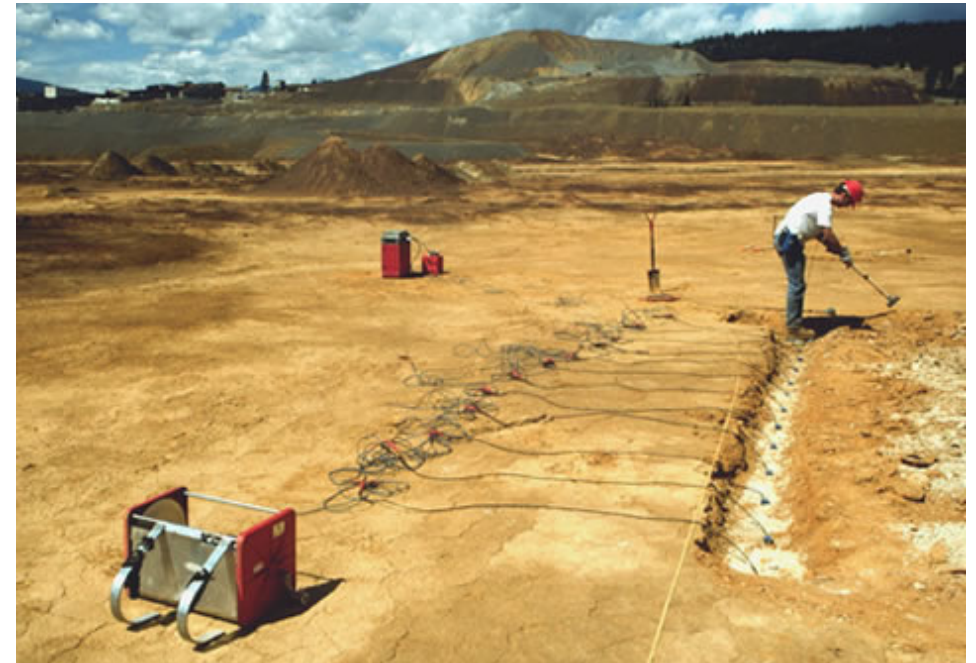
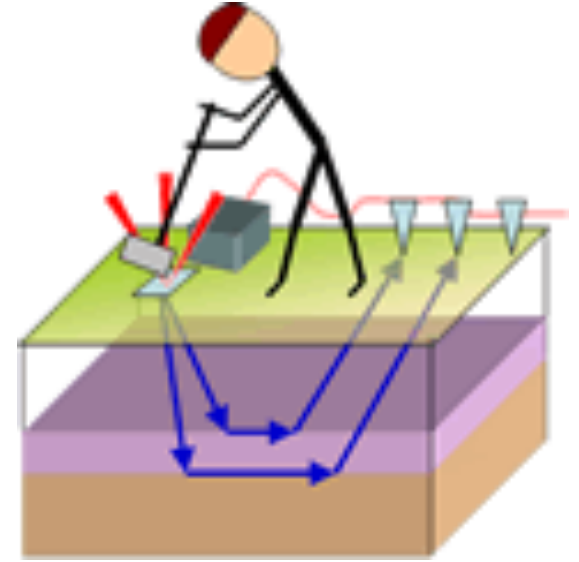


Seismology

EOSC 350

Applied geophysics: seismology

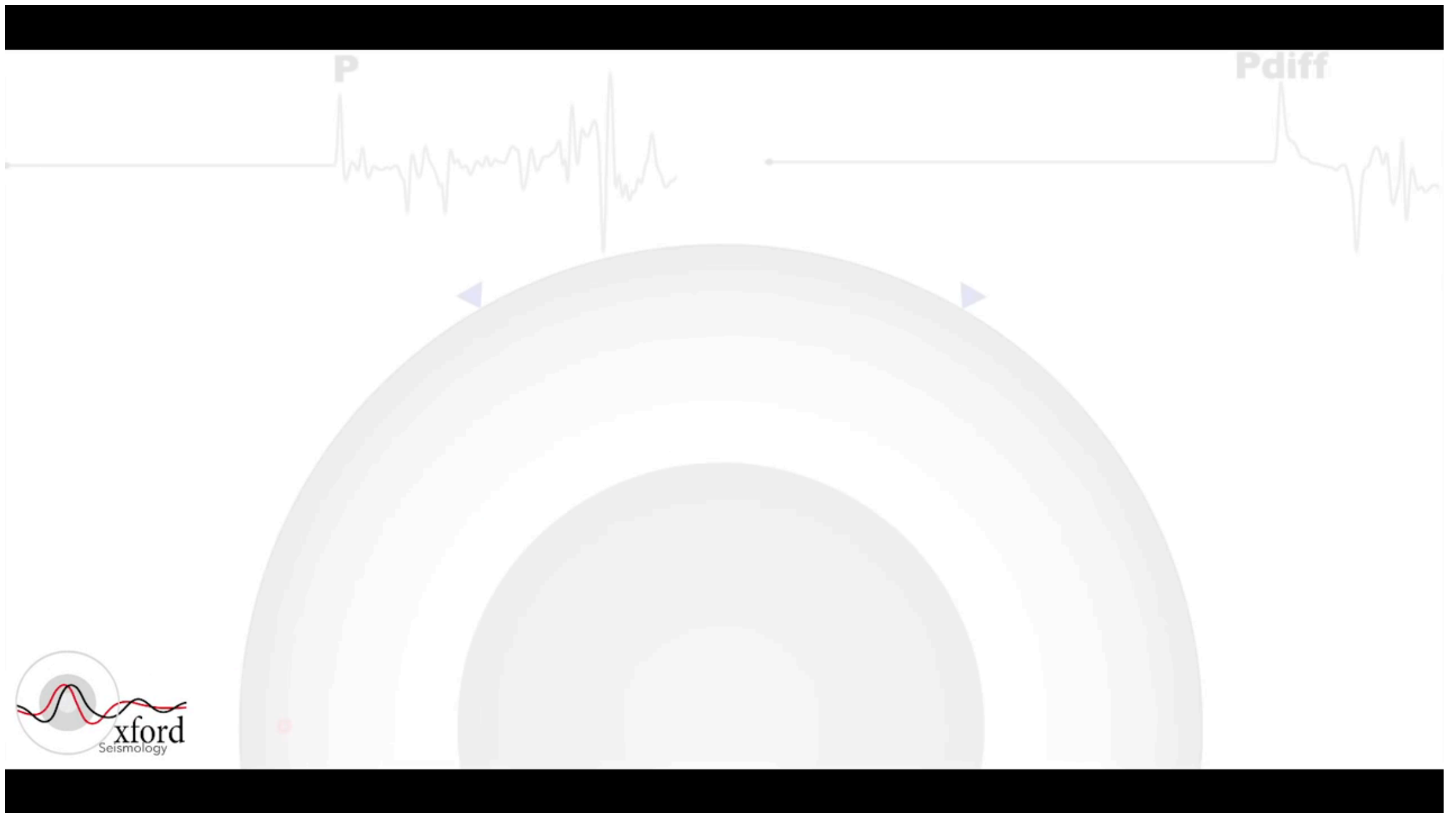
- Introduction
- Physical property
- Refraction
- Reflection
- MASW



