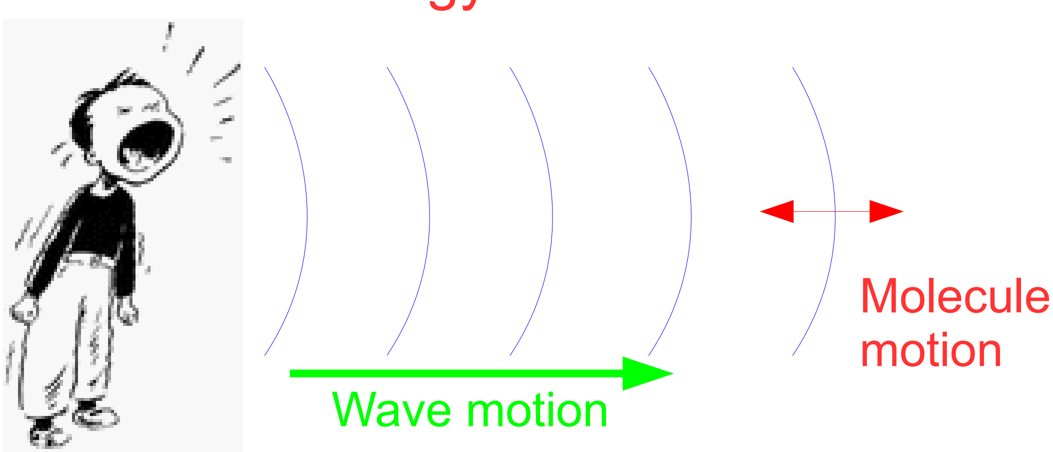
MECHANICAL WAVES AND SOUND

Waves

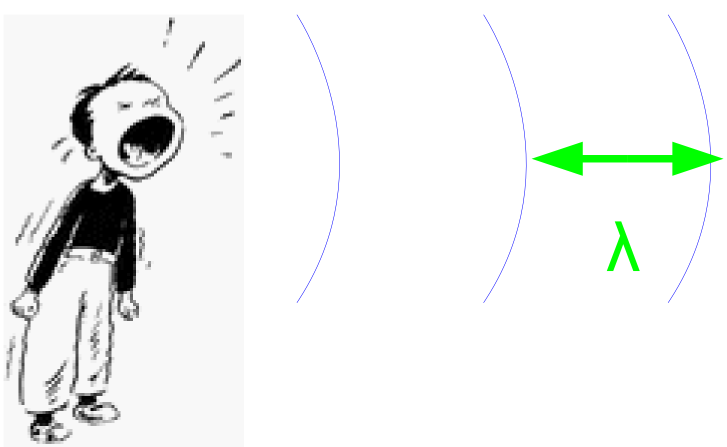
- Substances have a "stable equilibrium state"
  - Uniform pressure everywhere throughout the substance
  - "Atomic springs" are at their equilibrium length
  - Can make a wave by disturbing the equilibrium

- Physics definition of a wave
  - A vibration which moves through a substance
  - Each individual molecule undergoes SHM...
  - ...but energy moves from molecule to molecule



Wavelength

- Vibrational motion repeats itself after one period
  - Notice that the wave is moving during this time
- Wavelength
  - Distance moved by a wave during one period



Wavelength is symbolized by the Greek letter lambda: λ

Wave Speed

$$Wave\,Speed = \frac{wavelength}{period} = wavelength \times frequency \longrightarrow \boxed{v = \lambda f}$$

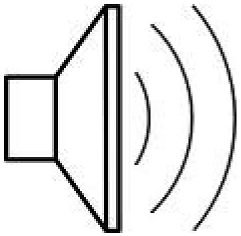
- Calculating wave speed
  - Wave moves one wavelength every period

- Wave speed depends on the substance
  - Called the "medium" of the wave
  - Wave speed is a constant in a specific medium

- So if the frequency of a wave increases...
  - ...Wavelength must decrease!

