Applied Computational Fluid Dynamics Using OpenFOAM

Value Added Course
College/University: AEC
Spring 2025

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Contents

- Numerical stability
- Advection equation
- Exercise – 7 (i) and (ii)

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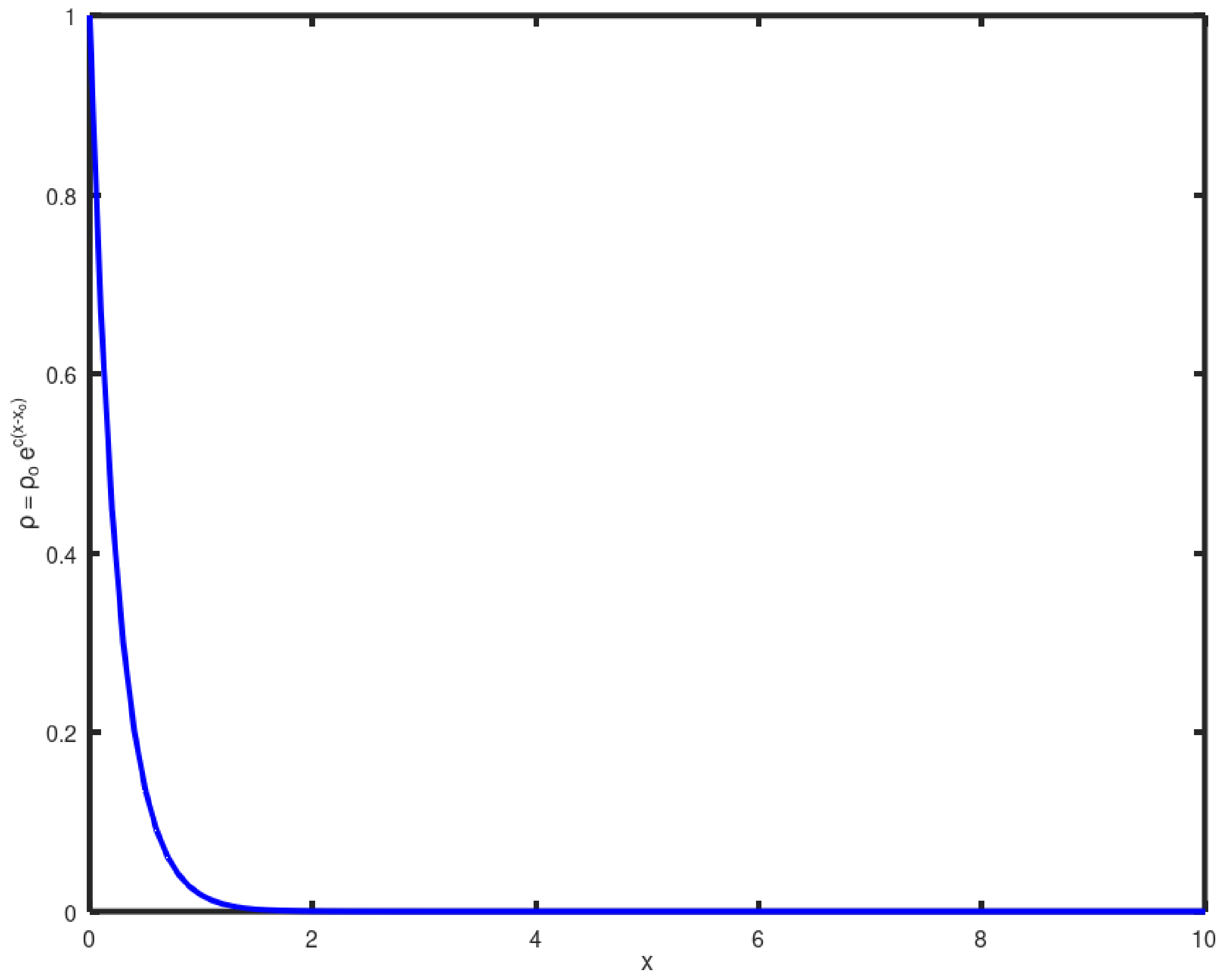
Numerical Stability

- Numerical approach should not magnify the error that appears in the solution.

$$\frac{d\rho}{dx} = -c\rho$$

$$\int_{\rho_o}^{\rho} \frac{d\rho}{\rho} = \int_{x_o}^{x} -c\,dx$$

Analytical $\boxed{\rho = \rho_o e^{-c(x - x_o)}}$



$c = 4, x_o = 0, \rho_o = 1, x \in [0,10]$

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Numerical Stability

- Numerical discretization

$$\frac{d\rho}{dx} = -c\rho$$

$$\frac{\rho_{i+1} - \rho_i}{\Delta x} = -c\rho_i$$

Numerical $\boxed{\rho_{i+1} = \rho_i(1 - c\Delta x)}$

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Numerical Stability

- Numerical discretization

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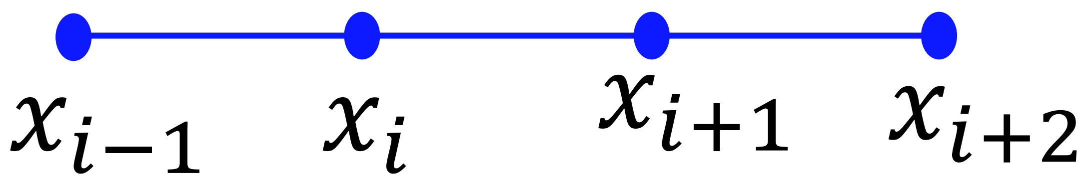
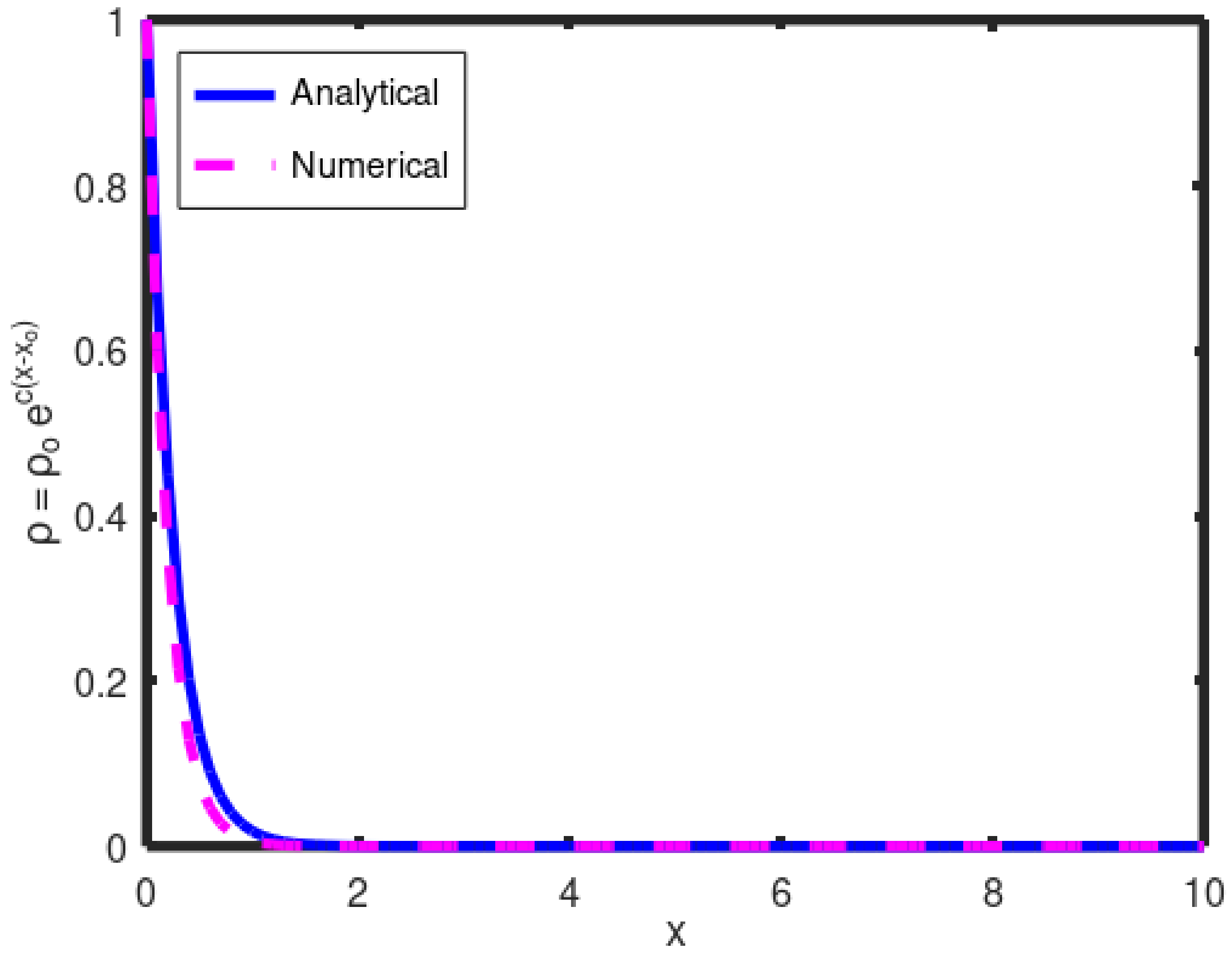
$$\frac{\rho_{i+1} - \rho_i}{\Delta x} = -c\rho_i$$

