NAD 2023 Standard ER3 (Properties of Waves)

Credits

- This Slideshow was developed to accompany the textbook
  - *OpenStax High School Physics*
    - *Available for free at https://openstax.org/details/books/physics*
    - *By Paul Peter Urone and Roger Hinrichs*
    - *2020 edition*
- Some examples and diagrams are taken from the *OpenStax College Physics, Physics,* and *Cutnell & Johnson Physics* 6th ed.

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OpenStax High School Physics 13.1, 2
OpenStax College Physics 2e 16.9, 16.2

10-01 Waves

Waves

- A traveling disturbance
- Carries energy from place to place

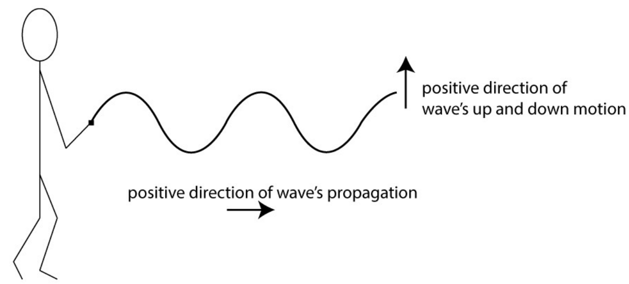
- When a boat makes a wave,
  - the water itself does not get up and move
  - the water pushes a little, then moves back
  - energy is transferred in the wave and is what you feel

If the water moved in bulk, then there would be a hole in the water.

10-01 Waves

- Transverse
  - Up and down disturbance
  - Wave travels left or right
  - Disturbance is perpendicular to direction of travel

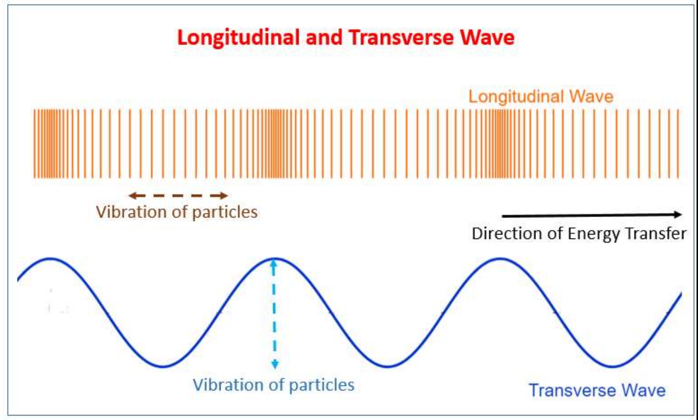
  - Examples:
    - Radio waves, light waves, microwaves, stringed instruments



Demonstrate with a slinky

10-01 Waves

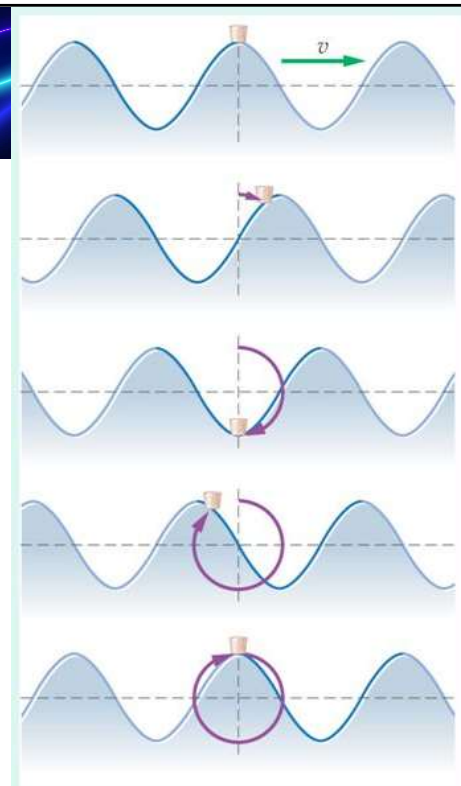
- Longitudinal Waves
  - Disturbance is left and right
  - Direction of travel is left or right
  - Disturbance and direction of travel are parallel
  - Series of compressed and stretched regions
  - Example:
    - Sound



Demonstrate with a slinky

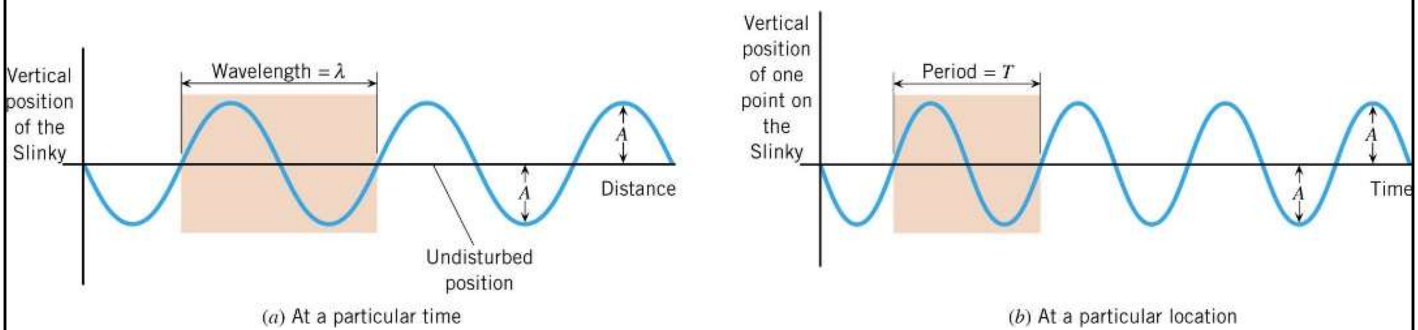
10-01 Waves

- Other
  - Water waves are a combination
  - Water at the surface of a water wave travels in small circles



10-01 Waves

- Periodic → pattern is regularly repeated
- Cycle → one unit of pattern
- Wavelength (λ) → Distance of one cycle
- Amplitude (A) → height from equilibrium to crest



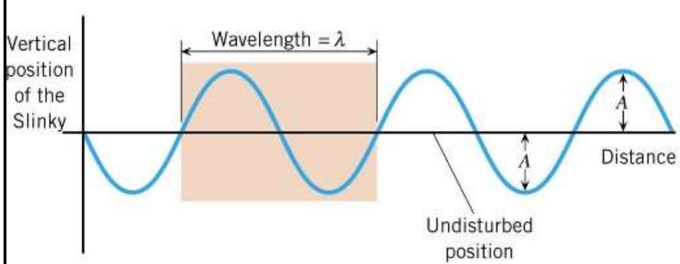
Put drawing on board and label the parts

The amplitude of a longitudinal wave is the amount of compression instead of a height

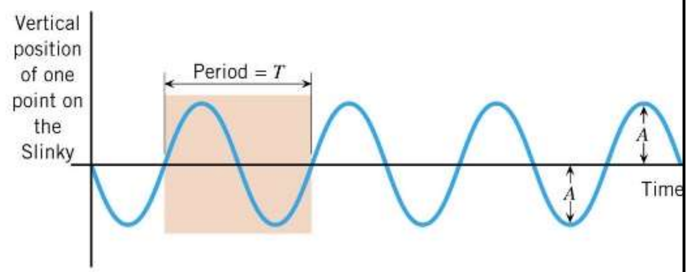
10-01 Waves

- Period (T) → time it takes for one cycle
  - Unit: s
- Frequency (f) → # of cycles per second
  - Unit: 1/s = 1 hertz (Hz)

- $f = \frac{1}{T}$
- $v = \frac{\lambda}{T} = f \cdot \lambda$



(a) At a particular time



(b) At a particular location

10-01 Waves

- WAUS operates at a frequency of 90.7 MHz. These waves travel at 2.99×10^8 m/s. What is the wavelength and period of these radio waves?

- $\lambda = 3.30$ m
- $T = 1.10 \times 10^{-8}$ s

$$v = f\lambda$$
$$2.99 \times 10^8 \frac{m}{s} = 90.7 \times 10^6\ Hz\,\lambda$$
$$\lambda = 3.30\ m$$

$$f = \frac{1}{T} \rightarrow 90.7 \times 10^6\ Hz = \frac{1}{T} \rightarrow T = \frac{1}{90.7 \times 10^6\ Hz} = 1.10 \times 10^{-8}\ s$$

10-01 Waves

- You are sitting on the beach and notice that a gull floating on the water moves up and down 15 times in 1 minute. What is the frequency of the water waves?

