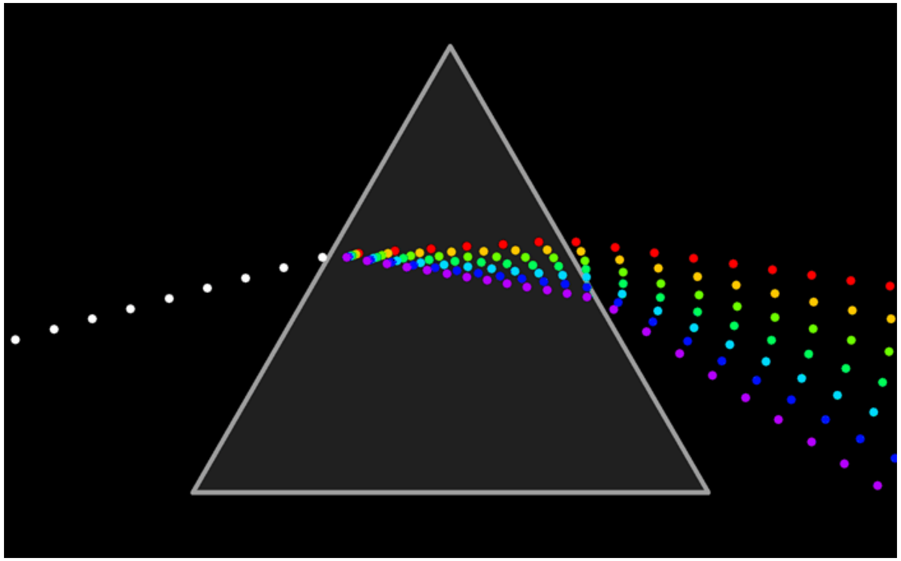
Today's experiment

- Goal – answer the question "**What does the speed of a wave depend on?**"
- Materials: Wave on a String PHeT Simulation (link in schedule) and Wave Machine
- Write a CER in pairs.
- Think about the components of a wave and explore the materials at your disposal to determine what variables could affect wave speed.
- Think about how you'll measure wave speed

Reflection: What happens to a wave pulse on a string when it hits the heavier section of the rope?
What happens when the pulse starts in the heavier section and moves to the lighter section?

Refraction: when a wave moves from a fast medium to slow medium (or slow to fast), the wave changes direction and speed.

$$\frac{sin\theta_i}{sin\theta_r} = \frac{v_i}{v_r}$$

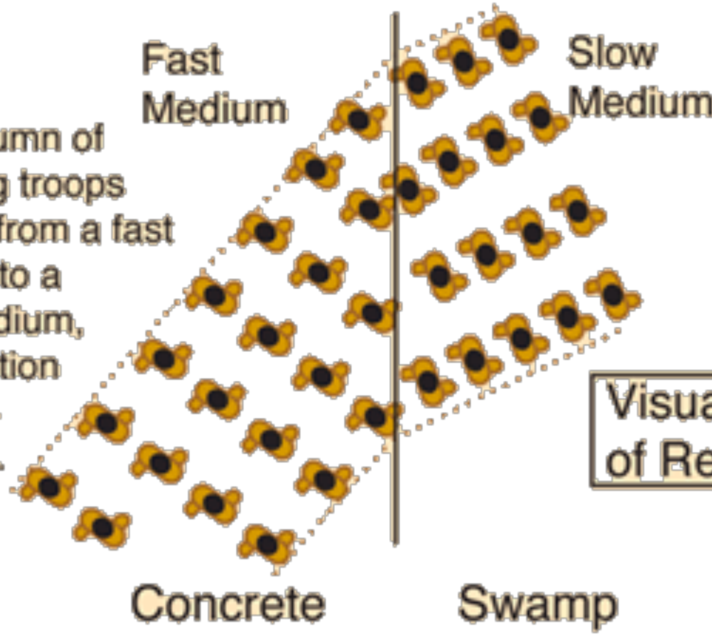


θ_i = angle of incidence
θ_r = angle of refraction
These angles are between the wave and a plane perpendicular to the surface

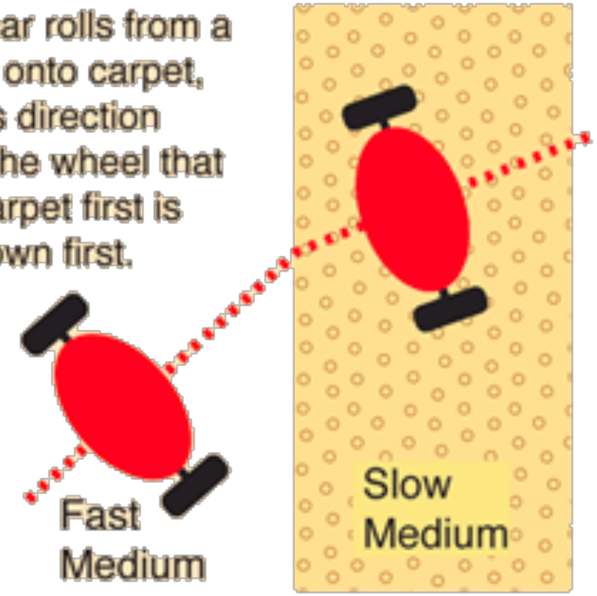
How much the wave gets refracted is dependent on the wavelength of the wave: The speed of light in the prism is slower than the speed of light in air. Frequency of wave remains constant.

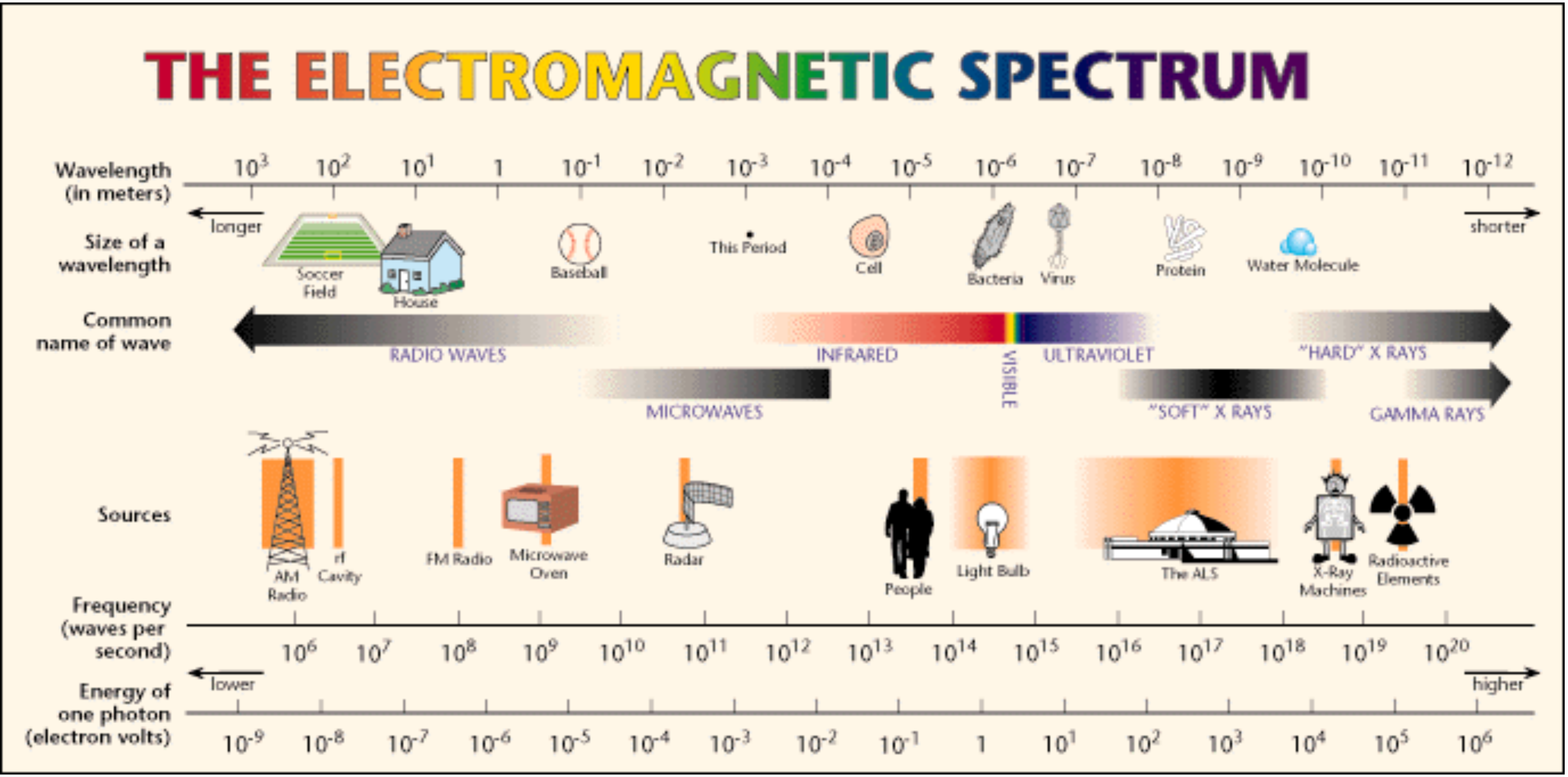
Visualizations of Refraction

As a column of marching troops crosses from a fast medium to a slow medium, the direction of march changes.



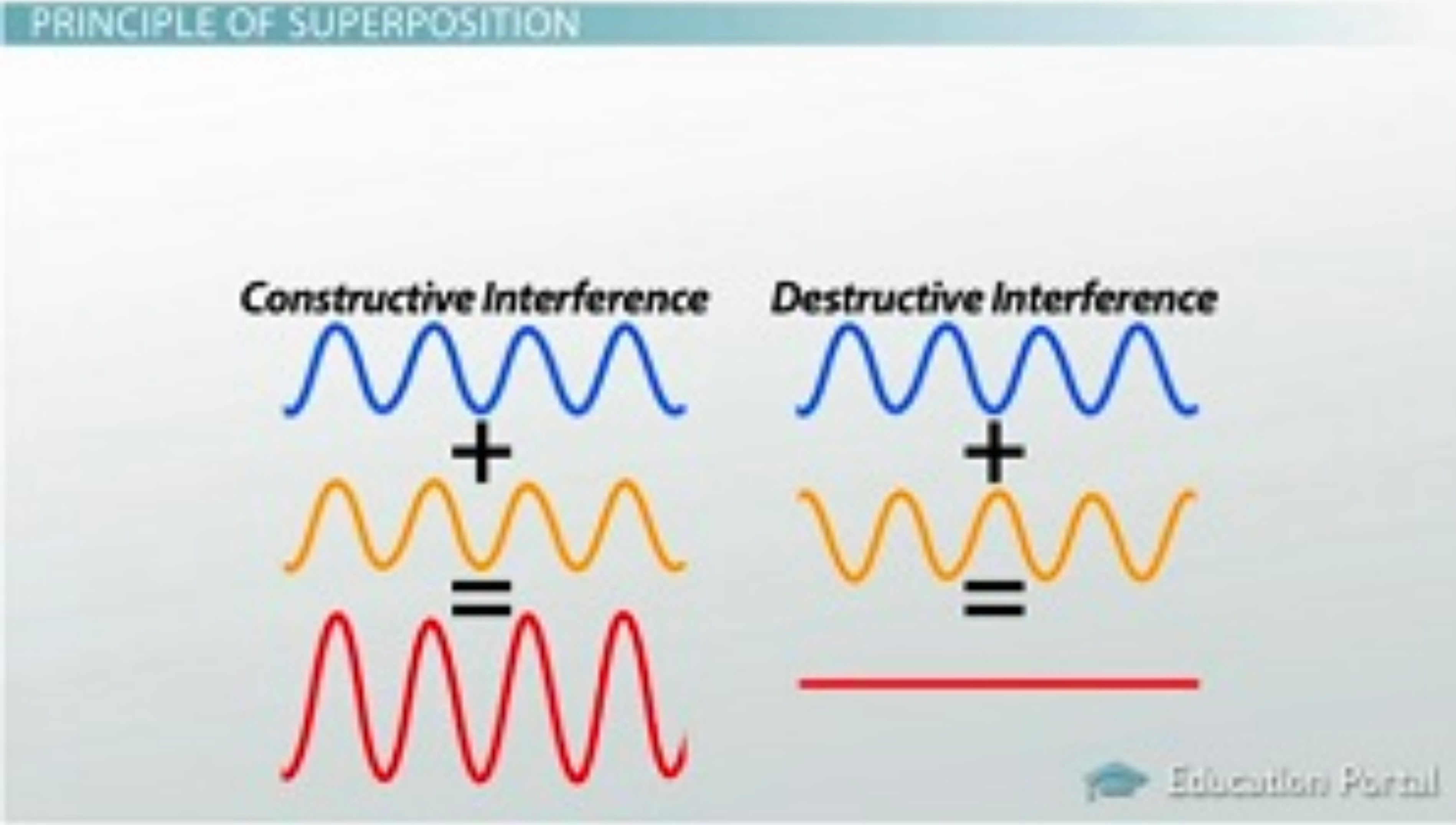
As a toy car rolls from a hard floor onto carpet, it changes direction because the wheel that hits the carpet first is slowed down first.



