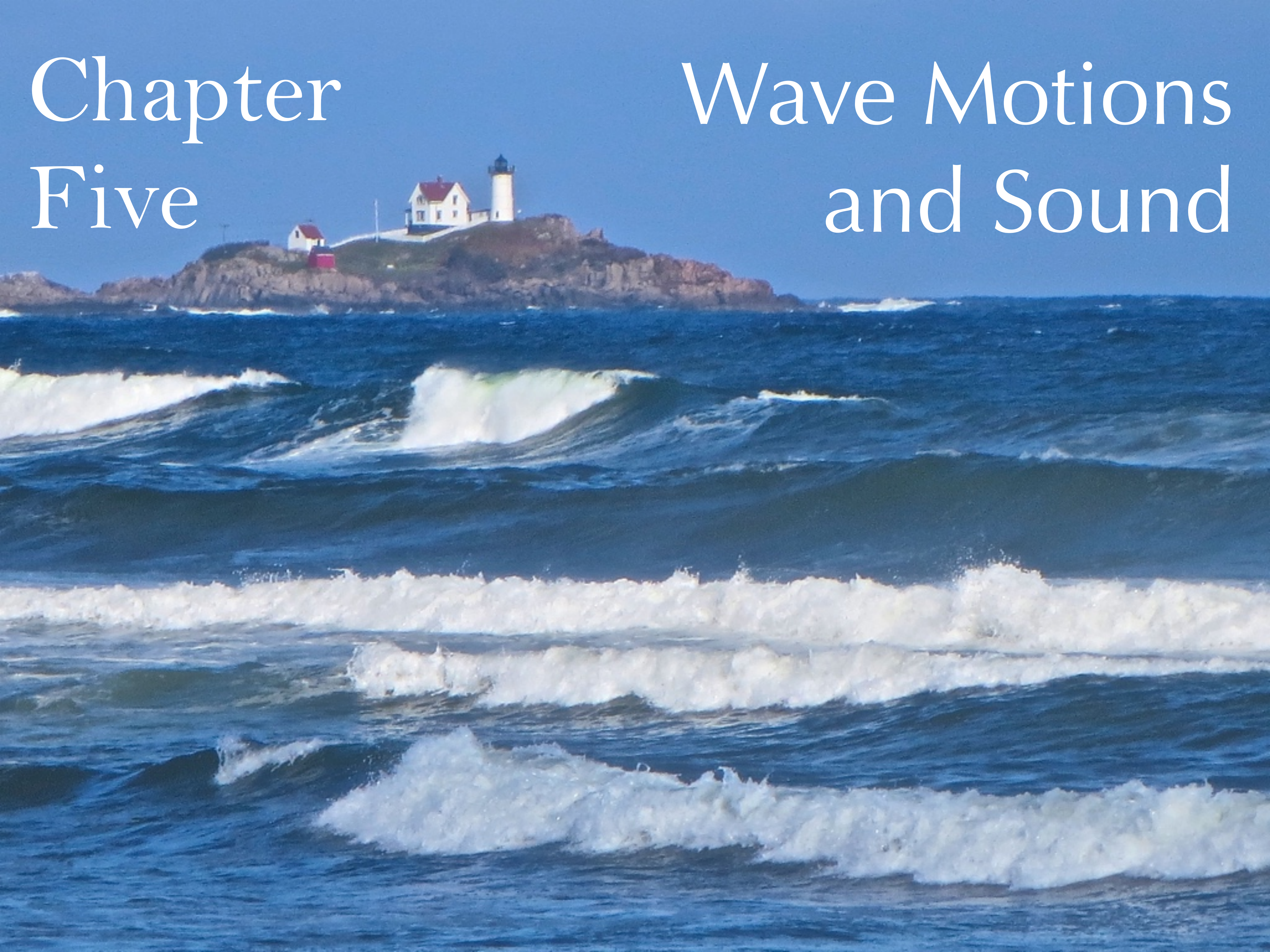
Chapter Five

Wave Motions and Sound



Section 5.1

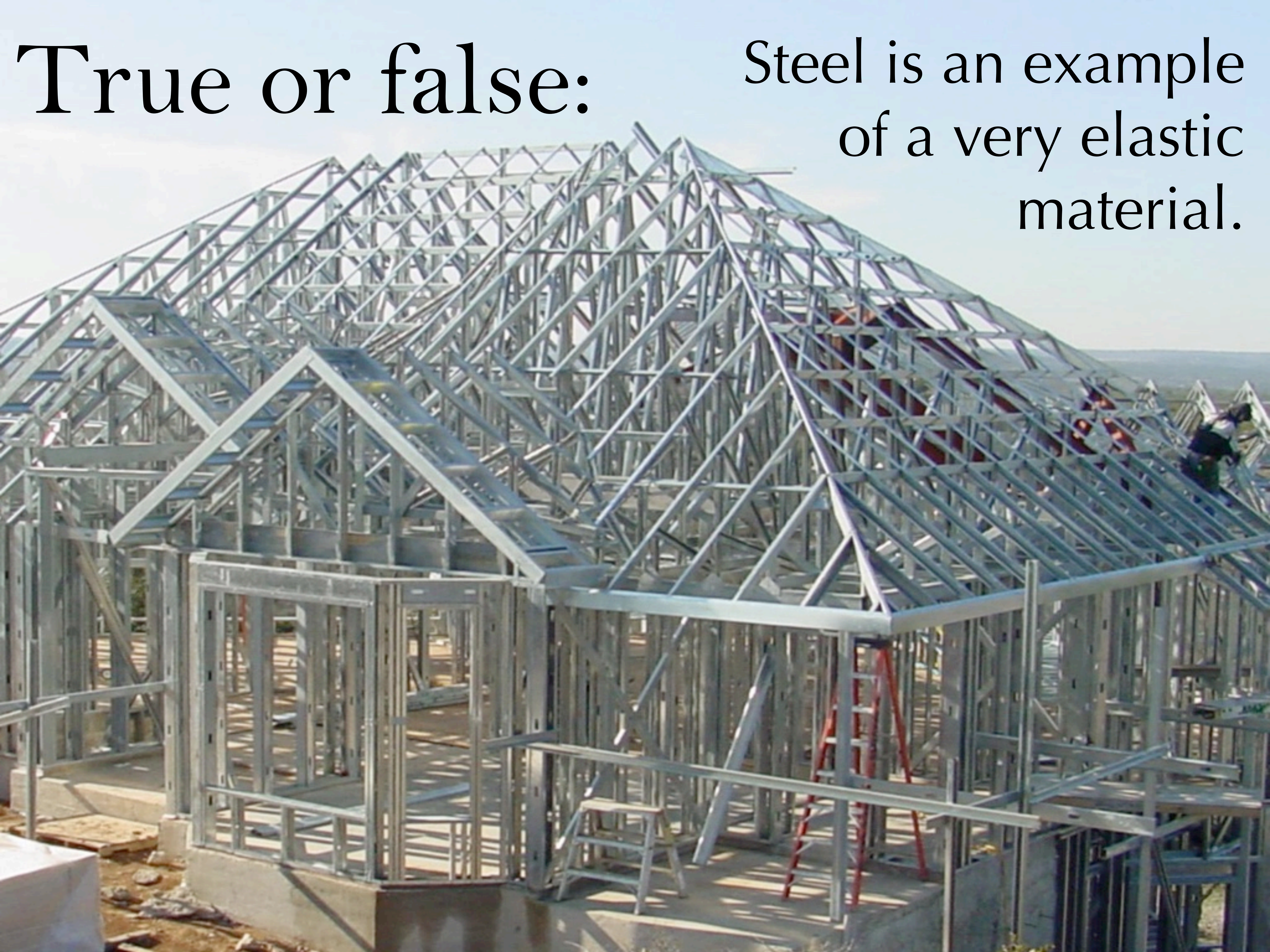
Forces and Elastic Materials

Elasticity

- It's not just the stretch, it's the snap back
- An elastic material will return to its original shape when stretched
- An inelastic material will either break (brittle like glass) or remain deformed (plastic like putty)

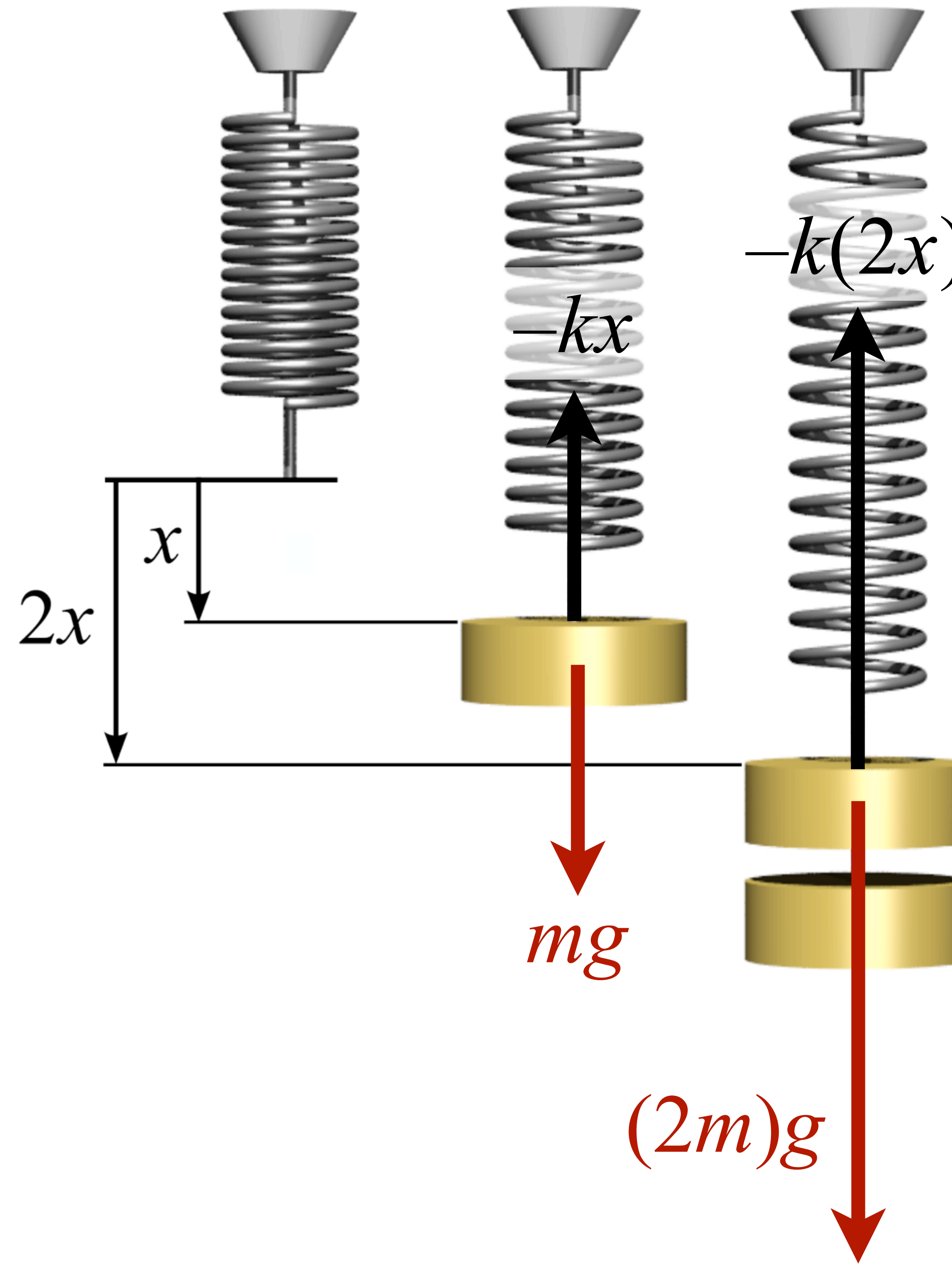
True or false:

Steel is an example of a very elastic material.



Hooke's Law: $F = -kx$

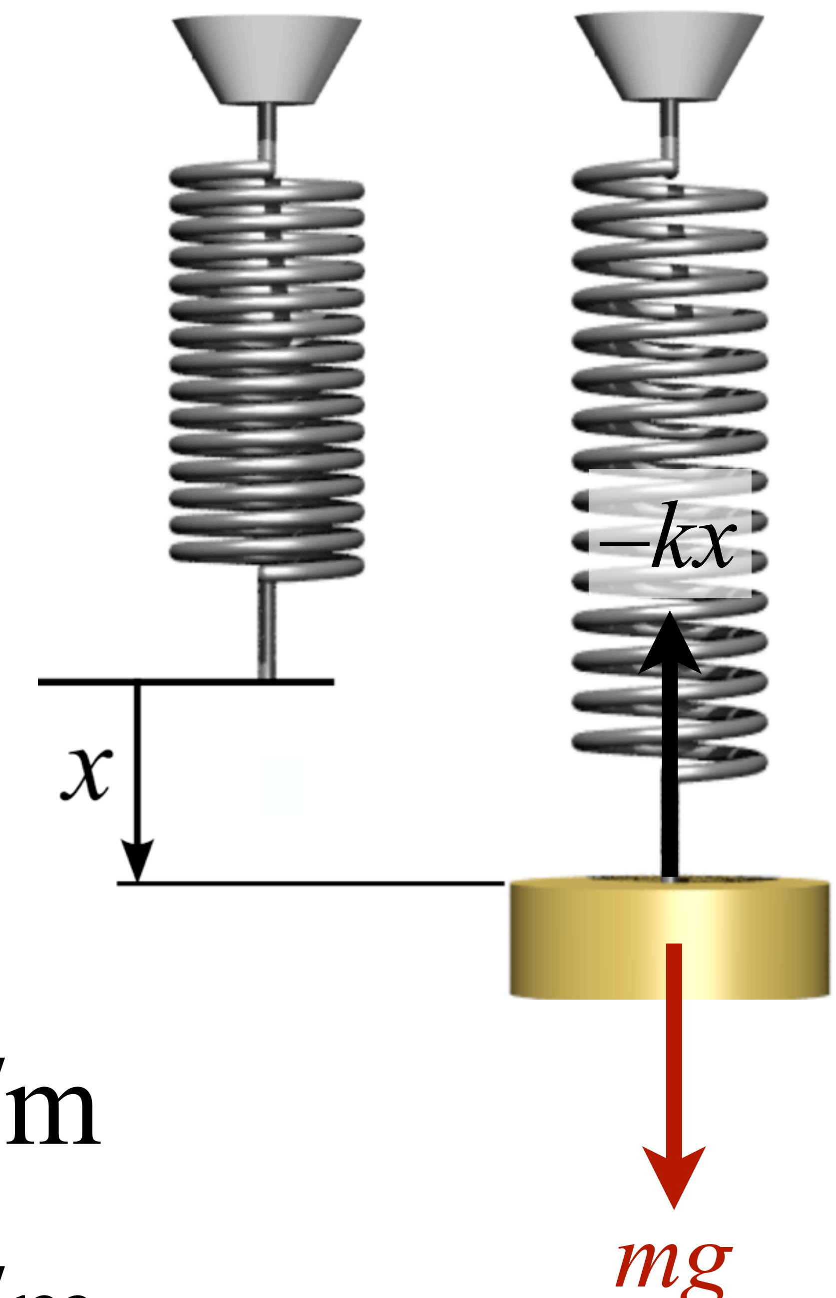
- F (N): Force exerted by the spring
- k (N/m): Stiffness of spring (higher k, harder to stretch)
- x (m): Amount by which spring is stretched
- Negative: Spring pushes or pulls in the direction opposite its displacement



A mass m=5kg stretches a spring by 6cm (x=0.06m). What is the spring constant k?

$$\sum F = 0 \Rightarrow mg - kx = 0$$

$$k = \frac{mg}{x} = \frac{(5\text{kg})(9.8\text{m/s}^2)}{(0.06\text{m})}$$



A) $k = 0.06$ N/m

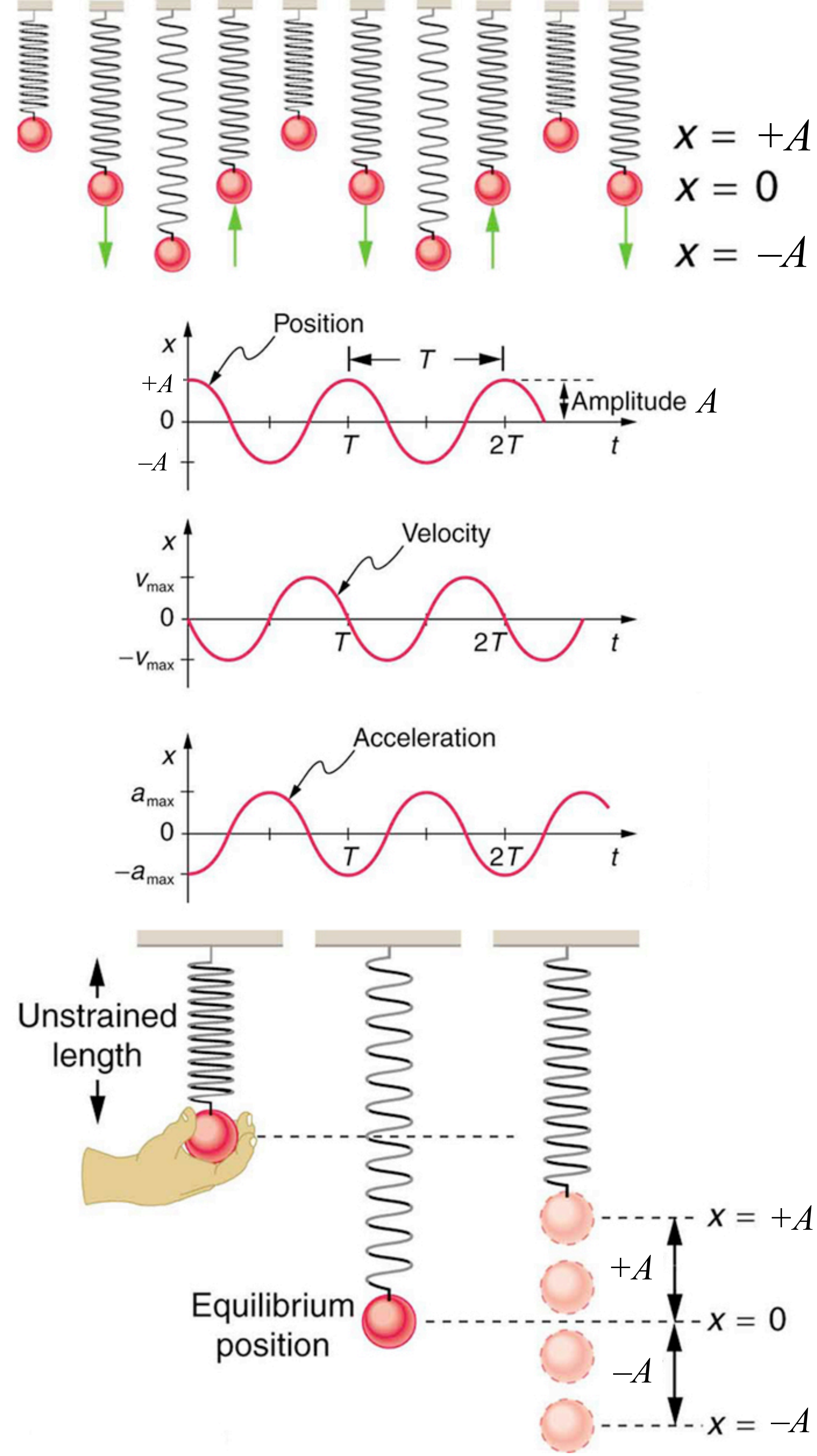
B) $k = 0.30$ N/m

C) $k = 2.94$ N/m

D) $k = 5$ N/m

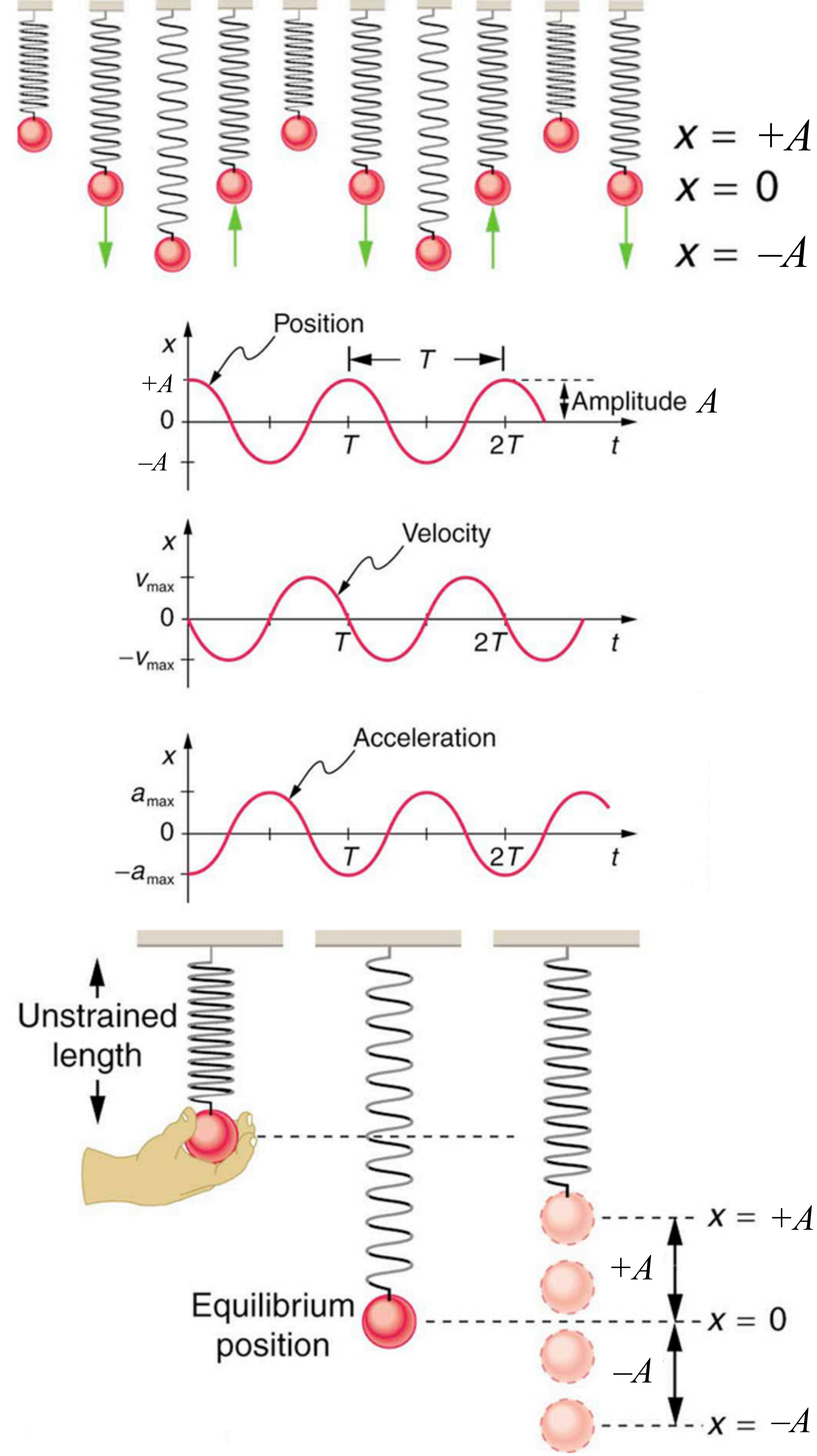
E) $k = 294$ N/m

F) $k = 817$ N/m



Forces and Vibrations

- Vibration or oscillation? Meh, this time they really are interchangeable
- Back-and-forth (up-down, side-to-side, whatever) motion: You keep doing it, but you don't actually get anywhere
- Periodic refers to the repeat: Same pattern, same amount of time