- f = 0.25 Hz

$$Frequency\ is\ \frac{cycles}{seconds}$$
$$f = \frac{15}{60\ s} = 0.25\ Hz$$

10-01 Homework

- Wave hello to some exercises.
- Read
  - OpenStax College Physics 2e 16.10
  - OR
  - OpenStax High School Physics 13.3

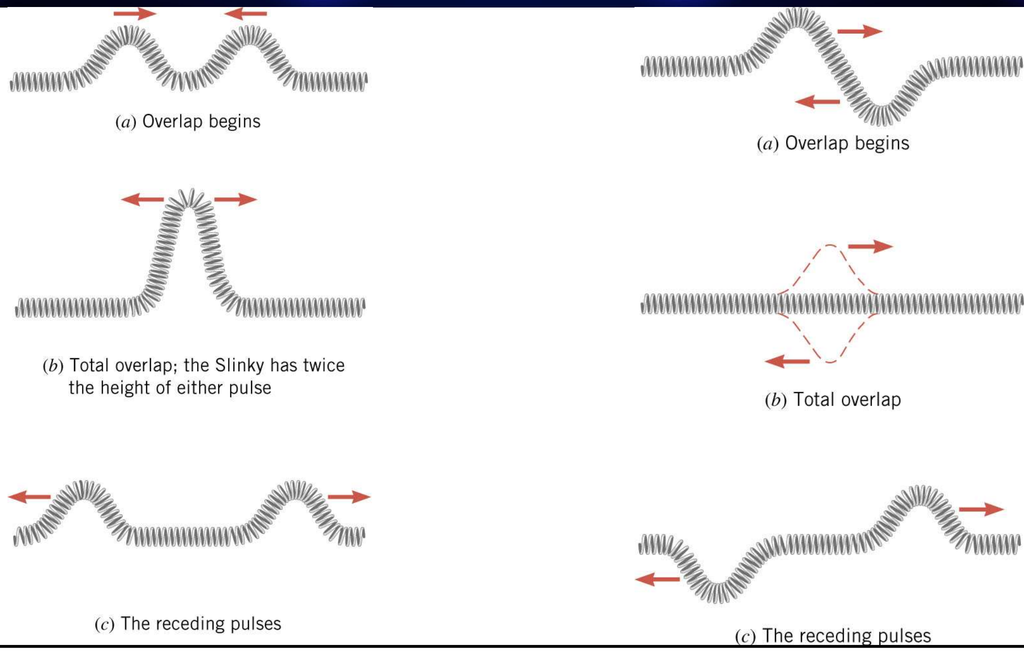
OpenStax High School Physics 13.3
OpenStax College Physics 2e 16.10

10-02 Superposition and Interference

- Often two or more wave pulses move through the same space at once

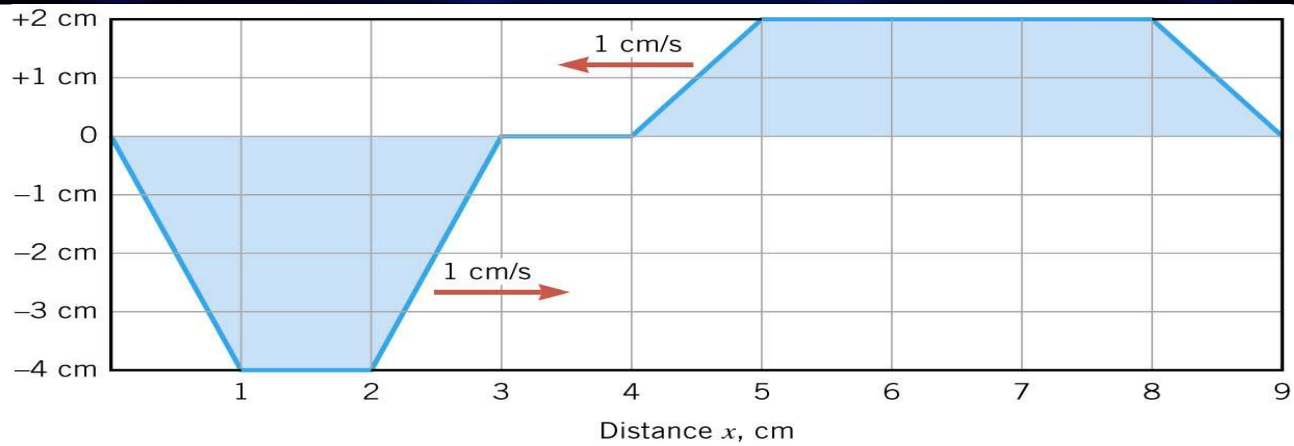
- When two or more waves are present simultaneously at the same place, the resultant disturbance is the sum of the disturbances from individual waves

10-02 Superposition and Interference



Try to demonstrate with spring or wave tank

10-02 Superposition and Interference

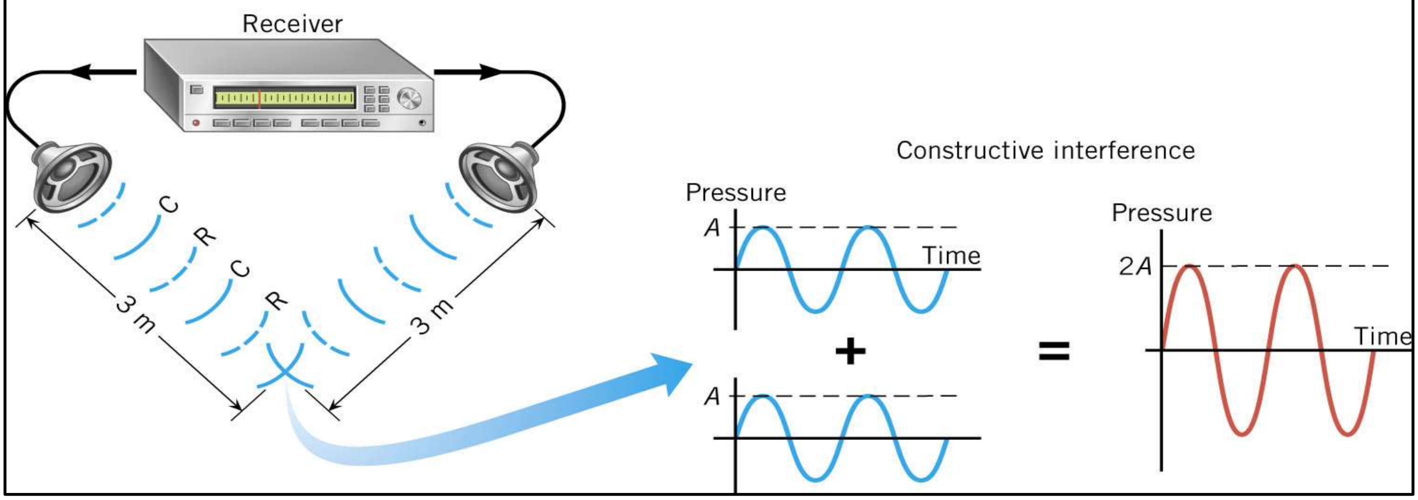


- After 2 seconds, what is the height of the resultant pulse at x = 2, 4, and 6 cm?

Draw the result on the pull down graph
0, -2, 2

10-02 Superposition and Interference

- Imagine that there are 2 speakers facing each other. Both speakers produce the same sound at the same time. λ = 1 m

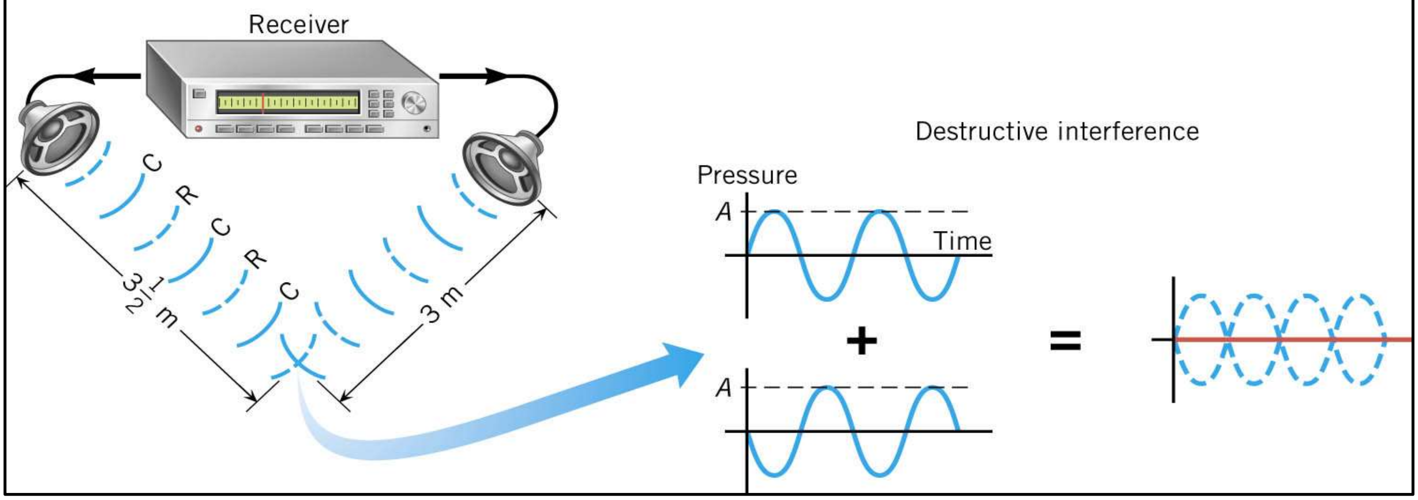


At a point between the speakers where each of the sounds have moved full wavelengths

- Condensation meats condensation and rarefaction meets rarefaction all the time
- Linear superposition says the sound louder
- Called constructive interference (exactly in phase)

10-02 Superposition and Interference

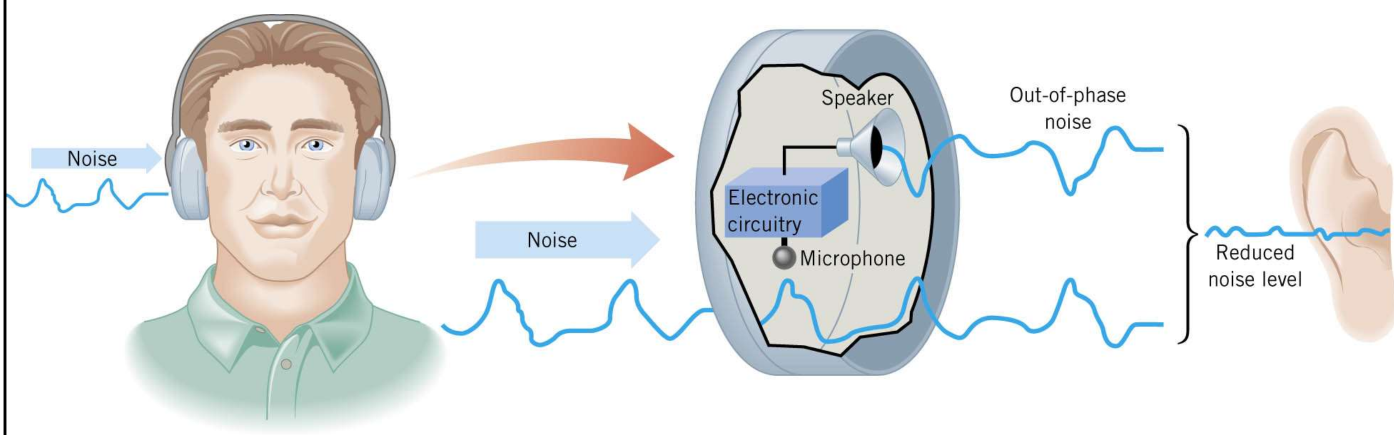
- One of the speakers is moved back half a wavelength