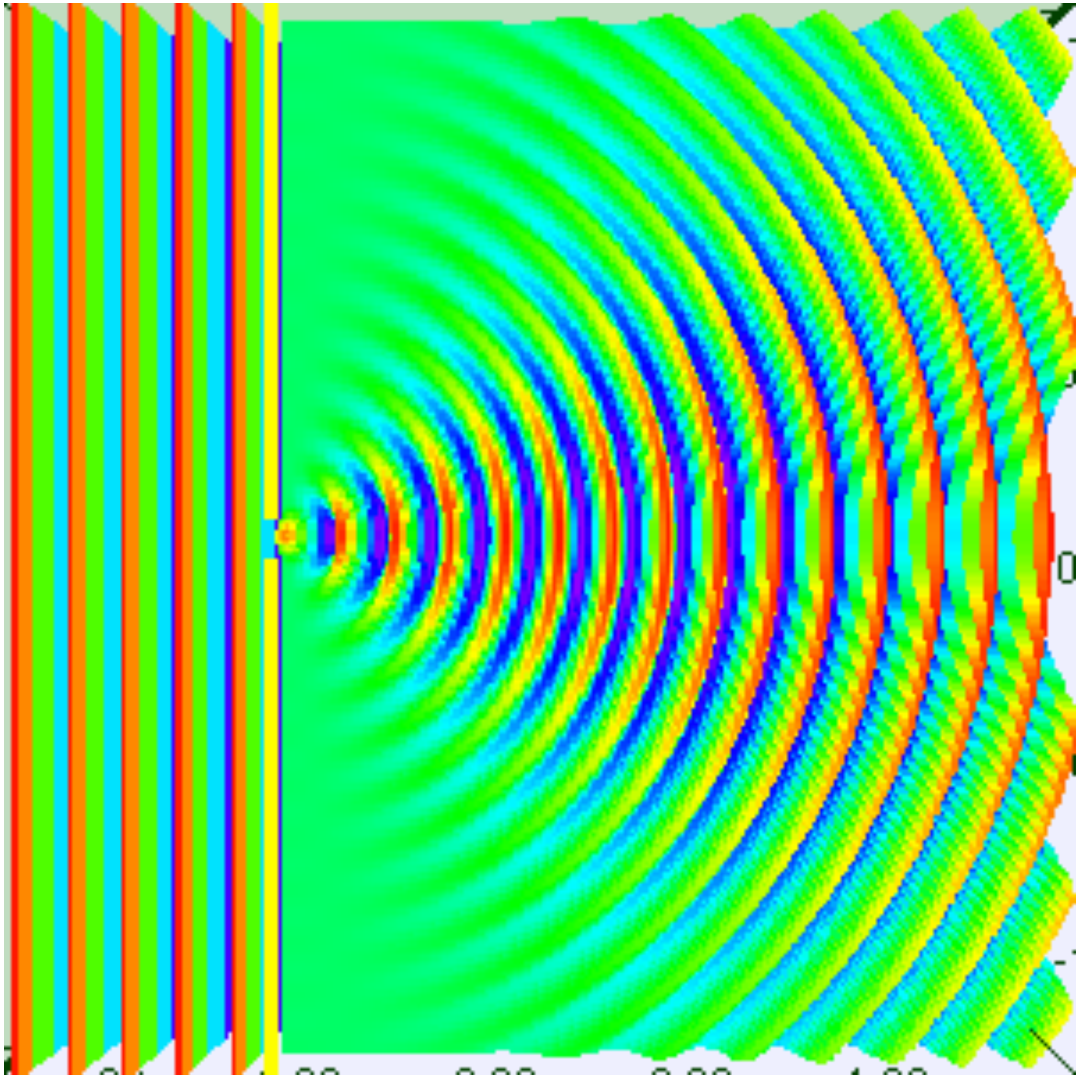

THE ELECTROMAGNETIC SPECTRUM
Wavelength (in meters)
10^3 10^2 10^1 1 10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9} 10^{-10} 10^{-11} 10^{-12}
longer
shorter
Size of a wavelength
Soccer Field
House
Baseball
This Period
Cell
Bacteria
Virus
Protein
Water Molecule
Common name of wave
RADIO WAVES
INFRARED
VISIBLE
ULTRAVIOLET
"HARD" X RAYS
MICROWAVES
"SOFT" X RAYS
GAMMA RAYS
Sources
AM Radio
rf Cavity
FM Radio
Microwave Oven
Radar
People
Light Bulb
The ALS
X-Ray Machines
Radioactive Elements
Frequency (waves per second)
10^6 10^7 10^8 10^9 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16} 10^{17} 10^{18} 10^{19} 10^{20}
lower
higher
Energy of one photon (electron volts)
10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10^1 10^2 10^3 10^4 10^5 10^6

Interference (click here for double slit experiment video)

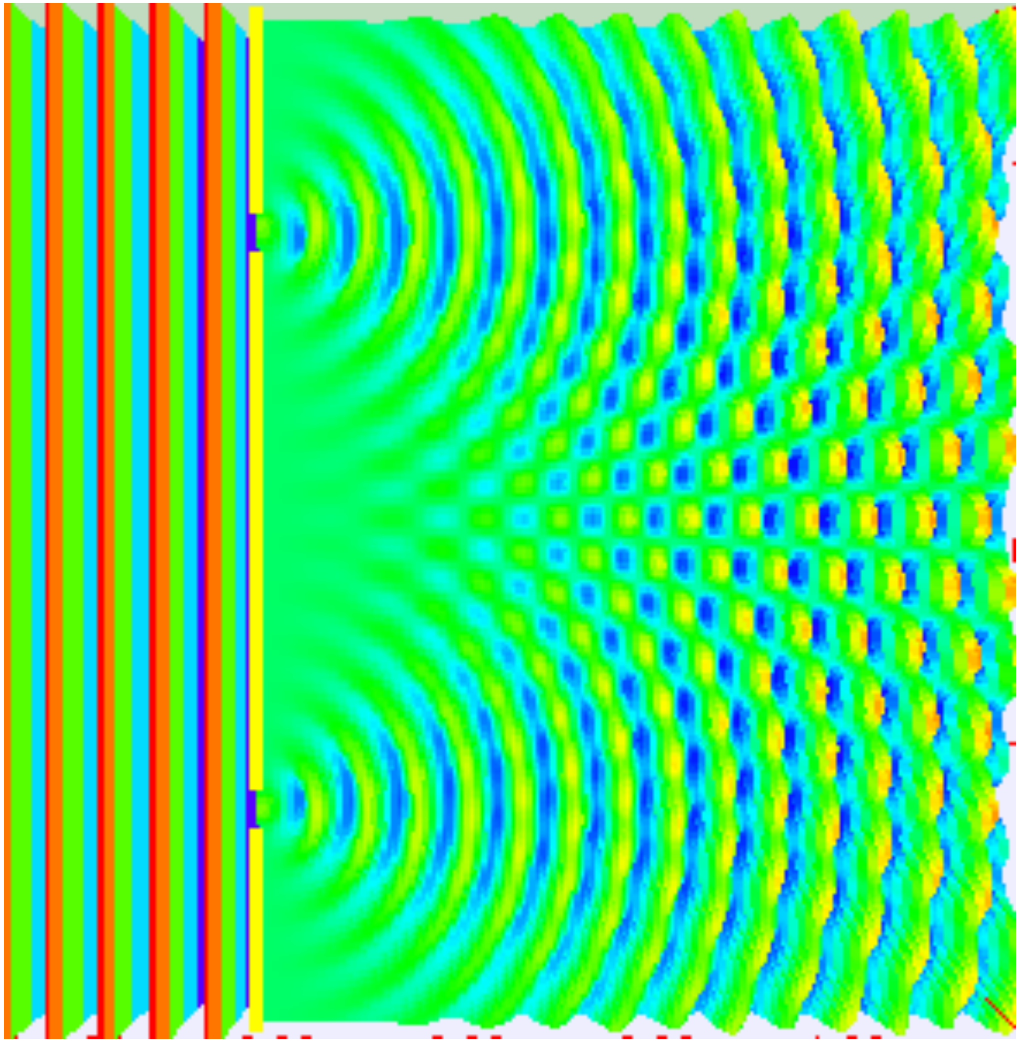
- Occurs when two of more waves meet
- Parts of the waves may overlap and form an interference pattern
  - Wave effects may be increased, decreased, or neutralized
- When the crest of one wave overlaps with the crest of another, their individual effects add up
  - Called constructive interference
- When the crest of one wave meets the trough of another, their individual effects decrease
  - Called destructive interference
- Characteristic of all wave motion, whether water waves, sound waves, or light waves



PRINCIPLE OF SUPERPOSITION
Constructive Interference
Destructive Interference
+
=
Education Portal



- **<u>Diffraction</u>**: Spreading out of waves around a boundary
- **<u>Reflection</u>**: waves bouncing off a boundary



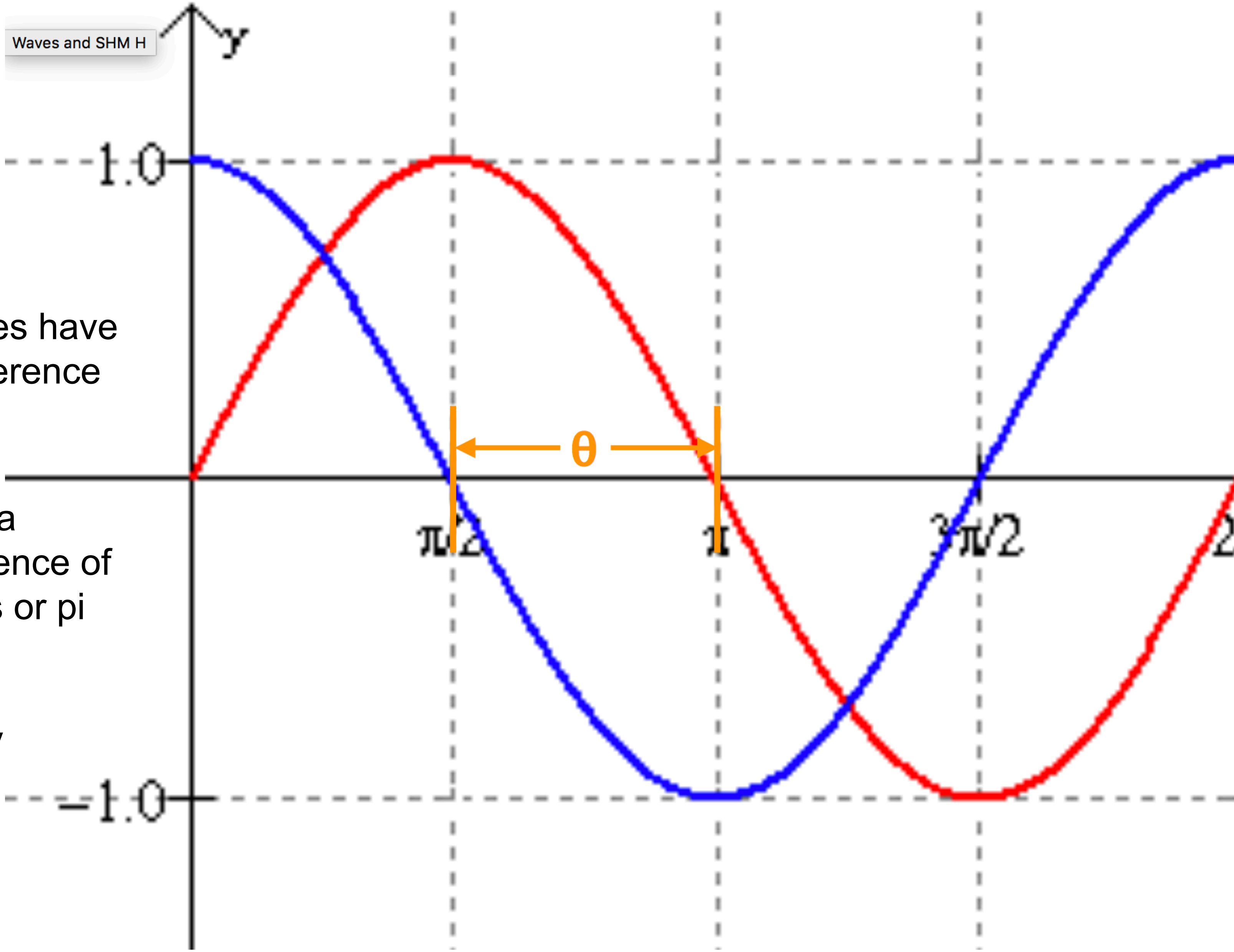
- Constructively interfere: extra large crests and troughs
- Destructively interfere - green sections

Phase

- Phase is the relationship between the period of a wave and an external reference point
  - Two waves which are *in phase* are in synch
  - Two waves which are *out of phase* are out of synch

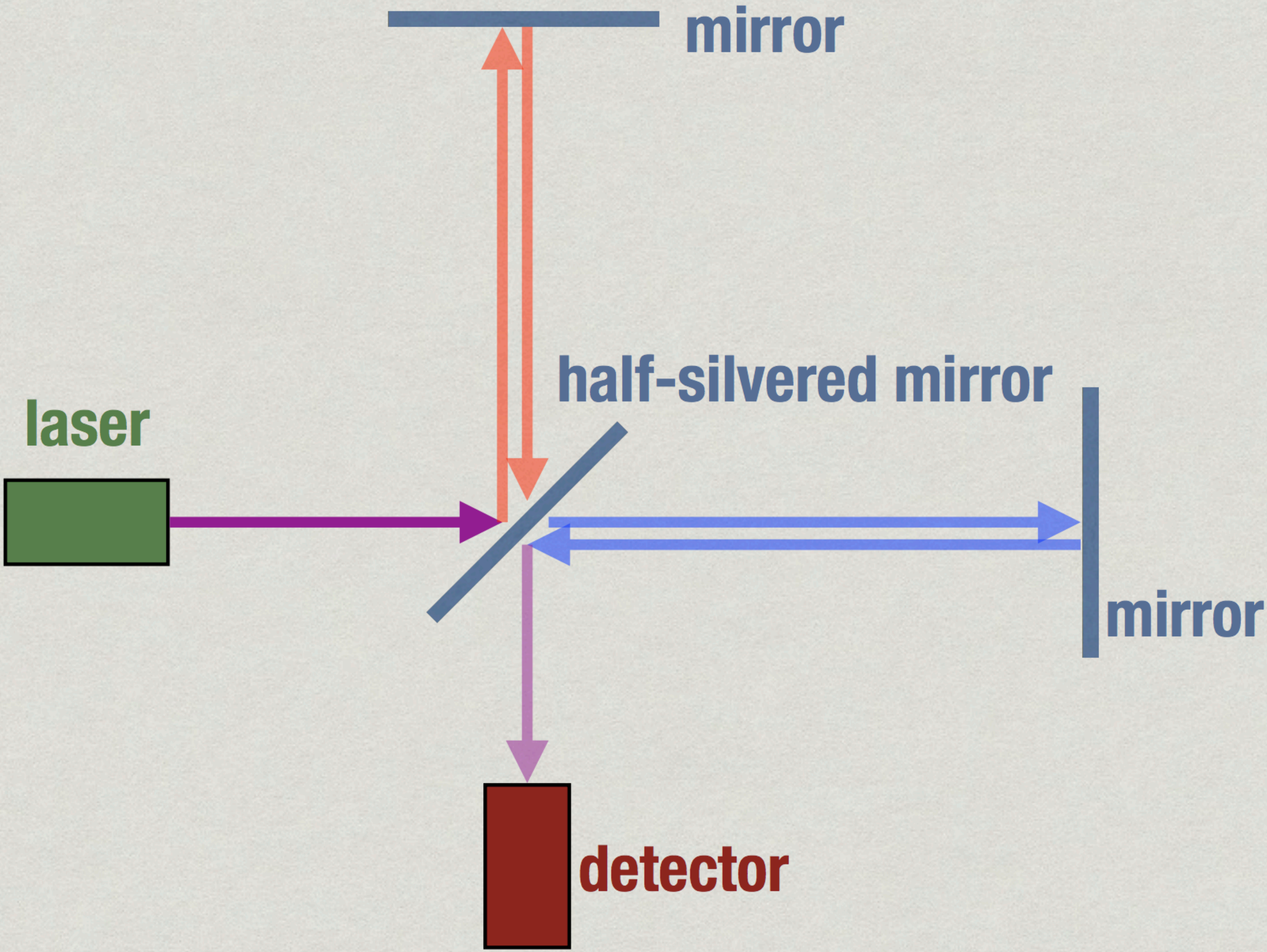
θ= “phase difference”
-These waves have a phase difference of $\frac{\pi}{2}$ radians