$$\rho_{i+1} = \rho_i(1 - c\Delta x)$$





$c = 4, x_o = 0, \rho_o = 1, x \in [0,10], \Delta x = 0.1$

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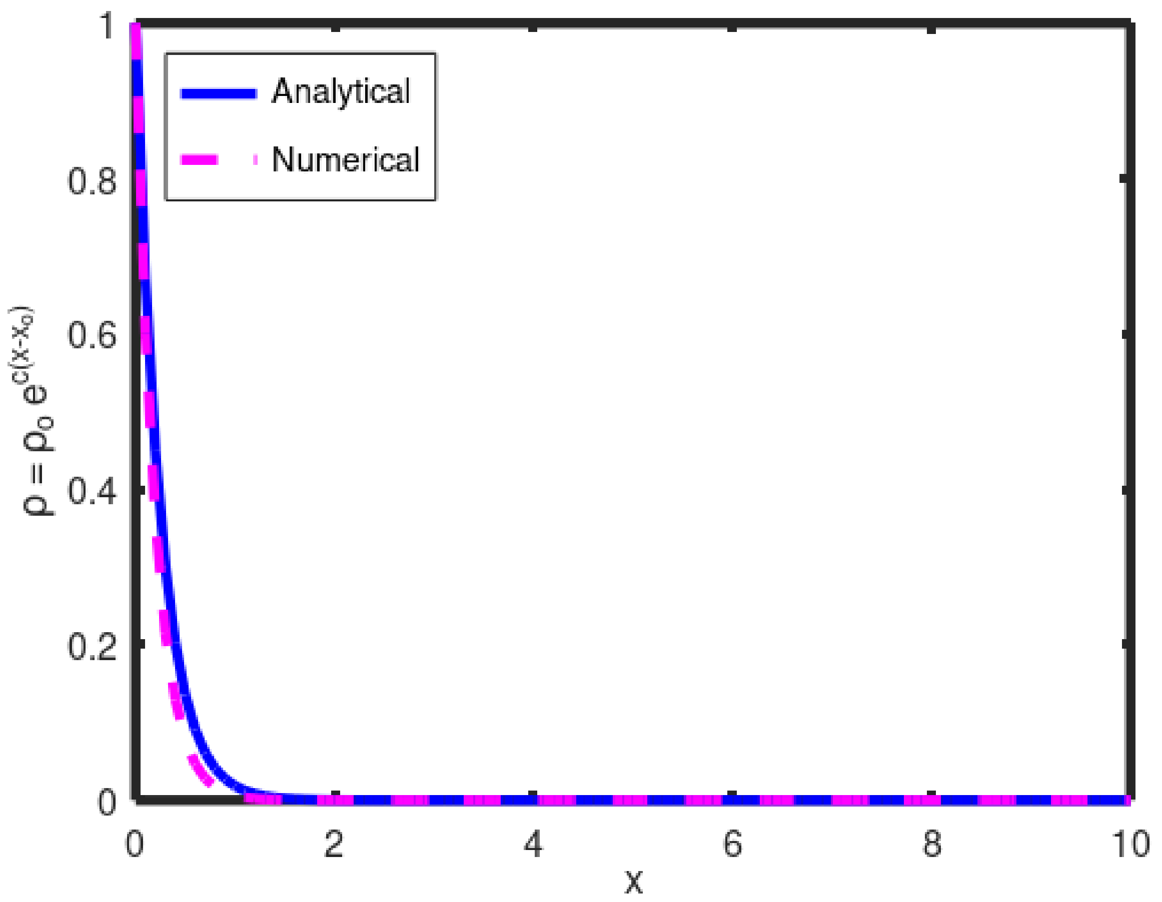
Numerical Stability

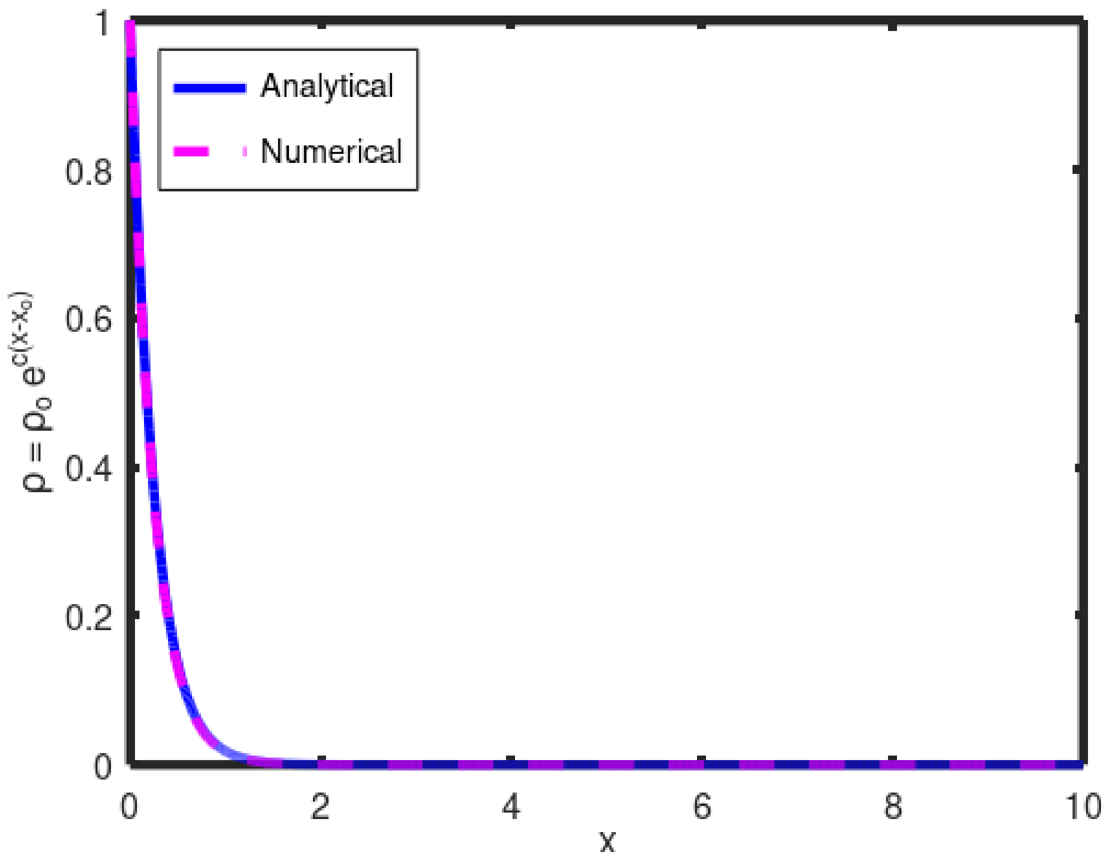
$$\frac{d\rho}{dx} = -c\rho$$

$$\rho_{i+1} = \rho_i(1 - c\Delta x)$$

x_{i-1} x_i x_{i+1} x_{i+2}



$c = 4, x_o = 0, \rho_o = 1, x \in [0,10],$
$\Delta x = 0.1$



$c = 4, x_o = 0, \rho_o = 1, x \in [0,10],$
$\Delta x = 0.01$

Stability Condition

$$\left|\frac{\rho_{i+1}}{\rho_i}\right| < 1$$

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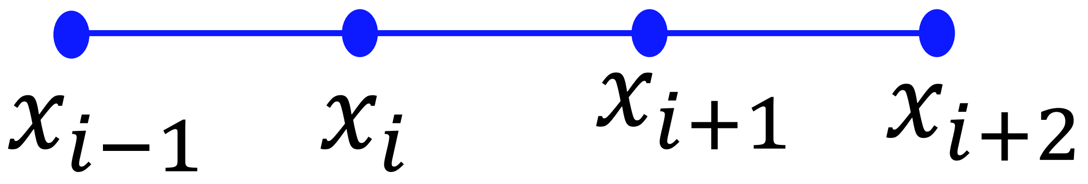
Numerical Stability

$$\frac{d\rho}{dx} = -c\rho$$



Stability Condition

$$\boxed{\left|\frac{\rho_{i+1}}{\rho_i}\right| < 1}$$

$$\rho_{i+1} = \rho_i(1 - c\Delta x)$$

$$\left|\frac{\rho_{i+1}}{\rho_i}\right| = |(1 - c\Delta x)| < 1$$

$$-1 < (1 - c\Delta x) < 1$$

$$0 < \Delta x < 2/c$$

$$\boxed{\Delta x < 2/c}$$

$$\Delta x < \frac{2}{c}$$

$$\frac{2}{c} = \frac{2}{4} = 0.5$$

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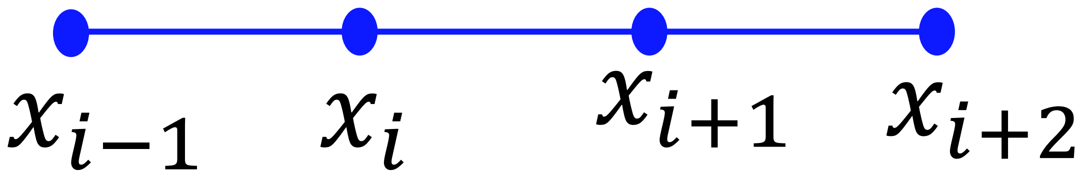
Numerical Stability

