1^j \, T_2^{d-j}, \tag{36.1.8}$$

where $f_j \in A$ for every j. Of course, $f(T) \in LP_{A,d}(T_1, T_2)$ exactly when $f_j = 0$ for all but finitely many integers j.

Observe that

$$\begin{aligned} (Hf)(T) &= \sum_{j=-\infty}^{\infty} (j - (d - j)) \cdot f_j \, T_1^j \, T_2^{d-j} \\ &= \sum_{j=-\infty}^{\infty} (2\,j - d) \cdot f_j \, T_1^j \, T_2^{d-j}. \end{aligned} \tag{36.1.9}$$

Similarly,

$$\begin{aligned} (Xf)(T) &= \sum_{j=-\infty}^{\infty} (d - j) \cdot f_j \, T_1^{j+1} \, T_2^{d-j-1} \\ &= \sum_{j=-\infty}^{\infty} (d - j + 1) \cdot f_{j-1} \, T_1^j \, T_2^{d-j} \end{aligned} \tag{36.1.10}$$

and

$$\begin{aligned} (Yf)(T) &= \sum_{j=-\infty}^{\infty} j \cdot f_j \, T_1^{j-1} \, T_2^{d-j+1} \\ &= \sum_{j=-\infty}^{\infty} (j + 1) \cdot f_{j+1} \, T_1^j \, T_2^{d-j}. \end{aligned} \tag{36.1.11}$$

36.2 Some submodules of $LS_{A,d}(T_1, T_2)$

Let us continue with the same notation and hypotheses as in the previous section. In particular, if $f(T) \in LS_{A,d}(T_1, T_2)$ and $j \in \mathbf{Z}$, then we let f_j be the coefficient in A of $T_1^j \, T_2^{d-j}$ in $f(T)$, as in (36.1.8).

If $l \in \mathbf{Z}$, then put

$$LS^{l,+}_{A,d}(T_1, T_2) = \{f(T) \in LS_{A,d}(T_1, T_2) : f_j = 0 \text{ for every } j < l\}. \tag{36.2.1}$$

Similarly, put

$$LS^{l,-}_{A,d}(T_1, T_2) = \{f(T) \in LS_{A,d}(T_1, T_2) : f_j = 0 \text{ for every } j > l\}. \tag{36.2.2}$$

Note that these are submodules of $LS_{A,d}(T_1, T_2)$, as a module over k. If $r \in \mathbf{Z}$ and $l \le r$, then

$$LS^{r,+}_{A,d}(T_1, T_2) \subseteq LS^{l,+}_{A,d}(T_1, T_2), \tag{36.2.3}$$

$$LS^{l,-}_{A,d}(T_1, T_2) \subseteq LS^{r,-}_{A,d}(T_1, T_2). \tag{36.2.4}$$

Let us also put

$$\begin{aligned} LP^{l,+}_{A,d}(T_1, T_2) &= LS^{l,+}_{A,d}(T_1, T_2) \cap LP_{A,d}(T_1, T_2) \\ &= \{f(T) \in LP_{A,d}(T_1, T_2) : f_j = 0 \text{ for every } j < l\} \end{aligned} \tag{36.2.5}$$

and

$$\begin{aligned} LP^{l,-}_{A,d}(T_1, T_2) &= LS^{l,-}_{A,d}(T_1, T_2) \cap LP_{A,d}(T_1, T_2) \\ &= \{f(T) \in LP_{A,d}(T_1, T_2) : f_j = 0 \text{ for every } j > l\}. \end{aligned} \tag{36.2.6}$$

These are submodules of $LP_{A,d}(T_1, T_2)$, as a module over k. If $l \le r$, then

$$LP^{r,+}_{A,d}(T_1, T_2) \subseteq LP^{l,+}_{A,d}(T_1, T_2), \tag{36.2.7}$$

$$LP^{l,-}_{A,d}(T_1, T_2) \subseteq LP^{r,-}_{A,d}(T_1, T_2), \tag{36.2.8}$$

as before.

Observe that

$$H(LS^{l,+}_{A,d}(T_1, T_2)) \subseteq LS^{l,+}_{A,d}(T_1, T_2), \tag{36.2.9}$$

$$H(LS^{l,-}_{A,d}(T_1, T_2)) \subseteq LS^{l,-}_{A,d}(T_1, T_2) \tag{36.2.10}$$

for every $l \in \mathbf{Z}$, by (36.1.9). Similarly,

$$H(LP^{l,+}_{A,d}(T_1, T_2)) \subseteq LP^{l,+}_{A,d}(T_1, T_2), \tag{36.2.11}$$

$$H(LP^{l,-}_{A,d}(T_1, T_2)) \subseteq LP^{l,-}_{A,d}(T_1, T_2) \tag{36.2.12}$$

for every $l \in \mathbf{Z}$.

One can check that

(36.2.13) $$X(LS^{l,+}_{A,d}(T_1,T_2)) \subseteq LS^{l+1,+}_{A,d}(T_1,T_2),$$

(36.2.14) $$X(LS^{l,-}_{A,d}(T_1,T_2)) \subseteq LS^{l+1,-}_{A,d}(T_1,T_2)$$

for every $l \in \mathbf{Z}$, using (36.1.10). Similarly,

(36.2.15) $$X(LP^{l,+}_{A,d}(T_1,T_2)) \subseteq LP^{l+1,+}_{A,d}(T_1,T_2),$$

(36.2.16) $$X(LP^{l,-}_{A,d}(T_1,T_2)) \subseteq LP^{l+1,-}_{A,d}(T_1,T_2)$$

for each $l \in \mathbf{Z}$.

If $l \in \mathbf{Z}$, then one can check that

(36.2.17) $$Y(LS^{l,+}_{A,d}(T_1,T_2)) \subseteq LS^{l-1,+}_{A,d}(T_1,T_2),$$

(36.2.18) $$Y(LS^{l,-}_{A,d}(T_1,T_2)) \subseteq LS^{l-1,-}_{A,d}(T_1,T_2),$$

using (36.1.11). Similarly,

(36.2.19) $$Y(LP^{l,+}_{A,d}(T_1,T_2)) \subseteq LP^{l-1,+}_{A,d}(T_1,T_2),$$

(36.2.20) $$Y(LP^{l,-}_{A,d}(T_1,T_2)) \subseteq LP^{l-1,-}_{A,d}(T_1,T_2)$$

for every $l \in \mathbf{Z}$.

If $l \in \mathbf{Z}$, then $LS_{A,d}(T_1,T_2)$ corresponds to the direct sum of $LS^{l,+}_{A,d}(T_1,T_2)$ and $LS^{l-1,-}_{A,d}(T_1,T_2)$, as a module over k. Similarly, $LP_{A,d}(T_1,T_2)$ corresponds to the direct sum of $LP^{l,+}_{A,d}(T_1,T_2)$ and $LP^{l-1,-}_{A,d}(T_1,T_2)$, as a module over k.

36.3 Submodules over $s_2(k)$

Let us continue with the same notation and hypotheses as in the previous two sections. If $l = d$, then we can improve (36.2.14) and (36.2.16). More precisely, one can verify that

(36.3.1) $$X(LS^{d,-}_{A,d}(T_1,T_2)) \subseteq LS^{d,-}_{A,d}(T_1,T_2),$$

(36.3.2) $$X(LP^{d,-}_{A,d}(T_1,T_2)) \subseteq LP^{d,-}_{A,d}(T_1,T_2),$$

using (36.1.10). Similarly, if $l = 0$, then we can improve (36.2.17) and (36.2.19). That is to say, one can verify that

(36.3.3) $$Y(LS^{0,+}_{A,d}(T_1,T_2)) \subseteq LS^{0,+}_{A,d}(T_1,T_2),$$

(36.3.4) $$Y(LP^{0,+}_{A,d}(T_1,T_2)) \subseteq LP^{0,+}_{A,d}(T_1,T_2),$$

using (36.1.11).

It follows that

(36.3.5) $LS^{d,-}_{A,d}(T_1,T_2)$ is a submodule of $LS_{A,d}(T_1,T_2)$, as a module over $s_2(k)$, by (36.2.10), (36.3.1), and (36.2.18). Similarly,

(36.3.6) $$LP^{d,-}_{A,d}(T_1, T_2) \text{ is a submodule of } LP_{A,d}(T_1, T_2), \text{ as a module over } s_2(k),$$

by (36.2.12), (36.3.2), and (36.2.20). We also get that

(36.3.7) $$LS^{0,+}_{A,d}(T_1, T_2) \text{ is a submodule of } LS_{A,d}(T_1, T_2), \text{ as a module over } s_2(k),$$

by (36.2.9), (36.2.13), and (36.3.3). Similarly,

(36.3.8) $$LP^{0,+}_{A,d}(T_1, T_2) \text{ is a submodule of } LP_{A,d}(T_1, T_2), \text{ as a module over } s_2(k),$$

by (36.2.11), (36.2.15), and (36.3.4).

Note that

(36.3.9)
$$\begin{aligned} & LS^{d,-}_{A,d}(T_1, T_2) \cap LS^{0,+}_{A,d}(T_1, T_2) \\ = \quad & LP^{d,-}_{A,d}(T_1, T_2) \cap LP^{0,+}_{A,d}(T_1, T_2) \\ = \quad & A_d[T_1, T_2] \quad \text{when } d \ge 0 \\ = \quad & \{0\} \qquad\qquad \text{when } d < 0. \end{aligned}$$

Let us now take $d = -1$. Observe that

(36.3.10) $LS_{A,-1}(T_1, T_2)$ corresponds to the direct sum of $LS^{0,+}_{A,-1}(T_1, T_2)$ and $LS^{-1,-}_{A,-1}(T_1, T_2)$, as a module over $s_2(k)$.

Similarly,

(36.3.11) $LP_{A,-1}(T_1, T_2)$ corresponds to the direct sum of $LP^{0,+}_{A,-1}(T_1, T_2)$ and $LP^{-1,-}_{A,-1}(T_1, T_2)$, as a module over $s_2(k)$.

36.4 Characteristic 0, $A = k$

Let us continue with the same notation and hypotheses as in the previous three sections, now with k a field of characterisctic 0, and $A = k$, as a module over itself. If $j \in \mathbf{Z}$, then $T_1^j \, T_2^{d-j} \in LP_{k,d}(T_1, T_2)$, and

(36.4.1) $$H(T_1^j \, T_2^{d-j}) = (2\,j - d)\, T_1^j \, T_2^{d-j}.$$

This means that $T_1^j \, T_2^{d-j}$ has weight $2\,j - d$ in $LP_{k,d}(T_1, T_2)$, as a module over $s_2(k)$, or equivalently $sl_2(k)$, as in Section 15.1.

Observe that

(36.4.2) $$X(T_1^d) = 0.$$

Thus T_1^d is a maximal or primitive vector of weight d in $LP_{k,d}(T_1, T_2)$, as in Section 15.2. More precisely, T_1^d may be considered as a maximal or primitive vector of weight d in the submodule $LP_{k,d}^{d,-}(T_1, T_2)$ of $LP_{k,d}(T_1, T_2)$.

If $d \geq 0$, then T_1^d may be considered as a maximal or primitive vector of weight d in the submodule $k_d[T_1, T_2]$ of $LP_{k,d}^{d,-}(T_1, T_2)$. In this case, it is easy to see that $Y^l(T_1^d)$, $l = 0, \ldots, d$, forms a basis for $k_d[T_1, T_2]$, as a vector space over k, while $Y^{d+1}(T_1^d) = 0$. As in Section 15.5, this implies that $k_d[T_1, T_2]$ is isomorphic as a module over $sl_2(k)$ to the module discussed in Section 15.4, with $m = d$.

If $d < 0$, then $Y^l(T_1^d)$, $l \geq 0$, forms a basis for $LP_{k,d}^{d,-}(T_1, T_2)$, as a vector space over k. Let $Z_0(\mu_0)$ be as in Section 34.2, and let us take

$$\mu_0 = d \cdot 1 \tag{36.4.3}$$

in k. Under these conditions, we get that $LP_{k,d}^{d,-}(T_1, T_2)$ is isomorphic to $Z_0(\mu_0)$, as a module over $sl_2(k)$, as in Section 34.3.

36.5 Some helpful projections

Let us return to the notation and hypotheses in Sections 36.1 and 36.2. Thus k is a commutative ring with a multiplicative identity element again, and A is a module over k. Let $f(T) = \sum_{j=-\infty}^{\infty} f_j\, T_1^j\, T_2^{d-j} \in LS_{A,d}(T_1, T_2)$ be given. If $l \in \mathbf{Z}$, then put

$$P_{l,+}(f(T)) = \sum_{j=l}^{\infty} f_j\, T_1^j\, T_2^{d-j}, \tag{36.5.1}$$

$$P_{l,-}(f(T)) = \sum_{j=-\infty}^{l} f_j\, T_1^j\, T_2^{d-j}. \tag{36.5.2}$$

These define homomorphisms from $LS_{A,d}(T_1, T_2)$ into itself, as a module over k.

Note that

$$P_{l,+}(LS_{A,d}(T_1, T_2)) = LS_{A,d}^{l,+}(T_1, T_2), \tag{36.5.3}$$

$$P_{l,-}(LS_{A,d}(T_1, T_2)) = LS_{A,d}^{l,-}(T_1, T_2) \tag{36.5.4}$$

for each $l \in \mathbf{Z}$. Similarly,

$$P_{l,+}(LP_{A,d}(T_1, T_2)) = LP_{A,d}^{l,+}(T_1, T_2), \tag{36.5.5}$$

$$P_{l,-}(LP_{A,d}(T_1, T_2)) = LP_{A,d}^{l,-}(T_1, T_2) \tag{36.5.6}$$

for every $l \in \mathbf{Z}$. More precisely, $P_{l,+}$ is equal to the identity mapping on $LS_{A,d}^{l,+}(T_1, T_2)$, and $P_{l,-}$ is equal to the identity mapping on $LS_{A,d}^{l,-}(T_1, T_2)$.

We also have that

$$\text{the kernel of } P_{l,+} \text{ on } LS_{A,d}(T_1, T_2) \text{ is equal to } LS_{A,d}^{l-1,-}(T_1, T_2) \tag{36.5.7}$$

and

$$\text{the kernel of } P_{l,-} \text{ on } LS_{A,d}(T_1, T_2) \text{ is equal to } LS_{A,d}^{l+1,+}(T_1, T_2) \tag{36.5.8}$$

for every $l \in \mathbf{Z}$. It follows that

$$\text{the kernel of } P_{l,+} \text{ on } LP_{A,d}(T_1, T_2) \text{ is equal to } LP_{A,d}^{l-1,-}(T_1, T_2) \tag{36.5.9}$$

and

$$\text{the kernel of } P_{l,-} \text{ on } LP_{A,d}(T_1, T_2) \text{ is equal to } LP_{A,d}^{l+1,+}(T_1, T_2) \tag{36.5.10}$$

for every $l \in \mathbf{Z}$.

If $l \in \mathbf{Z}$, then we may consider the quotients

$$LS_{A,d}(T_1, T_2)/LS_{A,d}^{l,+}(T_1, T_2) \tag{36.5.11}$$

and

$$LS_{A,d}(T_1, T_2)/LS_{A,d}^{l,-}(T_1, T_2) \tag{36.5.12}$$

as modules over k. We may consider the quotients

$$LP_{A,d}(T_1, T_2)/LP_{A,d}^{l,+}(T_1, T_2) \tag{36.5.13}$$

and

$$LP_{A,d}(T_1, T_2)/LP_{A,d}^{l,-}(T_1, T_2) \tag{36.5.14}$$

as modules over k too. The natural inclusion mapping from $LP_{A,d}(T_1, T_2)$ into $LS_{A,d}(T_1, T_2)$ leads to injective homomorphisms from (36.5.13) into (36.5.11), and from (36.5.14) into (36.5.12), as modules over k.

We can use $P_{l-1,-}$ to identify (36.5.11) with $LS_{A,d}^{l-1,-}(T_1, T_2)$, as a module over k, in which case (36.5.13) corresponds to $LP_{A,d}^{l-1,-}(T_1, T_2)$. Similarly, we can use $P_{l+1,+}$ to identify (36.5.12) with $LS_{A,d}^{l+1,+}(T_1, T_2)$, as a module over k, so that (36.5.14) corresponds to $LP_{A,d}^{l+1,+}(T_1, T_2)$.

36.6 Projections and H, X, Y

Let us continue with the same notation and hypotheses as in the previous section. It is easy to see that

$$H \circ P_{l,+} = P_{l,+} \circ H, \tag{36.6.1}$$

$$H \circ P_{l,-} = P_{l,-} \circ H \tag{36.6.2}$$

on $LS_{A,d}(T_1, T_2)$ for each $l \in \mathbf{Z}$, using (36.1.9). If $l \in \mathbf{Z}$, then H maps each of $LS^{l,+}_{A,d}(T_1, T_2)$, $LS^{l,-}_{A,d}(T_1, T_2)$, $LP^{l,+}_{A,d}(T_1, T_2)$, and $LP^{l,-}_{A,d}(T_1, T_2)$ into itself, as in Section 36.2. This means that H induces a mapping on each of the quotients (36.5.11), (36.5.12), (36.5.13), and (36.5.14), that is linear over k. These induced mappings correspond to H on $LS^{l-1,-}_{A,d}(T_1, T_2)$, $LS^{l+1,+}_{A,d}(T_1, T_2)$, $LP^{l-1,-}_{A,d}(T_1, T_2)$, and $LP^{l+1,+}_{A,d}(T_1, T_2)$, respectively, with respect to the identifications mentioned before, by (36.6.1) and (36.6.2).

Remember that

$$X(LS^{l,+}_{A,d}(T_1, T_2)) \subseteq LS^{l+1,+}_{A,d}(T_1, T_2) \subseteq LS^{l,+}_{A,d}(T_1, T_2) \tag{36.6.3}$$

for each $l \in \mathbf{Z}$, as in Section 36.2. Of course, there are analogous inclusions for Laurent polynomials, so that X induces a mapping on each of the quotients (36.5.11) and (36.5.13) that is linear over k. If $l \in \mathbf{Z}$, then

$$P_{l-1,-} \circ X = 0 \quad \text{on } LS^{l-1,+}_{A,d}(T_1, T_2), \tag{36.6.4}$$

because of the first inclusion in (36.6.3), with l replaced by $l - 1$. We also have that

$$P_{l-1,-} \circ X = X \quad \text{on } LS^{l-2,-}_{A,d}(T_1, T_2), \tag{36.6.5}$$

because $X(LS^{l-2,-}_{A,d}(T_1, T_2)) \subseteq LS^{l-1,-}_{A,d}(T_1, T_2)$, as in (36.2.14). This determines $P_{l-1,-} \circ X$ on $LS_{A,d}(T_1, T_2)$.

As before, we can use $P_{l-1,-}$ to identify the quotients (36.5.11) and (36.5.13) with $LS^{l-1,-}_{A,d}(T_1, T_2)$ and $LP^{l-1,-}_{A,d}(T_1, T_2)$, respectively, as modules over k. Using this, the mapping induced by X on each of these quotients corresponds to the restriction of $P_{l-1,-} \circ X$ to $LS^{l-1,-}_{A,d}(T_1, T_2)$ and $LP^{l-1,-}_{A,d}(T_1, T_2)$, respectively.

Similarly,

$$Y(LS^{l,-}_{A,d}(T_1, T_2)) \subseteq LS^{l-1,-}_{A,d}(T_1, T_2) \subseteq LS^{l,-}_{A,d}(T_1, T_2) \tag{36.6.6}$$

for each $l \in \mathbf{Z}$, as in Section 36.2 again. It follows that Y induces a mapping on each of the quotients (36.5.12) and (36.5.14) that is linear over k, using also the analogue of (36.6.6) for Laurent polynomials. If $l \in \mathbf{Z}$, then

$$P_{l+1,+} \circ Y = 0 \quad \text{on } LS^{l+1,-}_{A,d}(T_1, T_2), \tag{36.6.7}$$

because of the first inclusion in (36.6.6), with l replaced with $l + 1$. In addition,

$$P_{l+1,+} \circ Y = Y \quad \text{on } LS^{l+2,+}_{A,d}(T_1, T_2), \tag{36.6.8}$$

because $Y(LS^{l+2,+}_{A,d}(T_1,T_2)) \subseteq LS^{l+1,+}_{A,d}(T_1,T_2)$, as in (36.2.17). This determines $P_{l+1,+} \circ Y$ on $LS_{A,d}(T_1,T_2)$.

As usual, we can use $P_{l+1,+}$ to identify the quotients (36.5.12) and (36.5.14) with $LS^{l+1,+}_{A,d}(T_1,T_2)$ and $LP^{l+1,+}_{A,d}(T_1,T_2)$, respectively, as modules over k. The mapping induced by Y on each of these quotients corresponds to the restriction of $P_{l+1,+} \circ Y$ to $LS^{l+1,+}_{A,d}(T_1,T_2)$ and $LP^{l+1,+}_{A,d}(T_1,T_2)$, respectively.

One can check that

$$X \circ P_{d+1,+} = P_{d+1,+} \circ X \tag{36.6.9}$$

on $LS_{A,d}(T_1,T_2)$, using (36.1.10). Alternatively, both sides are equal to 0 on $LS^{d,-}_{A,d}(T_1,T_2)$, by definition of $P_{d+1,+}$, and because X maps $LS^{d,-}_{A,d}(T_1,T_2)$ into itself, as in Section 36.3. Both sides are equal to X on $LS^{d+1,+}_{A,d}(T_1,T_2)$, by definition of $P_{l+1,+}$, and because X maps $LS^{d+1,+}_{A,d}(T_1,T_2)$ into itself, as in Section 36.2.

Similarly, one can verify that

$$Y \circ P_{-1,-} = P_{-1,-} \circ Y \tag{36.6.10}$$

on $LS_{A,d}(T_1,T_2)$, using (36.1.11). Alternatively, both sides are equal to 0 on $LS^{0,+}_{A,d}(T_1,T_2)$, by definition of $P_{-1,-}$, and because Y maps $LS^{0,+}_{A,d}(T_1,T_2)$ into itself, as in Section 36.3 again. Both sides are equal to Y on $LS^{-1,-}_{A,d}(T_1,T_2)$, by definition of $P_{-1,-}$, and because Y maps $LS^{-1,-}_{A,d}(T_1,T_2)$ into itself, as in Section 36.2.

36.7 Some related quotient modules

Let us continue with the same notation and hypotheses as in the previous two sections. Remember that $s_2(k)$ is a Lie algebra over k, as in Section 36.1, and that $LS^{d,-}_{A,d}(T_1,T_2)$ and $LS^{0,+}_{A,d}(T_1,T_2)$ are submodules of $LS_{A,d}(T_1,T_2)$, as a module over $s_2(k)$, as in Section 36.3. Thus the quotients

$$LS_{A,d}(T_1,T_2)/LS^{d,-}_{A,d}(T_1,T_2) \tag{36.7.1}$$

and

$$LS_{A,d}(T_1,T_2)/LS^{0,+}_{A,d}(T_1,T_2) \tag{36.7.2}$$

may be considered as modules over $s_2(k)$ as well. We may identify these quotients with $LS^{d+1,+}_{A,d}(T_1,T_2)$ and $LS^{-1,-}_{A,d}(T_1,T_2)$, respectively, as modules over k, using $P_{d+1,+}$ and $P_{-1,-}$, respectively, as in Section 36.5.

Remember that the actions of H induced on these quotients by the action of H on $LS_{A,d}(T_1,T_2)$ correspond to the usual actions of H on $LS^{d+1,+}_{A,d}(T_1,T_2)$ and $LS^{-1,-}_{A,d}(T_1,T_2)$, as in (36.6.1) and (36.6.2). Similarly, the action of X induced on (36.7.1) by the action of X on $LS_{A,d}(T_1,T_2)$ corresponds to the usual action of X on $LS^{d+1,+}_{A,d}(T_1,T_2)$, because of (36.6.9). We also have that the action of

Y induced on (36.7.2) by the action of Y on $LS_{A,d}(T_1, T_2)$ corresponds to the usual action of Y on $LS_{A,d}^{-1,-}(T_1, T_2)$, because of (36.6.10).

The action of Y induced on (36.7.1) by the action of Y on $LS_{A,d}(T_1, T_2)$ corresponds to

(36.7.3) $$\text{the restriction of } P_{d+1,+} \circ Y \text{ to } LS_{A,d}^{d+1,+}(T_1, T_2),$$

as in the previous section. This mapping is described by (36.6.7) and (36.6.8), with $l = d$. Similarly, the action of X induced on (36.7.2) by the action of X on $LS_{A,d}(T_1, T_2)$ corresponds to

(36.7.4) $$\text{the restriction of } P_{-1,-} \circ X \text{ to } LS_{A,d}^{-1,-}(T_1, T_2),$$

as before. This mapping is described by (36.6.4) and (36.6.5), with $l = 0$.

Of course, $LP_{A,d}(T_1, T_2)$ is a submodule of $LS_{A,d}(T_1, T_2)$, as a module over $s_2(k)$. Remember that $LP_{A,d}^{d,-}(T_1, T_2)$ and $LP_{A,d}^{0,+}(T_1, T_2)$ are submodules of $LP_{A,d}(T_1, T_2)$, as a module over $s_2(k)$, as in Section 36.3. This means that the quotients

(36.7.5) $$LP_{A,d}(T_1, T_2)/LP_{A,d}^{d,-}(T_1, T_2)$$

and

(36.7.6) $$LP_{A,d}(T_1, T_2)/LP_{A,d}^{0,+}(T_1, T_2)$$

may be considered as modules over $s_2(k)$, as before. Note that (36.7.5) and (36.7.6) may be considered as submodules of (36.7.1) and (36.7.2), respectively, as modules over $s_2(k)$. We may also identify (36.7.5) and (36.7.6) with $LP_{A,d}^{d+1,+}(T_1, T_2)$ and $LP_{A,d}^{-1,-}(T_1, T_2)$, respectively, as modules over k, using $P_{d+1,+}$ and $P_{-1,-}$, respectively, as before.

Suppose for the moment that $d \geq 0$, so that

(36.7.7) $$\begin{aligned} & LS_{A,d}^{d,-}(T_1, T_2) \cap LS_{A,d}^{0,+}(T_1, T_2) \\ = \; & LP_{A,d}^{d,-}(T_1, T_2) \cap LP_{A,d}^{0,+}(T_1, T_2) = A_d[T_1, T_2], \end{aligned}$$

as in Section 36.3. In particular, $A_d[T_1, T_2]$ is a submodule of $LS_{A,d}^{d,-}(T_1, T_2)$, $LS_{A,d}^{0,+}(T_1, T_2)$, $LP_{A,d}^{d,-}(T_1, T_2)$, and $LP_{A,d}^{0,+}(T_1, T_2)$, as modules over $s_2(k)$. This means that the quotients

(36.7.8) $$LS_{A,d}^{0,+}(T_1, T_2)/A_d[T_1, T_2],$$

(36.7.9) $$LS_{A,d}^{d,-}(T_1, T_2)/A_d[T_1, T_2],$$

(36.7.10) $$LP_{A,d}^{0,+}(T_1, T_2)/A_d[T_1, T_2],$$

(36.7.11) $$LP_{A,d}^{d,-}(T_1, T_2)/A_d[T_1, T_2],$$

may be considered as modules over $s_2(k)$ too. Of course, (36.7.10) and (36.7.11) correspond to submodules of (36.7.8) and (36.7.9), respectively, as modules over $s_2(k)$.

It is easy to see that these modules are isomorphic to (36.7.1), (36.7.2), (36.7.5), and (36.7.6), respectively, in a natural way, as modules over $s_2(k)$. Indeed, the natural quotient mapping from $LS_{A,d}(T_1, T_2)$ onto (36.7.1) maps $LS^{0,+}_{A,d}(T_1, T_2)$ onto (36.7.1) under these conditions, because $LS_{A,d}(T_1, T_2)$ is generated by $LS^{0,+}_{A,d}(T_1, T_2)$ and $LS^{d,-}_{A,d}(T_1, T_2)$, as a module over k. The kernel of the restriction to $LS^{0,+}_{A,d}(T_1, T_2)$ of the natural quotient mapping from $LS_{A,d}(T_1, T_2)$ onto (36.7.1) is equal to $A_d[T_1, T_2]$, by (36.7.7). This leads to the desired module isomorphism, and the other cases are analogous.

Suppose now that $d < 0$, so that

$$LS^{d,-}_{A,d}(T_1, T_2) \cap LS^{0,+}_{A,d}(T_1, T_2) = LP^{d,-}_{A,d}(T_1, T_2) \cap LP^{0,+}_{A,d}(T_1, T_2) = \{0\}, \tag{36.7.12}$$

as in Section 36.3 again. This implies that the restriction to $LS^{0,+}_{A,d}(T_1, T_2)$ of the natural quotient mapping from $LS_{A,d}(T_1, T_2)$ onto (36.7.1) is injective. Thus $LS^{0,+}_{A,d}(T_1, T_2)$ corresponds to a submodule of the quotient (36.7.1), as a module over $s_2(k)$. Similarly, $LS^{d,-}_{A,d}(T_1, T_2)$, $LP^{0,+}_{A,d}(T_1, T_2)$, and $LP^{d,-}_{A,d}(T_1, T_2)$ correspond to submodules of (36.7.2), (36.7.5), and (36.7.6), respectively, as modules over $s_2(k)$, in this case. If $d = -1$, then each of these submodules is the same as the corresponding quotient module.

36.8 Quotients and characteristic 0, $A = k$

Let us continue with the same notation and hypotheses as in the previous three sections, and take k to be a field of characteristic 0, and $A = k$, as a module over itself. Observe that $T_1^{-1}\, T_2^{d+1}$ is an element of $LP^{-1,-}_{k,d}(T_1, T_2)$, with

$$H(T_1^{-1}\, T_2^{d+1}) = (-d - 2)\, T_1^{-1}\, T_2^{d+1}, \tag{36.8.1}$$

as in (36.4.1). We also have that

$$X(T_1^{-1}\, T_2^{d+1}) = (d + 1)\, T_2^d \in LP^{0,+}_{k,d}(T_1, T_2). \tag{36.8.2}$$

The image of $T_1^{-1}\, T_2^{d+1}$ in

$$LP_{k,d}(T_1, T_2)/LP^{0,+}_{k,d}(T_1, T_2) \tag{36.8.3}$$

under the natural quotient mapping from $LP_{k,d}(T_1, T_2)$ is clearly nonzero. It follows that the image of $T_1^{-1}\, T_2^{d+1}$ in (36.8.3) is a maximal or primitive vector of weight $-d - 2$, as in Section 15.2.