Waves with a phase difference of 180 degrees or pi radians will perfectly destructively interfere



Interferometry

- A family of techniques in which you use interference patterns to extract information about the wave is called **interferometry**
- Usually measures difference between light waves (especially lasers)
- How we discovered gravitational waves

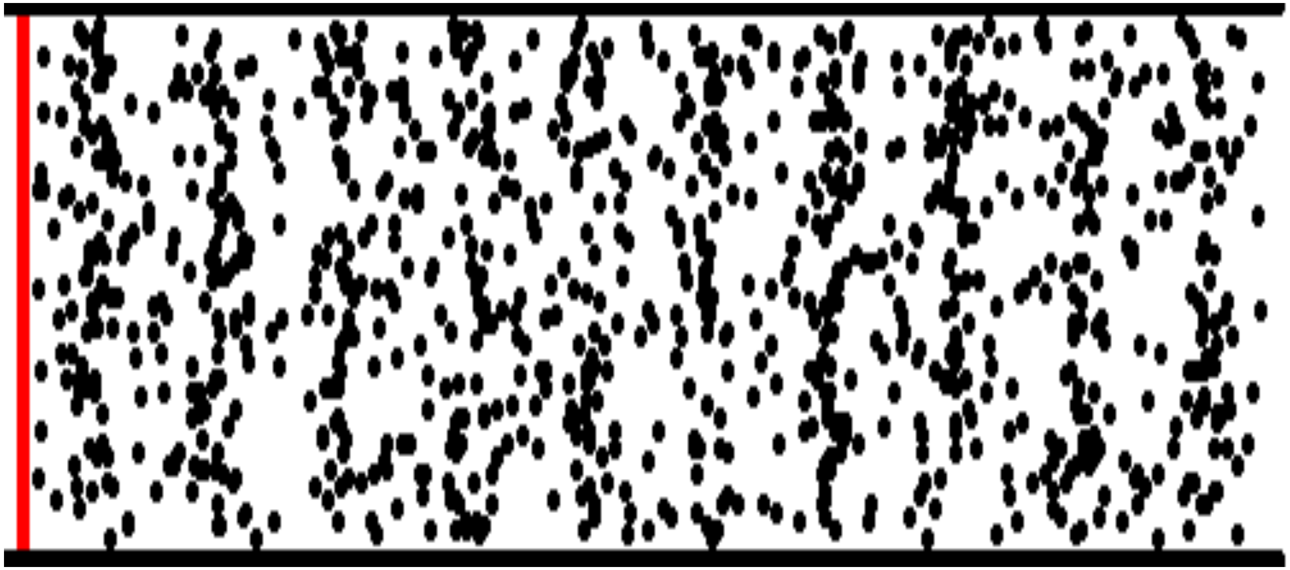

mirror
half-silvered mirror
laser
mirror
detector

Transverse vs. Longitudinal Waves

- Transverse
  - Motion of the medium is perpendicular to the direction in which the wave travels
  - Examples: Ripples in the water, A whip, Light, Earthquake secondary waves
- Longitudinal
  - Motion of the medium is in the same direction as in which the wave travels
  - Also called compression waves
  - Examples: Earthquake primary waves, Sound

Sound waves are longitudinal “pressure waves”

- Compressions of air molecules (wave crests, areas of high pressure) and rarefactions (wave troughs, areas of low pressure)



http://www.kettering.edu/~drussell/Demos/waves/wavemotion.html

Sound Waves

Transmission of Sound waves –

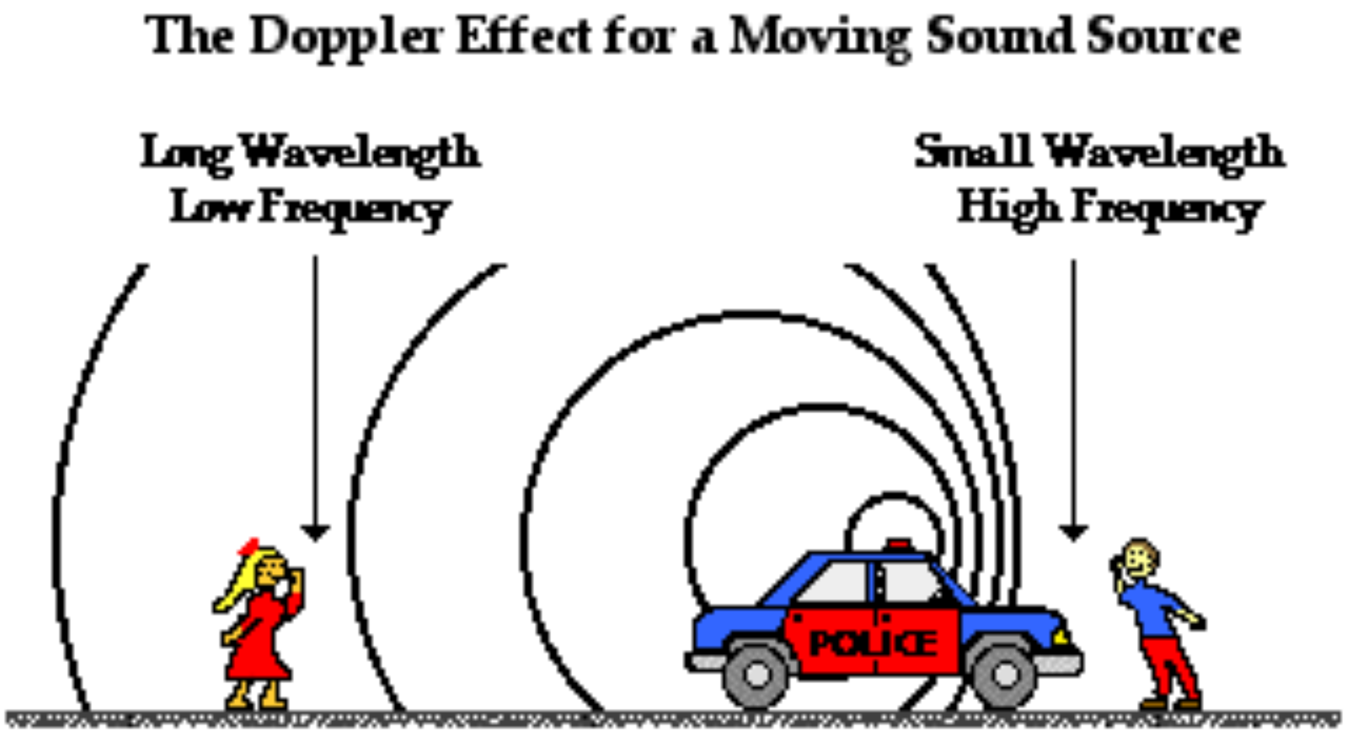
- Vibration of source (such as vocal cord)
- Causes compression waves through media (such as air)
- Causes vibration of our eardrums
- Causes electrical signals in our brain.

Loudness: brain's interpretation of intensity

- Intensity (I) is proportional to A^2 and $1/r^2$. (A = amplitude of the sound wave)
    - If you double the distance from a sound source, the intensity decreases by a factor of 4.
- More compression of the air molecules = higher amplitude (A).

Pitch is our brain's interpretation of frequency.

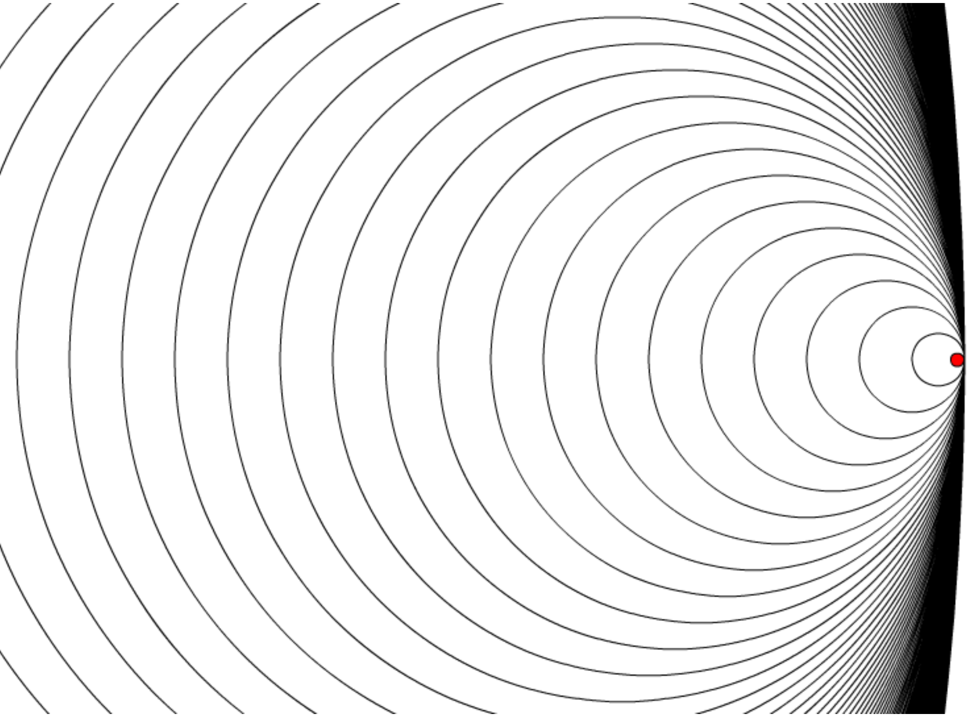
- Average young person can hear pitches from around 20 Hz to 20000Hz
- Below 20 Hz: infrasonic frequency
- Above 20,000 Hz: ultrasonic frequency



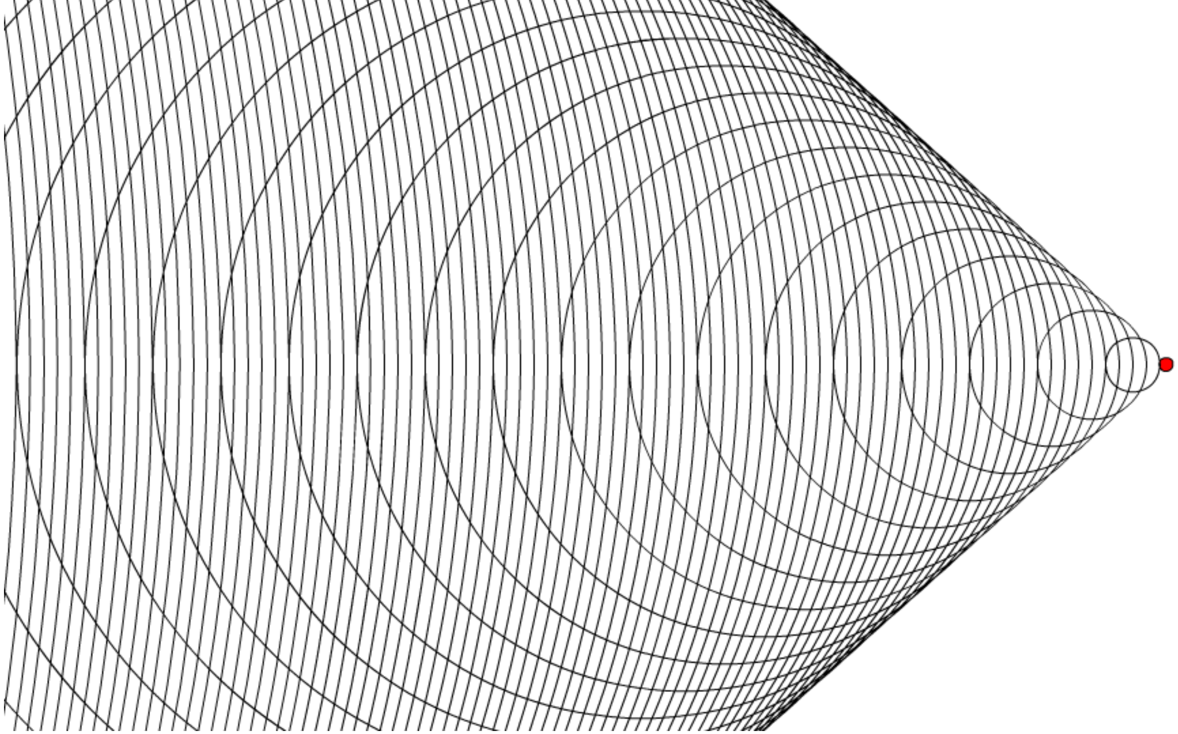
Doppler effect: apparent change in frequency due to the motion of source or receiver

$f' = f_{actual}(\frac{v-}{})$, where v = speed of sound in air and v_s= speed of sound source

V_o = speed of observer



Air molecules bunching up, drag increases due to large compression of air molecules – this is the “sound barrier”