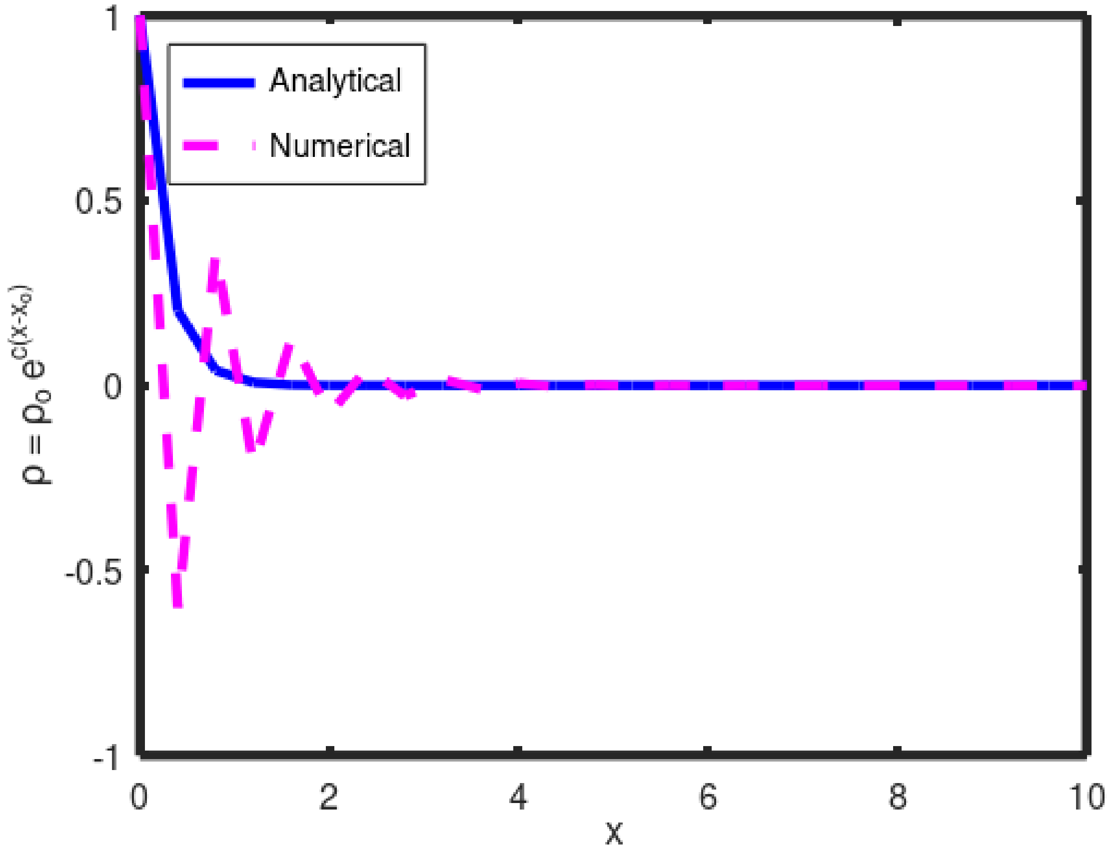
$$\frac{d\rho}{dx} = -c\rho$$

$$\rho_{i+1} = \rho_i(1 - c\Delta x)$$

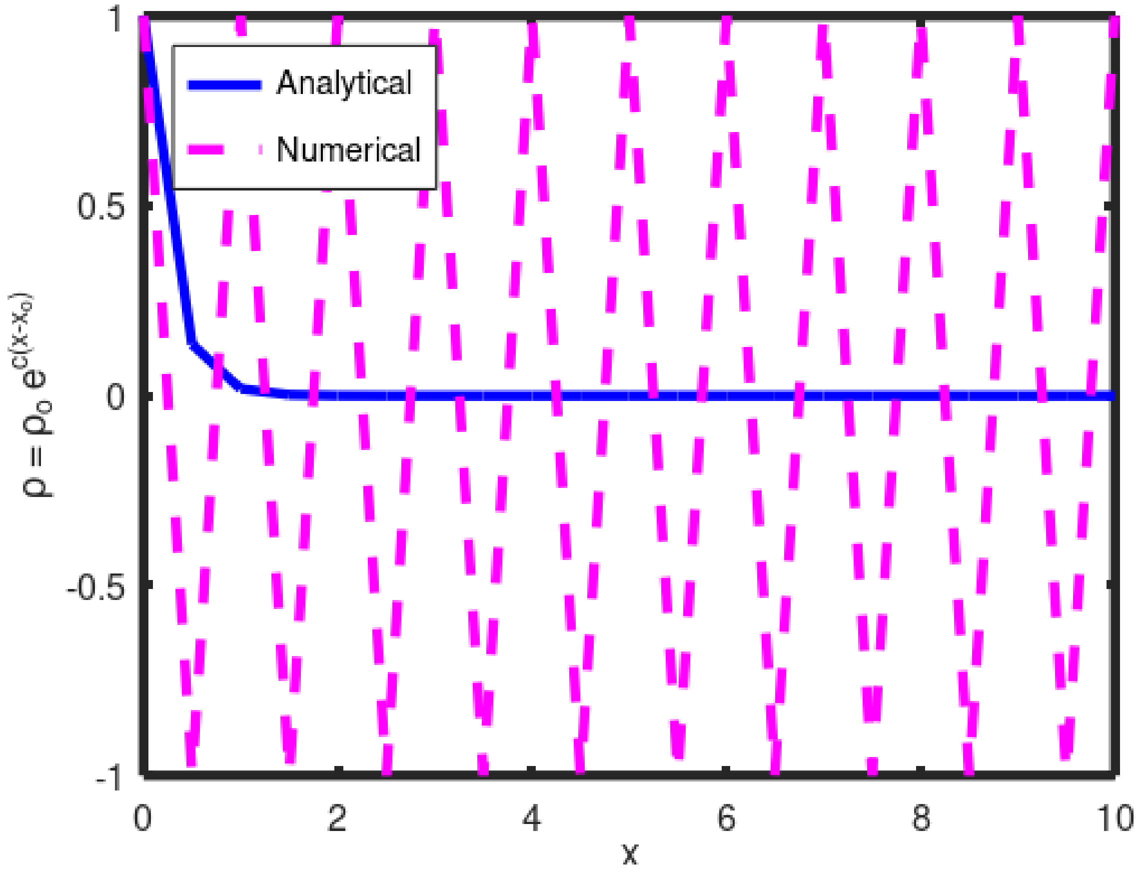


$$\Delta x < \frac{2}{c}$$

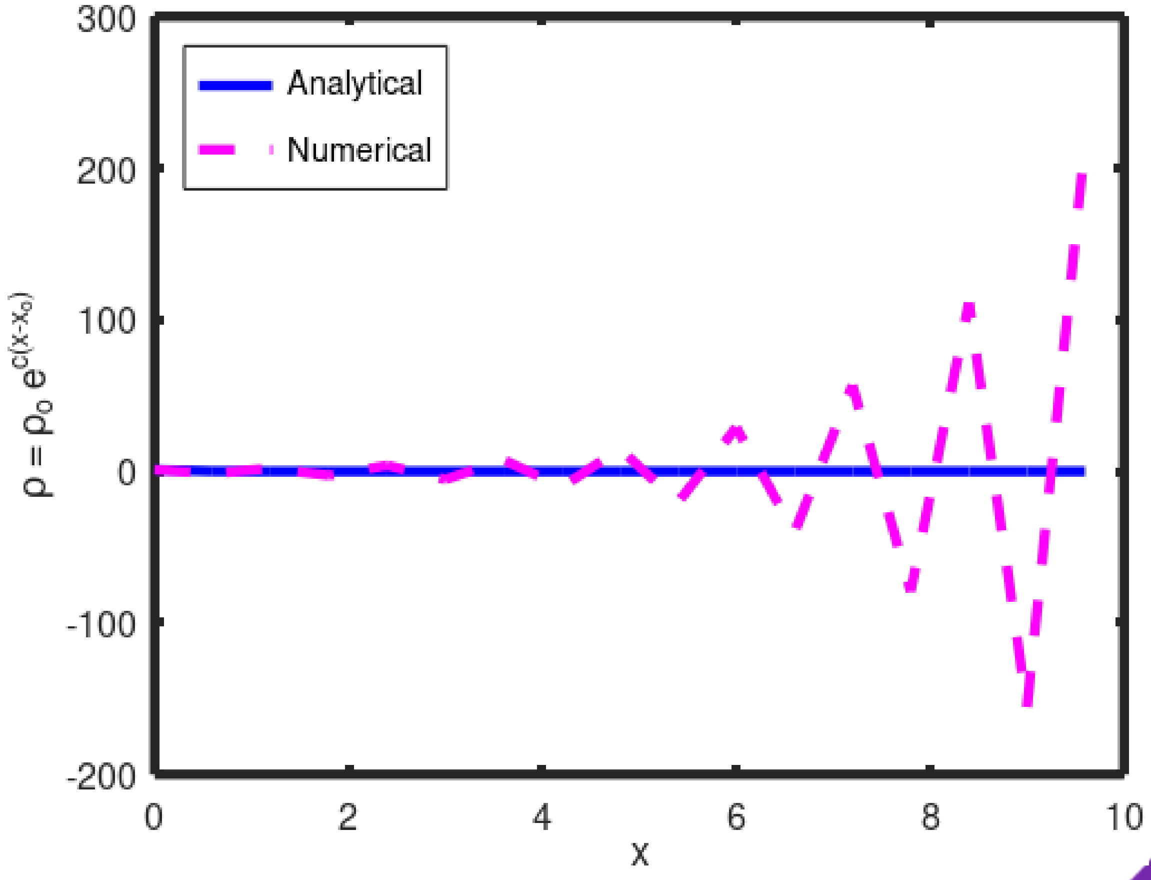
$$\frac{2}{c} = \frac{2}{4} = 0.5$$



$c = 4, x_o = 0, \rho_o = 1, x \in [0,10],$
$\Delta x = 0.4$



$c = 4, x_o = 0, \rho_o = 1, x \in [0,10],$
$\Delta x = 0.5$



$c = 4, x_o = 0, \rho_o = 1, x \in [0,10],$
$\Delta x = 0.6$

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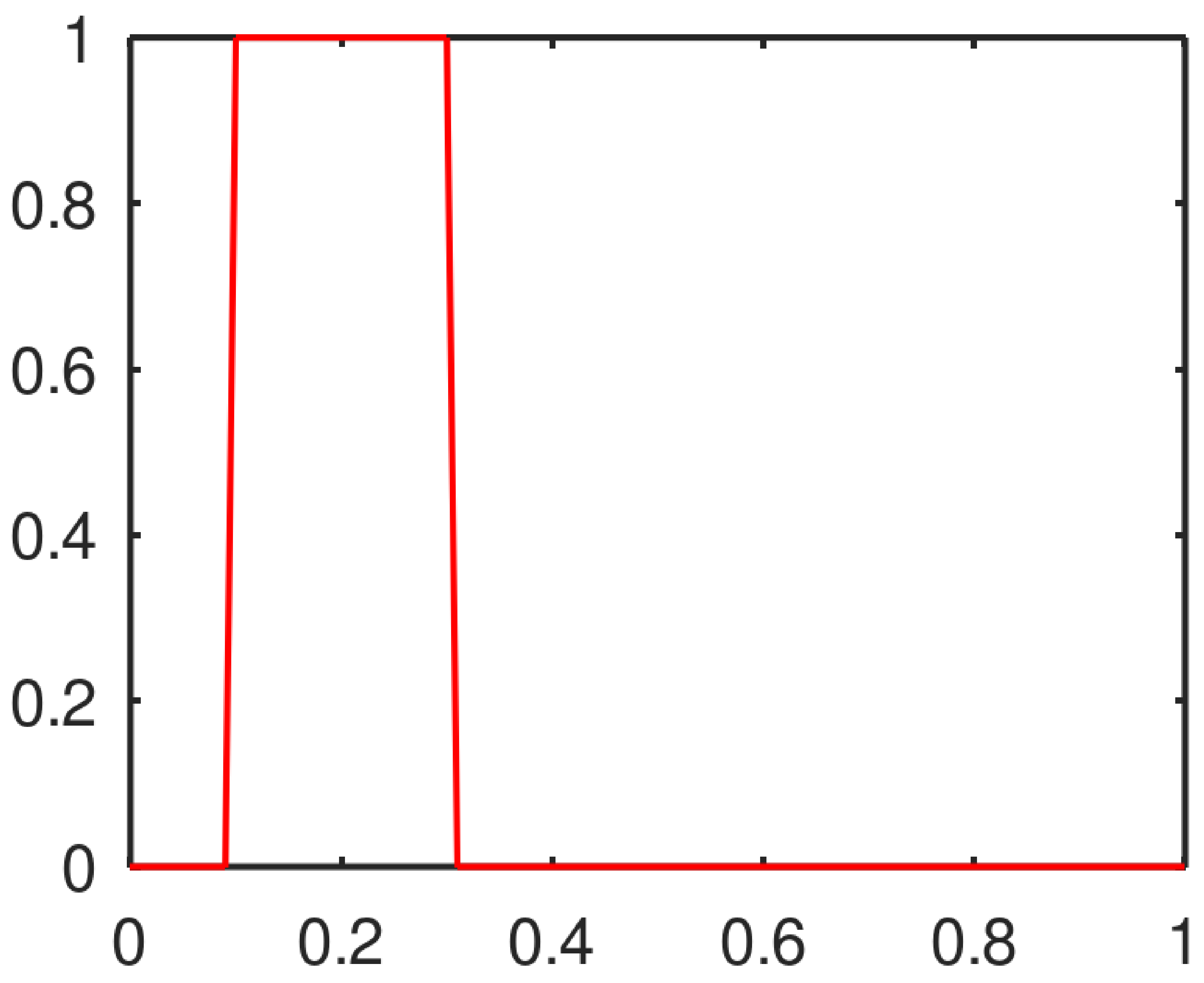
Numerical Stability - Advection equation




```
for i = 1 : length(x)
  if (x(i, 1) >= 0.1) && (x(i, 1) <= 0.3)
    u(i, 1) = 1;
  endif
end
```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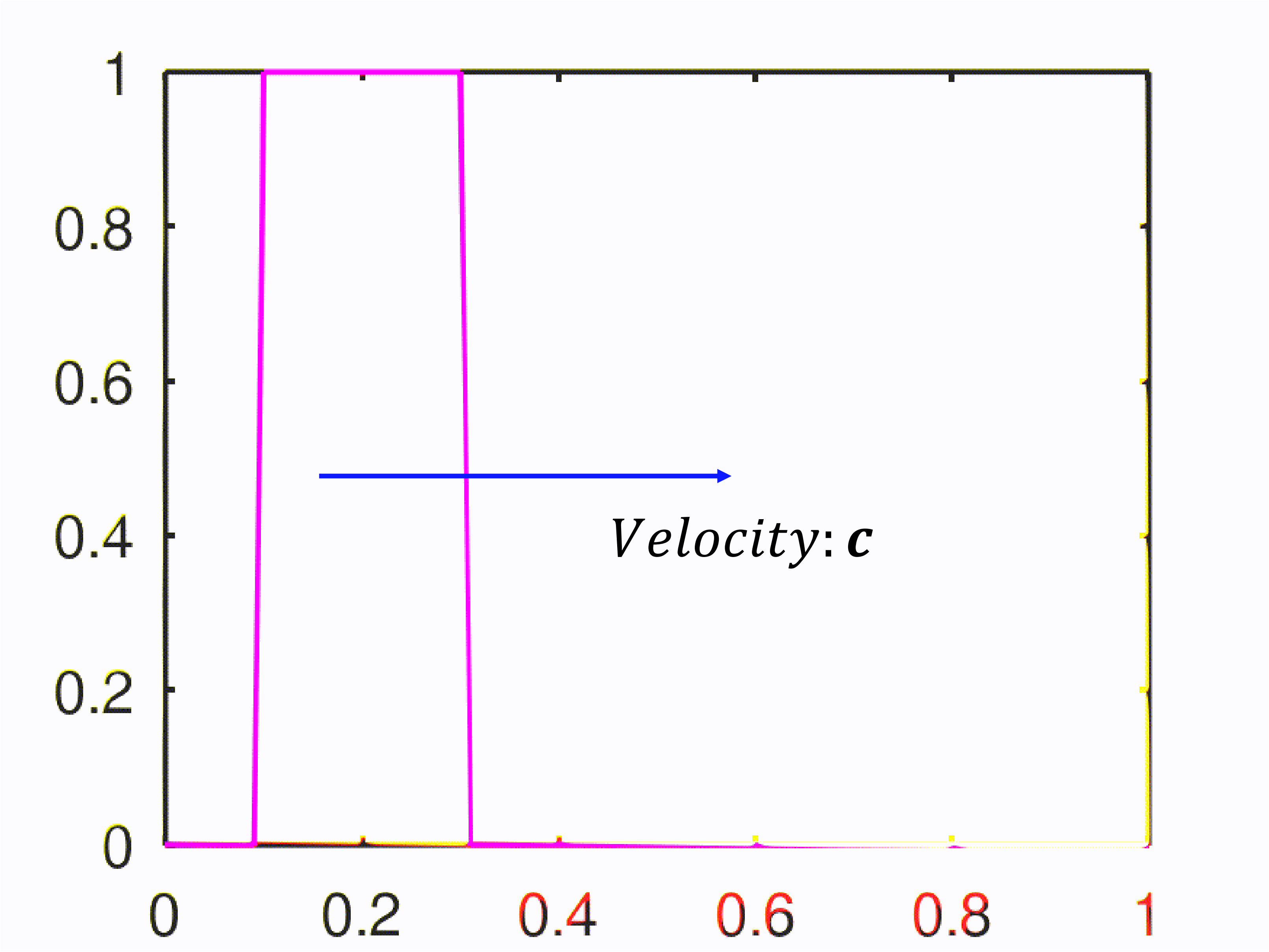