One can check that $Y^l(T_1^{-1}\, T_2^{d+1})$, $l \geq 0$, form a basis for $LP^{-1,-}_{k,d}(T_1, T_2)$, as a vector space over k. This means that the images of these vectors in the quotient (36.8.3) form a basis there. Let $Z_0(\mu_0)$ be as in Section 34.2, and let us take

$$\mu_0 = (-d - 2) \cdot 1 \tag{36.8.4}$$

in k. Thus (36.8.3) is isomorphic to $Z_0(\mu_0)$, as modules over $sl_2(k)$, as in Section 34.3.

If $d \geq 0$, then $k_d[T_1, T_2]$ is a submodule of $LP^{d,-}_{k,d}(T_1, T_2)$, as a module over $s_2(k)$. In this case, (36.8.3) is isomorphic to

$$LP^{d,-}_{k,d}(T_1, T_2)/k_d[T_1, T_2] \tag{36.8.5}$$

as modules over $s_2(k)$, as in the previous section. If $d < 0$, then $LP^{d,-}_{k,d}(T_1, T_2)$ corresponds to a submodule of (36.8.3), as a module over $s_2(k)$, as before. In particular, if $d = -1$, then (36.8.3) is isomorphic to $LP^{-1,-}_{k,-1}(T_1, T_2)$, as a module over $s_2(k)$. Note that the remarks in the preceding paragraph correspond to some of those in Section 36.4 in this case.

If $d \leq -2$, so that $m = -d-2 \geq 0$, then we get a proper submodule $Z_{0,m}(\mu_0)$ of $Z_0(\mu_0)$, as a module over $sl_2(k)$, as in Section 34.2. One can verify that this corresponds to $LP^{d,-}_{k,d}(T_1, T_2)$ as a submodule of (36.8.3) under these conditions.

36.9 Some more submodules and quotients

Let k be a commutative ring with a multiplicative identity element, and let B be a Lie algebra over k. Also let V be a module over k that is a module over B, as a Lie algebra over k, and let W, Z be submodules of V, as a module over k and B. Thus $W + Z$ and $W \cap Z$ are submodules of V as well, as a module over k and B.

The quotients V/W, V/Z may be considered as modules over k and B too, as usual. The natural quotient mapping from V onto V/W maps Z and $W+Z$ onto $(W+Z)/W$, and the kernel of the restriction to Z of the quotient mapping is equal to $W \cap Z$. Thus $(W+Z)/W$ is isomorphic in a natural way to $Z/(W \cap Z)$, as a module over k and B. Similarly, $(W + Z)/Z$ is isomorphic to $W/(W \cap Z)$ in a natural way, as a module over k and B.

Of course,

$$(W/(W \cap Z)) \cap (Z/(W \cap Z)) = \{0\} \tag{36.9.1}$$

in $V/(W \cap Z)$. This implies that

$$(W + Z)/(W \cap Z) = (W/(W \cap Z)) + (Z/(W \cap Z)) \tag{36.9.2}$$

corresponds to the direct sum of $W/(W \cap Z)$ and $Z/(W \cap Z)$ in $V/(W \cap Z)$, as a module over k and B.

The natural quotient mapping from V onto $V/(W + Z)$ has kernel $W + Z$, which leads to natural homomorphisms from V/W and V/Z onto $V/(W + Z)$, as modules over k and B. The kernels of these homomorphisms are $(W+Z)/W$ and $(W + Z)/Z$, respectively. This leads to natural isomorphisms from

$$(V/W)/((W + Z)/W), \quad (V/Z)/((W + Z)/Z) \tag{36.9.3}$$

onto $V/(W + Z)$, as modules over k and B.

Let us now return to the same notation and hypotheses as in Section 36.7. Thus k is still a commutative ring with a multiplicative identity element, and A is a module over k. Suppose for the moment that $d \geq 0$, so that (36.7.7) holds. We may consider

$$LP_{A,d}(T_1, T_2)/A_d[T_1, T_2] \tag{36.9.4}$$

and

$$LS_{A,d}[T_1, T_2]/A_d[T_1, T_2] \tag{36.9.5}$$

as modules over $s_2(k)$, as a Lie algebra over k, because $A_d[T_1, T_2]$ is a submodule of $LP_{A,d}[T_1, T_2]$ and $LS_{A,d}(T_1, T_2)$, as modules over $s_2(k)$. Note that (36.9.4) may be considered as a submodule of (36.9.5), as a module over $s_2(k)$.

It is easy to see that

$$LP_{A,d}(T_1, T_2) = LP^{0,+}_{A,d}(T_1, T_2) + LP^{d,-}_{A,d}(T_1, T_2) \tag{36.9.6}$$

and

$$LS_{A,d}(T_1, T_2) = LS^{0,+}_{A,d}(T_1, T_2) + LS^{d,-}_{A,d}(T_1, T_2), \tag{36.9.7}$$

because $d \geq 0$. In fact, (36.9.4) corresponds to the direct sum of (36.7.10) and (36.7.11), as a module over $s_2(k)$. Similarly, (36.9.5) corresponds to the direct sum of (36.7.8) and (36.7.9), as a module over $s_2(k)$. This follows from the analogous statement for (36.9.2) mentioned earlier.

Suppose now that $d < 0$, so that (36.7.12) holds. We may consider

$$LP_{A,d}(T_1, T_2)/(LP^{0,+}_{A,d}(T_1, T_2) + LP^{d,-}_{A,d}(T_1, T_2)) \tag{36.9.8}$$

and

$$LS_{A,d}(T_1, T_2)/(LS^{0,+}_{A,d}(T_1, T_2) + LS^{d,-}_{A,d}(T_1, T_2)) \tag{36.9.9}$$

as modules over $s_2(k)$, as a Lie algebra over k. If $d = -1$, then (36.9.6) and (36.9.7) hold, and so (36.9.8) and (36.9.9) are equal to 0. Otherwise, we have that

$$LS_{A,d}(T_1, T_2) = LS^{0,+}_{A,d}(T_1, T_2) + LS^{d,-}_{A,d}(T_1, T_2) + LP_{A,d}(T_1, T_2). \tag{36.9.10}$$

This implies that (36.9.8) is isomorphic to (36.9.9), as modules over $s_2(k)$.

Under these conditions, (36.9.8) can be described as in (36.9.3). This means that (36.9.8) is isomorphic in a natural way to quotients of (36.7.5) and (36.7.6) by submodules corresponding to $LP^{0,+}_{A,d}(T_1, T_2)$ and $LP^{d,-}_{A,d}(T_1, T_2)$, respectively, as a module over $s_2(k)$.

36.10 Some additional submodules

Let k be a field of characteristic 0, and let us continue with the same notation and hypotheses as in Sections 36.1 and 36.2, with $A = k$. Put

$$f_0(T) = \exp(T_1^{-1}\, T_2) = \sum_{j=0}^{\infty} (1/j!)\, T_1^{-j}\, T_2^j, \tag{36.10.1}$$

which is an element of $LS_{k,0}(T_1, T_2)$, using the natural embedding of $\mathbf{Q}$ into k. More precisely, $f_0(T) \in LS^{0,-}_{k,0}(T_1, T_2)$, in the notation of Section 36.2.

It is easy to see that

$$\partial_1 f_0(T) = -T_1^{-2}\, T_2\, f_0(T) \tag{36.10.2}$$

and

$$\partial_2 f_0(T) = T_1^{-1}\, f_0(T). \tag{36.10.3}$$

This implies that

$$H(f_0(T)) = -2\, T_1^{-1}\, T_2\, f_0(T), \tag{36.10.4}$$

$$X(f_0(T)) = f_0(T), \tag{36.10.5}$$

$$Y(f_0(T)) = -T_1^{-2}\, T_2^2\, f_0(T). \tag{36.10.6}$$

Note that

$$H(T_1^{-m}\, T_2^m) = -2\, m\, T_1^{-m}\, T_2^m, \tag{36.10.7}$$

$$X(T_1^{-m}\, T_2^m) = m\, T_1^{1-m}\, T_2^{m-1}, \tag{36.10.8}$$

$$Y(T_1^{-m}\, T_2^m) = -m\, T_1^{-m-1}\, T_2^{m+1} \tag{36.10.9}$$

for every $m \in \mathbf{Z}$.

Put

$$f_m(T) = T_1^{-m}\, T_2^m\, f_0(T) \tag{36.10.10}$$

for every $m \in \mathbf{Z}$, which is the same as $f_0(T)$ when $m = 0$. By construction,

$$f_m(T) \in LS^{-m,-}_{k,0}(T_1, T_2) \tag{36.10.11}$$

for every $m \in \mathbf{Z}$, using the notation in Section 36.2 again. We also have that the coefficient of $T_1^{-m}\, T_2^m$ in $f_m(T)$ is equal to 1. One can check that the $f_m(T)$'s are linearly independent in $LS_{k,0}(T_1, T_2)$, using these two properties.

If $m \in \mathbf{Z}$, then

$$\begin{aligned} H(f_m(T)) &= H(T_1^{-m}\, T_2^m)\, f_0(T) + T_1^{-m}\, T_2^m\, H(f_0(T)) \\ &= -2\, m\, T_1^{-m}\, T_2^m\, f_0(T) + T_1^{-m}\, T_2^m\, (-2 T_1^{-1}\, T_2\, f_0(T)) \\ &= -2\, m\, f_m(T) - 2\, f_{m+1}(T). \end{aligned} \tag{36.10.12}$$

Similarly,

$$\begin{aligned} X(f_m(T)) &= X(T_1^{-m}\, T_2^m)\, f_0(T) + T_1^{-m}\, T_2^m\, X(f_0(T)) \\ &= m\, T_1^{1-m}\, T_2^{m-1}\, f_0(T) + T_1^{-m}\, T_2^m\, f_0(T) \\ &= m\, f_{m-1}(T) + f_m(T). \end{aligned} \tag{36.10.13}$$

In the same way,

$$\begin{aligned} Y(f_m(T)) &= Y(T_1^{-m}\, T_2^m)\, f_0(T) + T_1^{-m}\, T_2^m\, Y(f_0(T)) \\ &= -m\, T_1^{-m-1}\, T_2^{m+1}\, f_0(T) + T_1^{-m}\, T_2^m\, (-T_1^{-2}\, T_2^2\, f_0(T)) \\ &= -m\, f_{m+1}(T) - f_{m+2}(T). \end{aligned} \tag{36.10.14}$$

Let $E_k(T_1, T_2)$ be the linear span of the $f_m(T)$'s, $m \in \mathbf{Z}$, in $LS_{k,0}(T_1, T_2)$, as a vector space over k. This is a submodule of $LS_{k,0}(T_1, T_2)$, as a module over $s_2(k)$, as in the preceding paragraph.

Similarly, let $E_k^0(T_1, T_2)$ be the linear span of the $f_m(T)$'s, $m \geq 0$. It is easy to see that this is a submodule of $E_k(T_1, T_2)$, as a module over $s_2(k)$.

One can check that there is no nonzero eigenvector of H in $E_k(T_1, T_2)$, using (36.10.12) and the linear independence of the $f_m(T)$'s.

One can verify that $E_k^0(T_1, T_2)$ is irreducible as a module over $s_2(k)$. To see this, observe that

$$(X - I)(f_m(T)) = m\, f_{m-1}(T) \tag{36.10.15}$$

for every $m \in \mathbf{Z}$, where I is the identity mapping. This implies that every nonzero element of $E_k^0(T_1, T_2)$ is mapped to a nonzero multiple of $f_0(T)$ by a suitable power of $X - I$. It follows that any nonzero submodule of $E_k^0(T_1, T_2)$ contains $f_m(T)$ for every $m \geq 0$, because of (36.10.12).

This is related to part (c) of Exercise 2 on p111 of [14].

Chapter 37

Formal Laurent series, 3

37.1 Some commutativity conditions

Let k be a commutative ring with a multiplicative identity element, let m, n be positive integers, and let $T_1, \ldots, T_n$, $R_1, \ldots, R_m$, be $n + m$ commuting indeterminates. Also let A be a module over k, and let us use

$$f(T, R) = f(T_1, \ldots, T_n, R_1, \ldots, R_m) \tag{37.1.1}$$

to denote a formal Laurent series in $T_1, \ldots, T_n$, $R_1, \ldots, R_m$ with coefficients in A. The corresponding formal derivatives of $f(T, R)$ in T_j and R_l may be expressed as

$$\partial_{T_j} f(T, R) = \frac{\partial}{\partial T_j} f(T, R), \quad \partial_{R_l} f(T, R) = \frac{\partial}{\partial R_l} f(T, R), \tag{37.1.2}$$

respectively, for each $j = 1, \ldots, n$, $l = 1, \ldots, m$.

Let $\partial_{T_1}, \ldots, \partial_{T_n}$, $\partial_{R_1}, \ldots, \partial_{R_m}$ be $n + m$ commuting formal symbols, which may be used to represent partial derivatives in the T_j's and R_l's. Suppose that for each $j = 1, \ldots, n$ and $l = 1, \ldots, m$,

$$\zeta^{j,l}(T, R) = \zeta^{j,l}(T_1, \ldots, T_n, R_1, \ldots, R_m) \tag{37.1.3}$$

is a formal Laurent polynomial in $T_1, \ldots, T_n$, $R_1, \ldots, R_m$ with coefficients in k. Put

$$\delta_j = \partial_{T_j} + \sum_{l=1}^{m} \zeta^{j,l}(T, R)\, \partial_{R_l} \tag{37.1.4}$$

for each $j = 1, \ldots, n$. This is a formal first-order differential operator in $\partial_{T_1}, \ldots, \partial_{T_n}$, $\partial_{R_1}, \ldots, \partial_{R_m}$ with coefficients in

$$LS_k(T, R) = LP_k(T_1, \ldots, T_n, R_1, \ldots, R_m). \tag{37.1.5}$$

Let $1 \le j_1, j_2 \le n$ be given, and observe that

$$\delta_{j_1}\,\delta_{j_2} - \delta_{j_2}\,\delta_{j_1} = \sum_{l=1}^{m} (\delta_{j_1}(\zeta^{j_2,l}(T,R)) - \delta_{j_2}(\zeta^{j_1,l}(T,R)))\,\partial_{R_l}. \tag{37.1.6}$$

Thus

$$\delta_{j_1}\,\delta_{j_2} = \delta_{j_2}\,\delta_{j_1} \tag{37.1.7}$$

if and only if

$$\delta_{j_1}(\zeta^{j_2,l}(T,R)) = \delta_{j_2}(\zeta^{j_1,l}(T,R)) \tag{37.1.8}$$

for every $l = 1, \ldots, m$.

Let $f(T,R)$ be a formal Laurent series in $T_1, \ldots, T_n$, $R_1, \ldots, R_m$ with coefficients in A, and suppose that we were interested in substituting R_l with something that depends on $T_1, \ldots, T_n$, for each $l = 1, \ldots, m$. In order to differentiate the result in T_j for some $j = 1, \ldots, n$, we should differentiate f in T_j, and add to that the derivative of f in R_l times the derivative in T_j of the expression being substituted for R_l for each $l = 1, \ldots, m$. This corresponds to $\delta_j(f(T,R))$, where the derivative in T_j of the expression being substituted for R_l is given by $\zeta^{j,l}(T,R)$. The commutativity condition (37.1.7) says exactly that these total derivatives in T_{j_1} and T_{j_2} should commute. This holds exactly when the total derivatives in T_{j_1} and T_{j_2} of the expression being substituted for R_l commute for each $l = 1, \ldots, m$, as in (37.1.8).

Let us suppose for the rest of the section that (37.1.8) holds for every $j_1, j_2 = 1, \ldots, n$ and $l = 1, \ldots, m$. Of course, we may identify $LS_A(T_1, \ldots, T_n)$ with a submodule of

$$LS_A(T,R) = LS_A(T_1, \ldots, T_n, R_1, \ldots, R_m), \tag{37.1.9}$$

as a module over k, in the obvious way. The restriction of the mapping on $LS_A(T,R)$ determined by δ_j to $LS_A(T_1, \ldots, T_n)$ is the same as ∂_{T_j} for each $j = 1, \ldots, n$, by construction. If $\alpha = (\alpha_1, \ldots, \alpha_n)$ is a multi-index of length n, then let

$$\delta^\alpha = \delta_1^{\alpha_1} \cdots \delta_n^{\alpha_n} \tag{37.1.10}$$

be the corresponding product of the δ_j's. This is a formal differential operator in $\partial_{T_1}, \ldots, \partial_{T_n}$, $\partial_{R_1}, \ldots, \partial_{R_m}$ with coefficients in $LP_k(T,R)$.

Let β be a multi-index of length n, and let $b^\beta(T,R)$ be a formal Laurent polynomial in $T_1, \ldots, T_n$, $R_1, \ldots, R_m$ with coefficients in k. If $1 \le j \le n$, then

$$\delta_j\,(b^\beta(T,R)\,\delta^\beta) = (\delta_j(b^\beta(T,R)))\,\delta^\beta + b^\beta(T,R)\,\delta_j\,\delta^\beta, \tag{37.1.11}$$

as a formal differential operator in $\partial_{T_1}, \ldots, \partial_{T_n}$, $\partial_{R_1}, \ldots, \partial_{R_n}$ with coefficients in $LP_k(T,R)$. If $b^\beta(T)$ is a formal Laurent polynomial in $T_1, \ldots, T_n$ with coefficients in k, then we get that

$$\delta_j\,(b^\beta(T)\,\delta^\beta) = (\partial_{T_j}(b^\beta(T)))\,\delta^\beta + b^\beta(T)\,\delta_j\,\delta^\beta. \tag{37.1.12}$$

Let $a(T) = (a^1(T), \ldots, a^n(T))$ be an n-tuple of formal Laurent polynomials in $T_1, \ldots, T_n$ with coefficients in k, and put

$$\widetilde{D}_{a(T)} = \sum_{j=1}^{n} a^j(T)\, \delta_j. \tag{37.1.13}$$

This is a formal first-order differential operator in $\partial_{T_1}, \ldots, \partial_{T_n}$, $\partial_{R_1}, \ldots, \partial_{R_n}$ with coefficients in $LP_k(T, R)$. If $b(T) = (b^1(T), \ldots, b^n(T))$ is another n-tuple of formal Laurent polynomials in $T_1, \ldots, T_n$ with coefficients in k, then

$$\begin{aligned}(37.1.14)\qquad & \widetilde{D}_{a(T)}\, \widetilde{D}_{b(T)} - \widetilde{D}_{b(T)}\, \widetilde{D}_{a(T)} \\ &= \sum_{j=1}^{n} \sum_{r=1}^{n} (a^j(T)\, \partial_{T_j} b^r(T) - b^j(T)\, \partial_{T_j} a^r(T))\, \delta_r,\end{aligned}$$

as in Section 35.7. Put

$$c^r(T) = \sum_{j=1}^{n} (a^j(T)\, \partial_{T_j} b^r(T) - b^j(T)\, \partial_{T_j} a^r(T)) \tag{37.1.15}$$

for each $r = 1, \ldots, n$, which defines a formal Laurent polynomial in $T_1, \ldots, T_n$ with coefficients in k, as before. Thus

$$\widetilde{D}_{a(T)}\, \widetilde{D}_{b(T)} - \widetilde{D}_{b(T)}\, \widetilde{D}_{a(T)} = \widetilde{D}_{c(T)}, \tag{37.1.16}$$

where $c(T) = (c^1(T), \ldots, c^n(T))$.

Put

$$\widetilde{g}_n(k) = \{\widetilde{D}_{a(T)} : a(T) \in (k_1[T_1, \ldots, T_n])^n\}, \tag{37.1.17}$$

which is a Lie subalgebra of the algebra of formal differential operators in $\partial_{T_1}, \ldots, \partial_{T_n}$, $\partial_{R_1}, \ldots, \partial_{R_n}$ with coefficients in $LP_k(T, R)$. Remember that if $a(T) \in (k_1[T_1, \ldots, T_n])^n$, then $a^j(T)$ can be expressed as $\sum_{r=1}^{n} a_r^j\, T_r$ for each $j = 1, \ldots, n$, where $a_r^j \in k$ for every $j, r = 1, \ldots, n$. Put

$$\widetilde{s}_n(k) = \left\{\widetilde{D}_{a(T)} : a(T) \in (k_1[T_1, \ldots, T_n])^n,\ \sum_{j=1}^{n} a_j^j = 0\right\}, \tag{37.1.18}$$

which is a Lie subalgebra of $\widetilde{g}_n(k)$. As in Section 5.15, $\widetilde{g}_n(k)$ is isomorphic to $gl_n(k)$ as a Lie algebra over k, and $\widetilde{s}_n(k)$ corresponds to $sl_n(k)$ under this isomorphism. In particular,

$$[\widetilde{g}_n(k), \widetilde{g}_n(k)] \subseteq \widetilde{s}_n(k), \tag{37.1.19}$$

as before.

37.2 Simpler coefficients

Let us continue with the same notation and hypotheses as in the previous section. Suppose now that $\theta^{j,l}(T)$ is a formal Laurent polynomial in $T_1, \ldots, T_n$ with coefficients in k for each $j = 1, \ldots, n$ and $l = 1, \ldots, m$. We would like to consider the remarks in the previous section with

$$\zeta^{j,l}(T, R) = \theta^{j,l}(T)\, R_l \tag{37.2.1}$$

for every $j = 1, \ldots, n$ and $l = 1, \ldots, m$. Thus we take

$$\delta_j = \partial_{T_j} + \sum_{l=1}^{m} \theta^{j,l}(T)\, R_l\, \partial_{R_l} \tag{37.2.2}$$

for each $j = 1, \ldots, n$. We also ask that

$$\delta_{j_1}(\theta^{j_2,l}(T)\, R_l) = \delta_{j_2}(\theta^{j_1,l}(T)\, R_l) \tag{37.2.3}$$

for every $j_1, j_2 = 1, \ldots, n$ and $l = 1, \ldots, m$, as in (37.1.8). In this case, this reduces to asking that

$$\partial_{T_{j_1}} \theta^{j_2,l}(T) = \partial_{T_{j_2}} \theta^{j_1,l}(T) \tag{37.2.4}$$

for every $j_1, j_2 = 1, \ldots, n$ and $l = 1, \ldots, m$. This means that δ_{j_1} commutes with δ_{j_2}, as before.

Let $\gamma \in \mathbf{Z}^m$ be given, so that R^γ is defined as a formal Laurent monomial in $R_1, \ldots, R_m$. Note that

$$LS_A(T_1, \ldots, T_n)\, R^\gamma = \{f(T)\, R^\gamma : f(T) \in LS_A(T_1, \ldots, T_n)\} \tag{37.2.5}$$

is a submodule of $LS_A(T, R)$, as a module over k. More precisely, this is a submodule of $LS_A(T, R)$, as a module over $LP_k(T_1, \ldots, T_n)$. It is easy to see that

$$\delta_j(LS_A(T_1, \ldots, T_n)\, R^\gamma) \subseteq LS_A(T_1, \ldots, T_n)\, R^\gamma \tag{37.2.6}$$

for every $j = 1, \ldots, n$. Similarly,

$$LP_A(T_1, \ldots, T_n)\, R^\gamma = \{f(T)\, R^\gamma : f(T) \in LP_A(T_1, \ldots, T_n)\} \tag{37.2.7}$$

is a submodule of $LP_A(T, R)$, as a module over k, and over $LP_k(T_1, \ldots, T_n)$. We also have that

$$\delta_j(LP_A(T_1, \ldots, T_n)\, R^\gamma) \subseteq LP_A(T_1, \ldots, T_n)\, R^\gamma \tag{37.2.8}$$

for every $j = 1, \ldots, n$. If $a(T) = (a^1(T), \ldots, a^n(T))$ is an n-tuple of elements of $LP_k(T_1, \ldots, T_n)$, and $\widetilde{D}_{a(T)}$ is as in (37.1.13), then we get that

$$\widetilde{D}_{a(T)}(LS_A(T_1, \ldots, T_n)\, R^\gamma) \subseteq LS_A(T_1, \ldots, T_n)\, R^\gamma \tag{37.2.9}$$

and

$$\widetilde{D}_{a(T)}(LP_A(T_1,\ldots,T_n)\,R^\gamma) \subseteq LP_A(T_1,\ldots,T_n)\,R^\gamma. \tag{37.2.10}$$

Suppose that

$$\theta^{j,l}(T) \in LP_{k,-1}(T_1,\ldots,T_n) \tag{37.2.11}$$

for every $j = 1,\ldots,n$ and $l = 1,\ldots,m$, in the notation of Section 35.8. One can check that

$$\delta_j(LS_{A,d}(T_1,\ldots,T_n)\,R^\gamma) \subseteq LS_{A,d-1}(T_1,\ldots,T_n)\,R^\gamma \tag{37.2.12}$$

for every $j = 1,\ldots,n$ and $d \in \mathbf{Z}$. Similarly,

$$\delta_j(LP_{A,d}(T_1,\ldots,T_n)\,R^\gamma) \subseteq LP_{A,d-1}(T_1,\ldots,T_n)\,R^\gamma \tag{37.2.13}$$

for every $j = 1,\ldots,n$ and $d \in \mathbf{Z}$. If $d(a(T)) \in \mathbf{Z}$ and

$$a^j(T) \in LP_{k,d(a(T))}(T_1,\ldots,T_n) \tag{37.2.14}$$

for every $j = 1,\ldots,n$, then it follows that

$$\widetilde{D}_{a(T)}(LS_{A,d}(T_1,\ldots,T_n)\,R^\gamma) \subseteq LS_{A,d(a(T))+d-1}(T_1,\ldots,T_n)\,R^\gamma \tag{37.2.15}$$

and

$$\widetilde{D}_{a(T)}(LP_{A,d}(T_1,\ldots,T_n)\,R^\gamma) \subseteq LP_{A,d(a(T))+d-1}(T_1,\ldots,T_n)\,R^\gamma \tag{37.2.16}$$

for every $d \in \mathbf{Z}$. In particular, if $d(a(T)) = 1$, then

$$\widetilde{D}_{a(T)}(LS_{A,d}(T_1,\ldots,T_n)\,R^\gamma) \subseteq LS_{A,d}(T_1,\ldots,T_n)\,R^\gamma \tag{37.2.17}$$

and

$$\widetilde{D}_{a(T)}(LP_{A,d}(T_1,\ldots,T_n)\,R^\gamma) \subseteq LP_{A,d}(T_1,\ldots,T_n)\,R^\gamma \tag{37.2.18}$$

for every $d \in \mathbf{Z}$.

Suppose for the moment that δ_j is as in the previous section again, where the coefficients satisfy (37.1.8), as before. Under these conditions,

(37.2.19) we may consider $LS_A(T,R)$ as a module over $\widetilde{g}_n(k)$ or $\widetilde{s}_n(k)$,

as Lie algebras over k, and

(37.2.20) $LP_A(T,R)$ is a submodule of $LS_A(T,R)$,

as a module over $\widetilde{g}_n(k)$ or $\widetilde{s}_n(k)$. Note that

(37.2.21) $LS_A(T_1,\ldots,T_n)$ is a submodule of $LS_A(T,R)$

and

(37.2.22) $LP_A(T_1,\ldots,T_n)$ is a submodule of $LP_A(T,R)$, as modules over $\widetilde{g}_n(k)$ or $\widetilde{s}_n(k)$. The actions of $\widetilde{g}_n(k)$, $\widetilde{s}_n(k)$ on $LS_A(T_1, \ldots, T_n)$ correspond exactly to the actions of $g_n(k)$, $s_n(k)$, respectively, as in Section 35.10, in a natural way, by construction.

With δ_j as in (37.2.2), we get that

(37.2.23) $LS_A(T_1, \ldots, T_n)\, R^\gamma$ is a submodule of $LS_A(T, R)$

and

(37.2.24) $LP_A(T_1, \ldots, T_n)\, R^\gamma$ is a submodule of $LP_A(T, R)$,

as modules over $\widetilde{g}_n(k)$ or $\widetilde{s}_n(k)$. Of course, these reduce to (37.2.21) and (37.2.22), respectively, when $\gamma = 0$. If (37.2.11) holds, then we obtain that

(37.2.25) $LS_{A,d}(T_1, \ldots, T_n)\, R^\gamma$ is a submodule of $LS_A(T_1, \ldots, T_n)\, R^\gamma$

and

(37.2.26) $LP_{A,d}(T_1, \ldots, T_n)\, R^\gamma$ is a submodule of $LP_A(T_1, \ldots, T_n)\, R^\gamma$

for every $d \in \mathbf{Z}$, as modules over $\widetilde{g}_n(k)$ or $\widetilde{s}_n(k)$.

37.3 Some actions on $LS_A(T_1, T_2, R)$

Let k be a commutative ring with a multiplicative identity element, let A be a module over k, and let T_1, T_2, and R be commuting indeterminates. We would like to consider formal Laurent polynomials and series in T_1, T_2, and R with coefficients in k or A, as in the previous two sections, with $n = 2$ and $m = 1$. If $f(T_1, T_2, R)$ is a formal Laurent series in T_1, T_2, R with coefficients in A, then its formal derivatives in T_1, T_2, and R may be expressed as $\partial_{T_j} f(T_1, T_2, R) = \frac{\partial}{\partial T_j} f(T_1, T_2, R)$, $j = 1, 2$, and $\partial_R f(T_1, T_2, R) = \frac{\partial}{\partial R} f(T_1, T_2, R)$, as before.

Let ∂_{T_1}, ∂_{T_2}, and ∂_R be commuting formal symbols, which may be used to represent partial derivatives in T_1, T_2, and R, respectively, as usual. Let $\nu_0 \in k$ be given, and put

$$\delta_1 = \partial_{T_1} + \nu_0\, T_1^{-1}\, R\, \partial_R, \quad \delta_2 = \partial_{T_2}. \tag{37.3.1}$$

Note that δ_1 and δ_2 commute, as formal differential operators in ∂_{T_1}, ∂_{T_2}, and ∂_R with coefficients in $LP_k(T_1, T_2, R)$.

If $f(T_1, T_2, R) \in LS_A(T_1, T_2, R)$, then we may be interested in trying to substitute R with something that depends on T_1 and T_2, as in Section 37.1. The derivative of the result in T_j, $j = 1, 2$, should include the derivative of f in R times the derivitive in T_j of the expression being substituted for R, as before. Here we think of substituting R with an expression whose derivative in T_1 is $\nu_0\, T_1^{-1}\, R$, and whose derivative in T_2 is equal to 0. In effect, we may think of substituting R with T_1 to the power ν_0, formally.