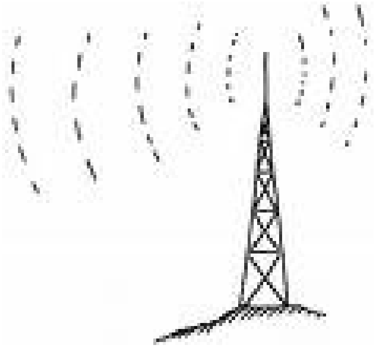
Common Wave Examples

- Sound waves → produced by:
  - Quick changes in pressure
  - Vibrating objects



- Waves on a string:
  - String under tension → "shaking" it produces a wave

- Water surface waves
  - Produced by disturbing a flat water surface



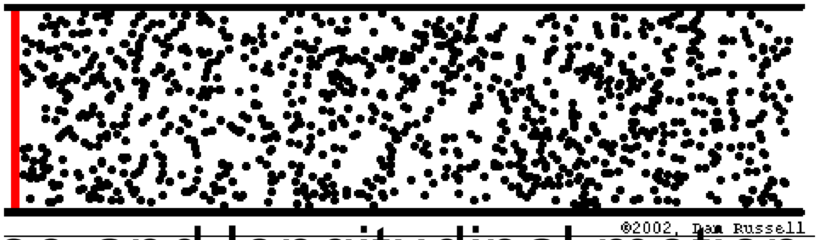
- Electromagnetic waves
  - Produced by "wiggling" charged particles

Transverse vs. Longitudinal Waves

- Two different motions to describe in a wave:
  - Motion of the wave's energy
  - Motion of individual molecules of the wave

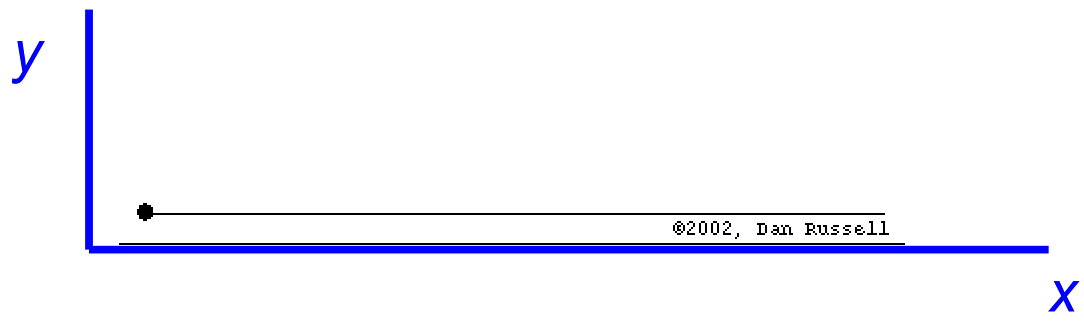
- Transverse waves → Two motions are perpendicular
  - Waves on a string, water surface waves

- Longitudinal waves → Two motions are parallel
  - Sound waves



- Waves can have both transverse and longitudinal motion
  - Earthquakes, ocean waves produce "rolling" motion

Waves On a String



- Medium (string) is 1-Dimensional
  - Relatively simple mathematically → $y(x,t)$
  - Easy to visualize

$$v_{wave} = \sqrt{\frac{F_T}{\mu}}$$

- Wave speed on a string
  - Depends on the string tension F_T and mass density μ
  - *Speed is the same for all frequencies and wavelengths!*

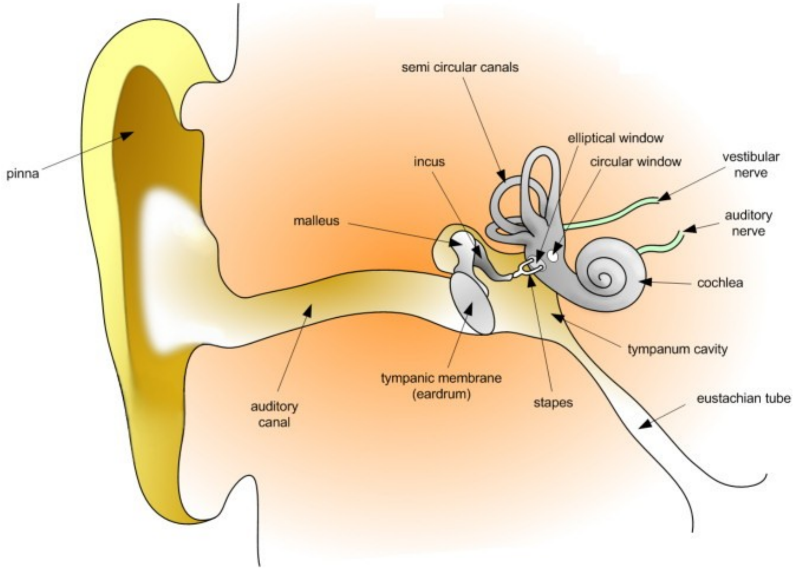
<u>Sound and Hearing</u>

- Sound wave → <u>created</u> by push/pull on a medium
  - Usually by <u>vibrating</u> an object at some frequency
  - Vocal cords;   guitar string;   loudspeaker