Numerical Stability - Advection equation



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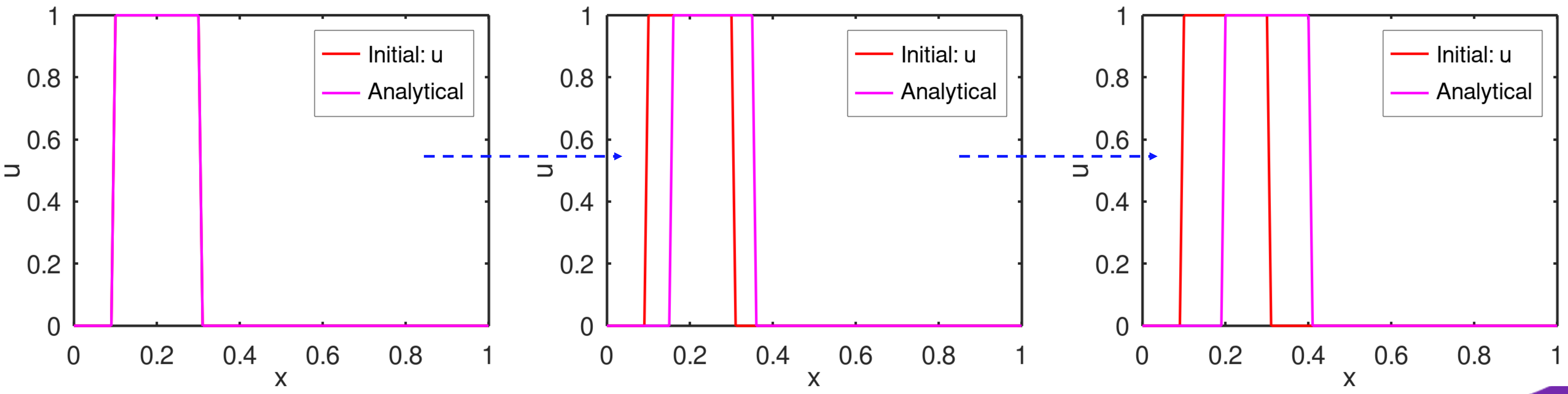
Numerical Stability - Advection equation

$$\frac{\partial u}{\partial t} + c\frac{\partial u}{\partial x} = 0$$ Advection equation

```
for i = 1 : length(x)
  if (x(i, 1) >= 0.1+c*t) && (x(i, 1) <= 0.3+c*t)
    u_analytical(i, 1) = 1;
  endif
end
```



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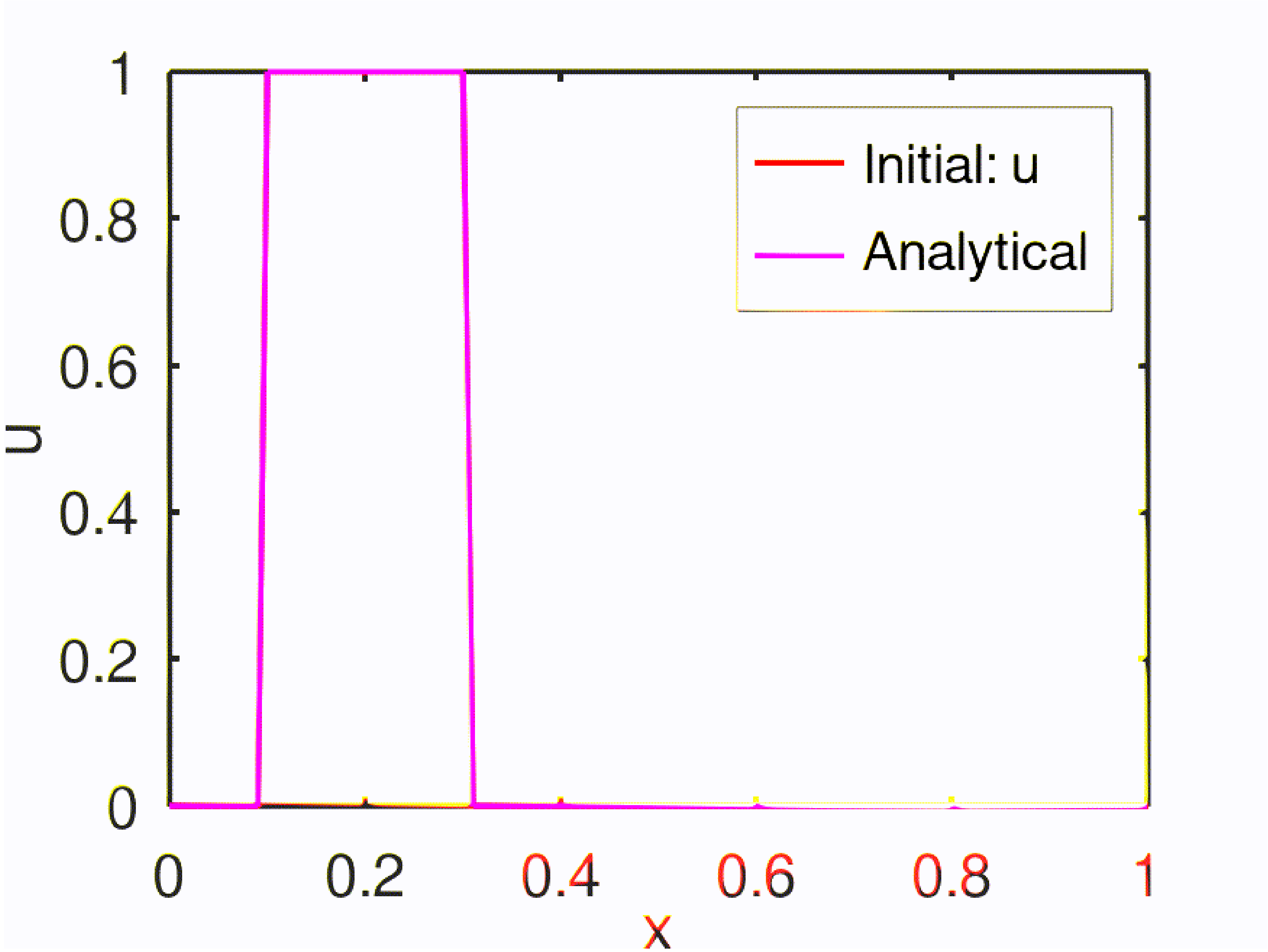
Numerical Stability - Advection equation




```
for i = 1 : length(x)
  if (x(i, 1) >= 0.1+c*t) && (x(i, 1) <= 0.3+c*t)
    u_analytical(i, 1) = 1;
  endif
end
```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Exercise – 7 (i)

