

Math 211

Lecture #16

Geometry of Solution Sets

October 3, 2001

Systems and Solutions

- The system

$$\begin{aligned} 3x + 4y - 5z &= 3 \\ -2x + 3z &= -7 \end{aligned} \Leftrightarrow \mathbf{Ax} = \mathbf{b}$$

where

$$A = \begin{pmatrix} 3 & 4 & -5 \\ -2 & 0 & 3 \end{pmatrix},$$

$$\mathbf{x} = (x, y, z)^T, \quad \mathbf{b} = (3, -7)^T.$$

- A *solution* is a vector \mathbf{x} such that $\mathbf{Ax} = \mathbf{b}$.
 $(2, -2, -1)^T$ is a solution.

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Solution Sets

- The *solution set* is set of *all* solutions to a system of linear equations.
 - What kinds of sets can be solution sets?
 - Can a circle be the solution set for a system of linear equations?
- We will examine *all* possibilities in 2 and 3 dimensions.
- Geometry will tell us the answer.

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One Equation in Two Variables

Example: $2x - 3y = 1$

- The solution set is a line in the plane.
- Solve for y : $y = (-1 + 2x)/3$
- The solution set consists of all vectors $(x, y)^T$, where $y = (-1 + 2x)/3$.

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The Solution Set

- consists of all vectors of the form

$$\begin{aligned} \begin{pmatrix} x \\ y \end{pmatrix} &= \begin{pmatrix} x \\ (-1 + 2x)/3 \end{pmatrix} \\ &= \begin{pmatrix} 0 \\ -1/3 \end{pmatrix} + \begin{pmatrix} x \\ 2x/3 \end{pmatrix} \\ &= \begin{pmatrix} 0 \\ -1/3 \end{pmatrix} + x \begin{pmatrix} 1 \\ 2/3 \end{pmatrix} \end{aligned}$$

- x is a free parameter.

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[Example](#)

[Solution set](#)

Parametric Equation for a Line

$$\mathbf{u} = \mathbf{u}_0 + x\mathbf{v}$$

- In our case $\mathbf{u}_0 = (0, -1/3)^T$ and $\mathbf{v} = (1, 2/3)^T$
- The vector \mathbf{u}_0 locates one point on the line.
- The vector \mathbf{v} gives the direction of the line.
- The number x tells how far the point \mathbf{u} is from \mathbf{u}_0 .

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Two Equations in Two Variables

Example:

$$2x - 3y = 1$$

$$x + y = 3$$

- In matrix form

$$\begin{pmatrix} 2 & -3 \\ 1 & 1 \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} 1 \\ 3 \end{pmatrix}$$

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Two Equations — Two Lines

- In general there are three possibilities
- In this case the lines intersect in one point $(2, 1)^T$.
- Other possibilities:
 - ♦ The two lines are the same line, and intersect in a line.
 - ♦ The two lines are parallel, and the intersection is empty. Such equations are *inconsistent*.

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Possible Solution Sets in Dimension 2

Three possibilities:

- The empty set.
- A single point.
- A line.
- Can a circle be the solution set for a system of linear equations?

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One Equation in Three Variables

Example: $2x - 3y + 4z = 1$

- Solution set is a plane in 3-space.
- Solve for z : $z = (1 - 2x + 3y)/4$.
- The solution set is all vectors $(x, y, z)^T$, where $z = (1 - 2x + 3y)/4$.

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The Solution Set

- consists of all vectors of the form

$$\begin{aligned} \begin{pmatrix} x \\ y \\ z \end{pmatrix} &= \begin{pmatrix} x \\ y \\ (1 - 2x + 3y)/4 \end{pmatrix} \\ &= \begin{pmatrix} 0 \\ 0 \\ 1/4 \end{pmatrix} + \begin{pmatrix} x \\ y \\ -x/2 + 3y/4 \end{pmatrix} \end{aligned}$$

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[Example](#)

The Solution Set (cont)

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 1/4 \end{pmatrix} + x \begin{pmatrix} 1 \\ 0 \\ -1/2 \end{pmatrix} + y \begin{pmatrix} 0 \\ 1 \\ 3/4 \end{pmatrix}$$

- x and y are free parameters.

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[Line](#)

Parametric Equation for a Plane

$$\mathbf{u} = \mathbf{u}_0 + x\mathbf{v} + y\mathbf{w}$$

- In our case $\mathbf{u}_0 = (0, 0, 1/4)^T$, $\mathbf{v} = (1, 0, -1/2)^T$, and $\mathbf{w} = (0, 1, 3/4)^T$
- \mathbf{u}_0 locates one point on the plane.
- \mathbf{v} and \mathbf{w} give two different directions in the plane.
- \mathbf{u} differs from \mathbf{u}_0 by the linear combination of \mathbf{v} and \mathbf{w} with coefficients x & y .

Return

Line

Two Equations in Three Variables

Example:

$$2x - 3y + 4z = 1$$

$$x + y - z = 3$$

- In matrix form

$$\begin{pmatrix} 2 & -3 & 4 \\ 1 & 1 & -1 \end{pmatrix} \begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} 1 \\ 3 \end{pmatrix}$$

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Two Equations — Two Planes

- In general there are three possibilities — \emptyset , a line, or a plane.
- In this case the two planes intersect in a line.
- Solve for z & y in terms of x :
 $y = 13 - 6x$ and $z = 10 - 5x$

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The Solution Set

- consists of all vectors

$$\begin{aligned} \begin{pmatrix} x \\ y \\ z \end{pmatrix} &= \begin{pmatrix} x \\ 13 - 6x \\ 10 - 5x \end{pmatrix} \\ &= \begin{pmatrix} 0 \\ 13 \\ 10 \end{pmatrix} + x \begin{pmatrix} 1 \\ -6 \\ -5 \end{pmatrix} \end{aligned}$$

- This is a line in 3-space.

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Plane

Three Equations in Three Variables

Example:

$$2x - 3y + 4z = 1$$

$$x + y - z = 3$$

$$3x - y + 3z = 5$$

- In matrix form

$$\begin{pmatrix} 2 & -3 & 4 \\ 1 & 1 & -1 \\ 3 & -1 & 3 \end{pmatrix} \begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} 1 \\ 3 \\ 5 \end{pmatrix}$$

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Three Equations — Three Planes

- In general there are four possibilities — \emptyset , a point, a line, or a plane.
- In this case the three planes intersect in a point.
- Solve to find that $(x, y, z)^T = (2, 1, 0)^T$

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Possible Solution Sets in Dimension 3

Four possibilities:

- The empty set.
- A single point.
- A line.
- A plane.
- Can a sphere be a solution set of a system of linear equations?

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[Dimension 2](#)

Solution Sets in Higher Dimension

By analogy with dimensions 2 & 3, we expect

- The solution set could be \emptyset or a point.
- If a solution set contains 2 points, then it contains the line through them.
- If a solution set contains 3 points not on the same line, then it contains the plane through them.

[2D](#)

[3D](#)

Solution Sets of Homogeneous Equations

- $\mathbf{0}$ is the vector with all entries = 0. $\mathbf{0}$ is referred to as the *0 vector* or the *origin*.
- A *homogeneous system* is one of the form

$$A\mathbf{x} = \mathbf{0}.$$

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Example:

$$2x - 3y + 4z = 0$$

$$x + y - z = 0$$

$$3x - y + 3z = 0$$

- A homogeneous system always has $\mathbf{0}$ as a solution.
- Hence the solution set of a homogeneous system is never the empty set.