Note that δ_1, δ_2 satisfy the conditions mentioned at the beginning of the previous section. As in Section 37.1, we may identify $LS_A(T_1, T_2)$ with a submodule of $LS_A(T_1, T_2, R)$, as a module over k, in the obvious way. If $\gamma \in \mathbf{Z}$, then

$$LS_A(T_1, T_2)\, R^\gamma = \{f(T_1, T_2)\, R^\gamma : f(T_1, T_2) \in LS_A(T_1, T_2)\} \tag{37.3.2}$$

is a submodule of $LS_A(T_1, T_2, R)$ too, as a module over k. In fact, this is a submodule of $LS_A(T_1, T_2, R)$, as a module over $LP_k(T_1, T_2)$, as before. Similarly,

$$LP_A(T_1, T_2)\, R^\gamma = \{f(T_1, T_2)\, R^\gamma : f(T_1, T_2) \in LP_A(T_1, T_2)\} \tag{37.3.3}$$

is a submodule of $LP_A(T_1, T_2, R)$, as a module over k, and over $LP_k(T_1, T_2)$.

It is easy to see that

$$\delta_j(LS_A(T_1, T_2)\, R^\gamma) \subseteq LS_A(T_1, T_2)\, R^\gamma \tag{37.3.4}$$

for $j = 1, 2$, as in the previous section. Similarly,

$$\delta_j(LP_A(T_1, T_2)\, R^\gamma) \subseteq LP_A(T_1, T_2)\, R^\gamma \tag{37.3.5}$$

for $j = 1, 2$. If $a(T) = (a^1(T), a^2(T))$ is an ordered pair of elements of formal Laurent polynomials in T_1, T_2 with coefficients in k, then put

$$\widetilde{D}_{a(T)} = a^1(T)\, \delta_1 + a^2(T)\, \delta_2, \tag{37.3.6}$$

as in Section 37.1. Under these conditions,

$$\widetilde{D}_{a(T)}(LS_A(T_1, T_2)\, R^\gamma) \subseteq LS_A(T_1, T_2)\, R^\gamma \tag{37.3.7}$$

and

$$\widetilde{D}_{a(T)}(LP_A(T_1, T_2)\, R^\gamma) \subseteq LP_A(T_1, T_2)\, R^\gamma. \tag{37.3.8}$$

More precisely, if $d \in \mathbf{Z}$, then

$$\delta_j(LS_{A,d}(T_1, T_2)\, R^\gamma) \subseteq LS_{A,d-1}(T_1, T_2)\, R^\gamma \tag{37.3.9}$$

for $j = 1, 2$, using the notation in Section 35.8. Similarly,

$$\delta_j(LP_{A,d}(T_1, T_2)\, R^\gamma) \subseteq LP_{A,d-1}(T_1, T_2)\, R^\gamma \tag{37.3.10}$$

for $j = 1, 2$, as in the previous section. In these inclusions, we use the same type of notation as in (37.3.2) and (37.3.3). If $d(a(T)) \in \mathbf{Z}$ and

$$a^j(T) \in LP_{k,d(a(T))}(T_1, T_2) \tag{37.3.11}$$

for $j = 1, 2$, then we get that

$$\widetilde{D}_{a(T)}(LS_{A,d}(T_1, T_2)\, R^\gamma) \subseteq LS_{A,d(a(T))+d-1}(T_1, T_2)\, R^\gamma \tag{37.3.12}$$

and

$$\widetilde{D}_{a(T)}(LP_{A,d}(T_1, T_2)\, R^\gamma) \subseteq LP_{A,d(a(T))+d-1}(T_1, T_2)\, R^\gamma, \tag{37.3.13}$$

as before.

Remember that

$$\widetilde{g}_2(k) = \{\widetilde{D}_{a(T)} : a(T) \in (k_1[T_1, T_2])^2\}, \tag{37.3.14}$$

as in Section 37.1. If $a(T) \in (k_1[T_1, T_2])^2$, then $a^j(T)$ can be expressed as $a_1^j\, T_1 + a_2^j\, T_2$ for $j = 1, 2$, where $a_l^j \in k$ for $j, l = 1, 2$, and

$$\widetilde{s}_2(k) = \{\widetilde{D}_{a(T)} : a(T) \in (k_1[T_1, T_2])^2, a_1^1 + a_2^2 = 0\}, \tag{37.3.15}$$

as before. As in the previous section,

(37.3.16) we may consider $LS_A(T_1, T_2, R)$ as a module over $\widetilde{g}_2(k)$ or $\widetilde{s}_2(k)$,

as Lie algebras over k, and

(37.3.17) $LP_A(T_1, T_2, R)$ is a submodule of $LS_A(T_1, T_2, R)$,

as a module over $\widetilde{g}_2(k)$ or $\widetilde{s}_2(k)$. We also have that

(37.3.18) $LS_A(T_1, T_2)\, R^\gamma$ is a submodule of $LS_A(T_1, T_2, R)$

and

(37.3.19) $LP_A(T_1, T_2)\, R^\gamma$ is a submodule of $LP_A(T_1, T_2, R)$,

as modules over $\widetilde{g}_2(k)$ or $\widetilde{s}_2(k)$. If $d \in \mathbf{Z}$, then

(37.3.20) $LS_{A,d}(T_1, T_2)\, R^\gamma$ is a submodule of $LS_A(T_1, T_2)\, R^\gamma$

and

(37.3.21) $LP_{A,d}(T_1, T_2)\, R^\gamma$ is a submodule of $LP_A(T_1, T_2)\, R^\gamma$,

as modules over $\widetilde{g}_2(k)$ and $\widetilde{s}_2(k)$.

37.4 The action of $\widetilde{s}_2(k)$

Let us continue with the same notation and hypotheses as in the previous section. Put

$$\widetilde{H} = T_1\, \delta_1 - T_2\, \delta_2 = T_1 \partial_{T_1} + \nu_0\, R\, \partial_R - T_2\, \partial_{T_2}, \tag{37.4.1}$$

$$\widetilde{X} = T_1\, \delta_2 = T_1\, \partial_{T_2}, \tag{37.4.2}$$

$$\widetilde{Y} = T_2\, \delta_1 = T_2\, \partial_{T_1} + \nu_0\, T_1^{-1}\, T_2\, R\, \partial_R, \tag{37.4.3}$$

which are formal differential operators in ∂_{T_1}, ∂_{T_2}, and ∂_R with coefficients in $LP_{k,1}(T_1, T_2, R)$, in the notation of Section 35.8. Note that

$$\widetilde{H}, \widetilde{X}, \widetilde{Y} \in \widetilde{s}_2(k), \tag{37.4.4}$$

and that $\widetilde{s}_2(k)$ is freely generated by $\widetilde{H}$, $\widetilde{X}$, and $\widetilde{Y}$, as a module over k.

Remember that $\widetilde{s}_2(k)$ is a Lie subalgebra of $\widetilde{g}_2(k)$, as a Lie algebra over k, as in Section 37.1. One can check that

$$[\widetilde{X}, \widetilde{Y}] = \widetilde{H}, \tag{37.4.5}$$

$$[\widetilde{H}, \widetilde{X}] = 2 \cdot \widetilde{X}, \tag{37.4.6}$$

$$[\widetilde{H}, \widetilde{Y}] = -2 \cdot \widetilde{Y}. \tag{37.4.7}$$

This shows that $\widetilde{s}_2(k)$ is isomorphic to $sl_2(k)$ as a Lie algebra over k, where $\widetilde{H}$, $\widetilde{X}$, and $\widetilde{Y}$ correspond to the usual elements h, x, and y of $sl_2(k)$ as in Section 34.1, respectively. This is basically the same as in Section 36.1 when $\nu_0 = 0$.

As in the previous section, we may consider $LS_A(T_1, T_2, R)$ as a module over $\widetilde{s}_2(k)$, as a Lie algebra over k. Thus $LS_A(T_1, T_2, R)$ may be considered as a module over $sl_2(k)$, as a Lie algebra over k, using the isomorphism mentioned in the preceding paragraph. This means that the actions of h, x, and y on $LS_A(T_1, T_2, R)$ are given by $\widetilde{H}$, $\widetilde{X}$, and $\widetilde{Y}$, respectively. Note that $LS_A(T_1, T_2)$ is a submodule of $LS_A(T_1, T_2, R)$, as a module over $\widetilde{s}_2(k)$ or $sl_2(k)$. More precisely, the actions of $\widetilde{H}$, $\widetilde{X}$, and $\widetilde{Y}$ on $LS_A(T_1, T_2)$, as a submodule of $LS_A(T_1, T_2, R)$, as a module over k, are the same as the actions of H, X, and Y from Section 36.1, respectively.

Remember that $LP_A(T_1, T_2, R)$ is a submodule of $LS_A(T_1, T_2, R)$, as a module over $\widetilde{s}_2(k)$, or equivalently $sl_2(k)$. Let γ and d be integers, as in the previous section, so that $LS_{A,d}(T_1, T_2)\, R^\gamma$ is a submodule of $LS_A(T_1, T_2, R)$, as a module over $\widetilde{s}_2(k)$ or $sl_2(k)$. Similarly, $LP_{A,d}(T_1, T_2)\, R^\gamma$ is a submodule of $LP_A(T_1, T_2, R)$, as a module over $\widetilde{s}_2(k)$ or $sl_2(k)$.

Let $f(T_1, T_2) = \sum_{j=-\infty}^{\infty} f_j\, T_1^j\, T_2^{d-j} \in LS_A(T_1, T_2)$ be given, so that

$$f(T_1, T_2)\, R^\gamma = \sum_{j=-\infty}^{\infty} f_j\, T_1^j\, T_2^{d-j}\, R^\gamma \tag{37.4.8}$$

is an element of $LS_{A,d}(T_1, T_2)\, R^\gamma$. Thus $f_j \in A$ for every j, and $f(T_1, T_2)$ is an element of $LP_A(T_1, T_2)$ exactly when $f_j = 0$ for all but finitely many j. It is easy to see that

$$\begin{aligned} \widetilde{H}(f(T_1, T_2)\, R^\gamma) &= \sum_{j=-\infty}^{\infty} (j + \nu_0\, \gamma - (d-j)) \cdot f_j\, T_1^j\, T_2^{d-j}\, R^\gamma \\ &= \sum_{j=-\infty}^{\infty} (2\, j - d + \nu_0\, \gamma) \cdot f_j\, T_1^j\, T_2^{d-j}\, R^\gamma. \end{aligned} \tag{37.4.9}$$

Here we are implicitly using the natural ring homomorphism from $\mathbf{Z}$ into k, which sends an integer to the corresponding multiple of the multiplicative identity element in k. Similarly,

$$\begin{aligned} \widetilde{X}(f(T_1, T_2)\, R^\gamma) &= \sum_{j=-\infty}^{\infty} (d-j) \cdot f_j\, T_1^{j+1}\, T_2^{d-j-1}\, R^\gamma \\ &= \sum_{j=-\infty}^{\infty} (d-j+1) \cdot f_{j-1}\, T_1^j\, T_2^{d-j}\, R^\gamma \end{aligned} \tag{37.4.10}$$

and

$$\widetilde{Y}(f(T_1, T_2)\, R^\gamma) = \sum_{j=-\infty}^{\infty} (j + \nu_0\, \gamma) \cdot f_j\, T_1^{j-1}\, T_2^{d-j+1}\, R^\gamma$$

$$= \sum_{j=-\infty}^{\infty} (j + 1 + \nu_0\, \gamma) \cdot f_{j+1}\, T_1^j\, T_2^{d-j}\, R^\gamma. \tag{37.4.11}$$

Note that these expressions correspond to those in Section 36.1 when $\gamma = 0$, and when $\nu_0 = 0$.

37.5 Some submodules of $LS_{A,d}(T_1, T_2)\, R^\gamma$

We continue with the same notation and hypotheses as in the previous two sections. In particular, if $f(T_1, T_2) \in LS_{A,d}(T_1, T_2)$ and $j \in \mathbf{Z}$, then

$$f_j \text{ denotes the coefficient in } A \text{ of } T_1^j\, T_2^{d-j} \text{ in } f(T_1, T_2), \tag{37.5.1}$$

as before.

If $l \in \mathbf{Z}$, then $LS^{l,+}_{A,d}(T_1, T_2)$ is the space of $f(T_1, T_2) \in LS_{A,d}(T_1, T_2)$ such that $f_j = 0$ for every $j > l$, as in Section 36.2. Similarly, $LS^{l,-}_{A,d}(T_1, T_2)$ is the space of $f(T_1, T_2) \in LS_{A,d}(T_1, T_2)$ such that $f_j = 0$ for every $j > l$, as before. Of course, these ars submodules of $LS_{A,d}(T_1, T_2)$, as a module over k. Remember that $LP^{l,+}_{A,d}(T_1, T_2)$ and $LP^{l,-}_{A,d}(T_1, T_2)$ are defined to be the intersections of $LS^{l,+}_{A,d}(T_1, T_2)$ and $LS^{l,-}_{A,d}(T_1, T_2)$ with $LP_{A,d}(T_1, T_2)$, respectively. These are submodules of $LP_{A,d}(T_1, T_2)$, as a module over k.

Thus

$$LS^{l,+}_{A,d}(T_1, T_2)\, R^\gamma, \quad LS^{l,-}_{A,d}(T_1, T_2)\, R^\gamma \tag{37.5.2}$$

are submodules of $LS_{A,d}(T_1, T_2)\, R^\gamma$, as a module over k, using the same type of notation for the former as before. More precisely, $LS_{A,d}(T_1, T_2)\, R^\gamma$ corresponds to the direct sum of these two submodules, as a module over k. Similarly,

$$LP^{l,+}_{A,d}(T_1, T_2)\, R^\gamma, \quad LP^{l,-}_{A,d}(T_1, T_2)\, R^\gamma \tag{37.5.3}$$

are submodules of $LP_{A,d}(T_1, T_2)\, R^\gamma$, as a module over k, and $LP_{A,d}(T_1, T_2)\, R^\gamma$ corresponds to the direct sum of these two submodules.

If $r \in \mathbf{Z}$ and $l \le r$, then

$$LS^{r,+}_{A,d}(T_1, T_2)\, R^\gamma \subseteq LS^{l,+}_{A,d}(T_1, T_2)\, R^\gamma, \tag{37.5.4}$$

$$LS^{l,-}_{A,d}(T_1, T_2)\, R^\gamma \subseteq LS^{r,-}_{A,d}(T_1, T_2)\, R^\gamma, \tag{37.5.5}$$

as in Section 36.2. Similarly,

$$LP^{r,+}_{A,d}(T_1, T_2)\, R^\gamma \subseteq LP^{l,+}_{A,d}(T_1, T_2)\, T^\gamma, \tag{37.5.6}$$

$$LP^{l,-}_{A,d}(T_1, T_2)\, R^\gamma \subseteq LP^{r,-}_{A,d}(T_1, T_2)\, R^\gamma. \tag{37.5.7}$$

It is easy to see that

$$\widetilde{H}(LS^{l,+}_{A,d}(T_1, T_2)\, R^\gamma) \subseteq LS^{l,+}_{A,d}(T_1, T_2)\, R^\gamma, \tag{37.5.8}$$

$$\widetilde{H}(LS^{l,-}_{A,d}(T_1, T_2)\, R^\gamma) \subseteq LS^{l,-}_{A,d}(T_1, T_2)\, R^\gamma \tag{37.5.9}$$

for every $l \in \mathbf{Z}$, using (37.4.9). Similarly,

$$\widetilde{H}(LP^{l,+}_{A,d}(T_1, T_2)\, R^\gamma) \subseteq LP^{l,+}_{A,d}(T_1, T_2)\, R^\gamma, \tag{37.5.10}$$

$$\widetilde{H}(LP^{l,-}_{A,d}(T_1, T_2)\, R^\gamma) \subseteq LP^{l,-}_{A,d}(T_1, T_2)\, R^\gamma \tag{37.5.11}$$

for every $l \in \mathbf{Z}$.

One can verify that

$$\widetilde{X}(LS^{l,+}_{A,d}(T_1, T_2)\, R^\gamma) \subseteq LS^{l+1,+}_{A,d}(T_1, T_2)\, R^\gamma, \tag{37.5.12}$$

$$\widetilde{X}(LS^{l,-}_{A,d}(T_1, T_2)\, R^\gamma) \subseteq LS^{l+1,-}_{A,d}(T_1, T_2)\, R^\gamma \tag{37.5.13}$$

for every $l \in \mathbf{Z}$, using (37.4.10). Similarly,

$$\widetilde{X}(LP^{l,+}_{A,d}(T_1, T_2)\, R^\gamma) \subseteq LP^{l+1,+}_{A,d}(T_1, T_2)\, R^\gamma, \tag{37.5.14}$$

$$\widetilde{X}(LP^{l,-}_{A,d}(T_1, T_2)\, R^\gamma) \subseteq LP^{l+1,-}_{A,d}(T_1, T_2)\, R^\gamma \tag{37.5.15}$$

for each $l \in \mathbf{Z}$.

One can also verify that

$$\widetilde{Y}(LS^{l,+}_{A,d}(T_1, T_2)\, R^\gamma) \subseteq LS^{l-1,+}_{A,d}(T_1, T_2)\, R^\gamma, \tag{37.5.16}$$

$$\widetilde{Y}(LS^{l,-}_{A,d}(T_1, T_2)\, R^\gamma) \subseteq LS^{l-1,-}_{A,d}(T_1, T_2)\, R^\gamma \tag{37.5.17}$$

for every $l \in \mathbf{Z}$, using (37.4.11). Similarly,

$$\widetilde{Y}(LP^{l,+}_{A,d}(T_1, T_2)\, R^\gamma) \subseteq LP^{l-1,+}_{A,d}(T_1, T_2)\, R^\gamma, \tag{37.5.18}$$

$$\widetilde{Y}(LP^{l,-}_{A,d}(T_1, T_2)\, R^\gamma) \subseteq LP^{l-1,-}_{A,d}(T_1, T_2)\, R^\gamma \tag{37.5.19}$$

for each $l \in \mathbf{Z}$. Of course, these inclusions are analogous to those in Section 36.2.

37.6 Submodules over $\widetilde{s}_2(k)$

Let us continue with the same notation and hypotheses as in the previous three sections. If $l = d$, then we can improve (37.5.13) and (37.5.15), as in Section 36.3. Indeed, one can check that

$$\widetilde{X}(LS^{d,-}_{A,d}(T_1, T_2)\, R^\gamma) \subseteq LS^{d,-}_{A,d}(T_1, T_2)\, R^\gamma, \tag{37.6.1}$$

$$\widetilde{X}(LP^{d,-}_{A,d}(T_1, T_2)\, R^\gamma) \subseteq LP^{d,-}_{A,d}(T_1, T_2)\, R^\gamma, \tag{37.6.2}$$

using (37.4.10). It follows that

(37.6.3) $LS^{d,-}_{A,d}(T_1, T_2)\, R^\gamma$ is a submodule of $LS_{A,d}(T_1, T_2)\, R^\gamma$, as a module over $\widetilde{s}_2(k)$, by (37.5.9), (37.6.1), and (37.5.17). Similarly,

$$LP^{d,-}_{A,d}(T_1, T_2)\, R^\gamma \text{ is a submodule of } LP_{A,d}(T_1, T_2)\, R^\gamma, \text{ as a module over } \widetilde{s}_2(k), \tag{37.6.4}$$

by (37.5.11), (37.6.2), and (37.5.19).

Suppose that there is an integer m such that

$$m \cdot 1 + \gamma \cdot \nu_0 = 0 \tag{37.6.5}$$

in k. In particular, this holds with $m = 0$ when $\gamma = 0$ or $\nu_0 = 0$. Under these conditions, we can improve (37.5.16) and (37.5.18) when $l = m$, as in Section 36.3. More precisely, one can check that

$$\widetilde{Y}(LS^{m,+}_{A,d}(T_1, T_2)\, R^\gamma) \subseteq LS^{m,+}_{A,d}(T_1, T_2)\, R^\gamma, \tag{37.6.6}$$

$$\widetilde{Y}(LP^{m,+}_{A,d}(T_1, T_2)\, R^\gamma) \subseteq LP^{m,+}_{A,d}(T_1, T_2)\, R^\gamma, \tag{37.6.7}$$

using (37.4.11).

In this case, we get that

$$LS^{m,+}_{A,d}(T_1, T_2)\, R^\gamma \text{ is a submodule of } LS_{A,d}(T_1, T_2)\, R^\gamma, \text{ as a module over } \widetilde{s}_2(k), \tag{37.6.8}$$

by (37.5.8), (37.5.12), and (37.6.6). Similarly,

$$LP^{m,+}_{A,d}(T_1, T_2)\, R^\gamma \text{ is a submodule of } LP_{A,d}(T_1, T_2)\, R^\gamma, \text{ as a module over } \widetilde{s}_2(k), \tag{37.6.9}$$

by (37.5.10), (37.5.14), and (37.6.7).

Consider the mapping from $LS_{A,d}(T_1, T_2)\, R^\gamma$ into $LS_{A,d-m}(T_1, T_2)$ with

$$f(T_1, T_2)\, R^\gamma \mapsto f(T_1, T_2)\, T_1^{-m} \tag{37.6.10}$$

for every $f(T_1, T_2) \in LS_A(T_1, T_2)$. Equivalently, this mapping is defined by multiplication by $T_1^{-m}\, R^{-\gamma}$. This is an isomorphism from $LS_{A,d}(T_1, T_2)\, R^\gamma$ onto $LS_{A,d-m}(T_1, T_2)$, as modules over k. This mapping also sends $LP_{A,d}(T_1, T_2)\, R^\gamma$ onto $LP_{A,d-m}(T_1, T_2)$.

Let $f(T_1, T_2) = \sum_{j=-\infty}^{\infty} f_j\, T_1^j\, T_2^{d-j} \in LS_{A,d}(T_1, T_2)$ be given, so that

$$f(T_1, T_2)\, T_1^{-m} = \sum_{j=-\infty}^{\infty} f_j\, T_1^{j-m}\, T_2^{d-j} = \sum_{j=-\infty}^{\infty} f_{j-m}\, T_1^j\, T_2^{d-m-j}. \tag{37.6.11}$$

Remember that H, X, and Y are as defined in Section 36.1. Observe that

$$\begin{aligned} H(f(T_1, T_2)\, T_1^{-m}) &= \sum_{j=-\infty}^{\infty} ((j-m) - (d-j)) \cdot f_j\, T_1^{j-m}\, T_2^{d-j} \\ &= \sum_{j=-\infty}^{\infty} (2\, j - m - d) \cdot f_j\, T_1^{j-m}\, T_2^{d-j}. \end{aligned} \tag{37.6.12}$$

Similarly,

$$(37.6.13)\quad X(f(T_1,T_2)\,T_1^{-m}) = \sum_{j=-\infty}^{\infty} (d-j)\cdot f_j\,T_1^{j-m+1}\,T_2^{d-j-1} = \sum_{j=-\infty}^{\infty} (d-j+1)\cdot f_{j-1}\,T_1^{j-m}\,T_2^{d-j}$$

and

$$(37.6.14)\quad Y(f(T_1,T_2)\,T_1^{-m}) = \sum_{j=-\infty}^{\infty} (j-m)\cdot f_j\,T_1^{j-m-1}\,T_2^{d-j+1} = \sum_{j=-\infty}^{\infty} (j+1-m)\cdot f_{j+1}\,T_1^{j-m}\,T_2^{d-j}.$$

Let us compare these expressions with (37.4.9), (37.4.10), and (37.4.11), using (37.6.5). It is easy to see that

$$(37.6.15)\quad \widetilde{H}(f(T_1,T_2)\,R^\gamma)\,T_1^{-m}\,R^{-\gamma} = H(f(T_1,T_2)\,T_1^{-m}),$$

$$(37.6.16)\quad \widetilde{X}(f(T_1,T_2)\,R^\gamma)\,T_1^{-m}\,R^{-\gamma} = X(f(T_1,T_2)\,T_1^{-m}),$$

$$(37.6.17)\quad \widetilde{Y}(f(T_1,T_2)\,R^\gamma)\,T_1^{-m}\,R^{-\gamma} = Y(f(T_1,T_2)\,T_1^{-m}).$$

This shows that (37.6.10) defines an isomorphism from $LS_{A,d}(T_1,T_2)\,R^\gamma$ onto $LS_{A,d-m}(T_1,T_2)$, as modules over $sl_2(k)$. More precisely, this uses the isomorphisms between $sl_2(k)$ and $s_2(k)$, $\widetilde{s}_2(k)$, as Lie algebras over k, mentioned in Sections 36.1, 37.4, respectively. Similarly, (37.6.10) defines an isomorphism from $LP_{A,d}(T_1,T_2)\,R^\gamma$ onto $LP_{A,d-m}(T_1,T_2)$, as modules over $sl_2(k)$.

37.7 Characteristic 0 and $LP_{k,d}(T_1,T_2)\,R^\gamma$

Let us continue with the same notation and hypotheses as in the previous four sections, and suppose now that k is a field of characteristic 0, and that $A = k$, as a module over itself. Observe that

$$(37.7.1)\quad \widetilde{H}(T_1^j\,T_2^{d-j}\,R^\gamma) = (2\,j - d + \gamma\,\nu_0)\,T_1^j\,T_2^{d-j}\,R^\gamma$$

for each $j \in \mathbf{Z}$, by the definition (37.4.1) of $\widetilde{H}$. This can be obtained from (37.4.9) as well. Thus $T_1^j\,T_2^{d-j}\,R^\gamma$ has weight

$$(37.7.2)\quad 2\,j - d + \gamma\,\nu_0$$

in $LP_{k,d}(T_1,T_2)\,R^\gamma$, as a module over $sl_2(k)$, as in Section 15.1. Of course, this uses the isomorphism between $sl_2(k)$ and $\widetilde{s}_2(k)$, as Lie algebras over k, mentioned in Section 37.4.

Using the definition (37.4.2) of $\widetilde{X}$, we get that

$$\widetilde{X}(T_1^d\, R^\gamma) = 0. \tag{37.7.3}$$

This means that $T_1^d\, R^\gamma$ is a maximal or primitive vector of weight

$$d + \gamma\, \nu_0 \tag{37.7.4}$$

in $LP_{k,d}(T_1, T_2)\, R^\gamma$, as a module over $sl_2(k)$, as in Section 15.2. Remember that $LP_{k,d}^{d,-}(T_1, T_2)\, R^\gamma$ is a submodule of $LP_{k,d}(T_1, T_2)\, R^\gamma$, as a module over $\widetilde{s}_2(k)$, or equivalently $sl_2(k)$, as in the previous section. Clearly

$$T_1^d\, R^\gamma \in LP_{k,d}^{d,-}(T_1, T_2)\, R^\gamma. \tag{37.7.5}$$

Thus $T_1^d\, R^\gamma$ may be considered as a maximal or primitive vector of weight (37.7.4) in $LP_{k,d}^{d,-}(T_1, T_2)\, R^\gamma$, as a module over $sl_2(k)$.

Note that

$$\widetilde{Y}(T_1^j\, T_2^{d-j}\, R^\gamma) = (j + \gamma\, \nu_0)\, T_1^{j-1}\, T_2^{d-j+1}\, R^\gamma \tag{37.7.6}$$

for every integer j, by the definition (37.4.3) of $\widetilde{Y}$. If l is a nonnegative integer, then $\widetilde{Y}^l(T_1^d\, R^\gamma)$ is a multiple of $T_1^{d-l}\, T_2^l\, R^\gamma$ by an element of k. Suppose that

(37.7.7) $\quad d + \gamma\, \nu_0$ does not correspond to a nonnegative integer,

under the natural embedding of $\mathbf{Q}$ into k. Under these conditions, we get that $\widetilde{Y}^l(T_1^d\, R^\gamma)$ is a nonzero multiple of $T_1^{d-l}\, T_2^l\, R^\gamma$ for each $l \geq 0$. This implies that $\widetilde{Y}^l(T_1^d\, R^\gamma)$, $l \geq 0$, is a basis for $LP_{k,d}^{d,-}(T_1, T_2)\, R^\gamma$, as a vector space over k.

Let $Z_0(\mu_0)$ be as in Section 34.2, and let us take

$$\mu_0 = d \cdot 1 + \gamma \cdot \nu_0 \tag{37.7.8}$$

in k. If (37.7.7) holds, then we get that $LP_{k,d}^{d,-}(T_1, T_2)\, R^\gamma$ is isomorphic to $Z_0(\mu_0)$, as a module over $sl_2(k)$, as in Section 34.3.

Of course, $d + \gamma\, \nu_0$ corresponds to an integer under the natural embedding of $\mathbf{Q}$ into k if and only if $\gamma\, \nu_0$ corresponds to an integer. In this case, if m is an integer that satisfies (37.6.5), then $LP_{k,d}(T_1, T_2)\, R^\gamma$ is isomorphic to $LP_{k,d-m}(T_1, T_2)$ as modules over $sl_2(k)$, as in the previous section. This permits us to use the remarks in Section 36.4, with d replaced with $d - m$.

37.8 Helpful projections on $LS_{A,d}(T_1, T_2)\, R^\gamma$

Let us return to the notation and hypotheses in Section 37.6, so that k is a commutative ring with a multiplicative identity element again, and A is a module over k. Let $f(T_1, T_2) = \sum_{j=-\infty}^{\infty} f_j \, T_1^j \, T_2^{d-j} \in LS_{A,d}(T_1, T_2)$ and $l \in \mathbf{Z}$ be given, and put

$$P_{l,+}^{\gamma}(f(T_1, T_2) \, R^{\gamma}) = \sum_{j=l}^{\infty} f_j \, T_1^j \, T_2^{d-j} \, R^{\gamma}, \tag{37.8.1}$$

$$P_{l,-}^{\gamma}(f(T_1, T_2) \, R^{\gamma}) = \sum_{j=-\infty}^{l} f_j \, T_1^j \, T_2^{d-j} \, R^{\gamma}. \tag{37.8.2}$$

Equivalently,

$$P_{l,+}^{\gamma}(f(T_1, T_2) \, R^{\gamma}) = P_{l,+}(f(T_1, T_2)) \, R^{\gamma}, \tag{37.8.3}$$

$$P_{l,-}^{\gamma}(f(T_1, T_2) \, R^{\gamma}) = P_{l,-}(f(T_1, T_2)) \, R^{\gamma}, \tag{37.8.4}$$

in the notation of Section 36.5. Note that these define homomorphisms from $LS_{A,d}(T_1, T_2) \, R^{\gamma}$ into itself, as a module over k.