1. Solve the following advection equation analytically in octave

$$\frac{\partial u}{\partial t} + c\frac{\partial u}{\partial x} = 0$$

2. Upload in GitHub

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Numerical Stability - Advection equation

$$\boxed{\frac{\partial u}{\partial t} + c\frac{\partial u}{\partial x} = 0}$$

$$\boxed{\frac{u_i^{n+1} - u_i^n}{\Delta t} + c\left(\frac{\partial u}{\partial x}\right)_i^n = 0}$$

$$\left(\frac{d\rho}{dx}\right)_i \approx \frac{\rho(x_{i+1}) - \rho(x_i)}{\Delta x_i}$$

$$\left(\frac{d\rho}{dx}\right)_i \approx \frac{\rho(x_{i+1}) - \rho(x_{i-1})}{2\Delta x_i}$$

$$u_i^{n+1} = u_i^n - c\Delta t \boxed{\left(\frac{\partial u}{\partial x}\right)_i^n}$$

$$\left(\frac{\partial u}{\partial x}\right)_i^n \approx \frac{u_{i+1}^n - u_i^n}{\Delta x_i}$$

Simple forward difference scheme

$$\left(\frac{\partial u}{\partial x}\right)_i^n \approx \frac{u_{i+1}^n - u_{i-1}^n}{2\Delta x_i}$$

Central difference

(Explicit) First order - Forward Euler

(only one unknown (n+1) with other knowns at n^{th} node)

→ conditionally stable

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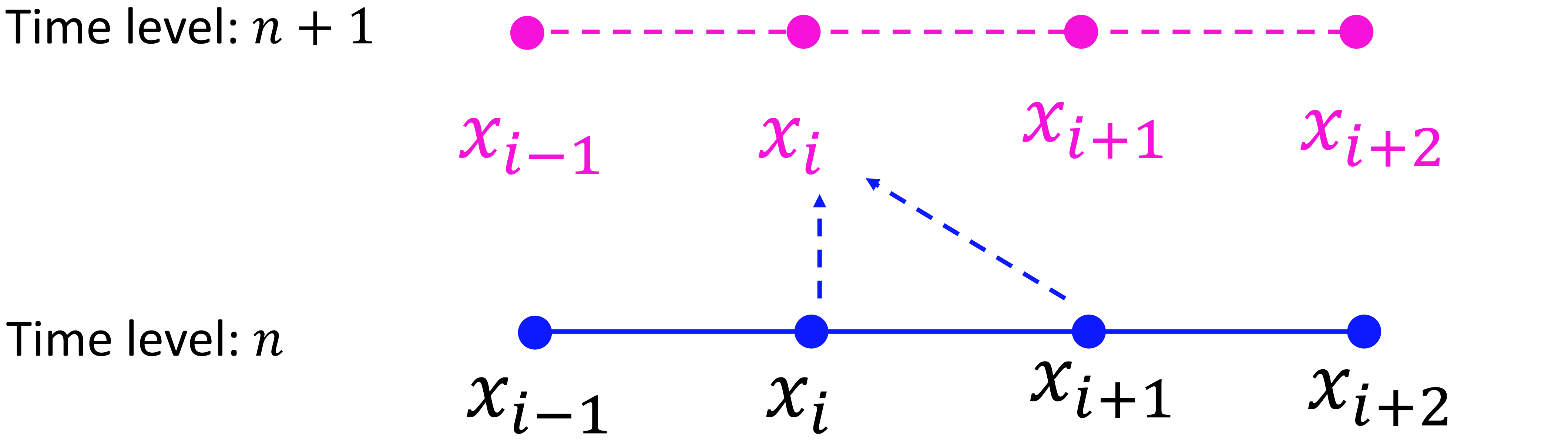
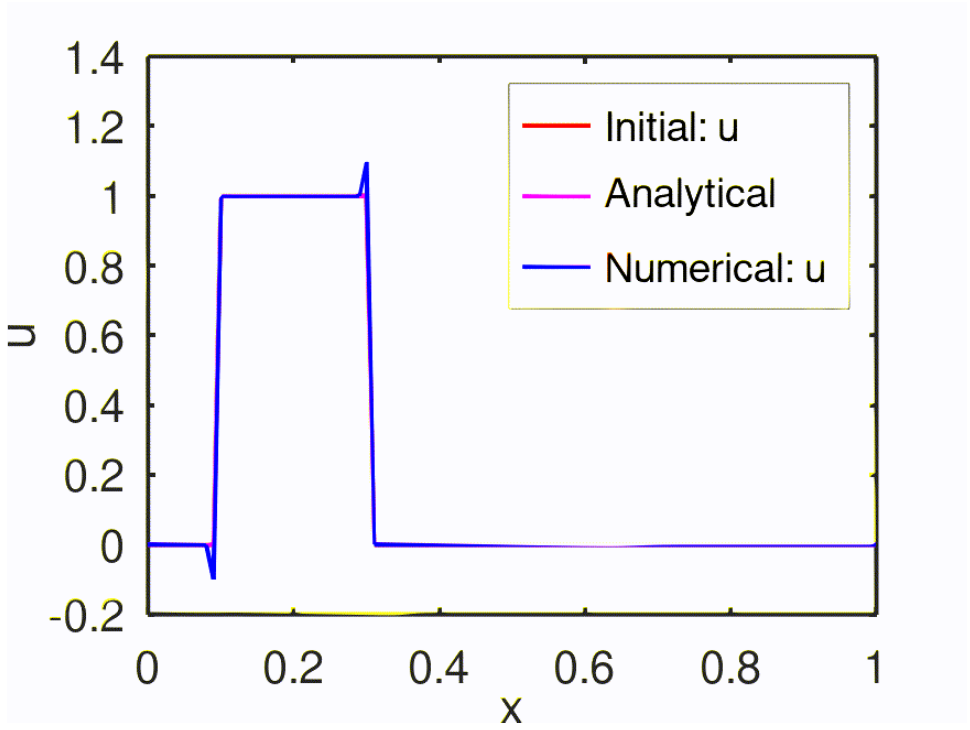
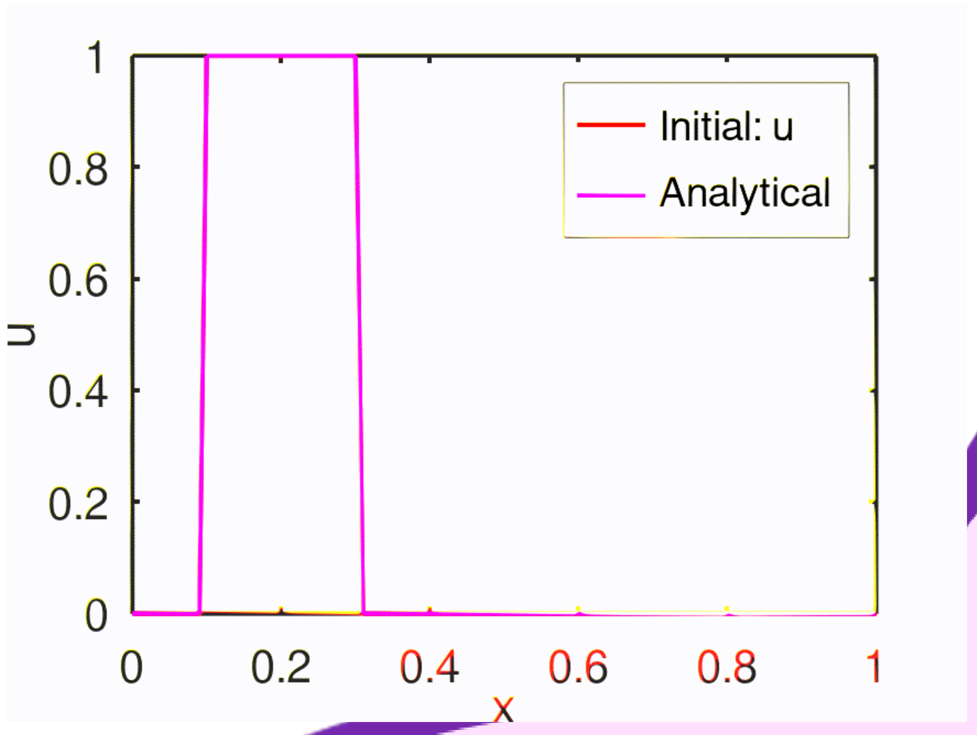
Numerical Stability - Advection equation



Information from right to left end





$$u_i^{n+1} = u_i^n - c\Delta t \left(\frac{\partial u}{\partial x}\right)_i^n$$

$$\left(\frac{\partial u}{\partial x}\right)_i^n \approx \frac{u_{i+1}^n - u_i^n}{\Delta x_i}$$ Simple forward difference scheme

$$\left(\frac{\partial u}{\partial x}\right)_i^n \approx \frac{u_{i+1}^n - u_{i-1}^n}{2\Delta x_i}$$ Central difference

