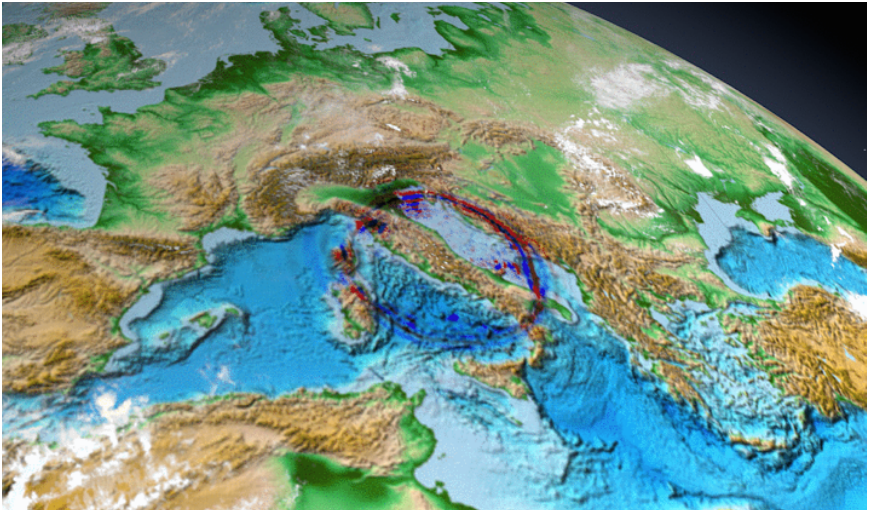
Computational Seismology: A Practical Introduction

Introduction



Goals of the course

- Understand methods that allow the calculation of **seismic wavefields in heterogeneous media**
- Prepare you to be able to understand Earth science papers that are based on **3-D wave simulation tools** (e.g., seismic exploration, full waveform imaging, shaking hazard, volcano seismology)
- Know **the dangers, traps, and risks of using simulation tools** (as black boxes -> turning black boxes into white boxes)
- Providing you with basic knowledge about common **numerical methods**:
- Knowing **application domains** of the various methods and guidelines what method works best for various problems

Course structure

- **Introduction**
    - What is computational seismology?
    - When and why do we need numerical maths?
- **Elastic waves in the Earth**
    - What to expect when simulating seismic wave fields?
    - Wave equations
    - Seismic waves in simple media (benchmarks)
    - Seismic sources and radiation patterns
    - Green's functions, linear systems
- **Numerical approximations of the 1 (2, 3) -D wave equation**
    - Finite-difference method
    - Pseudospectral method
    - Spectral-element method
    - Discontinuous Galerkin method
- **Applications in the Earth Sciences**

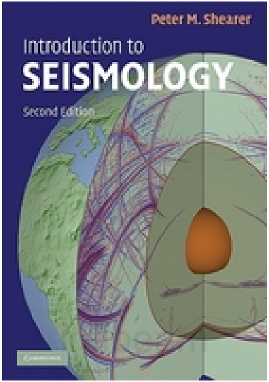
Who needs Computational Seismology

Many problems rely on the analysis of **elastic wavefields**

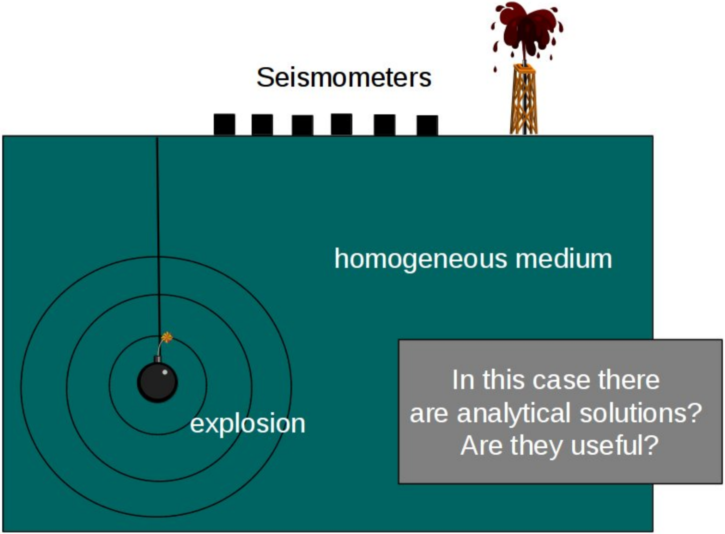
- **Global seismology** and tomography of the Earth's interior
- The quantification of **strong ground motion - seismic hazard**
- The understanding of the **earthquake source process**
- The monitoring of **volcanic processes** and the forecasting of eruptions
- **Earthquake early warning** systems
- **Tsunami early warning** systems
- Local, regional, and global **earthquake services**
- Global monitoring of **nuclear tests**
- **Laboratory scale analysis** of seismic events
- Ocean generated **noise measurements** and cross-correlation techniques
- **Planetary seismology**
- **Exploration geophysics**, reservoir scale seismics
- **Geotechnical engineering** (non-destructive testing, small scale tomography
- and, and, and...

