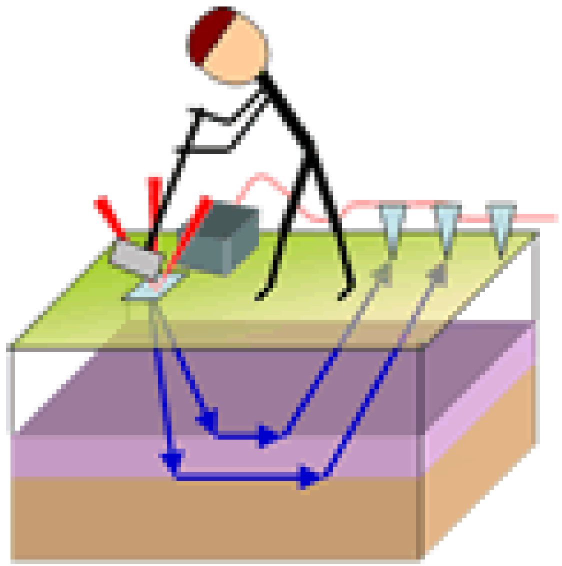
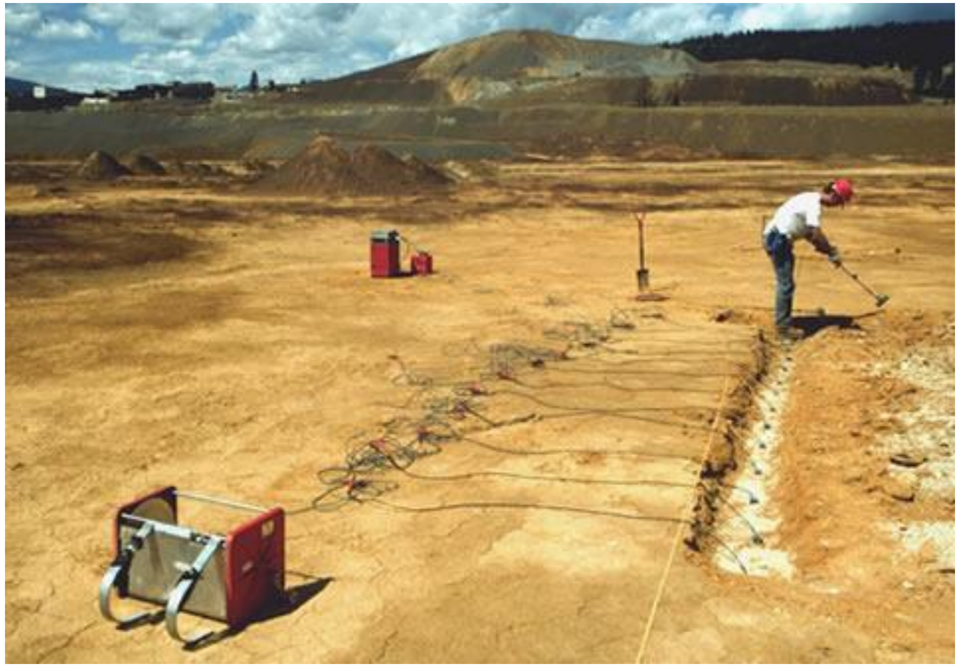
# Seismology

EOSC 350

# Today’s Topics

- Introduction
- Physical Properties
- Basic Principles
  - Wave fronts and ray paths
  - Reflection

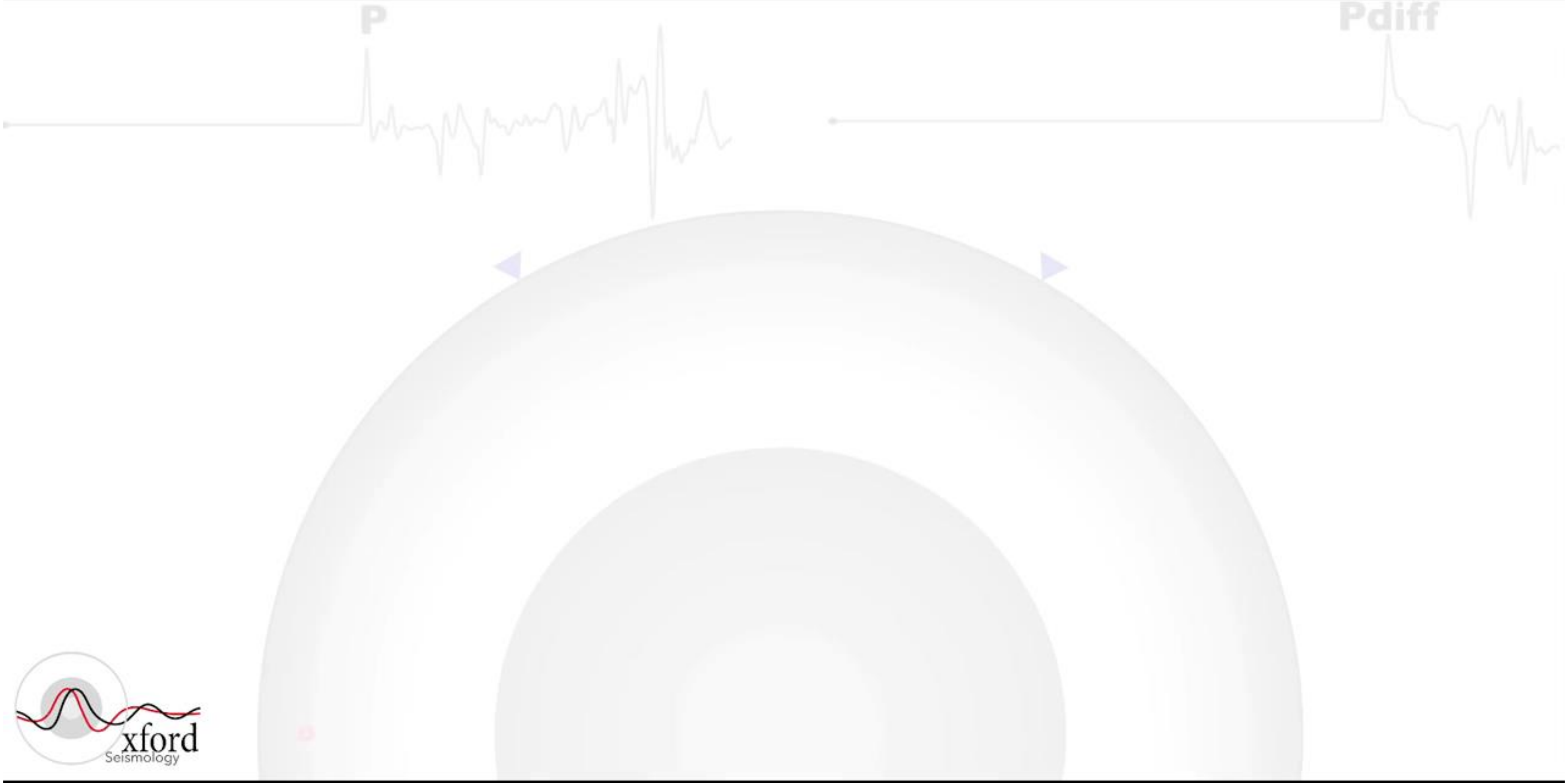




# Introduction

Reading on the GPG:

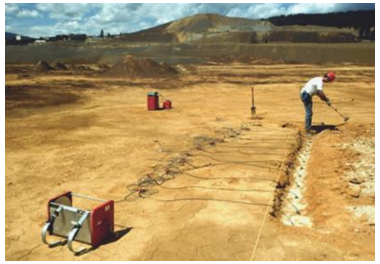
http://gpg.geosci.xyz/content/seismic/index.html


P
Pdiff

# The seismic survey

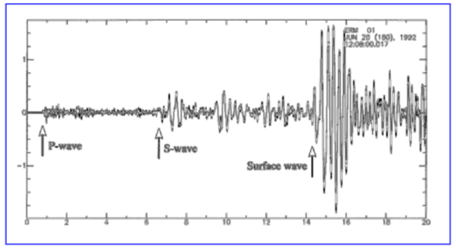
Source

Data



Input energy

Measure response




Subsurface

Physical property: velocity

# 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

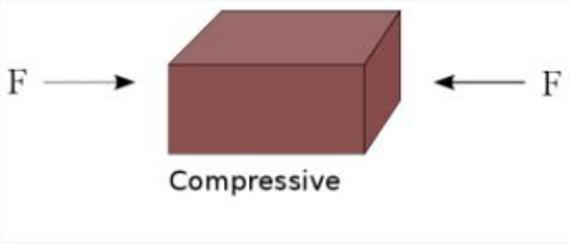


*Fig. 9 Compressive normal stress*

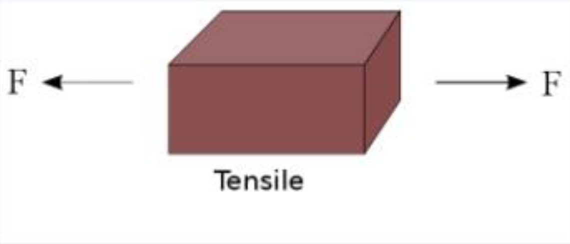


*Fig. 10 Tensile normal stress*

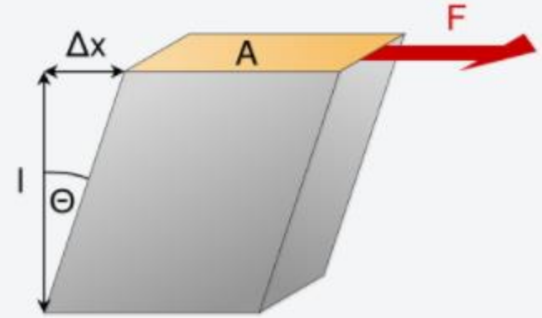


*Fig. 11 Shear stress*

# 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?

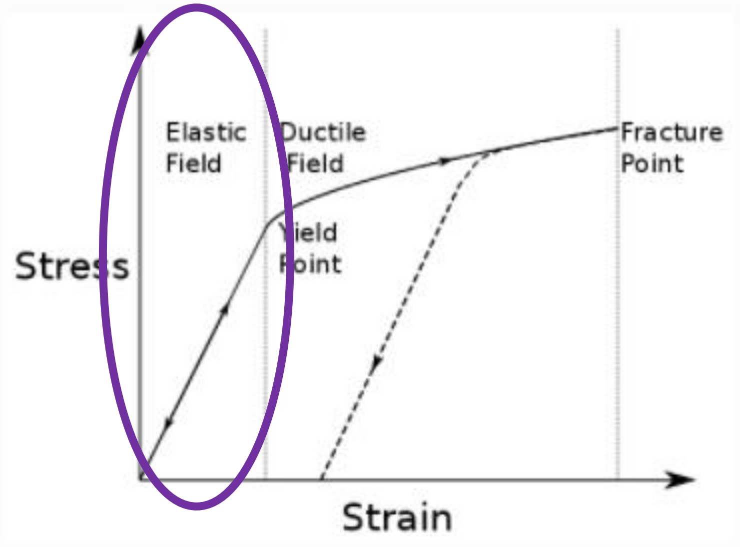


Fig. 12 Elastic and plastic deformation

# 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

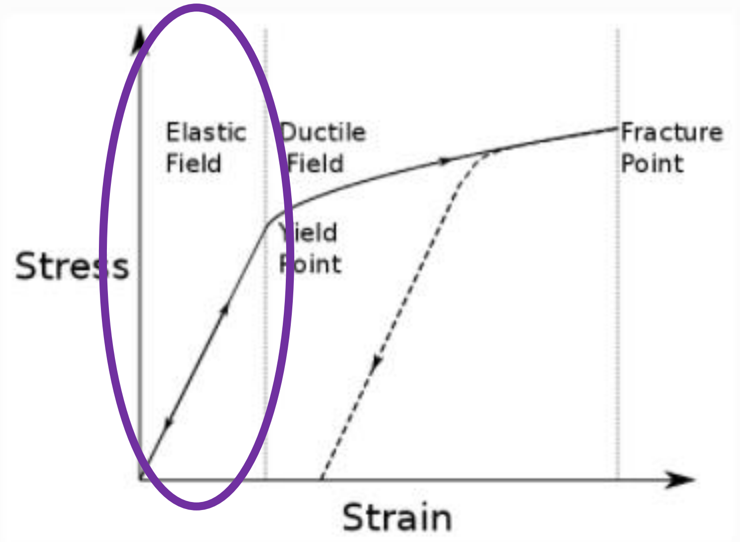



*Fig. 12 Elastic and plastic deformation*

# 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
  - $\Delta P$ = applied pressure
  - $\Delta V$ = change in volume

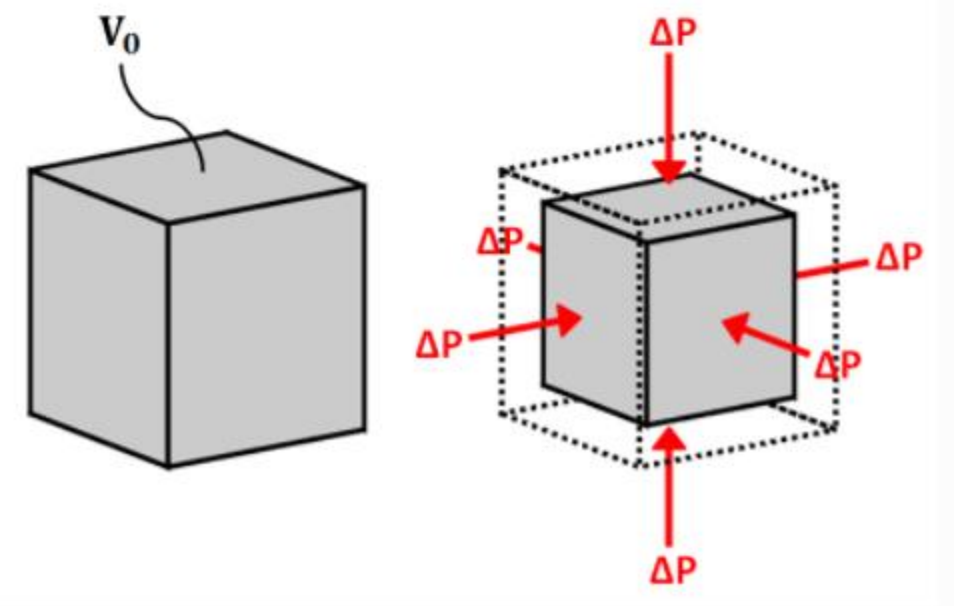



*Fig. 13 Bulk modulus diagram.*

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”