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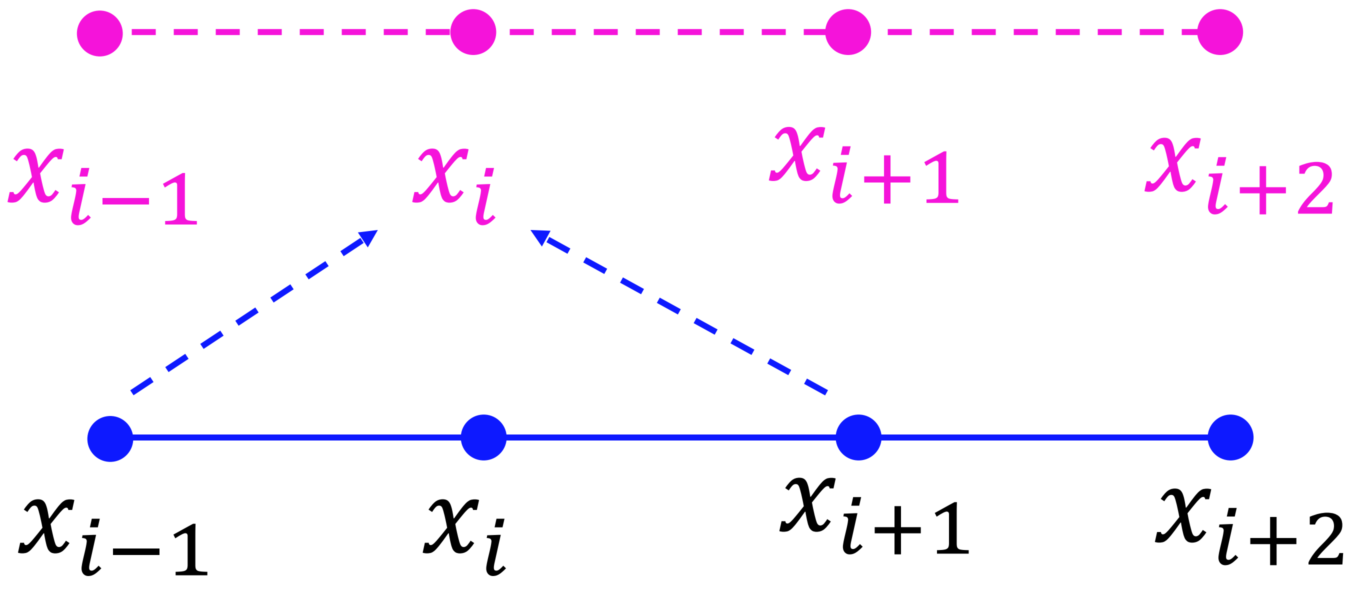
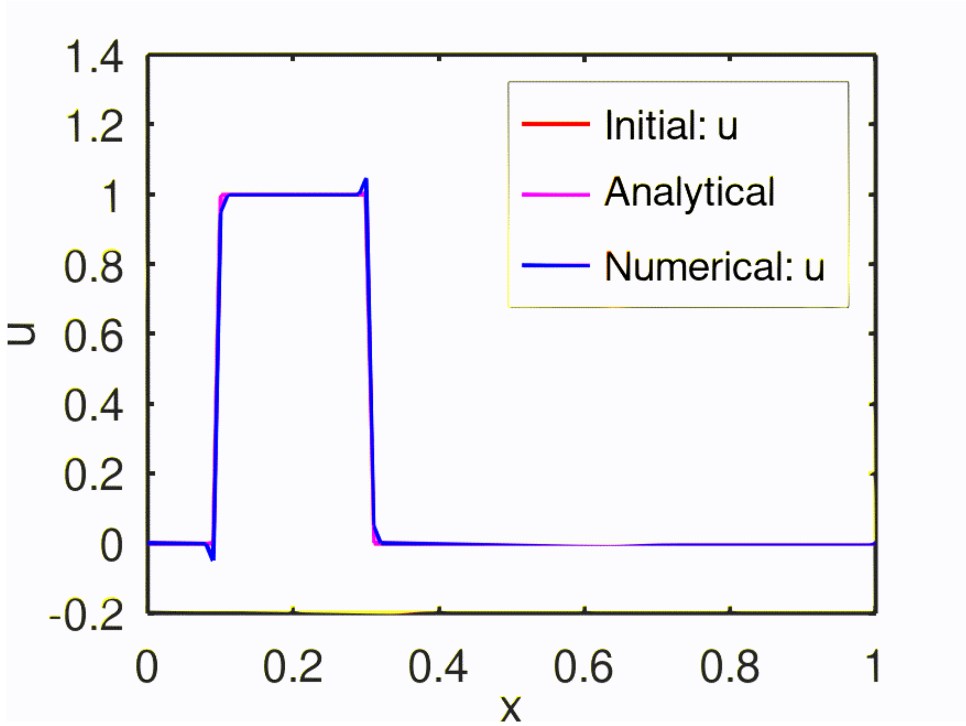
Application: Differential equation used in physics, weather forecasting, stoke markets behaviors (based on probability, past and present information and predicting future information)

Numerical Stability - Advection equation

Time level: $n+1$

Time level: n



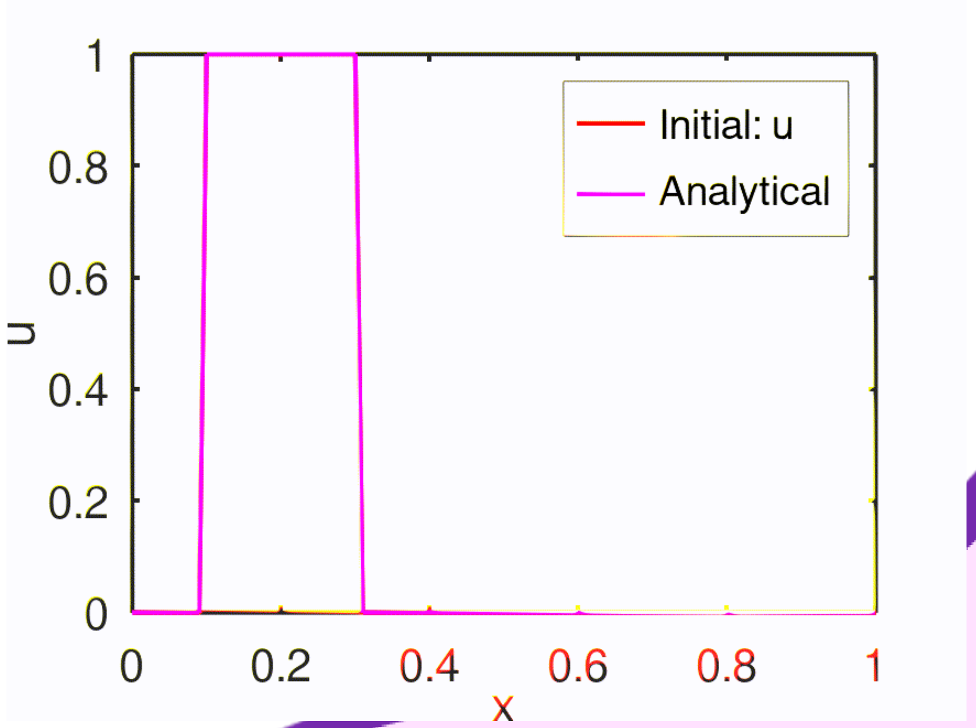


Information from left and right ends

$$u_i^{n+1} = u_i^n - c\Delta t \boxed{\left(\frac{\partial u}{\partial x}\right)_i^n}$$

$$\left(\frac{\partial u}{\partial x}\right)_i^n \approx \frac{u_{i+1}^n - u_i^n}{\Delta x_i}$$ Simple forward difference scheme

$$\left(\frac{\partial u}{\partial x}\right)_i^n \approx \frac{u_{i+1}^n - u_{i-1}^n}{2\Delta x_i}$$ Central difference



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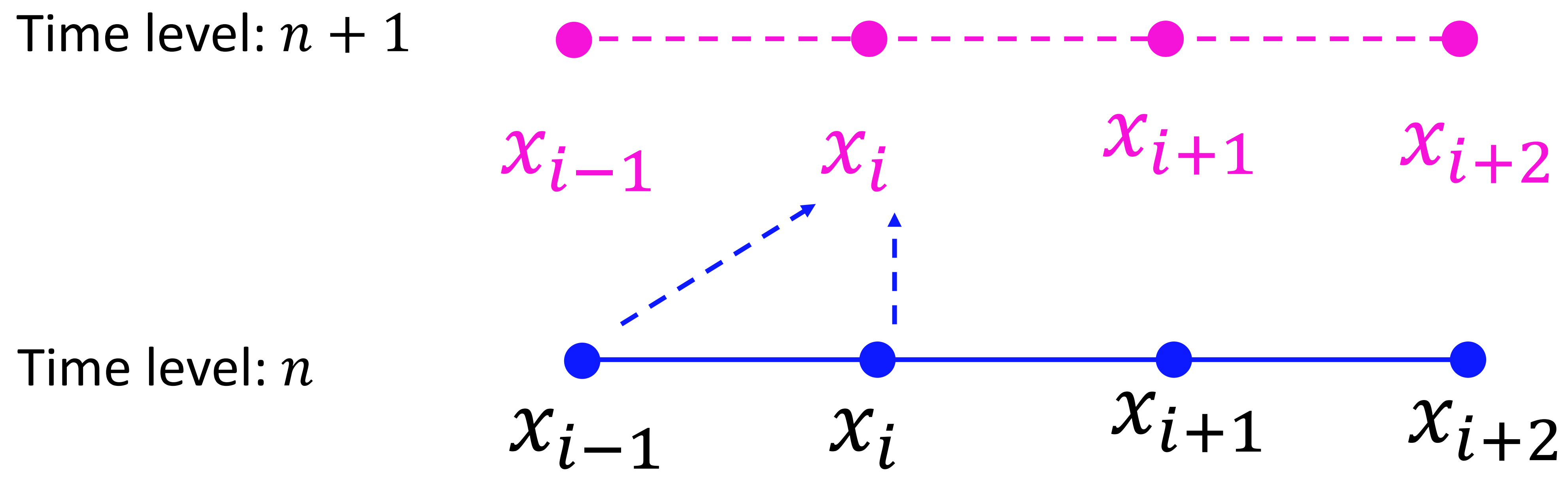
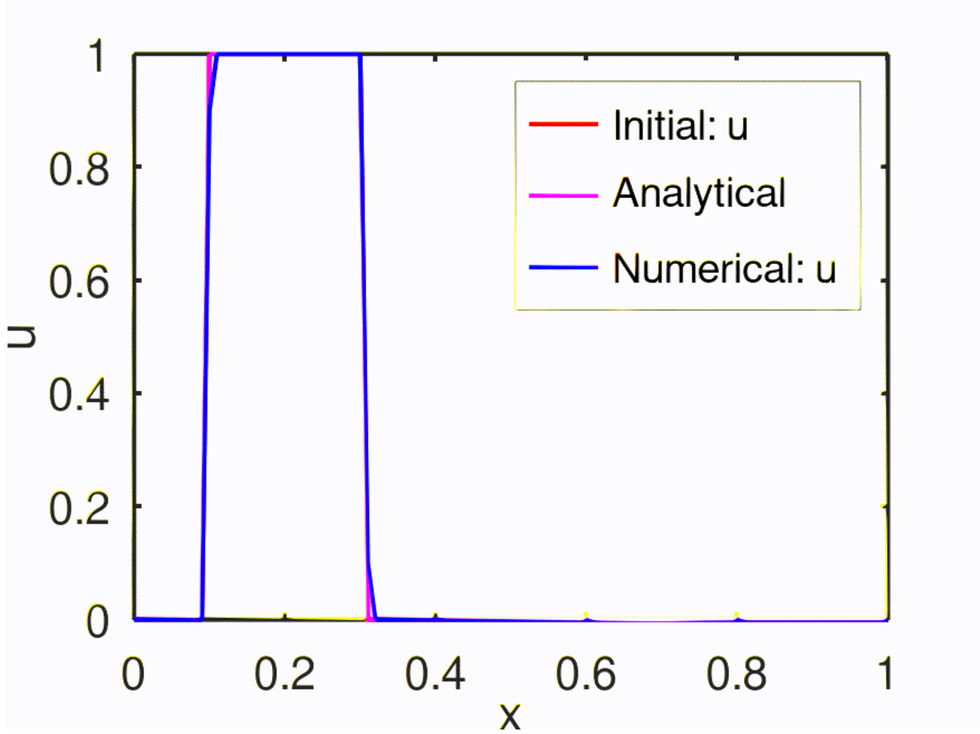
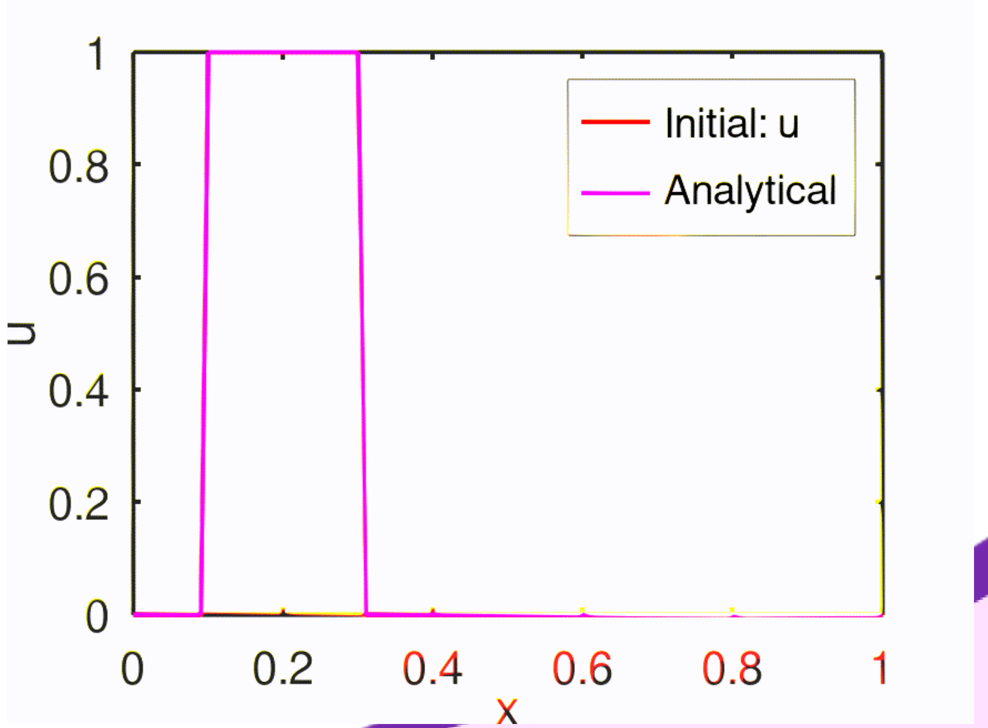
Numerical Stability - Advection equation