- <u>Detecting</u> a sound wave
  - Allow vibrating medium to push/pull on an object...
  - ...and measure the <u>vibrations</u>

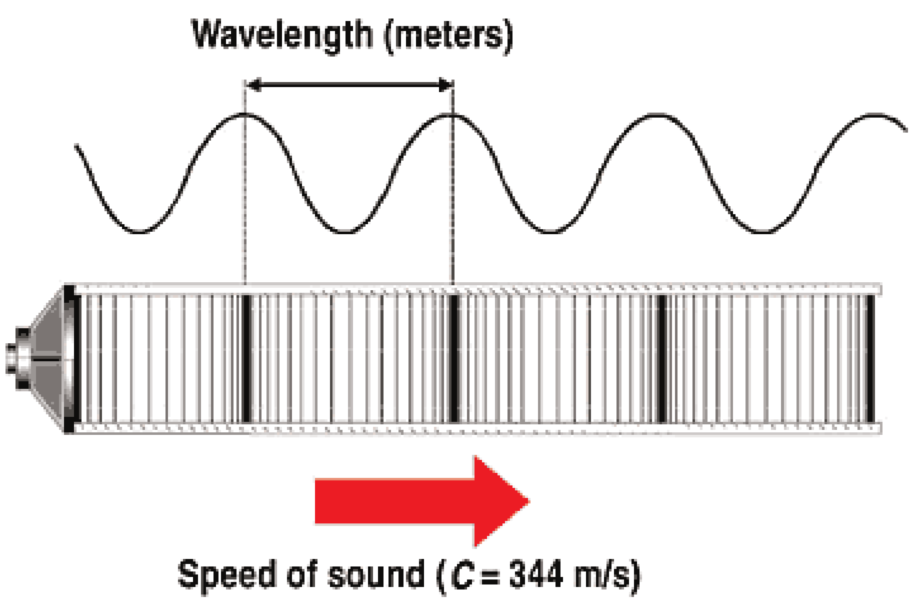
Human ear can detect sound waves with frequencies from 20 Hz to 20,000 Hz

(This range narrows with age)



Compressions and Rarefactions

- Sound is a longitudinal wave
  - Each molecule moves parallel to the energy of the wave
- Molecules are pushed/pulled by air pressure
  - Air is compressed in some spots; stretched in others



Compressed areas are called compressions

Stretched areas are called rarefactions

Speed of Sound Waves

- Two factors affect the speed of sound waves:
  - Density of the medium
  - "Stiffness" of the medium → atomic "springs"
- Solids and liquids are more rigid than gases
  - So sound waves move faster!

- Speed of sound in air
  - About 340 m/sec → varies strongly with temperature
  - Relatively slow → at large distance, can notice delay

Loudness of Sound Waves – Decibels

- Amplitude of sound wave → pressure variations
  - How far above/below atmospheric pressure
- Decibel scale
  - Converts intensity of pressure variations to a "loudness"
  - Far from sound source → intensity weakens

$$I \,\alpha\, \frac{1}{r^2}$$

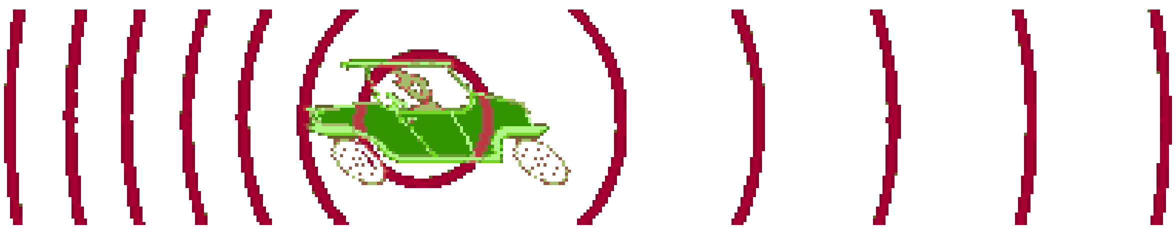
- Decibel scale: Based on human ears
  - Quietest sound a human can hear = 0 dB
  - Normal conversation = 60 dB
  - Loud rock concert = 110 dB

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

$$I_0 = 10^{-12} \frac{W}{m^2}$$

Doppler Effect

- If a wave source or listener moves:
  - Wavelength and frequency of the wave are affected
  - During one wave period → source-listener distance changes