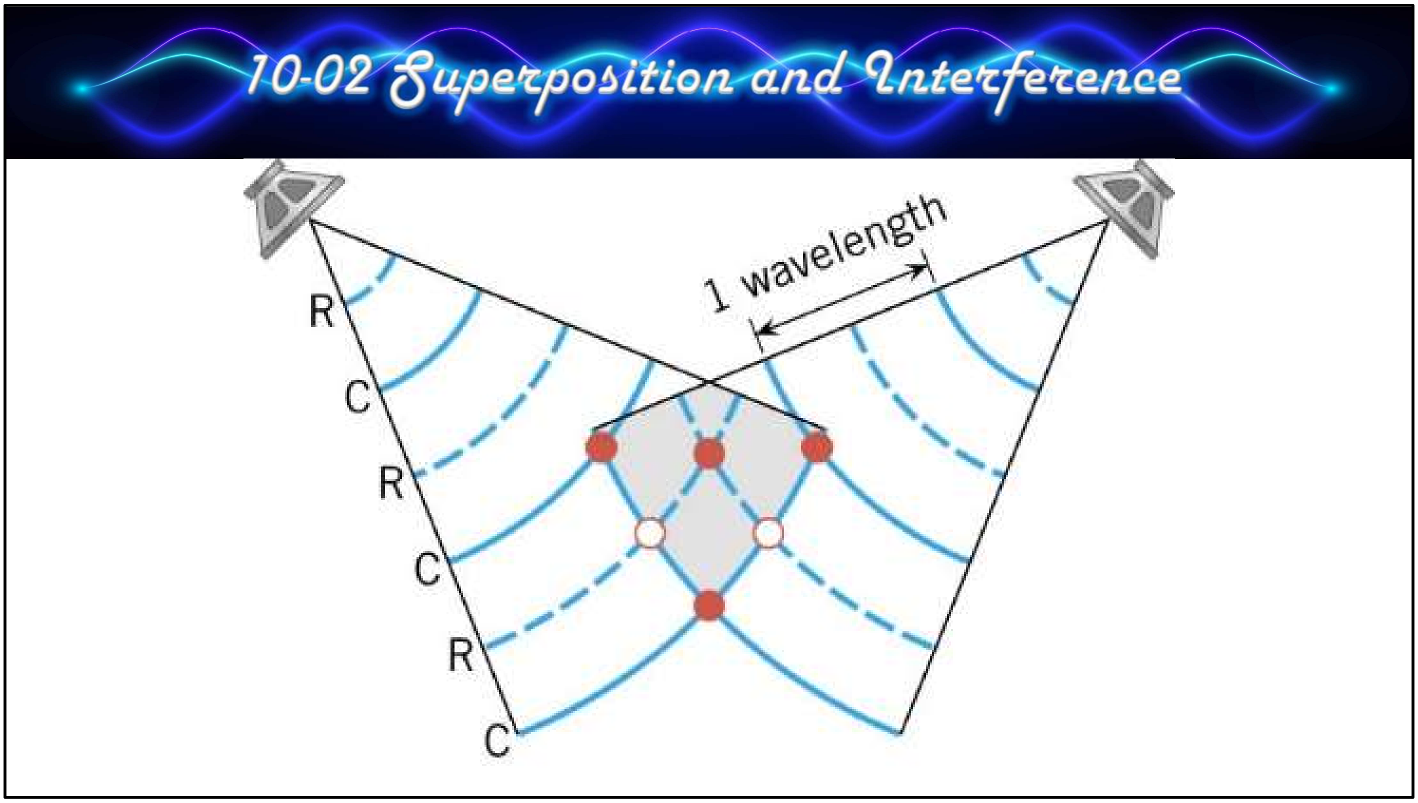
Now a condensation always meets a rarefaction, so cancel into nothing
Called Destructive interference (exactly out of phase)

Sound Wave Interference

10-02 Superposition and Interference



A microphone hears the noise
The electronics invert the noise
A speaker plays the inverted noise and destructive interference results so you don't hear much

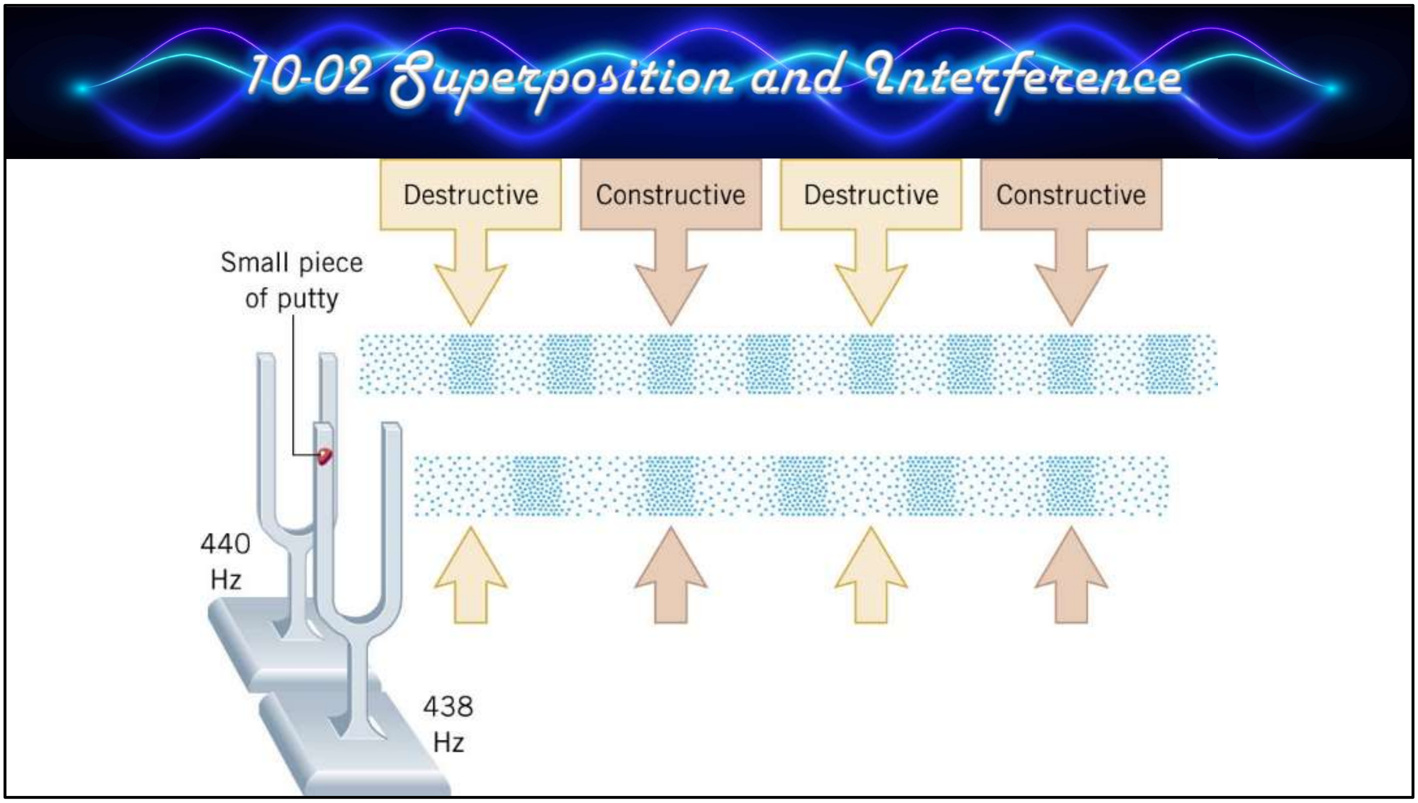


Solid lines are condensations, dashed lines are rarefactions
2 fixed speakers
where two condensations or rarefactions meet = constructive interference (red dots)
Where a condensation and rarefaction meet = destructive interference (white dots)
So as you move throughout the room the noise intensities change depending on your position
Follows law of conservation of energy

- At constructive interference → twice as much energy
- At destructive interference → no energy
- Add it all up and you get constant energy (1 + 1 = 2 + 0)

10-02 Superposition and Interference

- Beats
  - When two frequencies are the same
  - Constructive and Destructive Interference give twice the amplitude or no amplitude
  - What if the two frequencies are just slightly different?