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

  - $F$ = force
  - $A$ = unit area

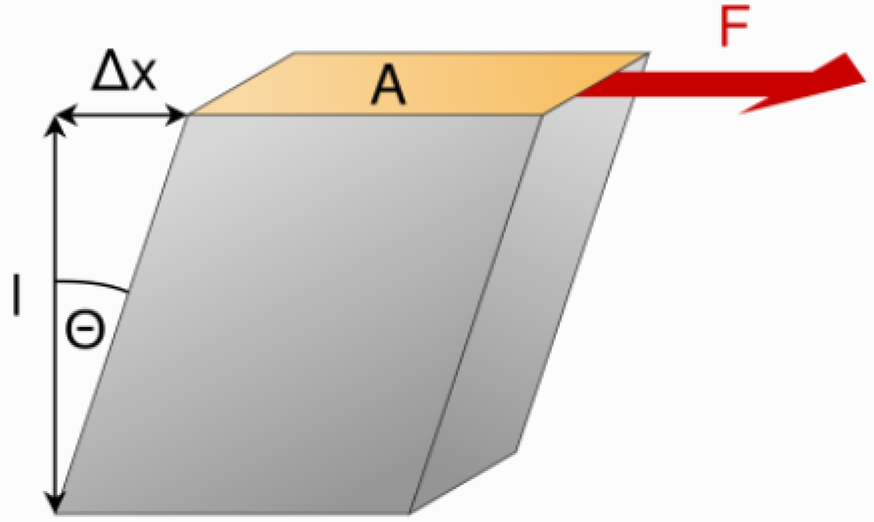



Fig. 14 Shear modulus diagram.

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

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 Vp and Vs and is strongly controlled by Vs

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

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

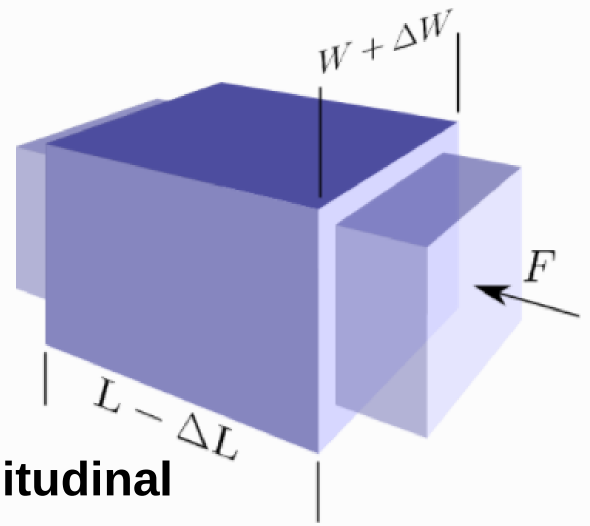



*Fig. 15 Young's modulus and Poisson's ratio diagram. Image from Subsurface Wiki, licensed under CC BY 3.0.*

# 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: $\sigma$ can be zero!
    - Example: The decrease in length could be compensated by a decrease in pore space (eg, cork)

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

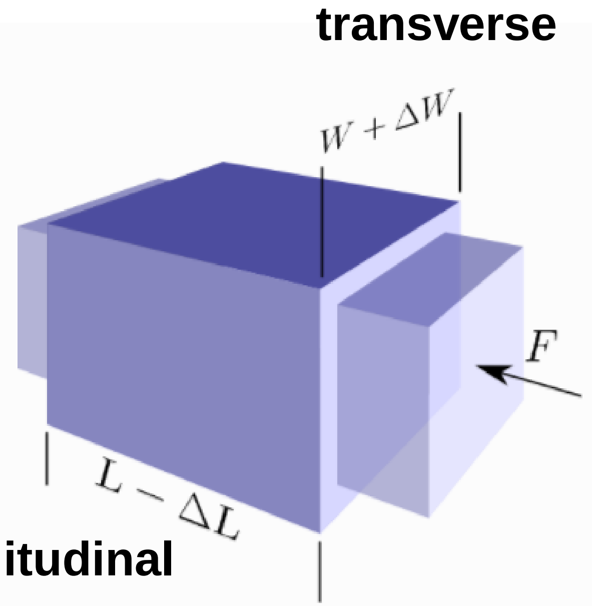
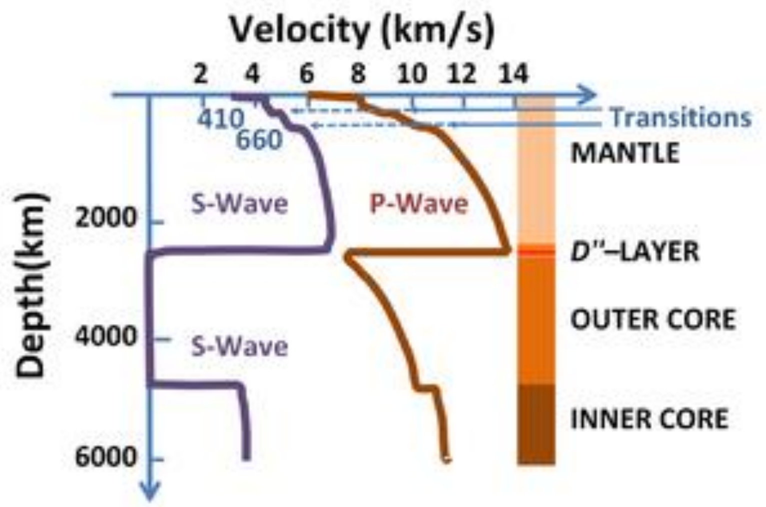



*Fig. 15 Young’s modulus and Poisson’s ratio diagram. Image from Subsurface Wiki, licensed under CC BY 3.0.*

# 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 van be expressed in terms of elastic properties

**Young's modulus**

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

**Shear modulus**

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

# Waves propagate in the earth

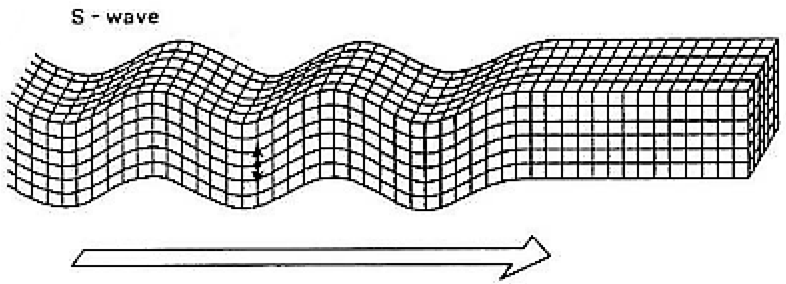
- Different types of waves
  - Body waves (P, S)
  - Surface waves (Rayleigh, Love)
- Velocities from three properties:
  - Density ($\rho$)
  - Bulk modulus (compressibility)($k$)
  - Shear modulus (twistability)($\mu$)

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

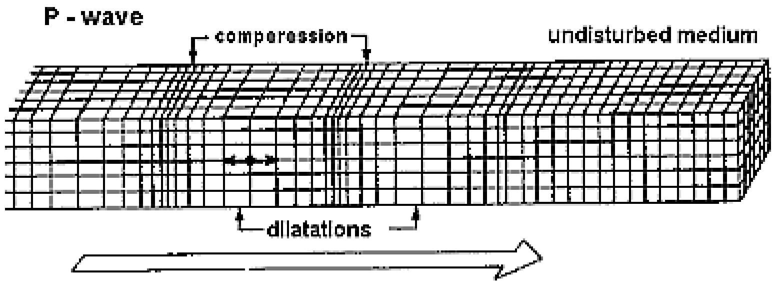
$$\boldsymbol{v_s} = \sqrt{\frac{\boldsymbol{\mu}}{\boldsymbol{\rho}}}$$