Describing Vibrations

- **Amplitude** (m): A = maximum displacement from equilibrium
- **Cycle** (no units): One full pattern of repetition (back to where you started, ready to repeat the whole thing over again)
- **Period** (s): T = time to complete one full cycle
- **Frequency** (1/s=Hz): f = cycles completed per second ($f = 1/T$)

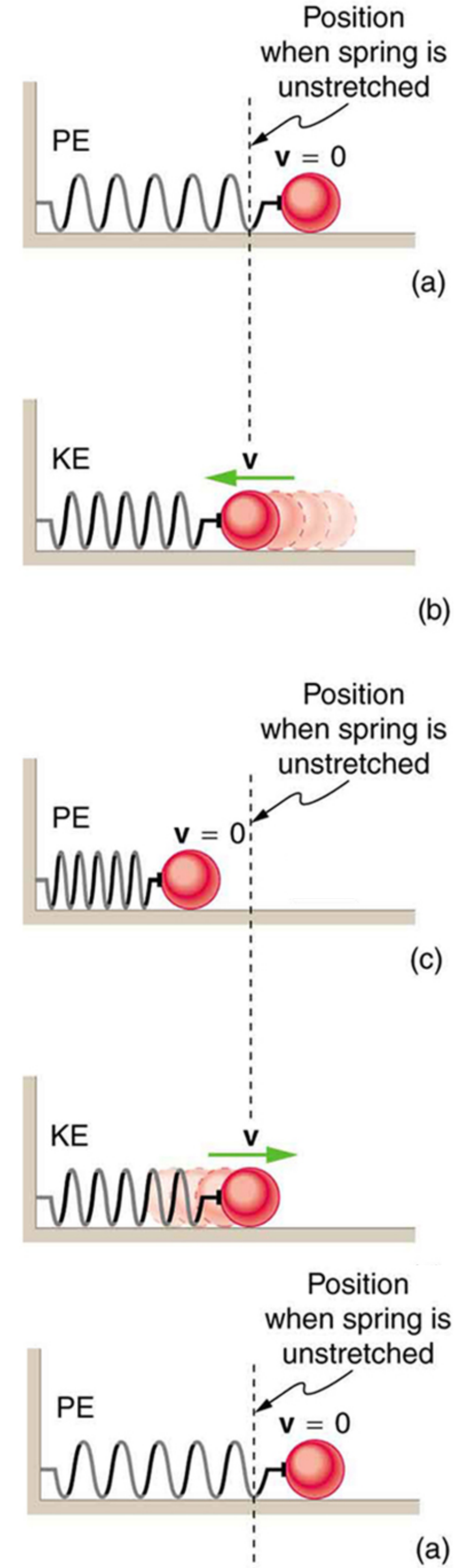
The mass shown is attached to a spring, and completes one full cycle of oscillation every 1.25 seconds.

Calculate the frequency of the oscillation.

$$T = 1.25\text{s}$$

$$f = \frac{1}{T} = \frac{1}{1.25\text{s}}$$

$$f = 0.8\text{Hz}$$

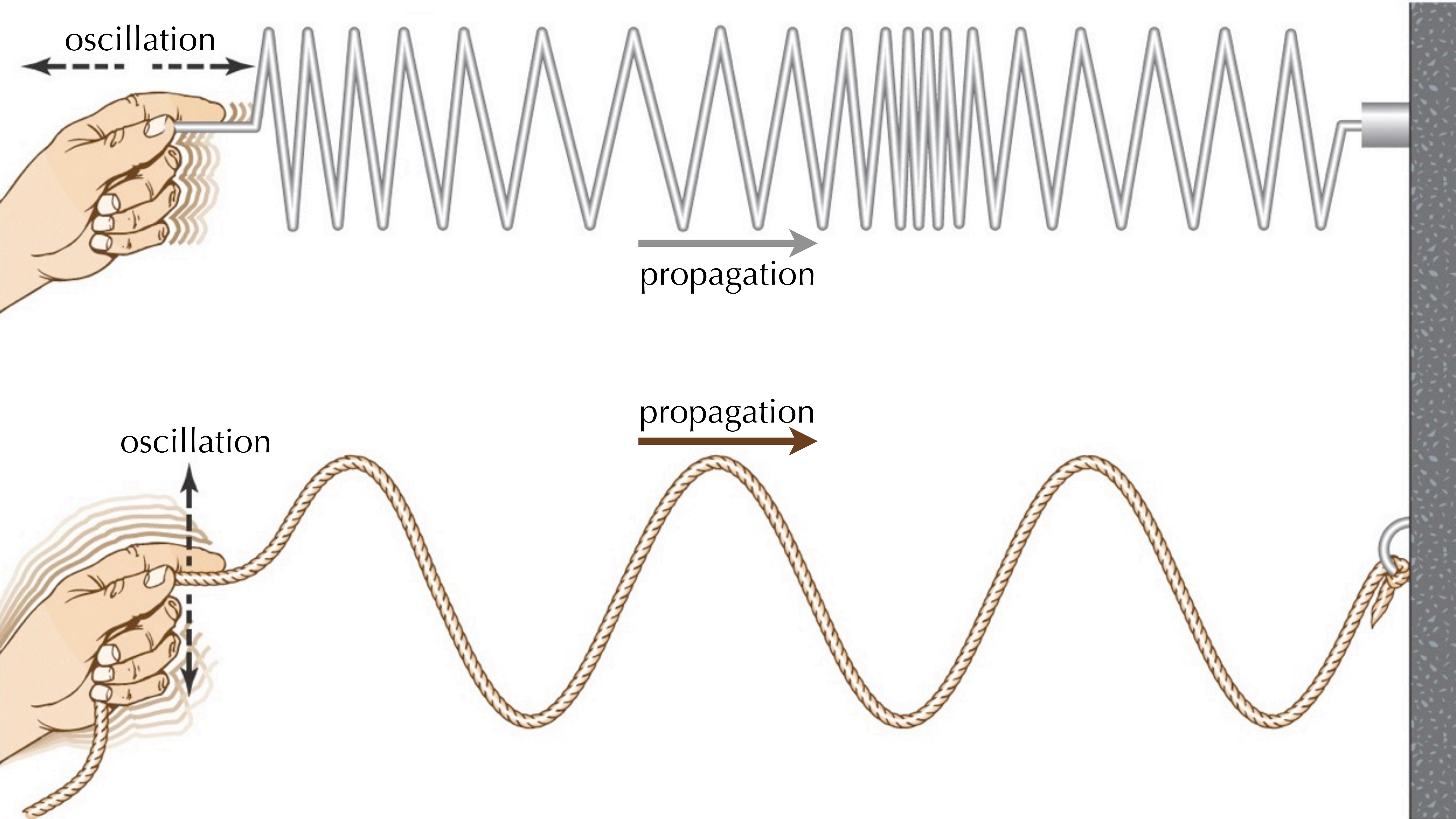


Section 5.2

Waves

What Makes It A Wave?

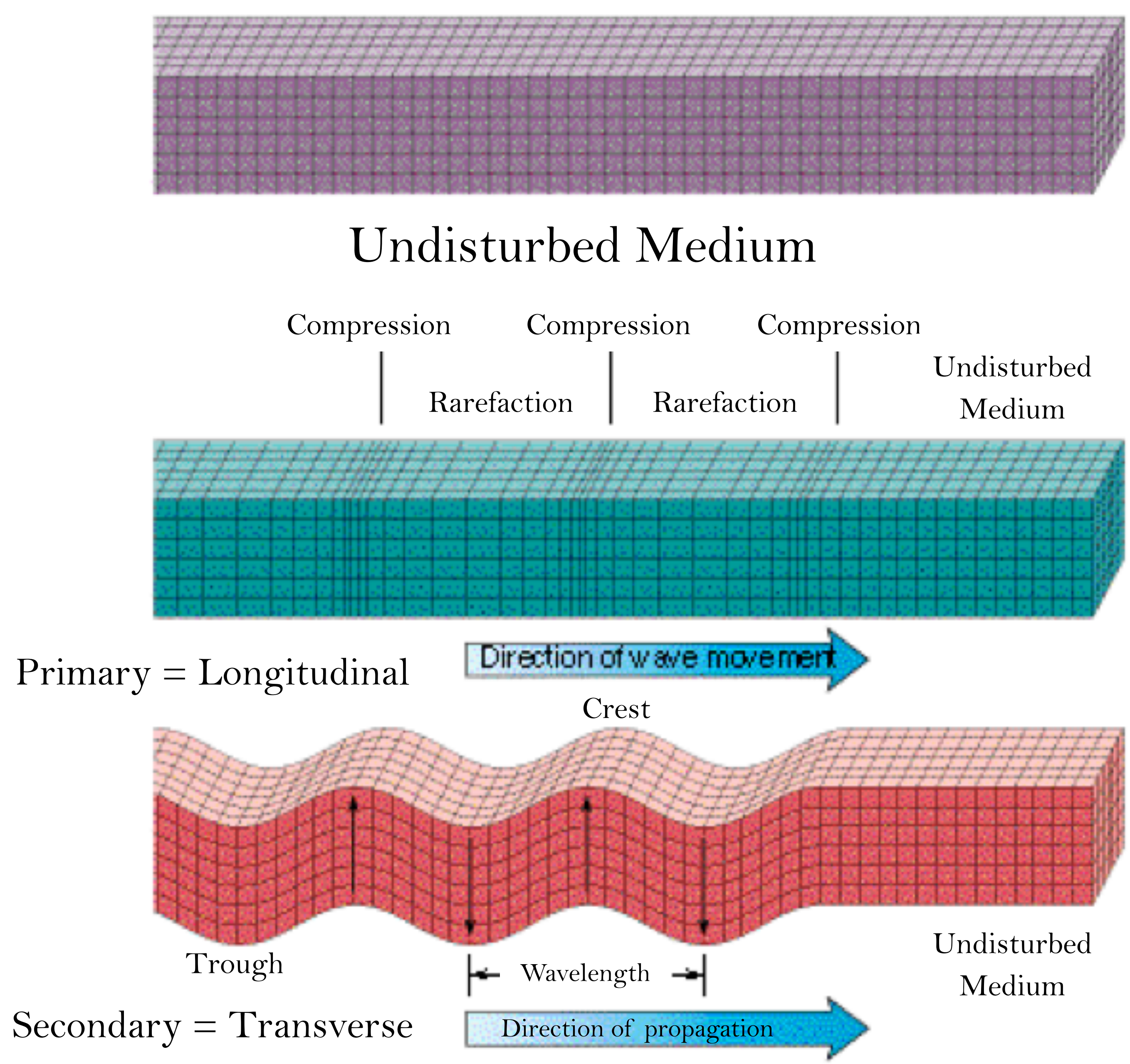
- Oscillation (vibration) by itself ≠ wave
- Propagation (forward motion) ≠ wave
- Oscillation + propagation = wave

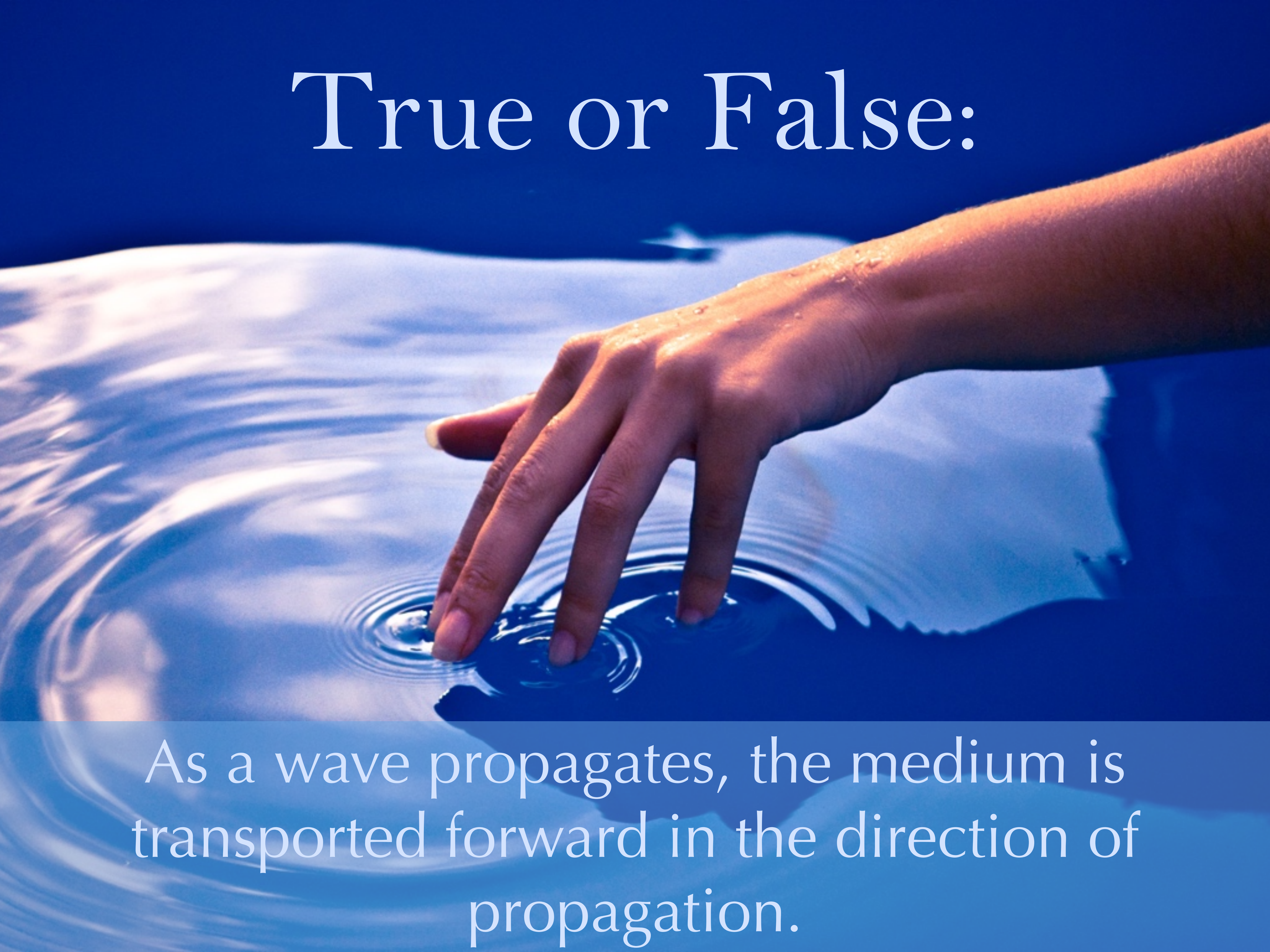


Kinds of Mechanical Waves

- **Longitudinal:** Oscillation is **parallel** to propagation
- **Transverse:** Oscillation is **perpendicular** to propagation

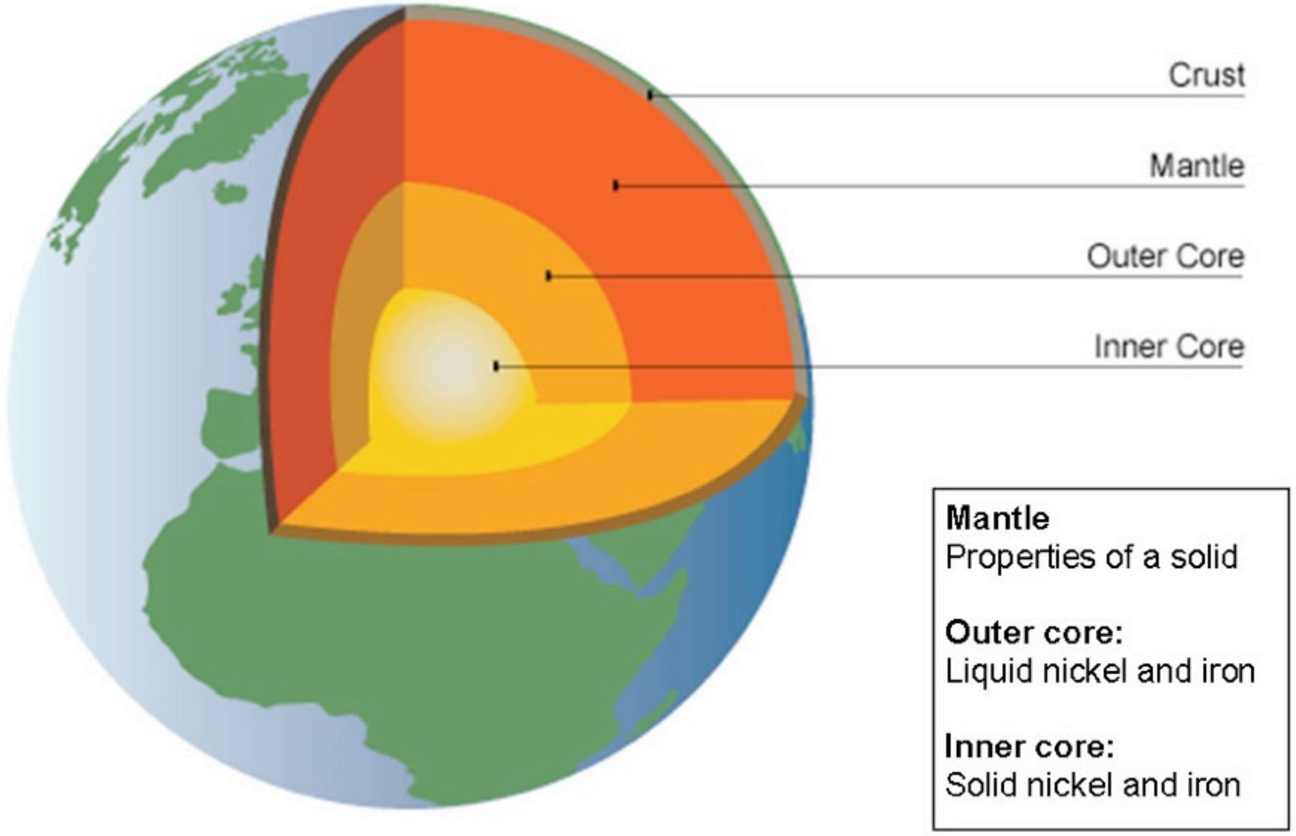
Seismic Waves



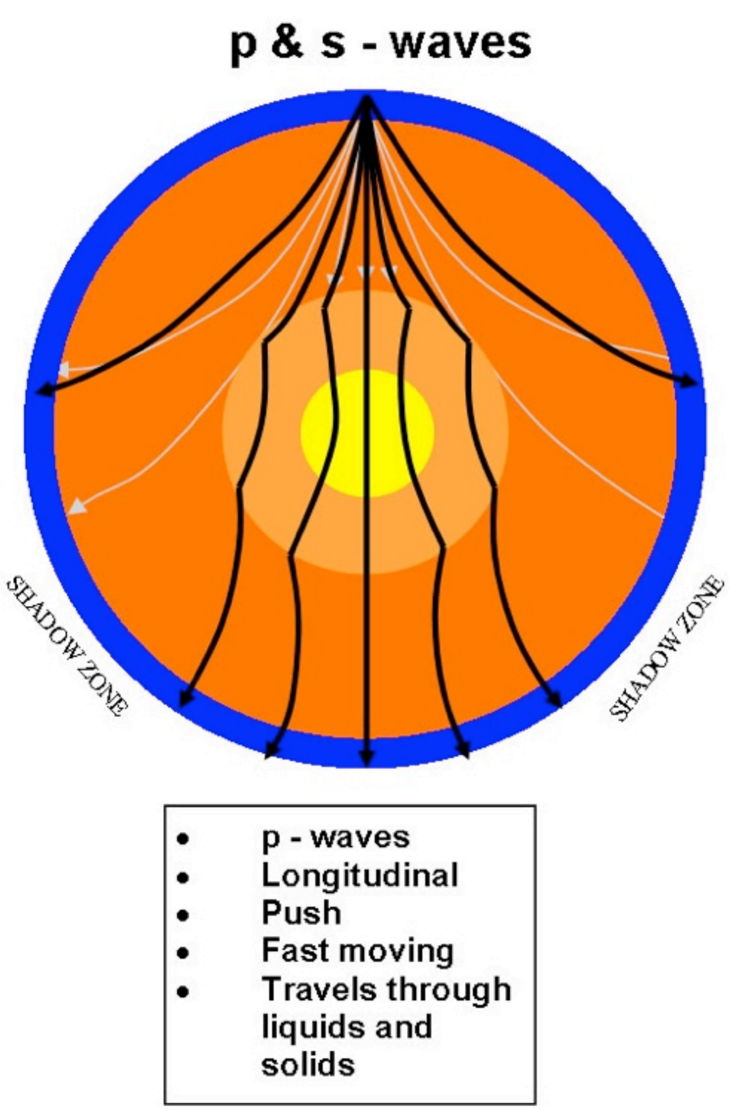

True or False:
As a wave propagates, the medium is transported forward in the direction of propagation.