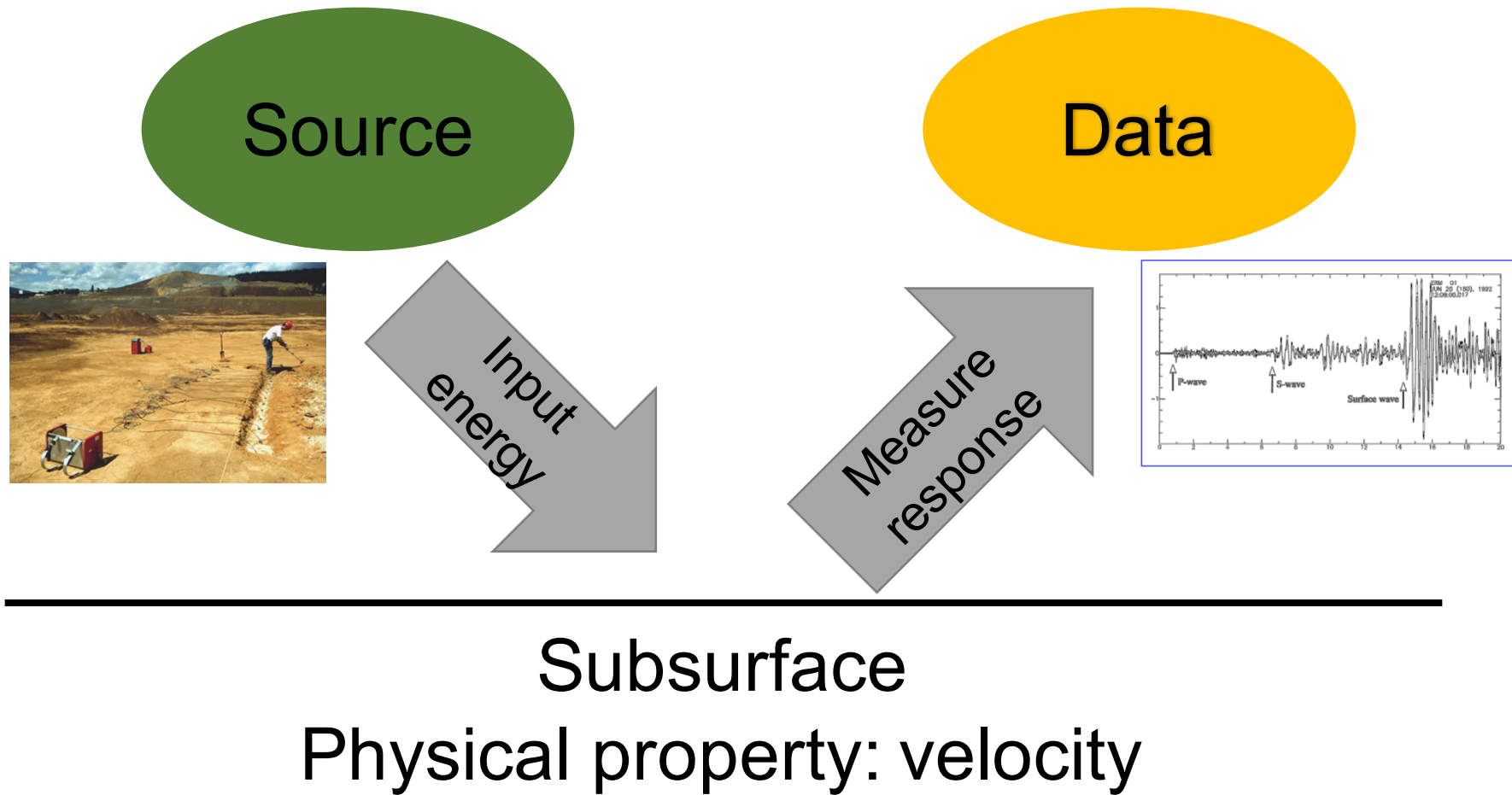
Introduction

Reading on the GPG:

<http://gpg.geosci.xyz/content/seismic/index.html>



The seismic survey



Physical property

Reading on the GPG:

http://gpg.geosci.xyz/content/physical_properties/seismic_velocity_duplicate.html

http://gpg.geosci.xyz/content/seismic/elastic_properties.html

Seismic velocity and elastic parameters

- Seismic surveys are sensitive to the **velocity** of seismic waves in the earth
- **Velocity** depends on the elastic properties and density of the material the wave is traveling through.
- Different descriptions of elastic properties
 - Young's modulus, Poisson's ratio
 - Bulk modulus, shear modulus
 - P-wave, S-wave velocities

Elastic deformation

- When a force is applied to a material, it may change in volume and/or shape
- Stress
 - Unit: N/m^2
 - Normal stress: perpendicular to the surface of an object
 - Shear stress: tangential to the surface of an object

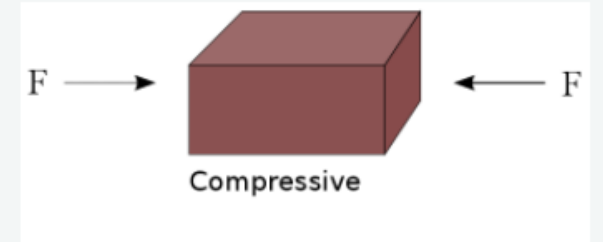


Fig. 9 Compressive normal stress

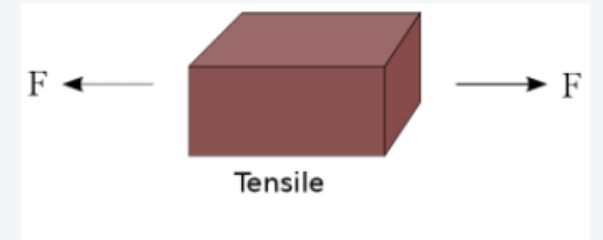


Fig. 10 Tensile normal stress

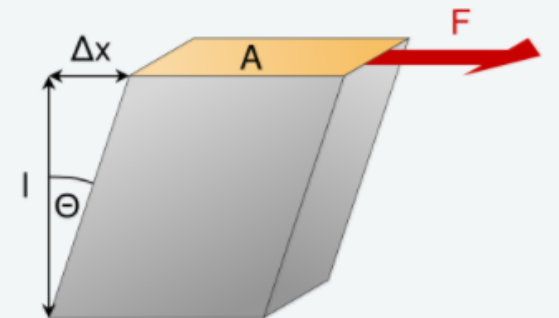


Fig. 11 Shear stress

Strain

- Strain is the deformation of a material due to an applied stress
- Elastic strain
 - Body recovers its original shape/volume when stress is removed
 - Here we will assume linear, elastic deformation
 - Meaning, we assume a linear relationship between stress and strain
 - Example?
- Plastic strain:
 - Body deforms permanently and may even fracture
 - Example?

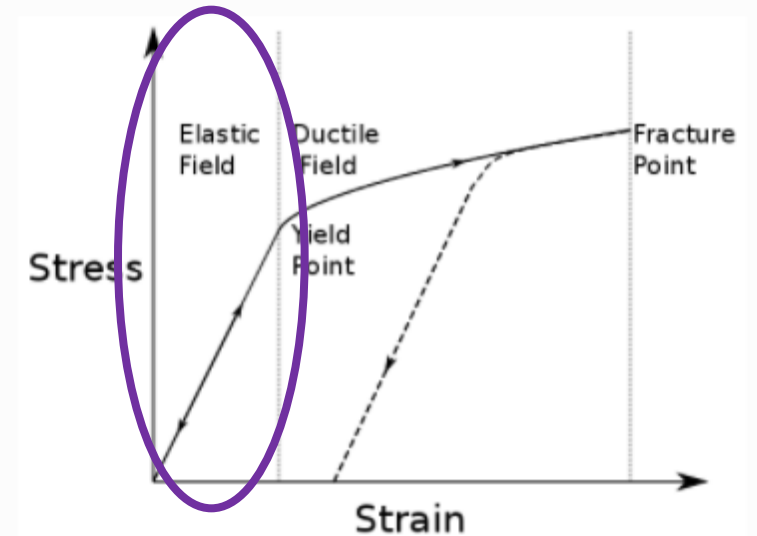


Fig. 12 Elastic and plastic deformation

Moduli

- “Moduli” describe strain caused by stress

- Bulk modulus
 - Shear modulus
 - Young’s modulus
 - Poisson’s ratio
- } Most common ones
- Plus others we won’t talk about here

- For geotechnical engineers, likely the most important are Shear modulus and Young’s modulus