Literature

- Computational seismology: a practical introduction (book draft, to appear in 2016)
- Shearer: Introduction to Seismology (2nd edition, 2009,Chapter 3.7-3.9)
- Aki and Richards, Quantitative Seismology (1st edition, 1980)
- Mozco, The Finite-Difference Method for Seismologists. An Introduction. (pdf available at spice-rtn.org), also as book Cambridge University Press
- Fichtner, Full Seismic Waveform Modelling and Inversion, Springer Verlag, 2010.

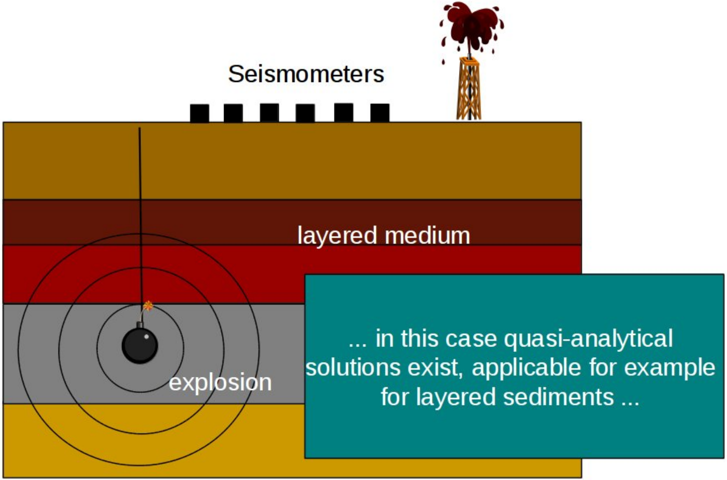


Why numerical methods?



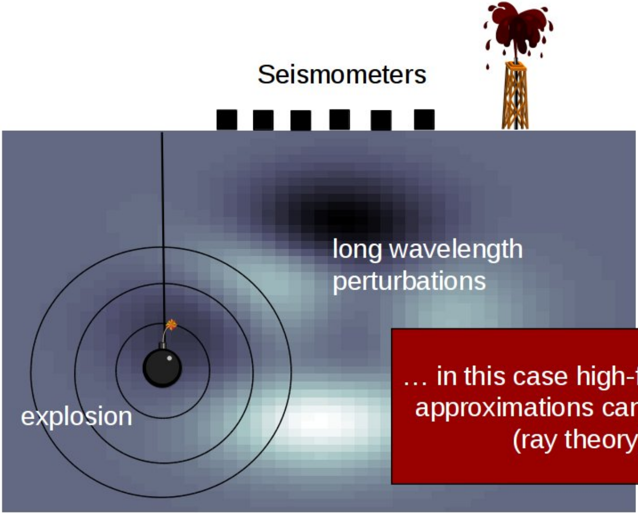
In this case there are analytical solutions? Are they useful?

Why numerical methods?



... in this case quasi-analytical solutions exist, applicable for example for layered sediments ...

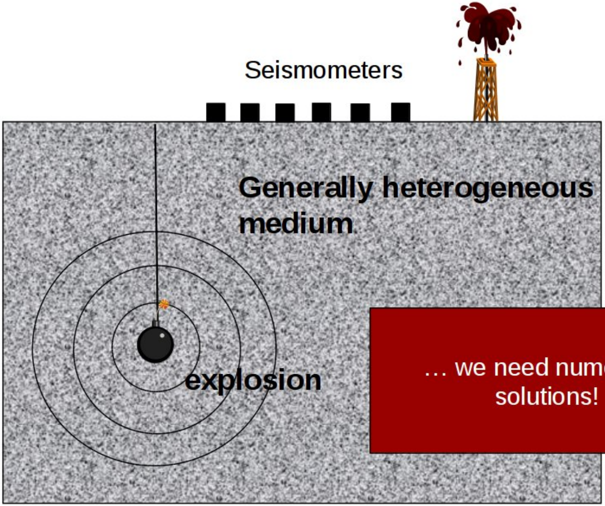
Why numerical methods?



… in this case high-frequency approximations can be used (ray theory)

Why numerical methods?

Nature is three-dimensional...



… we need numerical solutions!

What is Computional Seismology?