Condensation allows us to see the shock wave

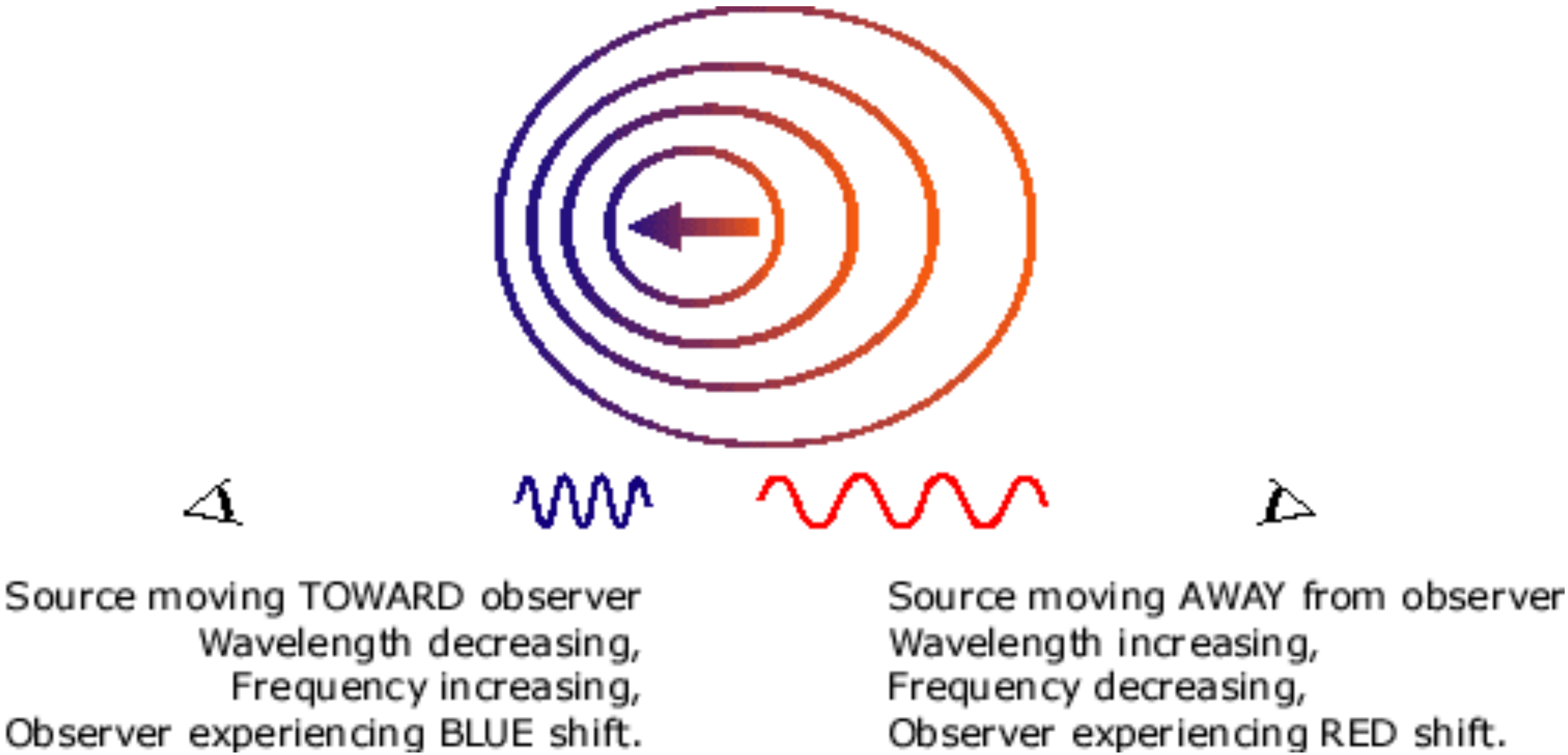
Subsonic = less than the speed of sound

Supersonic = more than the speed of sound

Mach # = speed of object/speed of sound

What's the difference between ultrasonic, infrasonic, subsonic, and supersonic?

Sonic boom is due to interference of sound waves at the edge of the cone. Get large amplitude, so hear loud boom



Doppler effect also used for light: shows expanding universe.

Sanity check:

When a source of a sound wave moves toward you, do you measure an increase in speed, decrease in speed, or neither?

- Neither: it's the frequency that changes. The speed remains the same.

Sound needs a material medium through which to travel

- Can’t travel in a vacuum (like space).
- Speed depends on elasticity of medium.
- Elasticity of solids >liquids> gases, so speed of sound solids > liquids> gases

Speed of sound in dry air at 20 C =343 m/s
Speed of sound in 20 C fresh water = 1498 m/s
Speed of sound in steel = 5920 m/s

In addition to being faster, clearer and louder sound too

How far away is a storm if you notice a 3 second delay between a lightning flash and the sound of thunder?

D = vt = 343 m/s x 3 seconds = 1029 m. = 0.64 miles

Measuring Speed of Sound

- Groups of 3
- In 10 min, come up with a proposal of how to measure the speed of sound
- You can use the tools we have in this room or tools you have on you
- *Minimize error*
- *Note: the average human reaction time is 0.22 seconds*

Acoustic Levitation

Forced vibrations - When vibrations in one medium cause, or force, vibrations in another medium

- Virtually unavoidable, but much more interesting when used in clever ways
- Such as by utilizing the natural frequency of the vibrating medium

Natural frequency - Frequency at which minimum energy is required to produce and sustain forced vibrations

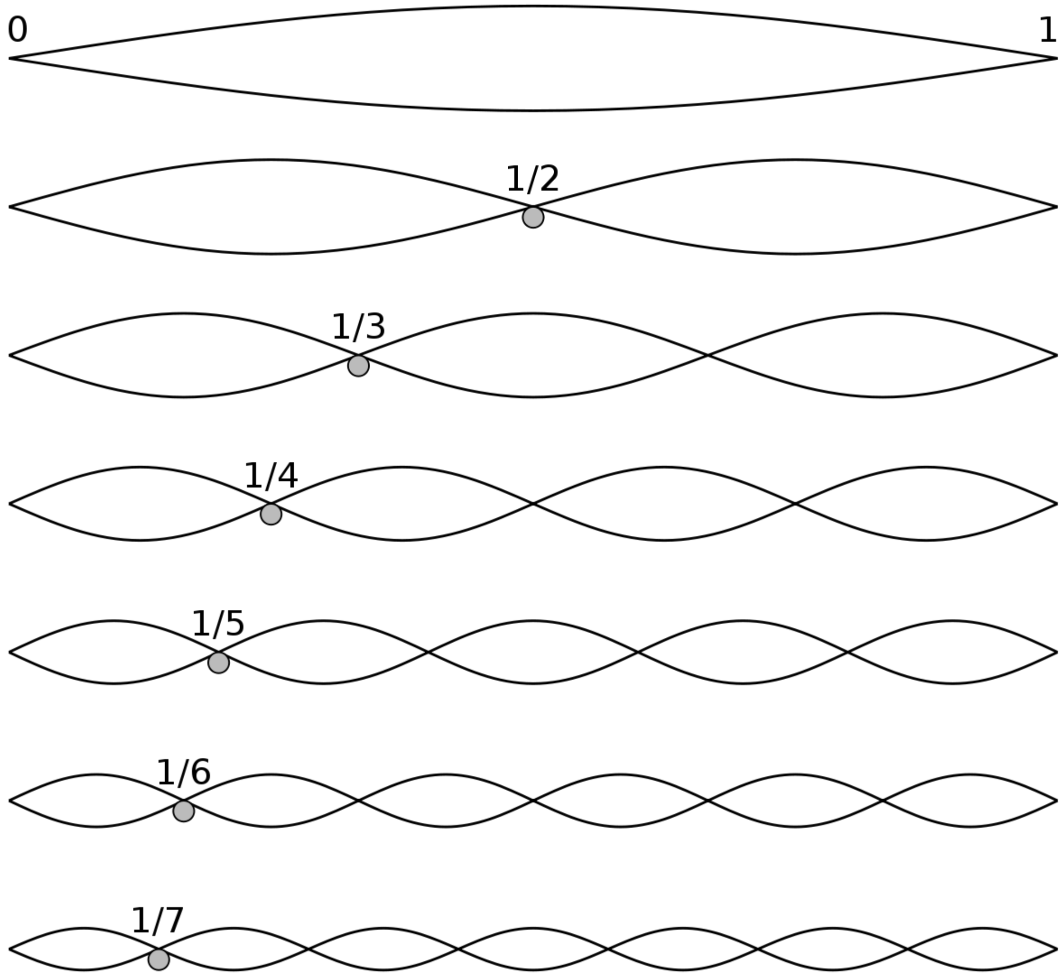
- Depends on the elasticity and shape of the vibrating object
- When the frequency of a forced vibration on an object matches the object's natural frequency, a dramatic increase in amplitude occurs
- This phenomenon is called **resonance**
- Ex. Pushing someone on a swing

Standing waves - Also known as a stationary wave

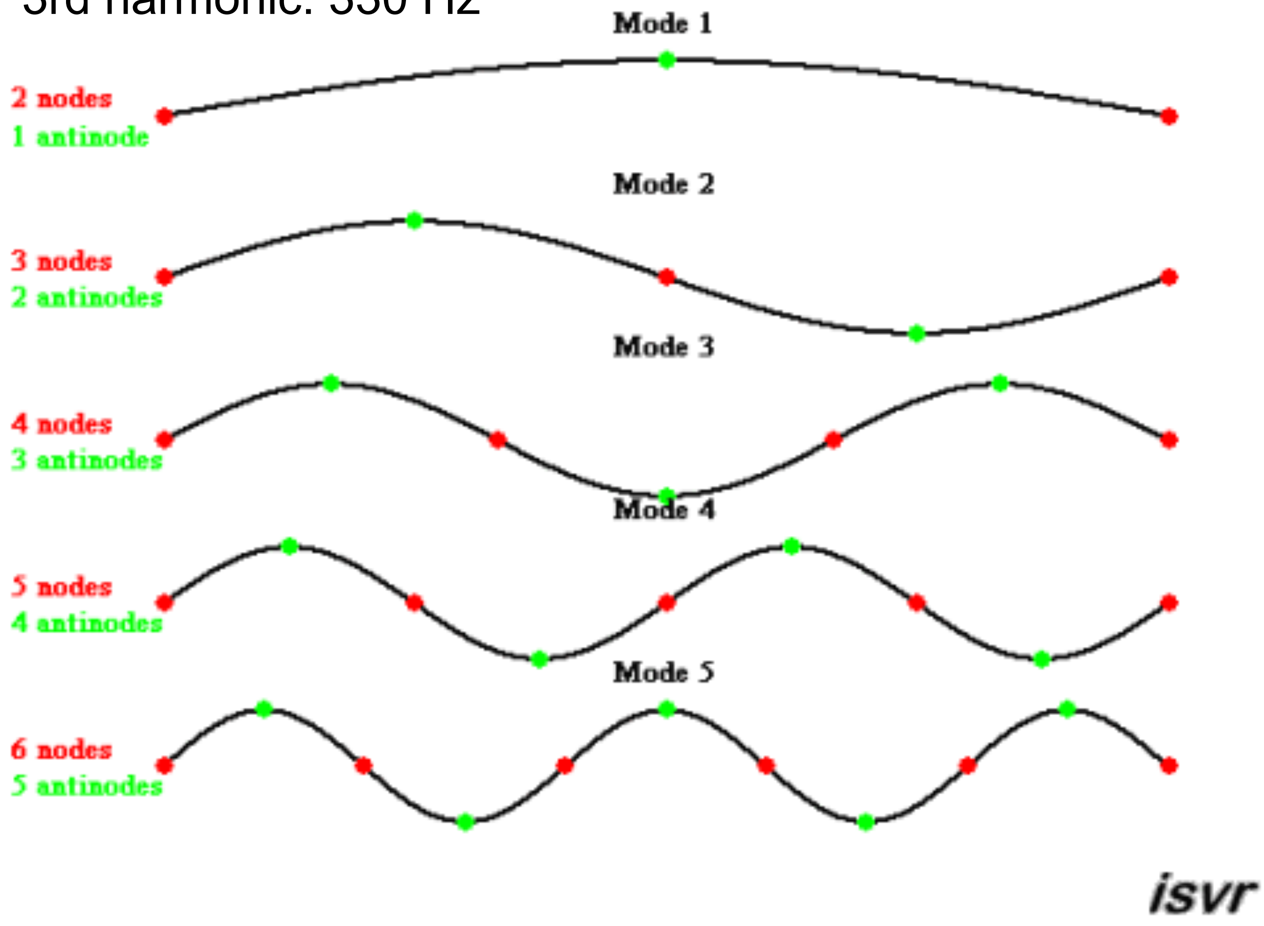
- A standing wave is one where particular points on the wave are “fixed,” or stationary
- Fixed points on a standing wave are called nodes
- Positions on a standing wave with the largest amplitudes are called antinodes
- Antinodes occur halfway between nodes

Standing waves are the result of interference

- Two waves of equal amplitude and wavelength pass through each other in opposite directions



Harmonic corresponds to number of antinodes
The sequence off all multiples of a base frequency
E.g. base frequency, 1st harmonic: 110 Hz
2nd harmonic: 220 Hz
3rd harmonic: 330 Hz