- More information on GPG:

http://gpg.geosci.xyz/content/seismic/elastic_properties.html

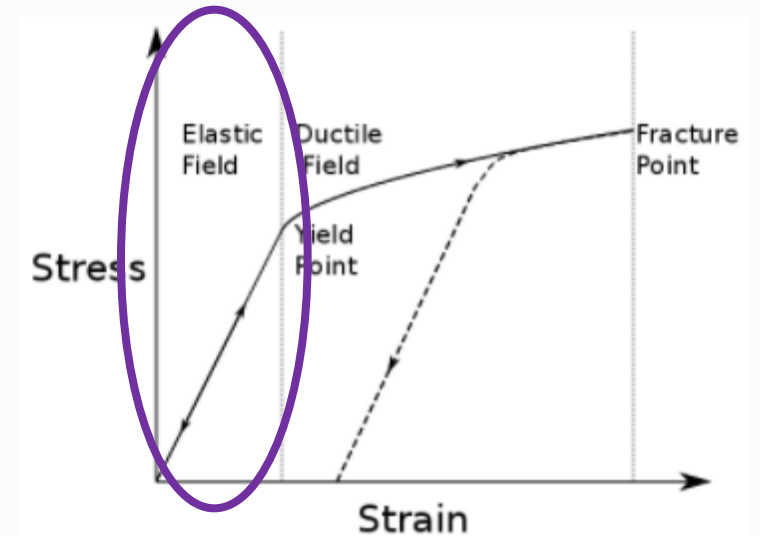


Fig. 12 Elastic and plastic deformation

Moduli

- “Moduli” describe strain caused by stress
- Bulk modulus
 - Resistance of a material to elastic compression
 - “modulus of incompressibility”

$$K = -V_0 \frac{\Delta P}{\Delta V}$$

- V_0 = original volume
- ΔP = applied pressure
- ΔV = change in volume

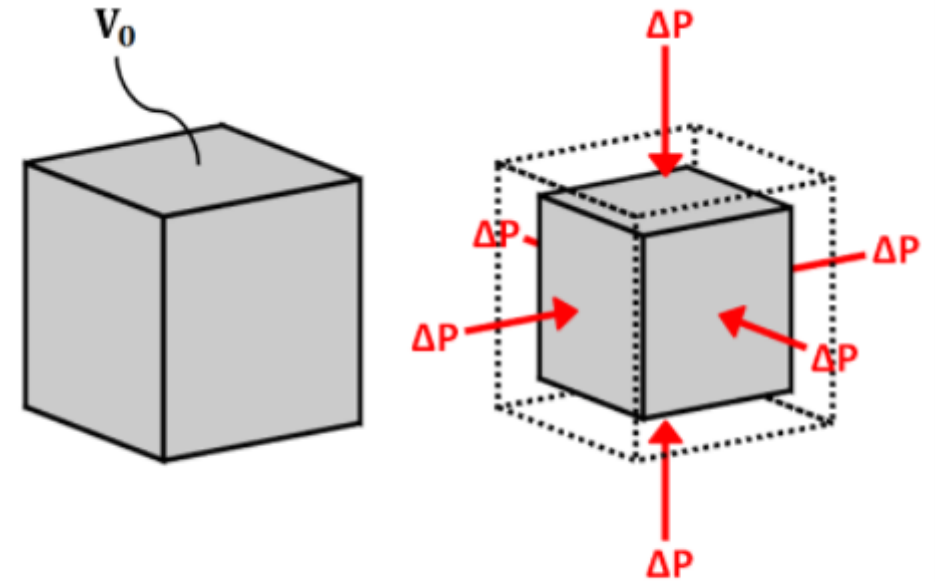


Fig. 13 Bulk modulus diagram.

Large K : hard to compress
Small K : easy to compress

Moduli

- “Moduli” describe strain caused by stress

- Shear modulus

- Resistance of a material to shear stress
 - “modulus of rigidity”

$$\mu = \frac{\text{Stress}}{\text{Strain}} = \frac{Fl}{\Delta x A}$$

- F = force
 - A = unit area

- Depends on V_s , ρ is density $\mu = \rho V_s^2$

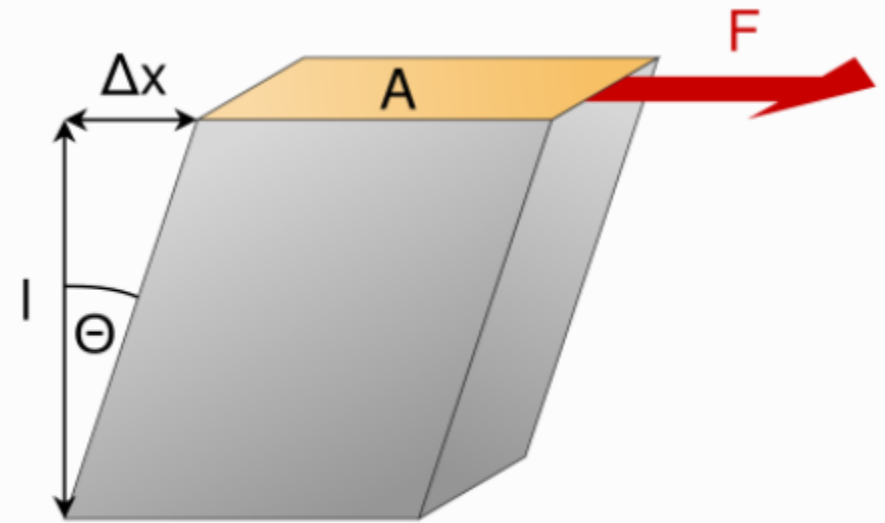


Fig. 14 Shear modulus diagram.

How about water?

Moduli

- “Moduli” describe strain caused by stress
- Young’s modulus
 - Ratio of longitudinal normal stress to longitudinal normal strain
 - Depends on both V_p and V_s and is strongly controlled by V_s

$$E = \rho V_s^2 \frac{3 \left(\frac{V_p}{V_s} \right)^2 - 4}{\left(\frac{V_p}{V_s} \right)^2 - 1}$$

$$E = \frac{P}{\Delta L / L}$$

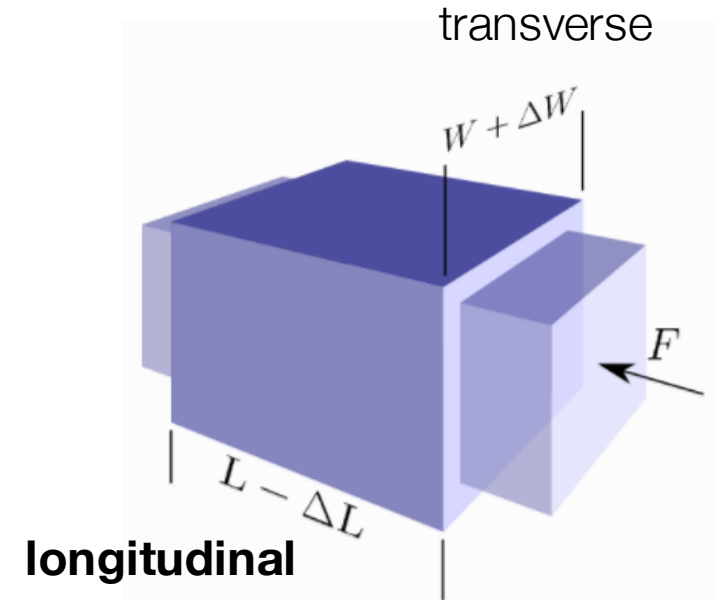


Fig. 15 Young’s modulus and Poisson’s ratio diagram. Image from [Subsurface Wiki](#), licensed under [CC BY 3.0](#).