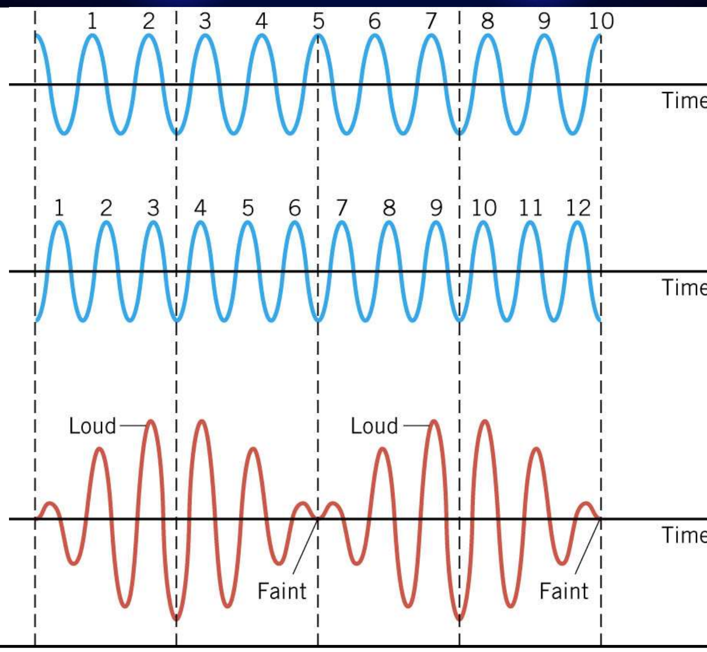
When the frequencies are slightly different, Constructive and destructive interference still happens

Where two condensations are at the same place, you get louder

Where 1 condensation and 1 rarefaction are at the same place, you get softer

You get some places with loud and some soft and in between

10-02 Superposition and Interference



What the ear hears is the rising and falling of volume of the combined frequency
How often the loudness rises and falls is the **beat frequency**
Beat frequency obtained from subtracting the two frequencies of the sounds.
In the picture, the number above each blue wave indicates the number of complete cycles

The top wave is 10 Hz, the bottom is 12 Hz

The beat frequency is 12 – 10 = 2 Hz as seen in the red wave

10-02 Superposition and Interference

- Beat Frequency = difference of the two source frequencies
- Beats = $|f_1 - f_2|$

10-02 Superposition and Interference

- A simple way to tune musical instruments is with beats
- If the notes are out of tune, you hear beats
- Adjust the tuning and try again
- If the frequency of the beats is higher, adjust the other way
- Keep adjusting until there are no more beats

10-02 Superposition and Interference

- Two car horns have an average frequency of 420 Hz and a beat frequency of 40 Hz. What are the frequencies of both horns?

- 440 Hz, 400 Hz

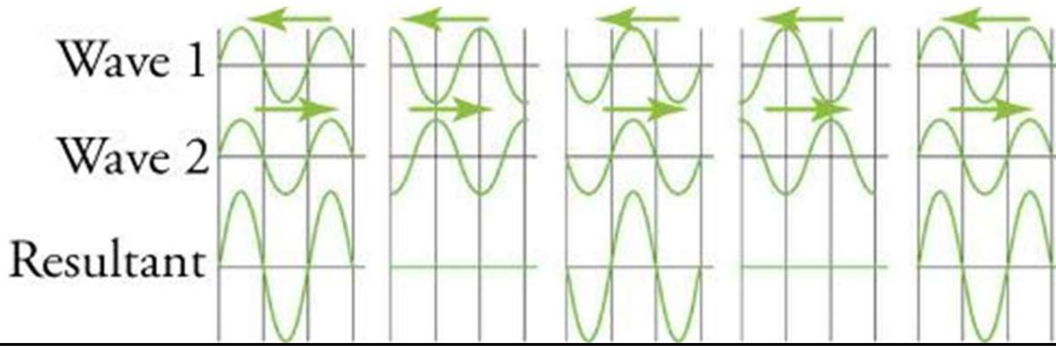
$$f_{ave} = \frac{f_1 + f_2}{2}$$
$$f_B = f_1 - f_2$$

$$420\ Hz = \frac{f_1 + f_2}{2}$$
$$40\ Hz = f_1 - f_2$$

$$840\ Hz = f_1 + f_2$$
$$\underline{40\ Hz = f_1 - f_2}$$
$$880\ Hz = 2f_1$$
$$f_1 = 440\ Hz$$
$$f_2 = 400\ Hz$$

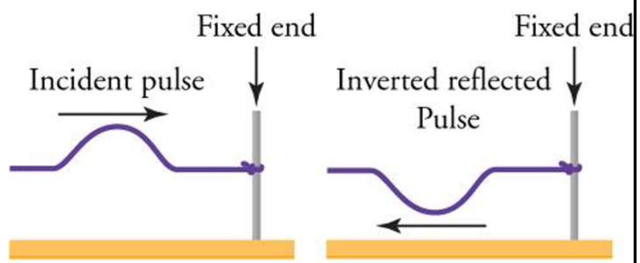
10-02 Superposition and Interference

- Standing Waves
  - Waves that don't appear to move
  - Formed by the superposition of two waves moving in opposite directions
  - If the waves have the same amplitude and wavelength, then they alternate between constructive and destructive interference

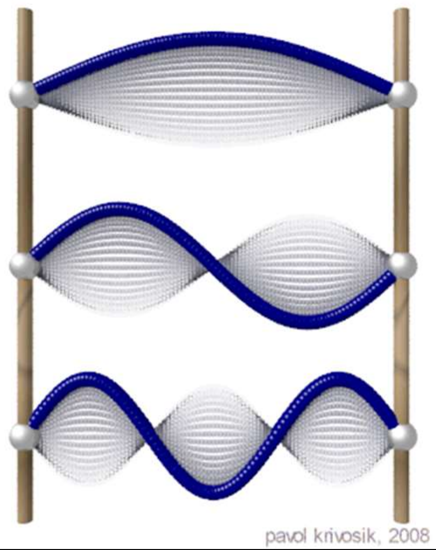


10-02 Superposition and Interference

- How Standing Waves are Created
- The wave travels along the string until it hits the other end
- The wave reflects off the other end and travels in the opposite direction, but upside down
- The returning wave hits the vibrating end and reflects again (this side the wave is right side up)
- If the timing is just right the reflecting wave and the new wave will coincide



10-02 Superposition and Interference

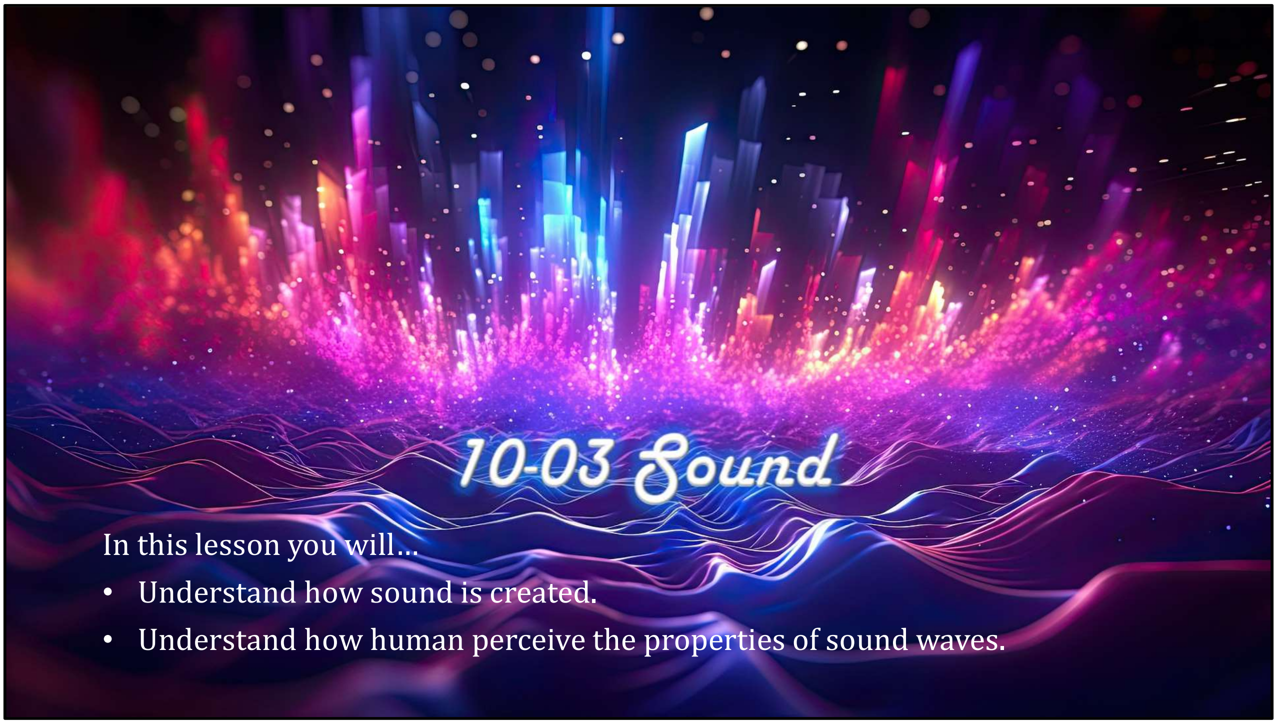


- One end of a string is attached to a fixed point.
- The other end is vibrated up and down.
- The standing wave is formed.
- Nodes – No move
- Antinodes – most movement

10-02 Homework

- Don't beat around the bush, start the problems now!