Information from left to right end

Wind is flowing from left end (bird moves from left to right)

$$u_i^{n+1} = u_i^n - c\Delta t \boxed{\left(\frac{\partial u}{\partial x}\right)_i^n} \longrightarrow \left(\frac{\partial u}{\partial x}\right)_i^n \approx \frac{u_i^n - u_{i-1}^n}{\Delta x_i}$$

Simple backward difference scheme

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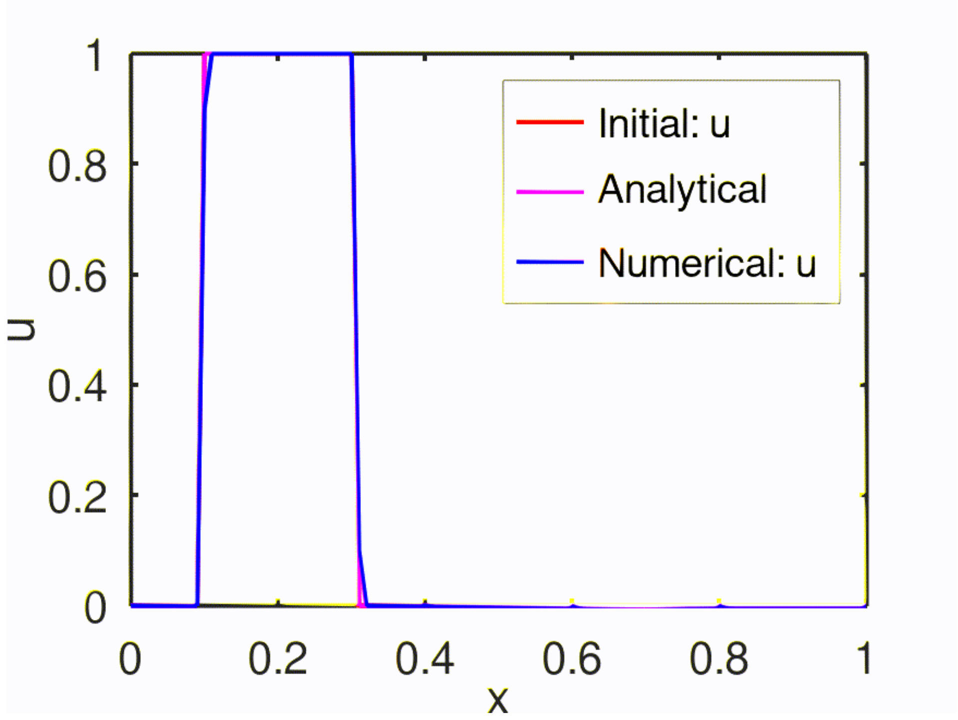
Numerical Stability - Advection equation

$$\boxed{\frac{\partial u}{\partial t} + c\frac{\partial u}{\partial x} = 0}$$

$$u_i^{n+1} = u_i^n - c\Delta t \left(\frac{\partial u}{\partial x}\right)_i^n \rightarrow \boxed{\left(\frac{\partial u}{\partial x}\right)_i^n \approx \frac{u_i^n - u_{i-1}^n}{\Delta x_i}}$$

Simple backward difference scheme

Upwind scheme



Information from left to right end

Wind is flowing from left end (Flowing towards the source of the wind)

$$u_i^{n+1} = u_i^n - c\Delta t \left(\frac{\partial u}{\partial x}\right)_i^n \rightarrow \left(\frac{\partial u}{\partial x}\right)_i^n \approx \frac{u_{i+1}^n - u_i^n}{\Delta x_i}$$

Simple forward difference scheme

Downwind scheme

Wind is flowing from right end (Flowing away from the source of wind)

CFL = 0.1 $CFL: \frac{c\Delta t}{\Delta x}$

Courant - Friedrichs - Lewy Number

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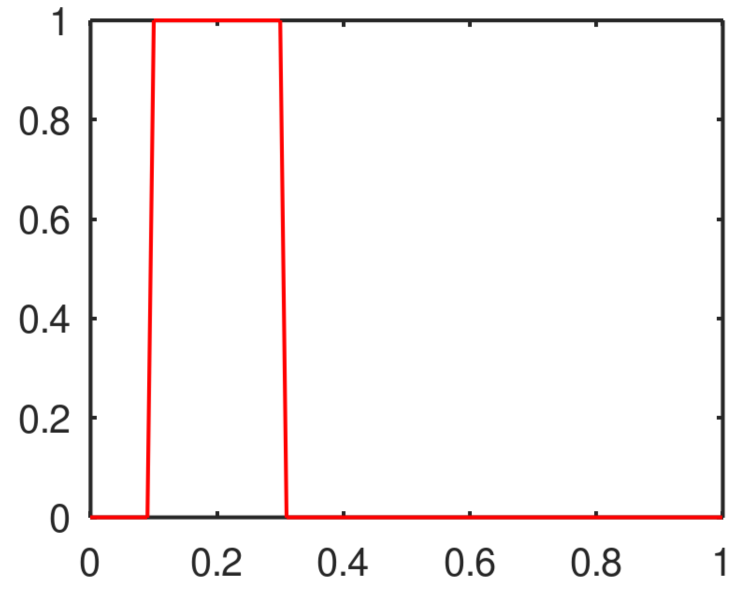
Numerical Stability - Advection equation