Moduli

- “Moduli” describe strain caused by stress
- Poisson’s ratio
 - Ratio of transverse strain to longitudinal strain due to a longitudinal stress
 - For example, as a result of longitudinal stress, the cross-sectional area can increase because the length was decreased
 - Note: σ can be zero!
 - Example: The decrease in length could be compensated by a decrease in pore space (eg, cork)

$$\sigma = \frac{\Delta W / W}{\Delta L / L}$$

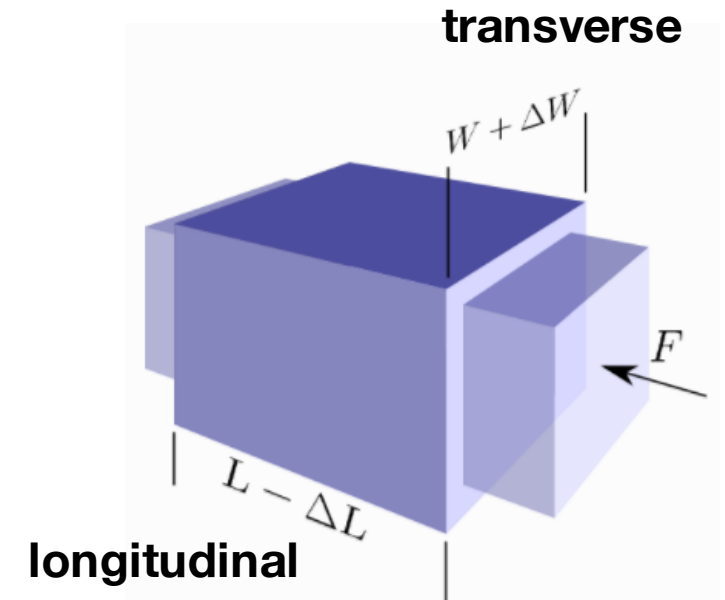


Fig. 15 Young's modulus and Poisson's ratio diagram. Image from [Subsurface Wiki](#), licensed under [CC BY 3.0](#).

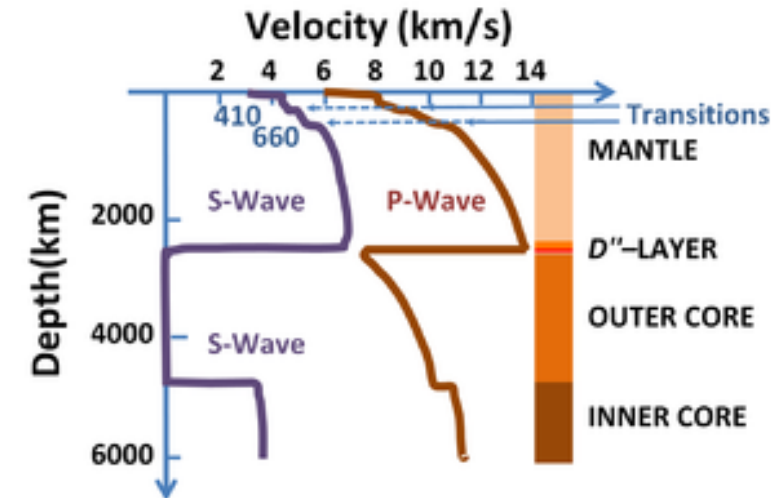
Seismic wave velocities

- Elastic properties characterize rocks and other materials
- BUT **seismic velocities** are more practical set of **physical properties** for seismic methods
- Seismic velocities: the speed at which various elastic deformations propagate through materials
- Seismic velocities can be expressed in terms of elastic properties

$$E = \rho V_s^2 \frac{3 \left(\frac{V_p}{V_s} \right)^2 - 4}{\left(\frac{V_p}{V_s} \right)^2 - 1}$$

Shear modulus

$$\mu = \rho V_s^2$$



Waves propagate in the earth

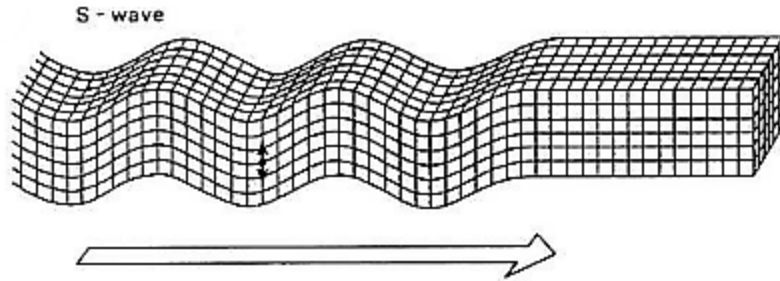
- Different types of waves
 - Body waves (P, S)
 - Surface waves (Rayleigh, Love)
- Velocities from three properties:
 - Density (ρ)
 - Bulk modulus (compressibility)(k)
 - Shear modulus (twistability)(μ)

$$v_p = \sqrt{\frac{k + \frac{4}{3}\mu}{\rho}}$$

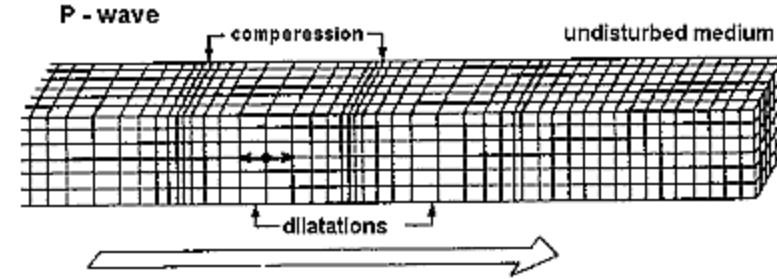
$$v_s = \sqrt{\frac{\mu}{\rho}}$$

2 body wave types, 2 surface wave types

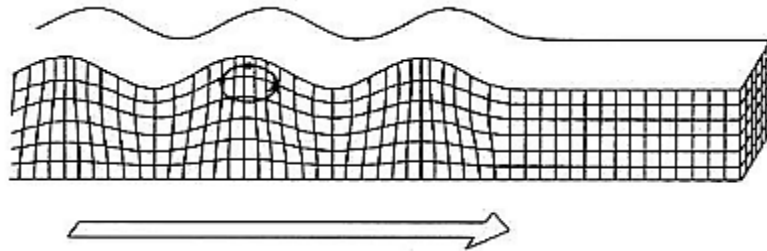
- S-waves



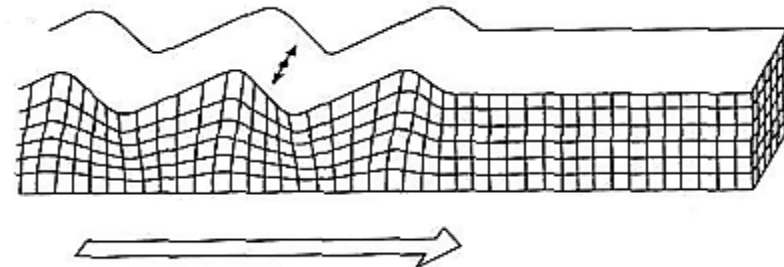
- P-waves



- Rayleigh waves



- Love waves



Student participation

- Seismic waves propagating along a line of students!
- What happens to the speed?
- What happens to the amplitude?
- What kind of wave are we acting out?

Thinking about waves...

- P-wave velocity is always faster than S-wave velocity.
 - Why is that?
- S-waves do not travel through liquids.
 - Why is that?

Thinking about waves...

- Body waves travel through materials
- Surface waves propagate along boundaries between materials
 - Such as the air/earth interface
 - What's an example of a natural event that creates surface waves?
 - These can cause a lot of structural damage.

Wave velocity and particle velocity

- Seismic waves velocity: 2-7 km/s
 - This is the velocity at which the energy moves, NOT the particles themselves
 - Wave energy can be measured many km/s from the source, even if the source is small
 - The velocity and displacement of actual particles in the rocks are very small
 - Typical particle speeds: 10^{-8} m/s
 - Typical ground displacements: 10^{-10} m/s
- Let's compare...
 - Water velocity
 - Sound travels ~0.33 km/s
- Let's think...
 - What affects seismic velocities?