Clearly

$$P_{l,+}^{\gamma}(LS_{A,d}(T_1, T_2) \, R^{\gamma}) = LS_{A,d}^{l,+}(T_1, T_2) \, R^{\gamma}, \tag{37.8.5}$$

$$P_{l,-}^{\gamma}(LS_{A,d}(T_1, T_2) \, R^{\gamma}) = LS_{A,d}^{l,-}(T_1, T_2) \, R^{\gamma}. \tag{37.8.6}$$

In fact, $P_{l,+}^{\gamma}$ is the same as the identity mapping on $LS_{A,d}^{l,+}(T_1, T_2) \, R^{\gamma}$, and $P_{l,-}^{\gamma}$ is the identity mapping on $LS_{A,d}^{l,-}(T_1, T_2) \, R^{\gamma}$. Similarly,

$$P_{l,+}^{\gamma}(LP_{A,d}(T_1, T_2) \, R^{\gamma}) = LP_{A,d}^{l,+}(T_1, T_2) \, R^{\gamma}, \tag{37.8.7}$$

$$P_{l,-}^{\gamma}(LP_{A,d}(T_1, T_2) \, R^{\gamma}) = LP_{A,d}^{l,-}(T_1, T_2) \, R^{\gamma}. \tag{37.8.8}$$

By construction,

(37.8.9) the kernel of $P_{l,+}^{\gamma}$ on $LS_{A,d}(T_1, T_2) \, R^{\gamma}$ is equal to $LS_{A,d}^{l-1,-}(T_1, T_2) \, R^{\gamma}$,

and

(37.8.10) the kernel of $P_{l,-}^{\gamma}$ on $LS_{A,d}(T_1, T_2) \, R^{\gamma}$ is equal to $LS_{A,d}^{l+1,+}(T_1, T_2) \, R^{\gamma}$.

Similarly,

(37.8.11) the kernel of $P_{l,+}^{\gamma}$ on $LP_{A,d}(T_1, T_2) \, R^{\gamma}$ is equal to $LP_{A,d}^{l-1,-}(T_1, T_2) \, R^{\gamma}$,

and

(37.8.12) the kernel of $P_{l,-}^{\gamma}$ on $LP_{A,d}(T_1, T_2) \, R^{\gamma}$ is equal to $LP_{A,d}^{l+1,+}(T_1, T_2) \, R^{\gamma}$.

The quotients

$$(LS_{A,d}(T_1, T_2)\, R^\gamma)/(LS^{l,+}_{A,d}(T_1, T_2)\, R^\gamma) \tag{37.8.13}$$

and

$$(LS_{A,d}(T_1, T_2)\, R^\gamma)/(LS^{l,-}_{A,d}(T_1, T_2)\, R^\gamma) \tag{37.8.14}$$

can be defined as modules over k in the usual way. Similarly, the quotients

$$(LP_{A,d}(T_1, T_2)\, R^\gamma)/(LP^{l,+}_{A,d}(T_1, T_2)\, R^\gamma) \tag{37.8.15}$$

and

$$(LP_{A,d}(T_1, T_2)\, R^\gamma)/(LP^{l,-}_{A,d}(T_1, T_2)\, R^\gamma) \tag{37.8.16}$$

are defined as modules over k too. The natural inclusion mapping

$$\text{from } LP_{A,d}(T_1, T_2)\, R^\gamma \text{ into } LS_{A,d}(T_1, T_2)\, R^\gamma \tag{37.8.17}$$

leads to natural injective homomorphisms from (37.8.15) into (37.8.13), and from (37.8.16) into (37.8.14), as modules over k.

We can use $P^\gamma_{l-1,-}$ to identify (37.8.13) with $LS^{l-1,-}_{A,d}(T_1, T_2)\, R^\gamma$, as a module over k, as in Section 36.5. Of course, (37.8.15) corresponds to $LP^{l-1,-}_{A,d}(T_1, T_2)$ with respect to this identification. Similarly, we can use $P^\gamma_{l+1,+}$ to identify (37.8.14) with $LS^{l+1,+}_{A,d}(T_1, T_2)\, R^\gamma$, as a module over k, in which case (37.8.16) corresponds to $LP^{l+1,+}_{A,d}(T_1, T_2)\, R^\gamma$.

37.9 Projections and $\widetilde{H}$, $\widetilde{X}$, $\widetilde{Y}$

We continue with the same notation and hypotheses as in the previous section. Observe that

$$\widetilde{H} \circ P^\gamma_{l,+} = P^\gamma_{l,+} \circ \widetilde{H}, \tag{37.9.1}$$

$$\widetilde{H} \circ P^\gamma_{l,-} = P^\gamma_{l,-} \circ \widetilde{H} \tag{37.9.2}$$

on $LS_{A,d}(T_1, T_2)\, R^\gamma$, by (37.4.9). Remember that $\widetilde{H}$ maps each of

$$LS^{l,+}_{A,d}(T_1, T_2)\, R^\gamma,\ LS^{l,-}_{A,d}(T_1, T_2)\, R^\gamma,\ LP^{l,+}_{A,d}(T_1, T_2)\, R^\gamma, \text{ and } LP^{l,-}_{A,d}(T_1, T_2)\, R^\gamma \tag{37.9.3}$$

into itself, as in Section 37.5. This implies that $\widetilde{H}$ induces a mapping on each of the quotients (37.8.13), (37.8.14), (37.8.15), and (37.8.16) that is linear over k. These induced mappings correspond to $\widetilde{H}$ on $LS^{l-1,-}_{A,d}(T_1, T_2)\, R^\gamma$, $LS^{l+1,+}_{A,d}(T_1, T_2)\, R^\gamma$, $LP^{l-1,-}_{A,d}(T_1, T_2)\, R^\gamma$, and $LP^{l+1,+}_{A,d}(T_1, T_2)\, R^\gamma$, respectively, with respect to the identifications mentioned in the prevous section, by (37.9.1) and (37.9.2).

As in Section 37.5,

$$\widetilde{X}(LS^{l,+}_{A,d}(T_1,T_2)\,R^\gamma) \subseteq LS^{l+1,+}_{A,d}(T_1,T_2)\,R^\gamma \subseteq LS^{l,+}_{A,d}(T_1,T_2)\,R^\gamma, \tag{37.9.4}$$

and similarly for the corresponding spaces of formal Laurent polynomials. Thus $\widetilde{X}$ induces mappings on the quotients (37.8.13) and (37.8.15) that are linear over k. Note that

$$P^\gamma_{l-1,-} \circ \widetilde{X} = 0 \quad \text{on } LS^{l-1,+}_{A,d}(T_1,T_2)\,R^\gamma, \tag{37.9.5}$$

because of the first inclusion in (37.9.4), with l replaced with $l-1$. It is easy to see that

$$P^\gamma_{l-1,-} \circ \widetilde{X} = \widetilde{X} \quad \text{on } LS^{l-2,-}_{A,d}(T_1,T_2)\,R^\gamma, \tag{37.9.6}$$

because $\widetilde{X}$ maps $LS^{l-2,-}_{A,d}(T_1,T_2)\,R^\gamma$ into $LS^{l-1,-}_{A,d}(T_1,T_2)\,R^\gamma$, as in (37.5.13). Of course, $P^\gamma_{l-1,-} \circ \widetilde{X}$ is determined on $LS_{A,d}(T_1,T_2)\,R^\gamma$ by (37.9.5) and (37.9.6).

We can use $P^\gamma_{l-1,-}$ to identify the quotients (37.8.13) and (37.8.15) with $LS^{l-1,-}_{A,d}(T_1,T_2)\,R^\gamma$ and $LP^{l-1,-}_{A,d}(T_1,T_2)\,R^\gamma$, respectively, as modules over k, as in the previous section. It is easy to see that the mappings induced by $\widetilde{X}$ on these quotients correspond to the restrictions of $P^\gamma_{l-1,-}\circ\widetilde{X}$ to $LS^{l-1,-}_{A,d}(T_1,T_2)\,R^\gamma$ and $LP^{l-1,-}_{A,d}(T_1,T_2)\,R^\gamma$, respectively, with respect to these identifications.

Similarly,

$$\widetilde{Y}(LS^{l,-}_{A,d}(T_1,T_2)\,R^\gamma) \subseteq LS^{l-1,-}_{A,d}(T_1,T_2)\,R^\gamma \subseteq LS^{l,-}_{A,d}(T_1,T_2)\,R^\gamma, \tag{37.9.7}$$

as in Section 37.5, and there are analogous inclusions for the corresponding spaces of formal Laurent polynomials. This implies that $\widetilde{Y}$ induces mappings on the quotients (37.8.14) and (37.8.16) that are linear over k. Observe that

$$P^\gamma_{l+1,+} \circ \widetilde{Y} = 0 \quad \text{on } LS^{l+1,-}_{A,d}(T_1,T_2)\,R^\gamma, \tag{37.9.8}$$

because of the first inclusion in (37.9.7), with l replaced with $l+1$. We also have that

$$P^\gamma_{l+1,+} \circ \widetilde{Y} = \widetilde{Y} \quad \text{on } LS^{l+2,+}_{A,d}(T_1,T_2)\,R^\gamma, \tag{37.9.9}$$

because $\widetilde{Y}$ maps $LS^{l+2,+}_{A,d}(T_1,T_2)\,R^\gamma$ into $LS^{l+1,+}_{A,d}(T_1,T_2)$, as in (37.5.16). As before, $P^\gamma_{l+1,+} \circ \widetilde{Y}$ is determined on $LS_{A,d}(T_1,T_2)\,R^\gamma$ by (37.9.8) and (37.9.9).

We can use $P^\gamma_{l+1,+}$ to identify the quotients (37.8.14) and (37.8.16) with $LS^{l+1,+}_{A,d}(T_1,T_2)\,R^\gamma$ and $LP^{l+1,+}_{A,d}(T_1,T_2)\,R^\gamma$, respectively, as modules over k, as in the previous section again. The mappings induced by $\widetilde{Y}$ on these quotients correspond to the restrictions of $P^\gamma_{l+1,+} \circ \widetilde{Y}$ to $LS^{l+1,+}_{A,d}(T_1,T_2)\,R^\gamma$ and $LP^{l+1,+}_{A,d}(T_1,T_2)\,R^\gamma$, respectively, with respect to these identifications.

One can verify that

$$\widetilde{X} \circ P^\gamma_{d+1,+} = P^\gamma_{d+1,+} \circ \widetilde{X} \tag{37.9.10}$$

on $LS_{A,d}(T_1, T_2)\, R^\gamma$, using (37.4.10). This can also be obtained using the fact that both sides of (37.9.10) are equal to 0 on $LS^{d,-}_{A,d}(T_1, T_2)\, R^\gamma$, by definition of $P^\gamma_{d+1,+}$, and because $\widetilde{X}$ maps $LS^{d,-}_{A,d}(T_1, T_2)\, R^\gamma$ into itself, as in Section 37.6. Similarly, both sides of (37.9.10) are equal to $\widetilde{X}$ on $LS^{d+1,+}_{A,d}(T_1, T_2)\, R^\gamma$, by definition of $P^\gamma_{d+1,+}$, and because $\widetilde{X}$ maps $LS^{d+1,+}_{A,d}(T_1, T_2)\, R^\gamma$ into itself, as in Section 37.5.

Suppose for the moment that there is an integer m such that $m \cdot 1 + \gamma \cdot \nu_0 = 0$ in k, as in Section 37.6. In this case, one can check that

$$\widetilde{Y} \circ P^\gamma_{m-1,-} = P^\gamma_{m-1,-} \circ \widetilde{Y} \tag{37.9.11}$$

on $LS_{A,d}(T_1, T_2)\, R^\gamma$, using (37.4.11). Alternatively, both sides of (37.9.11) are equal to 0 on $LS^{m,+}_{A,d}(T_1, T_2)\, R^\gamma$, by definition of $P^\gamma_{m-1,-}$, and because $\widetilde{Y}$ maps $LS^{m,+}_{A,d}(T_1, T_2)\, R^\gamma$ into itself, as in Section 37.6. Both sides of (37.9.11) are equal to $\widetilde{Y}$ on $LS^{m-1,-}_{A,d}(T_1, T_2)\, R^\gamma$, by definition of $P^\gamma_{m-1,-}$, and because $\widetilde{Y}$ maps $LS^{m-1,-}_{A,d}(T_1, T_2)\, R^\gamma$ into itself, as in Section 37.5.

37.10 Related quotients over $\widetilde{s}_2(k)$

Let us continue with the same notation and hypotheses as in the previous two sections. Remember that $LS^{d,-}_{A,d}(T_1, T_2)\, R^\gamma$ is a submodule of $LS_{A,d}(T_1, T_2)\, R^\gamma$, as a module over $\widetilde{s}_2(k)$, as in Section 37.6. This means that the quotient

$$(LS_{A,d}(T_1, T_2)\, R^\gamma)/(LS^{d,-}_{A,d}(T_1, T_2)\, R^\gamma) \tag{37.10.1}$$

may be considered as a module over $\widetilde{s}_2(k)$ as well. As a module over k, this quotient can be identified with $LS^{d+1,+}_{A,d}(T_1, T_2)\, R^\gamma$ using $P^\gamma_{d+1,+}$, as in Section 37.8.

The action of $\widetilde{H}$ induced on (37.10.1) by the action of $\widetilde{H}$ on $LS_{A,d}(T_1, T_2)\, R^\gamma$ corresponds to the usual action of $\widetilde{H}$ on $LS^{d+1,+}_{A,d}(T_1, T_2)\, R^\gamma$, as in (37.9.1). Similarly, the action of $\widetilde{X}$ induced on (37.10.1) corresponds to the usual action of $\widetilde{X}$ on $LS^{d+1,+}_{A,d}(T_1, T_2)\, R^\gamma$, as in (37.9.10). The action of $\widetilde{Y}$ induced on (37.10.1) by the action of $\widetilde{Y}$ on $LS_{A,d}(T_1, T_2)\, R^\gamma$ corresponds to

(37.10.2) the restriction of $P^\gamma_{d+1,+} \circ \widetilde{Y}$ to $LS^{d+1,+}_{A,d}(T_1, T_2)\, R^\gamma$,

as in the previous section. This mapping is described by (37.9.8) and (37.9.9), with $l = d$.

Remember that $LP_{A,d}(T_1, T_2)\, R^\gamma$ is a submodule of $LS_{A,d}(T_1, T_2)\, R^\gamma$, as a module over $\widetilde{s}_2(k)$. We also have that $LP^{d,-}_{A,d}(T_1, T_2)\, R^\gamma$ is a submodule of $LP_{A,d}(T_1, T_2)\, R^\gamma$, as a module over $\widetilde{s}_2(k)$, as in Section 37.6. It follows that the quotient

$$(LP_{A,d}(T_1, T_2)\, R^\gamma)/(LP^{d,-}_{A,d}(T_1, T_2)\, R^\gamma) \tag{37.10.3}$$

may be considered as a module over $\widetilde{s}_2(k)$ as well. This may be considered as a submodule of (37.10.1), as a module over $\widetilde{s}_2(k)$. This can also be identified with $LP_{A,d}^{d+1,+}(T_1, T_2)\, R^\gamma$, as a module over k, using $P_{d+1,+}^\gamma$, as before.

If there is an integer m such that $m \cdot 1 + \gamma \cdot \nu_0 = 0$ in k, then $LS_{A,d}^{m,+}(T_1, T_2)\, R^\gamma$ is a submodule of $LS_{A,d}(T_1, T_2)\, R^\gamma$, as a module over $\widetilde{s}_2(k)$, as in Section 37.6. In this case, the quotient

$$(LS_{A,d}(T_1, T_2)\, R^\gamma)/(LS_{A,d}^{m,+}(T_1, T_2)\, R^\gamma) \tag{37.10.4}$$

may be considered as a module over $\widetilde{s}_2(k)$, which can be described more precisely as before. One can also use the isomorphism mentioned in Section 37.6 to get that this quotient is isomorphic to the analogous one in Section 36.7, with d replaced with $d - m$.

Chapter 38

Representations and semisimplicity, 2

38.1 Weights and finite dimension

As before, we use the same notation and hypotheses as in Section 33.1. In particular, $(A, [\cdot,\cdot]_A)$ is a semisimple Lie algebra of positive finite dimension over a field k of characteristic 0, and A_0 is a Lie subalgebra of A consisting of ad-diagonalizable elements of A. We also let Δ be a base for the root system Φ, and B_Δ be the standard Borel subalgebra of A associated to A_0 and Δ, as before.

Let V be a vector space over k that is a module over A, as a Lie algebra over k. If $\mu \in A_0'$, then V_μ is the linear subspace of V consisting of $v \in V$ such that $w \cdot v = \mu(w)\, v$ for every $w \in A_0$, as in Section 33.5.

In this section, we suppose also that k is algebraically closed, and that V has finite dimension, as a vector space over k. Under these conditions, it is well known that

(38.1.1) $$V \text{ corresponds to the direct sum of } V_\mu \text{ for finitely many } \mu \in A_0', \text{ as a vector space over } k.$$

This is mentioned on p107 of [14], and corresponds to part (a) of Proposition 3 on p60 of [24], and to Proposition 2.2 on p57 of [25].

To see this, note that for each $w \in A_0$,

(38.1.2) $$v \mapsto w \cdot v$$

is diagonalizable on V, as in Section 14.9. These linear mappings on V commute with each other, because A_0 is commutative as a Lie subalgebra of A, and V is a module over A. This implies (38.1.1), which is the same as saying that the linear mappings (38.1.2) with $w \in A_0$ can be simultaneously diagonalized on V. This is the argument indicated in [14, 24].

Alternatively, let $\widehat{V}$ be the linear subspace of V spanned by the V_μ's, $\mu \in A_0'$, as in Section 33.5. Remember that $\widehat{V}$ corresponds to the direct sum of the V_μ's, and that $\widehat{V}$ is a submodule of V, as a module over A, as before. If $\widehat{V} \neq V$, then Weyl's theorem implies that V corresponds to the direct sum of $\widehat{V}$ and a nonzero submodule Y, as a module over A.

If $w \in A_0$, then (38.1.2) maps Y into itself, because Y is a submodule of V, as a module over A. This implies that (38.1.2) has a nonzero eigenvector in Y, because k is algebraically closed, and Y is a vector space over k of positive finite dimension. It follows that there is a nonzero element y of Y that is a simultaneous eigenvector of (38.1.2) for every $w \in A_0$, because these linear mappings commute on V and thus Y, as before. This means that $y \in V_\mu$ for some $\mu \in A_0'$, so that $y \in \widehat{V}$, which is a contradiction. This is the argument used in the proof of Proposition 2.2 on p57 of [25].

If $V \neq \{0\}$, then V has a primitive or maximal vector, in the sense of Section 33.6. This is mentioned on p108 of [14], and corresponds to part (c) of Proposition 3 on p60 of [24], and to Proposition 2.7 on p58 of [25]. To see this, remember that B_Δ is solvable as a Lie algebra over k, so that there is a nonzero element v of V that is an eigenvector of the action of every element of B_Δ on V, by Lie's theorem. This implies that v is a primitive or maximal vector, as before.

Another argument is mentioned on p58 of [25], as follows. Remember that $\mu \in A_0'$ is said to be a weight of V with respect to A_0 when $V_\mu \neq \{0\}$. In this case, the set of weights is finite, because V has finite dimension, and the set of weights is nonempty, because $V \neq \{0\}$. One can use this to find a weight μ of V such that for each $\alpha \in \Delta$, $\mu + \alpha$ is not a weight of V. This implies that any nonzero element of V_μ is primitive or maximal, because of (33.5.3), as desired.

Remember that for each $\alpha \in \Phi$, there is a unique element h_α of $[A_\alpha, A_{-\alpha}]$ such that $\alpha(h_\alpha) = 2 = 1 + 1$ in k, as in Section 33.1. Note that $h_{-\alpha} = -h_\alpha$ for every $\alpha \in \Phi$. If $\alpha \in \Phi$ and $\nu \in A_0'$ is a weight of V, then

$$\nu(h_\alpha) \in \mathbf{Z}, \tag{38.1.3}$$

using the natural embedding of $\mathbf{Q}$ into k. This is part (b) of Proposition 3 on p60 of [24], which corresponds to a remark after the statement of the theorem on p112 of [14]. It suffices to verify this when α is an element of the set Φ^+ of positive roots with respect to Δ.

Let $\alpha \in \Phi^+$ be given, let x_α be a nonzero element of A_α, and let y_α be an element of $A_{-\alpha}$ such that $[x_\alpha, y_\alpha]_A = h_\alpha$. The linear span of x_α, y_α, and h_α in A is a Lie subalgebra of A that is isomorphic to $sl_2(k)$. We may consider V as a module over this subalgebra of A, as a Lie algebra over k. The eigenvalues of the action of h_α on V correspond to integers, as in Section 15.9. These eigenvalues are the same as the values of the weights of V at h_α, as desired.

The condition (38.1.3) is also mentioned in Exercise 2 on p62 of [25], and could be obtained from Theorem 3.1 on p58 and Theorem 4.1 on p59 of [25].

38.2 Weights and a larger field

Let us continue with the same notation and hypotheses as in the previous section, except that we no longer ask k to be algebraically closed. Let k_1 be an algebraically closed field with $k \subseteq k_1$.

Remember that we can get a vector space $\widetilde{V}$ over k_1 from V as in Section 33.2. In particular, the dimension of $\widetilde{V}$ as a vector space over k_1 is the same as the dimension of V as a vector space over k, which is finite, by hypothesis. As before, we may consider V as a linear subspace of $\widetilde{V}$, as a vector space over k.

If T is a linear mapping from V into itself, then T may be considered as a linear mapping from V into $\widetilde{V}$, as a vector space over k. This has a unique extension to a linear mapping $\widetilde{T}$ from $\widetilde{V}$ into itself, as a vector space over k_1.

Suppose for the moment that $\widetilde{T}$ is diagonalizable on $\widetilde{V}$, with distinct eigenvalues $\lambda_1, \ldots, \lambda_l \in k_1$. This implies that

$$\prod_{j=1}^{l} (\widetilde{T} - \lambda_j \, I_{\widetilde{V}}) = 0 \tag{38.2.1}$$

as a linear mapping on $\widetilde{V}$, where $I_{\widetilde{V}}$ is the identity mapping on $\widetilde{V}$. If

$$\lambda_1, \ldots, \lambda_l \in k, \tag{38.2.2}$$

then it follows that

$$\prod_{j=1}^{l} (T - \lambda_j \, I_V) = 0 \tag{38.2.3}$$

on V, where I_V is the identity mapping on V. This means that T is diagonalizable on V, by standard results.

We also get a Lie algebra $(\widetilde{A}, [\cdot,\cdot]_{\widetilde{A}})$ over k_1 from A, as in Section 33.2. The action of A on V has a unique extension to an action of $\widetilde{A}$ on $\widetilde{V}$, that makes $\widetilde{V}$ a module over $\widetilde{A}$, as a Lie algebra over k_1, as before.

The conditions on A discussed in Section 33.1 lead to analogous properties of $\widetilde{A}$, as in Section 33.4. In particular, $\widetilde{A}$ is semisimple as a Lie algebra over k_1, which could also be obtained from the semisimplicity of A as in Section 11.5.

Let $\widetilde{(A_0)}$ be the linear subspace of $\widetilde{A}$ corresponding to A_0, which is a Lie subalgebra of $\widetilde{A}$ that is commutative as a Lie algebra over k_1, as in Section 33.4. Remember that the elements of $\widetilde{(A_0)}$ are ad-diagonalizable in $\widetilde{A}$.

Let $\widetilde{(A_0)}'$ be the dual of $\widetilde{(A_0)}$, as a vector space over k_1, as before. If $\mu \in \widetilde{(A_0)}'$, then we take $\widetilde{V}_\mu$ to be the set of $v \in \widetilde{V}$ such that $w \cdot v = \mu(w)\, v$ for every $w \in \widetilde{(A_0)}$, as in Section 33.5. Because k_1 is algebraically closed, we have that $\widetilde{V}$ corresponds to the direct sum of $\widetilde{V}_\mu$ for finitely many $\mu \in \widetilde{(A_0)}'$, as in the previous section.

If $\alpha \in A_0'$, then let $\widetilde{\alpha}$ be the unique extension of α to an element of $\widetilde{(A_0)}'$, as in Section 33.4. Remember that the analogue $\widetilde{\Phi}$ of Φ for $\widetilde{A}$ and $\widetilde{(A_0)}$ consists of $\widetilde{\alpha}$, $\alpha \in \Phi$.

If $\alpha \in \Phi$, then h_α is the unique element of $[A_\alpha, A_{-\alpha}]$ with $\alpha(h_\alpha) = 2$, as in Section 33.1. We may also consider h_α as an element of $\widetilde{A}$, and indeed it is the unique element of $[\widetilde{A}_{\widetilde{\alpha}}, \widetilde{A}_{-\widetilde{\alpha}}] = [\widetilde{(A_\alpha)}, \widetilde{(A_{-\alpha})}]$ with $\widetilde{\alpha}(h_\alpha) = 2$.

If $\alpha \in \Phi$ and $\nu \in \widetilde{(A_0)}'$ is a weight of $\widetilde{V}$, then $\nu(h_\alpha)$ corresponds to an integer, as in the previous section. This means that the action of h_α on $\widetilde{V}$ is diagonalizable, and that the eigenvalues of this action correspond to integers, and thus elements of k.

The action of h_α on $\widetilde{V}$ is the same as the unique extension of the action of h_α on V to a linear mapping from $\widetilde{V}$ into itself, by construction. It follows that the action of h_α on V is diagonalizable too, as before.

Remember that A_0 is spanned by the h_α's, $\alpha \in \Phi$, as in Section 33.1. This means that the action of any element of A_0 on V is diagonalizable, because the action of h_α is diagonalizable for every $\alpha \in \Phi$.

The actions of the elements of A_0 on V commute with each other, because A_0 is commutative as a Lie subalgebra of A, and V is a module over A, as a Lie algebra over k. This implies that the actions of the elements of A_0 on V can be simultaneously diagonalized, as in the previous section.

This shows that (38.1.1) holds, even if k is not necessarily algebraically closed. This corresponds to part of Exercise 2 on p62 of [25].

If $V \neq \{0\}$, then one can check that V has a primitive or maximal vector, using the statement in the preceding paragraph, and the second argument for the analogous assertion in the previous section. This corresponds to another part of Exercise 2 on p62 of [25].

If $V \neq \{0\}$ and V is irreducible as a module over A, then it follows that V is standard cyclic as a module over A, as in the remarks at the beginning of Section 33.10. This corresponds to the corollary to Proposition 3 on p60 of [24], and is mentioned in the proof of part (1) of Theorem 3.2 on p59 of [25]. This also corresponds to some remarks on p108f of [14].

38.3 Conditions for finite dimension

We continue to use the same notation and hypotheses as in Section 33.1. Let V be a vector space over k that is a module over A, as a Lie algebra over k. In this section, we suppose that V is irreducible as a module over A, and that V is standard cyclic of weight $\mu \in A_0'$.

Suppose for the moment that V has finite dimension, as a vector space over k. We would like to show that

(38.3.1) for every $\alpha \in \Phi^+$, $\mu(h_\alpha)$ is a nonnegative integer.

This corresponds to the theorem on p112 of [14], to part of Theorem 3 on p60 of [24], and part of Theorem 4.1 on p59 of [25].

Let $\alpha \in \Phi^+$ be given. Remember that $\mu(h_\alpha)$ corresponds to an integer, using the natural embedding of $\mathbf{Q}$ into k, as in (38.1.3). This also uses the remarks in the previous section, when k is not necessarily algebraically closed.

As before, let x_α be a nonzero element of A_α, and let y_α be an element of $A_{-\alpha}$ such that $[x_\alpha, y_\alpha]_A = h_\alpha$, so that the linear span of x_α, y_α, and h_α in A is a Lie subalgebra of A isomorphic to $sl_2(k)$. Thus V may be considered as a module over $sl_2(k)$ as well.

By hypothesis, there is a $v \in V$ that is primitive or maximal of weight μ in V, as a module over A. This implies that v is primitive or maximal of weight $\mu(h_\alpha)$ in V as a module over the linear span of x_α, y_α, and h_α, as in Section 15.2. It follows that $\mu(h_\alpha) \geq 0$, as in Section 15.3.

Conversely, it is well known that (38.3.1) implies that the dimension of V is finite under these conditions. This corresponds to part of the theorem on p113 of [14], to part of Theorem 3 on p60 of [24], and part of Theorem 4.1 on p59 of [25] when $A = sl_n(k)$. Before we begin the proof of this, let us review some facts related to inverse roots.

Remember from Section 33.1 that Φ is a reduced root system in the finite-dimensional vector space $E_{\mathbf{R}}$ over the real numbers. If $\alpha \in \Phi$, then λ_α is the linear functional on $E_{\mathbf{R}}$ associated to the symmetry on $E_{\mathbf{R}}$ with vector α that maps Φ onto itself in the usual way. We have seen that the collection Φ' of λ_α, $\alpha \in \Phi$, is a root system in the dual $E'_{\mathbf{R}}$ of $E_{\mathbf{R}}$, as in Section 19.8. Remember that Δ is a base for Φ, and let Δ' be the set of λ_α, $\alpha \in \Delta$. We have also seen that Δ' is a base for Φ', because Φ is reduced, as in Section 19.13.

Using Δ', we can define $(\Phi')^+ = (\Phi')^{+,\Delta'}$ to be the set of dual roots in Φ' that are positive with respect to Δ', which is to say that they can be expressed as linear combinations of the elements of Δ' with nonnegative coefficients. Equivalently, $(\Phi')^+$ consists exactly of λ_α, $\alpha \in \Phi^+$, as in Section 30.3.

If $\alpha \in \Phi$, then

$$\gamma(h_\alpha) = \lambda_\alpha(\gamma) \tag{38.3.2}$$

for every $\gamma \in \Phi$, as in (33.1.2). More precisely, the right side is an integer, by the definition of a root system, which corresponds to an element of k under the natural embedding of $\mathbf{Q}$ into k. Remember that h_α is uniquely determined by (38.3.2), because A'_0 is spanned by Φ, as in Section 33.1.

If $\alpha \in \Phi$, then λ_α can be expressed as a linear combination of λ_β, $\beta \in \Delta$, with integer coefficients, because Δ' is a base for Φ'. This implies that h_α can be expressed as a linear combination of h_β, $\beta \in \Delta$, with the same integer coefficients, because h_α is uniquely determined by (38.3.2). Similarly, if $\alpha \in \Phi^+$, then λ_α can be expressed as a linear combination of λ_β, $\beta \in \Delta$, with nonnegative integer coefficients, because $\lambda_\alpha \in \Phi^+$, as before. This means that h_α can be expressed as a linear combination of h_β, $\beta \in \Delta$, with the same nonnegative integer coefficients.

It follows that (38.3.1) holds when $\mu(h_\beta)$ is a nonnegative integer for every $\beta \in \Delta$. This corresponds to a remark just after Theorem 3 on p60 of [24]. Similarly, if $\nu \in A'_0$, then $\nu(h_\alpha)$ corresponds to an integer for every $\alpha \in \Phi$ if and only if $\nu(h_\beta)$ corresponds to an integer for every $\beta \in \Delta$.

38.4 Some initial steps

We continue to use the same notation and hypotheses as in Section 33.1. If α is in the base Δ for Φ, then let x_α be a nonzero element of A_α, and let y_α be an element of $A_{-\alpha}$ such that $[x_\alpha, y_\alpha]_A = h_\alpha$, as before. If $\alpha, \beta \in \Delta$ and $\alpha \neq \beta$, then $[x_\alpha, y_\beta]_A = 0$, as in Section 23.5. Indeed, it is easy to see that $\alpha - \beta \notin \Phi$ in this case, so that $A_{\alpha-\beta} = \{0\}$.