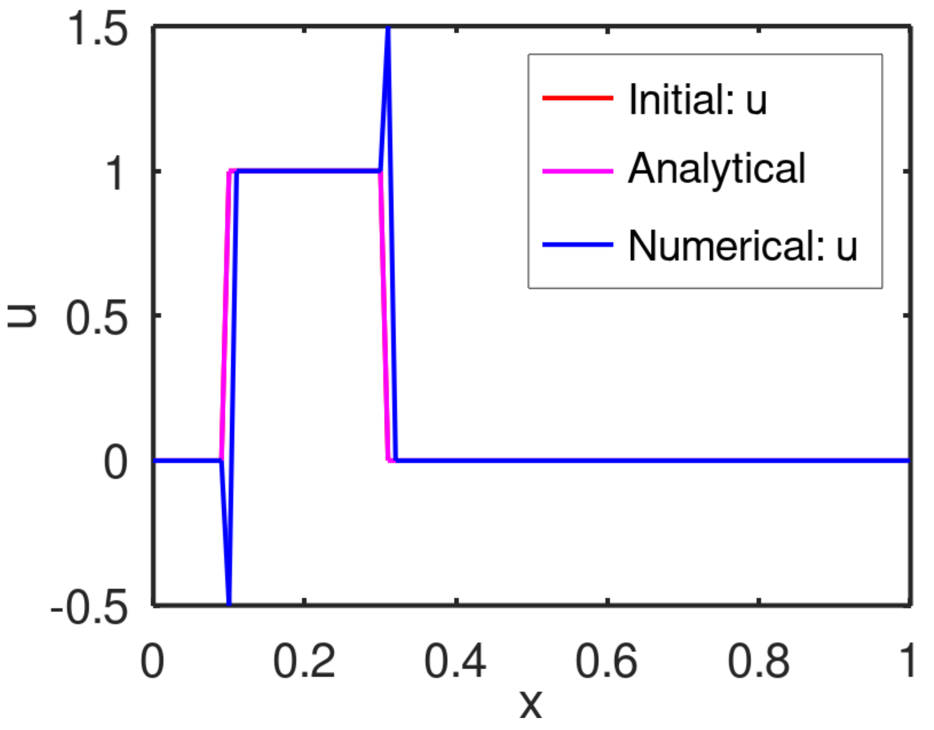


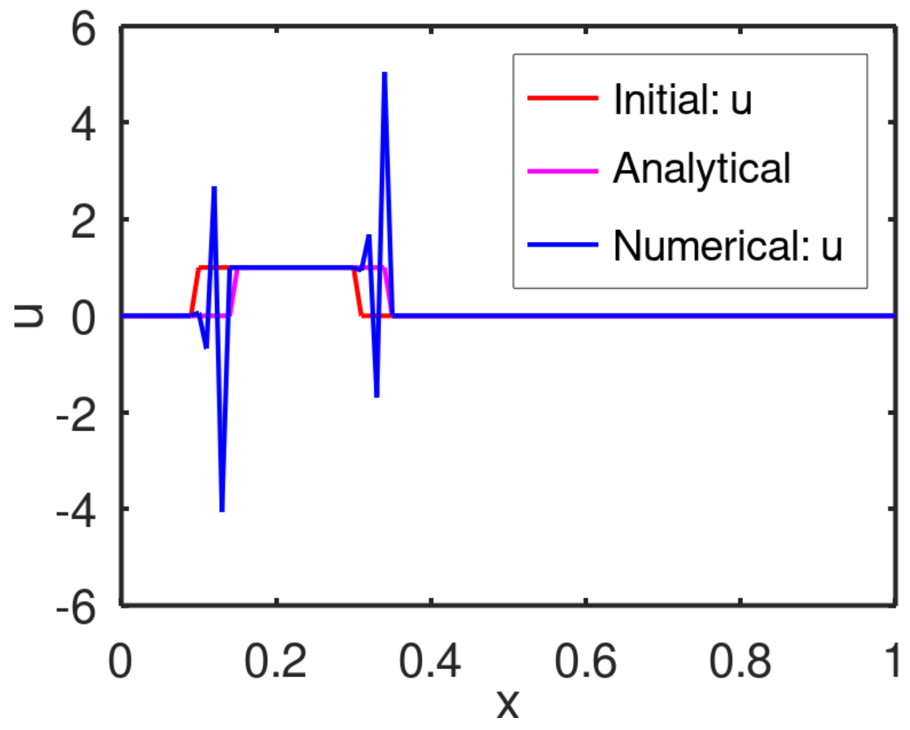
$$u_i^{n+1} = u_i^n - c\Delta t \left(\frac{\partial u}{\partial x}\right)_i^n \longrightarrow \left(\frac{\partial u}{\partial x}\right)_i^n \approx \frac{u_i^n - u_{i-1}^n}{\Delta x_i}$$

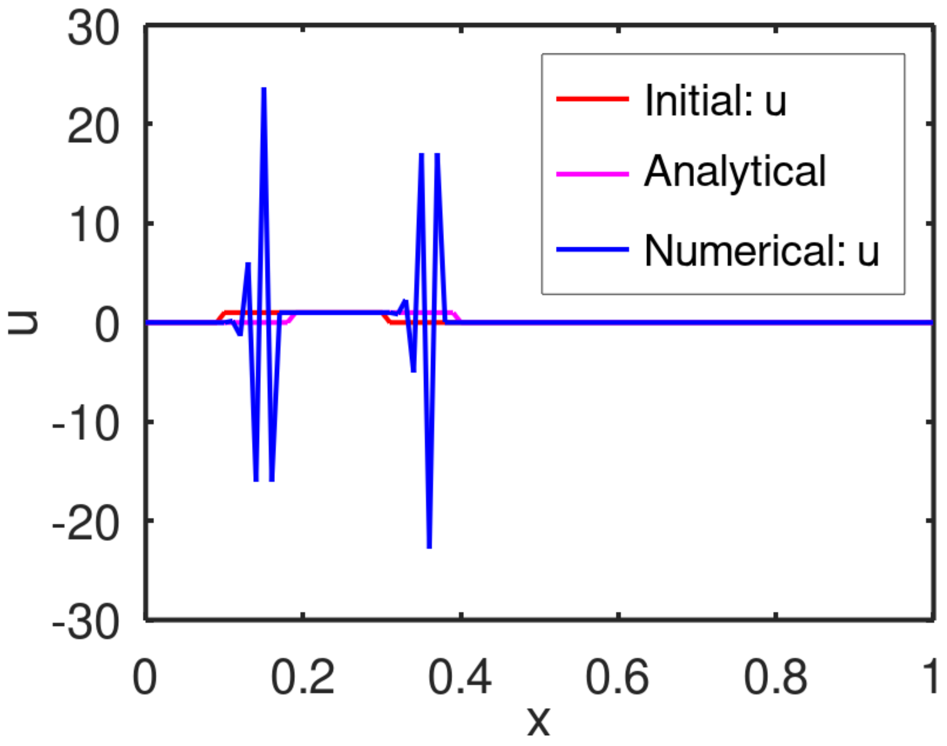
Simple backward difference scheme

Upwind scheme

$$CFL: \frac{c\Delta t}{\Delta x}$$







CFL = 1.5 Δt **increase**

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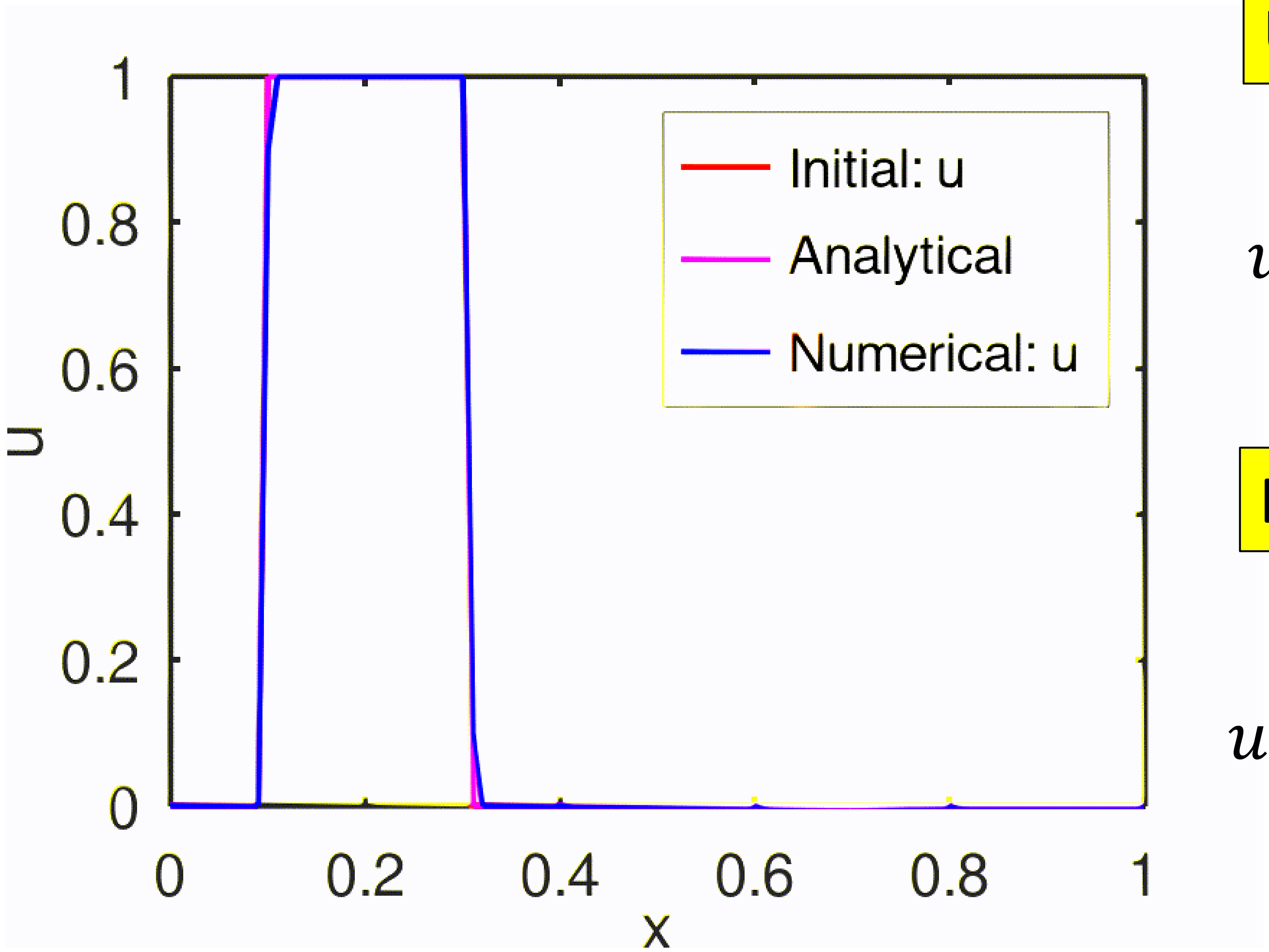
What did we discuss ?

- Proper discrete approximations need to be chosen based on the velocity field.
- CFL number is critical to ensure numerical stability.



Upwind scheme

$$u_i^{n+1} = u_i^n - c\Delta t \boxed{\left(\frac{\partial u}{\partial x}\right)_i^n} \longrightarrow \left(\frac{\partial u}{\partial x}\right)_i^n \approx \frac{u_i^n - u_{i-1}^n}{\Delta x_i}$$

Simple backward difference scheme

Downwind scheme

$$u_i^{n+1} = u_i^n - c\Delta t \boxed{\left(\frac{\partial u}{\partial x}\right)_i^n} \longrightarrow \left(\frac{\partial u}{\partial x}\right)_i^n \approx \frac{u_{i+1}^n - u_i^n}{\Delta x_i}$$

Simple forward difference scheme

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Exercise – 7 (ii)

1. Solve the following advection equation numerically in octave

$$\frac{\partial u}{\partial t} + c\frac{\partial u}{\partial x} = 0$$

   a) Central difference with CFL = 0.1 (dx = 0.01, c = 0.01, dt = 0.1, t_final = 5)

2. Upwind scheme (backward difference) with CFL = 0.1 (dx = 0.01, dt = 0.1, t_final = 5). Change the ”c” value between 0.01 and -0.01 and analyze the stability. Hint: Upwind scheme with c = -0.01 becomes unstable and act as downwind.

3. Downwind scheme (forward difference) with CFL = 0.1 (dx = 0.01, dt = 0.1, t_final = 5). Change the ”c” value between 0.01 and -0.01 and analyze the stability. Hint: Downwind scheme with c = -0.01 becomes stable and act as upwind.

4. Examine CFL numbers. Analyse the upwind scheme with CFL = 0.1, 1.0, and 10. Analyze the stability. (dx = 0.01, c = 0.01, dt = 0.1, t_final = 5)

5. Upload in GitHub.

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THANK YOU