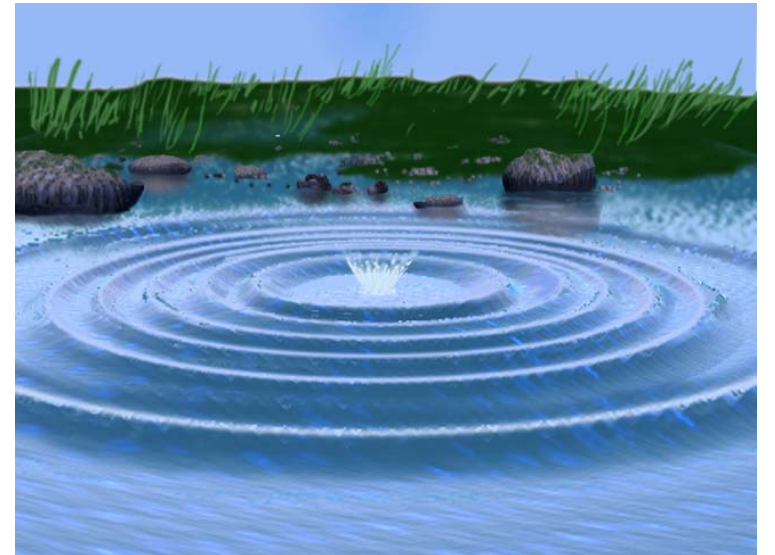
Basic principles

Reading on the GPG:

https://gpg.geosci.xyz/content/seismic/basic_principles.html

Waves, rays, and energy propagation

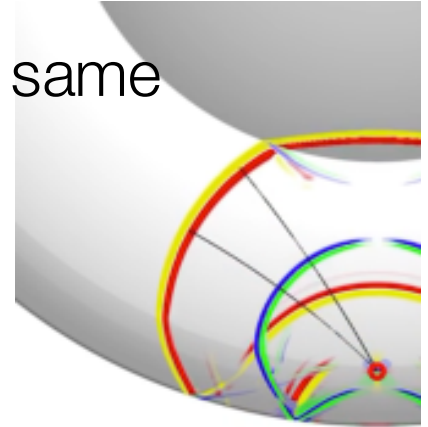
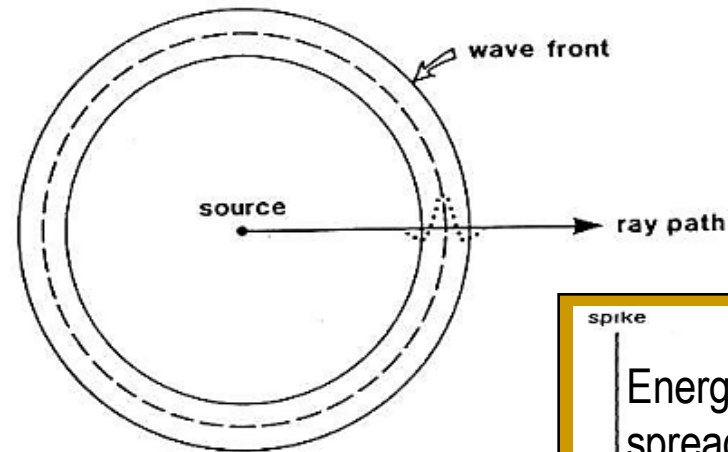
- A **wave** represents energy propagation
- Seismic sources: most can be approximated as a point source
- Energy propagates away from the source
 - Uniform medium: expanding spherical pattern
 - Like ripples in a pond
 - Rings propagate outward in time



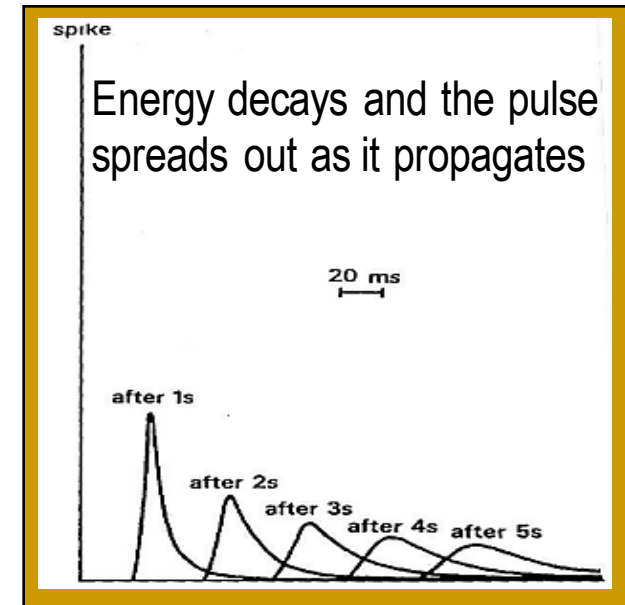
Waves, rays, and energy propagation

- **Wavefront**: set of locations at which the phase of the wave has the same value

- **Seismic rays**:
 - Imaginary lines perpendicular to the wavefront
 - Indicate the path along which the wavefront is traveling
 - Like a laser



- Amplitude reduces away from the source

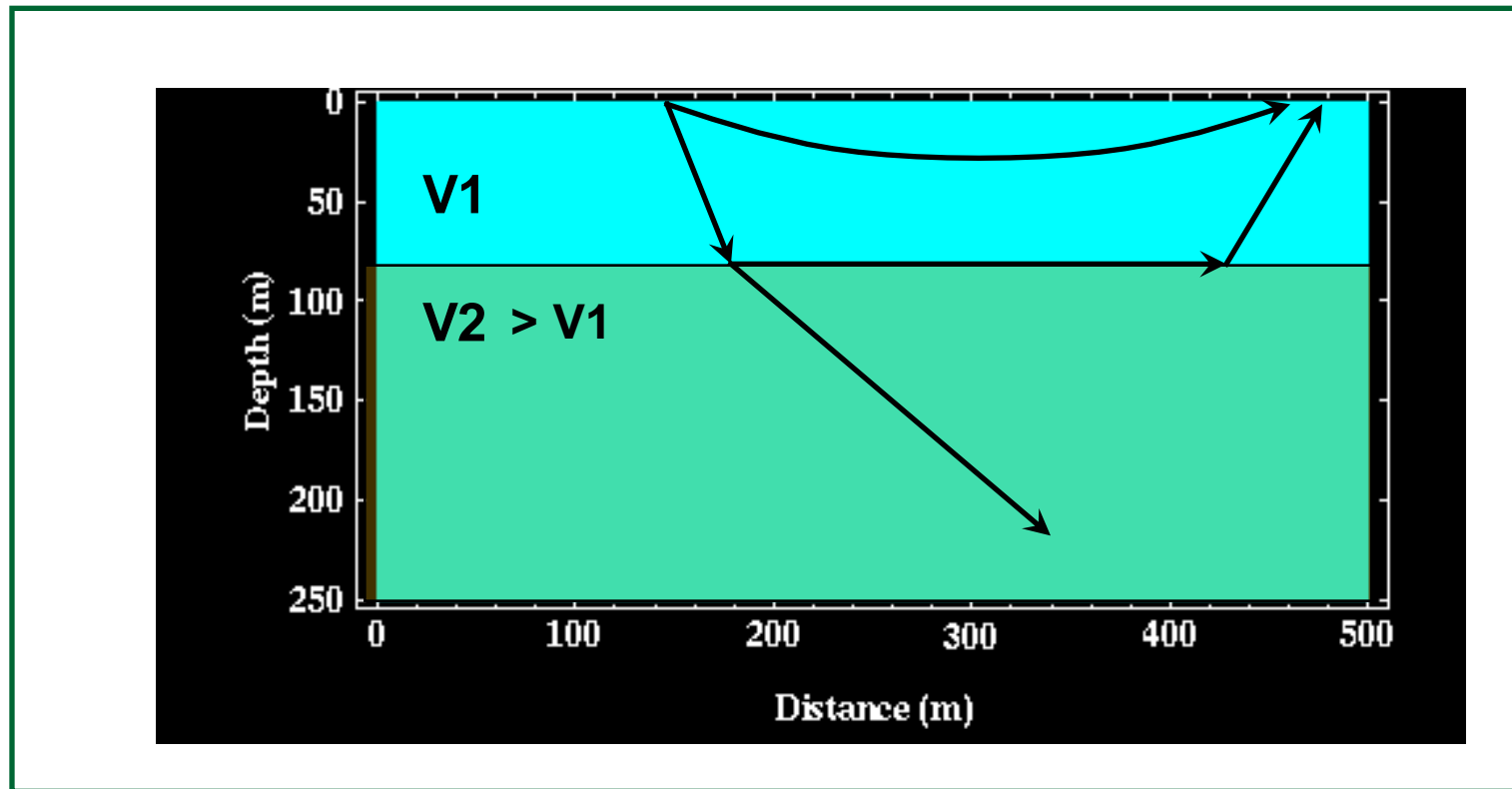


Waves at interfaces

- When a wave hits an interface between two materials with different physical properties, what happens?

