The Finite Difference Method

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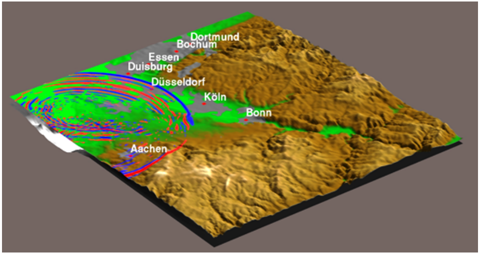
Outline

Motivation



- Simple concept
- Robust
- Easy to parallelize
- Regular grids
- Explicit method

History

- Several Pioneers of solving PDEs with finite-difference method (Lewis Fry Richardson, Richard Southwell, Richard Courant, Kurt Friedrichs, Hans Lewy, Peter Lax and John von Neumann)
- First application to elastic wave propagation (Alterman and Karal, 1968)
- Simulating Love waves and was the frst showing snapshots of seimsic wave fields (Boore, 1970)
- Concept of staggered-grids by solving the problem of rupture propagation (Madariaga, 1976 and Virieux and Madariaga, 1982)

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- Extension to 3D because of parallel computations (Frankel and Vidale, 1992; Olsen and Archuleta, 1996; etc.)
- Application to spherical geometry by Igel and Weber, 1995; Chaljub and Tarantola, 1997 and 3D spherical sections by Igel et al., 2002
- Incorporation in the first full waveform inversion schemes initially in 2D, e.g. (Crase et al., 1990) and later in 3D (Chen et al., 2007)

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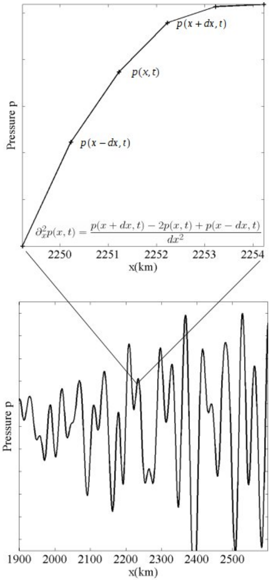
Finite Differences in a Nutshell



- Snapshot in space of the pressure field p
- Zoom into the wave field with grid points indicated by +
- Exact interpolate using Taylor series

1D acoustic wave equation

$$\ddot{p}(x,t) = c(x)^2\ \partial_x^2 p(x,t) + s(x,t)$$

p	pressure
c	acoustic velocity
s	source term

Approximation with a difference formula

$$\ddot{p}(x,t) \approx \frac{p(x,t+dt) - 2p(x,t) + p(x,t-dt)}{dt^2}$$

and equivalently for the space derivative

Finite Differences and Taylor Series

Finite Differences

Forward derivative

$$d_x f(x) = \lim_{dx \to 0} \frac{f(x+dx) - f(x)}{dx}$$

Centered derivative

$$d_x f(x) = \lim_{dx \to 0} \frac{f(x+dx) - f(x-dx)}{2dx}$$

Backward derivative

$$d_x f(x) = \lim_{dx \to 0} \frac{f(x) - f(x-dx)}{dx}$$

Finite Differences

Forward derivative

$$d_x f^+ \approx \frac{f(x+dx) - f(x)}{dx}$$

Centered derivative

$$d_x f^c \approx \frac{f(x+dx) - f(x-dx)}{2dx}$$

Backward derivative

$$d_x f^- \approx \frac{f(x) - f(x-dx)}{dx}$$

Finite Differences and Taylor Series

The approximate sign is important here as the derivatives at point x are not exact. Understanding the accuracy by looking at the definition of Taylor Series:

$$f(x+dx) = f(x) + f'(x)\,dx + \frac{1}{2!}\,f''(x)\,dx^2 + O(dx^3)$$

Subtraction with f(x) and division by dx leads to the definition of the forward derivative:

$$\frac{f(x+dx)-f(x)}{dx} = f'(x)\ + \frac{1}{2!}\,f''(x)\,dx + O(dx^2)$$

Finite Differences and Taylor Series

Using the same approach - adding the Taylor Series for $f(x+dx)$ and $f(x-dx)$ and dividing by $2dx$ leads to:

$$\frac{f(x+dx)-f(x-dx)}{2dx} = f'(x) + O(dx^2)$$

This implies a centered finite-difference scheme more rapidly converges to the correct derivative on a regular grid

$\Longrightarrow$ It matters which of the approximate formula one chooses

$\Longrightarrow$ It does not imply that one or the other finite-difference approximation is always the better one

Higher Derivatives

- The partial differential equations have often 2nd (seldom higher) derivatives
- Developing from first derivatives by mixing a forward and a backward definition yields to

$$\partial_x^2 f \approx \frac{\frac{f(x+dx)-f(x)}{dx} - \frac{f(x)-f(x-dx)}{dx}}{dx} = \frac{f(x+dx) - 2f(x) + f(x-dx)}{dx^2}$$