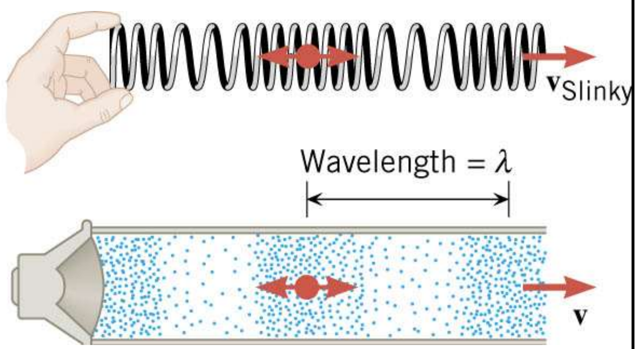
- Read
    - OpenStax College Physics 2e 17.1-17.2
    - OR
    - OpenStax High School Physics 14.1, 2



OpenStax High School Physics 14.1, 2
OpenStax College Physics 2e 17.1-17.2

10-03 Sound

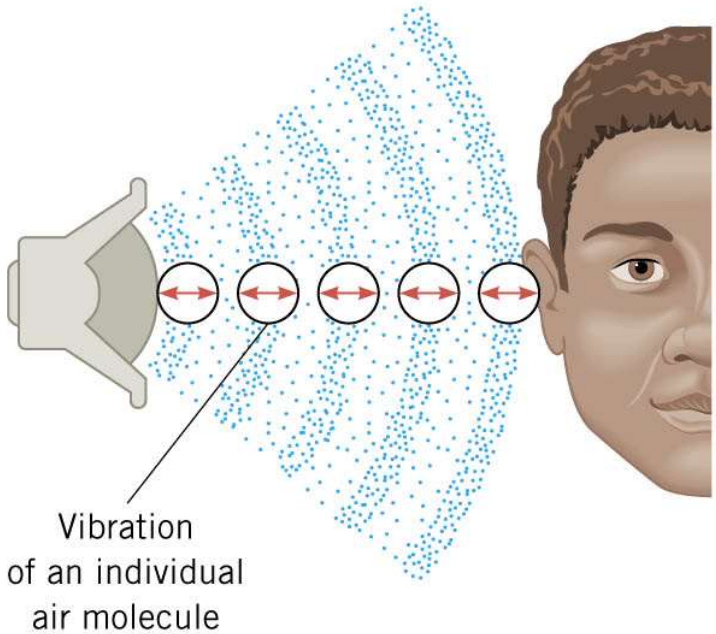
- How sound is made
  - Some vibrating object like a speaker moves and compresses the air
  - Air pressure rises called ***Condensation***
  - Condensation moves away at speed of sound
  - Object moves back creating less air pressure called ***Rarefaction***
  - Rarefaction moves away at speed of sound
  - Particles move back and forth



Maybe have big speaker with bouncing something on it

10-03 Sound

- Distance between consecutive condensations or rarefactions is wavelength
- String or speaker makes air molecule vibrate
- That molecule pushes the next one to vibrate and so on
- When it hits the ear, the vibrations are interpreted as sound



10-03 Sound

- 1 cycle = 1 condensation + 1 rarefaction
- Frequency = cycles / second
- 1000 Hz = 1000 cycles / second

- Each frequency has own tone
    - Sounds with 1 frequency called *Pure Tone*

- Healthy young people can hear frequencies of 20 to 20,000 Hz

10-03 Sound

- Brain can interpret frequency as pitch
  - High freq = high pitch
  - Subjective because most people don’t have perfect pitch

- Some electronic devices can produce and detect exact frequencies

10-03 Sound

- The condensations have more pressure than the rarefactions
- Amplitude = highest pressure

- Typical conversation, Amp = 0.03 Pa
- Atmospheric air pressure = 101,000 Pa

- Loudness is ear’s interpretation of pressure amplitude

Loudness is subjective, pressure is not.
Measure pressure to see if damaging

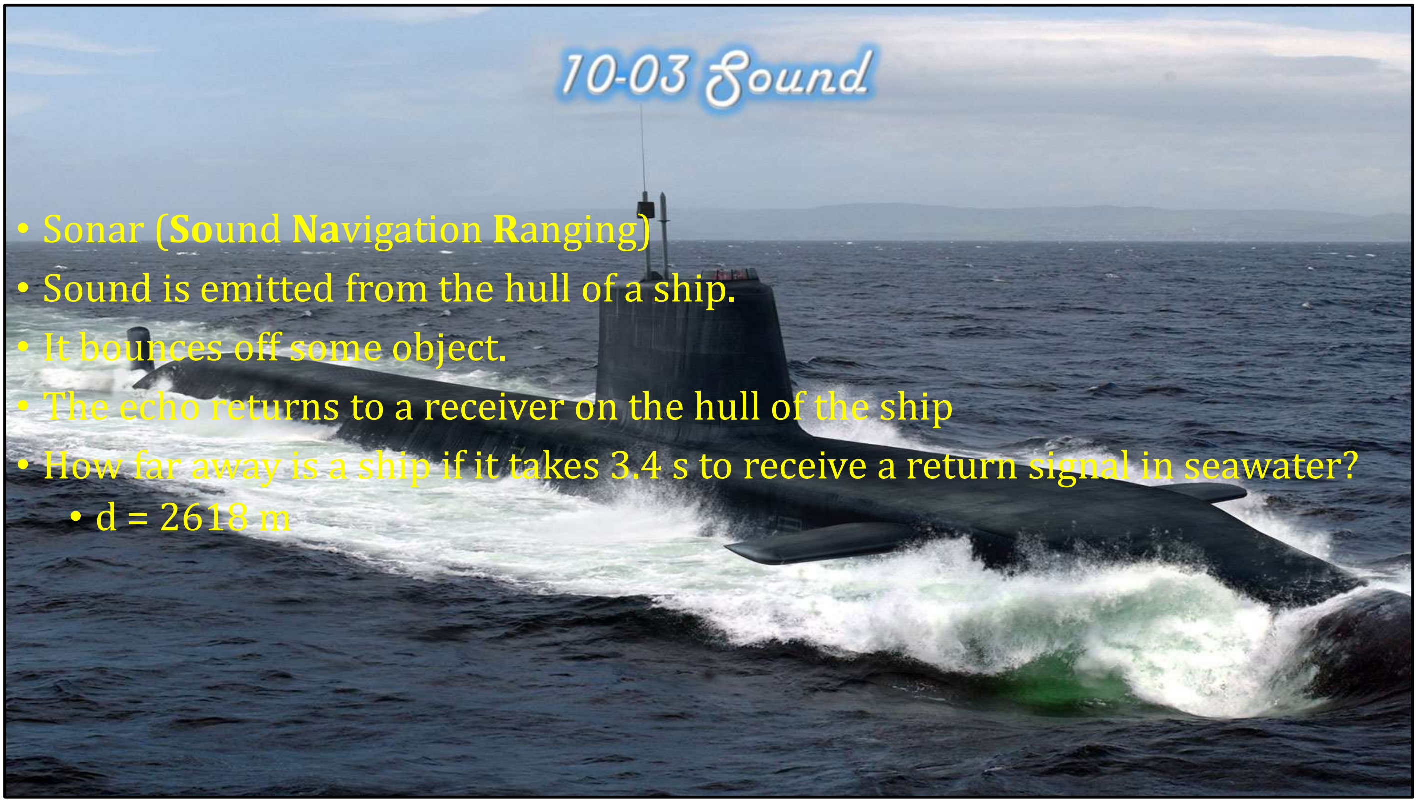
10-03 Sound

- For all waves

$$v_w = f\lambda$$

- Sound is transmitted only when molecules collide
- Sound travels slowest in gases, faster in liquids, and fastest in solids

- Air at 20 °C → 343 m/s
- Fresh Water → 1482 m/s
- Steel → 5960 m/s



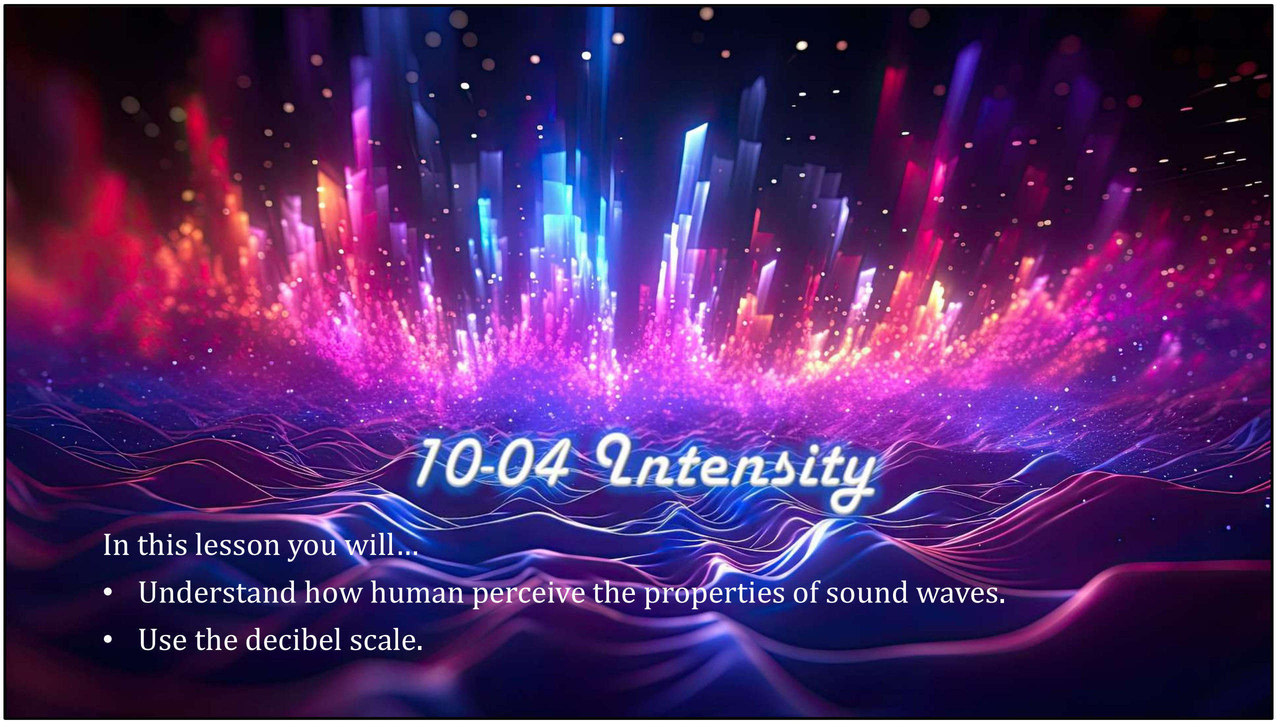
$$v = 1540\ m/s$$

$$x = vt \rightarrow x = \left(1540 \frac{m}{s}\right)(3.4\ s) \rightarrow x = 5236\ m$$