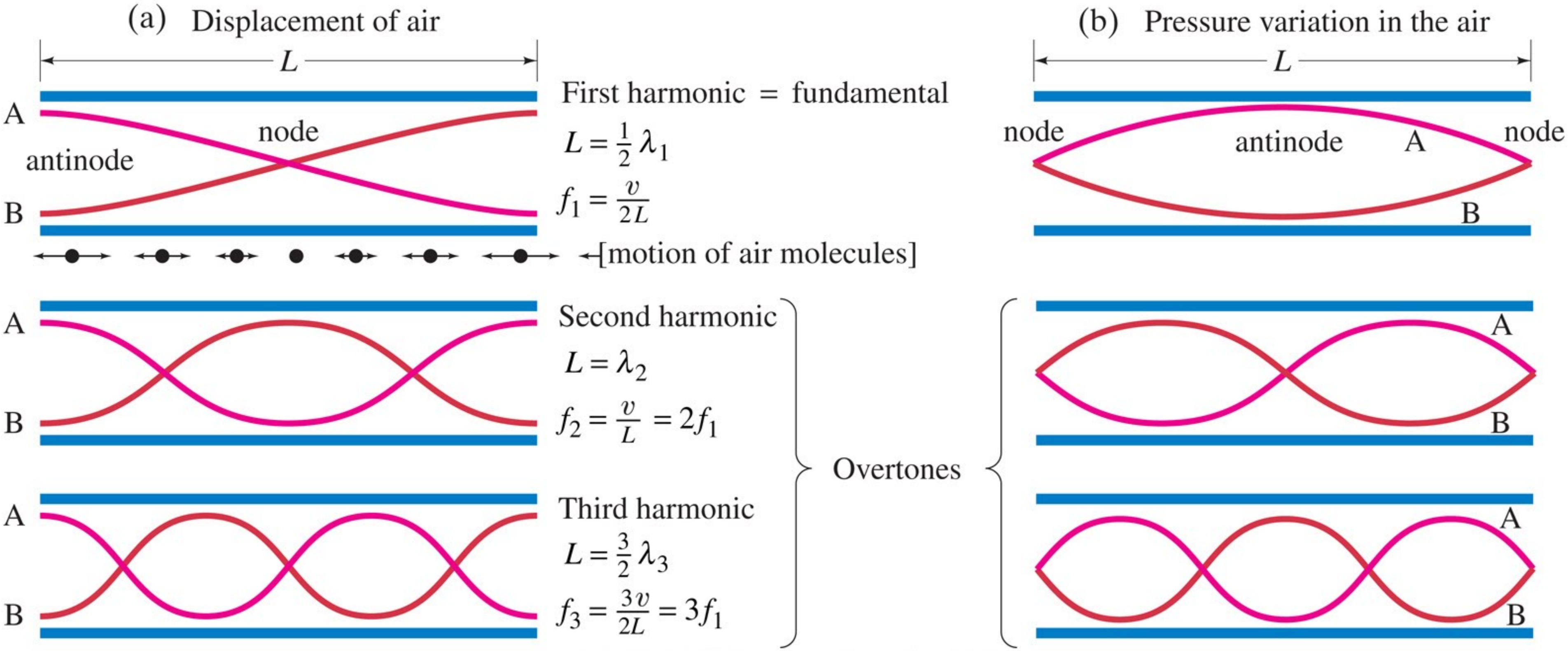


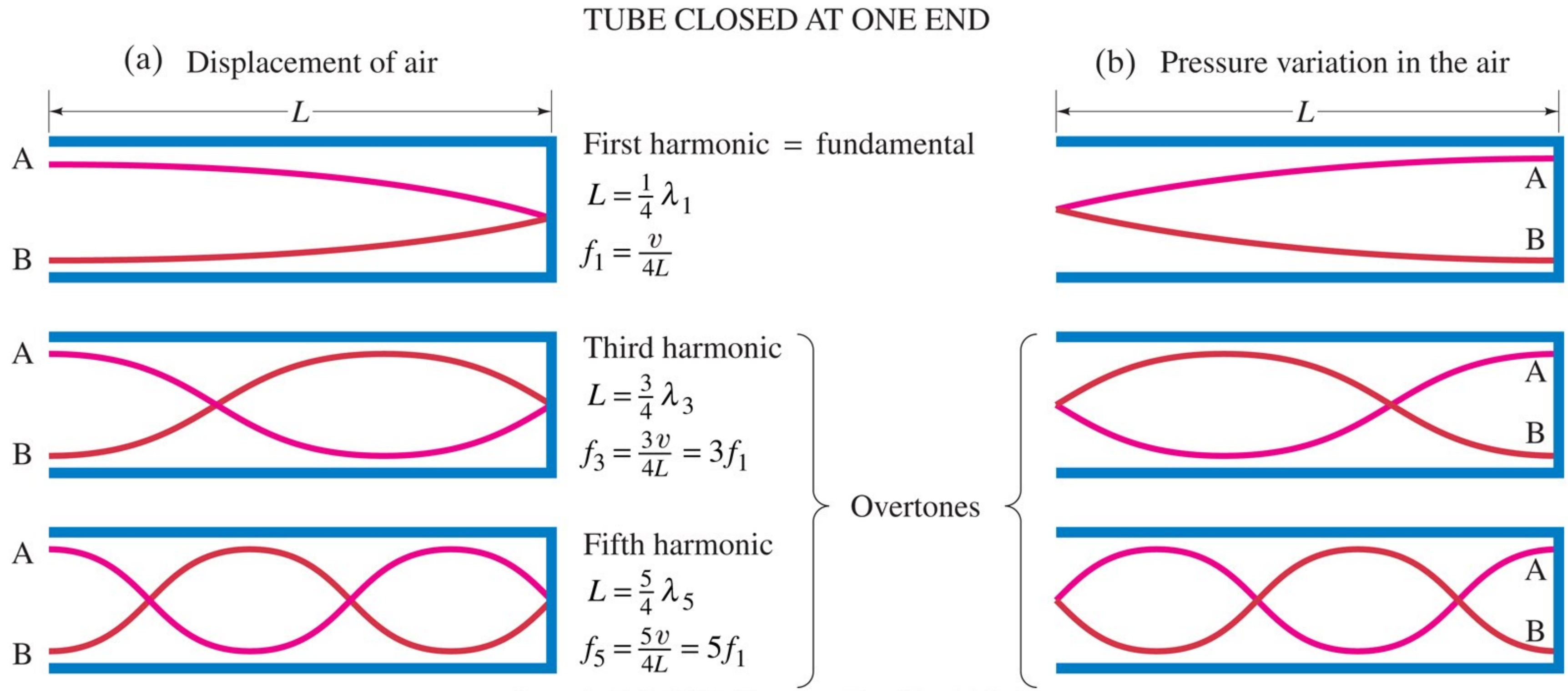
A 0.32-m-long violin string is tuned to play A above middle C at 440 Hz. What is the wavelength of the fundamental string vibration? What is the frequency and wavelength of the sound wave produced?

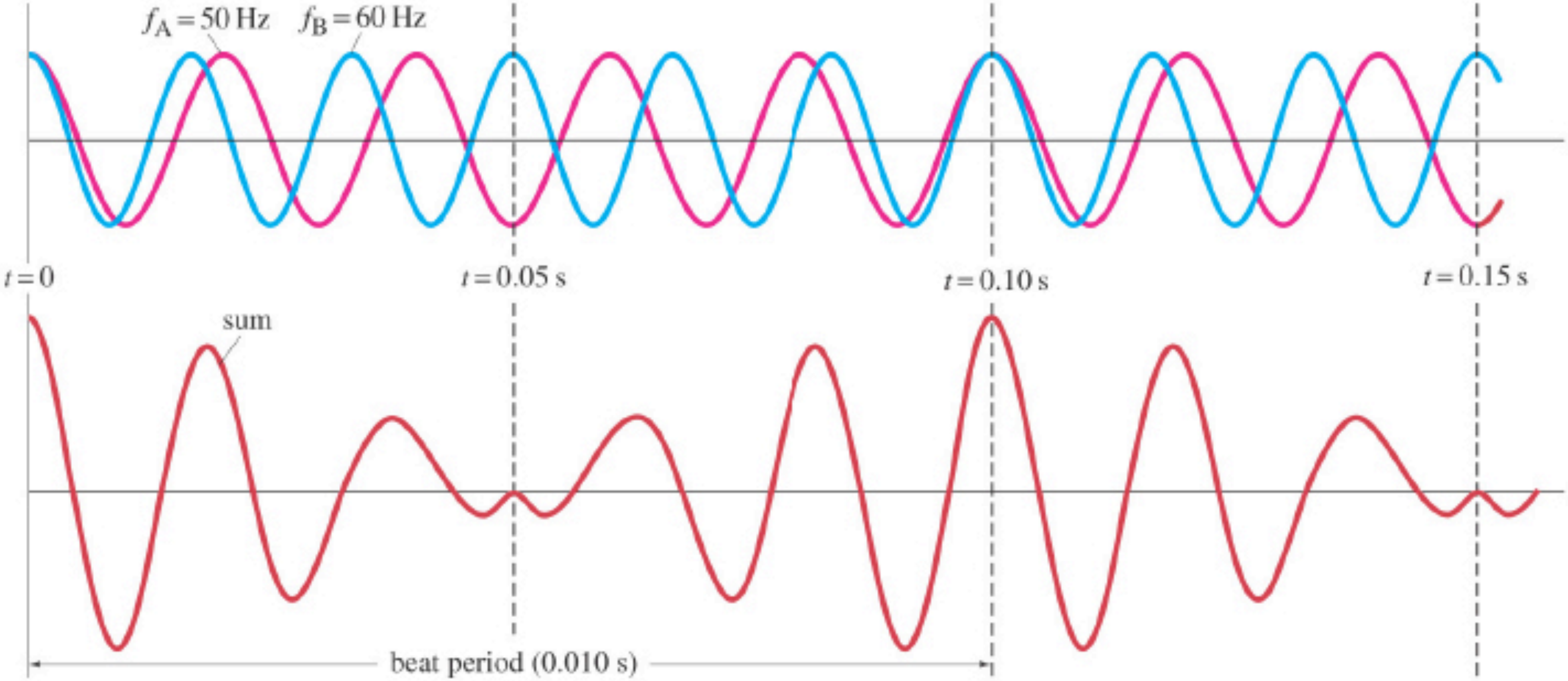
The wavelength of the fundamental is the wavelength of the standing wave on the string

- $\lambda = 2L = 0.64$ m, or 64 cm
- The sound wave that travels outward in the air has the same frequency, 440 Hz.
- Its wavelength is $\lambda = v/f = (343 \text{ m/s})/(440 \text{ Hz}) = 0.78$ m, or 78 cm
- Why is there a difference?
    - Speed of the wave is different in a different medium!

TUBE OPEN AT BOTH ENDS




TUBE CLOSED AT ONE END
(a) Displacement of air
(b) Pressure variation in the air
L
A
B
First harmonic = fundamental
$L = \frac{1}{4}\lambda_1$
$f_1 = \frac{v}{4L}$
Third harmonic
$L = \frac{3}{4}\lambda_3$
$f_3 = \frac{3v}{4L} = 3f_1$
Fifth harmonic
$L = \frac{5}{4}\lambda_5$
$f_5 = \frac{5v}{4L} = 5f_1$
Overtones



<u>What happens when you get interference of sound waves with slightly different frequencies?</u>

<u>Beats</u> – interference of sound waves when 2 sound sources are close in frequency but not exactly the same.

At t = 0.1 seconds, the sound waves interfere perfectly constructively again. So the beat period is the amount of time it takes to get from 1 beat to the next beat.

Beat frequency = difference in frequency of sources.
In the wave above, the beat frequency = 60 Hz - 50 Hz = 10 Hz

A 400 Hz tuning fork is held near a vibrating guitar string and 20 beats are counted in 5 seconds. What are the possible frequencies of the guitar string?

- **Ans = 396 and 404 Hz**

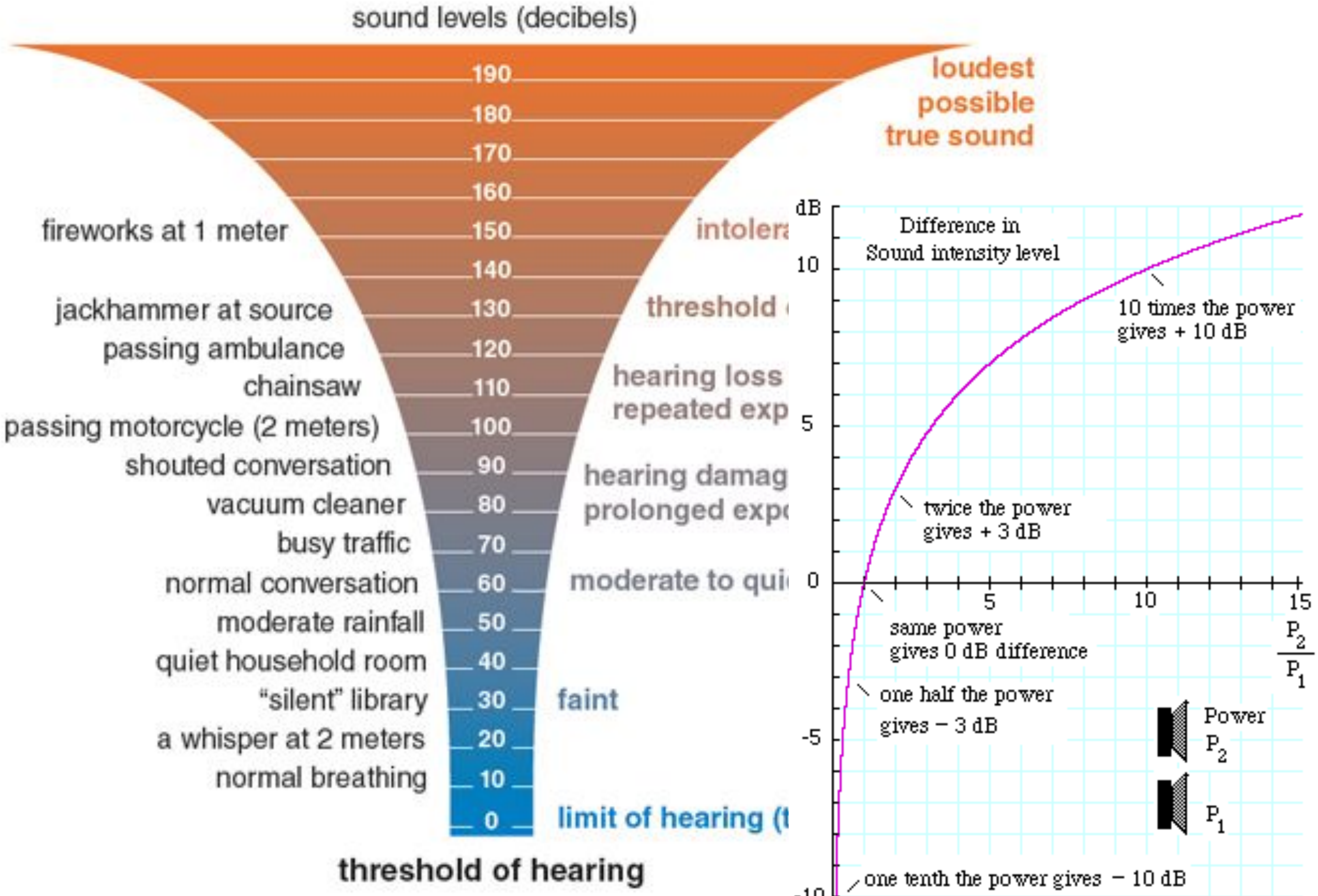
Intensity

- Loudness is the brain's interpretation of sound intensity
- Intensity = power/area = (energy/time)/area
  - Energy of a wave is proportional to amplitude squared ($E \propto A^2$)
  - $I \propto A^2$
  - For a spherical wave, I = power/$4\pi r^2$
    - So $I \propto 1/r^2$
    - Therefore, $A \propto 1/r$
      - Amplitude is inversely proportional to distance
- $\beta = 10 \log(I_1/I_0)$ (β =decibel level)
- $I_0 = 10^{-12}$ W/m^2
- Threshold of hearing
- Measure intensity in decibels (dB)