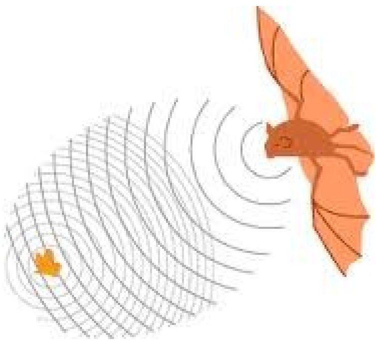
- Source/listener moving toward each other:
  - Wavelength is decreased; frequency is increased

$$f_L = \left(\frac{v \pm v_L}{v \pm v_S}\right) f_S$$

- Source/listener moving away:
  - Wavelength is increased; frequency is decreased

Example: Bat Sonar

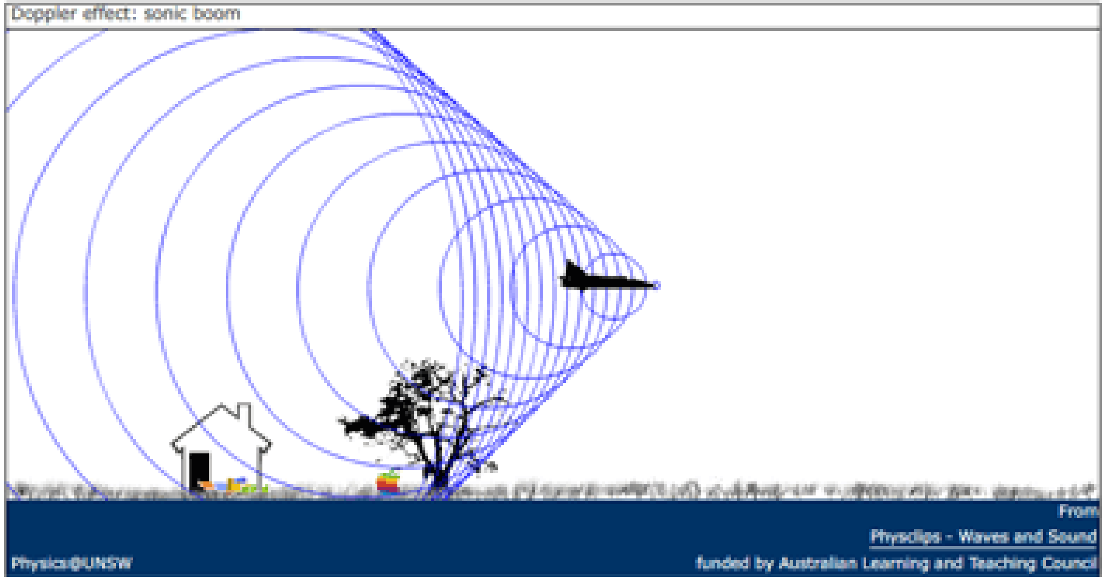
- Bats can locate small objects in the dark
  - Using sound waves!
  - Ultra-high frequency (> 40kHz)

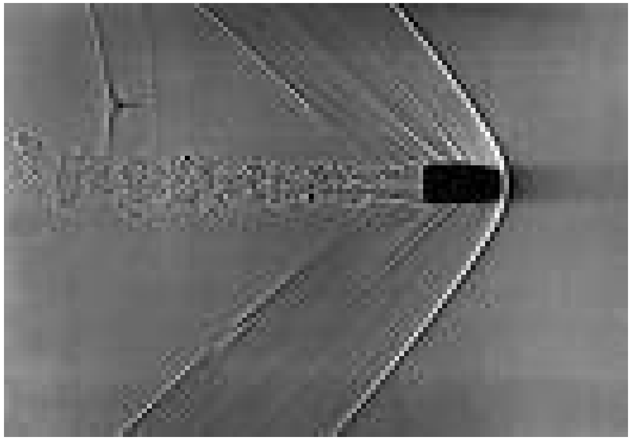


- Can detect location of object using delay time
  - i.e. a bat "knows" the speed of sound
- Can detect velocity of object using Doppler Effect
  - Because reflected wave has different frequency