Animation of waves in a layer over a halfspace

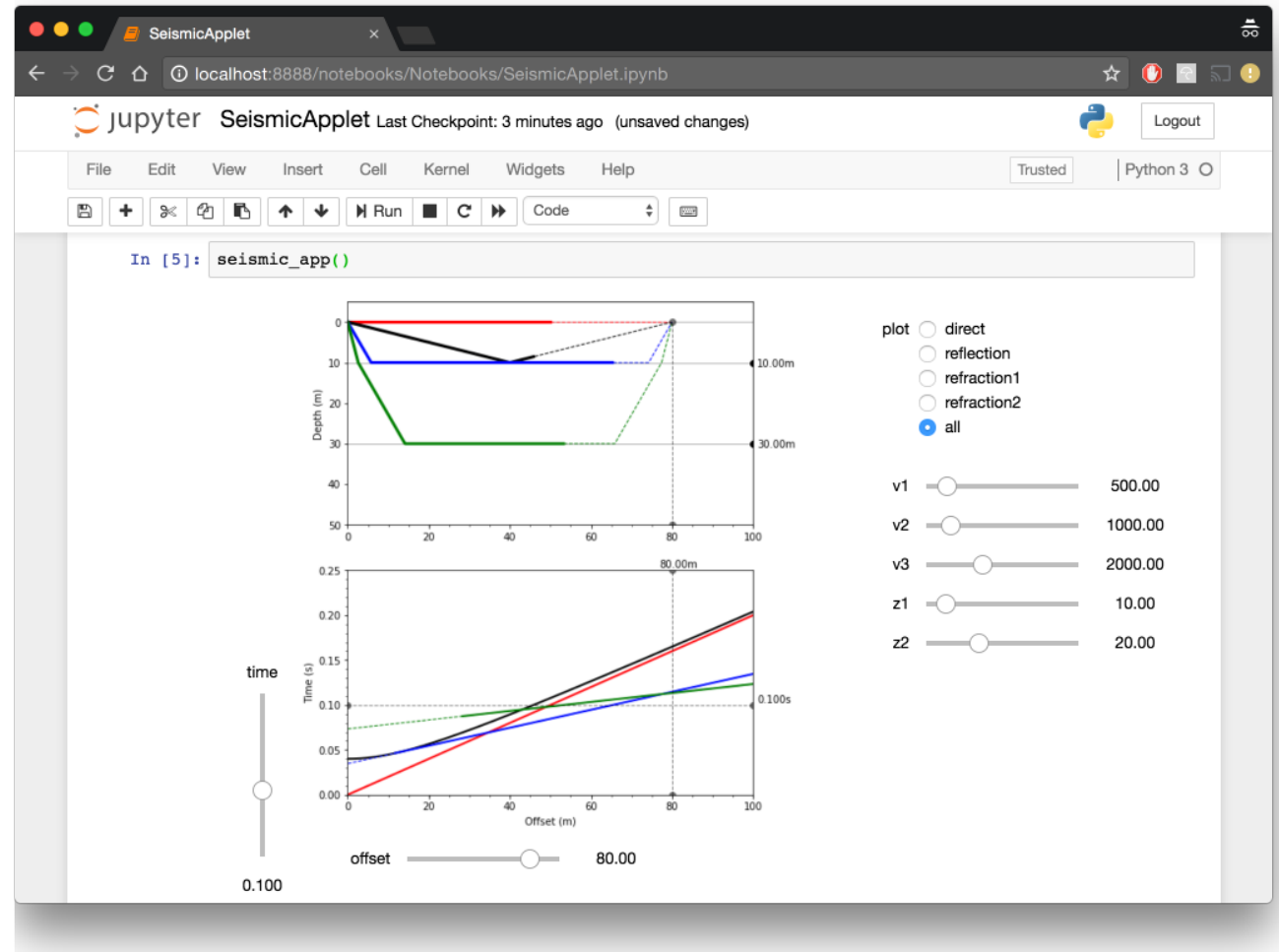
- Slower over faster (most common): $v_2 > v_1$



- Notice the relation between wavefronts and rays (arrows)

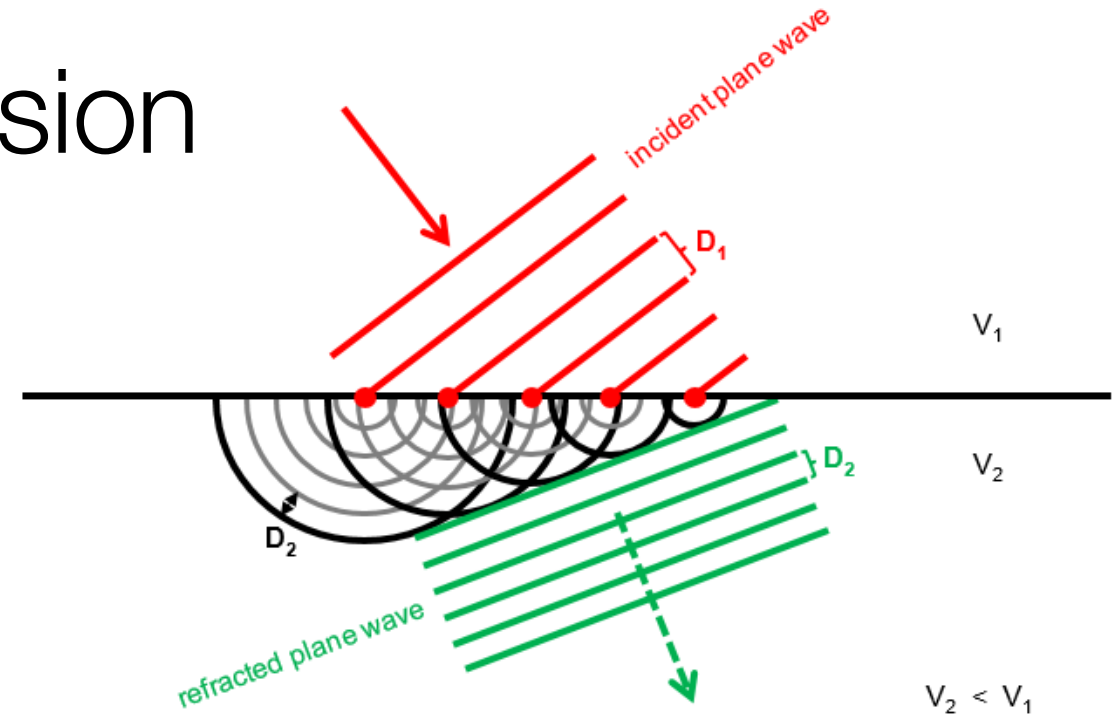
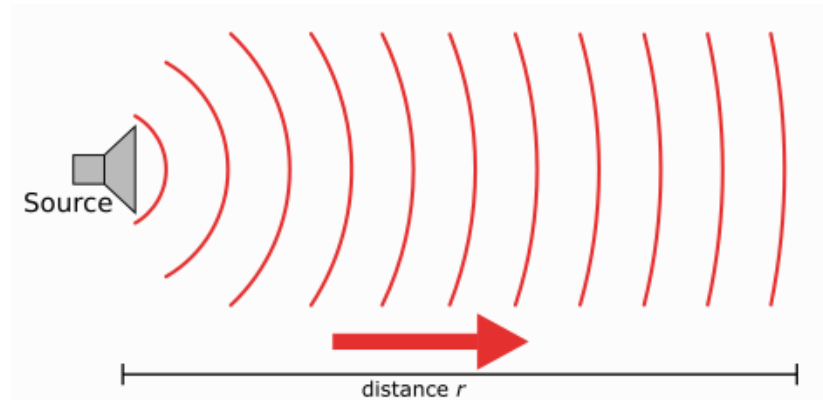
Seismic applet

- Direct wave
- Refracted wave
- Reflected wave



Reflection and transmission of plane waves

- Assume a plane wave
 - When can we assume this?