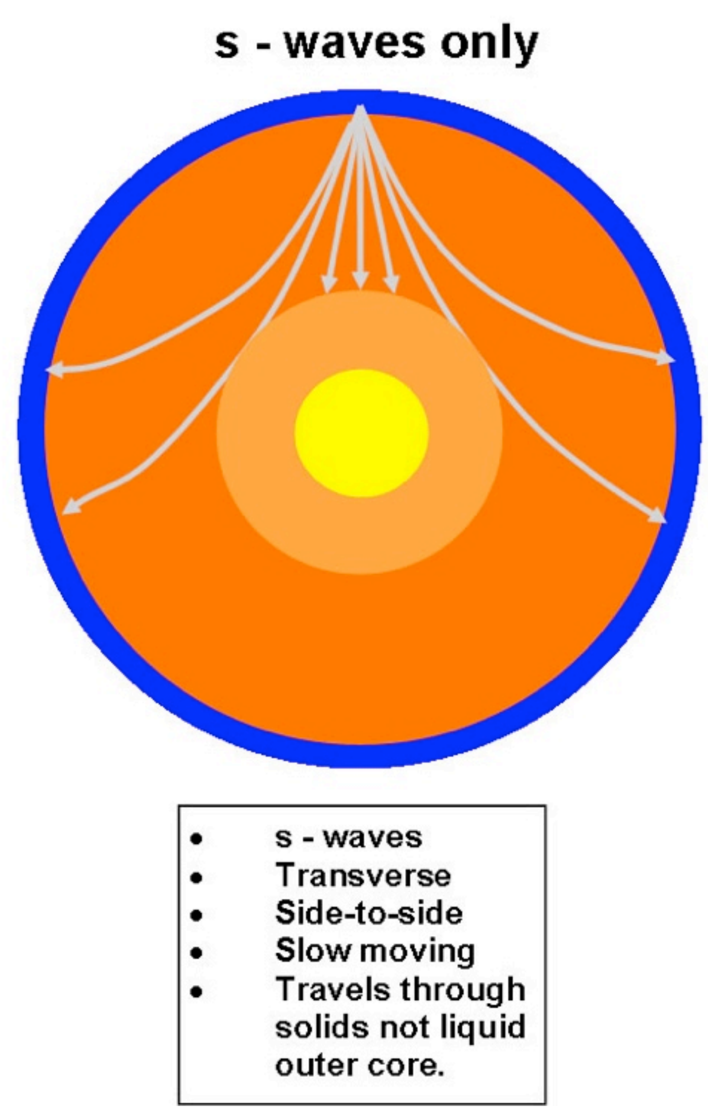
Propagation Through a Medium

- Most waves (not all!!!) require a medium to travel through
- Matter does not propagate! The energy propagates!
- Molecules vibrate, but do not propagate along with the wave



The Matter Matters





- **Solid:** Can transmit either longitudinal or transverse waves
- **Liquid:** Transmits longitudinal waves (only at surface can transverse propagate)
- **Gas:** Can only transmit longitudinal waves

Sound waves travel through the air. They must therefore be

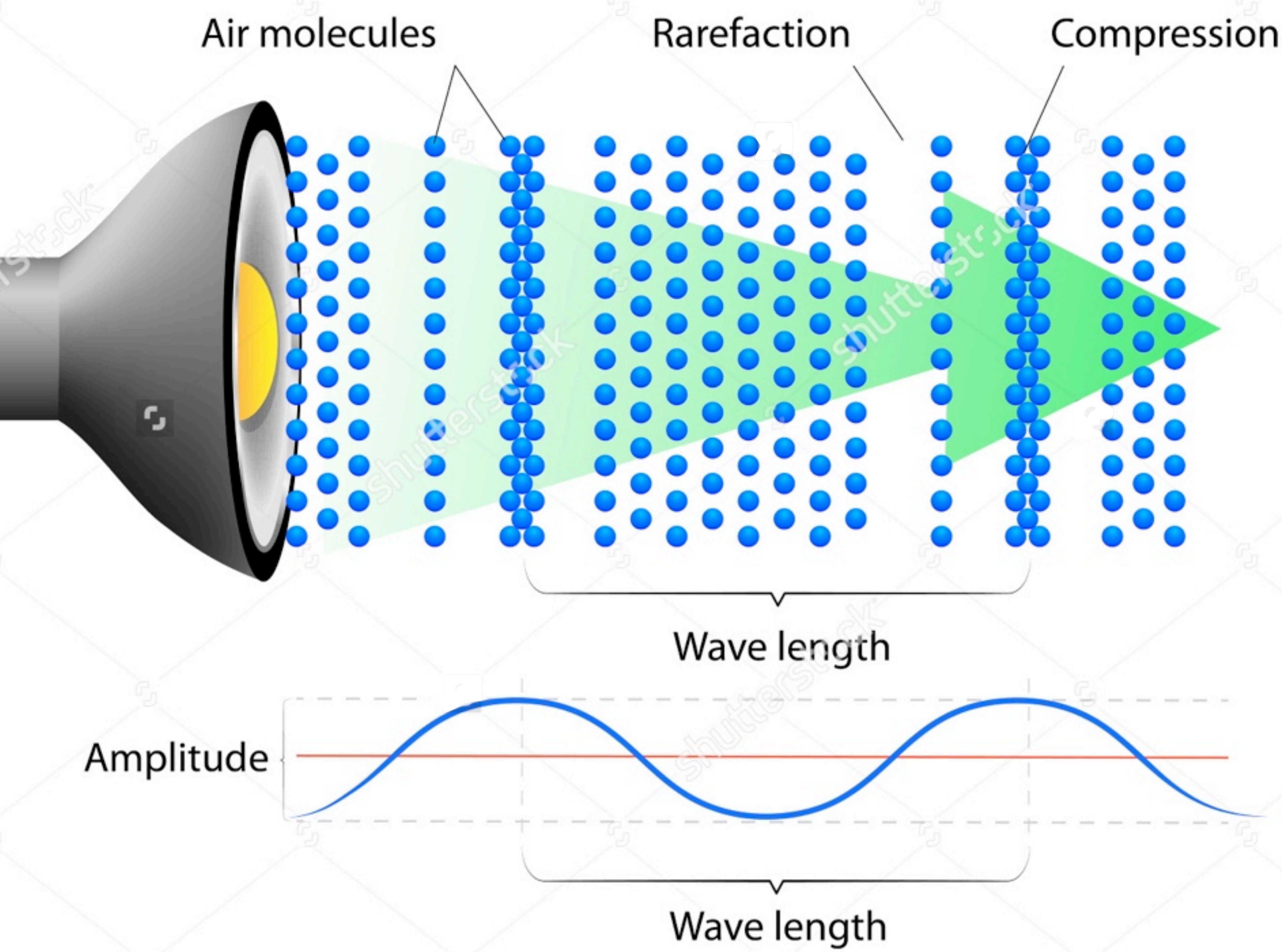
A) transverse.

B) longitudinal.

C) converse.

D) latitudinal.

Waves in Air



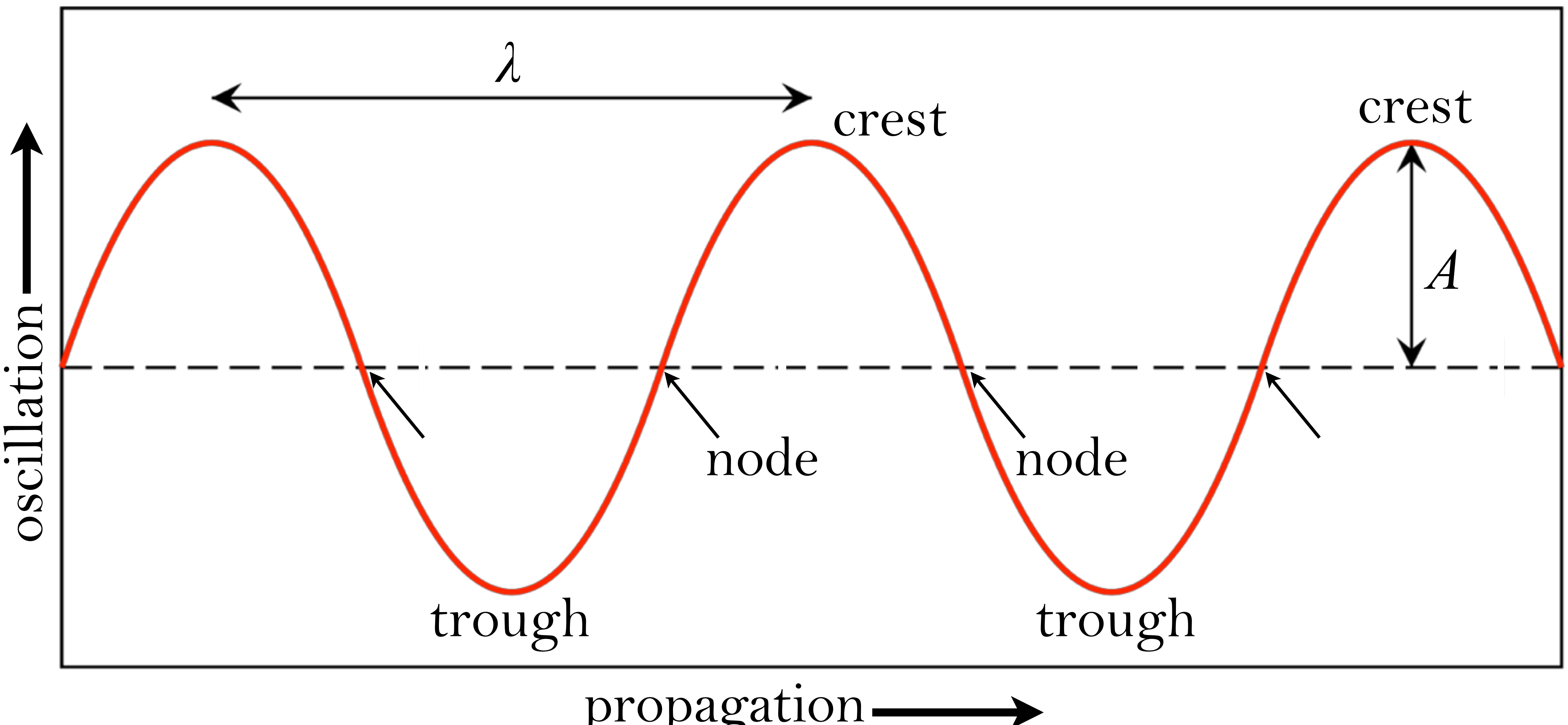
- Sound waves through air must be longitudinal
- Air molecules vibrate, but do not translate
- Compression (condensation): Molecules of the medium get slightly closer together than average (density increase)
- Rarefaction: Molecules of the medium get slightly farther apart than average (density decreases)

Section 5.3

Describing Waves

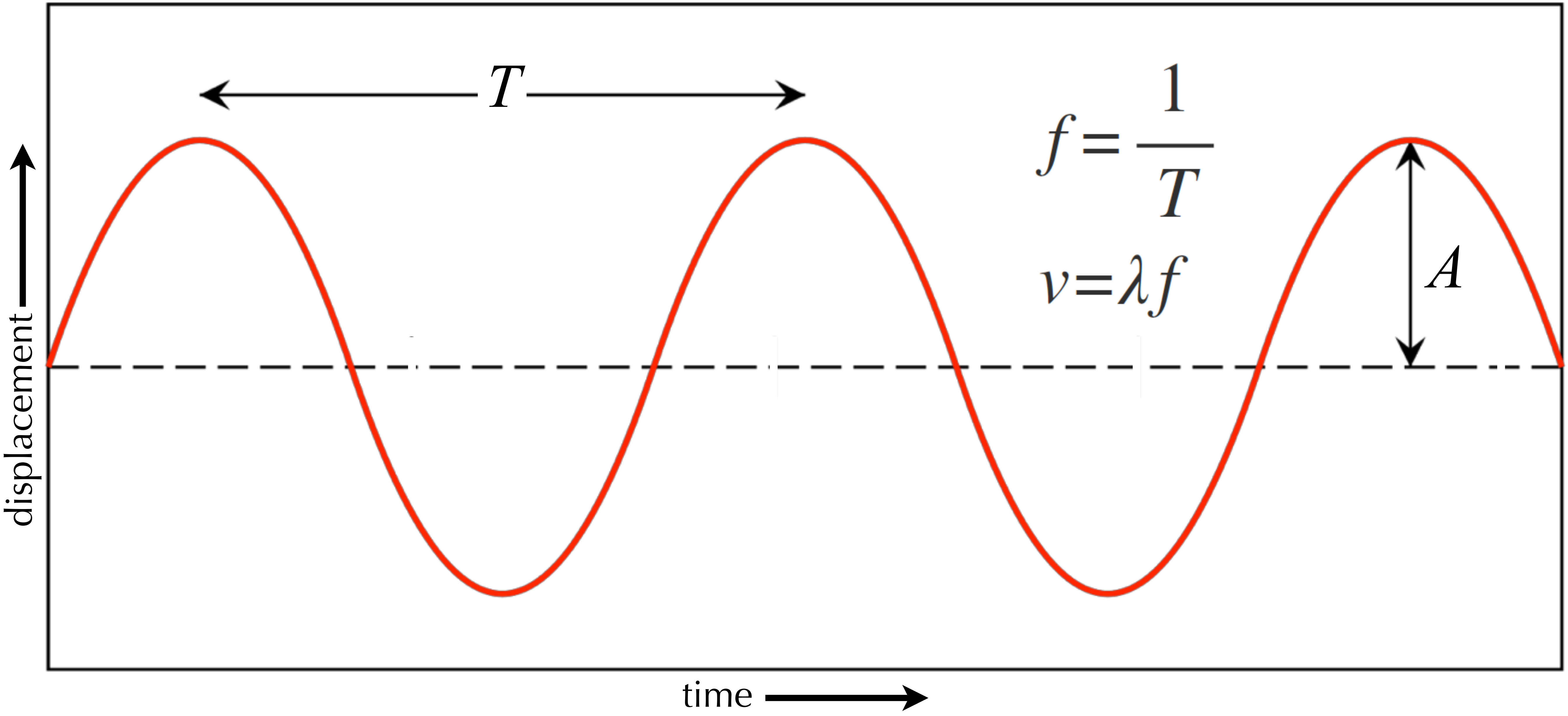
Parts of A Wave

- **Amplitude** (m): A = height of the crest or depth of the trough
- **Wavelength** (m): λ = distance crest–crest (compression–compression) or trough–trough (rarefaction–rarefaction)
- **Period** (s): T = time to complete one cycle of oscillation
- **Frequency** (Hz): f = cycles per second

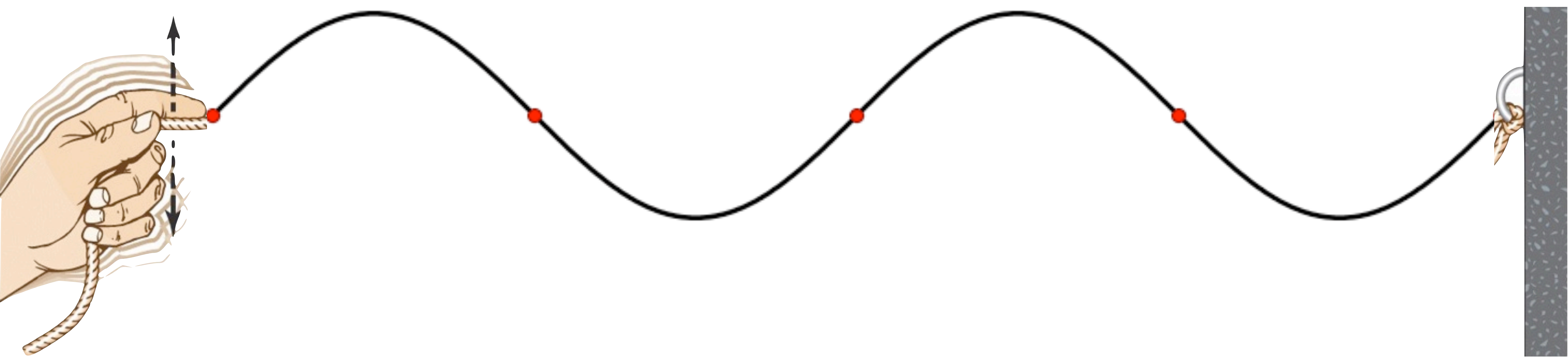


Motion of a Wave

- Frequency describes rate of oscillation
- Wave speed describes rate of propagation: distance/time = $v = \lambda/T$



You create a wave on a string by oscillating your hand with a frequency $f = 3$ Hz. The length of the string is 40cm ($l = 0.40$m), and you have exactly 2 complete wavelengths. What is the wave speed?