- Intensity is logarithmic
- For each increase in 10 dB, the intensity increases by a factor of 10 i.e. 10 dB is 10 times as intense as 0 dB and a tenth as intense as 20 dB
- Roughly speaking, the sensation of loudness follows the decibel scale
  - Thus, we say human hearing is approximately logarithmic

Sample Problem

- The audience at the circus roars with applause at the acrobat’s daring feats. The sound of the applause rings in at 68 dB. What is the intensity of the sound produced?
- $\beta = 10 \log(I_1/I_0)$
- Ans. $I_1 = 6.3\times10^{-6}$ W/m^2



sound levels (decibels)
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
loudest
possible
true sound
fireworks at 1 meter
jackhammer at source
passing ambulance
chainsaw
passing motorcycle (2 meters)
shouted conversation
vacuum cleaner
busy traffic
normal conversation
moderate rainfall
quiet household room
"silent" library
a whisper at 2 meters
normal breathing
intolera
threshold
hearing loss
repeated exp
hearing damag
prolonged exp
moderate to qui
faint
limit of hearing (t
threshold of hearing
dB
Difference in
Sound intensity level
10 times the power
gives + 10 dB
twice the power
gives + 3 dB
same power
gives 0 dB difference
one half the power
gives − 3 dB
one tenth the power gives − 10 dB
Power
P_2
P_1
$\frac{P_2}{P_1}$
10
5
0
-5
-10
5
10
15

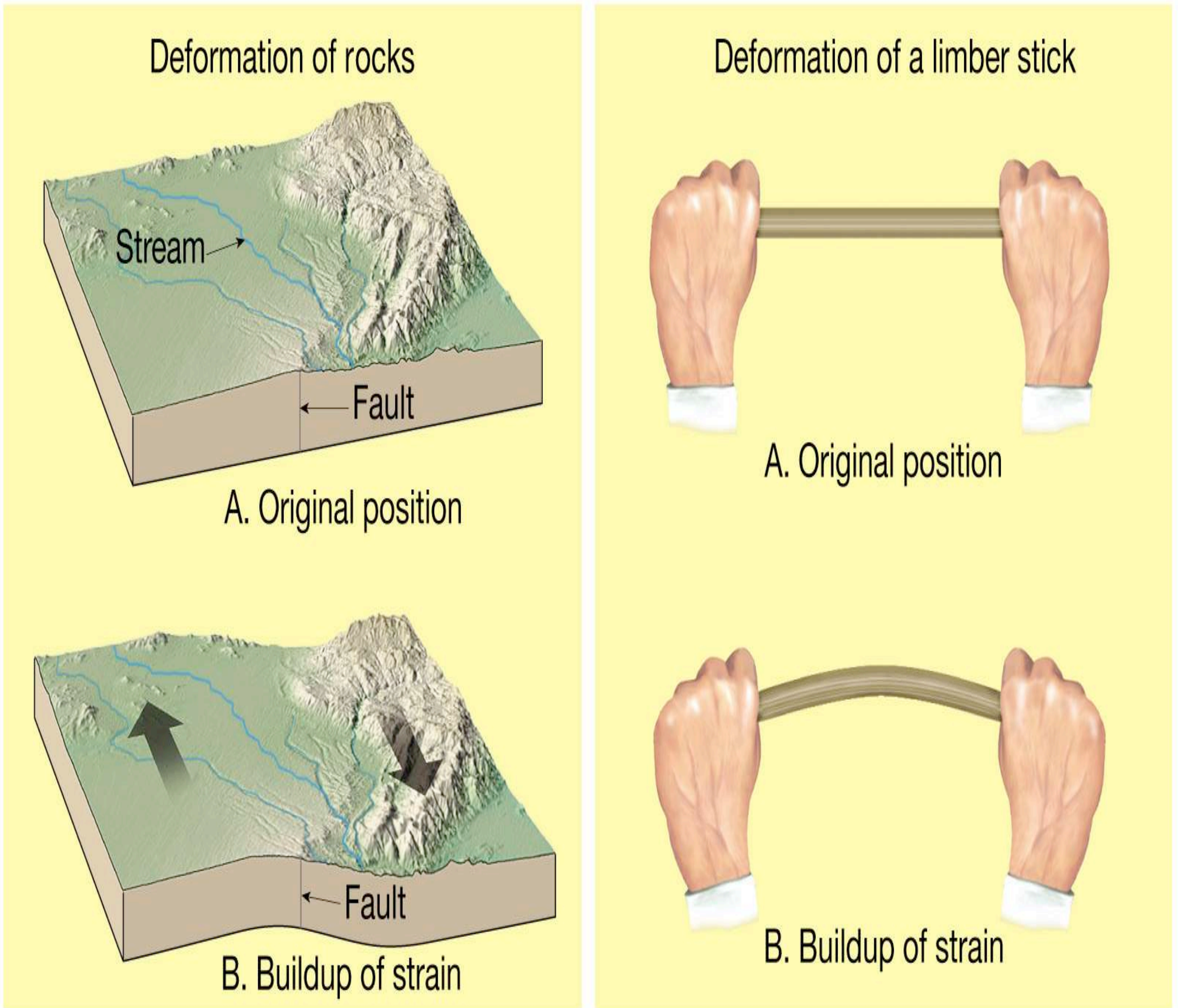
Earthquakes and seismic waves

- What I would like you to know:
  - Differences between P waves, S waves, and surface waves
  - How to figure out the epicenter of an earthquake
  - How to find the magnitude of an earthquake

How do earthquakes occur?

- Stresses build up in the crust, usually due to lithospheric plate motions

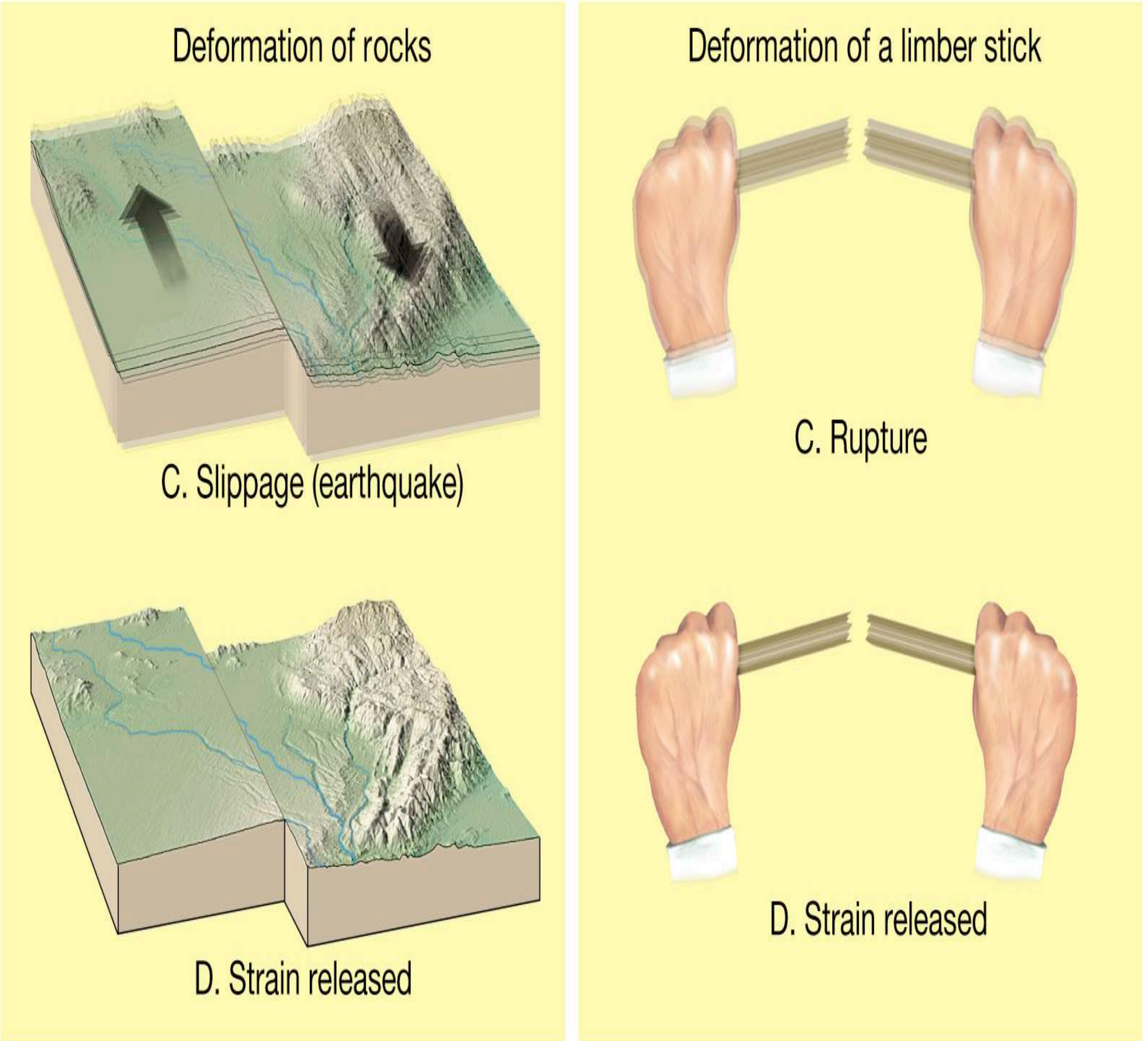
- Rock deform (strain) as the result of stress. The strain is energy stored in the rocks.



How do earthquakes occur?

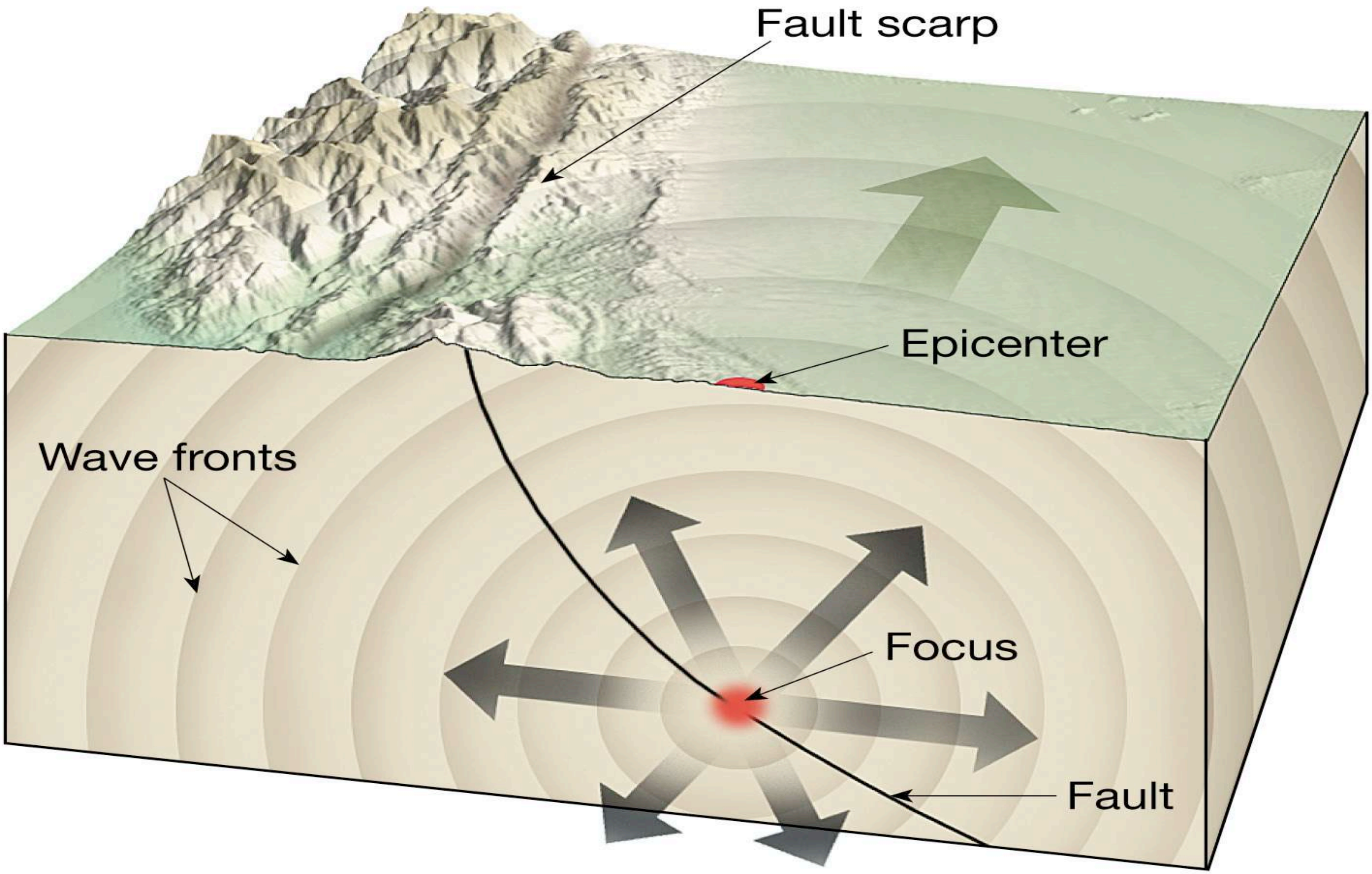
- When the rocks reach their elastic limit, they break, and energy is released in the form of seismic waves, radiating out from the earthquake focus

- The rocks return to their original shape, with a displacement (slip) along the fault