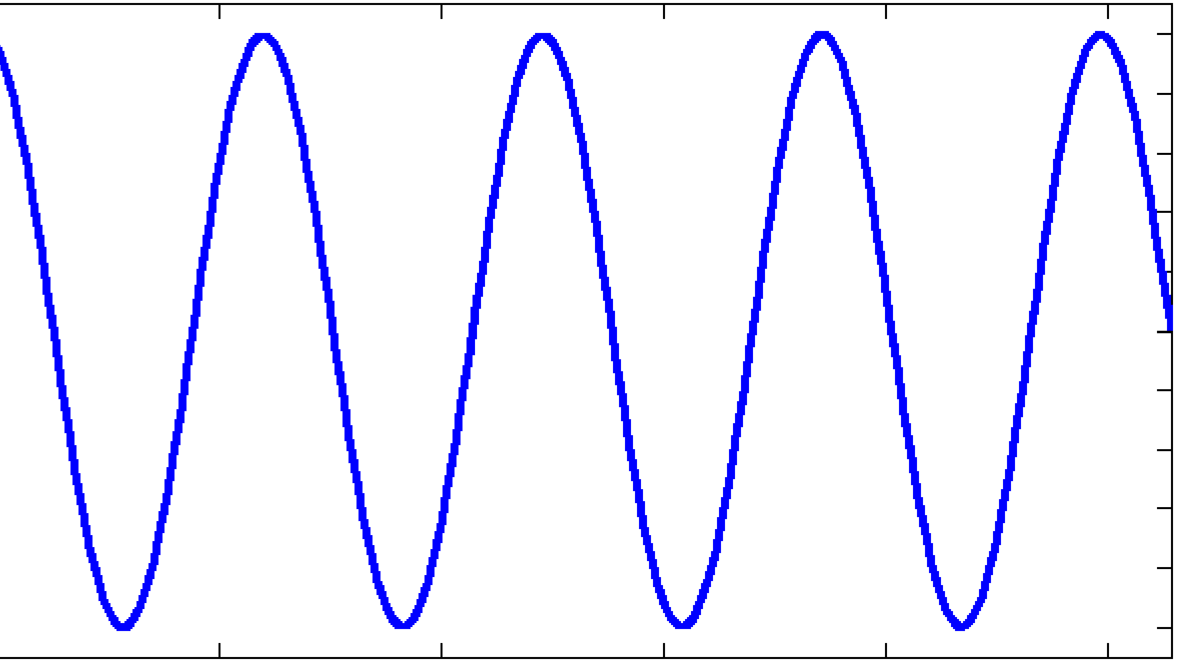
Shock Waves

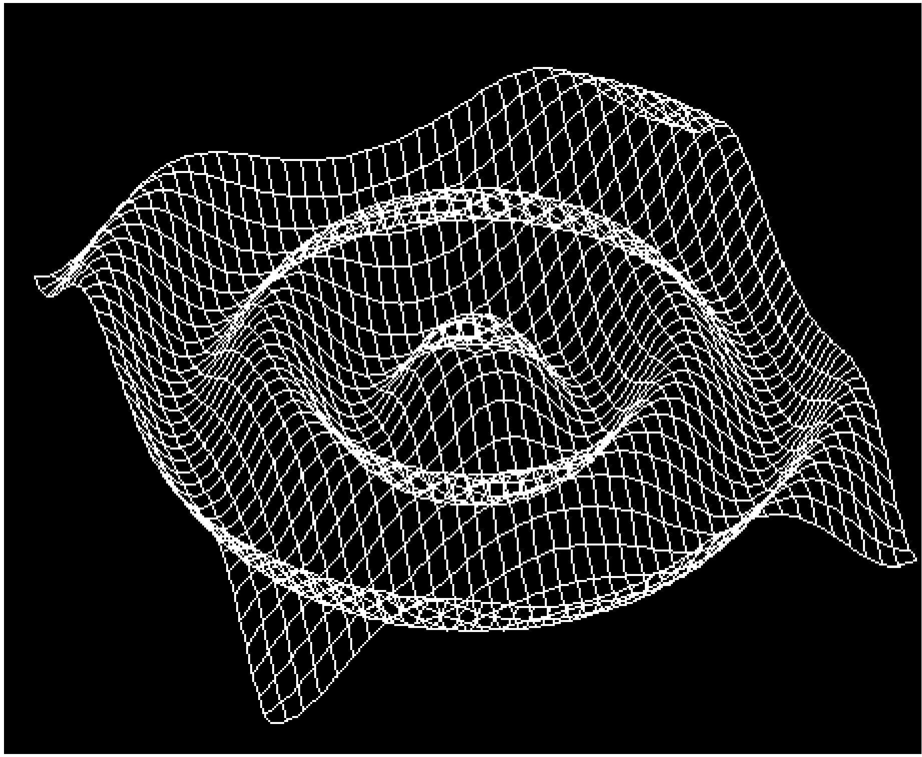
- Source moves through medium → Doppler effect
  - What if a source moves near the speed of sound?
  - Waves start to "overlap" and produce a shock wave
  - Shock waves take up small <u>volume</u> but have large <u>energy</u>