$\lambda = 0.20$m

$f = 3$Hz

$v = \lambda f$

A) 0.067 m/s

B) 0.20 m/s

C) 0.60 m/s

D) 1.2 m/s

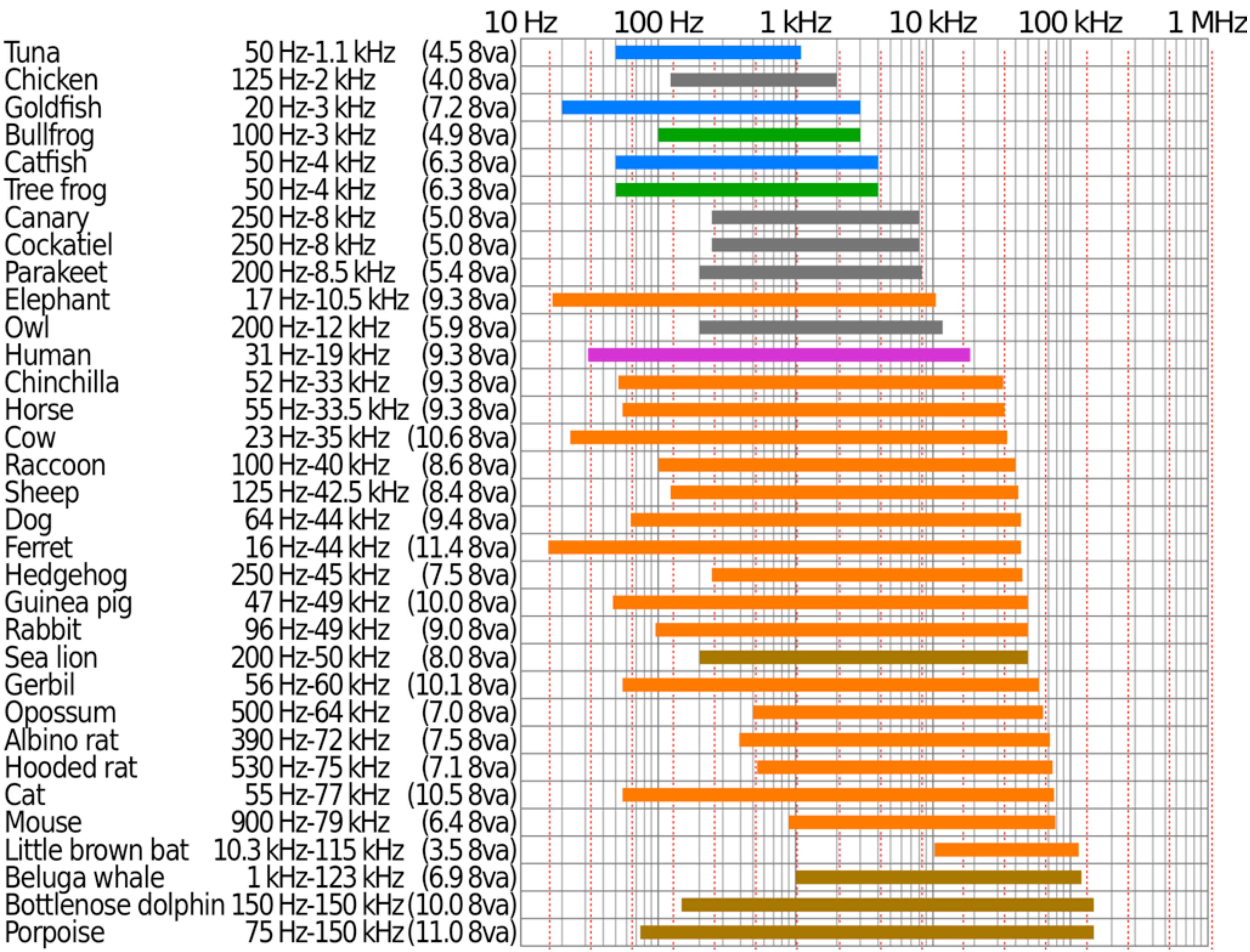
E) 3 m/s

F) 15 m/s

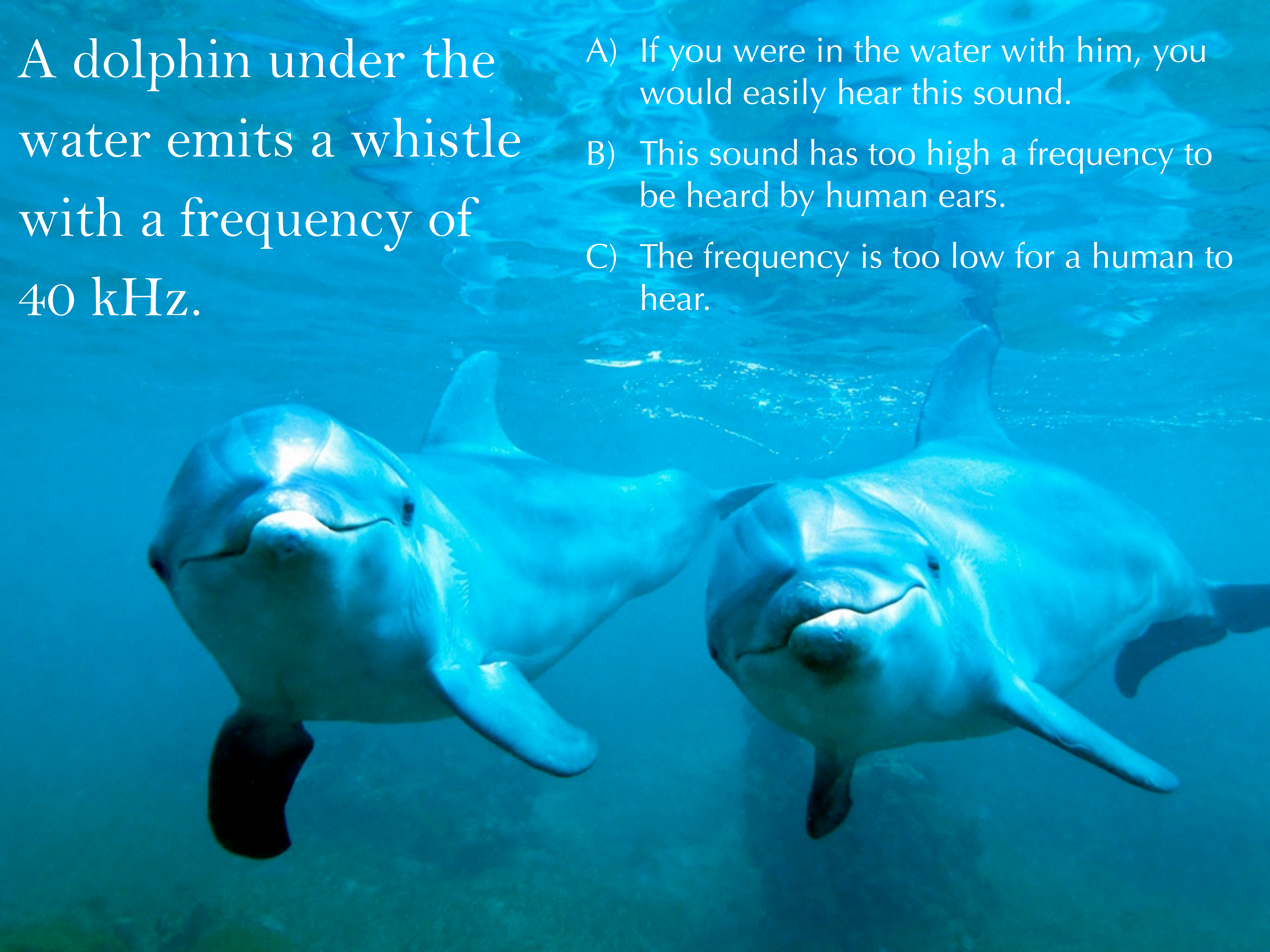
Section 5.4

Sound Waves

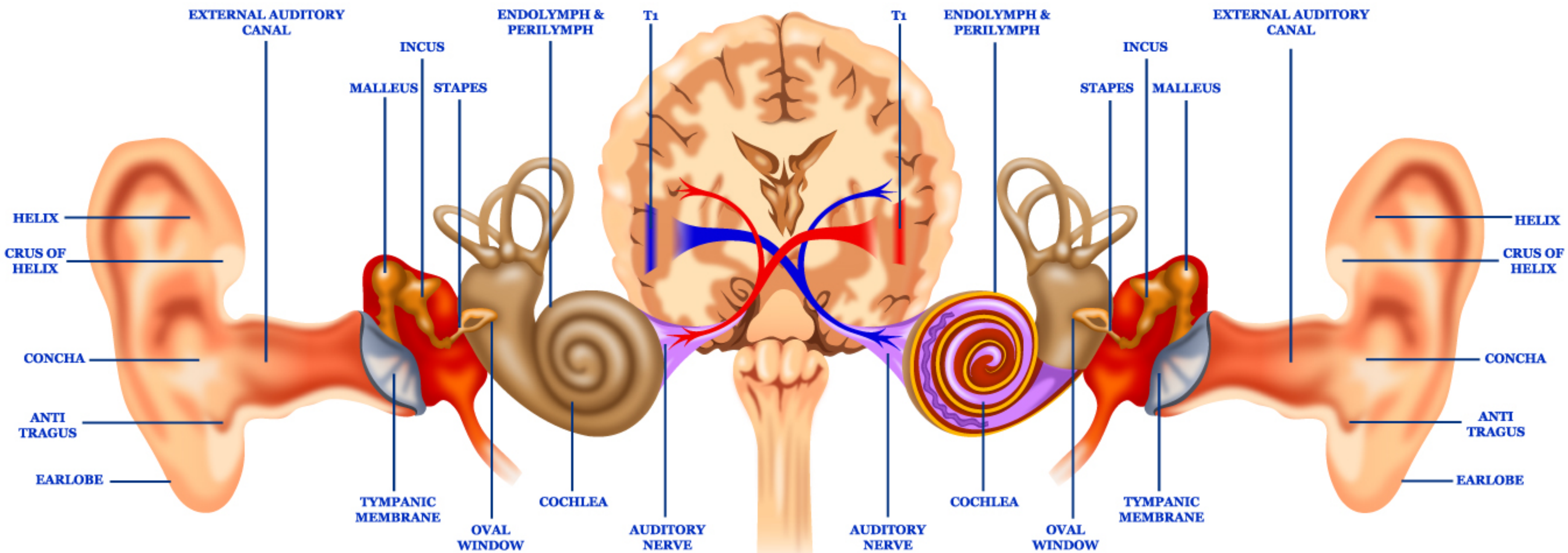
Sound Waves in Air and Hearing



- To be heard, a sound must have an audible frequency
- Human ears: Typically 20 Hz $\leq f \leq$ 20,000 Hz is the audible range
- **Infrasonic:** Frequency below human hearing ($f \lesssim$ 20 Hz)
- **Ultrasonic:** Frequency above human hearing ($f \gtrsim$ 20,000 Hz)


A dolphin under the water emits a whistle with a frequency of 40 kHz.
A) If you were in the water with him, you would easily hear this sound.
B) This sound has too high a frequency to be heard by human ears.
C) The frequency is too low for a human to hear.

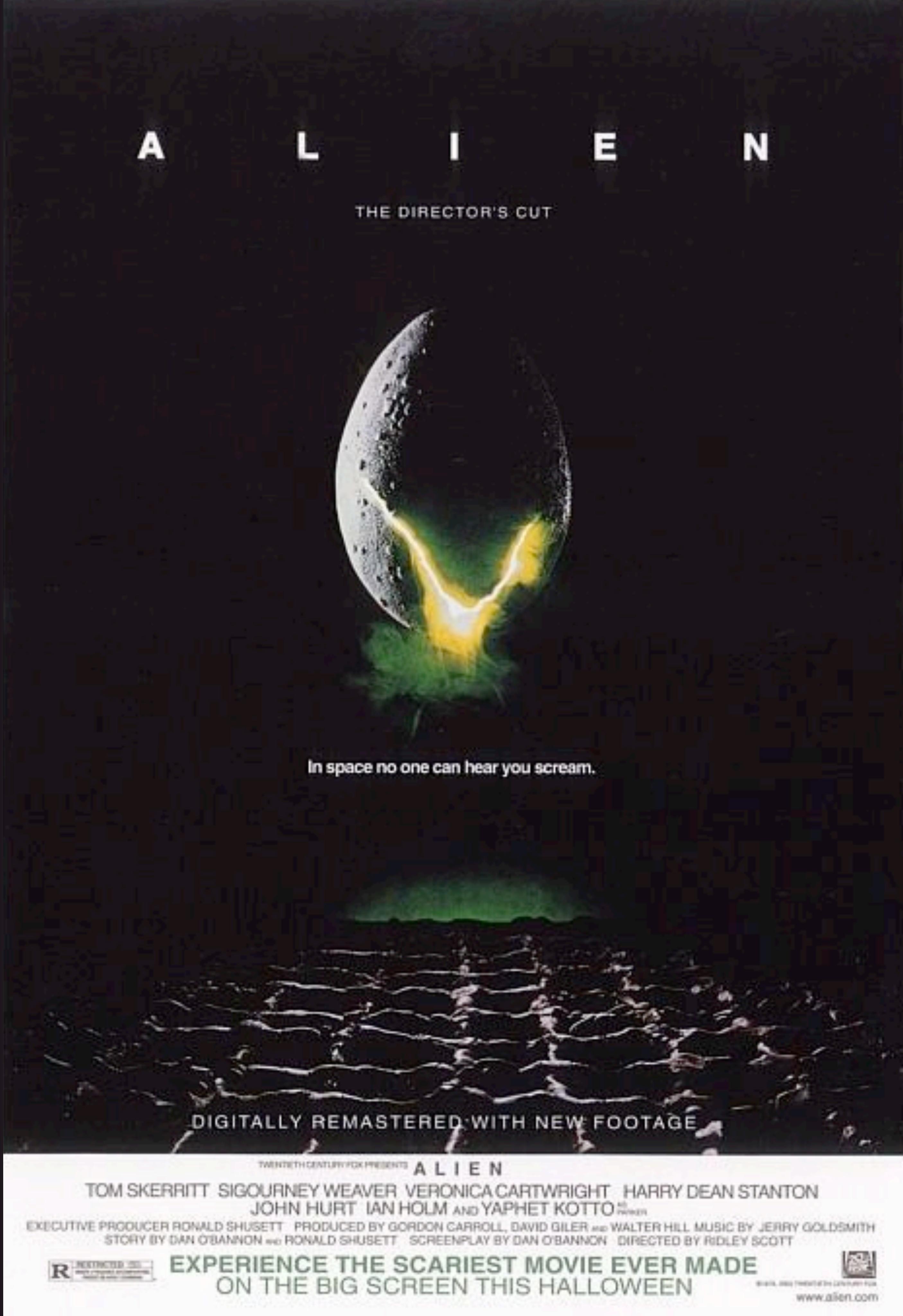
Different Person, Different Ears, But Same Mechanism



- You perceive a lower frequency sound as a lower pitch (higher f, higher pitch)
- Vibrating air molecules collide with your eardrum, set up mechanical vibration through the system
- Cochlea has tiny, tiny little hairs (cilia) which are tuned (length/thickness) for specific frequencies
- Damage the cilia, you lose those frequencies–forever (the cilia don't regenerate, can't be fixed)

True or False:

In space, no one can hear you scream.



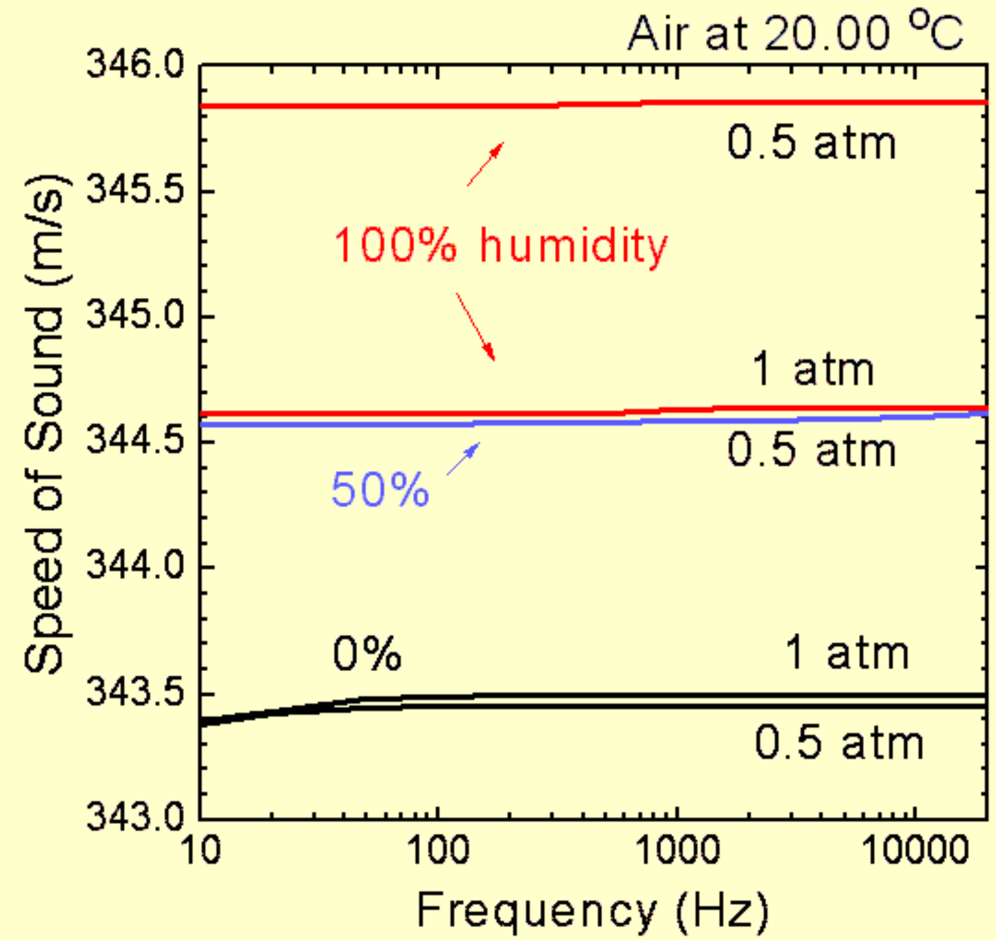
Medium Required

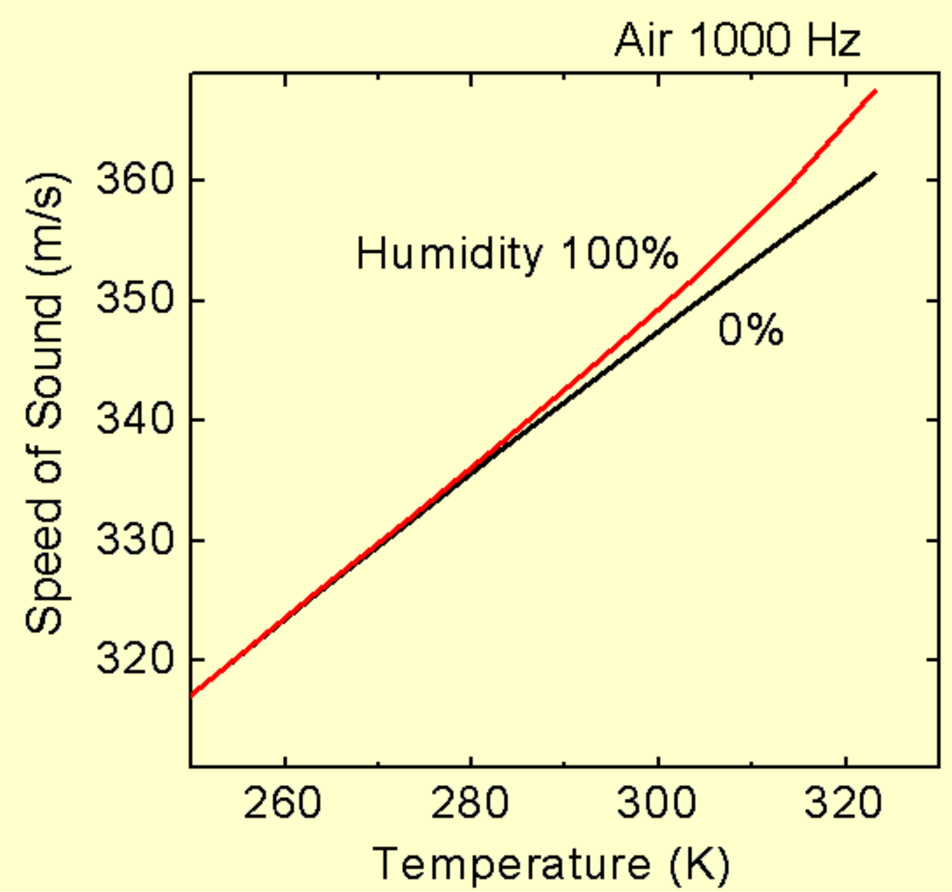
Material	Density (g/cm^3)	Temperature (°C)	Speed (m/s)
Solids			
Lead	11.3	20°	1960
Steel	7.9	20°	5960
Copper	8.9	20°	4600
Aluminum	2.7	20°	5100
Beryllium	1.9	20°	12890
Pyrex	2.2	20°	5640
Liquids			
Water	1	25°	1493
Glycerol	1.26	25°	1904
Kerosene	0.81	25°	1324
Methanol	0.79	25°	1143
Ethanol	0.79	25°	1207
Gases			
Air	0.00139	0°	331
Air	0.00139	20°	343
Hydrogen	0.0000899	0°	1286
Helium	0.000178	0°	972
CO_2	0.00198	0°	258

- Sound waves are matter waves: They cannot travel through vacuum, there must be molecules of something to propagate the energy
- Different medium, different speed
- Fluids: Less massive molecules mean faster speeds, given the same amount of energy
- Solids: Elasticity is much more important than density for rapid propagation

Velocity of Sound In Air

- Speed of sound = 331 m/s (but only if it's dry air at 0°C)
- Warm air is fast air: Warm air molecules are already moving faster than cold air molecules ($v = 331 + 0.6T$)
- Humid air is fast air: Water molecules are less massive than air molecules, so they are faster

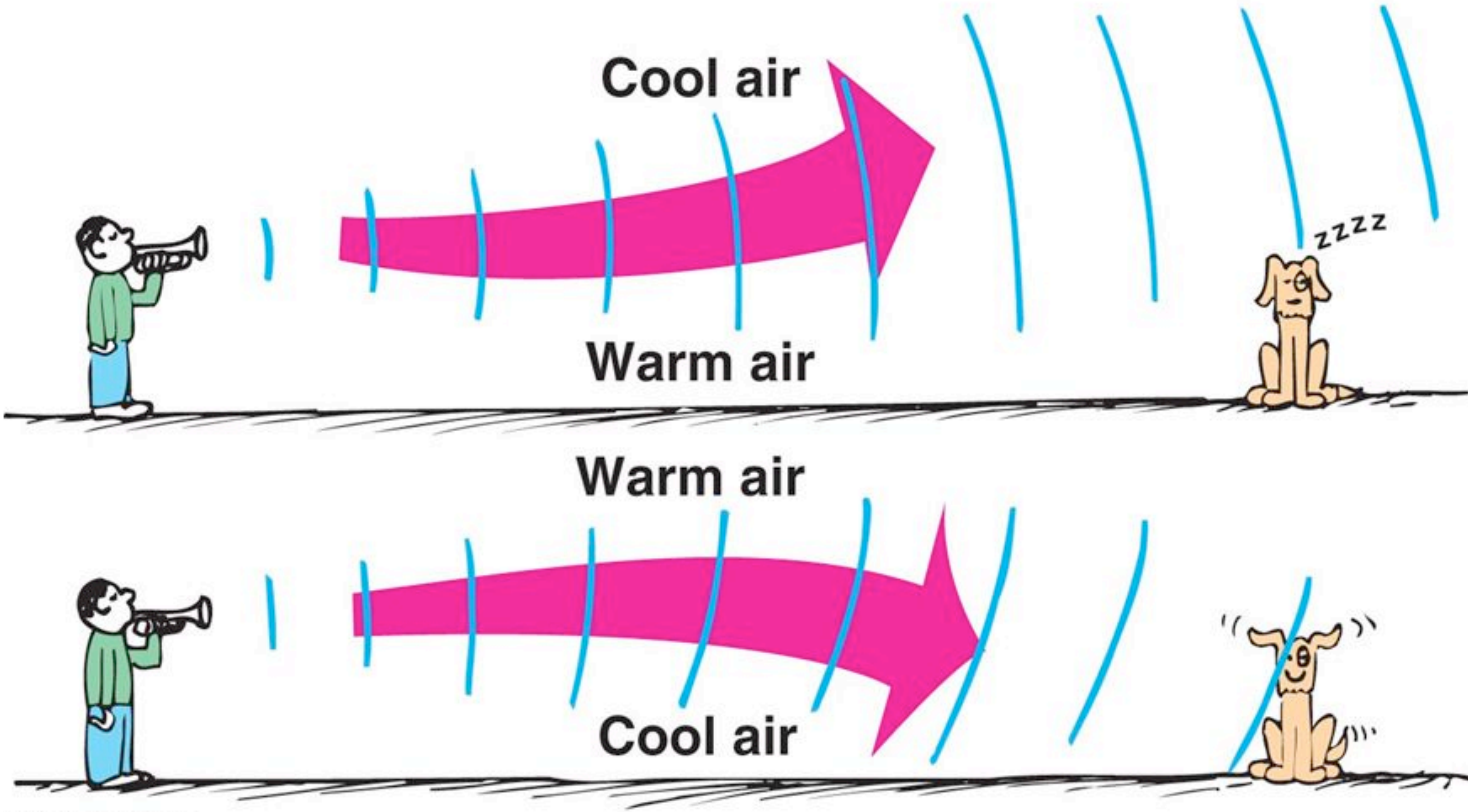




Reflection and Refraction

- What happens when a sound wave runs into an obstacle?
- An obstacle in this sense means a change in medium, like warm to cold air, or air to water, or air to solid matter
- Absorption, transmission, reflection