# 2 body wave types, 2 surface wave types

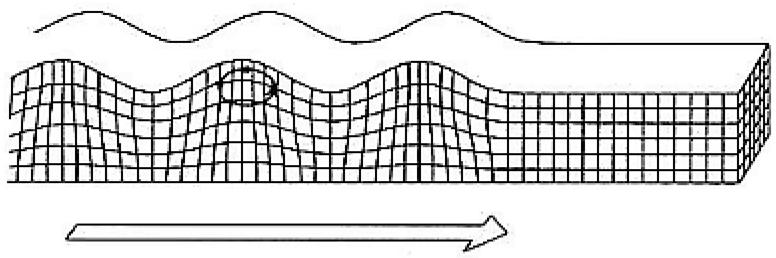
- S-waves



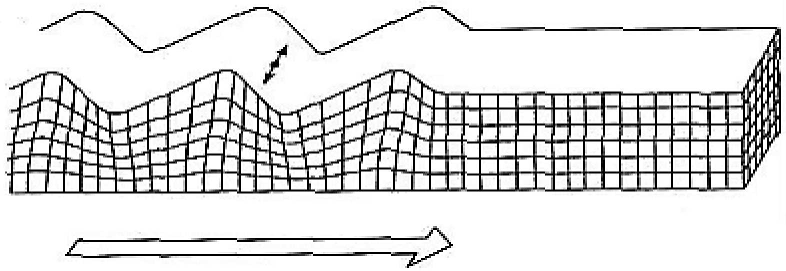

- P-waves




- Rayleigh waves



- Love waves



# 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?

# Recap

- Seismic waves are an elastic deformation that propagates

- There are body waves (p-waves and s-waves) that travel through materials

- There are surface waves (Rayleigh and Love waves) that travel along interfaces

- Wave velocity depends on density and elastic modulii

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

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

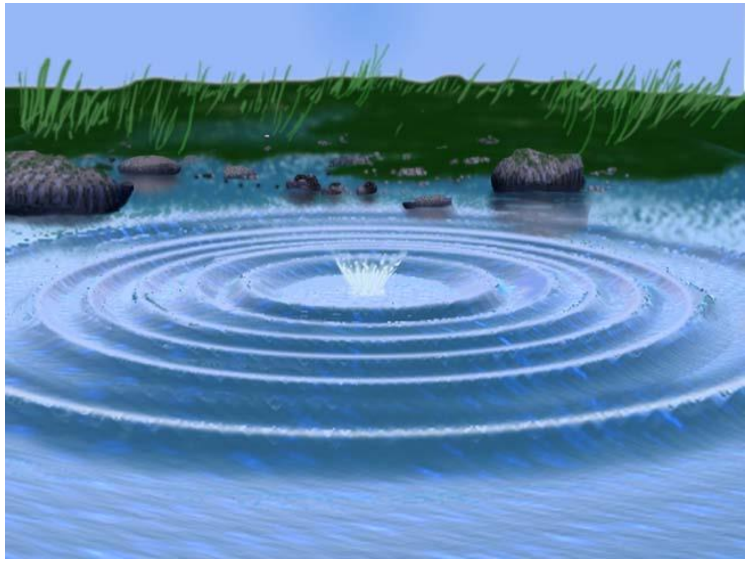
# Basic principles

Reading on the GPG:

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

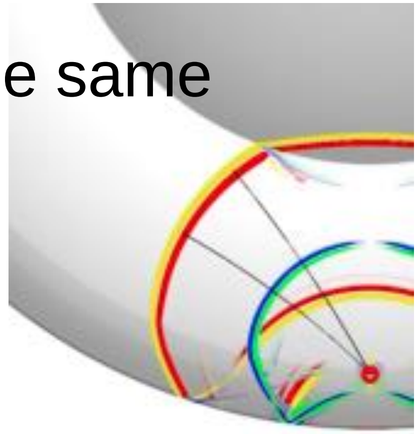
# Waves, rays, and energy propagation

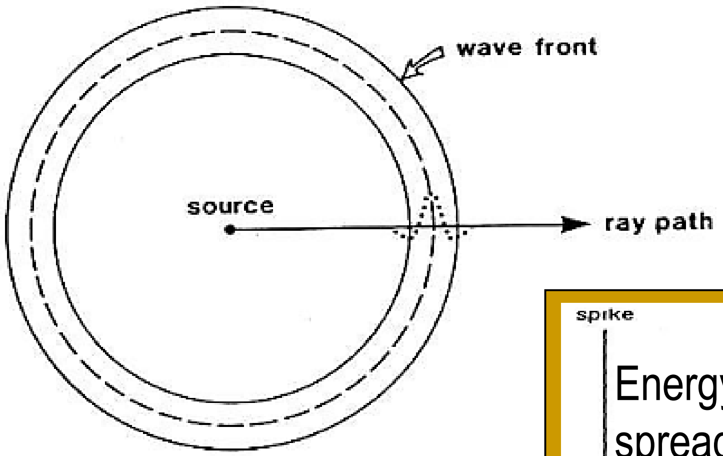
- A wave represents energy propagation
- Seismic sources:  most can be approximated as a point source
- Energy propagates away from the source
  - Uniform medium: expanding spherical pattern
  - Like ripples in a pond
  - Rings propagate outward in time



# Waves, rays, and energy propagation

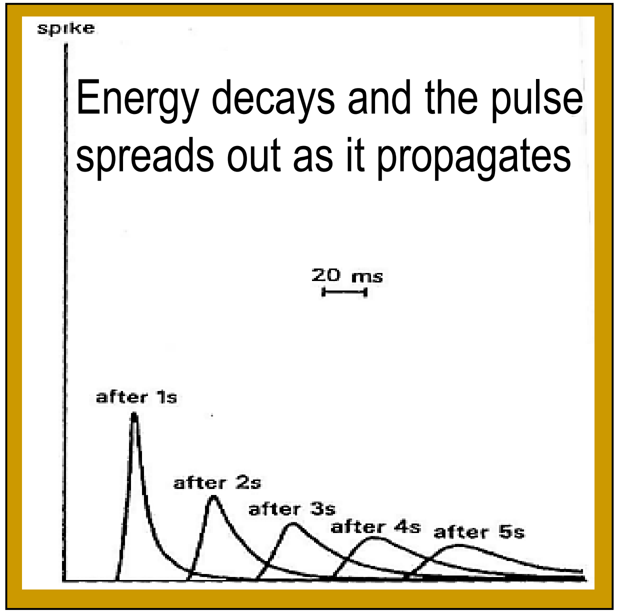
- Wavefront: set of locations at which the phase of the wave has the same value