Mathematics of Waves



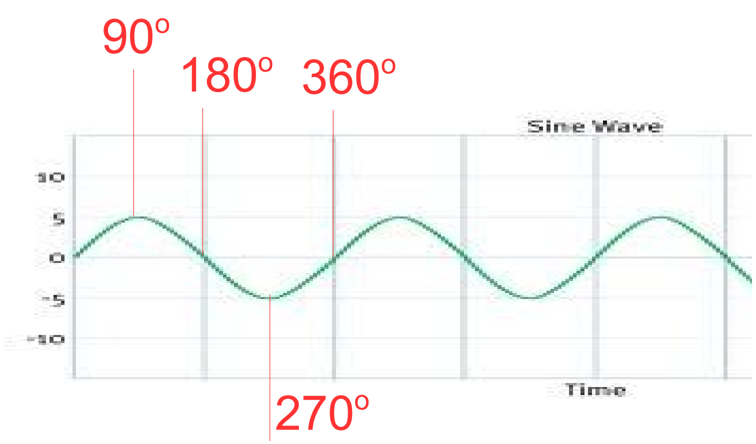


$$y(x,t) = A\sin(2\pi(\frac{t}{T} - \frac{x}{\lambda}))$$

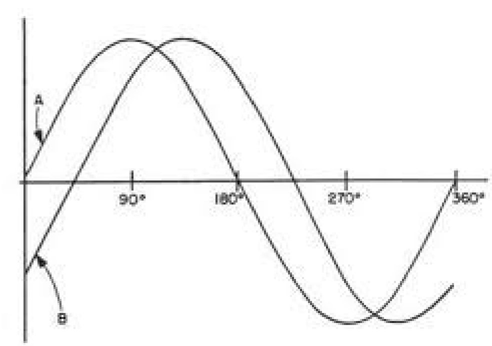
→ Accounts for the shape of the wave and its motion over time

Wave Phase

- "Phase" of a wave
  - Describes how far along in cycle a wave is
- sin() function repeats when argument increases by 360°
  - A whole wavelength has 360° of phase (or 2π radians)

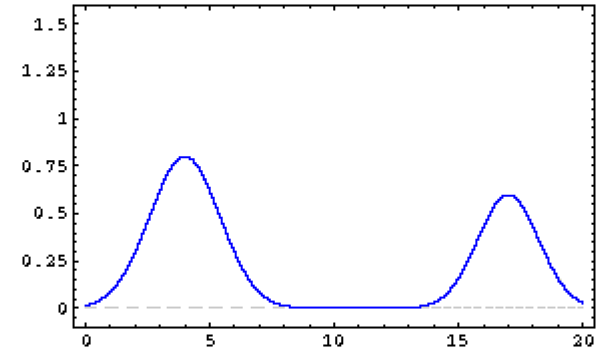


Two waves can have a "phase difference" or "relative phase" as shown below

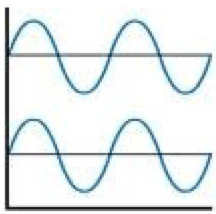


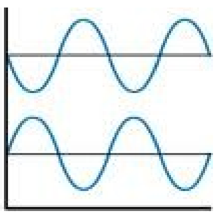
Wave Interference

- What happens when two waves collide?
  - They both push/pull on the medium



- Result is a mix of the two waves





Constructive Interference

- waves are "in phase"

- phase difference = 0

- total wave → large Amp

In General

- 0 < phase difference < 180°

- total wave → medium Amp

Destructive Interference

- waves are out of phase

- phase difference = 180°

- total wave → small Amp

Interference Examples

Path Length Difference

When 2 waves travel different distances to reach a point:

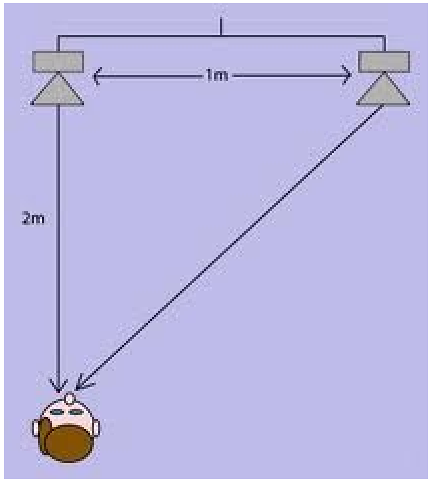
They develop a phase difference

Constructive

$$\Delta L = m\lambda$$

Destructive

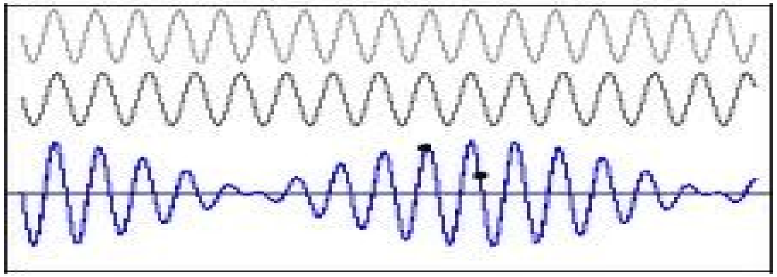
$$\Delta L = (m+\frac{1}{2})\lambda$$



Note: m = any integer (0, 1, 2, ...)

Beats

When adding 2 waves of slightly different frequencies:



Waves alternate between "in phase" and "out of phase"

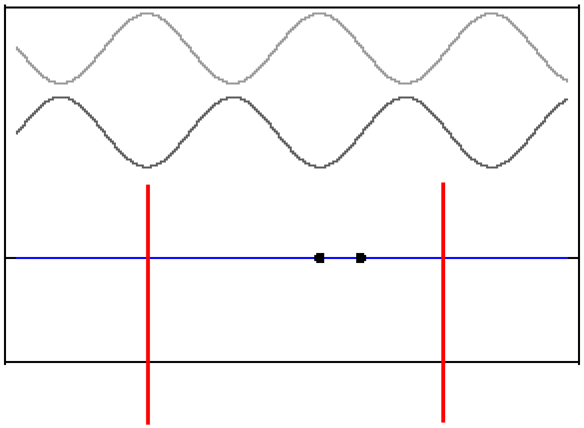
Amplitude goes up and down at "beat frequency"

$$f_{beat} = |f_1 - f_2|$$

Used in tuning musical instruments

Standing Waves

- When a wave interferes with its own reflection:



- Result → a wave pattern that "stands" instead of traveling

- Reflections are caused by a change in medium
  - To produce standing waves:
  - Generate a wave in a medium with boundaries

Stringed Instruments

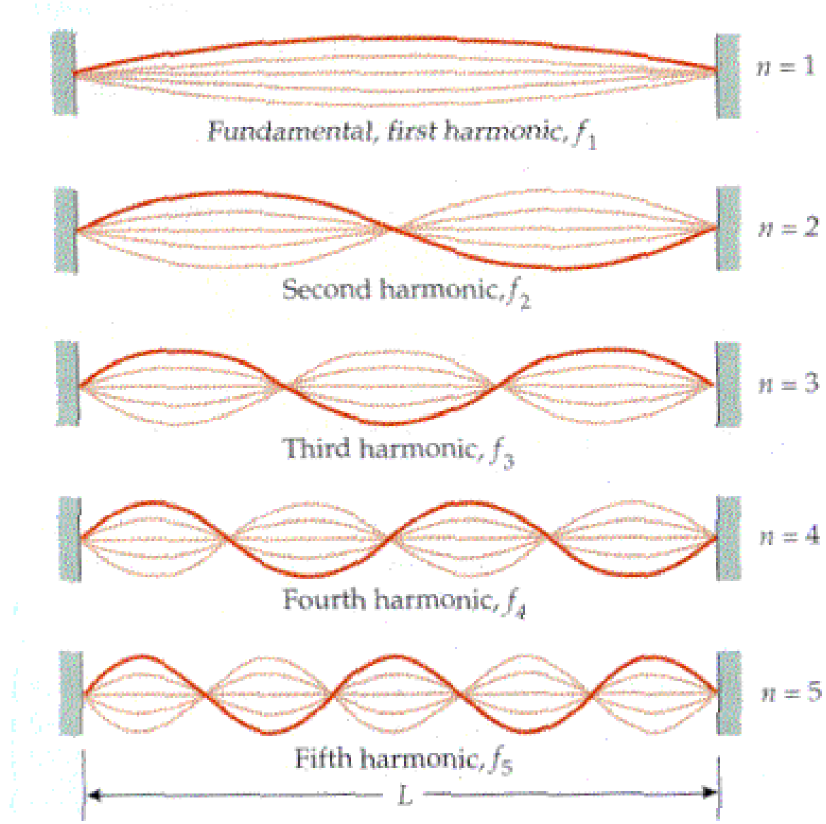
- Made from strings with fixed ends
  - Waves reflect from the ends to produce standing waves
  - Must have specific λ → like "resonances" of the string

$$\lambda_n = \frac{2L}{n}$$

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

$$f_n = n f_1$$

"Harmonic series"