Refraction



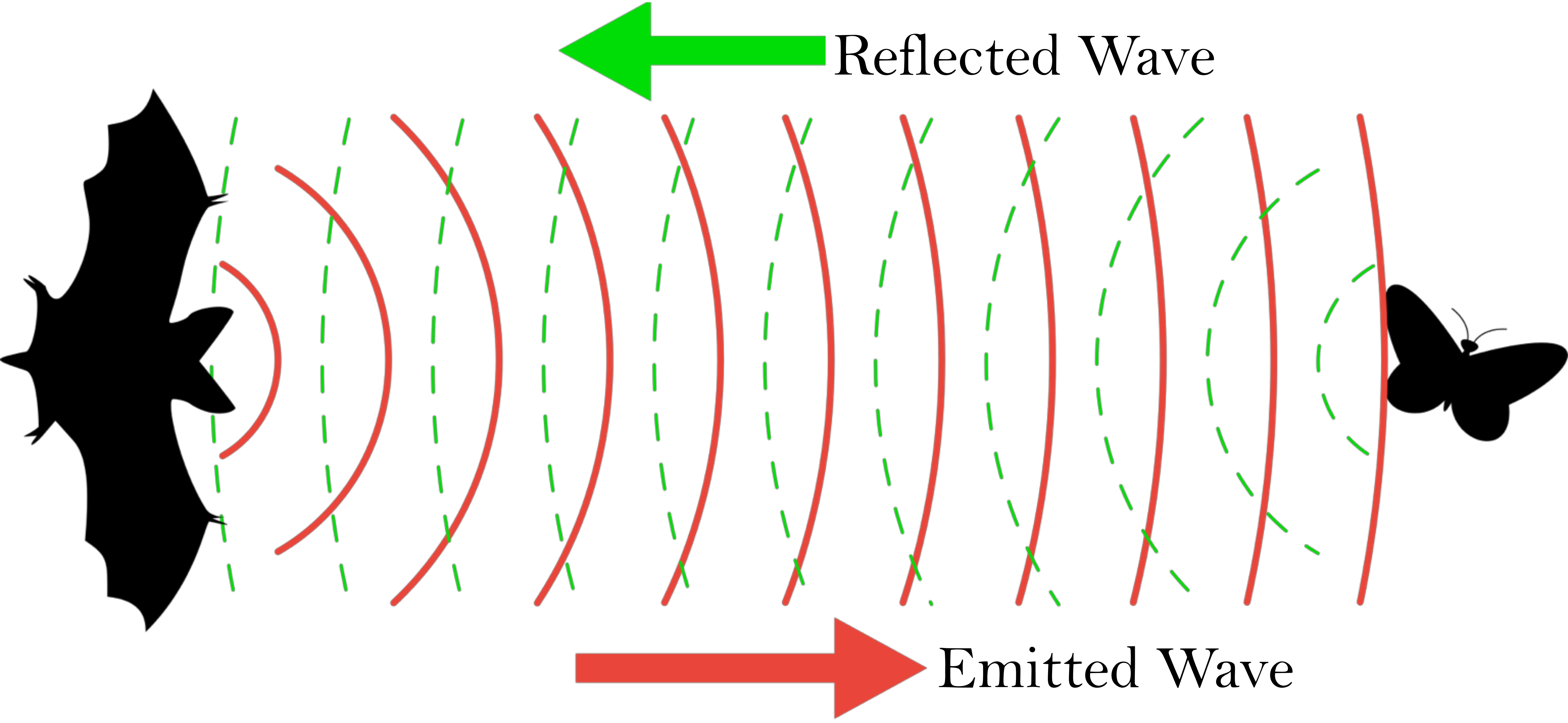
- Wave can keep moving through the new medium, but it's speed changes (warm air = faster than cold air, for example)
- Change in speed causes a change in direction of propagation: Wave bends
- Change in direction: Wave always bends toward the slower medium (away from the faster medium)

Reflection

- Wave strikes a boundary and bounces off: Only one rule applies, angle in = angle out
- Smooth, hard surfaces typically bounce sound waves better than soft or highly textured surfaces
- Acoustic design: Control how much sound gets absorbed, and where you want sound to be reflected

Echoes

- If you hear the sound reflection, that's an echo
- Echolocation: Bounce a sound wave off an object (on purpose), and use the time lapse to figure out where the object is
- Bats scream at insects "Get in my belly!" but the frequency is too high for you to hear

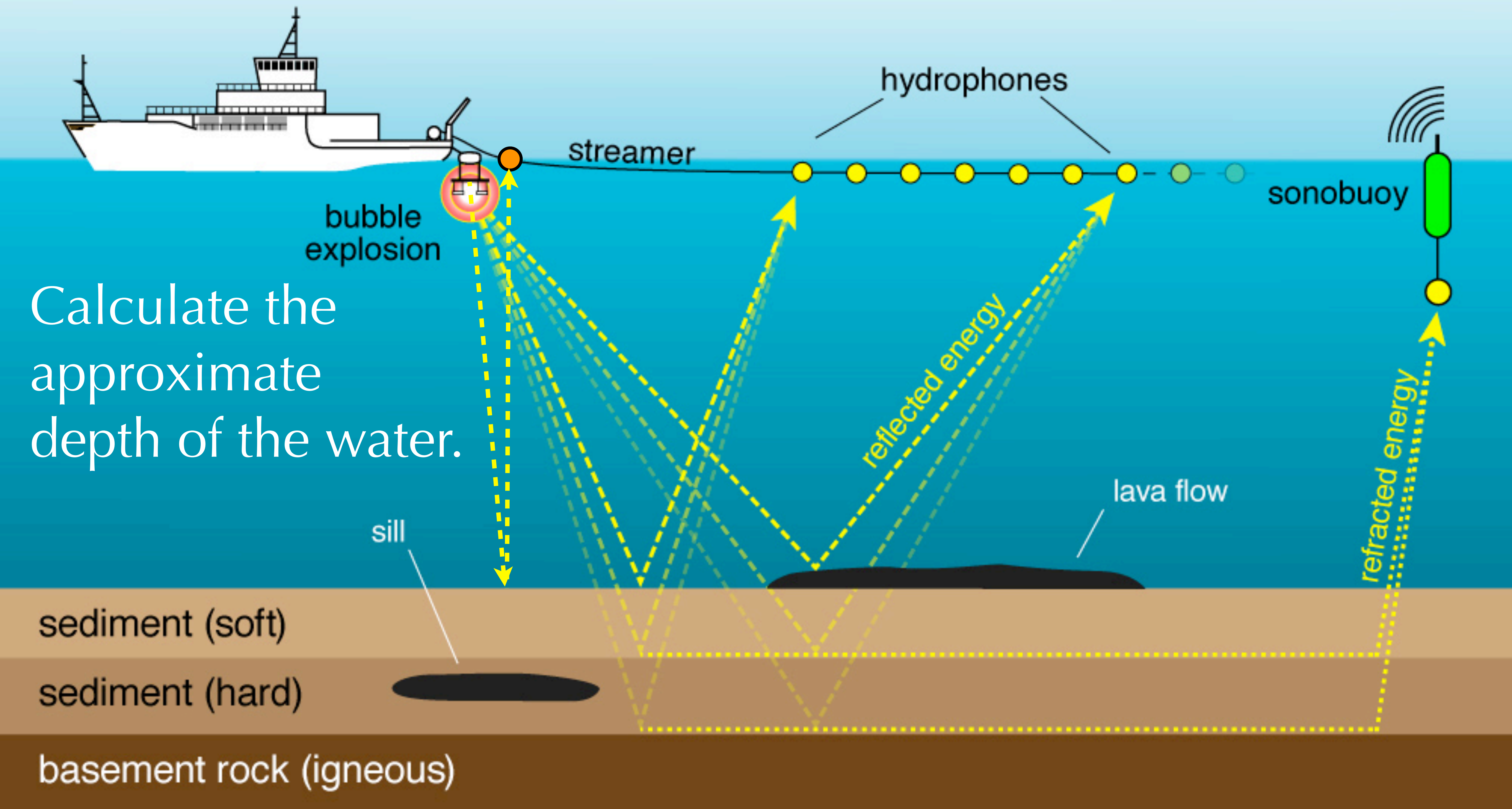


The depth-sounding ship shown emits an infrasonic test pulse. The speed of sound through seawater is $v = 1500$ m/s, and the time lag between sending the pulse and receiving the reflected signal is $t = 4$ s.

$$distance = speed \times time$$

$$2d = vt \Rightarrow d = \frac{vt}{2}$$

$$d = \frac{(1500\,\text{m/s})(4\text{s})}{2} = ?$$



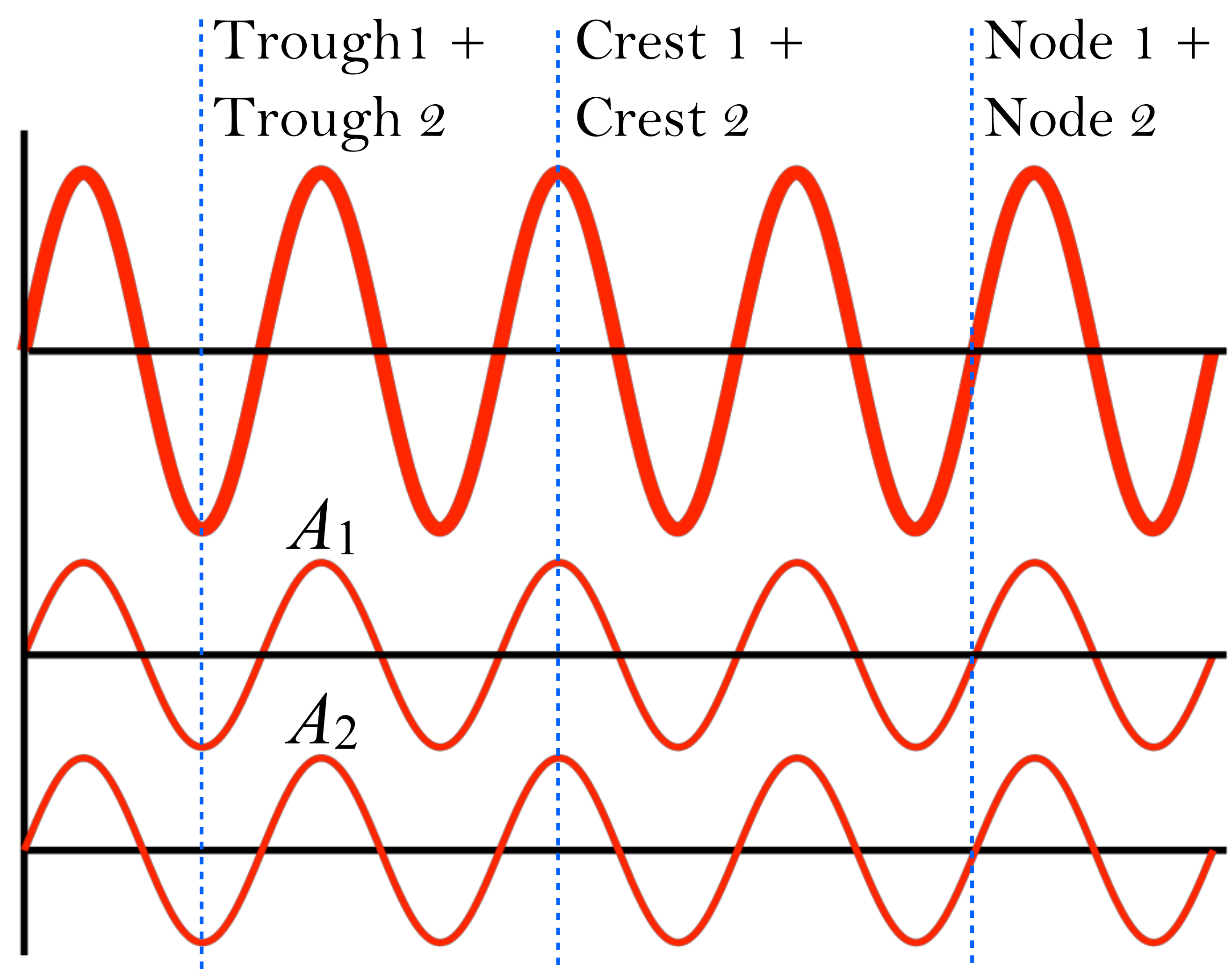
Calculate the approximate depth of the water.

Interference

- This is how you know for sure that waves are about energy, and not matter, propagation!
- Matter: You can't put two objects in the same place at the same time
- Energy: You can put two waves in the same place at the same time

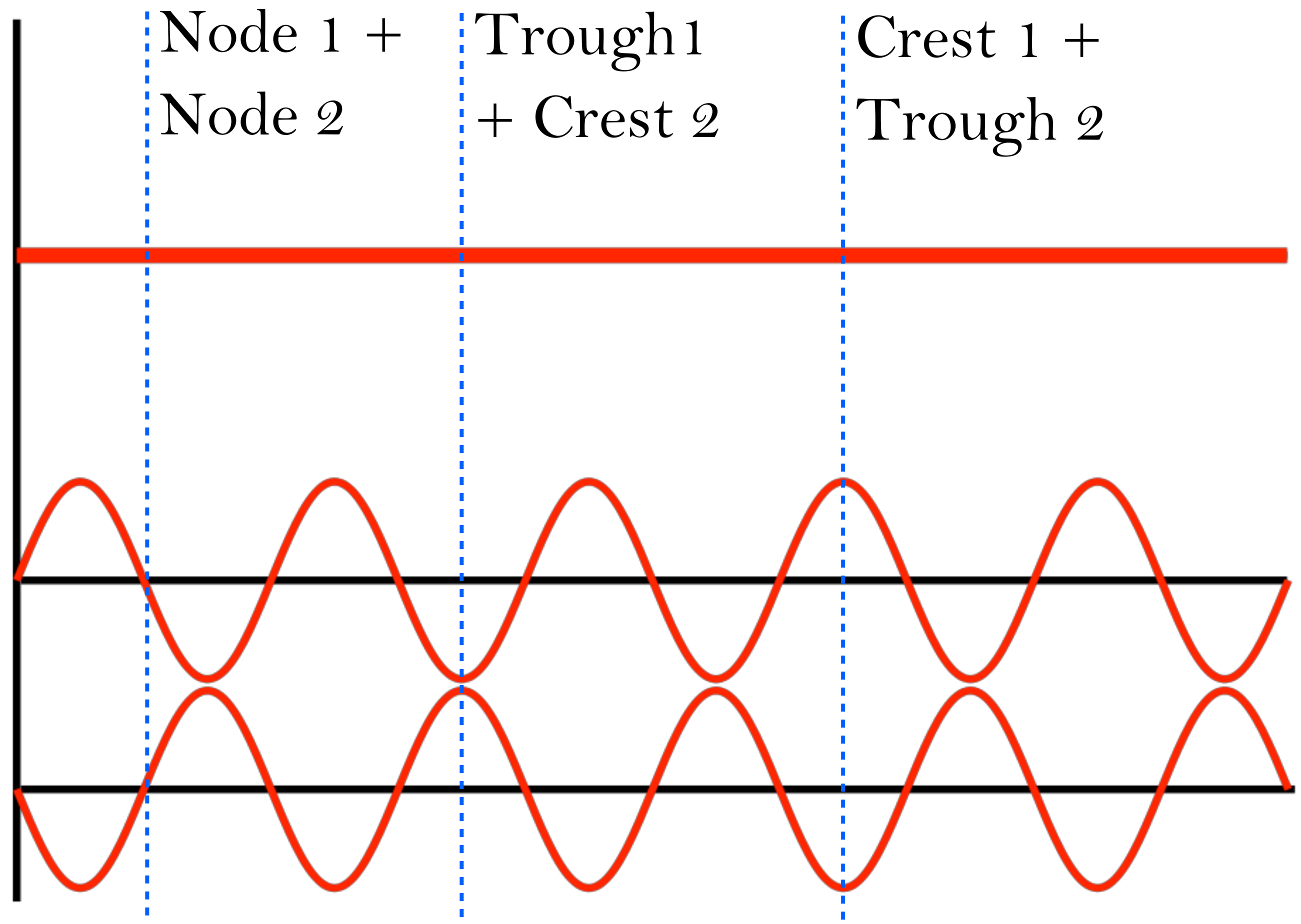
Constructive Interference

- In phase: Waves match up (crest for crest, or compression for compression) and reinforce
- The sound is amplified: Increase in amplitude, but same frequency (pitch)
- This is why you sound fantastic when you sing in the car: Your voice reflected off the windshield interferes constructively



Resulting wave has amplitude $A=A_1+A_2$. Note that waves 1 and 2 happen to have the same original wavelength (hence frequency) and amplitude. They don't necessarily *have* to.

Destructive Interference



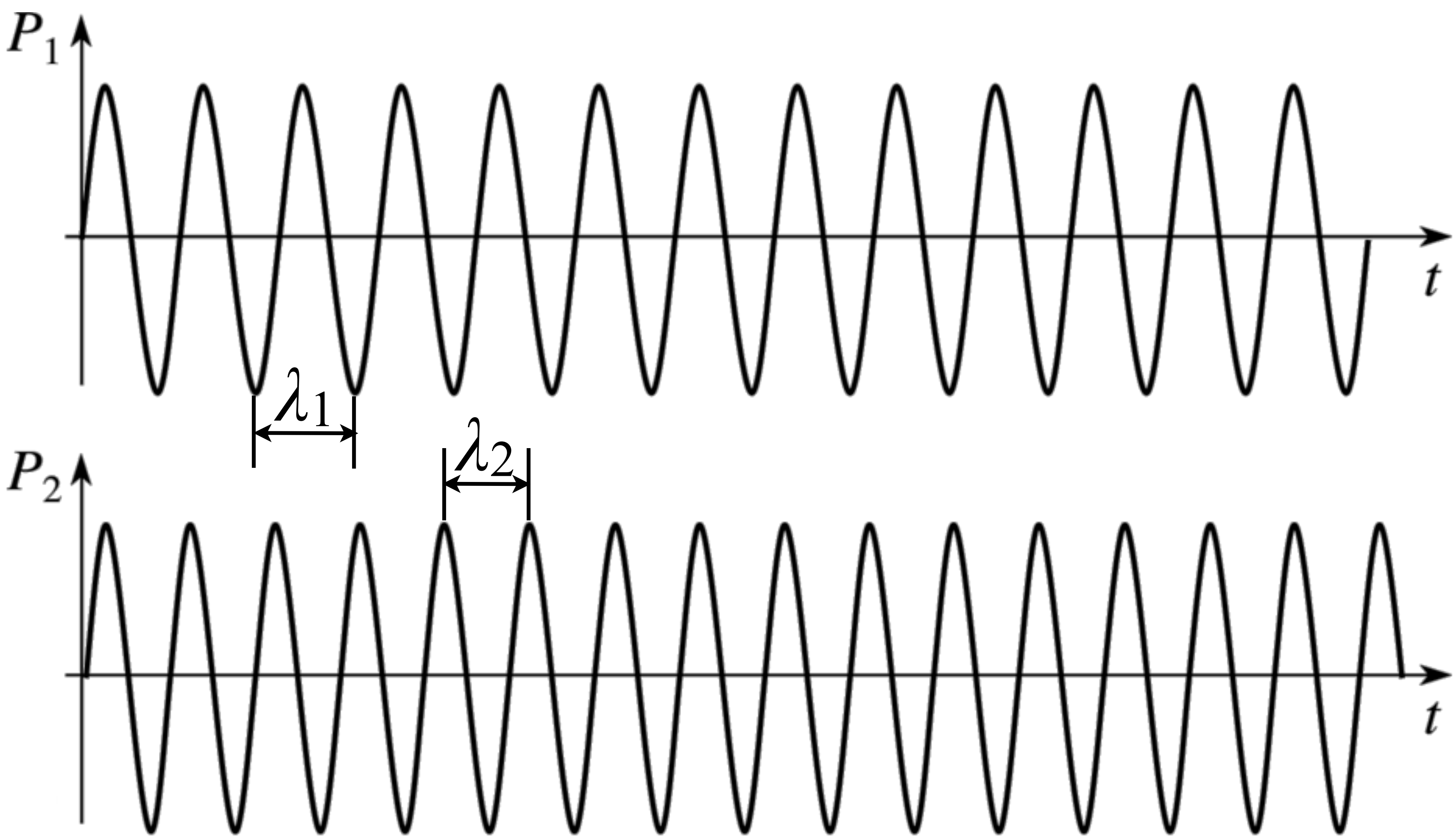
Resulting wave has amplitude $A=0$!

Note that waves 1 and 2 happen to have the same original wavelength (hence frequency) and amplitude. They are just exactly ½ wavelength out of phase.

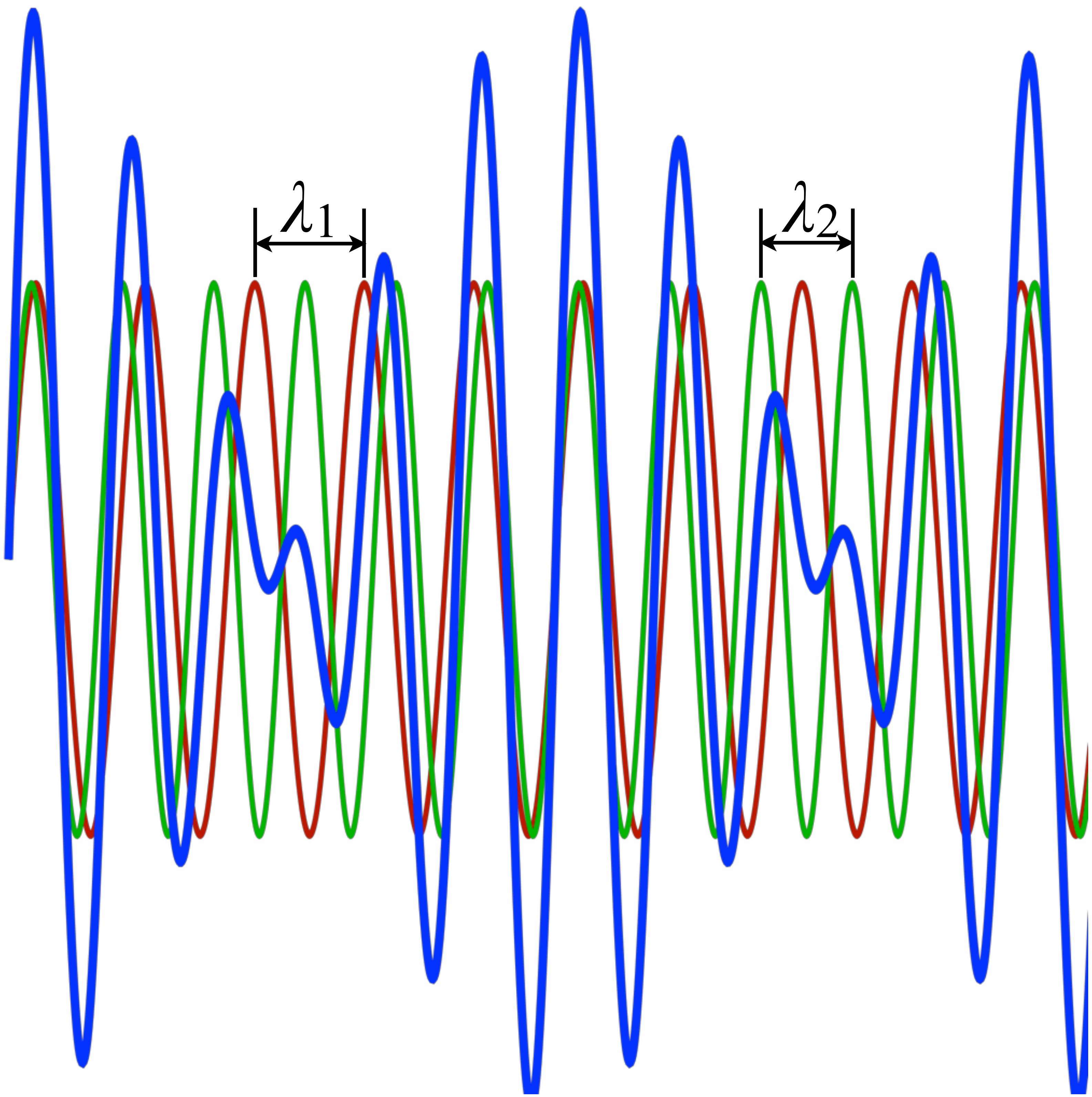
- Out of phase: Waves line up crest-trough (rarefaction-compression), and cancel out
- The sound is minimized: It might be partially cancelled, or completely cancelled
- This is how noise-cancellation headphones work

What happens here? Notice that the two waves have different wavelengths this time!