- 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

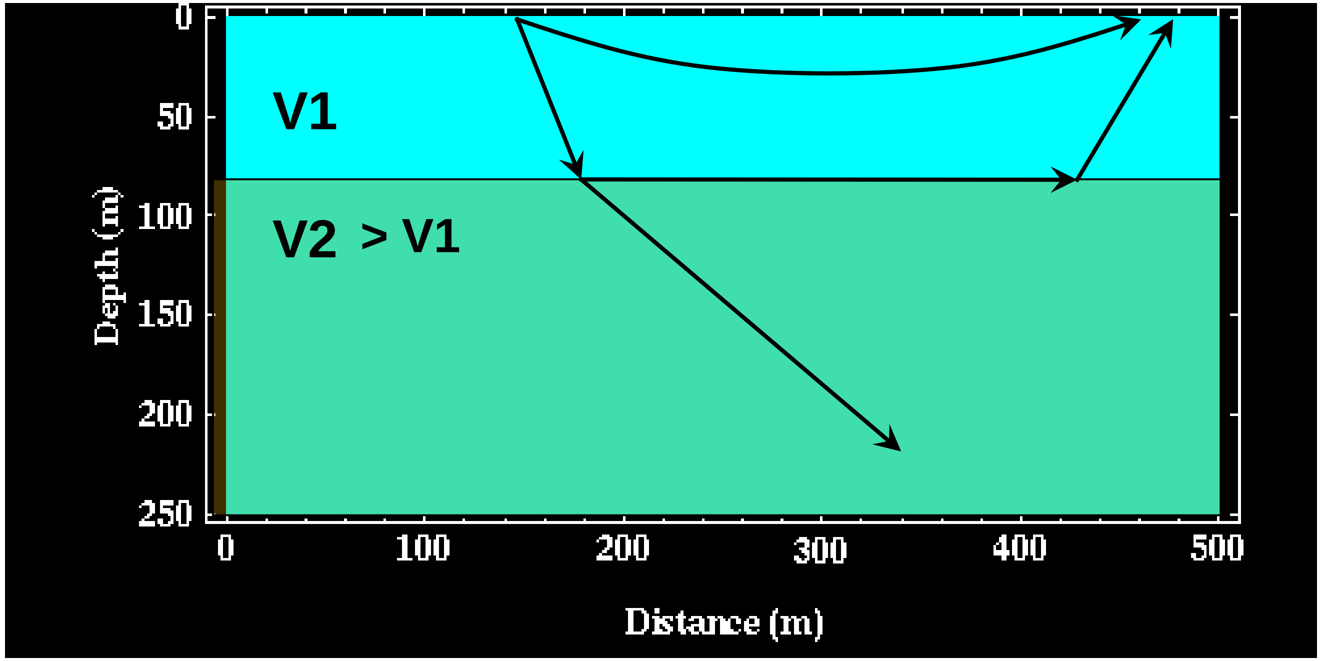


# Waves at interfaces

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

# Animation of waves in a layer over a halfspace

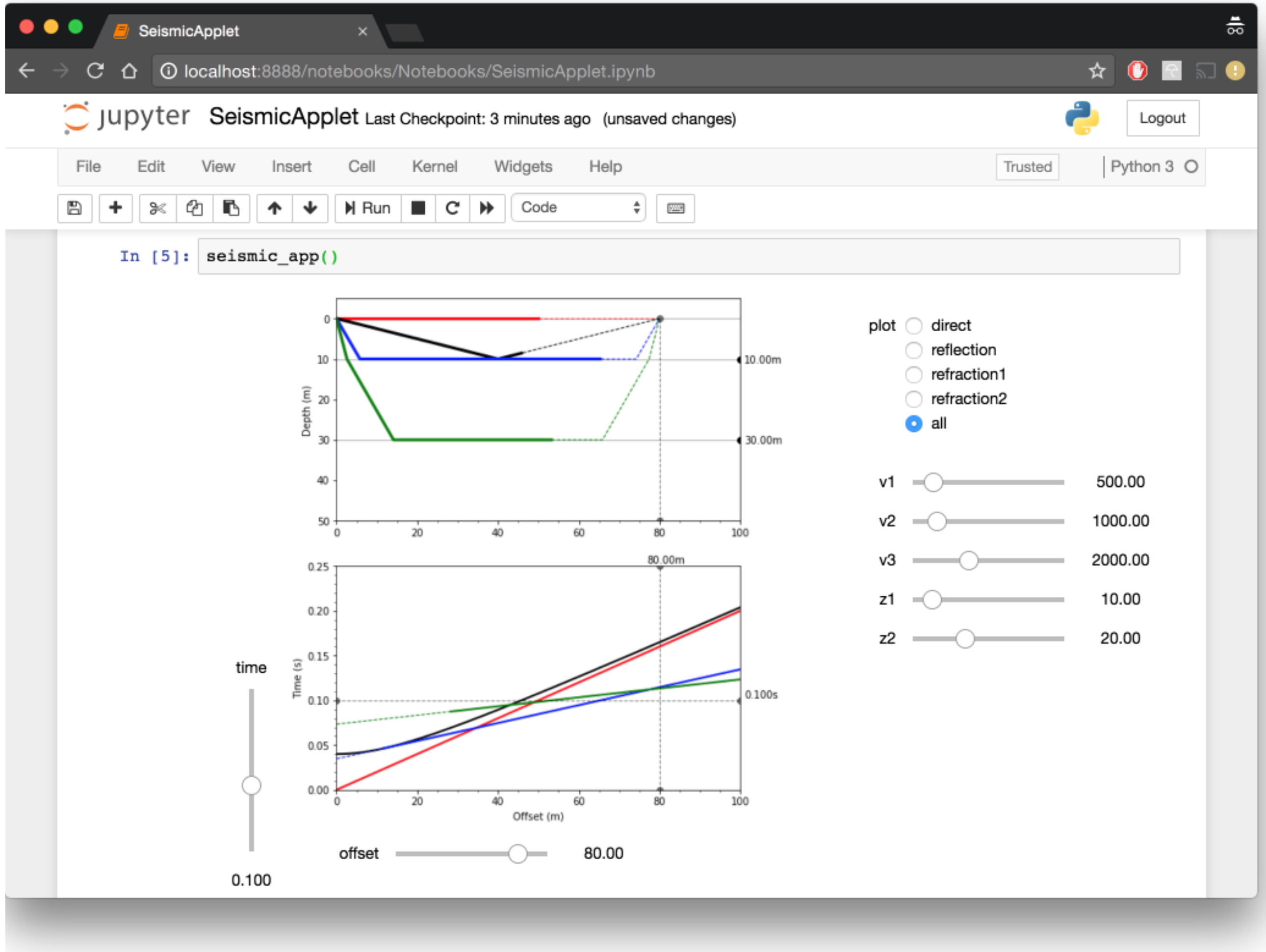
- Slower over faster (most common): v2 > v1




- Notice the relation between wavefronts and rays (arrows)