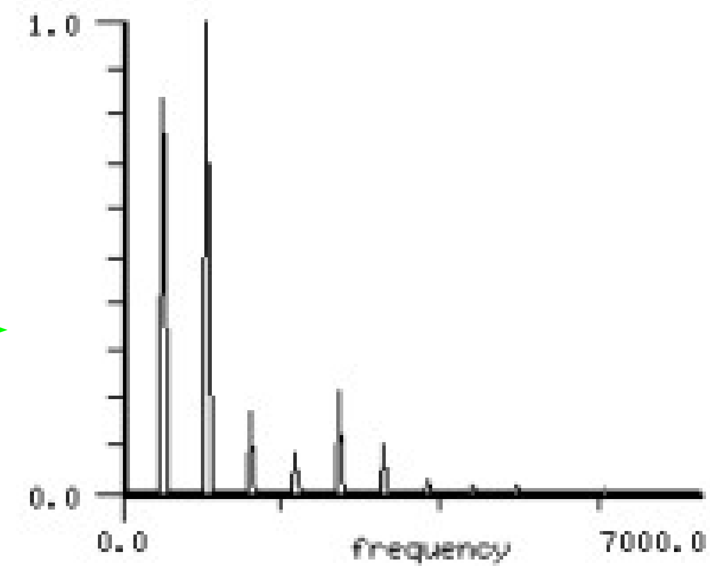


http://www.youtube.com/watch?v=BBA32xnhE1Q&feature=related

Harmonic Frequencies – “Timbre”

- Stringed instruments → <u>harmonic</u> frequencies
  - “Personality” of a particular instrument comes from its combination of harmonics

Oboe – sound “waveform”



Oboe – “recipe” of frequencies

A different instrument would have a different “recipe” of harmonic frequencies, even though it plays the same note

Wind Instruments

- Produce a standing wave in air
  - General rule: open ends of tube are antinodes

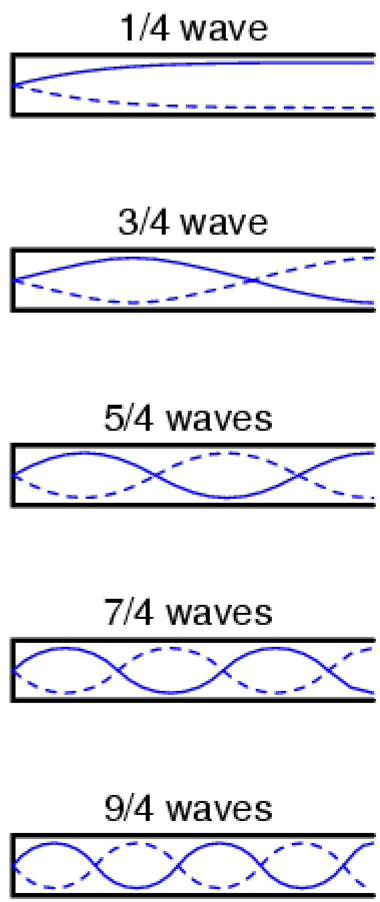
One end closed

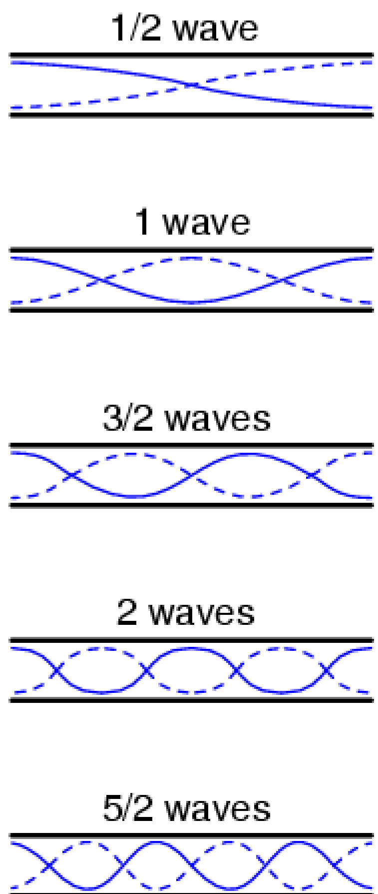
Odd n only!!

$$\lambda_n = \frac{4L}{n}$$

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

$$f_n = n f_1$$





Both ends open

$$\lambda_n = \frac{2L}{n}$$

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

$$f_n = n f_1$$

(same as for stringed instruments)