This the distance to the object and back again. So divide it by 2 → $x = 2618\ m$

10-03 Homework

- Speed your way through these sound problems.
- Read
  - OpenStax College Physics 2e 17.3
  - OR
  - OpenStax High School Physics 14.1, 2



OpenStax High School Physics 14.1,2
OpenStax College Physics 2e 17.3

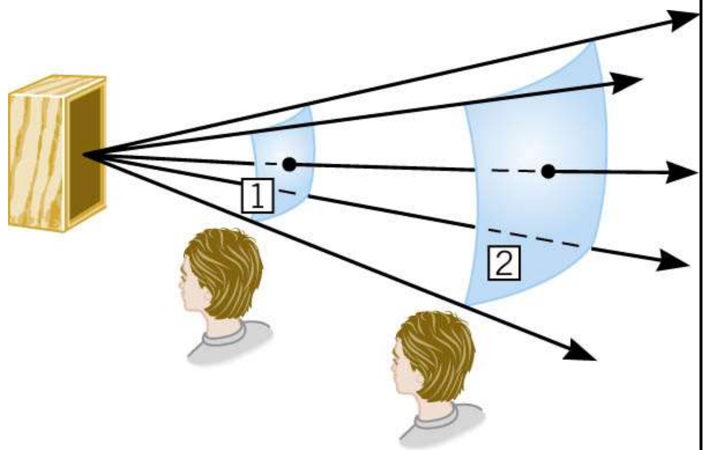
10-04 Intensity

- Sound waves carry energy that can do work
- Amount of energy transported per second = power
- Units: J/s = W

Work example causing ear drum to vibrate

10-04 Intensity

- As sound moves away from a source, it spreads out over a larger and larger area
- As the areas get bigger, intensity at any 1 point is less
- $I = \frac{P}{A}$
- Units: W/m^2



10-04 Intensity

10-04 Intensity

- Intensity is proportional to amplitude^2

$$I = \frac{(\Delta p)^2}{2\rho v_w}$$

  - where
    - Δp = pressure amplitude
    - ρ = density of the medium
    - v_w = speed of the wave

Used lowercase p for Pressure to keep from confusing with Power

10-04 Intensity

Sound Level and Decibels

- Unit of measure to compare two sound intensities.
- Based on how human ear perceives loudness.
- If you double the intensity, I, the sound isn't twice as loud.
- Use a logarithmic scale

10-04 Intensity

- Intensity Level

$$\beta = (10\ dB)\log\left(\frac{I}{I_0}\right)$$

  - Where
    - β = intensity level β
    - I and I_0 are intensities of two sounds
      - I_0 is usually 1.0×10^{-12} W/m^2
  - Unit: dB (decibel)
- An intensity level of zero only means that $I = I_0$ since log (1) = 0

I_0 is the threshold of hearing

10-04 Intensity

- Intensity can be measured
- Loudness is simply how ear perceives

- Doubling intensity does not double loudness

10-04 Intensity

- You double the intensity of sound coming from a stereo. What is the change in loudness?
- β = 3 dB
- Experiment shows that if the intensity level increases by 10 dB, the sound will seem twice as loud.
- See Table 17.2

$$\beta = (10\ dB)\log\left(\frac{I}{I_0}\right)$$
$$\beta = (10\ dB)\log\left(\frac{2I}{I}\right)$$
$$\beta = (10\ dB)\log 2$$
$$\beta \approx 3\ dB$$

Thus a 200 W stereo system will only sound twice as loud as a 20 W system.

10-04 Intensity

- What is the intensity of a 20 dB sound?

- $I = 10^{-10}\ W/m^2$

$$\beta = (10\ dB)\log\left(\frac{I}{I_0}\right)$$

$$20\ db = (10\ dB)\log\left(\frac{I}{10^{-12}\ W/m^2}\right)$$

$$2 = \log\left(\frac{I}{10^{-12}\ W/m^2}\right)$$

$$10^2 = \frac{I}{10^{-12}\ W/m^2}$$

$$I = 10^{-10}\ W/m^2$$

10-04 Homework

- This is intense!

- Read
  - OpenStax College Physics 2e 17.4
  - OR
  - OpenStax High School Physics 14.3

OpenStax High School Physics 14.3
OpenStax College Physics 2e 17.4

10-05 Lab

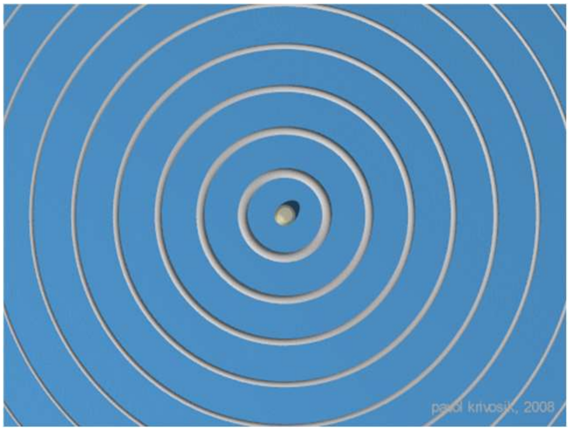
- Do the 10-04 Doppler Effect Lab

10-05 Doppler Effect

- Have you ever listened to a ambulance drive by quickly with their lights and sirens going?
- What did it sound like?
- High pitch as they were coming, low pitch as they were leaving.
- Called Doppler effect after Christian Doppler who first labeled it.

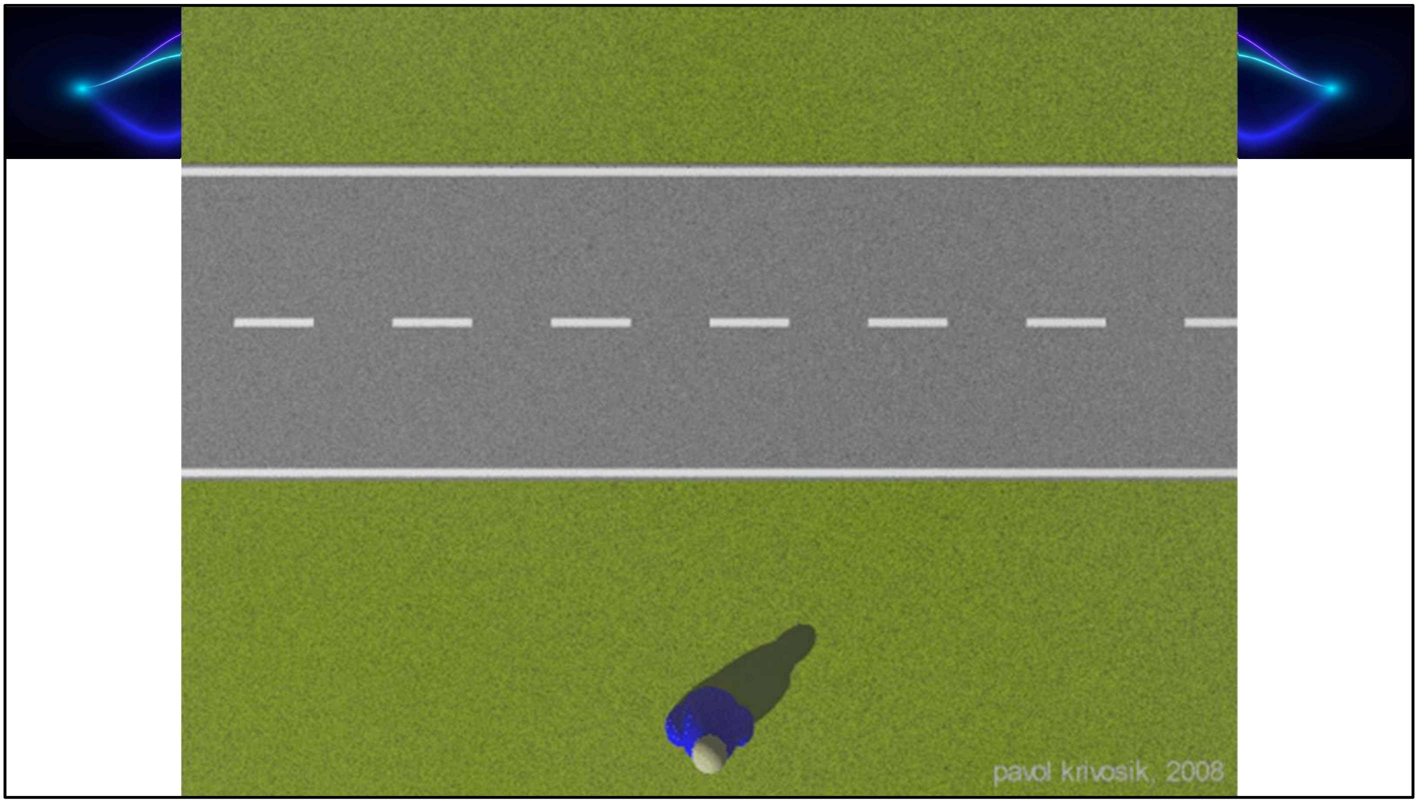
10-05 Doppler Effect

Stationary source of sound



Moving source of sound

When the truck is still, the sounds waves move outward in all the directions, the same speed



When the truck is moving.
It produces a condensation, moves, produces another condensation, moves, etc.
Since it moves between condensations, they are closer together in front of the truck and farther apart behind the truck.
Higher freq (short λ) = higher pitch
Lower freq (long λ) = lower pitch

10-05 Doppler Effect

- Deriving the formula
- Moving toward object

- $\lambda' = \lambda - v_s T$

- Where
  - λ = wavelength of wave
  - λ' = perceived wavelength
  - v_s = velocity of ***s***ource
  - T = Period of wave