- Acoustic impedance: $Z = \rho V$
 - The product of density and velocity (either for P or S waves)

Reflection and transmission

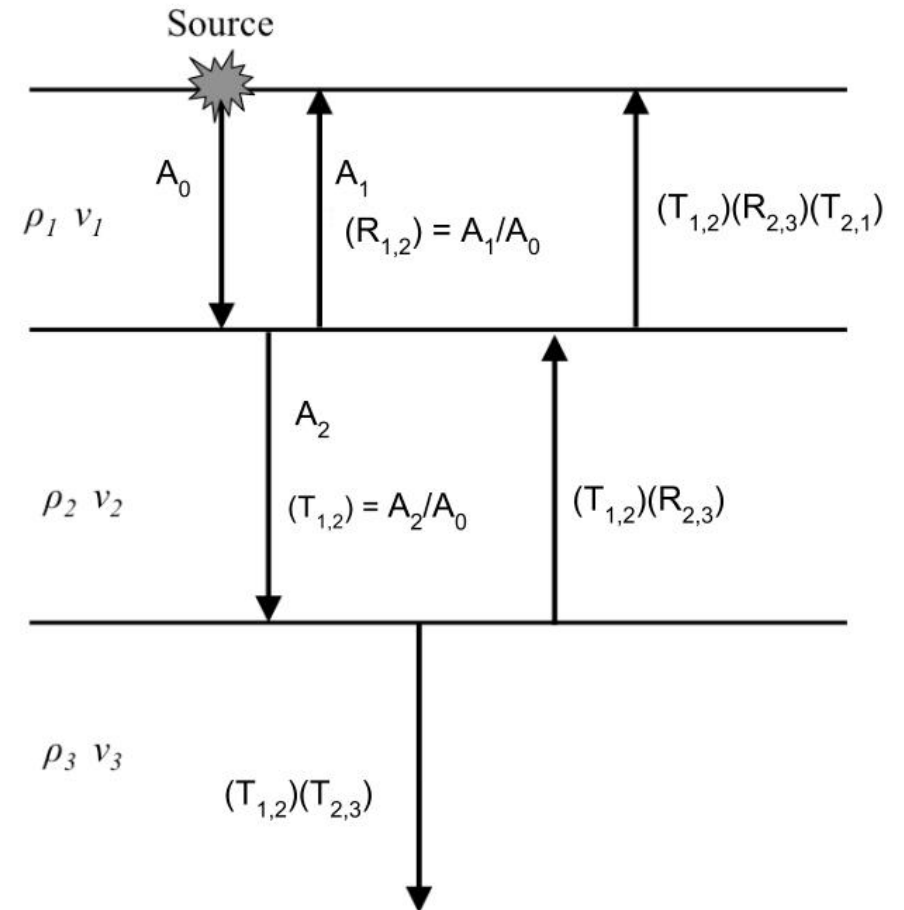
- Consider a plane wave striking an interface with the direction of propagation perpendicular to the interface

- Reflection coefficient:

$$R = \frac{A_1}{A_0} = \frac{Z_2 - Z_1}{Z_2 + Z_1}, -1 \leq R \leq 1$$

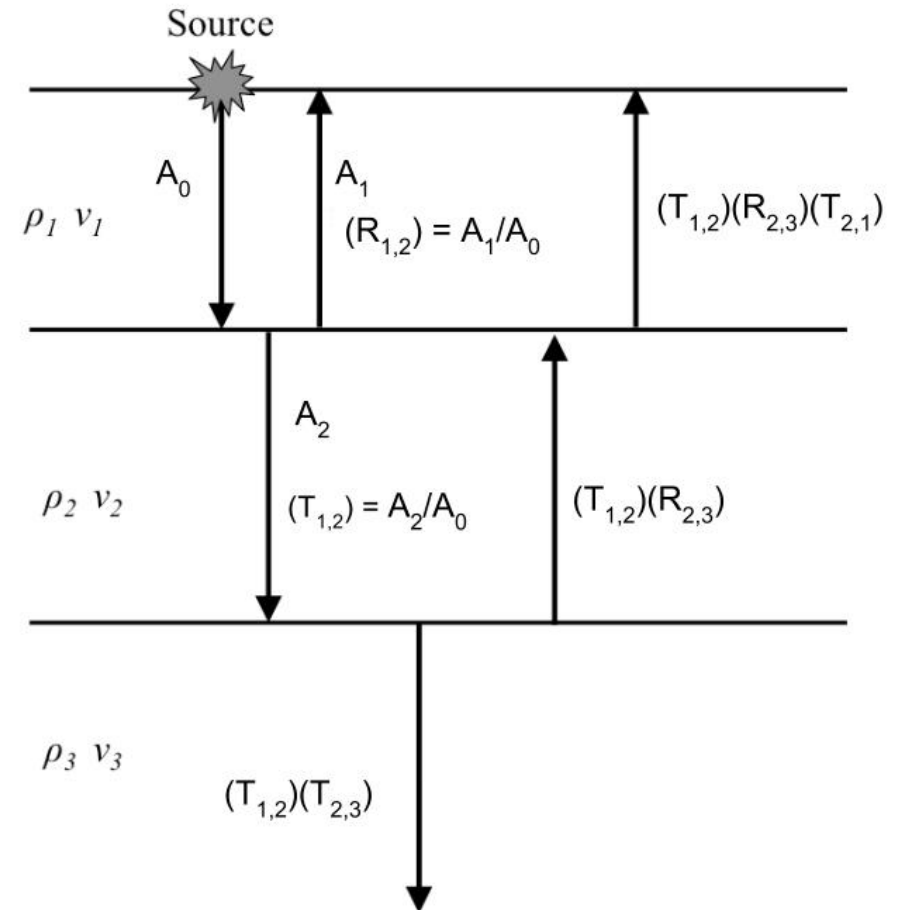
- Transmission coefficient:

$$T = \frac{A_2}{A_0} = \frac{2Z_1}{Z_2 + Z_1}, 0 \leq T \leq 2$$



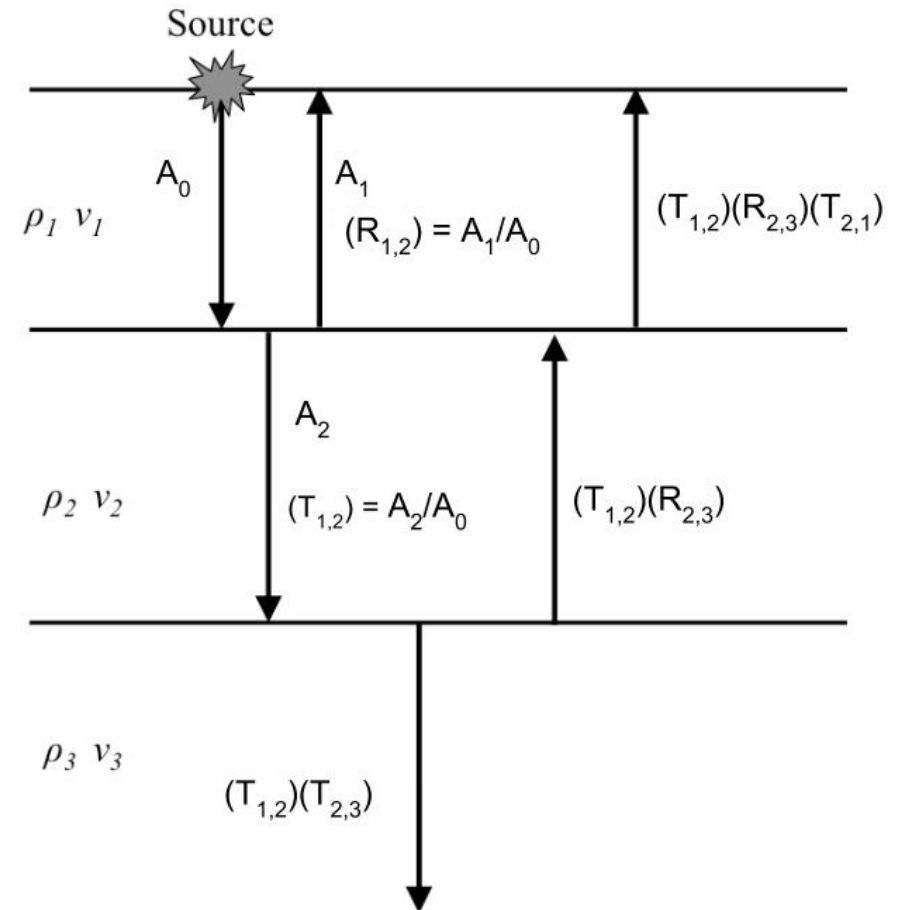
Reflection and transmission

- If $Z_2 = Z_1$, then what is R ? T ?
- If $Z_1 \gg Z_2$, then what is R ? T ?
- If $Z_2 \gg Z_1$, then what is R ? T ?



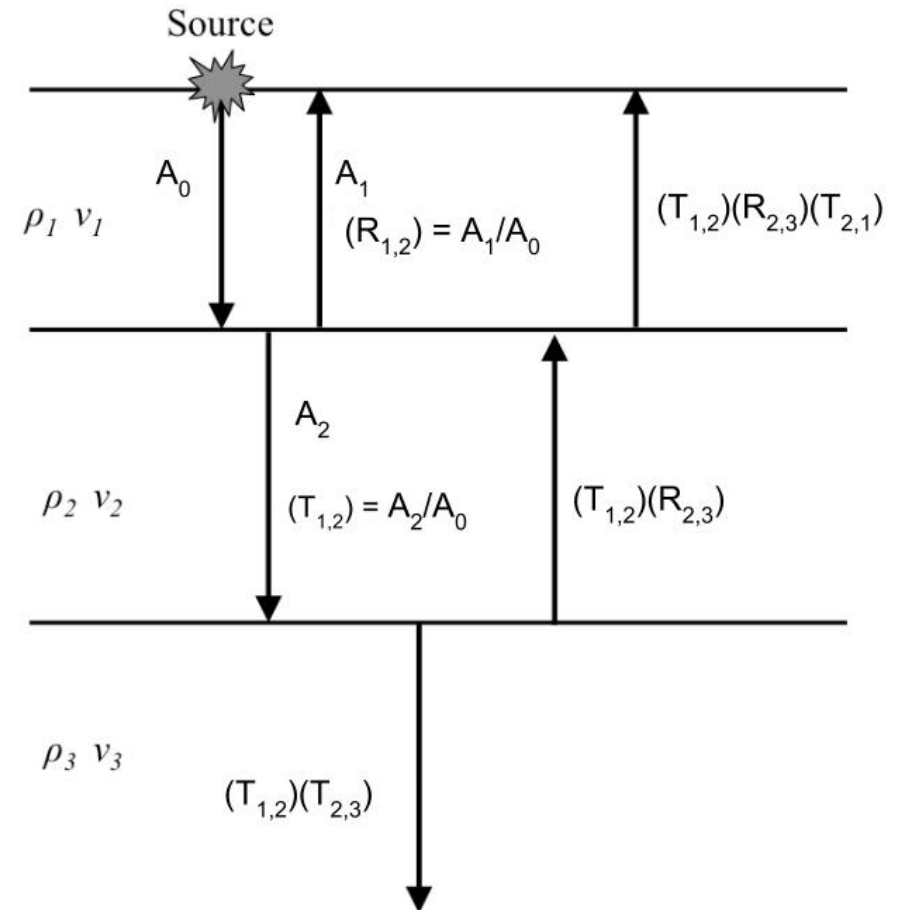
Reflection and transmission

- If $Z_2 = Z_1$, then what is R ? T ?
Answer: $R = 0, T = 1$
- If $Z_1 \gg Z_2$, then what is R ? T ?
- If $Z_2 \gg Z_1$, then what is R ? T ?



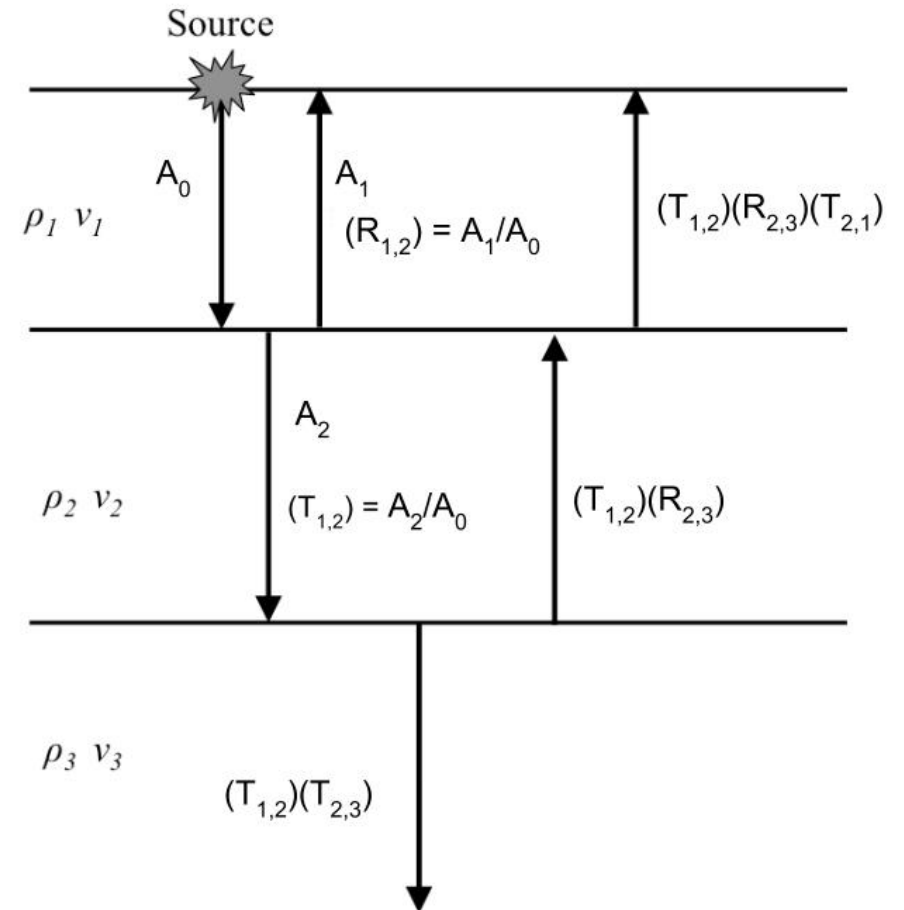
Reflection and transmission

- If $Z_2 = Z_1$, then what is R ? T ?
Answer: $R = 0, T = 1$
- If $Z_1 \gg Z_2$, then what is R ? T ?
Answer: $R = -1, T = 2$. Pulse will be reflected with a polarity change
- If $Z_2 \gg Z_1$, then what is R ? T ?



Reflection and transmission

- If $Z_2 = Z_1$, then what is R ? T ?
Answer: $R = 0, T = 1$
- If $Z_1 \gg Z_2$, then what is R ? T ?
Answer: $R = -1, T = 2$. Pulse will be reflected with a polarity change
- If $Z_2 \gg Z_1$, then what is R ? T ?
Answer: $R = 1, T = 0$. Example: wave travelling through air and hitting air-earth interface



See it for yourself

- Try the app: https://phet.colorado.edu/sims/html/wave-on-a-string/latest/wave-on-a-string_en.html
- Watch a video: <https://youtu.be/9OpL3OFuVXo>

End of Seismic lecture1