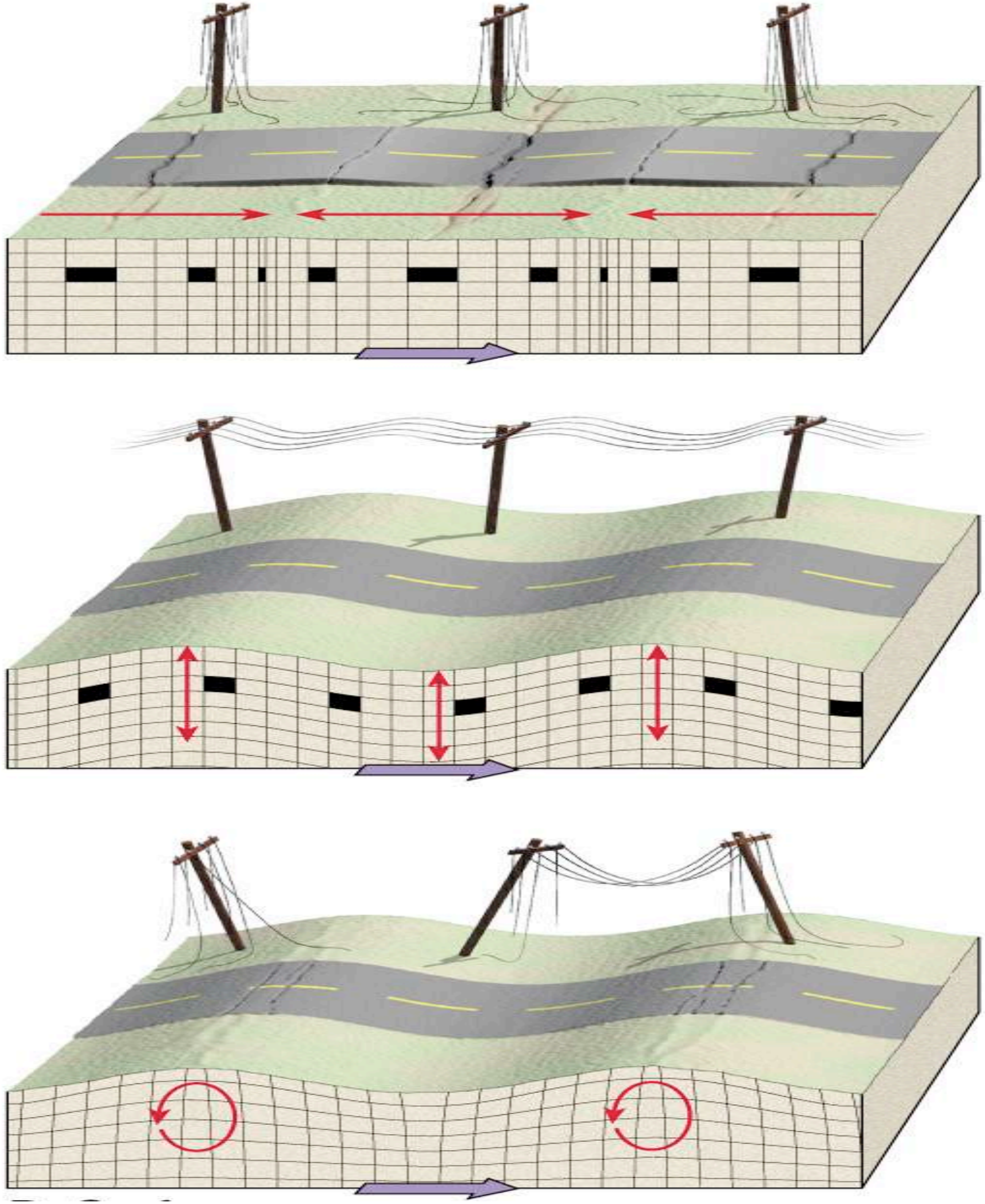
Earthquake focus*: center of rupture or slip, seismic waves radiate out from the *focus

***Earthquake epicenter* – the point on the Earth's surface over the focus**

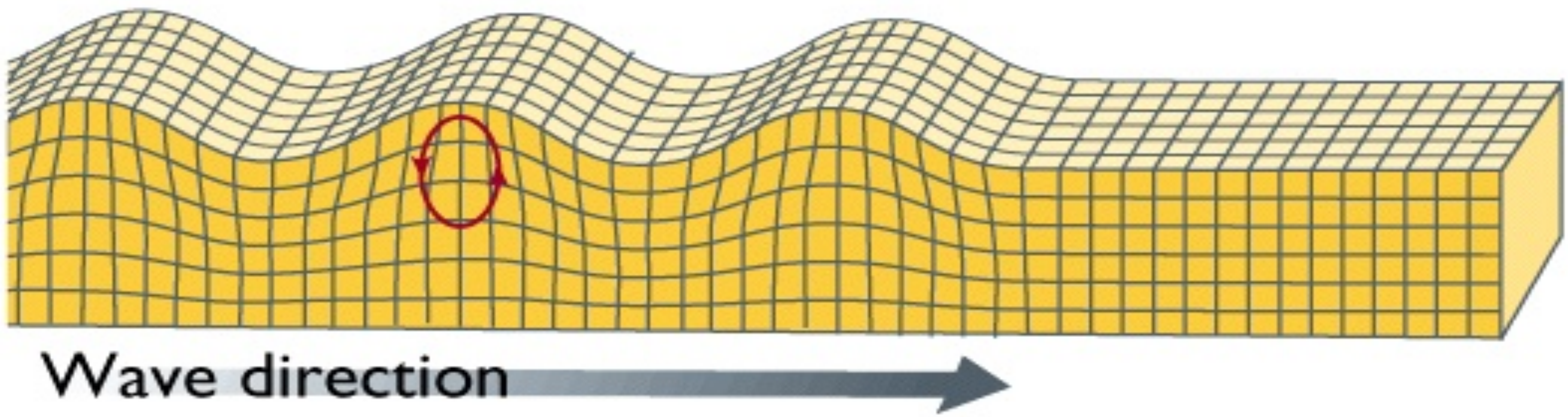


Kind of seismic waves

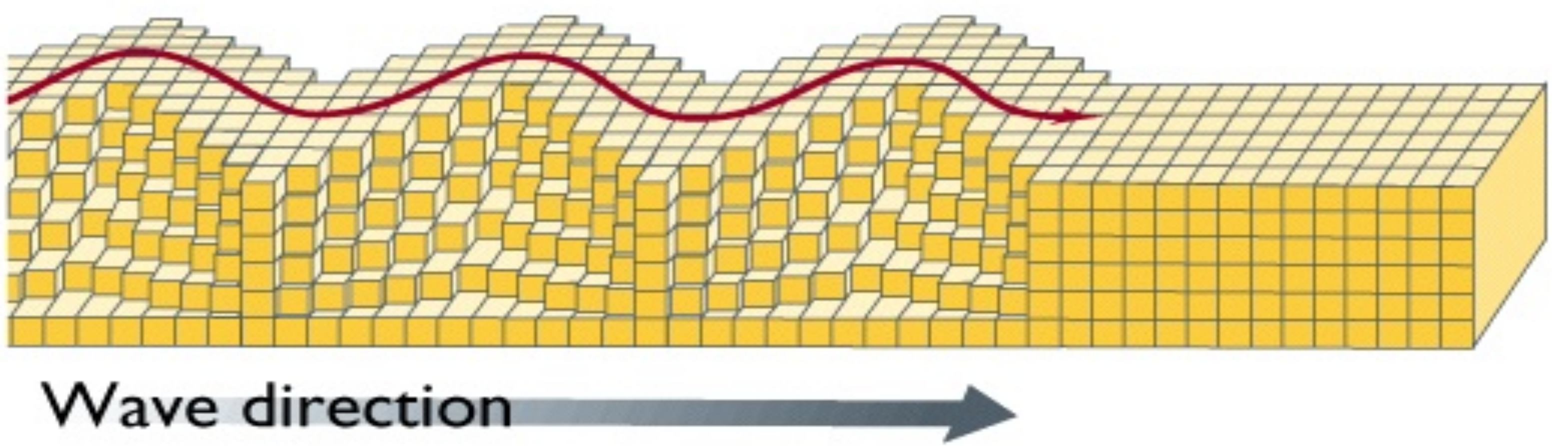
- **P-waves** – most rapid (8 km/sec)
  - longitudinal
- **S-waves** – slower (5 km/sec), cannot move through liquids
  - transverse
- **Surface waves** – even slower, move only on surface, most destructive



Surface waves

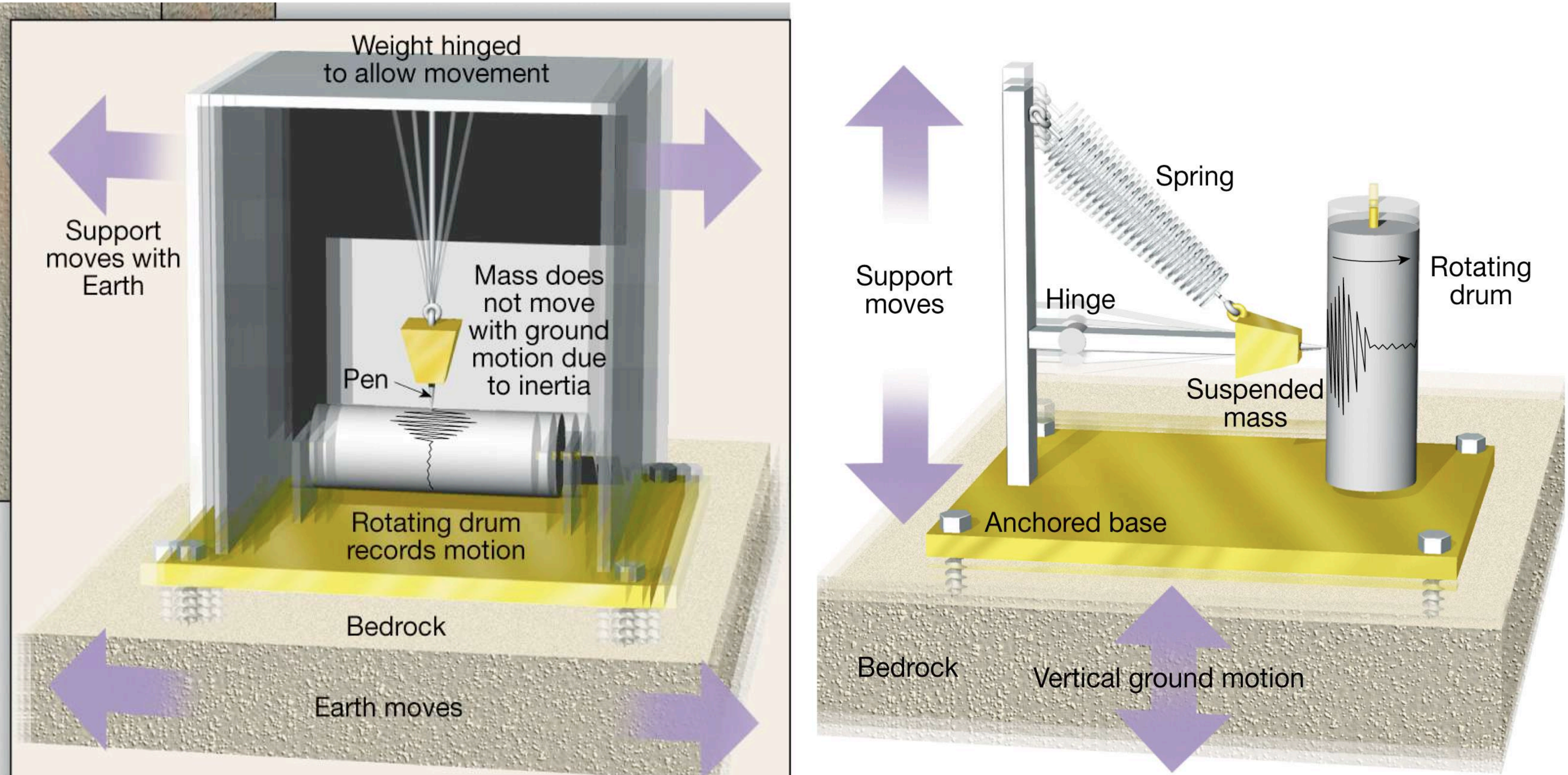


(a)



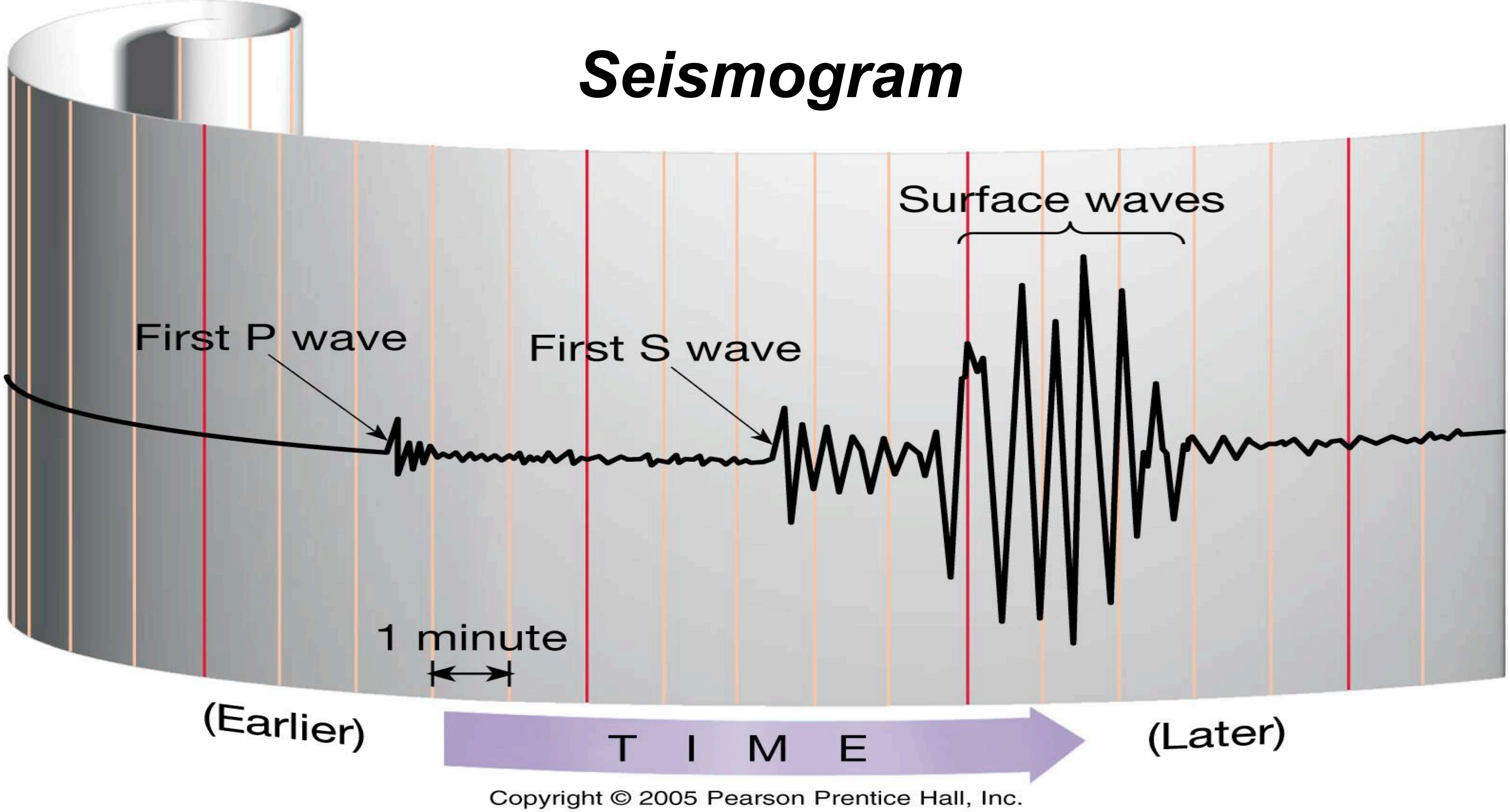
(b)