The perceived wavelength is shorted by the distance the source moves in one period.
(Period is time between condensations)

10-05 Doppler Effect

- $f_o = \frac{v_w}{\lambda'} = \frac{v_w}{\lambda - v_s T}$
- $\lambda = \frac{v_w}{f_s}$ $\quad T = \frac{1}{f_s}$
- $f_o = f_s \left(\frac{v_w}{v_w - v_s}\right)$

- λ' = perceived wavelength
- f_o = frequency observed
- f_s = frequency of source
- v_w = speed of wave
- v_s = speed of source

10-05 Doppler Effect

- Moving Observer
- Encounters more condensations than if standing still

- $f_o = f_s \left(\frac{v_w + v_o}{v_w} \right)$

Notice the differences between the two formulas

10-05 Doppler Effect

- General Case
- Combine the two formulas
- Both observer and source can be moving

$$f_o = f_s \left(\frac{v_w \pm v_o}{v_w \mp v_s} \right)$$

- WARNING!
  - v_w, v_s, and v_o are signless
  - Use the top signs when that object is moving ***towards*** the other object

10-05 Doppler Effect

- You are driving down the road at 20 m/s when you approach a car going the other direction at 15 m/s with their radio playing loudly. If you hear a certain note at 600 Hz, what is the original frequency? (Assume speed of sound is 343 m/s)

- 542 Hz

$$f_o = f_s\left(\frac{v_w \pm v_o}{v_w \mp v_s}\right)$$

$$600\ Hz = f_s\left(\frac{343\frac{m}{s} + 20\frac{m}{s}}{343\frac{m}{s} - 15\frac{m}{s}}\right)$$

$$600\ Hz = f_s(1.1)$$

$$f_s = 542\ Hz$$

10-05 Doppler Effect

- A duck is flying overhead while you stand still. As it moves away, you hear its quack at 190 Hz. Because you are a brilliant naturalist, you know that this type of duck quacks at 200 Hz. How fast is the duck flying?

- 18.1 m/s (40 mph)

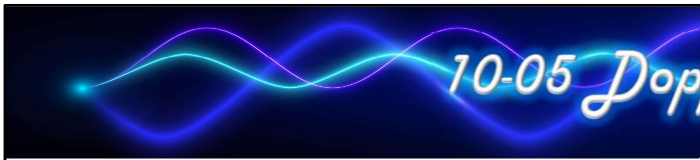
$$f_o = f_s\left(\frac{v_w \pm v_o}{v_w \mp v_s}\right)$$

$$190\ Hz = 200\ Hz\left(\frac{343\frac{m}{s} + 0}{343\frac{m}{s} + v_s}\right)$$

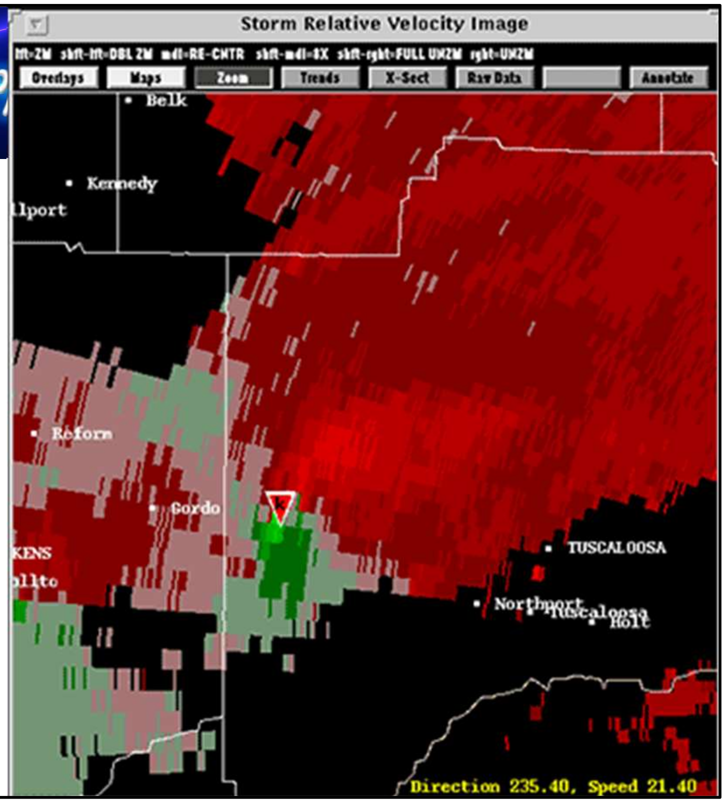
$$65170\ \frac{m}{s} + 190\ v_s = 68600\frac{m}{s}$$

$$190\ v_s = 3430\frac{m}{s}$$

$$v_s = 18.1\frac{m}{s}$$



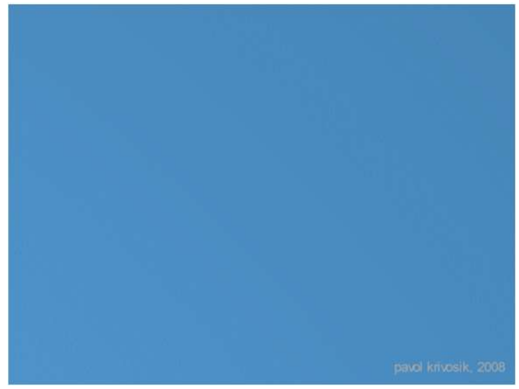
- Weather Radar
  - Sends out radio waves
  - Wave bounce off water drops in storms
  - Radar receives echoes
  - Computer checks to compare the frequencies
  - Can compute to see how fast the clouds are spinning



Water on one side of tornado move away, water on other side move towards radar
See the triangle in the picture.

10-05 Doppler Effect

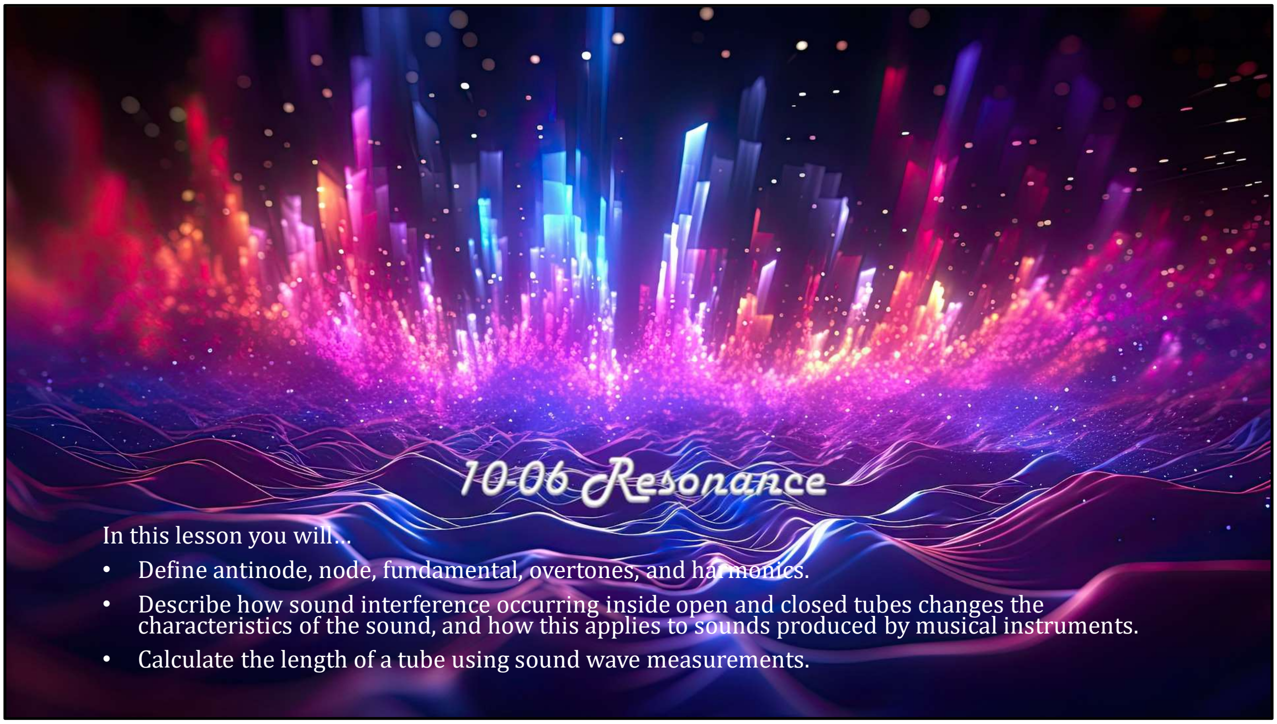
- Sonic boom when the plane goes the speed of sound, so all the forward moving waves pile up in one spot.



