

# Experiments with Schemes for Exponential Decay

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Dec 19, 2015

This report investigates the accuracy of three finite difference schemes for the ordinary differential equation  $u' = -au$  with the aid of numerical experiments. Numerical artifacts are in particular demonstrated.

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## 1 Mathematical problem

We address the initial-value problem

$$\begin{aligned}u'(t) &= -au(t), \quad t \in (0, T], & (1) \\u(0) &= I, & (2)\end{aligned}$$

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where  $a$ ,  $I$ , and  $T$  are prescribed parameters, and  $u(t)$  is the unknown function to be estimated. This mathematical model is relevant for physical phenomena featuring exponential decay in time, e.g., vertical pressure variation in the atmosphere, cooling of an object, and radioactive decay.

## 2 Numerical solution method

We introduce a mesh in time with points  $0 = t_0 < t_1 < \dots < t_{N_t} = T$ . For simplicity, we assume constant spacing  $\Delta t$  between the mesh points:  $\Delta t = t_n - t_{n-1}$ ,  $n = 1, \dots, N_t$ . Let  $u^n$  be the numerical approximation to the exact solution at  $t_n$ .

The  $\theta$ -rule [1] is used to solve (1) numerically:

$$u^{n+1} = \frac{1 - (1 - \theta)a\Delta t}{1 + \theta a\Delta t} u^n,$$

for  $n = 0, 1, \dots, N_t - 1$ . This scheme corresponds to

- The [Forward Euler](#) scheme when  $\theta = 0$
- The [Backward Euler](#) scheme when  $\theta = 1$
- The [Crank-Nicolson](#) scheme when  $\theta = 1/2$

## 3 Implementation

The numerical method is implemented in a Python function [2] `solver` (found in the `model` module):

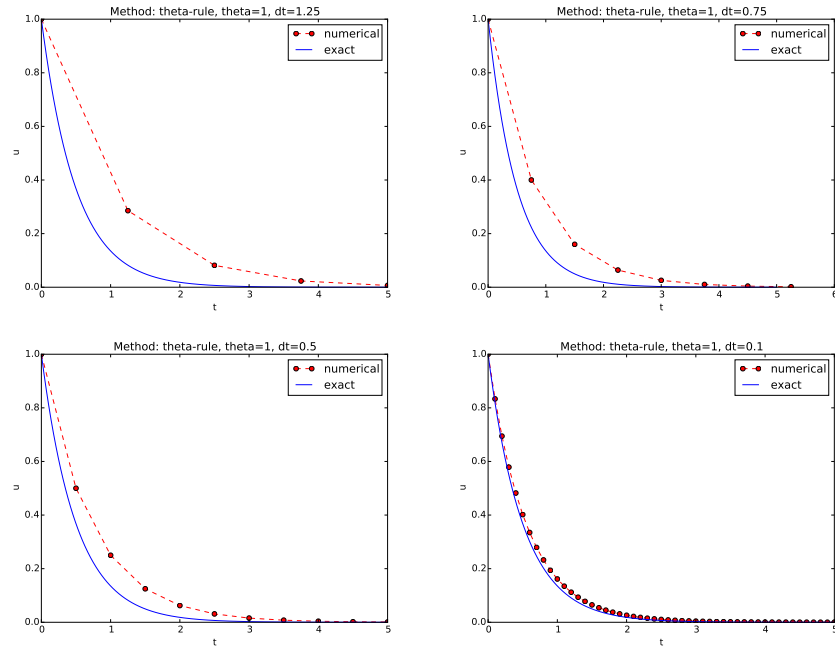
```
def solver(I, a, T, dt, theta):
    """Solve u'=-a*u, u(0)=I, for t in (0,T] with steps of dt."""
    dt = float(dt) # avoid integer division
    Nt = int(round(T/dt)) # no of time intervals
    T = Nt*dt # adjust T to fit time step dt
    u = zeros(Nt+1) # array of u[n] values
    t = linspace(0, T, Nt+1) # time mesh

    u[0] = I # assign initial condition
    for n in range(0, Nt): # n=0,1,...,Nt-1
        u[n+1] = (1 - (1-theta)*a*dt)/(1 + theta*dt*a)*u[n]
    return u, t
```

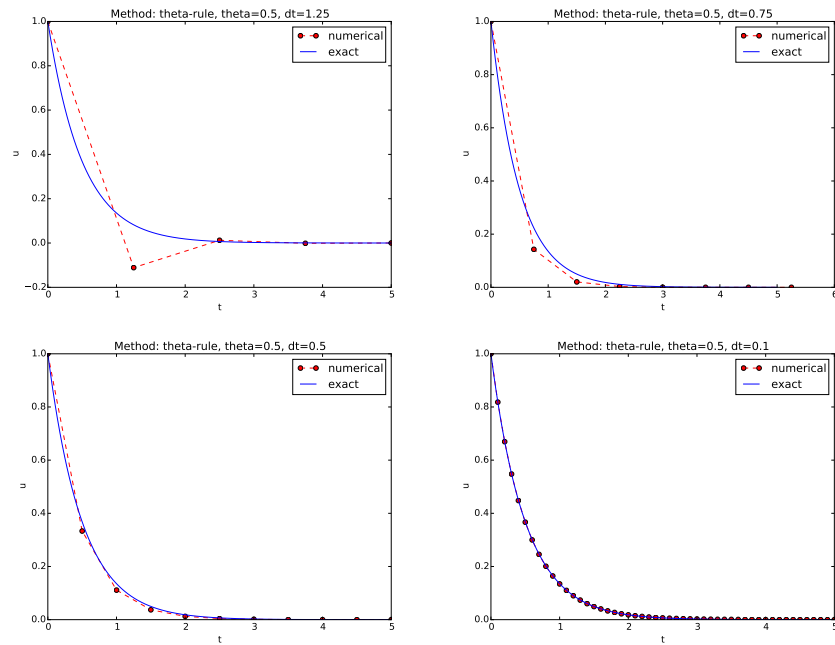
## 4 Numerical experiments

We define a set of numerical experiments where  $I$ ,  $a$ , and  $T$  are fixed, while  $\Delta t$  and  $\theta$  are varied. In particular,  $I = 1$ ,  $a = 2$ ,  $\Delta t = 1.25, 0.75, 0.5, 0.1$ .

