

# Problem Set 1

## Wave Equation

due date: November 23, 2023

C++ programming language using

NR\_Hydro

## A Solving the wave equation

In this problem set, we will consider a simple non-relativistic example and will investigate the one-dimensional wave equation for the scalar field  $\phi$

$$\frac{\partial^2 \phi(x, t)}{\partial t^2} = c^2 \frac{\partial^2 \phi(x, t)}{\partial x^2}, \quad (1)$$

with  $c = \text{const.}$

### (A.1) Fully first order formulation (10 Marks)

As a first task, rewrite the wave equation (Eq. (1)) in a fully first order form by using the auxiliary variables  $\eta = \partial_t \phi$  and  $\chi = \partial_x \phi$ . Collect them into the state vector  $\mathbf{u} = (\phi, \eta, \chi)$  and show that the vector equation can be written as

$$\partial_t \mathbf{u} + \mathbf{A} \partial_x \mathbf{u} = \mathbf{S}, \quad (2)$$

where  $\mathbf{A}$  is a matrix and  $\mathbf{S}$  is the vector of source terms. Analyze matrix  $\mathbf{A}$  by evaluating its eigenvalues and eigenvectors.

### (A.2) Solving the wave equation

In the next step, please consider the following initial condition

$$\phi(x, 0) = e^{\sin^2(\frac{\pi x}{L})} - 1, \quad 0 \leq x \leq L, \quad (3)$$

with periodic boundary condition

$$\phi(x, t) = \phi(x \pm L, t). \quad (4)$$

For simplicity, you should choose  $L = 1 = c$ .

Write a code to solve the system 2 numerically using

1. (15 Marks) second-order spatial finite differencing stencils and the forward Euler method, and
2. (25 Marks) forth-order spatial finite difference and the forth-order Runge-Kutta method.

For the spatial grid setting, you can discretize the equation in space using an N-points grid in cell center:

$$x_i = \left(i - \frac{1}{2}\right) \Delta x, \quad i = 1, 2, \dots, N, \quad (5)$$

with  $\Delta x = L/N$  and  $\mathbf{u}_i = \mathbf{u}(x_i)$ . Note that the time step for this hyperbolic system has to follow the Courant-Friedrich-Levy condition

$$\max |\lambda_i| \frac{\Delta t}{\Delta x} \leq C_{\max}, \quad (6)$$



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where  $\lambda_i$  is the characteristic speed of the system and  $C_{max}$  is the maximum allowed Courant number depending (where the exact number will depend on the exact discretization scheme; typically  $C_{max} = 1$ ). You can choose  $\Delta t = C \frac{\Delta x}{\max |\lambda_i|}$  for Courant number  $C \leq 1$  in this problem. Perform convergence test by varying the resolution  $\Delta x$  and  $\Delta t$  to verify your result.

### (A.3) Parallelization C++

In the following we will extend the program by employing different parallelization schemes, please parallelize your code using

1. (25 Marks) Open MP, and
2. (25 Marks) MPI

Show that your parallelized code gives the same result as the serial version and measure the performance of your code by performing a strong scaling test (i.e. fix your problem size and measure the execution time with different number of processors). You may need to use a large number of grid points  $N > 1000$  for the test.

– Please submit solutions to peter.nee@aei.mpg.de. –