A) Constructive interference!
B) Destructive interference!
C) Both!
D) Neither!
E) No idea! Could be anything!

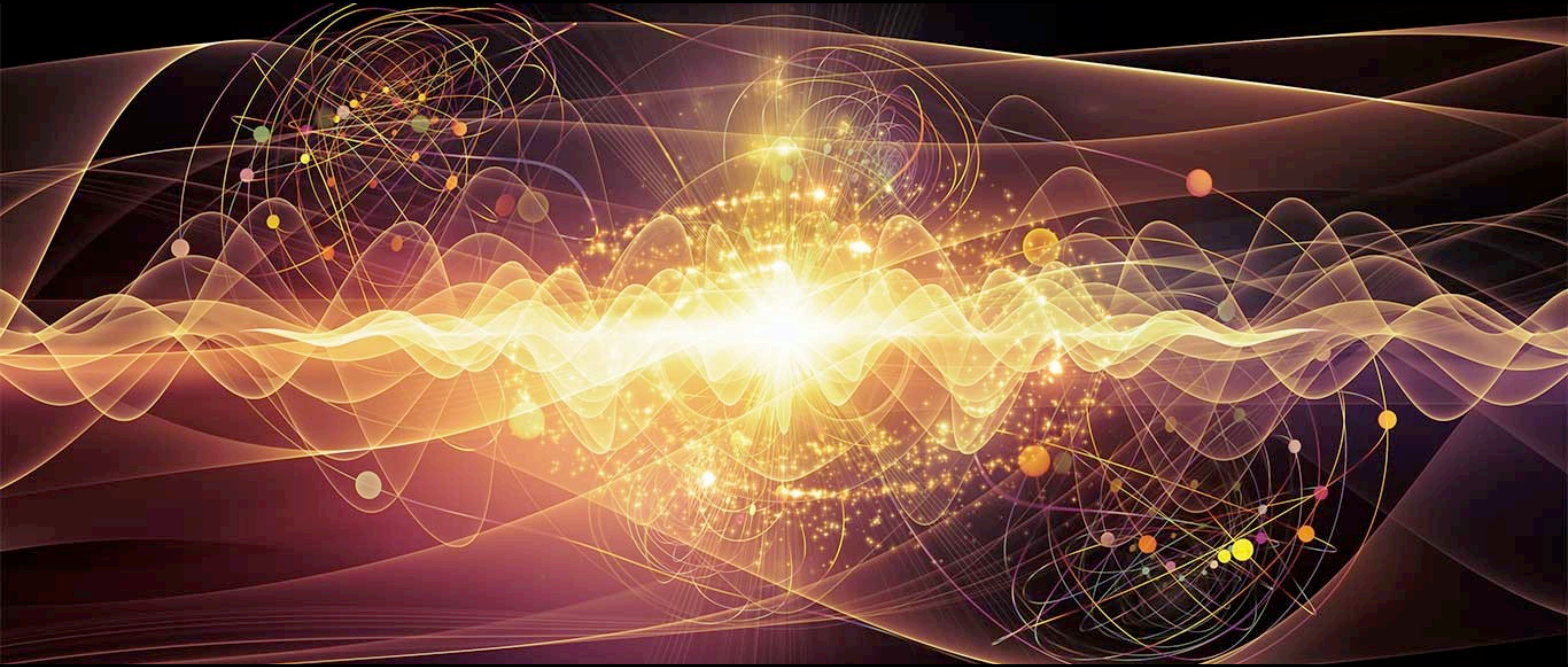


Beats



- Multiple sources at multiple frequencies will predictably line up (if you know the frequencies, you can calculate it)
- Turn signals: When you listen to your signal click and watch the car in front of you blink, you notice they move into phase (same time for click/blink), then slowly move out of phase, the back into phase

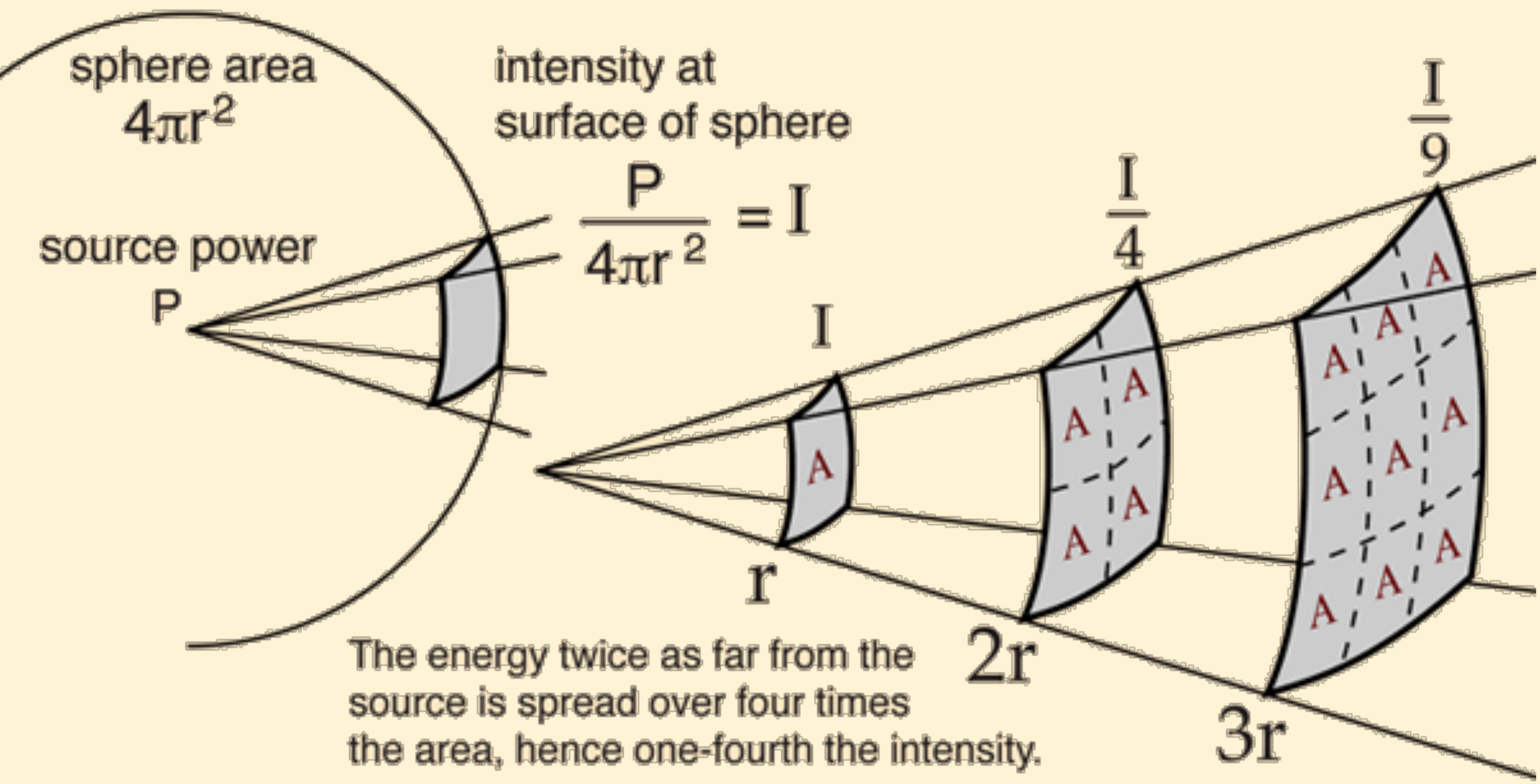
Section 5.5



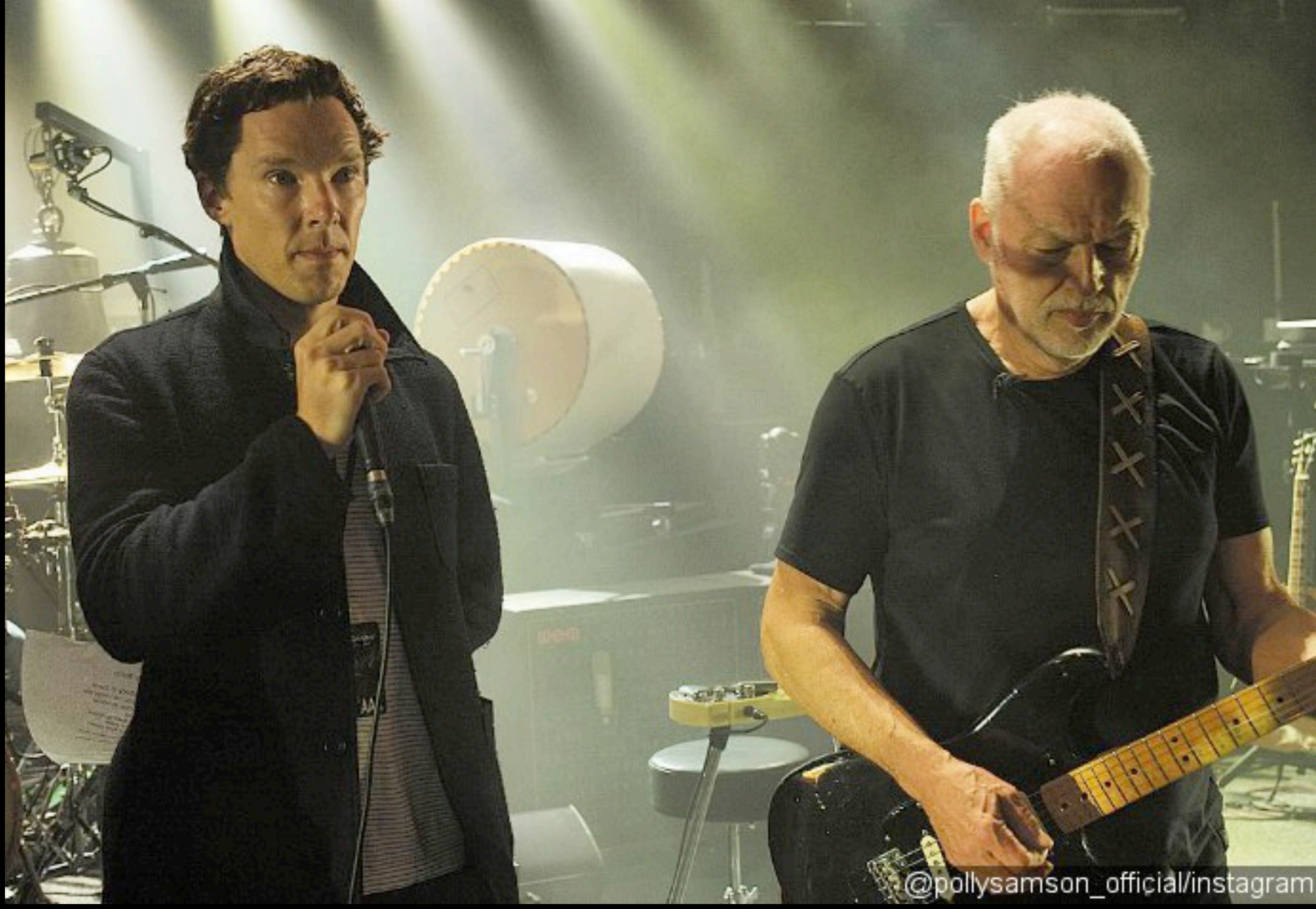
Energy of Waves

Sound Intensity

- Energy (J): Sound wave is the transmission of energy through a medium
- Per Time (1/s): The sound wave keeps coming for some duration of time
- Over Area (1/m^2): That sound wave hits the whole surface of your eardrum, not just at a point; the energy is spread out over the surface
- Intensity = (energy per time)/area: I = (J/s)/m^2 = W/m^2

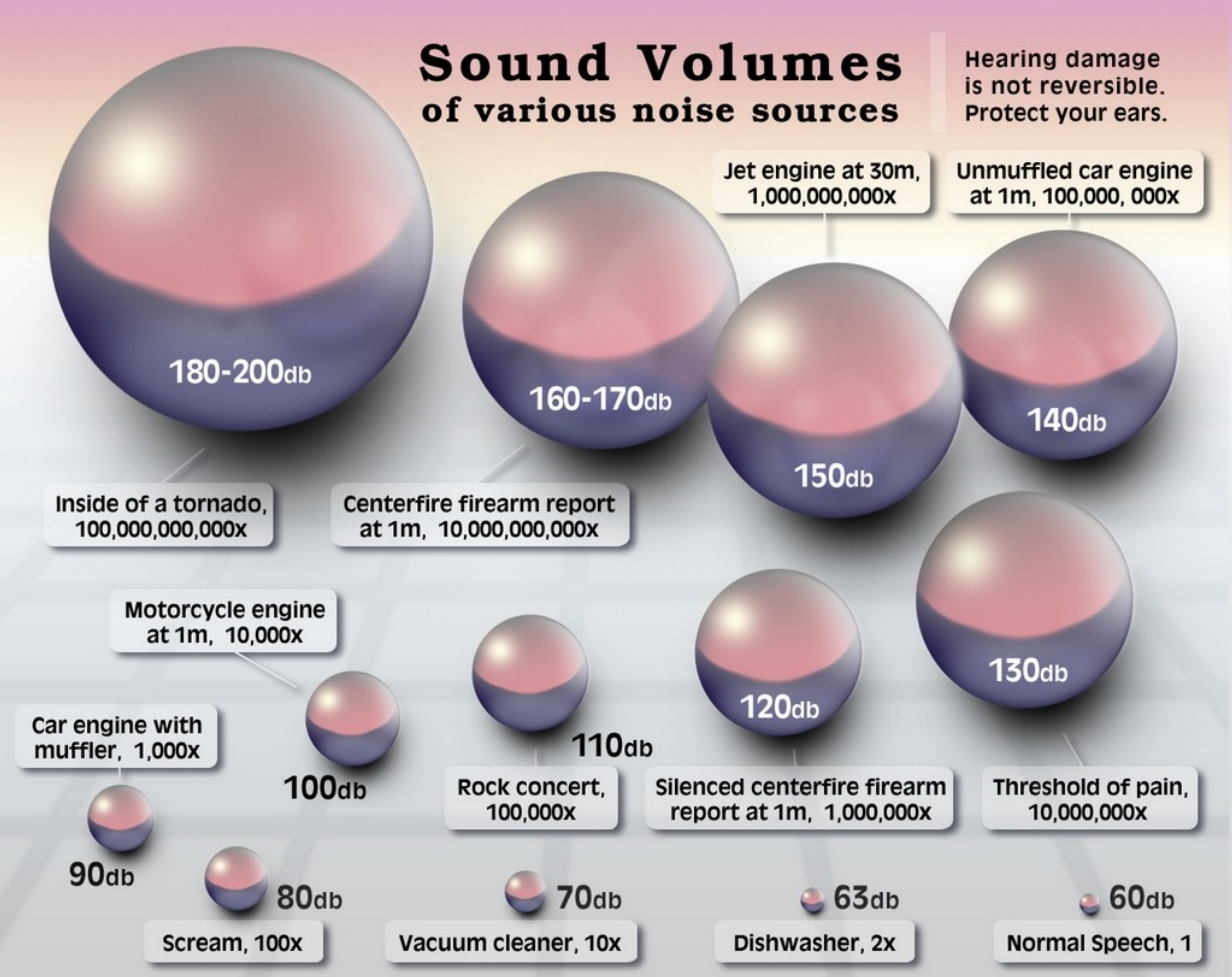


True or false?



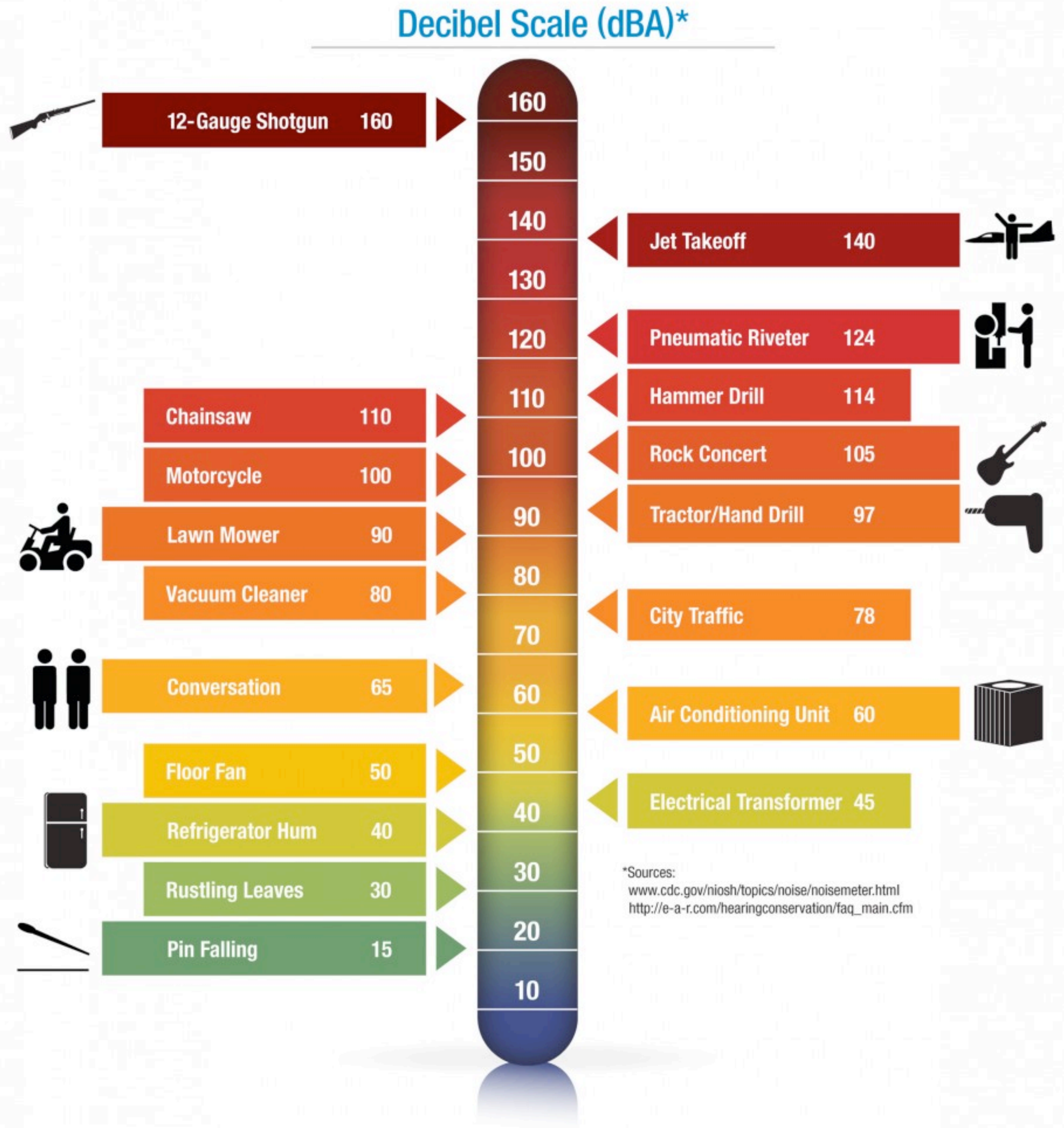
When you are only 2m from the stage, the music is almost painfully loud. Step back to 4m from the stage, and the intensity will only be half as much (and you have become comfortably numb).