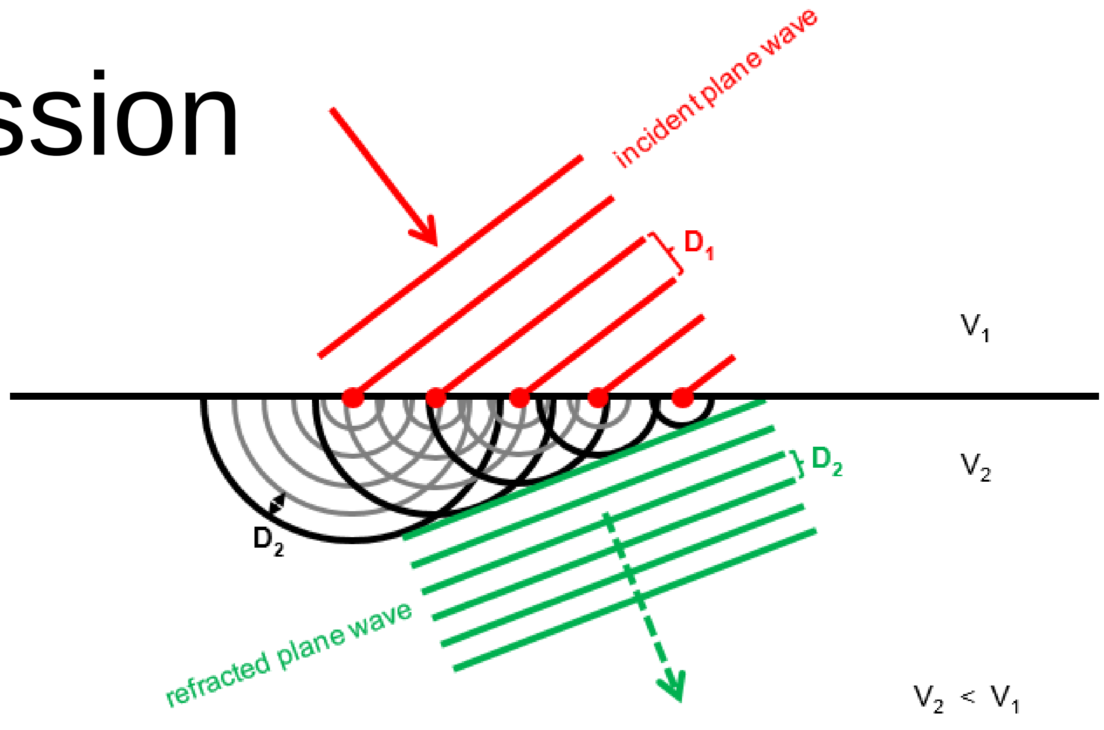
# Seismic applet

- Direct wave
- Refracted wave
- Reflected wave

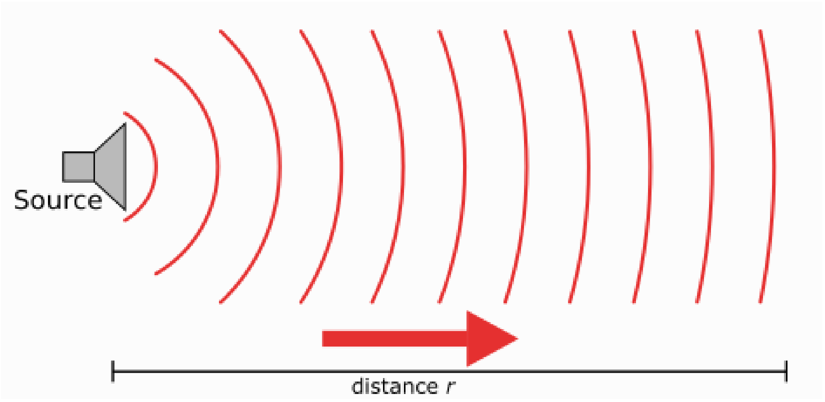



https://mybinder.org/v2/gh/geoscixyz/gpgLabs/master?filepath=notebooks%2SeisRefracSurvey.ipynb

# 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)

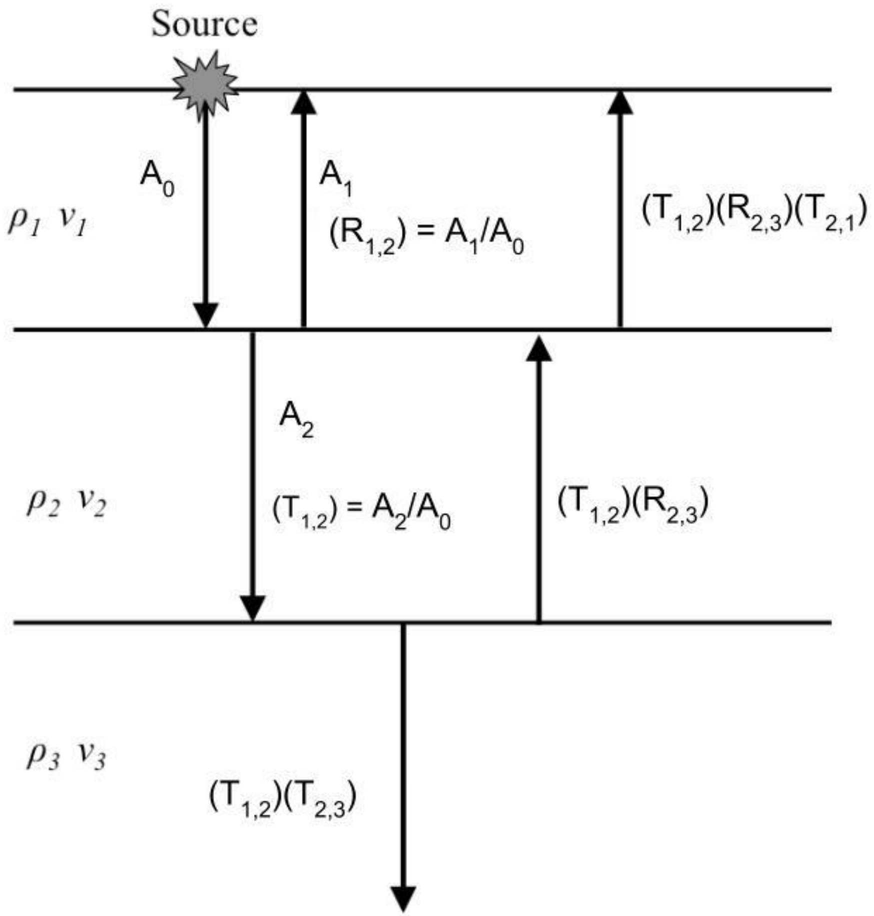
# Reflection and transmission

- 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:

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

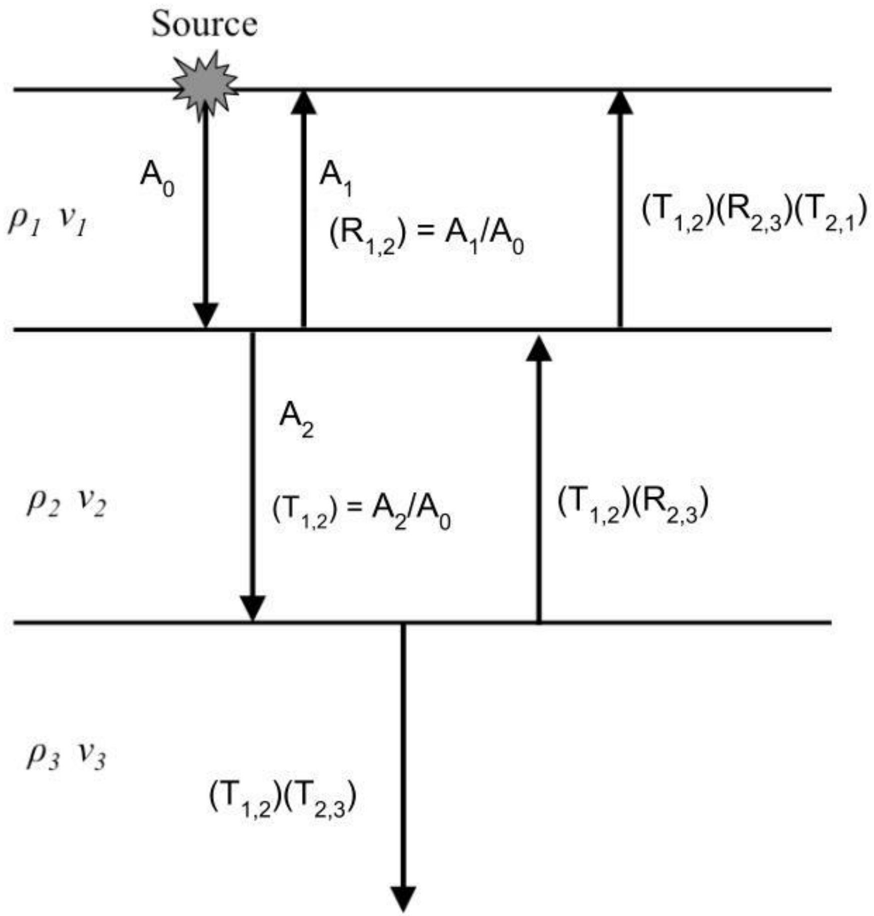


# Reflection and transmission

- 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 $R$? $T$?

