

# Math 211

Lecture #12

Numerical Methods — Euler's Method

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## Numerical Methods

- A numerical "solution" is not a solution.
- It is a discrete approximation to a solution.
- We make an error on purpose to enable us to compute an approximation.
- Extremely important to understand the size of the error.

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## Numerical Approximation

To numerically "solve"  $y' = f(t, y)$  with  $y(a) = y_0$  on the interval  $[a, b]$ , we find

- a discrete set of points  
 $a = t_0 < t_1 < t_2 < \dots < t_{N-1} < t_N = b$
- and values  $y_0, y_1, y_2, \dots, y_{N-1}, y_N$   
 with  $y_j$  approximately equal to  $y(t_j)$ .
- Making an error  $E_j = y(t_j) - y_j$ .

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## Types of Solvers

- We will discuss and use four solvers
  - ♦ Euler's method,
  - ♦ second order Runge-Kutta,
  - ♦ fourth order Runge-Kutta,
  - ♦ and ode45.
- Everything works for first order systems almost without change.

## Euler's Method

- Problem: Solve (approximately)

$$y' = f(t, y) \quad \text{with} \quad y(a) = y_0$$

on the interval  $[a, b]$ .

- Discrete set of values of  $t$ .
  - ♦  $t_0 = a$ , fixed step size  $h = (b - a)/N$ .
  - ♦  $t_1 = t_0 + h$ ,  $t_2 = t_1 + h = t_0 + 2h$ , etc,
  - ♦  $t_N = a + Nh = b$

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## Euler's Method – First Step

- At each step approximate the solution curve by the tangent line.
- First step:
  - ♦  $y(t_0 + h) \approx y(t_0) + y'(t_0)h$ .  $t_1 = t_0 + h$
  - ♦  $y(t_1) \approx y_0 + f(t_0, y_0)h$ .
  - ♦ Set  $y_1 = y_0 + f(t_0, y_0)h$ , so  $y(t_1) \approx y_1$ .

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## Euler's Method – Second Step

- At each step use the tangent line.
- Second step – start at  $(t_1, y_1)$ .
  - ♦ New solution  $\tilde{y}$  with initial value  $\tilde{y}(t_1) = y_1$ .
  - ♦  $\tilde{y}(t) \approx \tilde{y}(t_1) + \tilde{y}'(t_1)(t - t_1)$ ,  $t_2 = t_1 + h$
  - ♦  $\tilde{y}(t_2) \approx y_1 + f(t_1, y_1)h$ .
  - ♦ Set  $y_2 = y_1 + f(t_1, y_1)h$ , so  $y(t_2) \approx \tilde{y}(t_2) \approx y_2$ .

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## Euler's Method – Algorithm

Input  $t_0$  and  $y_0$ .

for  $k = 1$  to  $N$  set

$$y_k = y_{k-1} + f(t_{k-1}, y_{k-1})h$$

$$t_k = t_{k-1} + h$$

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Thus,

$$y_1 = y_0 + f(t_0, y_0)h \quad \text{and} \quad t_1 = t_0 + h$$

$$y_2 = y_1 + f(t_1, y_1)h \quad \text{and} \quad t_2 = t_1 + h$$

$$y_3 = y_2 + f(t_2, y_2)h \quad \text{and} \quad t_3 = t_2 + h$$

etc.

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## MATLAB routine eulerdemo.m

- Demonstrates truncation error.
- Demonstrates how truncation error can propagate exponentially.
- Demonstrates how the total error is the sum of propagated truncation errors.

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## Error Analysis – First Step

- Euler's approximation

$$y_1 = y_0 + f(t_0, y_0)h; \quad t_1 = t_0 + h$$

- Taylor's theorem

$$y(t_1) = y(t_0 + h) = y(t_0) + y'(t_0)h + R(h)$$

$$|R(h)| \leq Ch^2$$

- $y(t_1) - y_1 = R(h)$
- The truncation error at each step is the same as the Taylor remainder, and  $|R(h)| \leq Ch^2$ .

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## Error Analysis

- There are  $N = (b - a)/h$  steps.
- Truncation error can grow exponentially.
- Computation shows that

$$\text{Maximum error} \leq C \left( e^{L(b-a)} - 1 \right) h,$$

where  $C$  &  $L$  are constants that depend on  $f$ .

- Good news: the error decreases as  $h$  decreases.
- Bad news: the error can get exponentially large as the length of the interval [i.e.,  $b-a$ ] increases.

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## MATLAB routine eul.m

Syntax: `[t,y] = eul(derfile,[t0,tf],y0,h);`

- `derfile` - derivative m-file defining the equation.
- `t0` - initial time; `tf` - final time.
- `y0` - initial value.
- `h` - step size.

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Algorithm

## Derivative m-file

The derivative m-file describes the differential equation.

- Example:  $y' = y^2 - t$
- Derivative m-file:

```
function ypr = george(t,y)
ypr = y^2 - t;
```

- Save as `george.m`.

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## Use of `eul.m`

- Solve  $y' = y^2 - t$ .
- Use the derivative m-file `george.m`.
- Use  $t_0 = 0$ ,  $t_f = 10$ ,  $y_0 = 0.5$ , and several step sizes.
- Syntax: `[t,y] = eul('george',[0,10],0.5,h);`

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## Experimental Error Analysis

- IVP  $y' = \cos(t)/(2y - 2)$  with  $y(0) = 3$
- Exact solution:  $y(t) = 1 + \sqrt{4 + \sin t}$ .
- Solve using Euler's method and compare with the exact solution.
- Do this for several step sizes.

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Derivative m-file

Batch file

### Derivative m-file ben.m

```
function yprime = ben(t,y)
yprime = cos(t)/(2*y-2);
```

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### M-file batch.m

```
[teuler,yeuler]=eul('ben',[0,3],3,h);
t=0:0.05:3;
y=1+sqrt(4+sin(t));
plot(t,y,teuler,yeuler,'o')
legend('Exact','Euler')
shg
z=1+sqrt(4+sin(teuler));
maxerror=max(abs(z-yeuler))
```

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