Let UA be a universal enveloping algebra of A again, and let us identify A with its image in UA under the associated Lie algebra homomorphism, as before. If $\alpha, \beta \in \Delta$ and $\alpha \neq \beta$, then

$$[x_\alpha, y_\beta^l] = 0 \tag{38.4.1}$$

for every positive integer l. More precisely, y_β^l is defined as an element of UA, and the left side uses the commutator bracket associated to multiplication in UA. Of course, (38.4.1) holds when $l = 1$ as in the preceding paragraph, which implies the analogous statement for $l \geq 2$. This corresponds to part (a) of the lemma on p113 of [14].

If $\alpha, \beta \in \Delta$, then

$$[h_\alpha, y_\beta^l] = -l\, \beta(h_\alpha)\, y_\beta^l \tag{38.4.2}$$

for every positive integer l. If $l = 1$, then this reduces to the fact that $[h_\alpha, y_\beta]_A = -\beta(h_\alpha)$, because $h_\alpha \in A_0$ and $y_\beta \in A_{-\beta}$. Otherwise, one can use induction and the fact that the commutator with h_α defines a derivation on UA, as in Section 2.5. This corresponds to part (b) of the lemma on p113 of [14].

If $\alpha \in \Delta$, then

$$[x_\alpha, y_\alpha^l] = -l\, y_\alpha^{l-1}\, ((l-1) \cdot e - h_\alpha) \tag{38.4.3}$$

for every positive integer l, where $e = e_{UA}$ is the multiplicative identity element in UA. If $l = 1$, then y_α^{l-1} is interpreted as being equal to e, and (38.4.3) follows from the way that y_α was chosen. Otherwise, if $l \geq 2$, then

$$[x_\alpha, y_\alpha^l] = [x_\alpha, y_\alpha]\, y_\alpha^{l-1} + y_\alpha\, [x_\alpha, y_\alpha^{l-1}] = h_\alpha\, y_\alpha^{l-1} + y_\alpha\, [x_\alpha, y_\alpha^{l-1}], \tag{38.4.4}$$

because the commutator with x_α defines a derivation on UA, as before. Using induction, we may suppose that the analogue of (38.4.3) for $l - 1$ holds, to get that

$$[x_\alpha, y_\alpha^l] = h_\alpha\, y_\alpha^{l-1} - (l-1)\, y_\alpha^{l-1}\, ((l-2) \cdot e - h_\alpha). \tag{38.4.5}$$

Observe that

$$h_\alpha\, y_\alpha^{l-1} = [h_\alpha, y_\alpha^{l-1}] + y_\alpha^{l-1}\, h_\alpha = -2\,(l-1)\, y_\alpha^{l-1} + y_\alpha^{l-1}\, h_\alpha, \tag{38.4.6}$$

by (38.4.2). One can combine this with (38.4.5) to get (38.4.3), as desired. This corresponds to part (c) of the lemma on p113 of [14].

Let V be a vector space over k that is a module over A, as a Lie algebra over k. Suppose that V is irreducible as a module over A, that V is standard cyclic of weight $\mu \in A_0'$, and that

$$m_\alpha = \mu(h_\alpha) \tag{38.4.7}$$

is a nonnegative integer for every $\alpha \in \Delta$. We would like to show that V has finite dimension, as in the previous section.

By hypothesis, there is a primitive or maximal vector $v \in V$ of weight μ such that $V = (UA) \cdot v$. Let $\alpha \in \Delta$ be given, and put

$$v_\alpha = y_\alpha^{m_\alpha + 1} \cdot v. \tag{38.4.8}$$

If $\beta \in \Delta$ and $\alpha \neq \beta$, then

$$x_\beta \cdot v_\alpha = y_\alpha^{m_\alpha + 1} \cdot (x_\beta \cdot v) = 0. \tag{38.4.9}$$

This uses (38.4.1) in the first step, and the fact that v is primitive or maximal in the second step.

Observe that

$$\begin{aligned} x_\alpha \cdot v_\alpha &= ([x_\alpha, y_\alpha^{m_\alpha+1}]) \cdot v + y_\alpha^{m_\alpha+1} \cdot (x_\alpha \cdot v) \\ &= -(m_\alpha + 1)\, y_\alpha^{m_\alpha} \cdot ((m_\alpha \cdot e - h_\alpha) \cdot v), \end{aligned} \tag{38.4.10}$$

using (38.4.3) and the fact that $x_\alpha \cdot v = 0$ in the second step. However,

$$(m_\alpha \cdot e - h_\alpha) \cdot v = m_\alpha\, v - h_\alpha \cdot v = m_\alpha\, v - \mu(h_\alpha)\, v = 0, \tag{38.4.11}$$

because v has weight μ in V. Thus

$$x_\alpha \cdot v_\alpha = 0. \tag{38.4.12}$$

Note that v_α has weight $\mu - (m_\alpha + 1)\,\alpha$ with respect to A_0, as in Section 33.5. If $v_\alpha \neq 0$, then v_α would be a primitive or maximal vector in V, because of (38.4.9) and (38.4.12). This is not possible, because V is irreducible as a module over A and $m_\alpha \neq -1$, as in Section 33.10. This shows that

$$y_\alpha^{m_\alpha+1} \cdot v = v_\alpha = 0, \tag{38.4.13}$$

as in step (1) on p113 of [14].

Alternatively, the linear span of x_α, y_α, and h_α in A is a Lie subalgebra of A that is isomorphic to $sl_2(k)$. Thus V may be considered as a module over this subalgebra, and v is primitive or maximal of weight m_α in the sense of Section 15.2. One can use this to get (38.4.12) as in Section 15.3. This is the argument used on p61 of [24].

Using (38.4.13), we get that

(38.4.14) the linear subspace of V spanned by $y_\alpha^j \cdot v$, $j = 0, \ldots, m_\alpha$, is a submodule of V, as a module over the Lie subalgebra of A spanned by x_α, y_α, and h_α.

This follows from the remarks in Section 15.3, as on p61 of [24]. Alternatively, this linear subspace of V is mapped into itself by the action of y_α, because of (38.4.13). This linear subspace of V is also mapped into itself by the action of h_α, because $y_\alpha^j \cdot v$ has weight $\mu - j\,\alpha$ in V for each $j \geq 0$, as in Section 33.5. One can check that this linear subspace of V is mapped into itself by the action of x_α, using (38.4.3) and the fact that $x_\alpha \cdot v = 0$. This is the argument used in step (2) on p113 of [14]. Note that this linear subspace of V is nontrivial, because $v \neq 0$.

38.5 Submodules over subalgebras

Let k be a commutative ring with a multiplicative identity element, and let $(A, [\cdot,\cdot]_A)$ be a Lie algebra over k. Suppose that V is a module over k that is a module over A, as a Lie algebra over k. Let C be a Lie subalgebra of A, so that V may be considered as a module over C as well. Also let Z be a submodule of V, as a module over k, that is a submodule of V, as a module over C as well.

Consider the subset $A \cdot Z$ of V consisting of finite sums of elements of the form $a \cdot z$, where $a \in A$ and $z \in Z$. This is clearly a submodule of V, as a module over k. Let us check that $A \cdot Z$ is a submodule of V as a module over C. This corresponds to part of the argument in step (3) on p113 of [14], and to a remark on p61 of [24].

If $a \in A$, $c \in C$, and $z \in Z$, then

$$c \cdot (a \cdot z) = ([c, a]_A) \cdot z + a \cdot (c \cdot z). \tag{38.5.1}$$

Of course, $([c, a]_A) \cdot z \in A \cdot Z$ automatically, and $c \cdot z \in Z$, because Z is a submodule of V, as a module over C. It follows that $c \cdot (a \cdot z) \in A \cdot Z$, which implies that $A \cdot Z$ is a submodule of V, as a module over C.

Suppose now that k is a field, and that A has finite dimension, as a vector space over k. Let $V(C)$ be the linear subspace of V spanned by all finite-dimensional linear subspaces Z of V such that Z is a submodule of V, as a module over C. We would like to verify that $V(C)$ is a submodule of V, as a module over A. This corresponds to another part of the argument in step (3) on p113 of [14], and to another remark on p61 of [24].

Let Z be a finite-dimensional linear subspace of V that is a submodule of V, as a module over C. Thus $A \cdot Z$ is a submodule of V, as a module over C, as before. It is easy to see that $A \cdot Z$ has finite dimension as a vector space over k, because A and Z have finite dimension. This implies that

$$A \cdot Z \subseteq V(C). \tag{38.5.2}$$

One can use this to check that $V(C)$ is a submodule of V, as a module over A.

If $Z_1, \ldots, Z_n$ are finitely many finite-dimensional linear subspaces of V that are submodules of Z, as a module over C, then it is easy to see that the linear subspace of V spanned by $Z_1, \ldots, Z_n$ has finite dimension and is a submodule of V, as a module over C. This implies that every element of $V(C)$ is contained in a finite-dimensional linear subspace of V that is a submodule of V, as a module over C. Similarly, every finite-dimensional linear subspace of $V(C)$ is contained in a finite-dimensional linear subspace of V that is a submodule of V, as a module over C.

Let us return now to the same notation and hypotheses as in Section 33.1, so that A is a finite-dimensional Lie algebra over a field k of characteristic 0 in particular. Let V be a vector space over k that is a module over A again, as a Lie algebra over k, and suppose that V is irreducible as a module over A, that V is standard cyclic of weight $\mu \in A_0'$, and that $\mu(h_\alpha)$ corresponds to a nonnegative integer for each $\alpha \in \Delta$, with respect to the standard embedding of **Q** into k, as in the previous section. If $\alpha \in \Delta$, then let x_α and y_α be as before, and let C_α be the linear span of x_α, y_α, and h_α in A. Thus C_α is a Lie subalgebra of A that is isomorphic to $sl_2(k)$.

Under these conditions, there is a nontrivial finite-dimensional linear subspace of V that is a submodule of V, as a module over C_α, as in the previous section. This means that $V(C_\alpha) \neq \{0\}$, where $V(C_\alpha)$ is as defined earlier. It follows that

$$V(C_\alpha) = V, \tag{38.5.3}$$

because $V(C_\alpha)$ is a submodule of V, as a module over A, as before. This corresponds to step (3) on p113 of [14], and to an argument on p61 of [24].

38.6 Some related exponentials on V

Let us continue with the same notation and hypotheses as in the previous section, including those from Section 33.1. Thus V is a vector space over k that is a module over A, as a Lie algebra over k, V is irreducible as a module over A, V is standard cyclic of weight $\mu \in A_0'$, and $\mu(h_\alpha)$ corresponds to a nonnegative integer for every $\alpha \in \Delta$, with respect to the standard embedding of **Q** into k, as before. If $\alpha \in \Delta$, then we let $x_\alpha, y_\alpha \in A$ be as before, so that the linear span C_α of x_α, y_α, and h_α in A is a Lie subalgebra of A that is isomorphic to $sl_2(k)$.

Let ρ be the representation of A on V, so that $\rho_a(v) = a \cdot v$ for every $a \in A$ and $v \in V$. If Z is a finite-dimensional linear subspace of V that is a submodule of V, as a module over C_α, then ρ_{x_α} and ρ_{y_α} are nilpotent on Z. Indeed, Z is isomorphic as a module over C_α to a direct sum of finitely many irreducible finite-dimensional modules over C_α, by Weyl's theorem. Every irreducible finite-dimensional module over C_α is isomorphic to the module $W(m)$ described in Section 15.4 for some nonnegative integer m, as in Sections 15.5 and 15.9. It follows that ρ_{x_α} and ρ_{y_α} are nilpotent on Z, because of the analogous statement for $W(m)$, as in Section 15.8. This implies that ρ_{x_α} and ρ_{y_α} are locally nilpotent on V, as in Section 27.12, because of (38.5.3). This corresponds to step (4) on p114 of [14].

Of course, $\rho_{-y_\alpha} = -\rho_{y_\alpha}$ is locally nilpotent on V as well. Thus $\exp \rho_{x_\alpha}$ and $\exp \rho_{-y_\alpha}$ are defined as linear mappings from V into itself, as in Section 27.12. More precisely, these are one-to-one linear mappings from V onto itself, as before. It follows that

$$\theta_\alpha = (\exp \rho_{x_\alpha}) \circ (\exp \rho_{-y_\alpha}) \circ (\exp \rho_{x_\alpha}) \tag{38.6.1}$$

defines a one-to-one linear mapping from V onto itself, as in step (5) on p114 of [14].

Let us check that

$$\rho_{h_\alpha} \circ \theta_\alpha = -\theta_\alpha \circ \rho_{h_\alpha} \tag{38.6.2}$$

on V. It suffices to verify that this holds on any finite-dimensional linear subspace Z of V that is a submodule of V, as a module over C_α, because of (38.5.3). Remember that Z is isomorphic as a module over C_α to the direct sum of finitely many irreducible finite-dimensional modules over C_α, each of which is isomorphic to a module of the form $W(m)$ as in Section 15.4. Thus (38.6.2) follows from the analogous statement for $W(m)$, as in Section 15.8.

If $h \in A_0$ and $\alpha(h) = 0$, then $[h, x_\alpha]_A = [h, y_\alpha]_A = 0$. This means that ρ_h commutes with ρ_{x_α} and ρ_{y_α} on V, and thus with $\exp \rho_{x_\alpha}$, $\exp \rho_{-y_\alpha}$. It follows that

$$\rho_h \circ \theta_\alpha = \theta_\alpha \circ \rho_h \tag{38.6.3}$$

on V under these conditions.

Let $\nu \in A_0'$ be given, and let V_ν be the linear subspace of V consisting of vectors with weight ν with respect to A_0, as in Section 33.5. Thus V_ν consists of $z \in V$ such that $\rho_h(z) = \nu(h)\, z$ for every $h \in A_0$. More precisely, it suffices to check this when $h = h_\alpha$, and when $\alpha(h) = 0$, because A_0 is spanned by h_α and the kernel of α, as a vector space over k. This uses the fact that $\alpha(h_\alpha) = 2 = 1 + 1 \neq 0$ in k, because k has characteristic 0, by hypothesis.

Put

$$\tau_\alpha(\nu) = \nu - \nu(h_\alpha)\, \alpha, \tag{38.6.4}$$

which is also an element of A_0'. Note that $\tau_\alpha(\nu) = \nu$ on the kernel of α, that $(\tau_\alpha(\nu))(h_\alpha) = -\nu(h_\alpha)$, and that $\tau_\alpha(\nu)$ is uniquely determined in A_0' by these conditions. One can check that

$$\theta_\alpha(V_\nu) = V_{\tau_\alpha(\nu)}, \tag{38.6.5}$$

using (38.6.2) and (38.6.3). This corresponds to step (6) on p114 of [14], and to part of Remark (1) on p62 of [24].

It follows that

$$\dim V_\nu = \dim V_{\tau_\alpha(\nu)}, \tag{38.6.6}$$

as vector spaces over k. In particular, $V_\nu \neq \{0\}$ exactly when $V_{\tau_\alpha(\nu)} \neq \{0\}$. This is the same as saying that ν is a weight of V with respect to A_0 if and only if $\tau_\alpha(\nu)$ is a weight of V.

Alternatively, suppose that $V_\nu \neq \{0\}$, and let z be a nonzero element of V_ν. Because V is standard cyclic of weight μ as a module over A, ν can be expressed as μ minus a linear combination of roots with integer coefficients, as in Section 33.8. In particular, this implies that $\nu(h_\alpha)$ corresponds to an integer, under the standard embedding of $\mathbf{Q}$ into k, because $\mu(h_\alpha)$ corresponds to an integer, by hypothesis.

Let Z be a finite-dimensional linear subspace of V that is a submodule of V, as a module over C_α, such that $z \in Z$, as in the previous section. Put

$$\begin{aligned} u &= (\rho_{y_\alpha})^{\nu(h_\alpha)}(z) \quad \text{when } \nu(h_\alpha) \geq 0, \\ &= (\rho_{x_\alpha})^{-\nu(h_\alpha)}(z) \quad \text{when } \nu(h_\alpha) \leq 0, \end{aligned} \tag{38.6.7}$$

which is an element of Z. One can verify that $u \neq 0$, because Z is isomorphic as a module over C_α to the direct sum of finitely many modules over C_α of the form $W(m)$ as in Section 15.4, as before.

We also have that u has weight (38.6.4) in V with respect to A_0, as in Section 33.5. This implies that $V_{\tau_\alpha(\nu)} \ne \{0\}$, as before. Conversely, if $V_{\tau_\alpha(\nu)} \ne \{0\}$, then the same argument shows that $V_\nu \ne \{0\}$, because $\tau_\alpha(\tau_\alpha(\nu)) = \nu$. This corresponds to an argument on p61 of [24].

38.7 Weights and the Weyl group

We continue to use the same notation and hypotheses as in Section 33.1. Remember that Φ is a root system in $E_{\mathbf{R}}$, which is a vector space over the real numbers of positive finite dimension, and that $E_{\mathbf{Q}}$ is the same as the linear span of Φ in $E_{\mathbf{R}}$ as a vector space over $\mathbf{Q}$, as in Section 32.3. In particular, every automorphism of Φ maps $E_{\mathbf{Q}}$ onto itself.

As before, we let V be a vector space over k that is a module over A, as a Lie algebra over k, with V irreducible as a module over A, and standard cyclic with weight $\mu \in A_0'$, and se suppose that $\mu(h_\alpha)$ corresponds to a nonnegative integer for each $\alpha \in \Delta$, with respect to the standard embedding of $\mathbf{Q}$ into k. If $\nu \in A_0'$ is a weight of V with respect to A_0, then it follows that $\nu(h_\alpha)$ corresponds to an integer for every $\alpha \in \Delta$, as in the previous section. This implies that $\nu \in E_{\mathbf{Q}}$, as in Section 32.3.

If $\alpha \in \Phi$, then we let σ_α be the symmetry on $E_{\mathbf{R}}$ with vector α that maps Φ onto itself, and λ_α be the corresponding linear functional on $E_{\mathbf{R}}$, as usual. Remember that λ_α maps $E_{\mathbf{Q}}$ into $\mathbf{Q}$, because λ_α takes integer values on Φ. If $\nu \in E_{\mathbf{Q}} \subseteq A_0'$, then

$$\lambda_\alpha(\nu) = \nu(h_\alpha), \tag{38.7.1}$$

by (33.1.2), and using the natural embedding of $\mathbf{Q}$ into k. This implies that

$$\sigma_\alpha(\nu) = \nu - \lambda_\alpha(\nu)\,\alpha = \nu - \nu(h_\alpha)\,\alpha. \tag{38.7.2}$$

If $\nu \in E_{\mathbf{Q}}$ and σ is in the Weyl group of Φ, then we would like to check that ν is a weight of V with respect to A_0 if and only if $\sigma(\nu)$ has this property. If $\sigma = \sigma_\alpha$ for some $\alpha \in \Delta$, then this follows from the remarks in the previous section, because (38.7.2) is the same as (38.6.4). Otherwise, one can use the fact that the Weyl group of Φ is generated byσ_α, $\alpha \in \Delta$, as in Section 19.14. Similarly,

$$\dim V_\nu = \dim V_{\sigma(\nu)} \tag{38.7.3}$$

for every σ in the Weyl group of Φ. More precisely, this is the same as (38.6.6) when $\sigma = \sigma_\alpha$ for some $\alpha \in \Delta$.

The weights of V with respect to A_0 are elements of $E_{\mathbf{Q}}$, as before. The Weyl group of Φ maps the set of weights of V with respect to A_0 onto itself, as in the preceding paragraph. This and (38.7.3) correspond to step (7) on p114 of [14], and are included in the theorem on p113 of [14]. These statements also correspond to Remark (1) on p62 of [24].

We would like to show that there are only finitely many weights of V with respect to A_0. If ν is a weight of V, then ν can be expressed as μ minus a linear combination of the elements of Δ with nonnegative integer coefficients, as in Section 33.8. This means that $\nu \preceq \mu$, in the notation of Section 30.5.

If ν is a weight of V, then $\nu(h_\alpha)$ corresponds to an integer for every $\alpha \in \Delta$, so that $\nu \in \Upsilon$, as in Section 32.3. In this case, there is an element σ of the Weyl group of Φ such that $\sigma(\nu) \in \Upsilon^+$, as in Section 30.4. Note that $\sigma(\nu)$ is a weight of V as well, so that $\sigma(\nu) \preceq \mu$, as before.

However, there are only finitely many elements ρ of Υ^+ such that $\rho \preceq \mu$, as in Section 30.6. This implies that there are only finitely many weights of V, because there are only finitely many elements of the Weyl group of Φ. This corresponds to step (8) on p114 of [14].

Alternatively, if ν is a weight of V, then ν can be expressed as μ minus a linear combination of the elements of Δ with nonnegative integer coefficients, as before. In order to show that there are only finitely many weights of V, it suffices to find upper bounds for these coefficients that do not depend on ν, as on p61 of [24].

Of course, $\mu \in E_{\mathbf{Q}}$, because $\mu(h_\alpha)$ corresponds to an integer for every $\alpha \in \Delta$, by hypothesis. Remember that Δ is a basis for $E_{\mathbf{Q}}$ as a vector space over $\mathbf{Q}$, as in Section 33.1. Thus ν can be expressed in a unique way as a linear combination of elements of Δ with coefficients in $\mathbf{Q}$, and we would like to find lower bounds for these coefficients that do not depend on ν.

Remember that $-\Delta$ is a base for Φ too, so that there is an element σ of the Weyl group of Φ such that $\sigma(\Delta) = -\Delta$, as in Section 19.14. We also have that $\sigma(\nu)$ is a weight of V, because ν is a weight of V, as before. This means that $\sigma(\nu)$ can be expressed as μ minus a linear combination of elements of Δ with nonnegative integer coefficients, as in Section 33.8 again.

It follows that ν can be expressed as $\sigma^{-1}(\mu)$ minus a linear combination of the elements of $\sigma^{-1}(\Delta)$ with nonnegative integer coefficients. Equivalently, ν can be expressed as $\sigma^{-1}(\mu)$ plus a linear combination of elements of Δ with nonnegative integer coefficients. In particular, the coefficients of ν with respect to Δ are greater than or equal to the coefficients of $\sigma^{-1}(\mu)$.

This implies that the coefficients of ν with respect to Δ have lower bounds that do not depend on ν, because there are only finitely many elements of the Weyl group. It follows that there are only finitely many weights of V, as before.

Remember that V is spanned by its weight spaces, each of which has finite dimension, as in Section 33.8. This means that V has finite dimension, because there are only finitely many weights of V. This corresponds to step (9) on p114 of [14], and to the last step in the proof on p61 of [24].

38.8 Sums of weights

Let us continue to use the same notation and hypotheses as in Section 33.1. Let V^1, V^2 be vector spaces over k that are modules over A, as a Lie algebra over k. Consider the tensor product $V^1 \bigotimes V^2$, initially as a vector space over k. As in Section 7.12, $V^1 \bigotimes V^2$ may be considered as a module over A, where

$$a \cdot (z_1 \otimes z_2) = (a \cdot z_1) \otimes z_2 + z_1 \otimes (a \cdot z_2) \tag{38.8.1}$$

for every $a \in A$, $z_1 \in V^1$, and $z_2 \in V^2$.

Let $\nu_1, \nu_2 \in A_0'$ be given, and remember that $V^1_{\nu_1}$, $V^2_{\nu_2}$ consist of elements of V^1, V^2 with weight ν_1, ν_2, respectively, with respect to A_0, as in Section 33.5. If $w \in A_0$, $z_1 \in V^1_{\nu_1}$, and $z_2 \in V^2_{\nu_2}$, then

$$\begin{aligned} (38.8.2) \qquad w \cdot (z_1 \otimes z_2) &= (w \cdot z_1) \otimes z_2 + z_1 \otimes (w \cdot z_2) \\ &= (\nu_1(w)\, z_1) \otimes z_2 + z_1 \otimes (\nu_2(w)\, z_2) \\ &= (\nu_1(w) + \nu_2(w))\, (z_1 \otimes z_2). \end{aligned}$$

This means that $z_1 \otimes z_2$ is in the set $\big(V^1 \bigotimes V^2\big)_{\nu_1+\nu_2}$ of elements of $V^1 \bigotimes V^2$ with weight $\nu_1 + \nu_2$ with respect to A_0. The tensor product $V^1_{\nu_1} \bigotimes V^2_{\nu_2}$ may be considered as a linear subspace of $V^1 \bigotimes V^2$, and we get that

$$(38.8.3) \qquad V^1_{\nu_1} \bigotimes V^2_{\nu_2} \subseteq \big(V^1 \bigotimes V^2\big)_{\nu_1+\nu_2}.$$

Let $\mu_1, \mu_2 \in A_0'$ be given, and suppose that

(38.8.4) $v_1 \in V^1$, $v_2 \in V^2$ are primitive or maximal vectors of weight μ_1, μ_2, respectively,

as in Section 33.6. Under these conditions, it is easy to see that

(38.8.5) $v_1 \otimes v_2$ is a primitive or maximal vector in $V^1 \bigotimes V^2$ of weight $\mu_1 + \mu_2$.

If UA is a universal enveloping algebra of A, then

$$(38.8.6) \qquad V = (UA) \cdot (v_1 \otimes v_2)$$

is the submodule of $V^1 \bigotimes V^2$, as a module over A, generated by $v_1 \otimes v_2$, as before. Thus

(38.8.7) V is standard cyclic of weight $\mu_1 + \mu_2$,

as a module over A.

If V^1, V^2 have finite dimension as vector spaces over k, then $V^1 \bigotimes V^2$ has finite dimension as well, which implies that V has finite dimension too. This shows that

(38.8.8) if there are standard cyclic modules over A with weights μ_1, μ_2 that are finite dimensional as vector spaces over k, then there is a standard cyclic module over A with weight $\mu_1 + \mu_2$ that is finite dimensional as a vector space over k,

as in Proposition 4.4 on p61 of [25]. Of course, this also follows from the characterization of weights of finite-dimensional standard cyclic modules stated in Section 38.3. This more direct argument for sums is used in [25] to obtain the sufficiency of the condition in Section 38.3 when $A = sl_n(k)$.

38.9 Weights and tensor products

Let us continue with the same notation and hypotheses as in the previous section. If V is a vector space over k that is a module over A, then put

$$\Pi(V) = \{\nu \in A_0' : V_\nu \neq \{0\}\}, \tag{38.9.1}$$

which is the set of weights of V with respect to A_0. Observe that

$$\{\nu_1 + \nu_2 : \nu_1 \in \Pi(V^1),\, \nu_2 \in \Pi(V^2)\} \subseteq \Pi\big(V^1 \bigotimes V^2\big), \tag{38.9.2}$$

by (38.8.3).

Suppose that

(38.9.3) V^1, V^2 correspond to the direct sums of their weight spaces, as vector spaces over k.

This implies that

(38.9.4) $V^1 \bigotimes V^2$ corresponds to the direct sum of $V^1_{\nu_1} \bigotimes V^2_{\nu_2}$, $\nu_1 \in \Pi(V^1)$, $\nu_2 \in \Pi(V^2)$, as a vector space over k,

as in Section 7.14.

Under these conditions, we get that

$$\Pi\big(V^1 \bigotimes V^2\big) = \{\nu_1 + \nu_2 : \nu_1 \in \Pi(V^1),\, \nu_2 \in \Pi(V^2)\}, \tag{38.9.5}$$

using (38.8.3). More precisely, if $\nu \in A_0'$, then

(38.9.6) $(V^1 \bigotimes V^2)_\nu$ corresponds to the direct sum of $V^1_{\nu_1} \bigotimes V^2_{\nu_2}$, where $\nu_1 \in \Pi(V^1)$, $\nu_2 \in \Pi(V^2)$, and $\nu_1 + \nu_2 = \nu$, as a vector space over k.

Note that

(38.9.7) $V^1 \bigotimes V^2$ corresponds to the direct sum of its weight spaces, as a vector space over k,

in this case.

If V^1, V^2 have finite dimension as vector spaces over k, then $\Pi(V^1)$, $\Pi(V^2)$ have only finitely many elements. This implies that $\Pi\big(V^1 \bigotimes V^2\big)$ has only finitely many elements as well, by (38.9.5). If $\nu \in \Pi\big(V^1 \bigotimes V^2\big)$, then we get that

$$\dim \big(V^1 \bigotimes V^2\big)_\nu = \sum_{\nu_1+\nu_2=\nu} (\dim V^1_{\nu_1})\,(\dim V^2_{\nu_2}), \tag{38.9.8}$$

where more precisely the sum is taken over all $\nu_1 \in \Pi(V^1)$ and $\nu_2 \in \Pi(V^2)$ with $\nu_1 + \nu_2 = \nu$.

Suppose now that

$$V^1, V^2 \text{ are standard cyclic of weights } \mu_1,\, \mu_2 \in A_0', \text{ respectively, as modules over } A. \tag{38.9.9}$$

In particular, this implies that (38.9.3) holds, as in Section 33.8. Remember that the elements of $\Pi(V^1)$, $\Pi(V^2)$ can be expressed as μ_1, μ_2 minus linear combinations of elements of Δ with nonnegative integer coefficients, respectively, as in Section 33.8. It follows that

$$\text{the elements of } \Pi\big(V^1 \bigotimes V^2\big) \text{ can be expressed as } \mu_1 + \mu_2 \text{ minus linear combinations of elements of } \Delta \text{ with nonnegative integer coefficients.} \tag{38.9.10}$$

If $\nu_1 \in \Pi(V^1)$, $\nu_2 \in \Pi(V^2)$, then we get that

$$\nu_1 + \nu_2 = \mu_1 + \mu_2 \quad \text{only when} \quad \nu_1 = \mu_1,\, \nu_2 = \mu_2. \tag{38.9.11}$$

This implies that

$$(V^1 \bigotimes V^2)_{\mu_1+\mu_2} = V^1_{\mu_1} \bigotimes V^2_{\mu_2}, \tag{38.9.12}$$

as in (38.9.6). Remember that $V^1_{\mu_1}$, $V^2_{\mu_2}$ have dimension one as vector spaces over k, as in Section 33.8. This means that

$$\dim \big(V^1 \bigotimes V^2\big)_{\mu_1+\mu_2} = 1, \tag{38.9.13}$$

by (38.9.12).