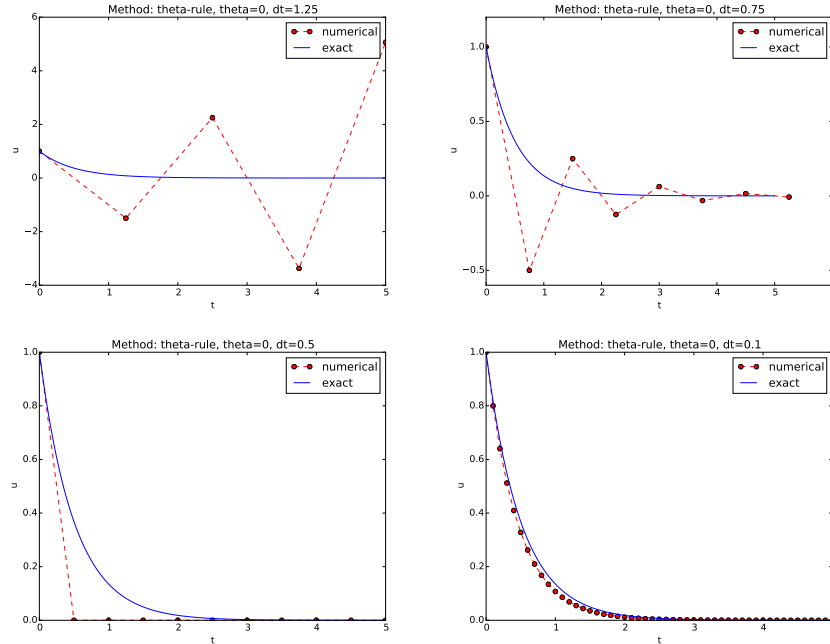
## 4.1 The Backward Euler method



## 4.2 The Crank-Nicolson method



### 4.3 The Forward Euler method



### 4.4 Error vs $\Delta t$

How  $E$  varies with  $\Delta t$  for  $\theta = 0, 0.5, 1$  is shown in Figure 1.



#### Observe:

The data points for the three largest  $\Delta t$  values in the Forward Euler method are not relevant as the solution behaves non-physically.

The numbers corresponding to the figure above are given in the table below.

$\Delta t$	$\theta = 0$	$\theta = 0.5$	$\theta = 1$
1.25	7.4630	0.2161	0.2440
0.75	0.6632	0.0744	0.1875
0.50	0.2797	0.0315	0.1397
0.10	0.0377	0.0012	0.0335



#### Summary

1.  $\theta = 1$ :  $E \sim \Delta t$  (first-order convergence).
2.  $\theta = 0.5$ :  $E \sim \Delta t^2$  (second-order convergence).
3.  $\theta = 1$  is always stable and gives qualitatively correct results.

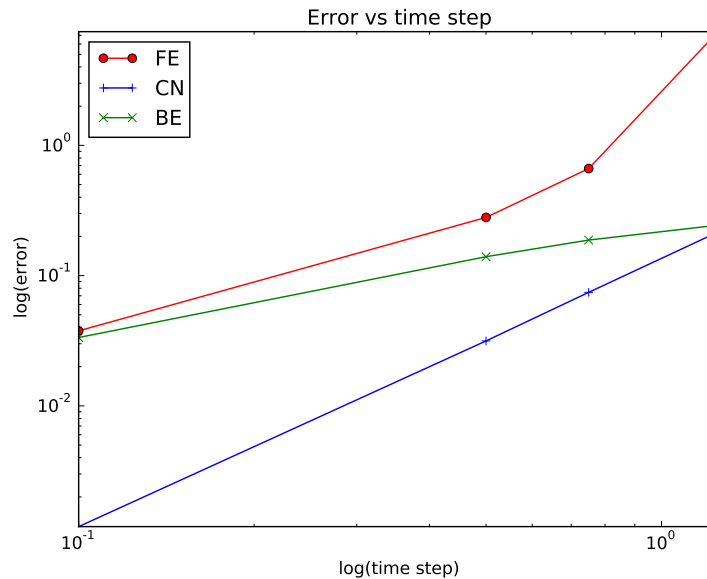


Figure 1: Variation of the error with the time step.

4.  $\theta = 0.5$  never blows up, but may give oscillating solutions if  $\Delta t$  is not sufficiently small.
5.  $\theta = 0$  suffers from fast-growing solution if  $\Delta t$  is not small enough, but even below this limit one can have oscillating solutions (unless  $\Delta t$  is sufficiently small).

## References

- [1] A. Iserles. *A First Course in the Numerical Analysis of Differential Equations*. Cambridge University Press, second edition, 2009.
- [2] H. P. Langtangen. *A Primer on Scientific Programming With Python*. Springer, fourth edition, 2014.