Detecting and measuring seismic waves



***Seismometers*:**
- **The paper roll moves with the ground**
- **The pen remains stationary, because of the spring, hinge and weight**

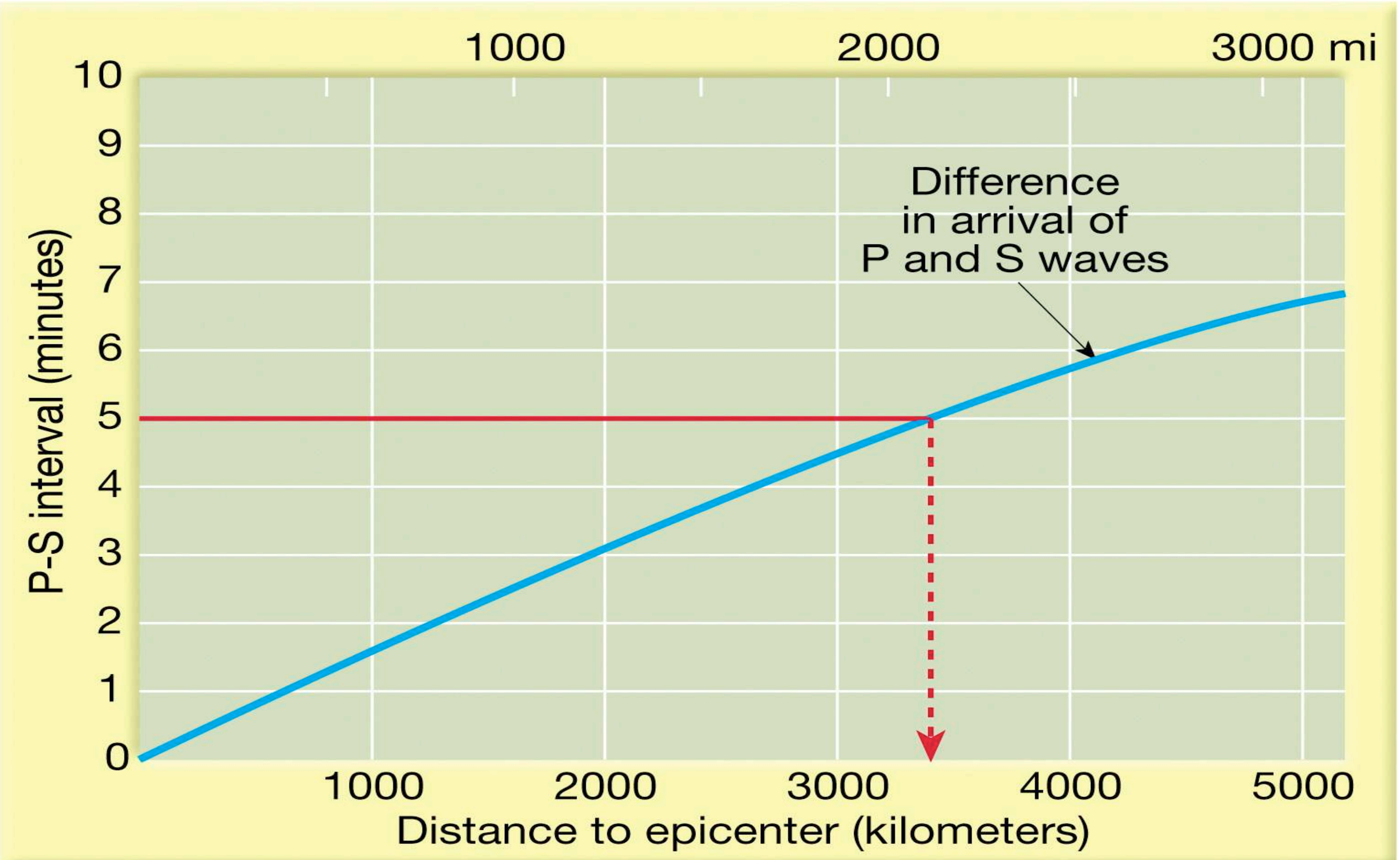
Seismogram



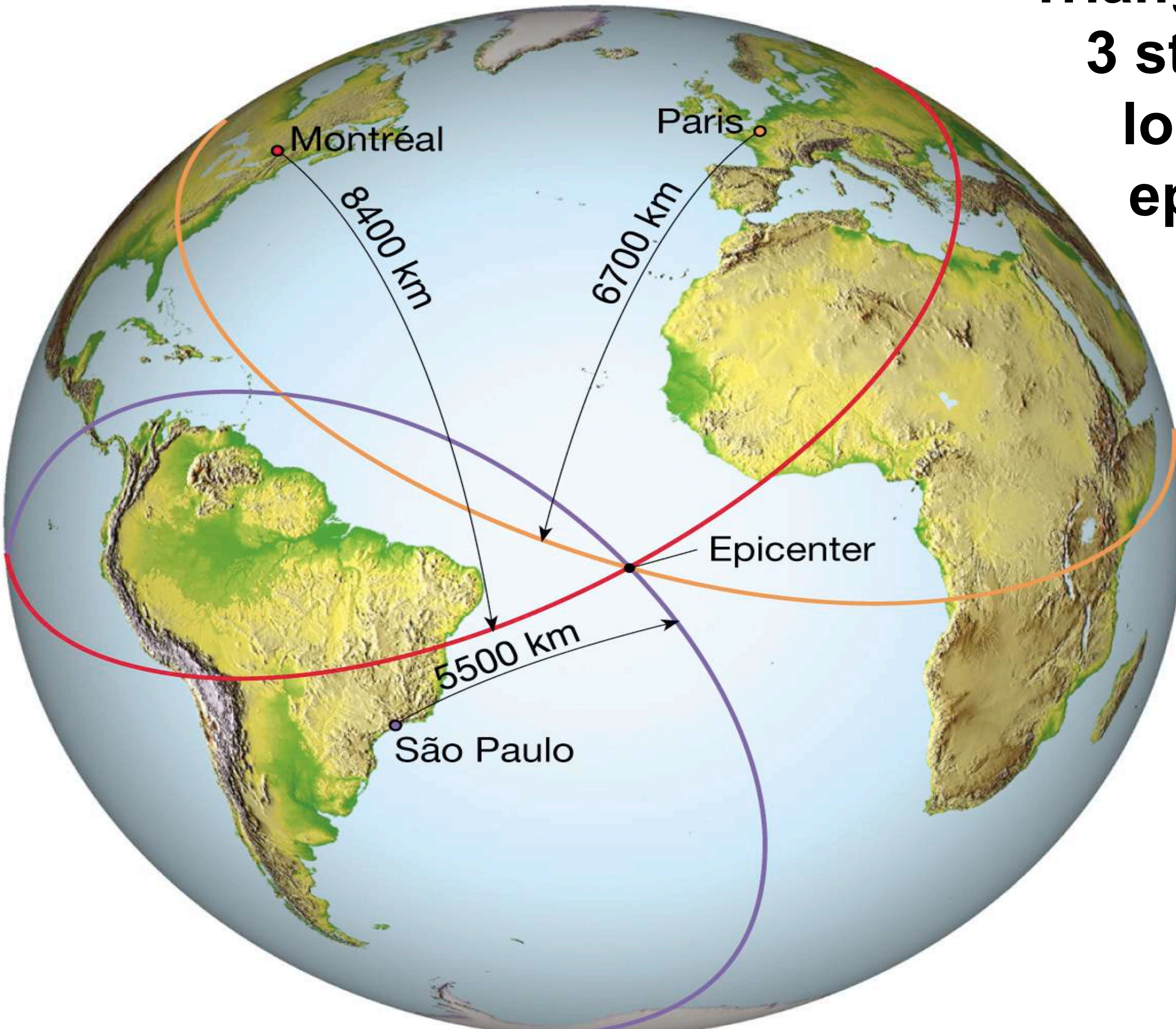
Tells you:

1) **How far away the earthquake occurred, based on the time difference between p and s –wave arrivals**
2) **Magnitude of ground motion, based on the amplitude of the surface waves**

The time interval between p and s-wave arrivals tells you how far away the epicenter is

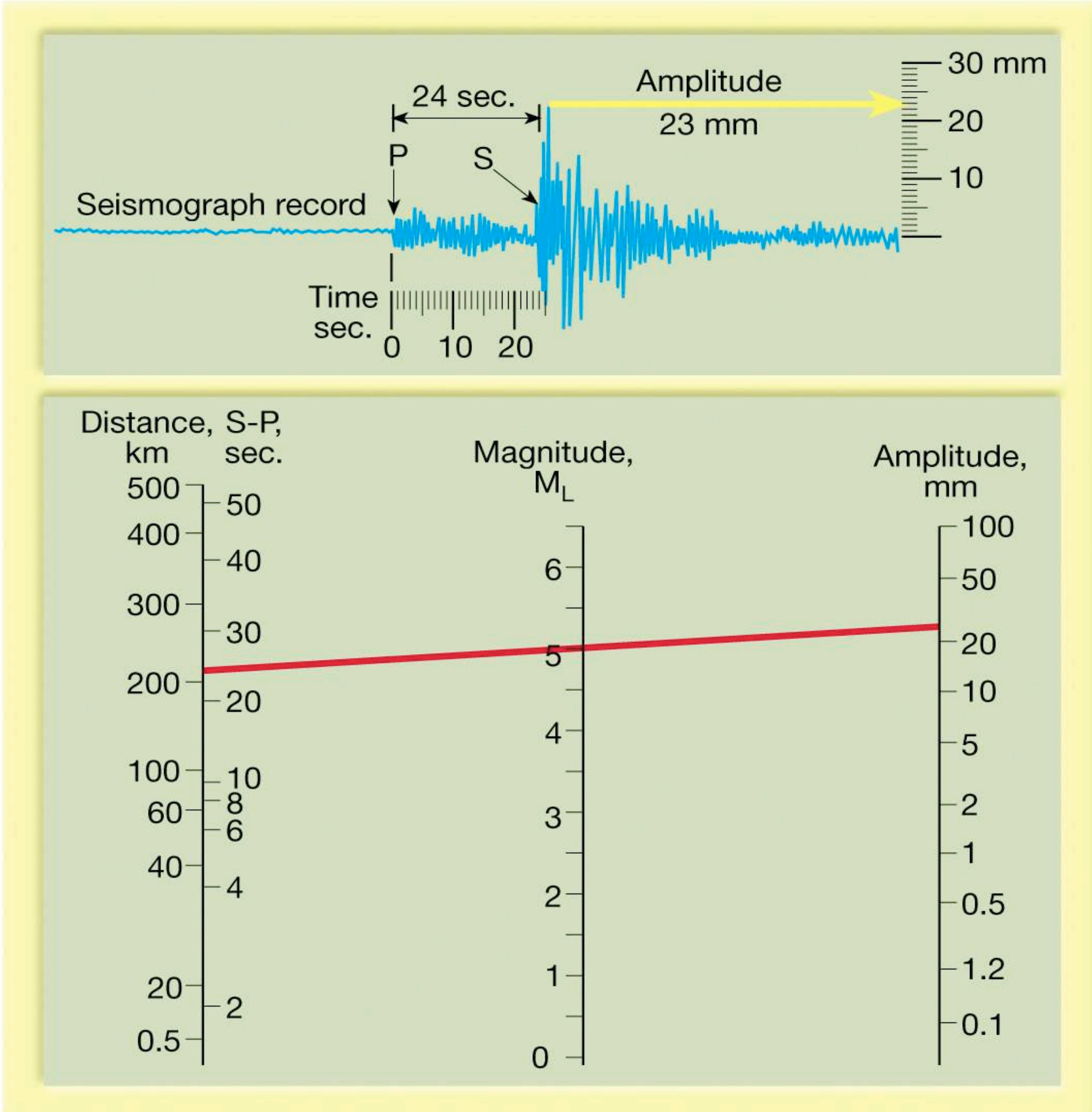


Triangulate from 3 stations to locate the epicenter

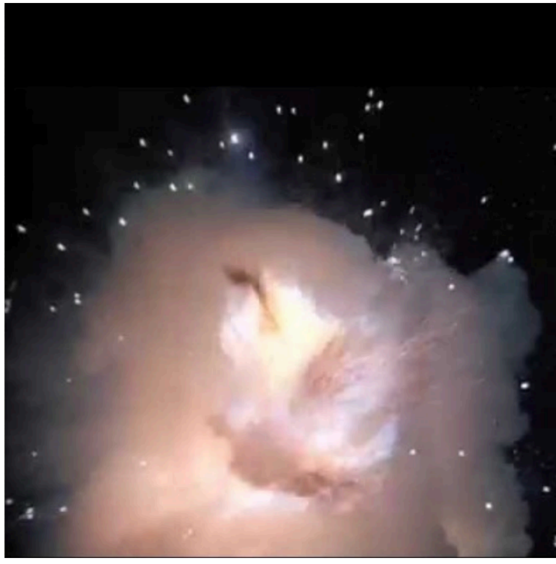


*Earthquake **magnitude** is related to the amount of energy released by the earthquake.*

*The **Richter magnitude M_L** is measured using the amplitude of the seismic waves. Another measure is called the **moment magnitude M_w***



- Richter Scale is log based and aims to scale the *energy* of the wave
- $M = \frac{2}{3}\log(E_1/E_0)$
  - $E_0 = 10^{4.4}$ J = "standard earthquake"
  - So a magnitude 18.6 earthquake releases $E_1 = 2.0 \times 10^{32}$ J, which is the gravitational binding energy of the Earth
  - The Death Star caused a M= 18.6 earthquake on Alderaan



- Your cell phone falling off the desk will hit the ground with about 1.2 J of energy. What magnitude earthquake will that create?
- $M = \frac{2}{3}\log(E_1/E_0)$

  $E_0 = 10^{4.4}$ J