If $\nu \in \Pi\big(V^1 \bigotimes V^2\big)$, then one can check that

$$\nu = \nu_1 + \nu_2 \text{ for only finitely many } \nu_1 \in \Pi(V^1),\, \nu_2 \in \Pi(V^2), \tag{38.9.14}$$

because ν_1, ν_2 can be expressed as μ_1, μ_2 minus linear combinations of elements of Δ with nonnegative integer coefficients, as before. Remember that $V^1_{\nu_1}$, $V^2_{\nu_2}$ have finite dimensions as vector spaces over k for every $\nu_1, \nu_2 \in A_0'$, as in Section 33.8. Thus

$$\big(V^1 \bigotimes V^2\big)_\nu \text{ has finite dimension} \tag{38.9.15}$$

as a vector space over k, because it corresponds to the direct sum of finitely many finite-dimensional subspaces, by (38.9.6). More precisely, the dimension of $\big(V^1 \bigotimes V^2\big)_\nu$ can be expressed as in (38.9.8) again.

This corresponds to Exercise 7 on p117 of [14], and to part of part (b) of Proposition 5 on p63 of [24].

38.10 Fundamental weights and modules

Let us return to some connections with abstract weights, as in Section 32.3. Remember that the collection Φ' of λ_α, $\alpha \in \Phi$, is a root system in the dual $E'_{\mathbf{R}}$

of $E_{\mathbf{R}}$, and that the set Δ' of λ_α, $\alpha \in \Delta$, is a base for Φ', because Φ is reduced as a root system in $E_{\mathbf{R}}$. In particular, Δ' is a basis for $E'_{\mathbf{R}}$, as a vector space over $\mathbf{R}$, and if $\alpha \in \Delta$, then there is a unique element μ_α of $E_{\mathbf{R}}$ such that

$$(38.10.1) \qquad \begin{aligned} \lambda_\beta(\mu_\alpha) &= 1 \quad \text{when } \beta = \alpha \\ &= 0 \quad \text{for every } \beta \in \Delta \text{ with } \beta \neq \alpha, \end{aligned}$$

as in Section 30.1. The μ_α's, $\alpha \in \Delta$, form a basis for $E_{\mathbf{R}}$ dual to the λ_β's, $\beta \in \Delta$, as before.

Remember that Υ consists of $z \in E_{\mathbf{R}}$ such that $\lambda_\beta(z) \in \mathbf{Z}$ for every $\beta \in \Phi$, or equivalently for every $\beta \in \Delta$, because Δ' is a base for Φ'. Thus $\mu_\alpha \in \Upsilon$ for every $\alpha \in \Delta$, as in Section 30.1. We also have that $\Upsilon \subseteq E_{\mathbf{Q}}$, as in Section 32.3, so that $\mu_\alpha \in E_{\mathbf{Q}} \subseteq A'_0$ for every $\alpha \in \Delta$.

Similarly, Υ^+ consists of $z \in \Upsilon$ such that $\lambda_\beta(z) \geq 0$ for every $\beta \in \Delta$, or equivalently for every $\beta \in \Phi$. Clearly $\mu_\alpha \in \Upsilon^+$ for every $\alpha \in \Delta$, as in Section 30.3. Remember that the μ_α's, $\alpha \in \Delta$, are called the fundamental (dominant) weights with respect to Δ, as in Section 30.1. It is easy to see that Υ^+ consists exactly of linear combinations of the μ_α's, $\alpha \in \Delta$, whose coefficients are nonnegative integers.

As in Section 32.3, Υ consists exactly of $\nu \in A'_0$ such that $\nu(h_\beta)$ corresponds to an integer for every $\beta \in \Delta$, or equivalently for every $\beta \in \Phi$. Similarly, Υ^+ consists exactly of $\mu \in A'_0$ such that $\mu(h_\beta)$ corresponds to a nonnegative integer for every $\beta \in \Delta$, or equivalently $\beta \in \Phi$. This is the same as the set of $\mu \in A'_0$ for which there is a finite-dimensional standard cyclic module over A with weight μ, as in Section 38.3. The modules associated to μ_α, $\alpha \in \Delta$, in this way are called the *fundamental modules* over A, or the *fundamental representations* of A, as in Remark (2) on p62 of [24].

If $\mu \in \Upsilon^+$, then μ can be expressed as a sum of μ_α's, $\alpha \in \Delta$, with suitable repetitions. One can use this to get a finite-dimensional standard cyclic module over A with weight μ as a submodule of a tensor product of fundamental modules over A, with suitable repetitions, as in Exercise 8 on p117 of [14]. This is analogous to the argument discussed in Section 38.8. This type of argument is used on p61 of [25], to get the existence of finite-dimensional standard cyclic modules over $A = sl_n(k)$ with any weight $\mu \in \Upsilon^+$.

38.11 Simple transitivity

Let us continue with the same notation and hypotheses as in Section 33.1. In particular, Φ is a reduced root system in the vector space $E_{\mathbf{R}}$ over $\mathbf{R}$ of positive finite dimension, and Δ is a base for Φ. Remember that any reduced root system can be as in Section 33.1, because of Serre's theorem, as in Section 27.8.

If σ is an element of the Weyl group of Φ such that

$$(38.11.1) \qquad \sigma(\Delta) = \Delta,$$

then σ is the identity mapping on $E_{\mathbf{R}}$. This was discussed in Section 20.1, and it can also be obtained using results about representations of the Lie algebra A, as in Proposition 4 on p62 of [24]. This corresponds to Exercise 1 on p116 of [14].

If $\beta \in \Phi$, then

$$\lambda_{\sigma(\beta)} = \lambda_\beta \circ \sigma^{-1}, \tag{38.11.2}$$

because σ is an automorphism of Φ, as in Section 19.4. Let μ_α, $\alpha \in \Delta$, be the fundamental weights with respect to Δ, as in the previous section. If $\alpha, \beta \in \Delta$, then

$$\begin{aligned} \lambda_{\sigma(\beta)}(\sigma(\mu_\alpha)) = \lambda_\beta(\mu_\alpha) &= 1 \quad \text{when } \beta = \alpha \\ &= 0 \quad \text{when } \beta \neq \alpha, \end{aligned} \tag{38.11.3}$$

by (38.11.2) and (38.10.1). This implies that

$$\sigma(\mu_\alpha) = \mu_{\sigma(\alpha)} \tag{38.11.4}$$

for every $\alpha \in \Delta$, because of (38.11.1).

Let $\alpha \in \Delta$ be given, and let V^α be a finite-dimensional standard cyclic module over A with weight μ_α. In particular, μ_α is a weight of V^α, which implies that (38.11.4) is a weight of V^α too, as in Section 38.7. It follows that

$$\mu_\alpha - \sigma(\mu_\alpha) = \mu_\alpha - \mu_{\sigma(\alpha)} \tag{38.11.5}$$

can be expressed as a linear combination of the elements of Δ, with coefficients that are nonnegative integers, as in Section 33.8.

Of course, the sum of (38.11.5) over $\alpha \in \Delta$ is equal to 0, by (38.11.1). This implies that (38.11.5) is equal to 0 for every $\alpha \in \Delta$, because Δ is a basis for $E_{\mathbf{R}}$, and the coefficients of (38.11.5) with respect to Δ are all nonnegative. It follows that σ is the identity mapping on $E_{\mathbf{R}}$, as desired.

38.12 Weights and saturated sets

We continue with the same notation and hypotheses as in Section 33.1. Let V be a finite-dimensional vector space over k, and suppose that V is a standard cyclic module over A of weight $\mu \in A_0'$. If $\nu \in A_0'$, then let V_ν be the linear subspace of V consisting of vectors of weight ν with respect to A_0, as in Section 33.5. Put

$$\Pi = \Pi(V) = \{\nu \in A_0' : V_\nu \neq \{0\}\}. \tag{38.12.1}$$

Note that Π has only finitely many elements, because V has finite dimension, by hypothesis.

If $\nu \in \Pi$ and $\alpha \in \Phi$, then $\nu(h_\alpha)$ corresponds to an integer under the standard embedding of $\mathbf{Q}$ into k, as in Sections 38.1 and 38.2. This means that

$$\Pi \subseteq \Upsilon, \tag{38.12.2}$$

where Υ is as in Section 32.3. We would like to show that

$$\Pi \text{ is saturated as a subset of } \Upsilon, \tag{38.12.3}$$

in the sense of Section 30.7. This corresponds to the first part of the proposition on p114 of [14].

Let $\nu \in \Pi$ and $\alpha \in \Phi$ be given, and remember that $\nu \in E_{\mathbf{Q}}$ and $\nu(h_\alpha) = \lambda_\alpha(\nu)$, as in Sections 32.2 and 32.3. Let x_α be a nonzero element of A_α, and let y_α be an element of $A_{-\alpha}$ such that $[x_\alpha, y_\alpha]_A = h_\alpha$, as usual. The linear span of x_α, y_α, and h_α in A is a Lie subalgebra of A that is isomorphic to $sl_2(k)$, as a Lie algebra over k.

Let Z be the linear subspace of V spanned by the subspaces of the form

$$V_{\nu + j\cdot\alpha},\ j \in \mathbf{Z}. \tag{38.12.4}$$

It is easy to see that Z is a submodule of V, as a module over the linear span of x_α, y_α, and h_α in A, using the remarks in Section 33.5.

Suppose that $j_1, j_2 \in \mathbf{Z}$ satisfy $j_1 \leq j_2$ and

$$\nu + j_1 \cdot \alpha,\ \nu + j_2 \cdot \alpha \in \Pi. \tag{38.12.5}$$

If $j \in \mathbf{Z}$ and $j_1 \leq j \leq j_2$, then we would like to verify that

$$\nu + j \cdot \alpha \in \Pi. \tag{38.12.6}$$

Of course, Z has finite dimension as a vector space over k, because V has finite dimension, by hypothesis. Thus we can use Weyl's theorem to get that Z corresponds to the direct sum of irreducible modules over the linear span of x_α, y_α, and h_α in A. Each of these irreducible modules is isomorphic to $W(m)$ in Section 15.4 for some nonnegative m, as a module over $sl_2(k)$, as in Sections 15.5 and 15.9. One can use this to get (38.12.6), because of the analogous property of $W(m)$.

Remember that elements of the Weyl group of Φ map Π onto itself, as in Section 38.7. In particular, $\sigma_\alpha(\nu) \in \Pi$, where σ_α is the symmetry on $E_{\mathbf{R}}$ with vector α that maps Φ onto itself, as usual. Equivalently,

$$\nu - \lambda_\alpha(\nu)\,\alpha \in \Pi, \tag{38.12.7}$$

where $\lambda_\alpha(\nu) = \nu(h_\alpha)$ corresponds to an integer under the natural embedding of $\mathbf{Q}$ into k, as before. If $j \in \mathbf{Z}$ is between 0 and $\lambda_\alpha(\nu)$, then (38.12.6) holds, because $\nu \in \Pi$, by hypothesis. This implies (38.12.3), as desired.

Let r, q be the largest integers such that

$$\nu - r \cdot \alpha,\ \nu + q \cdot \alpha \in \Pi, \tag{38.12.8}$$

so that $q, r \geq 0$, because $\nu \in \Pi$. It follows that (38.12.6) holds for some $j \in \mathbf{Z}$ if and only if $-r \leq j \leq q$. The sequence of elements of Π of the form

$$\nu + j \cdot \alpha, \tag{38.12.9}$$

with $j \in \mathbf{Z}$ and $-r \leq j \leq q$, is called the *α-string through ν*, as on p114 of [14]. It is easy to see that σ_α maps this sequence onto itself, but in the opposite order. This implies that

$$r - q = \lambda_\alpha(\nu), \tag{38.12.10}$$

as on p114 of [14].

Of course, $\mu \in \Pi$, and $\mu(h_\alpha)$ corresponds to a nonnegative integer for every $\alpha \in \Phi^+$, as in Section 38.3. This means that $\mu \in \Upsilon^+$, as in Section 32.3. In fact,

(38.12.11) $$\Pi \text{ has highest weight } \mu,$$

in the sense of Section 30.7. Indeed, if $\nu \in \Pi$, then ν can be expressed as μ minus a linear combination of elements of Δ with nonnegative integer coefficients, as in Section 33.8. Thus $\nu \preceq \mu$, in the notation of Section 30.5.

If $\rho \in \Upsilon^+$ and $\rho \preceq \mu$, then

(38.12.12) $$\rho \in \Pi,$$

as in Section 30.8. This implies that

(38.12.13) $$\sigma(\rho) \in \Pi$$

for every element σ of the Weyl group of Φ, as before.

If $\nu \in \Pi$ and σ is an element of the Weyl group of Φ, then $\sigma(\nu) \in \Pi$, so that

(38.12.14) $$\sigma(\nu) \preceq \mu,$$

as before. Conversely, if $\nu \in \Upsilon$ and (38.12.14) holds for every element σ of the Weyl group of Φ, then $\nu \in \Pi$. Indeed, if $\nu \in \Upsilon$, then there is an element σ of the Weyl group of Φ such that $\sigma(\nu) \in \Upsilon^+$, as in Section 30.4. This implies that $\sigma(\nu) \in \Pi$, and thus $\nu \in \Pi$, as in the preceding paragraph. This corresponds to the second part of the proposition on p114 of [14].

38.13 Formal characters in $\mathbf{Z}[\Upsilon]$

Let us continue with the same notation and hypotheses as in Section 33.1, and let Υ be as in Section 32.3 again. Remember that $\mathbf{Z}[\Upsilon]$ is the group ring of Υ with coefficients in $\mathbf{Z}$, and that e_ν, $\nu \in \Upsilon$, are the standard basis elements of $\mathbf{Z}[\Upsilon]$, as in Section 32.4.

Let V be a finite-dimensional vector space over k that is a module over A, as a Lie algebra over k. If $\nu \in A_0'$, then V_ν is the linear subspace of V consisting of vectors of weight ν with respect to A_0, as in Section 33.5. Remember that $V_\nu = \{0\}$ unless $\nu \in \Upsilon$, as in (38.12.2).

The *formal character of* V is defined as an element of $\mathbf{Z}[\Upsilon]$ by

(38.13.1) $$\operatorname{ch}(V) = \sum_{\nu \in \Upsilon} (\dim V_\nu)\, e_\nu,$$

as on p124 of [14], and p63 of [24]. More precisely, the dimension of V_ν as a vector space over k is a nonnegative integer for every $\nu \in \Upsilon$, which is equal to zero for all but finitely many $\nu \in \Upsilon$, because V has finite dimension. Thus the right side of (38.13.1) is an element of $\mathbf{Z}[\Upsilon]$.

Let V^1, V^2 be finite-dimensional vector spaces over k that are modules over A, as a Lie algebra over k. Under these conditions, the direct sum $V^1 \bigoplus V^2$ is also a finite-dimensional vector space over k that is a module over A, and it is easy to see that

$$\mathrm{ch}\left(V^1 \bigoplus V^2\right) = \mathrm{ch}(V^1) + \mathrm{ch}(V^2). \tag{38.13.2}$$

Similarly, the tensor product $V^1 \bigotimes V^2$ is a finite-dimensional vector space over k and a module over A, and one can check that

$$\mathrm{ch}\left(V^1 \bigotimes V^2\right) = \mathrm{ch}(V^1) \cdot \mathrm{ch}(V^2), \tag{38.13.3}$$

using the remarks in Section 38.9. This corresponds to Proposition B on p125 of [14], and part (b) of Proposition 5 on p63 of [24].

Remember that any automorphism of Φ in $E_{\mathbf{R}}$ maps Υ onto itself, as in Section 30.4. In fact, the restriction of any automorphism of Φ to Υ is an automorphism of Υ, as a commutative group with respect to addition. In particular, elements of the Weyl group of Φ determine automorphisms of Υ. These automorphisms of Υ lead to ring automorphisms of $\mathbf{Z}[\Upsilon]$, as in Section 32.4.

If V is irreducible as a module over A, then V is standard cyclic as a module over A, as in Section 38.2. In this case, we have seen that elements of the Weyl group of Φ map the set of weights of V to itself, and preserve the dimensions of the corresponding weight spaces, as in Section 38.7. It is easy to see that this holds when V is not necessarily irreducible as a module over A too, because V corresponds to the direct sum of finitely many irreducible submodules, by Weyl's theorem. This implies that

(38.13.4) $\mathrm{ch}(V)$ is invariant under the action of the Weyl group on $\mathbf{Z}[\Upsilon]$.

This corresponds to a remark on p125 of [14], and to part (a) of Proposition 5 on p63 of [24].

Let V, W be finite-dimensional vector spaces over k that are modules over A. If V and W are isomorphic as modules over A, then

$$\mathrm{ch}(V) = \mathrm{ch}(W). \tag{38.13.5}$$

Conversely, if (38.13.5) holds, then V and W are isomorphic as modules over A. This is part (c) of Proposition 5 on p63 of [24], which corresponds to a remark about Proposition A on p125 of [14].

Let $\Pi(V)$, $\Pi(W)$ be the sets of weights of V, W, respectively, as in (38.12.1). Suppose that (38.13.5) holds, which implies in particular that

$$\Pi(V) = \Pi(W) \tag{38.13.6}$$

and

$$\dim V = \dim W. \tag{38.13.7}$$

To show that V is isomorphic to W, one can use induction on the common dimension of V and W. Of course, this is trivial when the dimension if 0, and so we may suppose that the dimension is positive.

Observe that $\Pi(V) \neq \emptyset$, because $V \neq \{0\}$. One can find $\mu \in \Pi(V)$ such that for each $\alpha \in \Delta$, $\mu+\alpha \notin \Pi(V)$, because $\Pi(V)$ has only finitely many elements, as in Section 38.1. Let v be a nonzero element of V_μ, and note that v is primitive or maximal of weight μ, as in Section 38.1 again.

Let UA be a universal enveloping algebra of A, and put

$$V^1 = (UA) \cdot v. \tag{38.13.8}$$

This is the submodule of V, as a module over A, generated by v, as in Section 33.7. By construction, V^1 is standard cyclic of weight μ, as a module over A, as in Section 33.8. Of course, V^1 has finite dimension as a vector space over k, because V has finite dimension. This implies that V^1 is irreducible as a module over A, as in Section 33.9.

Note that $\mu \in \Pi(W)$ too, by (38.13.6). Let w be a nonzero element of W_μ, so that w is primitive or maximal of weight μ, as before. Put

$$W^1 = (UA) \cdot w, \tag{38.13.9}$$

which is the submodule of W, as a module over A, generated by w. Thus W^1 is standard cyclic of weight μ, as a module over A. We also have that W^1 is irreducible as a module over A, because it has finite dimension, as a vector space over k.

Under these conditions, V^1 and W^1 are isomorphic as modules over A, as in Section 33.10. This implies that

$$\mathrm{ch}(V^1) = \mathrm{ch}(W^1), \tag{38.13.10}$$

as before. Using Weyl's theorem, we get that there are submodules V^2, W^2 of V, W, respectively, as modules over A, such that V, W correspond to $V^1 \bigoplus V^2$, $W^1 \bigoplus W^2$, respectively, as modules over W. This means that

$$\mathrm{ch}(V) = \mathrm{ch}(V^1) + \mathrm{ch}(V^2), \quad \mathrm{ch}(W) = \mathrm{ch}(W^1) + \mathrm{ch}(W^2), \tag{38.13.11}$$

as in (38.13.2). It follows that

$$\mathrm{ch}(V^2) = \mathrm{ch}(W^2), \tag{38.13.12}$$

by (38.13.10).

The common dimension of V^2 and W^2 is strictly less than the common dimension of V and W, by construction. Thus we get that V^2 and W^2 are isomorphic as modules over A, by induction. This implies that V and W are isomorphic as modules over A, because of the analogous statement for V^1 and W^1, as desired.

38.14 Invariant elements of $\mathbf{Z}[\Upsilon]$

Let us continue with the same notation and hypotheses as in the previous section. Remember that elements of the Weyl group W of Φ in $E_{\mathbf{R}}$ determine ring automorphisms on $\mathbf{Z}[\Upsilon]$, as before. Let $\mathbf{Z}[\Upsilon]^W$ be the subring of $\mathbf{Z}[\Upsilon]$ consisting of elements that are invariant under the action of W. If V is a finite-dimensional vector space over k that is a module over A, as a lie algebra over k, then

$$\mathrm{ch}(V) \in \mathbf{Z}[\Upsilon]^W, \tag{38.14.1}$$

as in (38.13.4).

Let

$$z = \sum_{\nu \in \Upsilon} z_\nu \, e_\nu \tag{38.14.2}$$

be an element of $\mathbf{Z}[\Upsilon]$, so that $z_\nu \in \mathbf{Z}$ for every $\nu \in \Upsilon$, and $z_\nu = 0$ for all but finitely many $\nu \in \Upsilon$. Suppose that $z \in \mathbf{Z}[\Upsilon]^W$, which means that

$$z_{\sigma(\nu)} = z_\nu \tag{38.14.3}$$

for every $\nu \in \Upsilon$. This permits us to arrange the sum in (38.14.2) into a sum over orbits of W in Υ.

Remember that Υ^+ consists of the $\mu \in \Upsilon$ such that $\mu(h_\alpha) \geq 0$ for every $\alpha \in \Phi^+$, where Φ^+ is the set of positive roots with respect to the base Δ for Φ, as in Section 32.3. If $\mu \in \Upsilon^+$, then put

$$O(\mu) = \{\sigma(\mu) : \sigma \in W\}, \tag{38.14.4}$$

which is the orbit of W in Υ that contains ν. Every orbit of W in Υ contains exactly one element of Υ^+, as in Section 30.4. This means that every orbit of W in Υ is of the form (38.14.4) for exactly one $\nu \in \Upsilon^+$. Thus

$$z = \sum_{\mu \in \Upsilon^+} z_\mu \Big(\sum_{\nu \in O(\mu)} e_\nu \Big), \tag{38.14.5}$$

by (38.14.3).

If $\mu \in \Upsilon^+$, then there is a finite-dimensional module $V(\mu)$ over A that is standard cyclic of weight μ, as in Section 38.3. In particular, $\mathrm{ch}(V(\mu)) \in \mathbf{Z}[\Upsilon]^W$, as in (38.14.1). Note that $V(\lambda)$ is irreducible as a module over A, as in Section 33.9, and unique up to isomorphism, as in Section 33.10. Thus $\mathrm{ch}(V(\mu))$ only depends on μ, and not the choice of $V(\mu)$.

Proposition A on p125 of [14] says that every element of $\mathbf{Z}[\Upsilon]$ can be expressed in a unique way as a linear combination of finitely many $\mathrm{ch}(V(\mu))$'s, $\mu \in \Upsilon^+$, with coefficients in $\mathbf{Z}$. This is related to the corollary on p64 of [24]. To see this, let $z \in \mathbf{Z}[\Upsilon]^W$ be given, and let us show first that z can be expressed in this way.

Let $\preceq$ be the partial ordering defined on $E_{\mathbf{R}}$ as in Section 30.5, although we shall only use it on Υ here. If $\gamma \in \Upsilon^+$, then there are only finitely many $\beta \in \Upsilon^+$ such that $\beta \preceq \gamma$, as in Section 30.6. Of course, there are only finitely many $\gamma \in \Upsilon$ such that $z_\gamma \neq 0$. Put

$$M_z = \{\beta \in \Upsilon^+ : \beta \preceq \gamma \text{ for some } \gamma \in \Upsilon^+ \text{ such that } z_\gamma \neq 0\}. \tag{38.14.6}$$

Note that M_z has only finitely many elements, by the previous statements.

To show that z can be expressed as before, we use induction on the number of elements of M_z. If $M_z = \emptyset$, then $z_\gamma = 0$ for every $\gamma \in \Upsilon^+$. This implies that $z = 0$, as in (38.14.5).

Suppose now that $M_z \neq \emptyset$, so that $z_\gamma \neq 0$ for some $\gamma \in \Upsilon^+$. Let μ be an element of Υ^+ such that $z_\mu \neq 0$, and μ is maximal among $\gamma \in \Upsilon^+$ with $z_\gamma \neq 0$ with respect to $\preceq$. Also let $V(\mu)$ be as before, and put

$$\widetilde{z} = z - z_\mu \operatorname{ch}(V(\mu)). \tag{38.14.7}$$

Clearly $\widetilde{z} \in \mathbf{Z}[\Upsilon]^W$, and we let $M_{\widetilde{z}} \subseteq \Upsilon^+$ be defined as before.

If $\nu \in \Upsilon$ is a weight of $V(\mu)$, then $\nu \preceq \mu$, as in Section 33.8. Equivalently, this means that e_ν has nonzero coefficient in $\operatorname{ch}(V(\mu))$ only when $\nu \preceq \mu$. This implies that

$$M_{\widetilde{z}} \subseteq M_z, \tag{38.14.8}$$

because $\mu \in \Upsilon^+$ and $z_\mu \neq 0$, by construction.

The dimension of the weight space in $V(\mu)$ corresponding to μ is equal to one, as in Section 33.8. This means that the coefficient of e_μ in $\operatorname{ch}(V(\mu))$ is equal to one. It follows that the coefficient of e_μ in $\widetilde{z}$ is equal to zero, by construction. One can use this to check that

$$\mu \notin M_{\widetilde{z}}, \tag{38.14.9}$$

because of (38.14.8) and the maximality property of μ. This implies that

$$M_{\widetilde{z}} \neq M_z, \tag{38.14.10}$$

because $\mu \in M_z$, by construction.

Thus the number of elements of $M_{\widetilde{z}}$ is strictly less than than the number of elements of M_z. This permits us to use induction to get that $\widetilde{z}$ can be expressed in the desired way. It follows that z can be expressed similarly, by the definition of $\widetilde{z}$.

To get uniqueness, let $\mu_1, \ldots, \mu_r$ be finitely many distinct elements of Υ^+, and let $c_1, \ldots, c_r$ be finitely many nonzero integers. We would like to check that

$$\sum_{j=1}^{r} c_j \operatorname{ch}(V(\mu_j)) \tag{38.14.11}$$

is nonzero as an element of $\mathbf{Z}[\Upsilon]$. Let l be a positive integer such that $l \leq r$ and μ_l is maximal among $\mu_1, \ldots, \mu_r$, with respect to $\preceq$. Thus the coefficient of e_{μ_l} in $\operatorname{ch}(V(\mu_j))$ is equal to one when $j = l$, and to 0 otherwise, as in Section 33.8. This means that the coefficient of e_{μ_l} in (38.14.11) is $c_l \neq 0$, so that (38.14.11) is not zero.

Chapter 39

Dimensions of weight spaces

39.1 Casimir elements in UA

Let k be a field, and let $(A, [\cdot,\cdot]_A)$ be a Lie algebra over k that has positive finite dimension, as a vector space over k. Also let $b(\cdot,\cdot)$ be a nondegenerate symmetric bilinear form on A, and suppose that $b(\cdot,\cdot)$ is associative on A, or equivalently invariant with respect to the adjoint representation on A. Thus

$$b([x,w]_A, y) = b(x, [w,y]_A) \tag{39.1.1}$$

for every $w, x, y \in A$, as in Sections 6.10 and 7.7. Let $u_1, \ldots, u_n$ be a basis for A as a vector space over k, and let $w_1, \ldots, w_n$ be the corresponding dual basis for A with respect to $b(\cdot,\cdot)$, so that

$$b(u_j, w_l) = \delta_{j,l} \tag{39.1.2}$$

for every $j, l = 1, \ldots, n$. As usual, $\delta_{j,l} \in k$ is equal to 1 when $j = l$, and to 0 otherwise.

Let UA be a universal enveloping algebra of A, with multiplicative identity element $e = e_{UA}$ and mapping $i = i_{UA}$ from A into UA, as in Section 25.4. Remember that i is injective, by the Poincaré–Birkhoff–Witt theorem, as in Section 25.12, so that we may as well identify A with a Lie subalgebra of UA. The *Casimir element* of UA associated to b is

$$c_A(b) = \sum_{j=1}^{n} u_j\, w_j, \tag{39.1.3}$$

as on p46 of [25]. This corresponds to some remarks on p118 of [14], and was also mentioned in Section 13.4.

More precisely, remember that b leads to a one-to-one linear mapping from A onto its dual A' as a vector space over k, as in Section 13.4. This lead to a one-to-one linear mapping from $A \bigotimes A$ onto $A \bigotimes A'$, and thus onto the space $\mathcal{L}(A)$ of linear mappings from A into itself, as a vector space over k, as before.

The u_j's and w_j's were used to define an element of $A \bigotimes A$, that corresponds to the identity mapping as an element of $\mathcal{L}(A)$. In particular, this element of $A \bigotimes A$ does not depend on the choice of u_j's, from which the w_j's were obtained using b, as before.

There is a natural mapping from $A \times A$ into UA that is bilinear over k, which is defined using the natural mapping from A into UA and multiplication in UA. This leads to a mapping from $A \bigotimes A$ into UA that is linear over k, as usual. By construction, (39.1.3) is the image under this mapping of the element of $A \bigotimes A$ defined in Section 13.4 using the u_j's and w_j's. Note that (39.1.3) does not depend on the choice of u_j's, as on p46 of [25]. This corresponds to the second part of Exercise 2 on p125 of [14].

We also have that

(39.1.4) $$c_A(b) \text{ is in the center of } UA,$$

as an algebra over k, which is to say that $c_A(b)$ commutes with every element of UA. To see this, it suffices to check that $c_A(b)$ commutes with every element of A, because UA is generated as an algebra over k by A and e. This property corresponds to the fact that the analogous element of $A \bigotimes A$ is invariant with respect to the representation of A on $A \bigotimes A$ obtained from the adjoint representation of A on itself, as in Section 13.4. One can get this from the fact that the identity mapping on A is invariant with respect to the representation on $\mathcal{L}(A)$ obtained from the adjoint representation of A on itself, as on p46 of [25]. This corresponds to the first part of Exercise 2 on p125 of [14].

Let V be a vector space over k that is a module over A, as a Lie algebra over k. Thus V may be considered as a left module over UA, as an associative algebra over k, as in Section 25.6. The action of $c_A(b)$ on V is the same as the Casimir element of the space $\mathcal{L}(V)$ of linear mappings from V into itself associated to b as in Section 13.3, as mentioned in Section 13.4.

Using (39.1.4), we get that

(39.1.5) the action of $c_A(b)$ on V commutes with the actions of all other elements of UA on V,

which is the same as saying that the action of $c_A(b)$ on V commutes with the actions of all elements of A on V. This was verified directly in Section 13.3, and (39.1.4) can be obtained in the same way, as in the first part of Exercise 2 on p125 of [14].

39.2 Casimir elements and nice bases

Let us return now to the same notation and hypotheses as in Section 33.1. Also let $b(\cdot, \cdot)$ be a nondegenerate symmetric bilinear form on A that is associative on A, as in the previous section. If $\alpha, \beta \in A_0'$ and $\alpha + \beta \neq 0$, then

(39.2.1) $$b(x, y) = 0 \quad \text{for every } x \in A_\alpha,\ y \in A_\beta,$$

as in Section 17.3. This implies that the restriction of $b(\cdot,\cdot)$ to A_0 is nondegenerate, as before.