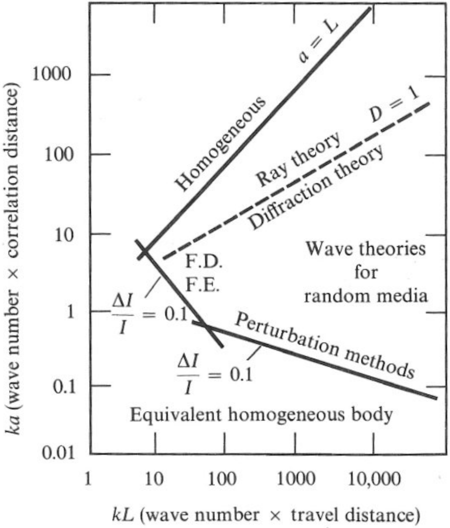
The complete solution of the governing 3-D partial differential equations require the adaptation of numerical methods developed in the field of applied mathematics. For the purpose of this course we define **computational seismology** such that it **involves the complete solution of the seismic wave propagation (and rupture) problem for arbitrary 3-D models by numerical means.**

Other (classical) approaches

- **High frequency approximations**
  - Ray methods
  - WKBJ methods
  - Generalized ray theory (incl. caustics)
- **Layered models**
  - Caignard method
  - Propagator matrices (reflectivity)
  - Normal-mode solutions (global wave propagation)

An attempt to classify the space of methodologies

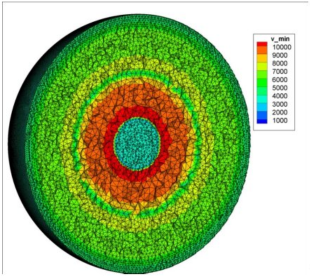
...following Aki and Richards (1980)

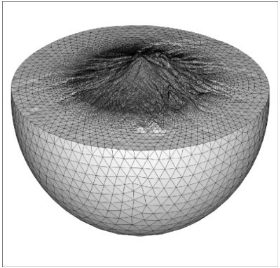


Computational Seismology, Memory, and Compute Power

Numerical solutions necessitate the discretization of Earth models. Estimate how much memory is required to store the Earth model and the required displacement fields.

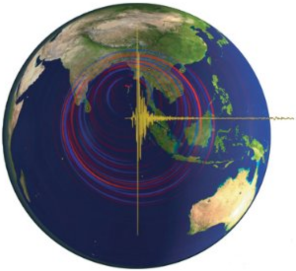
Are we talking laptop or supercomputer?





Exercise

You want to simulate global wave propagation. The highest frequencies that we observe for global wave fields is 1Hz. Let us for simplicity assume a homogeneous Earth (radius 6371km). The P velocity $v_p = 10 km/s$ and the vp/vs ratio is $\sqrt{3}$. Let us assume 20 grid points per wavelength are required to sample the wavefield. How many grid cells would you need (assume cubic cells). What would be their size? How much memory would you need to store one such field (e.g., density in single precision). You may want to make use of



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

Laptop or supercomputer?

Exercise- Solution

```
% Earth volume
v_e = 4/3 * pi * 6371^3;
% smallest velocity (ie, wavelength)
vp=10; vs=vp/sqrt(3);
% Shortest Period
T=10;
% Shortest Wavelength
lam=vs*T;
% Number of points per wavelength and
% required grid spacing
np_lambda = 20;
dx = lam/np_lambda;
% Required number of grid cells
nc = v_e/(dx^3);
% Memory requirement (TBytes)
mem = nc * 8/1000/1000/1000/1000;
```

$$\text{Results } (@T = 1s): \quad \text{360 TBytes}$$
$$\text{Results } (@T = 10s): \quad \text{360 GBytes}$$
$$\text{Results } (@T = 100s): \quad \text{360 MBytes}$$

Computational Seismology, Memory, and Compute Power

1960: 1 MFlops

1970: 10MFlops

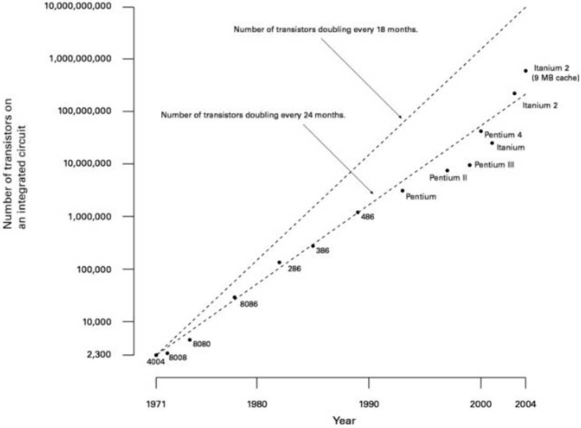
1980: 100MFlops

1990: 1 GFlops

1998: 1 TFlops

2008: 1 Pflops

20??: 1 EFlops



Summary

- Computational wave propagation (as defined here) is turning more and more into a routine tool for many fields of Earth sciences
- There is a zoo of methods and in many cases it is not clear which method works best for a specific problem
- For single researchers (groups, institutions) it is no longer possible to code, implement, maintain an algorithm efficiently
- More and more well engineered community codes become available (e.g., sofi3d, specfem, seissol)
- Community platforms (e.g., verce.eu) are developing facilitating simulation tasks

This course aims at understanding the theory behind these methods and understanding their domains of application.