8 Finite Differences: Partial Differential Equations

The world is defined by structure in space and time, and it is forever changing in complex ways that can't be solved exactly. Therefore the numerical solution of partial differential equations leads to some of the most important, and computationally intensive, tasks in all of numerical analysis (such as forecasting the weather). This chapter introduces *finite difference* techniques; the next two will look at other ways to discretize partial differential equations (finite elements and cellular automata). Just as we used a Taylor expansion to derive a numerical approximation for ordinary differential equations, the same procedure can be applied to partial differential equations. Because the discretization must be done in space as well as time, there are many more possible strategies for finding good (and bad) approximations.

We will start with two degrees of freedom, say one spatial variable x and a time t. Given a function $u(x,t)$, its spatial derivatives are found from the Taylor expansion

$$u(x+\Delta x,t) = u(x,t) + \Delta x \left.\frac{\partial u}{\partial x}\right|_{x,t} + \frac{(\Delta x)^2}{2!}\left.\frac{\partial^2 u}{\partial x^2}\right|_{x,t} + \mathcal{O}[(\Delta x)^3] \quad . \tag{8.1}$$

The first partial derivative can be approximated by the *forward difference*

$$\frac{u(x+\Delta x,t)-u(x,t)}{\Delta x} = \left.\frac{\partial u}{\partial x}\right|_{x,t} + \mathcal{O}[\Delta x] \quad . \tag{8.2}$$

If we replace Δx with $-\Delta x$, this becomes the equally reasonable *backwards difference* approximation

$$\frac{u(x,t)-u(x-\Delta x,t)}{\Delta x} = \left.\frac{\partial u}{\partial x}\right|_{x,t} + \mathcal{O}[\Delta x] \quad . \tag{8.3}$$

Their order can be raised by taking the difference between two time steps, which subtracts out the quadratic term:

$$\frac{u(x+\Delta x,t)-u(x-\Delta x,t)}{2\Delta x} = \left.\frac{\partial u}{\partial x}\right|_{x,t} + \mathcal{O}[(\Delta x)^2] \quad . \tag{8.4}$$

Although this might appear always to be preferable, we will see that it can have surprising undesirable stability properties.

The straightforward finite difference approximation to the second partial derivative is

Finite Differences And Partial Differential Equations

Gordon D. Smith

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