Let $\alpha \in \Phi$ and $x \in A_\alpha$ be given. If $w \in A_0$ and $y \in A_{-\alpha}$, then

$$b(w, [x,y]_A) = \alpha(w)\, b(x,y), \tag{39.2.2}$$

as in Section 17.3 again. If $x \neq 0$, then there is a $y \in A_{-\alpha}$ such that $b(x,y) \neq 0$, as before. Of course, this means that $b(x,y) \neq 0$ for every $y \in A_{-\alpha}$ with $y \neq 0$, because $A_{-\alpha}$ has dimension one as a vector space over k.

Remember that Δ is a base for Φ, and that h_α, $\alpha \in \Delta$, is a basis for A_0, as a vector space over k. If $\beta \in \Delta$, then there is a unique $w_\beta \in A_0$ such that

$$\begin{aligned} b(h_\alpha, w_\beta) &= 1 \quad \text{when } \alpha = \beta \\ &= 0 \quad \text{for every } \alpha \in \Delta \text{ with } \alpha \neq \beta, \end{aligned} \tag{39.2.3}$$

because the restriction of $b(\cdot,\cdot)$ to A_0 is nondegenerate. Note that w_β, $\beta \in \Delta$, is a basis for A_0, as a vector space over k.

Let x_α be a nonzero element of A_α for each $\alpha \in \Phi$. This leads to a unique $z_\alpha \in A_{-\alpha}$ such that

$$b(x_\alpha, z_\alpha) = 1 \tag{39.2.4}$$

for each $\alpha \in \Phi$.

Observe that

$$\{h_\alpha : \alpha \in \Delta\} \cup \{x_\alpha : \alpha \in \Phi\} \tag{39.2.5}$$

is a basis for A, as a vector space over k. Similarly,

$$\{w_\alpha : \alpha \in \Delta\} \cup \{z_\alpha : \alpha \in \Phi\} \tag{39.2.6}$$

is a basis for A. These two bases are dual to each other with respect to $b(\cdot,\cdot)$, by construction.

If $\alpha \in A_0'$, then there is a unique $t_{b,\alpha} \in A_0$ such that

$$\alpha(w) = b(w, t_{b,\alpha}) \tag{39.2.7}$$

for every $w \in A_0$, because the restriction of $b(\cdot,\cdot)$ to A_0 is nondegenerate, as in Section 17.5. If $\alpha \in \Phi$, then

$$[x_\alpha, z_\alpha]_A = t_{b,\alpha}, \tag{39.2.8}$$

by (39.2.2) and (39.2.4). Note that

$$\alpha(t_{b,\alpha}) = b(t_{b,\alpha}, t_{b,\alpha}) \tag{39.2.9}$$

for every $\alpha \in A_0'$.

If $\alpha \in \Phi$, then there is a unique $y_\alpha \in A_{-\alpha}$ such that $y_\alpha \neq 0$ and $[x_\alpha, y_\alpha]_A = h_\alpha$, as usual. This implies that

$$h_\alpha = [x_\alpha, y_\alpha]_A = b(x_\alpha, y_\alpha)\, t_{b,\alpha}, \tag{39.2.10}$$

by (39.2.2). It follows that

$$b(x_\alpha, y_\alpha)\,\alpha(t_{b,\alpha}) = \alpha(h_\alpha) = 2, \tag{39.2.11}$$

and in particular that $b(x_\alpha, y_\alpha), \alpha(t_{b,\alpha}) \neq 0$. We also have that

$$y_\alpha = b(x_\alpha, y_\alpha)\, z_\alpha, \tag{39.2.12}$$

because $A_{-\alpha}$ has dimension one as a vector space over k.

Let UA be a universal enveloping algebra of A again, and let $c_A(b)$ be the Casimir element of UA associated to b, as in the previous section. In this case, we can use the dual bases (39.2.5) and (39.2.6) to express $c_A(b)$ as

$$c_A(b) = \sum_{\alpha \in \Delta} h_\alpha\, w_\alpha + \sum_{\alpha \in \Phi} x_\alpha\, z_\alpha, \tag{39.2.13}$$

as on p118 of [14].

39.3 Adjusted bases for $sl_2(k)$ modules

Let us continue with the same notation and hypotheses as in the previous section. Let $\alpha \in \Phi$ be given, and remember that the linear span of x_α, y_α, and h_α in A is a Lie subalgebra of A, that is isomorphic to $sl_2(k)$, as a Lie algebra over k. Of course, this is the same as the linear span of x_α, z_α, and $t_{b,\alpha}$ in A.

Let m be a nonnegative integer, and let $W(m)$ be the module over the linear span of x_α, y_α, and h_α in A, as a Lie algebra over k, discussed in Section 15.4. Thus $W(m)$ is a vector space over k with a basis $v_0, v_1, \ldots, v_m$, and we put $v_{-1} = v_{m+1} = 0$ for convenience. The actions of x_α, y_α, and h_α on $W(m)$ are defined by

$$h_\alpha \cdot v_j = (m - 2\,j)\, v_j, \tag{39.3.1}$$

$$y_\alpha \cdot v_j = (j+1)\, v_{j+1}, \tag{39.3.2}$$

$$x_\alpha \cdot v_j = (m - j + 1)\, v_{j-1} \tag{39.3.3}$$

for $j = 0, 1, \ldots, m$, as before.

It will be convenient to use another basis for $W(m)$, to deal with the actions of x_α, z_α, and $t_{b,\alpha}$ on $W(m)$, as on p119 of [14]. Note that

$$z_\alpha = (\alpha(t_{b,\alpha})/2)\, y_\alpha, \tag{39.3.4}$$

$$t_{b,\alpha} = (\alpha(t_{b,\alpha})/2)\, h_\alpha, \tag{39.3.5}$$

by (39.2.10), (39.2.11), and (39.2.12). Put

$$u_j = j!\,(\alpha(t_{b,\alpha})^j/2^j)\, v_j \tag{39.3.6}$$

for $j = 0, 1, \ldots, m$, so that $u_0, u_1, \ldots, u_m$ is a basis for $W(m)$, as a vector space over k. As before, it is convenient to put $u_{-1} = u_{m+1} = 0$.

It is easy to see that

$$t_{b,\alpha} \cdot u_j = (m - 2\,j)\,(\alpha(t_{b,\alpha})/2)\,u_j, \tag{39.3.7}$$

$$z_\alpha \cdot u_j = u_{j+1}, \tag{39.3.8}$$

$$x_\alpha \cdot u_j = j\,(m - j + 1)\,(\alpha(t_{b,\alpha})/2)\,u_{j-1} \tag{39.3.9}$$

for $j = 0, 1, \ldots, m$. It follows that

$$x_\alpha \cdot (z_\alpha \cdot u_j) = (m - j)\,(j + 1)\,(\alpha(t_{b,\alpha})/2)\,u_j \tag{39.3.10}$$

for $j = 0, 1, \ldots, m$, as on p119 of [14].

39.4 Some preliminary subspaces

We continue with the same notation and hypotheses as in the previous two sections. Let V be a vector space over k of positive finite dimension that is an irreducible module over A, as a Lie algebra over k. Remember that if $\nu \in A_0'$, then V_ν is the linear subspace of V consisting of vectors of weight ν with respect to A_0, as in Section 33.5.

Let ρ be the given representation of A on V, and let $\alpha \in \Phi$ be given, as in the previous section. If $\nu \in A_0'$, then

$$\rho_{z_\alpha}(V_\nu) \subseteq V_{\nu-\alpha}, \tag{39.4.1}$$

because $z_\alpha \in A_{-\alpha}$, as in Section 33.5. Similarly,

$$\rho_{x_\alpha}(V_{\nu-\alpha}) \subseteq V_\nu, \tag{39.4.2}$$

because $x_\alpha \in A_\alpha$. Thus

$$\rho_{x_\alpha}(\rho_{z_\alpha}(V_\nu)) \subseteq V_\nu. \tag{39.4.3}$$

We would like to consider the trace of $\rho_{x_\alpha} \circ \rho_{z_\alpha}$ as a linear mapping from V_ν into itself, as on p119 of [14].

Let $\nu \in A_0'$ be a weight of V with respect to A_0, and suppose that

$$\nu + \alpha \text{ is not a weight of } V. \tag{39.4.4}$$

This implies that the α-string of weights through ν is of the form

$$\nu, \nu - \alpha, \ldots, \nu - m\,\alpha, \tag{39.4.5}$$

where m is a nonnegative integer given by

$$m = \lambda_\alpha(\nu), \tag{39.4.6}$$

as in Section 38.12.

Let W be the linear subspace of V spanned by

$$V_\nu, V_{\nu-\alpha}, \ldots, V_{\nu-m\,\alpha}. \tag{39.4.7}$$

More precisely, W corresponds to the direct sum of these linear subspaces, as a vector space over k, as in Section 33.5. Remember that the linear span of x_α, y_α, and h_α in A is a Lie subalgebra of A that is isomorphic to $sl_2(k)$, as a Lie algebra over k. It is easy to see that

(39.4.8) W is a submodule of V, as a module over the linear span of x_α, y_α, and h_α in A,

using the remarks in Section 33.5.

If j is an integer, then

$$(\nu - j\,\alpha)(h_\alpha) = \nu(h_\alpha) - 2\,j, \tag{39.4.9}$$

and these values are distinct in k, because k has characteristic 0. Of course, the elements of $V_{\nu - j\,\alpha}$ are eigenvectors of ρ_{h_α}, with eigenvalue (39.4.9). It follows that any nonzero eigenvector of ρ_{h_α} in W has eigenvalue of the form (39.4.9) for some integer j with $0 \le j \le m$, and that the eigenvector is in $V_{\nu - j\,\alpha}$.

Remember that $\nu(h_\alpha)$ corresponds to an integer under the natural embedding of $\mathbf{Q}$ into k, as in Sections 38.1 and 38.2. We also have that $\nu \in E_{\mathbf{Q}}$ and $\nu(h_\alpha) = \lambda_\alpha(\nu)$, as in Sections 32.2 and 32.3. Thus

$$\nu(h_\alpha) = m, \tag{39.4.10}$$

by (39.4.6), so that

$$(\nu - j\,\alpha)(h_\alpha) = m - 2\,j \tag{39.4.11}$$

for every integer j.

Let Z be a nontrivial linear subspace of W that is a submodule of W, as a module over the linear span of x_α, y_α, and h_α in A. Suppose that Z is irreducible as a module over the linear span of x_α, y_α, and h_α in A, as a Lie algebra over k. This implies that Z is isomorphic as a module over the linear span of x_α, y_α, and h_α in A to a module of the form $W(m_Z)$ as in the previous section for some nonnegative integer m_Z, as in Section 15.9.

Note that m_Z is the largest eigenvalue of ρ_{h_α} on Z, because of the analogous property of $W(m_Z)$. In particular, m_Z is an eigenvalue of ρ_{h_α} on W, so that

$$m_Z = m - 2\,j_Z \tag{39.4.12}$$

for some nonnegative integer j_Z, as before. We also have that

$$2\,j_Z \le m, \tag{39.4.13}$$

because $m_Z \ge 0$.

Of course, Z corresponds to the direct sum of one-dimensional eigenspaces of ρ_{h_α}, as a vector space over k, with eigenvalues $m_Z - 2\,l$, $l = 0, 1, \ldots, m_Z$. Equivalently, these eigenvalues are equal to $m - 2\,j_Z - 2\,l$, $l = 0, 1, \ldots, m_Z$. This means that the eigenvalues are as in (39.4.11), with

$$j_Z \le j \le m - j_Z. \tag{39.4.14}$$

It follows that

$$Z \cap V_{\nu - j\,\alpha} \tag{39.4.15}$$

has dimension one when (39.4.14) holds, and that Z corresponds to their direct sum, as a vector space over k.

Weyl's theorem implies that W corresponds to the direct sum of finitely many irreducible submodules, as a module over the linear span of x_α, y_α, and h_α in A. Each of these irreducible submodules corresponds to the direct sum of its intersections with the $V_{\nu - j\,\alpha}$'s, as a vector space over k, as in the preceding paragraph.

It follows that $V_{\nu - j\,\alpha}$, $j = 0, 1, \ldots, m$, corresponds to the direct sum of its intersections with the irreducible submodules of W whose direct sum is W, as in the preceding paragraph, as a vector space over k. More precisely, $V_{\nu - j\,\alpha}$ corresponds to the direct sum of its intersection with the irreducible submodules of W whose direct sum is W for which the corresponding j_Z as in (39.4.12) satisfies (39.4.14).

If j is a nonnegative integer with $2\,j \le m$ and Z is as before, then $j \le m - j_Z$, by (39.4.13). This means that (39.4.14) reduces to asking that $j_Z \le j$. In this case, we get that $V_{\nu - j\,\alpha}$ corresponds to the direct sum of its intersections with the irreducible submodules of W whose direct sum is W for which the corresponding j_Z is less than or equal to j, as a vector space over k.

If l is a nonnegative integer with $2\,l \le m$, then let n_l be the number of these irreducible submodules of W whose direct sum is W, and for which the corresponding j_Z as in is equal to l. It follows that

$$\dim V_{\nu - j\,\alpha} = \sum_{l=0}^{j} n_l \tag{39.4.16}$$

for $j = 0, 1, \ldots, [m/2]$, where $[m/2]$ is the integer part of $m/2$, as on p120 of [14].

39.5 Some traces of $\rho_{x_\alpha} \circ \rho_{z_\alpha}$

Let us continue with the same notation and hypotheses as in the previous sections. Let l be a nonnegative integer with $l \le m$. We would like to compute the trace of $\rho_{x_\alpha} \circ \rho_{z_\alpha}$ on $V_{\nu - l\,\alpha}$, as on p120f of [14].

Let Z be a nontrivial linear subspace of W that is an irreducible submodule of W, as a module over the linear span of x_α, y_α, and h_α, as in the previous section. Let j_Z be as in (39.4.12), and suppose that

$$j_Z \le l \le m - j_Z. \tag{39.5.1}$$

This implies that $Z \cap V_{\nu - l\,\alpha}$ has dimension one as a vector space over k, as before. More precisely, $Z \cap V_{\nu - l\,\alpha}$ is spanned by an eigenvector of ρ_{h_α}, with eigenvalue

$$(\nu - l\,\alpha)(h_\alpha) = m - 2\,l = m_Z - 2\,(l - j_Z). \tag{39.5.2}$$

Remember that Z is isomorphic as a module over the linear span of x_α, y_α, and h_α in A to a module of the form $W(m_Z)$ in Section 39.3. Using this isomorphism, $Z \cap V_{\nu - l\,\alpha}$ corresponds to the linear span of v_j in $W(m_Z)$, with $j = l - j_Z$. This is the same as the span of u_j in $W(m_Z)$, with $j = l - j_Z$. We have seen that $x_\alpha \cdot (z_\alpha \cdot u_j)$ can be expressed as a multiple of u_j, as in (39.3.10).

It follows that the restriction of $\rho_{x_\alpha} \circ \rho_{z_\alpha}$ to $Z \cap V_{\nu - l\,\alpha}$ is equal to multiplication by

$$(m_Z - (l - j_Z))\,(l - j_Z + 1)\,(\alpha(t_{b,\alpha})/2). \tag{39.5.3}$$

This is the same as

$$(m - l - j_Z)\,(l - j_Z + 1)\,(\alpha(t_{b,\alpha})/2), \tag{39.5.4}$$

by (39.4.12).

Suppose that

$$2\,l \le m. \tag{39.5.5}$$

This implies that $l \le m - j_Z$, by (39.4.13), so that (39.5.1) reduces to the condition that $j_Z \le l$, as before. Remember that W corresponds to the direct sum of finitely many irreducible submodules, as a module over the linear span of x_α, y_α, and h_α in A, as in the previous section. We have also seen that $V_{\nu - l\,\alpha}$ corresponds to the direct sum of its intersections with these irreducible submodules of W, as a vector space over k. More precisely, in this case $V_{\nu - l\,\alpha}$ corresponds to the direct sum of its intersections with the irreducible submodules of W whose direct sum is W and for which the corresponding j_Z is less than or equal to l.

If j is a nonnegative integer with $2\,j \le m$, then n_j is the number of the irreducible submodules of W whose direct sum is W and for which the corresponding j_Z is equal to j, as before. Remember that $\rho_{x_\alpha} \circ \rho_{z_\alpha}$ maps $V_{\nu - l\,\alpha}$ into itself, as in the previous section. The trace of the restriction of $\rho_{x_\alpha} \circ \rho_{z_\alpha}$ to $V_{\nu - l\,\alpha}$ is equal to

$$\mathrm{tr}_{V_{\nu - l\,\alpha}}(\rho_{x_\alpha} \circ \rho_{z_\alpha}) = \sum_{j=0}^{l} n_j\,(m - l - j)\,(l - j + 1)\,(\alpha(t_{b,\alpha})/2). \tag{39.5.6}$$

More precisely, for each $j = 0, 1, \ldots, l$, there are n_j terms in the trace of the form (39.5.4), with $j_Z = j$.

Observe that

$$n_j = \dim V_{\nu - j\,\alpha} - \dim V_{\nu - (j-1)\,\alpha} \tag{39.5.7}$$

for each $j = 0, 1, \ldots, [m/2]$, by (39.4.16). This uses (39.4.4) when $j = 0$, which says that

$$\dim V_{\nu + \alpha} = 0. \tag{39.5.8}$$

It follows that

$$\begin{aligned} \mathrm{tr}_{V_{\nu - l\,\alpha}}(\rho_{x_\alpha} \circ \rho_{z_\alpha}) \quad &= \quad \sum_{j=0}^{l} (\dim V_{\nu - j\,\alpha} - \dim V_{\nu - (j-1)\,\alpha}) \\ &\qquad \cdot (m - l - j)\,(l - j + 1)\,(\alpha(t_{b,\alpha})/2). \end{aligned} \tag{39.5.9}$$

The right side of (39.5.9) is equal to

$$\sum_{j=0}^{l} (\dim V_{\nu - j\,\alpha})\,(m - l - j)\,(l - j + 1)\,(\alpha(t_{b,\alpha})/2) \tag{39.5.10}$$

minus

$$\sum_{j=0}^{l} (\dim V_{\nu - (j-1)\,\alpha})\,(m - l - j)\,(l - j + 1)\,(\alpha(t_{b,\alpha})/2). \tag{39.5.11}$$

Note that the $j = 0$ term in (39.5.11) is equal to 0, by (39.5.8). It is easy to see that (39.5.11) is equal to

$$\sum_{j=0}^{l} (\dim V_{\nu - j\,\alpha})\,(m - l - j - 1)\,(l - j)\,(\alpha(t_{b,\alpha})/2), \tag{39.5.12}$$

because the $j = l$ term in this sum is equal to 0.

Observe that

$$\begin{aligned} &(m - l - j)\,(l - j + 1) - (m - l - j - 1)\,(l - j) \\ &= (m - l - j)\,(l - j) + (m - l - j) \\ &\quad -(m - l - j)\,(l - j) + (l - j) \\ &= m - 2\,j \end{aligned} \tag{39.5.13}$$

for each $j = 0, 1, \ldots, l$. Using this, we get that

$$\mathrm{tr}_{V_{\nu - l\,\alpha}}(\rho_{x_\alpha} \circ \rho_{z_\alpha}) = \sum_{j=0}^{l} (\dim V_{\nu - j\,\alpha})\,(m - 2\,j)\,(\alpha(t_{b,\alpha})/2). \tag{39.5.14}$$

More precisely, the right side is obtained by taking (39.5.10) minus (39.5.12), and using (39.5.13) for the factors in the middle of the terms in the sums. Remember that this holds when $2\,l \le m$, as in (39.5.5).

39.6 The case where $2\,l > m$

We continue with the same notation and hypotheses as in the previous sections. In particular, l is a nonnegative integer with $l \le m$, as in the preceding section, and we suppose that

$$2\,l > m \tag{39.6.1}$$

in this section. We would like to compute the trace of $\rho_{x_\alpha} \circ \rho_{z_\alpha}$ on $V_{\nu - l\,\alpha}$, as on p121 of [14].

Let us check that

$$\dim V_{\nu - j\,\alpha} = \dim V_{\nu - (m-j)\,\alpha} \tag{39.6.2}$$

for $j = 0, 1, \ldots, m$. Remember that the α-string of weights through ν is as in (39.4.5). The α-string through ν is mapped to itself by the symmetry σ_α on $E_{\mathbf{R}}$ that maps Φ onto itself, as in Section 38.12. More precisely, σ_α maps $\nu - j\,\alpha$ to $\nu - (m-j)\,\alpha$ for each $j = 0, 1, \ldots, m$, by (39.4.6). This implies (39.6.2), because the dimensions of the weight spaces are invariant under the action of the Weyl group of Φ on the weights of V, as in Section 38.7.

Let Z be a nontrivial linear subspace of W that is an irreducible submodule of W, as a module over the linear span of x_α, y_α, and h_α in A, as in Section 39.4. If j_Z is as in (39.4.12), then $2\,j_Z \le m$, as in (39.4.13), so that $j_Z < l$, by (39.6.1). This means that (39.5.1) holds exactly when $l \le m - j_Z$, which is the same as saying that

$$j_Z \le m - l. \tag{39.6.3}$$

In this case, $Z \cap V_{\nu - l\,\alpha}$ has dimension one as a vector space over k, as in the previous two sections. The restriction of $\rho_{x_\alpha} \circ \rho_{z_\alpha}$ to $Z \cap V_{\nu - l\,\alpha}$ is equal to multiplication by (39.5.4), as before.

Remember that W corresponds to the direct sum of finitely many irreducible submodules, as a module over the linear span of x_α, y_α, and h_α in A, as in Section 39.4. We also have that $V_{\nu - l\,\alpha}$ corresponds to the direct sum of its intersections with these irreducible submodules of W, as a vector space over k, as before. In this case we get more precisely that V corresponds to the direct sum of its intersections with the irrducible submodules of W whose direct sum is W and for which the corresponding j_Z satisfies (39.6.3). Note that

$$m - l < m/2, \tag{39.6.4}$$

by (39.6.1).

If j is a nonnegative integer with $j \le m - l$, then $j < m/2$, by (39.6.4). Remember that n_j is the number of the irreducible submodules of W whose direct sum is W and for which the corresponding j_Z is equal to j, as in the previous two sections. Of course, $\rho_{x_\alpha} \circ \rho_{z_\alpha}$ maps $V_{\nu - l\,\alpha}$ into itself, as in Section 39.4. The trace of the restriction of $\rho_{x_\alpha} \circ \rho_{z_\alpha}$ to $V_{\nu - l\,\alpha}$ is equal to

$$\operatorname{tr}_{V_{\nu - l\,\alpha}}(\rho_{x_\alpha} \circ \rho_{z_\alpha}) = \sum_{j=0}^{m-l} n_j\,(m - l - j)\,(l - j + 1)\,(\alpha(t_{b,\alpha})/2). \tag{39.6.5}$$

Indeed, for each $j = 0, 1, \ldots, m - l$, there are n_j terms in the trace of the form (39.5.4), with $j_Z = j$, as before.

Observe that the $j = m - l$ term in the sum on the right side of (39.6.5) is equal to 0. Thus

$$\operatorname{tr}_{V_{\nu - l\,\alpha}}(\rho_{x_\alpha} \circ \rho_{z_\alpha}) = \sum_{j=0}^{m-l-1} n_j\,(m - l - j)\,(l - j + 1)\,(\alpha(t_{b,\alpha})/2). \tag{39.6.6}$$

More precisely, if $l = m$, then the sum on the right should be interpreted as being equal to 0.

As in the previous section, we can use (39.5.7) to express the sum as

$$\sum_{j=0}^{m-l-1} (\dim V_{\nu - j\,\alpha})\,(m - l - j)\,(l - j + 1)\,(\alpha(t_{b,\alpha})/2) \tag{39.6.7}$$

minus

$$\sum_{j=0}^{m-l-1} (\dim V_{\nu - (j-1)\,\alpha})\,(m - l - j)\,(l - j + 1)\,(\alpha(t_{b,\alpha})/2). \tag{39.6.8}$$

The $j = 0$ term in (39.6.8) is equal to 0, by (39.5.8), as before. One can check that (39.6.8) is equal to

$$\sum_{j=0}^{m-l-1} (\dim V_{\nu - j\,\alpha})\,(m - l - j - 1)\,(l - j)\,(\alpha(t_{b,\alpha})/2), \tag{39.6.9}$$

because the $j = m - l - 1$ term in this sum is equal to 0. Of course, all of these sums should be interpreted as being equal to 0 when $l = m$, as in the preceding paragraph.

As before, we can use (39.5.13) to get that

$$\mathrm{tr}_{V_{\nu - l\,\alpha}}(\rho_{x_\alpha} \circ \rho_{z_\alpha}) = \sum_{j=0}^{m-l-1} (\dim V_{\nu - j\,\alpha})\,(m - 2\,j)\,(\alpha(t_{b,\alpha})/2). \tag{39.6.10}$$

The right side is obtained by taking (39.6.7) minus (39.6.9), and using (39.5.13) for the factors in the middle of the terms in the sums again. The sum on the right should be interpreted as being equal to 0 when $l = m$, as usual.

39.7 Some related expressions for traces

Let us continue with the same notations and hypotheses as in the previous sections. Let us check that

$$\mathrm{tr}_{V_{\nu - l\,\alpha}}(\rho_{x_\alpha} \circ \rho_{z_\alpha}) = \sum_{j=0}^{l} (\dim V_{\nu - j\,\alpha})\,(m - 2\,j)\,(\alpha(t_{b,\alpha})/2) \tag{39.7.1}$$

for every $l = 0, 1, \ldots, m$, as on p121 of [14]. This is the same as (39.5.14), which we have seen holds when $2\,l \le m$.

If $2\,l > m$, then $l > m - l$, and we would like to verify that

$$\sum_{j=m-l}^{l} (\dim V_{\nu - j\,\alpha})\,(m - 2\,j) = 0. \tag{39.7.2}$$

It is easy to see that (39.7.1) follows from (39.6.10) and (39.7.2). Observe that

$$m - 2\,(m - j) = -(m - 2\,j) \tag{39.7.3}$$

for every j. This implies that

$$(39.7.4) \quad (\dim V_{\nu-(m-j)\,\alpha})\,(m - 2\,(m-j)) = -(\dim V_{\nu-j\,\alpha})\,(m - 2\,j)$$

for $j = 0, 1, \ldots, m$, by (39.6.2). One can get (39.7.2) from (39.7.4), using also the fact that the $j = m/2$ term in the sum on the left side of (39.7.2) is equal to 0 when m is even.

Let $\alpha \in \Phi$ be given again, and suppose now that $\nu \in A_0'$ is any weight of V with respect to A_0. We do not ask that $\nu+\alpha$ not be a weight of V, as in (39.4.4). As in Section 38.12, we can take r, q to be the largest integers such that $\nu - r\,\alpha$ and $\nu + q\,\alpha$ are weights of V, so that $q, r \geq 0$, by hypothesis. Remember that $r - q = \lambda_\alpha(\nu)$, as before. Thus the previous remarks hold for $\nu + q\,\alpha$ in place of ν, and with

$$(39.7.5) \qquad m = r + q = \lambda_\alpha(\nu + q\,\alpha).$$

It follows that

$$(39.7.6) \quad \mathrm{tr}_{V_{\nu+(q-l)\,\alpha}}(\rho_{x_\alpha} \circ \rho_{z_\alpha}) = \sum_{j=0}^{l} (\dim V_{\nu+(q-j)\,\alpha})\,(m - 2\,j)\,(\alpha(t_{b,\alpha})/2)$$

for every $l = 0, 1, \ldots, m$, as in (39.7.1). In particular, we can take $l = q$, to get that

$$(39.7.7) \quad \mathrm{tr}_{V_\nu}(\rho_{x_\alpha} \circ \rho_{z_\alpha}) = \sum_{j=0}^{q} (\dim V_{\nu+(q-j)\,\alpha})\,(m - 2\,j)\,(\alpha(t_{b,\alpha})/2).$$

Equivalently,

$$(39.7.8) \quad \mathrm{tr}_{V_\nu}(\rho_{x_\alpha} \circ \rho_{z_\alpha}) = \sum_{j=0}^{q} (\dim V_{\nu+j\,\alpha})\,(m - 2\,(q-j))\,(\alpha(t_{b,\alpha})/2).$$

Observe that

$$(39.7.9) \qquad m - 2\,(q-j) = r - q + 2\,j = \lambda_\alpha(\nu) + 2\,j = \nu(h_\alpha) + 2\,j,$$

where the last step is as in Sections 32.2 and 32.3. This implies that

$$(39.7.10) \quad \mathrm{tr}_{V_\nu}(\rho_{x_\alpha} \circ \rho_{z_\alpha}) = \sum_{j=0}^{q} (\dim V_{\nu+j\,\alpha})\,(\nu(h_\alpha) + 2\,j)\,(\alpha(t_{b,\alpha})/2).$$

If $j > q$, then $\nu + j\,\alpha$ is not a weight of V, so that $\dim V_{\nu+j\,\alpha} = 0$. Thus

$$(39.7.11) \quad \mathrm{tr}_{V_\nu}(\rho_{x_\alpha} \circ \rho_{z_\alpha}) = \sum_{j=0}^{\infty} (\dim V_{\nu+j\,\alpha})\,(\nu(h_\alpha) + 2\,j)\,(\alpha(t_{b,\alpha})/2),$$

where the sum on the right reduces to a finite sum. This corresponds to some remarks on p121 of [14].

39.8 Related identities for suitable ν

Let us continue with the same notation and hypotheses as in the previous sections, and let Υ be as in Section 32.3. Let $\alpha \in \Phi$ be given again, and suppose that $\nu \in A_0'$ has the property that

(39.8.1) $$\nu + j_0\,\alpha \text{ is a weight of } V \text{ with respect to } A_0$$

for some integer j_0. This implies that $\nu + j_0\,\alpha \in \Upsilon$, as in Section 38.12. It follows that $\nu \in \Upsilon$, because Υ is a group with respect to addition that contains Φ.

Let q_0, r_0 be the maximal and minimal integers such that

(39.8.2) $$\nu + q_0\,\alpha,\ \nu + r_0\,\alpha \text{ are weights of } V \text{ with respect to } A_0,$$

respectively. Thus $r_0 \le j_0 \le q_0$. If $j \in \mathbf{Z}$ and $r_0 \le j \le q_0$, then

(39.8.3) $$\nu + j\,\alpha \text{ is a weight of } V \text{ with respect to } A_0,$$

as in Section 38.12. Equivalently,

(39.8.4) $$\nu + r_0\,\alpha, \ldots, \nu + q_0\,\alpha,$$

is the α-string through any of its terms, as before.