Higher Derivatives

Determining the weights with which the function values have to be multiplied to obtain derivative approximations

The Taylor series for two grid points at $x \pm dx$, include the function at the central point as well and multiply each by a real number

$$
\begin{aligned}
af(x+dx) &= a\left[f(x) + f'(x)\,dx + \tfrac{1}{2!}\,f''(x)\,dx^2 + \dots\right] \\
bf(x) &= b\left[f(x)\right] \\
cf(x-dx) &= c\left[f(x) - f'(x)\,dx + \tfrac{1}{2!}\,f''(x)\,dx^2 - \dots\right]
\end{aligned}
$$

Higher Derivatives

Summing up the right-hand sides of the previous equations and comparing coefficients leads to the following system of equations:

$$a + b + c = 0$$
$$a - c = 0$$
$$a + c = \frac{2!}{dx^2}$$

$$\Longrightarrow$$

$$a = \frac{1}{dx^2}$$
$$b = -\frac{2}{dx^2}$$
$$c = \frac{1}{dx^2}$$

High-Order Operators

What happens if we extend the *domain of influence* for the derivative(s) of our function f(x)?

Let us search for a 5-point operator for the second derivative

$$f'' \approx af(x+2dx) + bf(x+dx) + cf(x) + df(x-dx) + ef(x-2dx)$$

$$\begin{aligned} a + b + c + d + e &= 0 \\ 2a + b \quad - d - 2e &= 0 \\ 4a + b \quad + d + 4e &= \frac{1}{2\mathrm{d}x^2} \\ 8a + b \quad - d - 8e &= 0 \\ 16a + b \quad + d + 16e &= 0 \end{aligned}$$

High-Order Operators

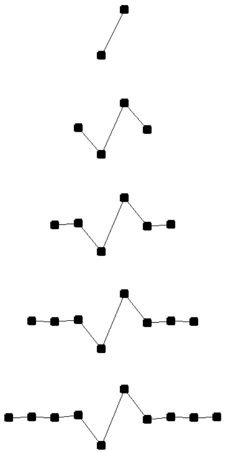
Using matrix inversion we obtain a unique solution

$$
\begin{aligned}
a &= -\frac{1}{12\mathrm{d}x^2} \\
b &= \frac{4}{3\mathrm{d}x^2} \\
c &= -\frac{5}{2\mathrm{d}x^2} \\
d &= \frac{4}{3\mathrm{d}x^2} \\
e &= -\frac{1}{12\mathrm{d}x^2} \ .
\end{aligned}
$$

with a leading error term for the 2nd derivative is $O(dx^4)$

$\Longrightarrow$ Accuracy improvement

High-Order Operators



Graphical illustration of the Taylor Operators for the first derivative for higher orders

The weights rapidly become small for increasing distance to central point of evaluation

Finite-Difference Approximation of Wave Equations

Acoustic waves in 1D

To solve the wave equation, we start with the simplemost wave equation:

The constant density acoustic wave equation in 1D

$$\ddot{p} = c^2 \, \partial_x^2 p + s$$

impossing pressure-free conditions at the two boundaries as

$$p(x) \mid_{x=0,L} = 0$$

Acoustic waves in 1D

The following dependencies apply:

$$
\begin{aligned}
p &\rightarrow p(\mathbf{x}, \mathbf{t}) && \text{pressure} \\
c &\rightarrow c(\mathbf{x}) && \text{P-velocity} \\
s &\rightarrow s(\mathbf{x}, \mathbf{t}) && \text{source term}
\end{aligned}
$$

As a first step we need to discretize space and time and we do that with a constant increment that we denote dx and dt.

$$
\begin{aligned}
x_j &= j\mathrm{d}x, \qquad j = 0, j_{max} \\
t_n &= n\mathrm{d}t, \qquad n = 0, n_{max}
\end{aligned}
$$

Acoustic waves in 1D

Starting from the continuous description of the partial differential equation to a discrete description. The upper index will correspond to the time discretization, the lower index will correspond to the spatial discretization

$$
\begin{aligned}
p_j^{n+1} &\rightarrow p(x_j, t_n + \mathrm{d}t) \\
p_j^{n} &\rightarrow p(x_j, t_n) \\
p_j^{n-1} &\rightarrow p(x_j, t_n - \mathrm{d}t) \\
p_{j+1}^{n} &\rightarrow p(x_j + \mathrm{d}x, t_n) \\
p_j^{n} &\rightarrow p(x_j, t_n) \\
p_{j-1}^{n} &\rightarrow p(x_j - \mathrm{d}x, t_n)
\end{aligned}
$$

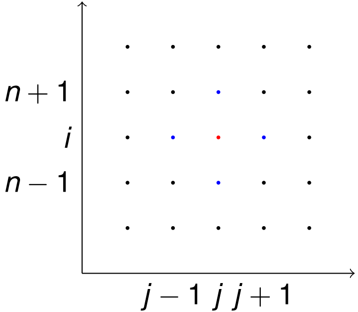
.