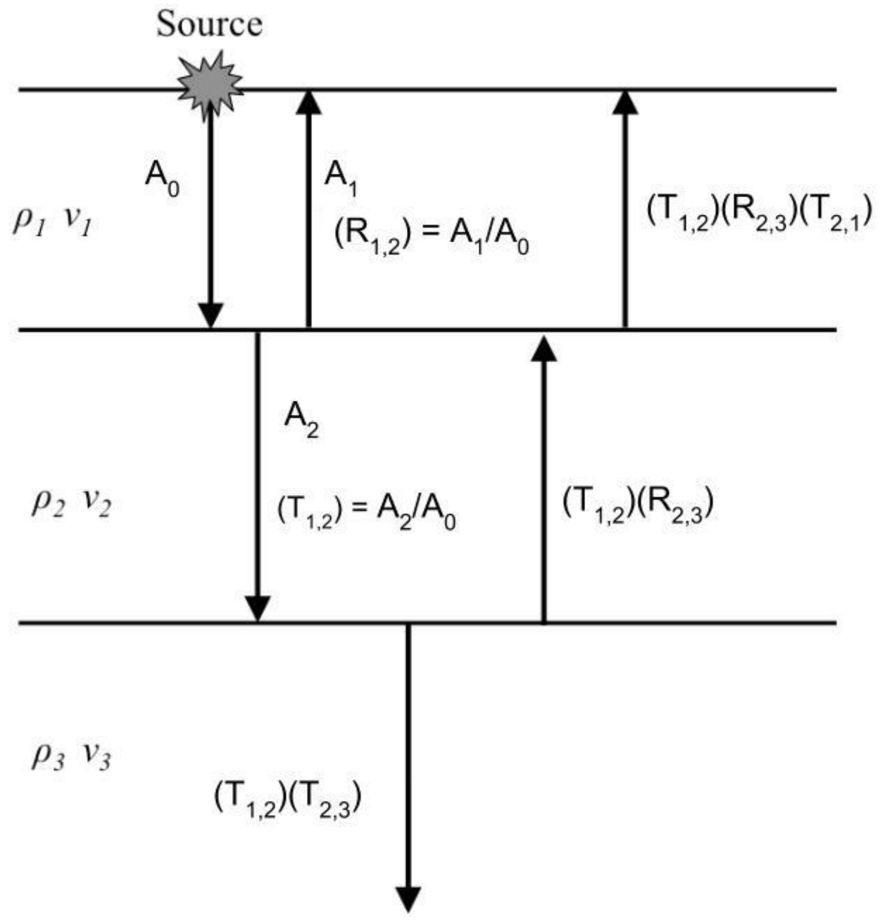


# Reflection and transmission

- 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 $R$? $T$?

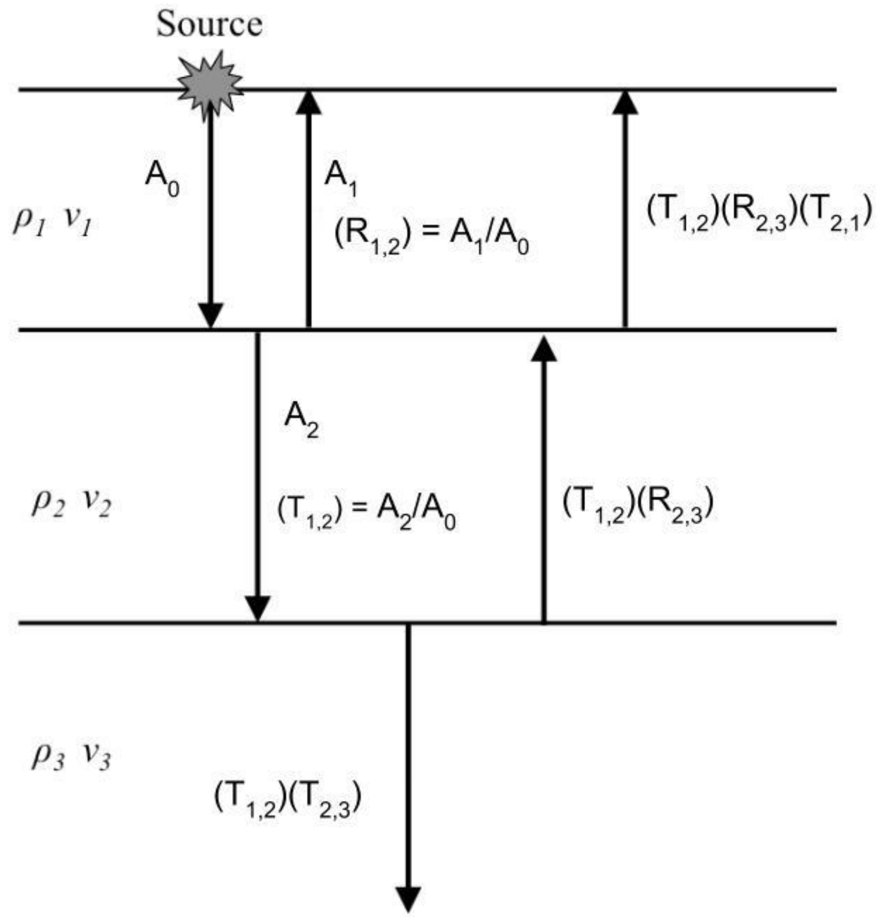


# Reflection and transmission

- 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 $R$? $T$?