Of course,

(39.8.5) $$\sigma_\alpha(\nu + j\,\alpha) = \nu + j\,\alpha - (\lambda_\alpha(\nu) + j\,\lambda_\alpha(\alpha))\,\alpha = \nu - (\lambda_\alpha(\nu) + j)\,\alpha$$

for every $j \in \mathbf{Z}$. Remember that the set of weights of V is invariant under the Weyl group of Φ, as in Section 38.7. This means that σ_α maps (39.8.4) onto itself, in the opposite order, as before. In particular,

(39.8.6) $$\sigma_\alpha(\nu + r_0\,\alpha) = \nu + q_0\,\alpha$$

It follows that

(39.8.7) $$-r_0 - q_0 = \lambda_\alpha(\nu),$$

which could also be obtained from the analogous statement in Section 38.12.

Note that

(39.8.8) $$\dim V_{\nu + j\,\alpha} = \dim V_{\sigma_\alpha(\nu + j\,\alpha)}$$

for every $j \in \mathbf{Z}$, because the dimensions of the weight spaces are invariant under elements of the Weyl group of Φ, as in Section 38.7 again. Thus

(39.8.9) $$\dim V_{\nu + j\,\alpha} = \dim V_{\nu - (\lambda_\alpha(\nu) + j)\,\alpha}$$

for every $j \in \mathbf{Z}$, which is the same as (39.6.2) when $q_0 = 0$. We also have that

(39.8.10) $$\lambda_\alpha(\nu) - 2\,(\lambda_\alpha(\nu) + j) = -(\lambda_\alpha(\nu) + 2\,j)$$

for every $j \in \mathbf{Z}$. It follows that

$$(\dim V_{\nu-(\lambda_\alpha(\nu)+j)\,\alpha})\,(\lambda_\alpha(\nu) - 2\,(\lambda_\alpha(\nu) + j)) = -(\dim V_{\nu+j\,\alpha})\,(\lambda_\alpha(\nu) + 2\,j) \tag{39.8.11}$$

for every $j \in \mathbf{Z}$, which is the same as (39.7.4) when $q_0 = 0$.

Let us check that

$$\sum_{j=-\infty}^{\infty} (\dim V_{\nu+j\,\alpha})\,(\lambda_\alpha(\nu) + 2\,j) = 0. \tag{39.8.12}$$

More precisely, the sum on the left reduces to a finite sum, because $\dim V_{\nu+j\,\alpha} = 0$ unless $\nu + j\,\alpha$ is a weight of V. If $\lambda_\alpha(\nu)$ is an even integer, then the term in the sum corresponding to $j = -\lambda_\alpha(\nu)/2$ is automatically equal to 0. If $j \in \mathbf{Z}$ and $j \neq -\lambda_\alpha(\nu)/2$, then the terms in the sum corresponding to j and to $-(\lambda_\alpha(\nu) + j)$ cancel with each other, because of (39.8.11). This means that the terms corresponding to $j > -\lambda_\alpha(\nu)/2$ and $j < -\lambda_\alpha(\nu)/2$ cancel in the sum.

Remember that $\lambda_\alpha(\nu) = \nu(h_\alpha)$, as in Sections 32.2 and 32.3. Thus (39.8.12) is the same as saying that

$$\sum_{j=-\infty}^{\infty} (\dim V_{\nu+j\,\alpha})\,(\nu(h_\alpha) + 2\,j) = 0. \tag{39.8.13}$$

In fact, this holds for every $\nu \in A_0'$. Indeed, if $\nu \in A_0'$ and $\nu + j\,\alpha$ is not a weight of V for any $j \in \mathbf{Z}$, then $\dim V_{\nu+j\,\alpha} = 0$ for every $j \in \mathbf{Z}$, and (39.8.13) holds trivially. This basically corresponds to (10) on p122 of [14].

If $\nu \in A_0'$ is not a weight of V, then

$$\sum_{j=1}^{\infty} (\dim V_{\nu+j\,\alpha})\,(\nu(h_\alpha) + 2\,j) = 0, \tag{39.8.14}$$

where the sum on the left reduces to a finite sum as before. This holds trivially when $\nu + j\,\alpha$ is not a weight of V for any positive integer j, as in the preceding paragraph. Otherwise, suppose that (39.8.1) holds for some $j_0 \geq 1$, and let r_0 be as in (39.8.2). In this case, $r_0 \geq 1$, because of (39.8.3). This means that (39.8.14) follows from (39.8.13), as on p121f of [14].

39.9 Some remarks about dual bases

We continue with the same notation and hypotheses as in the previous sections. Remember that Δ is a base for Φ, and that h_α, $\alpha \in \Delta$, is a basis for A_0, as a vector space over k.

If $\beta \in \Delta$, then there is a unique $\mu_\beta \in A_0'$ such that

$$\begin{aligned} \mu_\beta(h_\alpha) &= 1 \quad \text{when } \alpha = \beta \\ &= 0 \quad \text{for every } \alpha \in \Delta \text{ with } \alpha \neq \beta. \end{aligned} \tag{39.9.1}$$

The μ_β's, $\beta \in \Delta$, form a basis for A_0', as a vector space, which is the dual basis associated to h_α, $\alpha \in \Delta$.

If $\nu \in A_0'$, then there is a unique $t_{b,\nu} \in A_0$ such that

$$\nu(w) = b(w, t_{b,\nu}) \tag{39.9.2}$$

for every $w \in A_0$, because the restriction of $b(\cdot,\cdot)$ to A_0 is nondegenerate, as in Section 39.2. More precisely, $\nu \mapsto t_{b,\nu}$ is a one-to-one linear mapping from A_0' onto A_0.

In Section 39.2, we took w_β, $\beta \in \Delta$, to be the basis for A_0 that is dual to h_α, $\alpha \in \Delta$, with respect to the bilinear form $b(\cdot,\cdot)$ on A_0. If $\alpha, \beta \in \Delta$, then

$$\mu_\beta(h_\alpha) = b(h_\alpha, w_\beta) \tag{39.9.3}$$

by construction. This means that

$$b(h_\alpha, t_{b,\mu_\beta}) = b(h_\alpha, w_\beta) \tag{39.9.4}$$

for every $\alpha, \beta \in \Delta$, by (39.9.2). It follows that

$$t_{b,\mu_\beta} = w_\beta \tag{39.9.5}$$

for every $\beta \in \Delta$.

If $\nu \in A_0'$, then

$$\nu(h_\alpha) = \sum_{\beta \in \Delta} \nu(h_\beta)\, \mu_\beta(h_\alpha) \tag{39.9.6}$$

for every $\alpha \in \Delta$. This implies that

$$\nu = \sum_{\beta \in \Delta} \nu(h_\beta)\, \mu_\beta, \tag{39.9.7}$$

as elements of A_0'. Thus

$$t_{b,\nu} = \sum_{\beta \in \Delta} \nu(h_\beta)\, t_{b,\mu_\beta} = \sum_{\beta \in \Delta} \nu(h_\beta)\, w_\beta. \tag{39.9.8}$$

If $\nu_1, \nu_2 \in A_0'$, then put

$$b'(\nu_1, \nu_2) = b(t_{b,\nu_1}, t_{b,\nu_2}). \tag{39.9.9}$$

This defines a nondegenerate bilinear form on A_0', as in Section 17.10. Note that

$$b'(\nu_1, \nu_2) = \nu_2(t_{b,\nu_1}) \tag{39.9.10}$$

for every $\nu_1, \nu_2 \in A_0'$, by (39.9.2). It follows that

$$b'(\nu_1, \nu_2) = \sum_{\beta \in \Delta} \nu_1(h_\beta)\, \nu_2(w_\beta) \tag{39.9.11}$$

for every $\nu_1, \nu_2 \in A_0'$, by (39.9.8). This corresponds to some remarks on p121 of [14].

If $\alpha \in \Phi$, then

(39.9.12) $$b'(\alpha, \alpha) = \alpha(t_{b,\alpha}) \neq 0,$$

as in Section 39.2. We also have that

(39.9.13) $$h_\alpha = (2/\alpha(t_{b,\alpha}))\, t_{b,\alpha} = (2/b'(\alpha, \alpha))\, t_{b,\alpha},$$

because h_α is a multiple of $t_{b,\alpha}$, and $\alpha(h_\alpha) = 2$. If $\nu \in A_0'$, then we get that

(39.9.14) $$\nu(h_\alpha) = (2/\alpha(t_{b,\alpha}))\, \nu(t_{b,\alpha}) = (2/\alpha(t_{b,\alpha}))\, b'(\alpha, \nu).$$

39.10 Traces and b'

Let us continue with the same notation and hypotheses as in the previous sections, and let $\nu \in A_0'$ be a weight of V with respect to A_0 again. If $w \in A_0$, then the action of w on V_ν is the same as multiplication by $\nu(w)$, by definition of V_ν. If $\alpha \in \Delta$, then it follows that $\rho_{h_\alpha} \circ \rho_{w_\alpha}$ corresponds to multiplication by $\nu(h_\alpha)\, \nu(w_\alpha)$ on V_ν. In particular, $\rho_{h_\alpha} \circ \rho_{w_\alpha}$ maps V_ν into itself, with trace

(39.10.1) $$\mathrm{tr}_{V_\nu}(\rho_{h_\alpha} \circ \rho_{w_\alpha}) = (\dim V_\nu)\, \nu(h_\alpha)\, \nu(w_\alpha).$$

This implies that

(39.10.2) $$\sum_{\alpha \in \Delta} \mathrm{tr}_{V_\nu}(\rho_{h_\alpha} \circ \rho_{w_\alpha}) = (\dim V_\nu) \sum_{\alpha \in \Delta} \nu(h_\alpha)\, \nu(w_\alpha).$$

Thus

(39.10.3) $$\sum_{\alpha \in \Delta} \mathrm{tr}_{V_\nu}(\rho_{h_\alpha} \circ \rho_{w_\alpha}) = (\dim V_\nu)\, b'(\nu, \nu),$$

where $b'(\cdot, \cdot)$ is as in (39.9.9), by (39.9.11). This corresponds to (8) on p121 of [14].

Let $\alpha \in \Phi$ be given, and let us rewrite (39.7.11) using $b'(\cdot, \cdot)$. Namely,

(39.10.4) $$\mathrm{tr}_{V_\nu}(\rho_{x_\alpha} \circ \rho_{z_\alpha}) = \sum_{j=0}^{\infty} (\dim V_{\nu + j\,\alpha})\, b'(\alpha, \nu + j\,\alpha),$$

by (39.9.12) and (39.9.14). This corresponds to (7) on p121 of [14].

Let $c_A(b)$ be the Casimir element of UA associated to b, as in Section 39.1. The action of $c_A(b)$ on V leads to a linear mapping $c_{A,V}(b)$ from V into itself. Using the expression (39.2.13) for $c_A(b)$, we get that

(39.10.5) $$c_{A,V}(b) = \sum_{\alpha \in \Delta} \rho_{h_\alpha} \circ \rho_{w_\alpha} + \sum_{\alpha \in \Phi} \rho_{x_\alpha} \circ \rho_{z_\alpha}.$$

Thus

$$(39.10.6) \qquad \operatorname{tr}_{V_\nu} c_{A,V}(b) = (\dim V_\nu)\, b'(\nu,\nu) + \sum_{\alpha\in\Phi}\sum_{j=0}^{\infty}(\dim V_{\nu+j\,\alpha})\, b'(\alpha,\nu+j\,\alpha),$$

by (39.10.3) and (39.10.4). This corresponds to some remarks on p121 of [14].

Observe that

$$(39.10.7) \qquad \sum_{\alpha\in\Phi} b'(\alpha,\nu) = 0,$$

because the term corresponding to any $\alpha \in \Phi$ cancels with the term corresponding to $-\alpha$. This permits us to drop the $j = 0$ term from the sum on the right side of (39.10.6), to get that

$$(39.10.8) \qquad \operatorname{tr}_{V_\nu} c_{A,V}(b) = (\dim V_\nu)\, b'(\nu,\nu) + \sum_{\alpha\in\Phi}\sum_{j=1}^{\infty}(\dim V_{\nu+j\,\alpha})\, b'(\alpha,\nu+j\,\alpha).$$

This corresponds to some more remarks on p121 of [14].

If $\nu \in A_0'$ is not a weight of V, then

$$(39.10.9) \qquad \sum_{j=1}^{\infty}(\dim V_{\nu+j\,\alpha})\, b'(\alpha,\nu+j\,\alpha) = 0$$

for every $\alpha \in \Phi$. This follows from (39.8.14), using (39.9.12) and (39.9.14). Of course, $V_\nu = \{0\}$ in this case, so that the left side of (39.10.8) and the first term on the right side are equal to 0. In fact, (39.10.8) also holds under these conditions, because of (39.10.9). This corresponds to some remarks on p121f of [14].

Similarly, if $\nu \in A_0'$ and $\alpha \in \Phi$, then

$$(39.10.10) \qquad \sum_{j=-\infty}^{\infty}(\dim V_{\nu+j\,\alpha})\, b'(\alpha,\nu+j\,\alpha) = 0.$$

This follows from (39.8.13), using (39.9.12) and (39.9.14) again. Equivalently,

$$(39.10.11) \qquad \sum_{j=1}^{\infty}(\dim V_{\nu-j\,\alpha})\, b'(-\alpha,\nu-j\,\alpha) = (\dim V_\nu)\, b'(\alpha,\nu) + \sum_{j=1}^{\infty}(\dim V_{\nu+j\,\alpha})\, b'(\alpha,\nu+j\,\alpha).$$

Remember that Δ is a base for Φ, and that Φ^+ is the set of positive roots in Φ with respect to Δ. The sum over $\alpha \in \Phi$ in the right side of (39.10.8) can be expressed as

$$\sum_{\alpha\in\Phi^+}\sum_{j=1}^{\infty}(\dim V_{\nu+j\,\alpha})\,b'(\alpha,\nu+j\,\alpha) + \sum_{\alpha\in\Phi^+}\sum_{j=1}^{\infty}(\dim V_{\nu-j\,\alpha})\,b'(-\alpha,\nu-j\,\alpha). \tag{39.10.12}$$

Thus we can use (39.10.11) to get that

$$\operatorname{tr}_{V_\nu} c_{A,V}(b) = (\dim V_\nu)\,b'(\nu,\nu) + \sum_{\alpha\in\Phi^+}(\dim V_\nu)\,b'(\alpha,\nu) + 2\sum_{\alpha\in\Phi^+}\sum_{j=1}^{\infty}(\dim V_{\nu+j\,\alpha})\,b'(\alpha,\nu+j\,\alpha). \tag{39.10.13}$$

Put

$$\delta = \frac{1}{2}\sum_{\alpha\in\Phi^+}\alpha, \tag{39.10.14}$$

which was denoted ρ in Section 30.6. Using this, we get that

$$\operatorname{tr}_{V_\nu} c_{A,V}(b) = (\dim V_\nu)\,b'(\nu+2\,\delta,\nu) + 2\sum_{\alpha\in\Phi^+}\sum_{j=1}^{\infty}(\dim V_{\nu+j\,\alpha})\,b'(\alpha,\nu+j\,\alpha). \tag{39.10.15}$$

This corresponds to some remarks on p122 of [14].

39.11 Using an algebraically closed field

We continue with the same notations and hypotheses as in the previous sections, and suppose also for the moment that k is algebraically closed.

Remember that the Casimir element $c_A(b)$ of UA associated to b is in the center of UA, as in Section 39.1. This implies that the associated linear mapping $c_{A,V}(b)$ on V commutes with the action of any element of A on V.

Remember that V is supposed to be irreducible as a module over A, as in Section 39.4. Thus we can use Schur's lemma to get that

$$c_{A,V}(b) = c(A,b,V)\,I_V \tag{39.11.1}$$

for some $c(A,b,V)\in k$, where I_V is the identity mapping on V, as in Section 6.14.

Of course, V is supposed to have positive finite dimension as a vector space over k too. This implies that V has a primitive or maximal vector of some weight $\mu\in A_0'$, as in Section 38.1. It follows that V is standard cyclic of weight μ, because V is irreducible as a module over A, as in Section 33.10.

Remember that the weight space V_μ corresponding to μ has dimension one as a vector space over k, as in Section 33.8. This implies that

$$\mathrm{tr}_{V_\mu} c_{A,V}(b) = c(A, b, V). \tag{39.11.2}$$

If $\alpha \in \Phi^+$ and $j \in \mathbf{Z}_+$, then $\mu + j\,\alpha$ is not a weight of V, as in Section 33.8 again. Thus we can use (39.10.15) to get that

$$c(A, b, V) = b'(\mu + 2\,\delta, \mu). \tag{39.11.3}$$

This corresponds to some remarks on p122 of [14].

Otherwise, if we do not ask that k be algebraically closed, then let k_1 be an algebraically closed field that contains k as a subfield, as usual. We can get a vector space $\widetilde{V}$ over k_1 from V as in Section 33.2, as well as a Lie algebra $(\widetilde{A}, [\cdot,\cdot]_{\widetilde{A}})$ over k_1. Remember that the action of A on V has a unique extension to an action of $\widetilde{A}$ on $\widetilde{V}$ so that $\widetilde{V}$ becomes a module over $\widetilde{A}$, as a Lie algebra over k_1, as before. We have also seen that the conditions on A discussed in Section 33.1 lead to analogous properties of $\widetilde{A}$, as in Section 33.4.

Let $\widetilde{(A_0)}$ be the linear subspace of $\widetilde{A}$ that corresponds to A_0, and let $\widetilde{(A_0)}'$ be the dual of $\widetilde{(A_0)}$, as a vector space over k_1, as before. If $\nu \in A_0'$, then let $\widetilde{\nu}$ be the unique extension of ν to an element of $\widetilde{(A_0)}'$.

Remember that V is standard cyclic of some weight $\mu \in A_0$, as a module over A, as in Section 38.2. This uses the hypotheses that V have positive finite dimension as a vector space over k, and that V is irreducible as a module over A, as in Section 39.4.

It is easy to see that a primitive or maximal vector in V of weight μ is also primitive or maximal of weight $\widetilde{\mu}$ in $\widetilde{V}$, as a module over $\widetilde{A}$. Using this, one can check that $\widetilde{V}$ is standard cyclic of weight $\widetilde{\mu}$, as a module over $\widetilde{A}$. This implies that $\widetilde{V}$ is irreducible as a module over $\widetilde{A}$, because $\widetilde{V}$ has finite dimension as a vector space over k_1, as in Section 33.9.

The bilinear form $b(\cdot,\cdot)$ on A considered in Section 39.2 has a unique extension to a bilinear form $\widetilde{b}(\cdot,\cdot)$ on $\widetilde{A}$. One can verify that this extension satisfies the analogues of the conditions on $b(\cdot,\cdot)$ mentioned earlier. The basis for A and corresponding dual basis for A with respect to $b(\cdot,\cdot)$ mentioned in Section 39.2 can be used in $\widetilde{A}$ too.

One can use $\widetilde{b}(\cdot,\cdot)$ to get an associated Casimir element $\widetilde{c}_{\widetilde{A}}(\widetilde{b})$ as in Section 39.1. This can be expressed in terms of the bases for $\widetilde{A}$ mentioned in the preceding paragraph as in Section 39.2. This leads to a linear mapping $\widetilde{c}_{\widetilde{A},\widetilde{V}}(\widetilde{b})$ from V into itself, as in the previous section. This linear mapping can be expressed in terms of the bases for $\widetilde{A}$ mentioned in the preceding paragraph in the same way as before. In particular, $\widetilde{c}_{\widetilde{A},\widetilde{V}}(\widetilde{b})$ is the same as the natural extension of $c_{A,V}(b)$ to a mapping from $\widetilde{V}$ into itself that is linear over k_1.

Because k_1 is algebraically closed, we can use Schur's lemma to get that

$$\widetilde{c}_{\widetilde{A},\widetilde{V}}(\widetilde{b}) = \widetilde{c}(\widetilde{A}, \widetilde{b}, \widetilde{V})\, I_{\widetilde{V}} \tag{39.11.4}$$

for some $\widetilde{c}(\widetilde{A}, \widetilde{b}, \widetilde{V}) \in k_1$, where $I_{\widetilde{V}}$ is the identity mapping on $\widetilde{V}$, as before. We also get that

$$\operatorname{tr}_{\widetilde{V}_{\widetilde{\mu}}} \widetilde{c}_{\widetilde{A},\widetilde{V}}(\widetilde{b}) = \widetilde{c}(\widetilde{A}, \widetilde{b}, \widetilde{V}), \tag{39.11.5}$$

where $\widetilde{V}_{\widetilde{\mu}}$ is the weight space in $\widetilde{V}$ associated to $\widetilde{\mu}$, as before.

If $\gamma \in \widetilde{(A_0)}'$, then there is a unique element $\widetilde{t}_{\widetilde{b},\gamma}$ of $\widetilde{(A_0)}$ such that

$$\gamma(w) = \widetilde{b}(w, \widetilde{t}_{\widetilde{b},\gamma}) \tag{39.11.6}$$

for every $w \in \widetilde{(A_0)}$, because the restriction of $\widetilde{b}(\cdot, \cdot)$ to $\widetilde{(A_0)}$ is nondegenerate, as before. Note that $\gamma \mapsto \widetilde{t}_{\widetilde{b},\gamma}$ is a one-to-one linear mapping from $\widetilde{(A_0)}'$ onto $\widetilde{(A_0)}$, as before. If $\nu \in A_0'$, and $\widetilde{\nu}$ is its unique extension to an element of $\widetilde{(A_0)}'$, then it is easy to see that

$$\widetilde{t}_{\widetilde{b},\widetilde{\nu}} = t_{b,\nu}. \tag{39.11.7}$$

If $\gamma_1, \gamma_2 \in \widetilde{(A_0)}'$, then put

$$\widetilde{b}'(\gamma_1, \gamma_2) = \widetilde{b}(\widetilde{t}_{\widetilde{b},\gamma_1}, \widetilde{t}_{\widetilde{b},\gamma_2}), \tag{39.11.8}$$

which defines a bilinear form on $\widetilde{(A_0)}'$, as before. If $\nu_1, \nu_2 \in A_0'$ and $\widetilde{\nu}_1$, $\widetilde{\nu}_2$ are their unique extensions to elements of $\widetilde{(A_0)}'$, then

$$\widetilde{b}'(\widetilde{\nu}_1, \widetilde{\nu}_2) = b'(\nu_1, \nu_2), \tag{39.11.9}$$

by (39.11.7).

Remember that the analogue $\widetilde{\Phi}$ of Φ for $\widetilde{A}$ and $\widetilde{(A_0)}$ consists of $\widetilde{\alpha}$, $\alpha \in \Phi$, as in Section 33.4. Similarly, the collection $\widetilde{\Delta}$ of $\widetilde{\alpha}$, $\alpha \in \Delta$, is a base for $\widetilde{\Phi}$, as before. We have also seen that the collection $\widetilde{\Phi}^+$ of positive roots in $\widetilde{\Phi}$ with respect to $\widetilde{\Delta}$ consists exactly of $\widetilde{\beta}$, $\beta \in \Phi^+$. Thus the analogue of (39.10.14) for $\widetilde{\Phi}$ and $\widetilde{\Delta}$ is

$$\widetilde{\delta} = \frac{1}{2} \sum_{\alpha \in \Phi^+} \widetilde{\alpha}. \tag{39.11.10}$$

This is the same as the unique extension of (39.10.14) to an element of $\widetilde{(A_0)}'$.

Remember that V is standard cyclic of weight $\mu \in A_0'$, and that $\widetilde{V}$ is standard cyclic of weight $\widetilde{\mu}$. It follows that

$$\widetilde{c}(\widetilde{A}, \widetilde{b}, \widetilde{V}) = \widetilde{b}'(\widetilde{\mu} + 2\,\widetilde{\delta}, \widetilde{\mu}), \tag{39.11.11}$$

as in (39.11.3). This implies that

$$\widetilde{c}(\widetilde{A}, \widetilde{b}, \widetilde{V}) = b'(\mu + 2\,\delta, \mu), \tag{39.11.12}$$

by (39.11.9). In particular, this means that $\widetilde{c}(\widetilde{A}, \widetilde{b}, \widetilde{V})$ is an element of k.

Remember that $\widetilde{c}_{\widetilde{A},\widetilde{V}}(\widetilde{b})$ is the same as the natural extension of $c_{A,V}(b)$ to a mapping from $\widetilde{V}$ to itself that is linear over k. Thus we get that (39.11.1) holds, where $c(A, b, V)$ is as in (39.11.3), by (39.11.4) and (39.11.12).

39.12 Freudenthal's formula

Let us continue with the same notation and hypotheses as in the previous sections, where k is not asked to be algebraically closed. Thus

$$c_{A,V}(b) = b'(\mu + 2\,\delta, \mu)\, I_V, \tag{39.12.1}$$

by (39.11.1), (39.11.3), and their extensions to the case where k is not necessarily algebraically closed.

If $\nu \in A_0'$, then we get that

$$\mathrm{tr}_{V_\nu} c_{A,V}(b) = (\dim V_\nu)\, b'(\mu + 2\,\delta, \mu). \tag{39.12.2}$$

Combining this with (39.10.15), we obtain that

$$\begin{aligned}(\dim V_\nu)\, b'(\mu + 2\,\delta, \mu) &= (\dim V_\nu)\, b'(\nu + 2\,\delta, \nu) \\ &\quad + 2 \sum_{\alpha \in \Phi^+} \sum_{j=1}^{\infty} (\dim V_{\nu + j\,\alpha})\, b'(\alpha, \nu + j\,\alpha).\end{aligned} \tag{39.12.3}$$

Equivalently, this means that

$$\begin{aligned}&(\dim V_\nu)\, (b'(\mu + 2\,\delta, \mu) - b'(\nu + 2\,\delta, \nu)) \\ &\quad = 2 \sum_{\alpha \in \Phi^+} \sum_{j=1}^{\infty} (\dim V_{\nu + j\,\alpha})\, b'(\alpha, \nu + j\,\alpha).\end{aligned} \tag{39.12.4}$$

This is *Freudenthal's formula*, as on p122 of [14].

Of course, (39.12.4) is trivial unless $\nu + j\,\alpha$ is a weight of V for some nonnegative integer j. In this case, $\nu \in \Upsilon$, as in Section 39.8. In particular, this means that $\nu \in E_{\mathbf{Q}}$, as in Section 32.3.

Suppose from now on in this section that

$$b(\cdot, \cdot) \text{ is the Killing form } b_A(\cdot, \cdot) \text{ on } A. \tag{39.12.5}$$

Note that this satisfies the conditions mentioned in Section 39.2, including nondegeneracy, because A is semisimple.

Let $b_A'(\cdot, \cdot)$ be the corresponding bilinear form on A_0', as in Section 39.9. If $\nu_1, \nu_2 \in \Phi$, then $b_A'(\nu_1, \nu_2)$ corresponds to an element of $\mathbf{Q}$, under the natural embedding of $\mathbf{Q}$ into k, as in Section 17.11. This implies that $b_A'(\nu_1, \nu_2)$ corresponds to an element of $\mathbf{Q}$ when $\nu_1, \nu_2 \in E_{\mathbf{Q}}$.

Let $(\cdot, \cdot)_{E_{\mathbf{Q}}}$ be the restriction of $b_A'(\cdot, \cdot)$ to $E_{\mathbf{Q}}$, considered as taking values in $\mathbf{Q}$, as in Section 17.12. More precisely, this is a bilinear form on $E_{\mathbf{Q}}$, as a vector space over $\mathbf{Q}$. Note that $(\cdot, \cdot)_{E_{\mathbf{Q}}}$ is symmetric on $E_{\mathbf{Q}}$, because $b_A(\cdot, \cdot)$ is symmetric on A, and thus $b_A'(\cdot, \cdot)$ is symmetric on A_0'.

Let $(\cdot, \cdot)_{E_{\mathbf{R}}}$ be the natural extension of $(\cdot, \cdot)_{E_{\mathbf{Q}}}$ to a bilinear form on $E_{\mathbf{R}}$, as a vector space over $\mathbf{R}$. Of course, $(\cdot, \cdot)_{E_{\mathbf{R}}}$ is symmetric on $E_{\mathbf{R}}$, and in fact it is an inner product on $E_{\mathbf{R}}$, as a vector space over $\mathbf{R}$, as in Section 17.13.

If $\alpha \in \Phi$, then the symmetry on $E_{\mathbf{R}}$ with vector α that maps Φ onto itself is the same as the reflection on $E_{\mathbf{R}}$ associated to α with respect to $(\cdot,\cdot)_{E_{\mathbf{R}}}$, as in Section 22.1. This means that $(\cdot,\cdot)_{E_{\mathbf{R}}}$ is invariant under the Weyl group of Φ.

Remember that V is standard cyclic of weight $\mu \in A_0'$, as in the previous section. In particular, μ is a weight of V, so that $\mu \in \Upsilon$, and thus $\mu \in E_{\mathbf{Q}}$. Of course, $\delta \in E_{\mathbf{Q}}$ too, and it is easy to see that

$$\begin{aligned} b_A'(\mu + 2\,\delta, \mu) - b_A'(\nu + 2\,\delta, \nu) &= (\mu + 2\,\delta, \mu)_{E_{\mathbf{R}}} - (\nu + 2\,\delta, \nu)_{E_{\mathbf{R}}} \\ &= (\mu + \delta, \mu + \delta)_{E_{\mathbf{R}}} - (\nu + \delta, \nu + \delta)_{E_{\mathbf{R}}} \end{aligned} \tag{39.12.6}$$

for every $\nu \in E_{\mathbf{Q}}$. Combining this with (39.12.4), we get that

$$\begin{aligned} &(\dim V_\nu)\,((\mu + \delta, \mu + \delta)_{E_{\mathbf{R}}} - (\nu + \delta, \nu + \delta)_{E_{\mathbf{R}}}) \\ &\quad = \; 2 \sum_{\alpha \in \Phi^+} \sum_{j=1}^{\infty} (\dim V_{\nu + j\,\alpha})\,(\alpha, \nu + j\,\alpha)_{E_{\mathbf{R}}} \end{aligned} \tag{39.12.7}$$

for every $\nu \in E_{\mathbf{Q}}$.

Let $\Pi = \Pi(V)$ be the set of $\nu \in A_0'$ such that ν is a weight of V, so that $\Pi \subseteq \Upsilon$. Remember that Π is saturated as a subset of Υ, with highest weight μ, as in Section 38.12.

If $\nu \in \Pi$, then

$$(\nu + \delta, \nu + \delta)_{E_{\mathbf{R}}} \le (\mu + \delta, \mu + \delta)_{E_{\mathbf{R}}}, \tag{39.12.8}$$

with equality only when $\nu = \mu$, as in Section 30.11. This means that the left side of (39.12.7) is a positive number times the dimension of V_ν when $\nu \in \Pi$ and $\nu \neq \mu$. This corresponds to some remarks on p122 of [14].

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