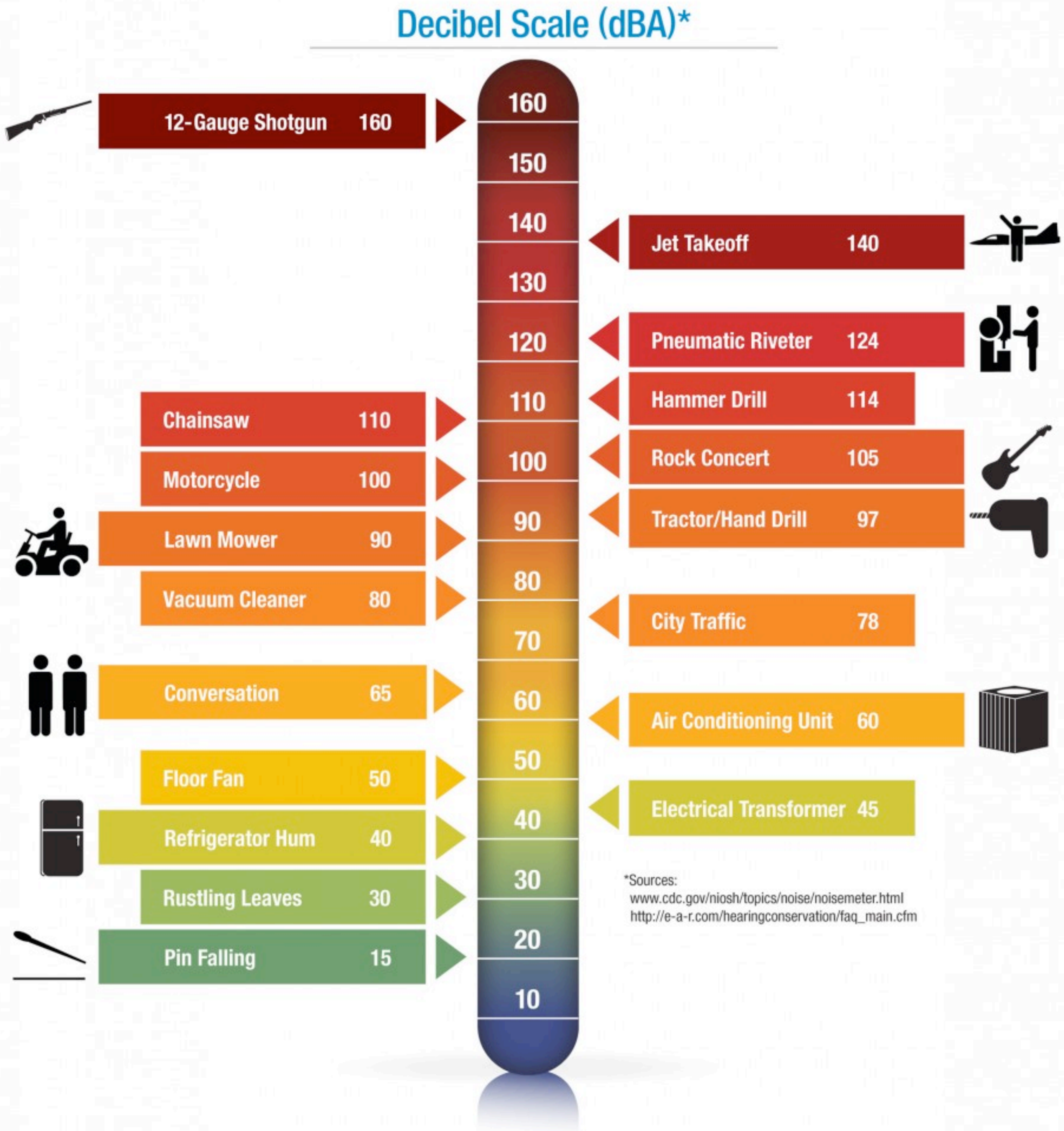
How Loud Is That Sound?



- Your ears are not linear; they are logarithmic!
- You do not perceive a sound with twice the intensity (hence twice the energy) as being twice as loud
- Everybody's ears are different, but in general it takes 10× the energy to perceive a sound as "twice as loud"

- Combines the objectively measurable (intensity) and the subjectively perceived (your hearing)
- Decibel scale is logarithmic because that's how your ears operate
- 0dB = threshold of hearing ≃ 1×10^{-12} W/m^2
- 120dB = threshold of pain ≃ 1 W/m^2





You are in the library, whispering to your friend.

A) Probably no more than 10dB.

B) More like 30–40dB.

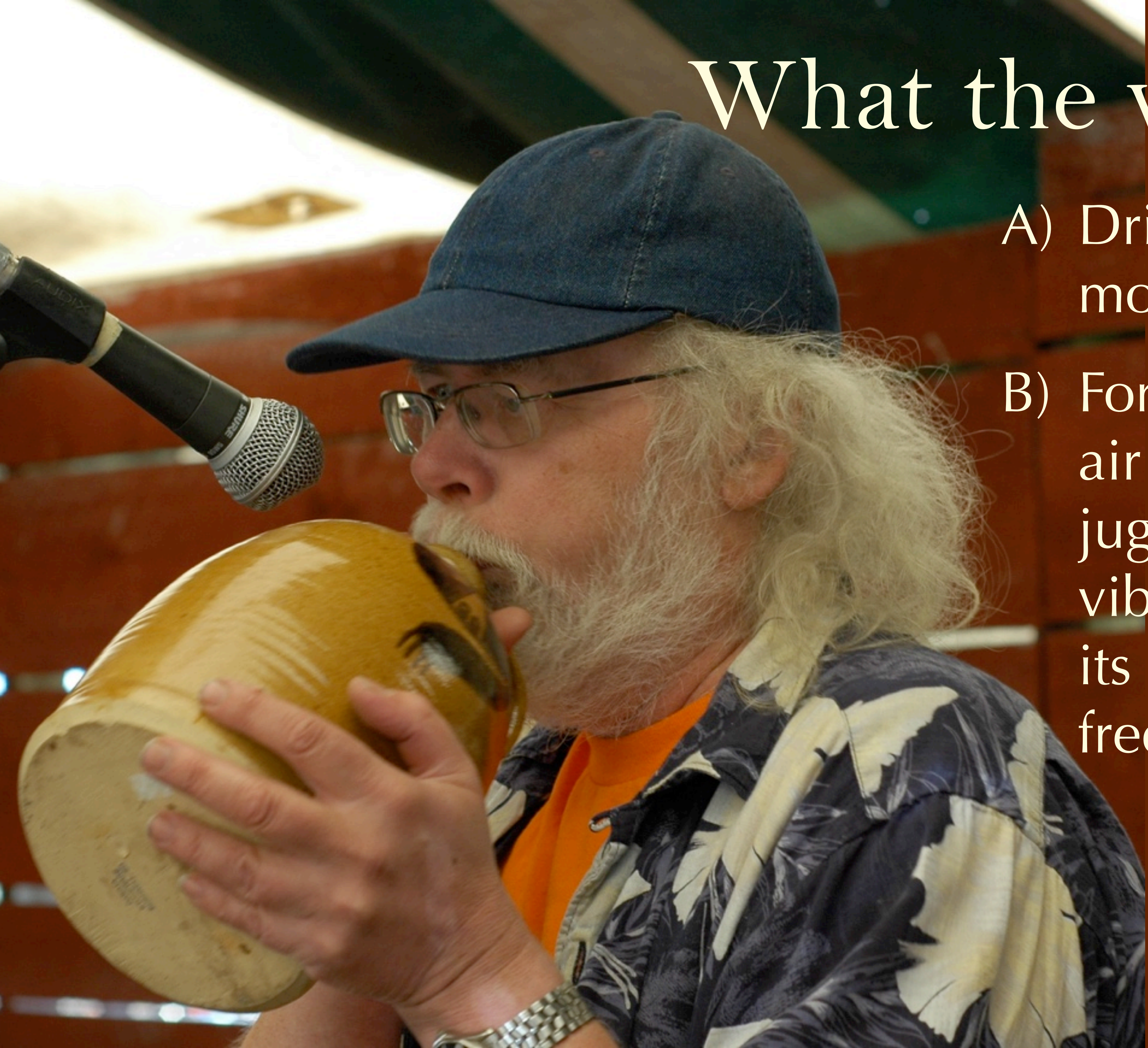
C) At least 70dB, but no more than 80dB.

D) Precisely 100dB!

E) Somewhere upwards of 140 dB.

Resonance

- Find the natural frequency of an object an amplify it!
- Natural frequency: Tuning fork is an obvious example; the fork wants to vibrate at a certain frequency, because of what it's made of, the shape/length of the tines
- Amplify the natural frequency: Apply a force with that same frequency (either on purpose or by accident)



What the what?

A) Drinkin' moonshine!

B) Forcing the air in the jug to vibrate at its resonant frequency.

Section 5.6

Sources of Sound

Zoe Keating, cello

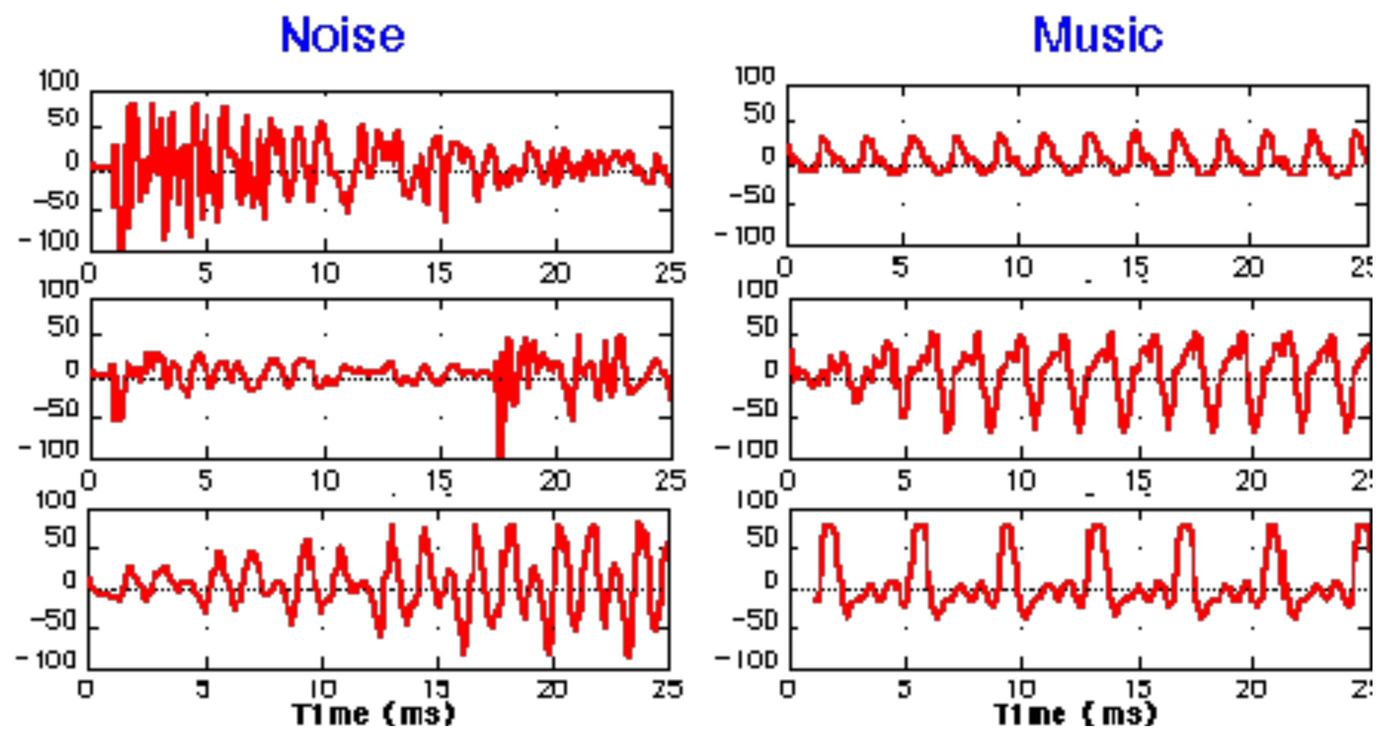
True or false:

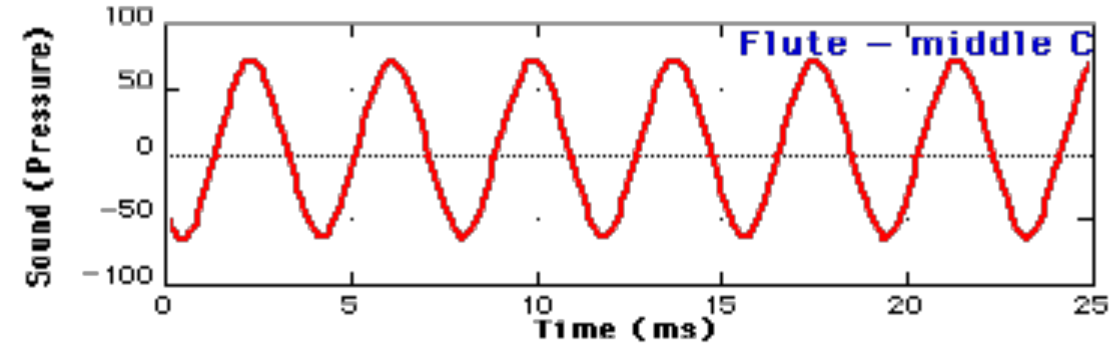
If a violin plays a certain frequency, and then a clarinet plays precisely the same frequency, a listener could not tell the difference.

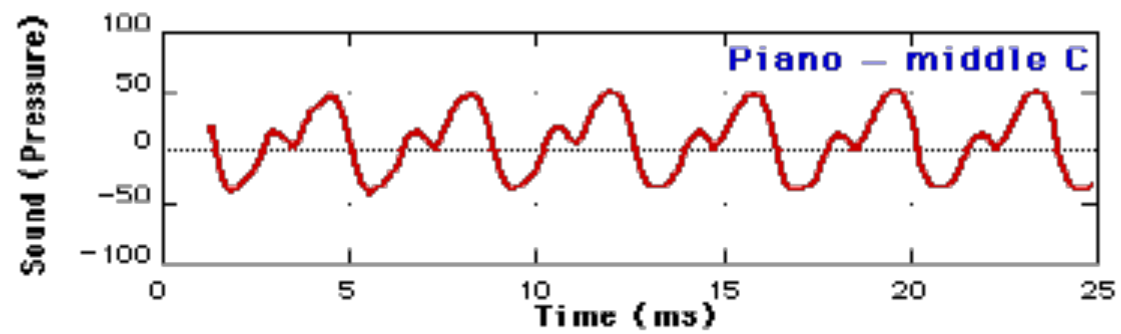
Jaehee Choi, clarinet and Wonkyung Chae, violin

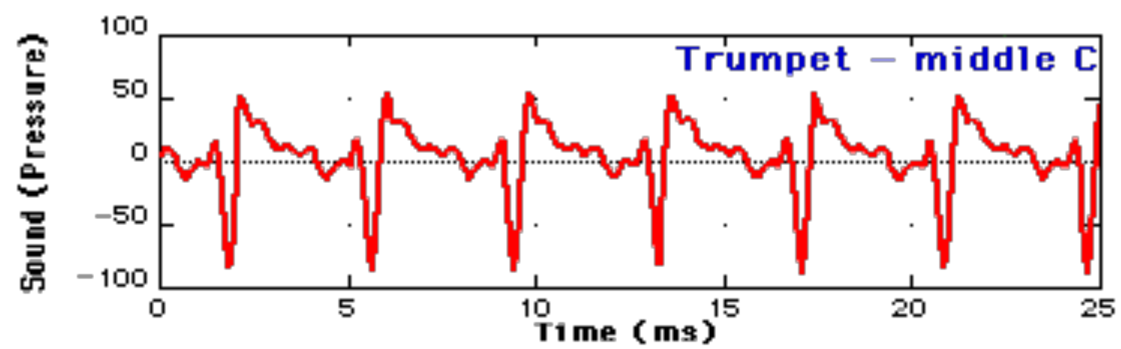
Music vs Noise

- Noise: Random frequencies, different amplitudes–you might have trouble making sense of the mess
- Pure Tone: A single frequency (like a tuning fork)
- Musical Note: You can tell the difference between the same note (same frequency) played on different instruments–why?