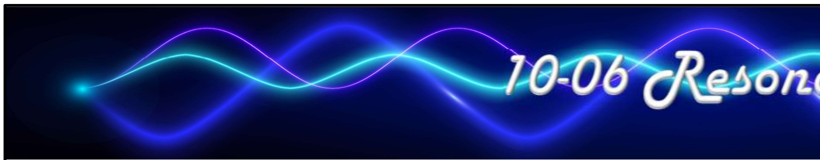
10-05 Homework

- Move yourselves to do these exercises

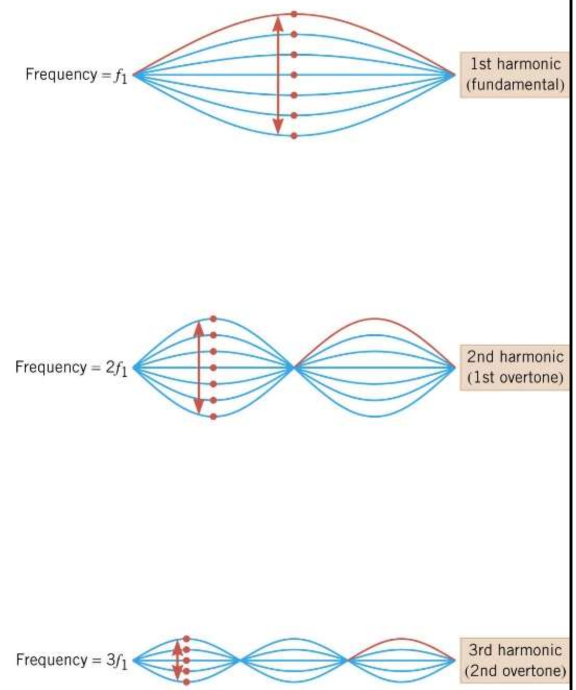
- Read
  - OpenStax College Physics 2e 17.5
  - OR
  - OpenStax High School Physics 14.4



OpenStax High School Physics 14.4
OpenStax College Physics 2e 17.5



- One end of a string is attached to a fixed point.
- The other end is vibrated up and down slightly.
- The standing wave is formed.
- Nodes – No move
- Antinodes – most movement



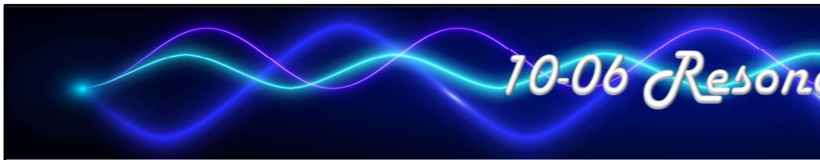
10-06 Resonance

- The wave travels along the string until it hits the other end
- The wave reflects off the other end and travels in the opposite direction, but upside down
- The returning wave hits the vibrating end and reflects again (this side the wave is right side up)
- Unless the timing is just right the reflecting wave and the new wave will not coincide
- When they do coincide, the waves add due to constructive interference
- When they don’t coincide; destructive interference

Why its reflected upside down. → the string pulls up on the wall, by Newton’s reaction force, the wall pulls down on the string

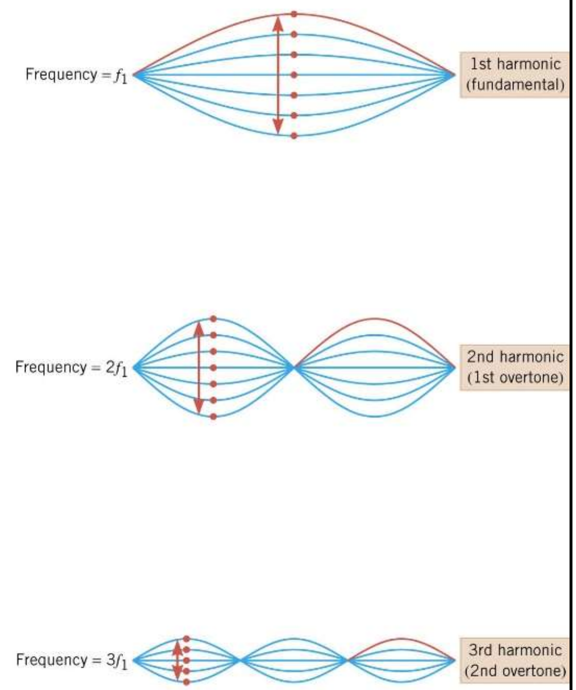
10-06 Resonance

- Harmonics
  - When you vibrate the string faster, you can get standing waves with more nodes and antinodes
  - Standing waves are named by number of antinodes
    - 1 antinode → 1^{st} harmonic (fundamental freq)
    - 2 antinodes → 2^{nd} harmonic (1^{st} overtone)
    - 3 antinodes → 3^{rd} harmonic (2^{nd} overtone)



- f_1 = fundamental frequency (1st harmonic)
- $f_2 = 2f_1$ (2nd harmonic)
- $f_3 = 3f_1$ (3rd harmonic)

- Harmonics Example
  - If the fundamental is 440 Hz (concert A)
  - 2nd harmonic = 2(440 Hz) = 880 Hz (High A)
  - 3rd harmonic = 3(440 Hz) = 1320 Hz



Multiply the fundamental frequency by an integer to obtain that integer's harmonic

10-06 Resonance

- To find the fundamental frequencies and harmonics of a string fixed at both ends

$$f_n = n\left(\frac{v_w}{2L}\right)$$

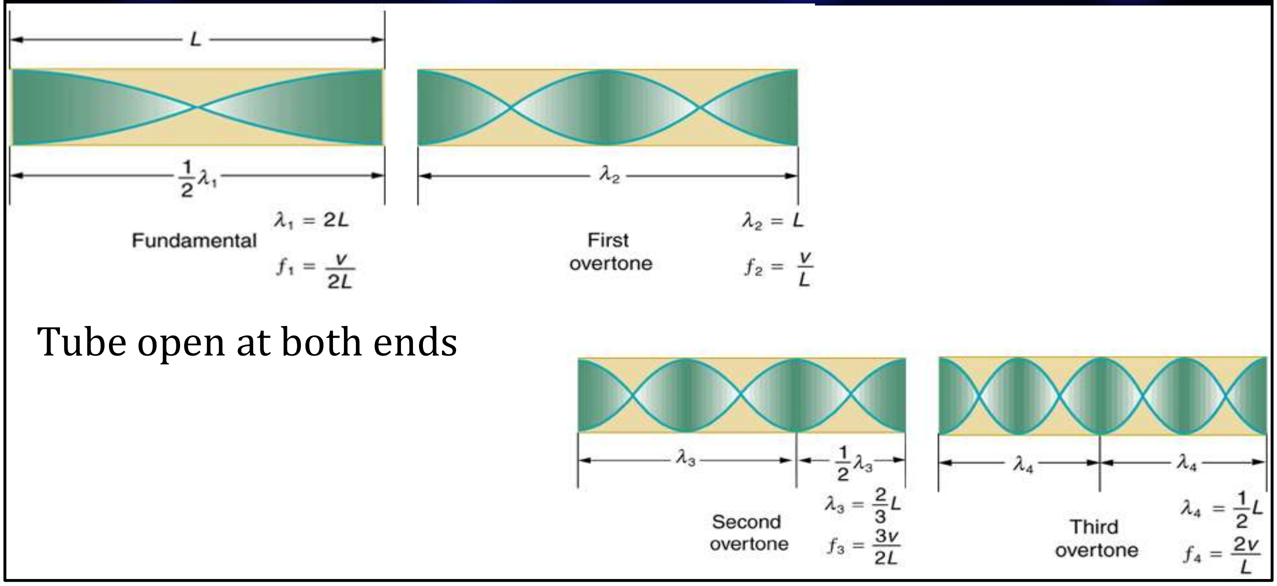
- Where
  - f_n = frequency of the n^{th} harmonic
  - n = integer (harmonic #)
  - v_w = speed of wave
  - L = length of string

10-06 Resonance

- Just like stringed instruments rely on standing transverse waves on strings
- Wind instruments rely on standing longitudinal sound waves in tubes
- The waves reflect off the open ends of tubes
- One difference at the ends are antinodes instead of nodes

Demonstrate antinodes at the end by making standing waves in a string by dangling a string and shaking it

10-06 Resonance



Tube open at both ends

10-06 Resonance

- Formula for Tube Open at Both Ends
  - Distance between antinodes = ½ λ
  - Tube must be integer number of ½ λ
    - $L = n\left(\frac{1}{2}\lambda_n\right)$ or $\lambda_n = \frac{2L}{n}$
  - $f_n = \frac{v_w}{\lambda_n}$

$$f_n = n\left(\frac{v_w}{2L}\right)$$

Demonstrate with tube

10-06 Resonance

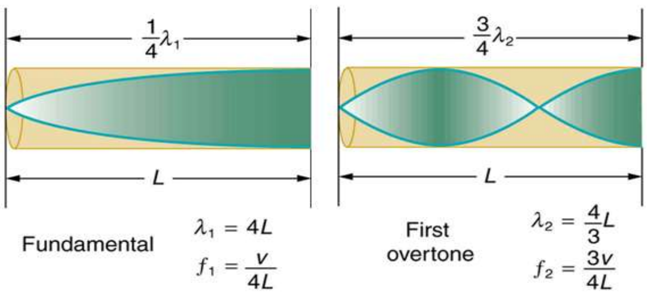
- What is the lowest frequency playable by a flute that is 0.60 m long if that air is 20 °C.

- f = 285.8 Hz

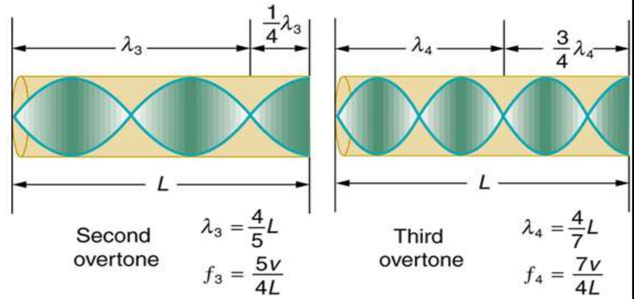
$$n = 1$$

$$f = 1\left(\frac{343\frac{m}{s}}{2(.6\,m)}\right) = 285.8\,Hz$$

10-06 Resonance



Tube open at one end



10-06 Resonance

- Tube Open at One End
  - Node at the closed end
  - Antinode at the open end
  - At fundamental frequency L = ¼ λ
  - The 2nd harmonic adds one more node or ½ λ
  - Thus the lengths are *odd integer* multiples of ¼ λ

$$f_n = n\left(\frac{v_w}{4L}\right)$$

  - Only odd harmonics

Where n is odd integers

10-06 Homework

- Try blowing your way through these problems