Acoustic waves in 1D

$$\frac{p_j^{n+1} - 2p_j^n + p_j^{n-1}}{\mathrm{d}t^2} = c_j^2 \left[\frac{p_{j+1}^n - 2p_j^n + p_{j-1}^n}{\mathrm{d}x^2} \right] + s_j^n \, .$$

the r.h.s. is defined at same time level n

the l.h.s. requires information from three different time levels



Acoustic waves in 1D

Assuming that information at time level n (the presence) and $n-1$ (the past) is known, we can solve for the unknown field p_j^{n+1}:

$$p_j^{n+1} \;=\; c_j^2 \frac{\mathrm{d}t^2}{\mathrm{d}x^2}\left[p_{j+1}^n - 2p_j^n + p_{j-1}^n\right] + 2p_j^n - p_j^{n-1} + \mathrm{d}t^2 s_j^n$$

The initial condition of our wave simulation problem is such that everything is at rest at time t = 0:

$$p(x,t)|_{t=0} \;=\; 0\;,\;\; \dot{p}(x,t)|_{t=0} \;=\; 0.$$

Acoustic waves in 1D

- Waves begin to radiate as soon as the source term $s(x,t)$ starts to act
- For simplicity: the source acts directly at a grid point with index j_s
- Temporal behaviour of the source can be calculated by Green's function

$$s(x,t) = \delta(x - x_s)\,\delta(t - t_s)$$

where x_s and t_s are source location and source time and $\delta()$ corresponds to the delta function

Acoustic waves in 1D

A delta function contains all frequencies and we cannot expect that our numerical algorithm is capable of providing accurate solutions Operating with a band-limited source-time function:

$$s(x, t) = \delta(x - x_s)\ f(t)$$

where the temporal behaviour f(t) is chosen according to our specific physical problem

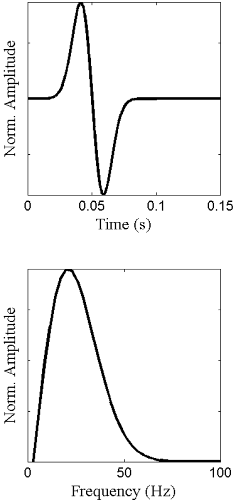
Example

Simulating acoustic wave propagation in a 10km column (e.g. the atmosphere) and assume an air sound speed of $c = 0.343m/s$. We would like to *hear* the sound wave so it would need a dominant frequency of at least 20 Hz. For the purpose of this exercise we initialize the source time function $f(t)$ using the first derivative of a Gauss function.

$$f(t) \ = \ -8 \ f_0 \ (t - t_0) \ e^{-\frac{1}{(4f_0)^2} \ (t-t_0)^2}$$

where t_0 corresponds to the time of the zero-crossing, f_0 is the dominant frequency

Example



- What is the minimum spatial wavelength that propagates inside the medium?
- What is the maximum velocity inside the medium?
- What is the propagation distance of the wavefield (e.g., in dominant wavelengths)?

Example

Sufficient to look at the relation between frequency and wavenumber:

$$c = \frac{\omega}{k} = \frac{\lambda}{T} = \lambda f$$

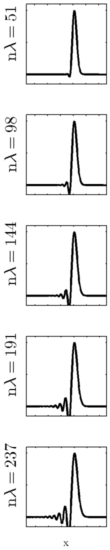
where c is velocity, T is period, λ is wavelength, f is frequency, and $\omega = 2\pi f$ is angular frequency

- dominant wavelength of $f_0 = 20Hz$
- substantial amount of energy in the wavelet is at frequencies above 20 Hz
- $\Longrightarrow \lambda = 17m$ and $\lambda = 7m$ for frequencies $20Hz$ and $50Hz$, respectively

Matlab code fragment

```
% Time extrapolation
for it = 1 : nt,
(...)
% Space derivatives
for j=2:nx-1
d2p(j)=(p(j+1)-2*p(j)+p(j-1))/dx^2;
end
% Extrapolation
pnew=2*p-pold+c^2*d2p*dt^2;
% Source input
pnew(isrc)=pnew(isrc)+src(it)*dt^2;
% Time levels
pold=p;
p=pnew;
(...)
```

Result



Choosing a grid increment of $dx = 0.5m \longrightarrow$ about 24 points per spatial wavelength for the dominant frequency

Setting time increment $dt = 0.0012 \longrightarrow$ around 40 points per dominant period

Summary

- Replacing the partial derivatives by finite differences allows partial differential equations such as the wave equation to be solved directly for (in principle) arbitrarily heterogeneous media
- The accuracy of finite-difference operators can be improved by using information from more grid points (i.e., longer operators). The weights for the grid points can be obtained using Taylor series