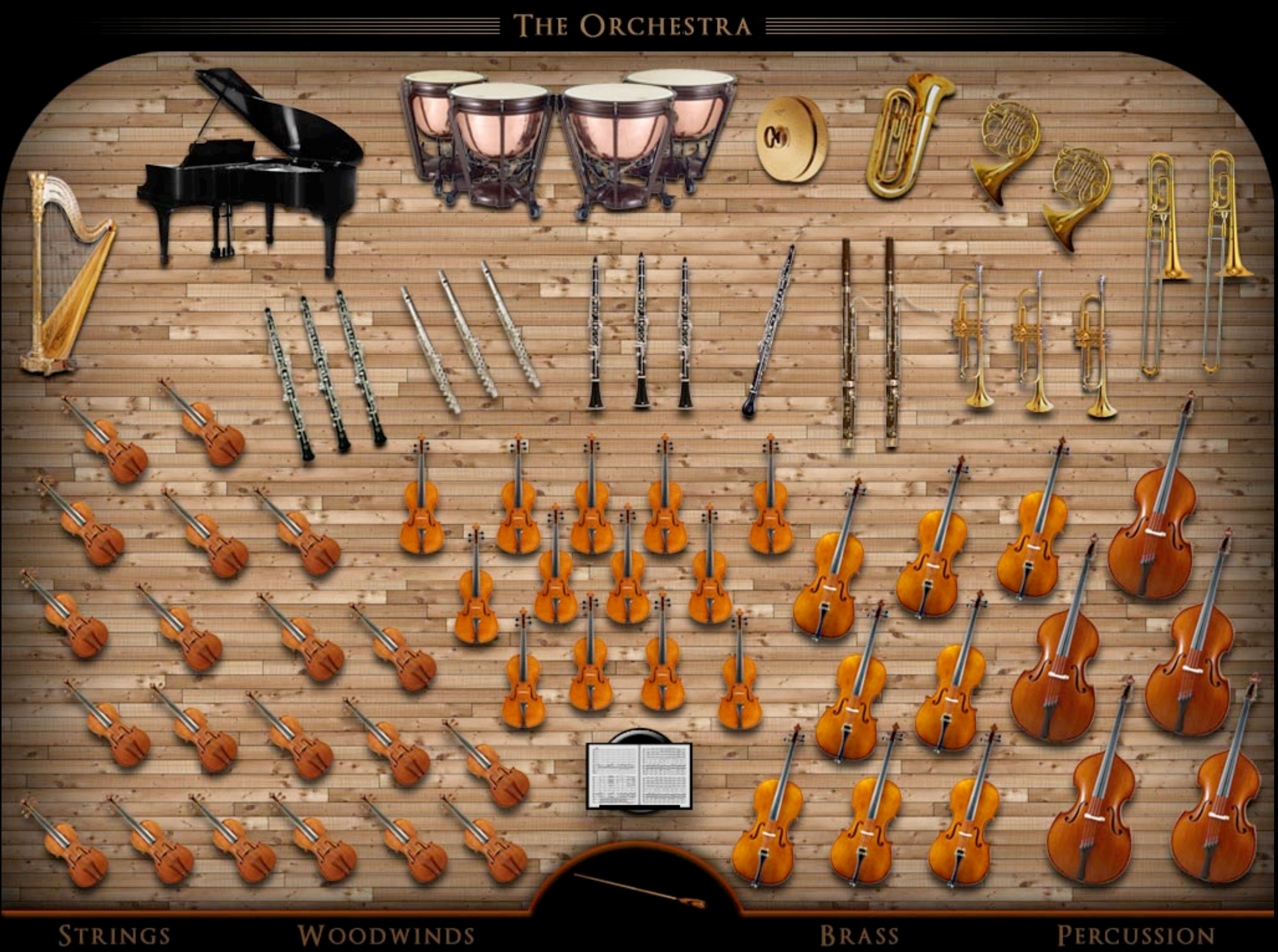






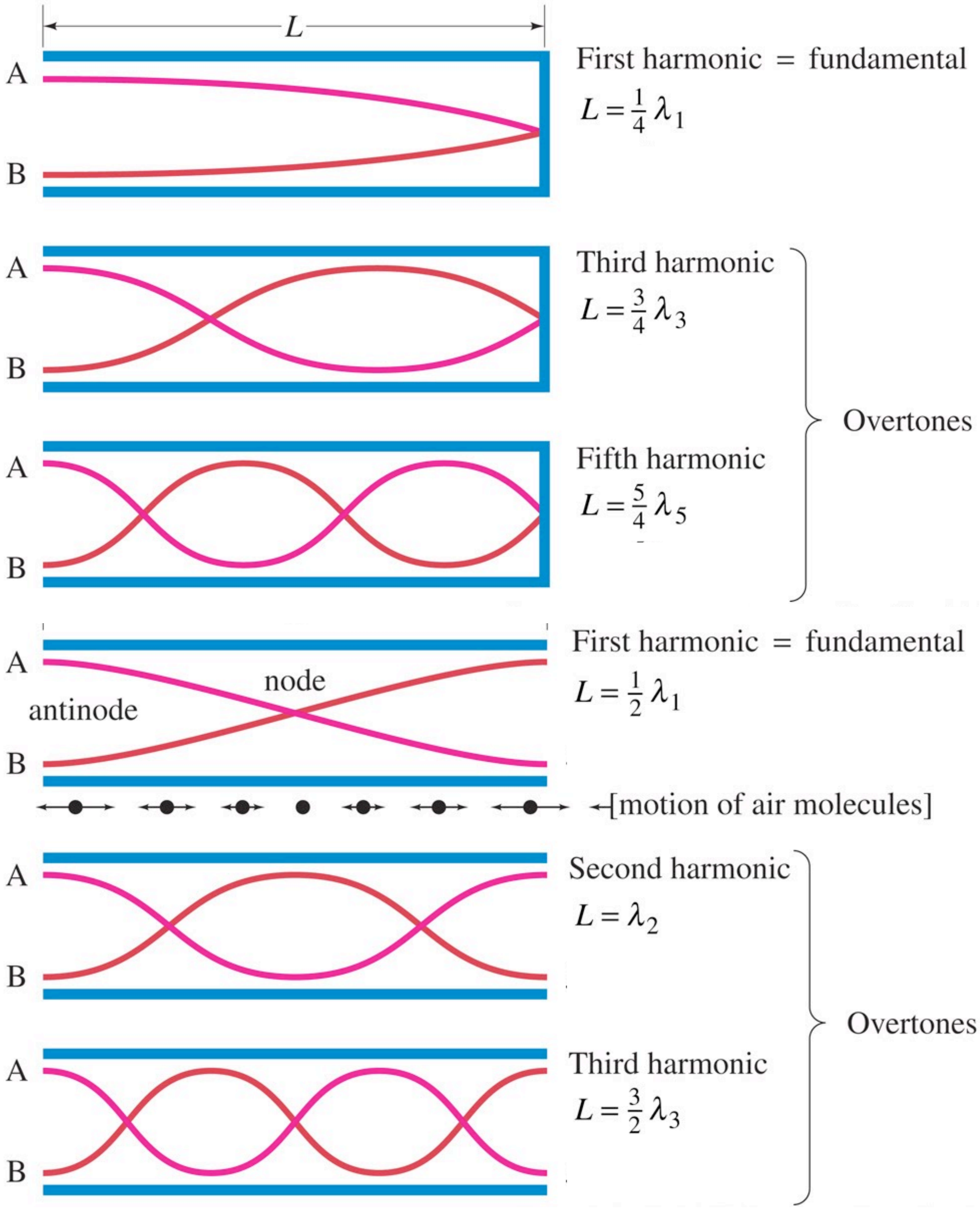


Vibrating Strings



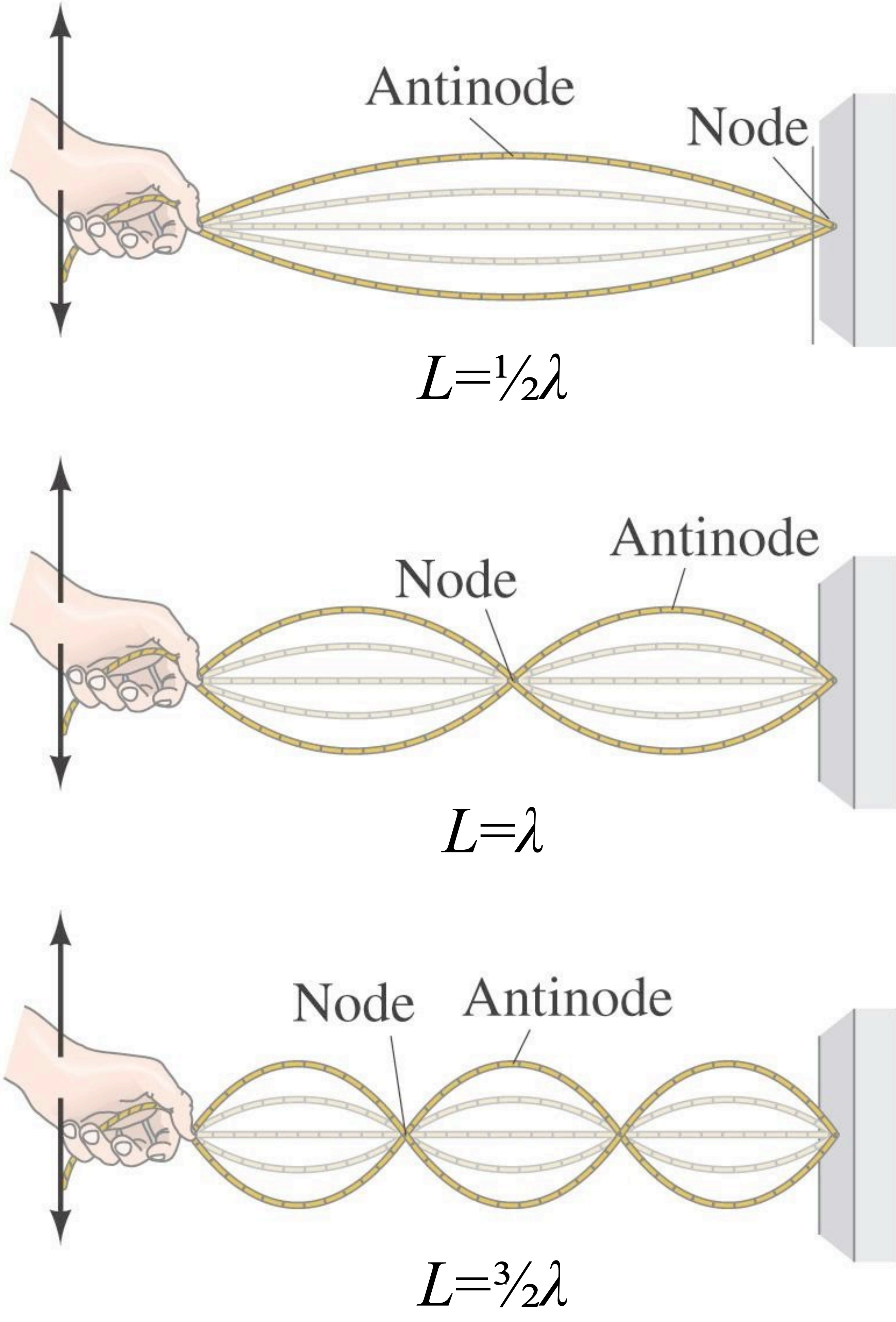
- Guitar, piano, banjo: Sounds very different, but mechanism is the same
- Same mechanism even if you don't have a string: Flute, saxophone, bassoon
- Vibrating a column of air gives you music the same way vibrating a string does

Standing Waves



- String or air column: Pick one, doesn't matter which
- One end fixed, the other end either free (flute) or fixed (guitar)
- Vibrate the medium at its natural frequency (blow or strum)
- The fixed end will reflect an incoming wave, and flip it

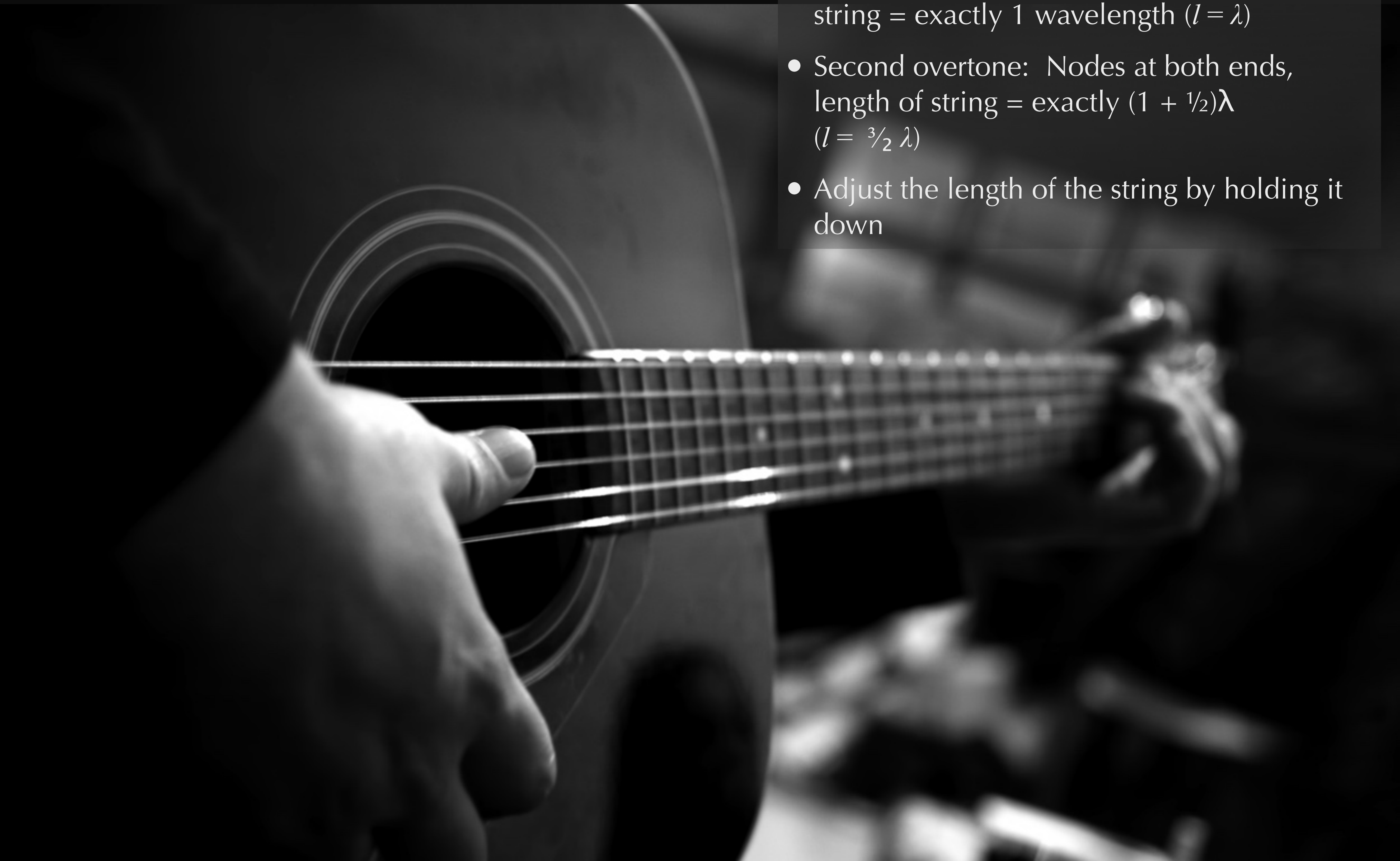
Nodes and Anti-Nodes



- Fixed ends are nodes: The amplitude is always zero
- Free ends are anti-nodes: The amplitude is maximum
- The wave and its reflection will interfere

Overtones

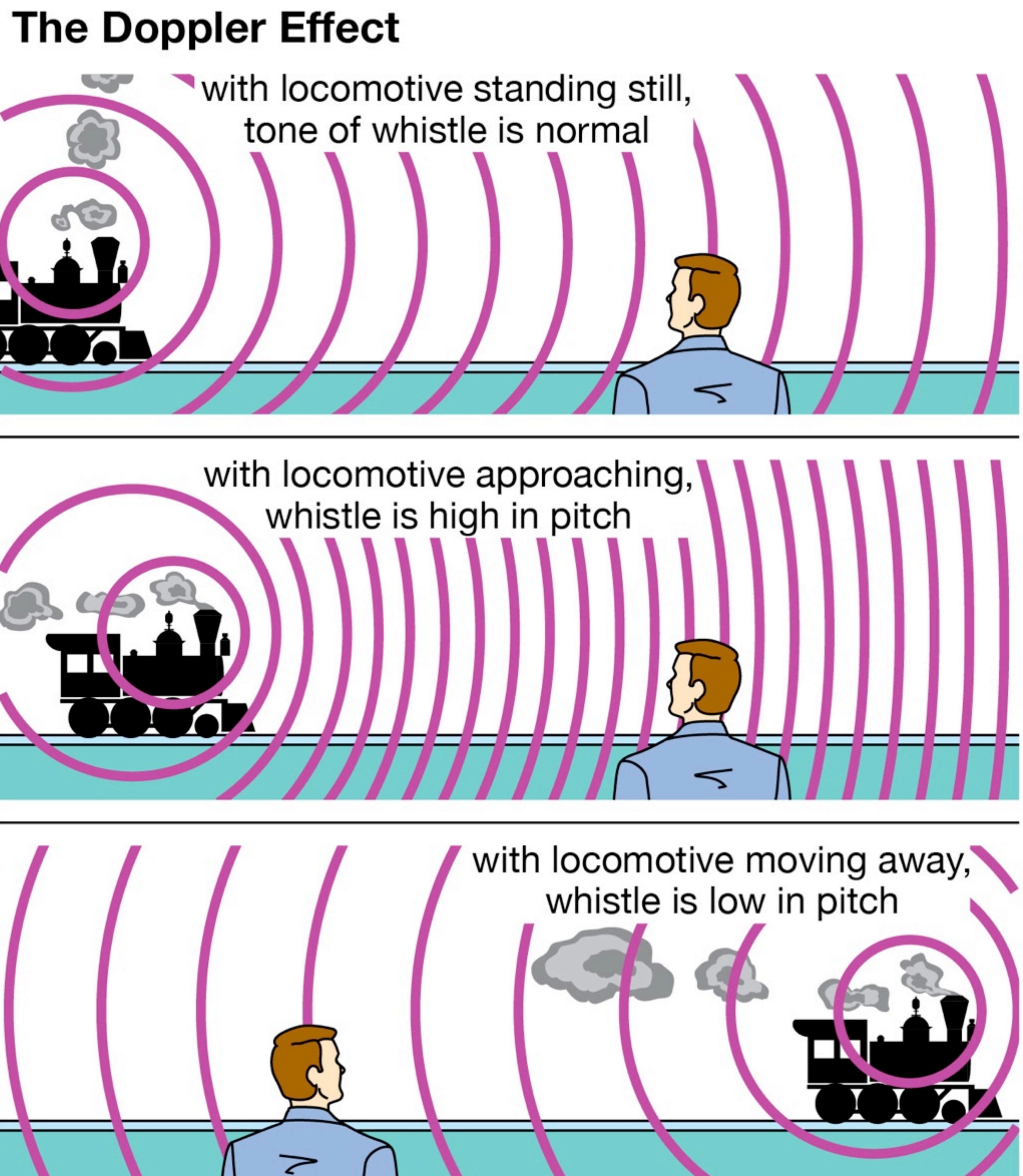
- Fundamental frequency: Nodes at both ends, length of string = exactly ½ wavelength ($l = \frac{1}{2}\lambda$)
- First overtone: Nodes at both ends, length of string = exactly 1 wavelength ($l = \lambda$)
- Second overtone: Nodes at both ends, length of string = exactly $(1 + \frac{1}{2})\lambda$ ($l = \frac{3}{2}\lambda$)
- Adjust the length of the string by holding it down



Sounds From Moving Sources

- The assumption we have been making (right up to this point) is that whatever is making the sound (source) and whatever is hearing the sound (receiver) are both stationary with respect to each other

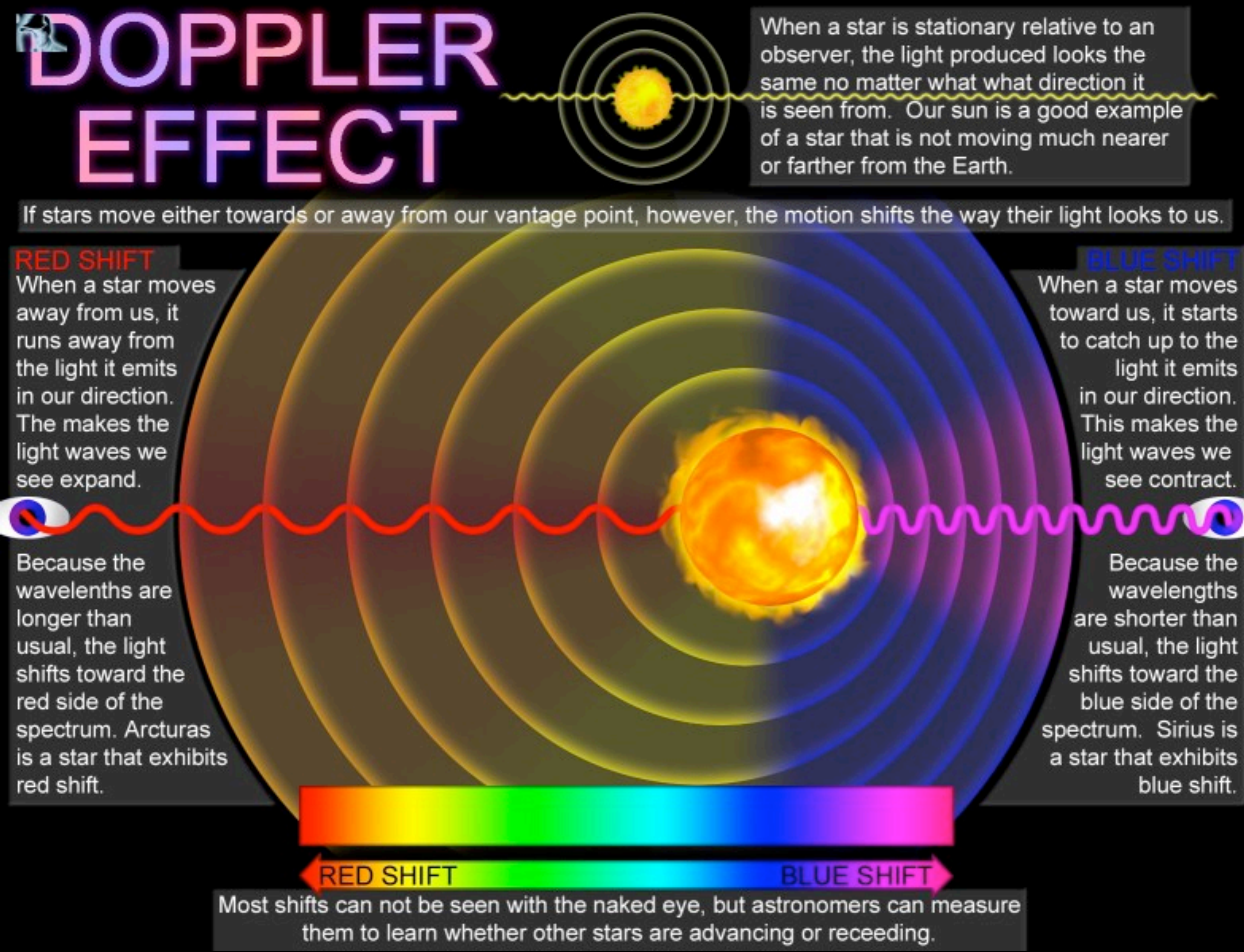
- What if the source gets closer or farther from the receiver?
- What if the receiver isn't staying put?
- What if both source and receiver are moving?



Doppler Effect

- It does not matter whether the source, receiver, or both are in motion
- Decrease the distance (approach): Receiver will perceive an increase in frequency
- Increase the distance (recede): Receiver will perceive a decrease in frequency
- Source (moving or not moving, does not matter) does not change the true frequency it is emitting

Light from a star that is moving towards the earth will be



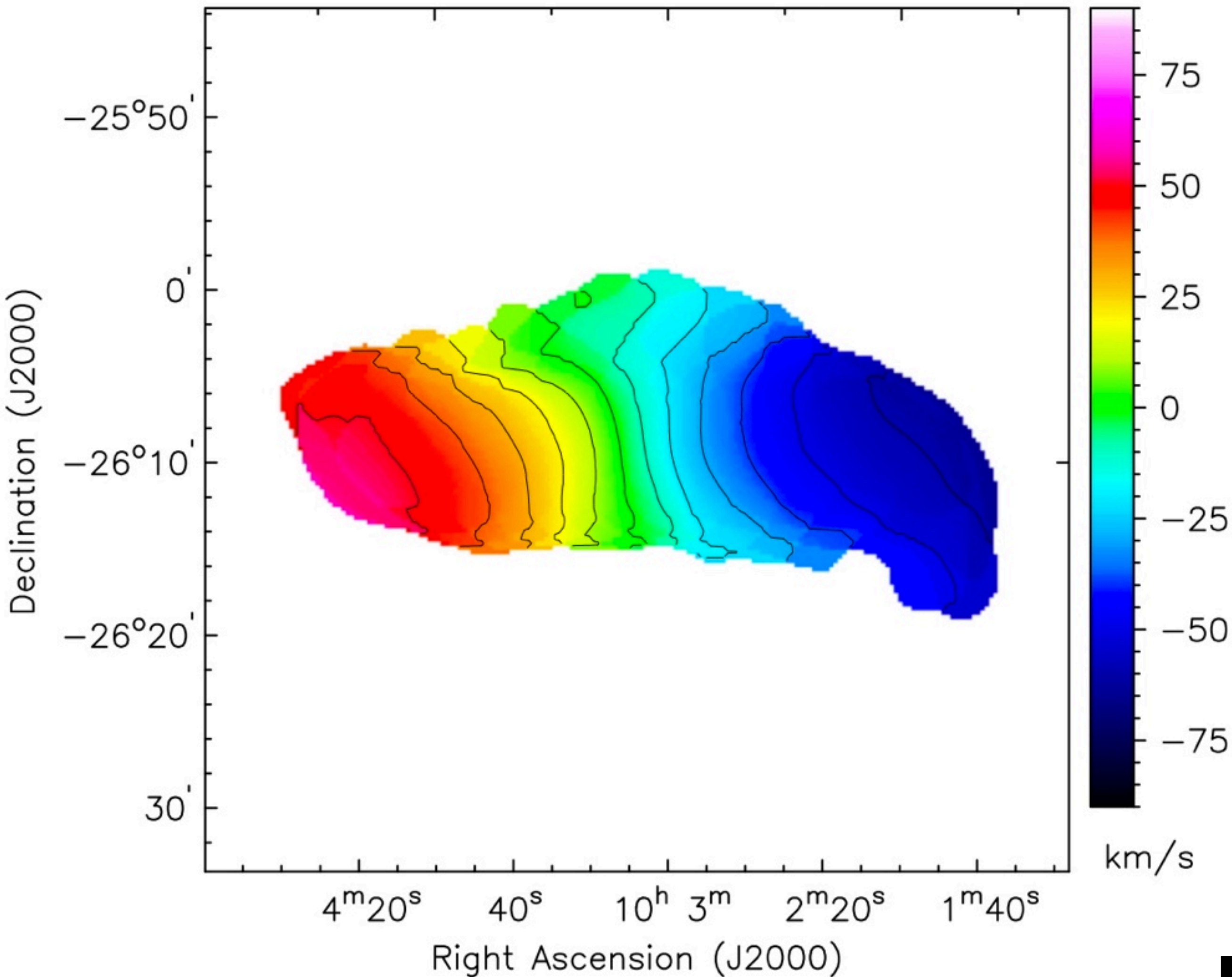
A) red-shifted.

B) blue-shifted.

C) up-shifted.

D) down-shifted.

E) un-shifted in any way.



Not Just For Sound Waves!

- Light waves do this as well: Doppler shift (red shift or blue shift) is used in Astronomy to determine radial velocity of distant stars, rotation rates, and is even a method for detecting extrasolar planets!

- Doppler Radar: Uses radio waves bounced off of storm systems (clouds, falling rain, hail, etc.) to determine the precise location, how much precipitation, how fast the storm is tracking, and whether it is spinning (and in which direction)