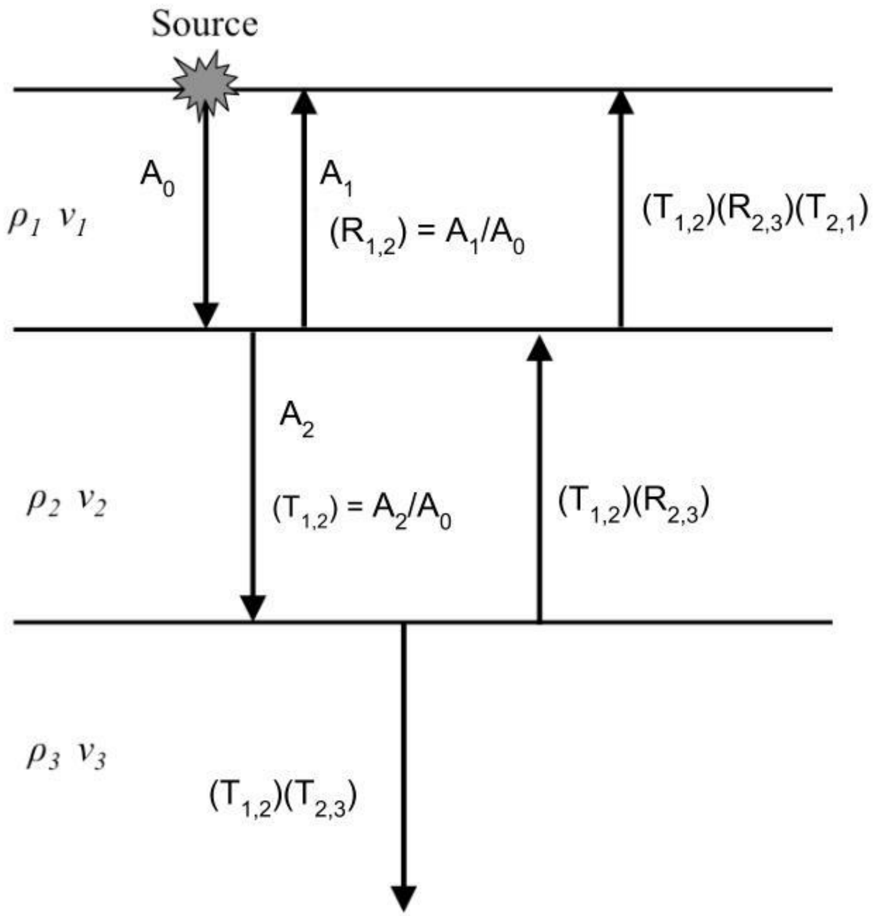


# Reflection and transmission

- 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

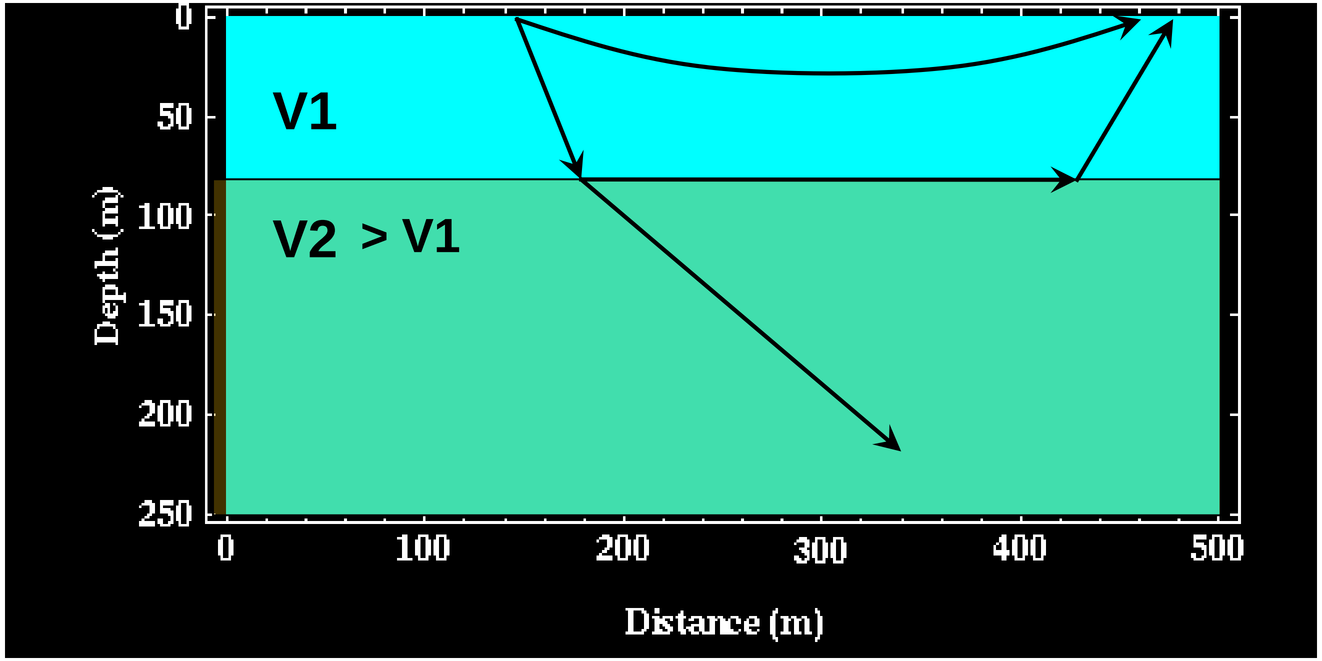
- Watch a video: https://youtu.be/9OpL3OFuVXo

# Recap

- **Ray path:** travel path that seismic signals can take to get from one point to another

- **Wave front:** shows the propagation of energy

- Seismic energy decays over time/distance



# Recap

- Seismic waves reflect, refract and transmit at interfaces

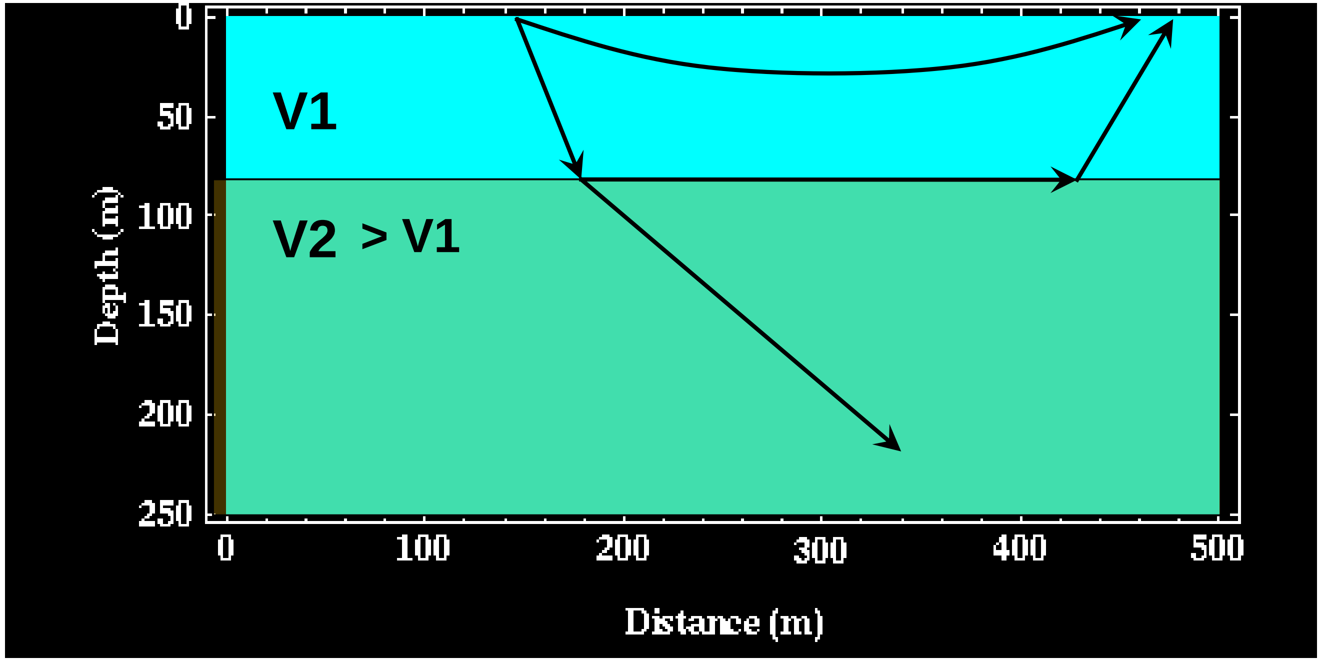
- Acoustic impedance

$$Z = \rho V$$

- Reflection depends on acoustic impedance

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

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



# Unit Activities

- **Labs: (Seismic I)**
  - Monday, September 30th
  - Tuesday, October 1st
- **Labs: (Seismic II)**
  - Monday, October 7th
  - Tuesday, October 8th
- **TBL:**
  - Monday, October 7th
- **Quiz:**
  - Monday, October 7th