VIBRATIONS & WAVES

"Someday, after mastering the winds, the waves, the tides and gravity, we shall harness for God the energies of love, and then, for a second time in the history of the world, man will have discovered fire."

-- Teilhard de Chardin
French Geologist

Water drops falling onto the surface of water produce a disturbance that moves outward as expanding rings. *But **WHAT** is moving outward*?

- The answer to the question is **ENERGY**, not MATTER!
- When matter is disturbed, it *emits* or *transmits* energy
  - Can be explained using Conservation Laws

Wave – the propagation or movement of a disturbance of energy

2 General Wave Classifications

- **Mechanical Waves** (*direct*)
  - Waves that require matter to transport energy
  - **Medium** – the matter/material thru which a wave passes
  - Mechanical Waves travel through the medium **without** actually moving the medium along with it.
- **Electromagnetic Waves** (*indirect*)
  - Waves that do NOT require matter to transport energy
  - Only type of wave that can travel thru space

Analogy

- How can information be sent between people?
  - Directly

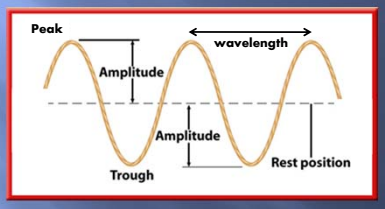
  - Indirectly


How are Mechanical Waves Produced?

- Vibration
  - Regularly repeated disturbance of a medium


- Pulse
  - A single disturbance of short duration

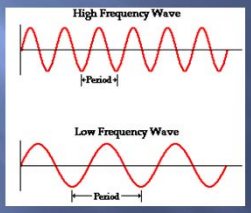

Wave Properties



Amplitude (A) – The maximum displacement from the rest or equilibrium position

Wavelength (λ) – the distance between two like points on a wave (*typically peak to peak for convenience*)

Wave Properties



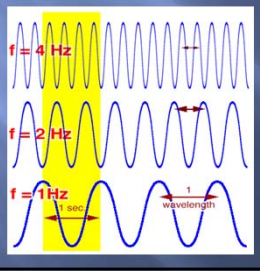
Period (T) – the time it takes to complete 1 vibration or cycle

Frequency (*f*) - # of vibrations per second (*units are* 1/s ≡ Hz (Hertz))

Relating Period and Frequency

Period and frequency are related through the expression:

$$f = \frac{1}{T} \quad or \quad T = \frac{1}{f}$$



T = 0.25 s

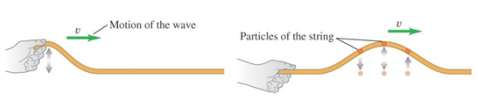
T = 0.5 s

T = 1.0 s

Types of Mechanical Waves

Transverse Wave

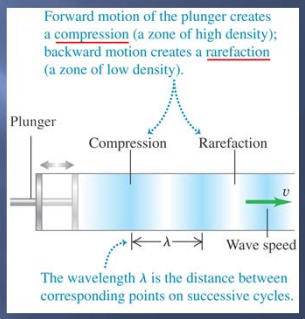
a wave that causes particles within the medium to vibrate in a direction ***perpendicular*** to the direction the wave is moving



Types of Mechanical Waves

Longitudinal Wave
(*Pressure Wave*)

a wave that causes particles within the medium to vibrate in the ***same*** direction as the motion of the wave



Certain mediums can transmit certain mechanical wave types

- Solid – Longitudinal & Transverse
- Liquid – Longitudinal (*mostly*)
- Gas – Longitudinal **Only**

Note:
Transverse waves can propagate only in medium in which the molecules have cohesion
(*solids only*)

- **BUT** they can propagate at the **SURFACE** of liquids because of ***surface tension***

Wave Speed

- The speed of a wave can be determined from our original definition of speed:

$$v = \frac{d}{t}$$

  - Replacing d and t with measurements of λ and T,

$$v = \frac{\lambda}{T}$$

  - Using frequency instead of the period,

$$v = \lambda f$$ ***Wave Speed Equation***

Example:

What is the frequency of a wave that is traveling at 20 m/s and has a wavelength of 2 m?

Example:

What is the speed of a wave that has a frequency of 480 Hz and has a wavelength of 0.715 m?

Wave Interactions

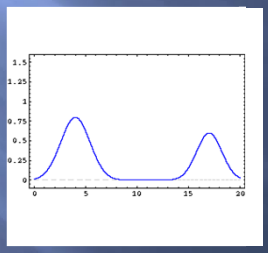
- What happens when two waves meet while traveling through the same medium?
- What affect will the meeting of the waves have upon the appearance of the medium?
- Will the two waves bounce off each other upon meeting (*much like two billiard balls would*) or will the two waves pass through each other?

- Wave interactions are based on Superposition.

  Superposition – the total is the sum of the parts

- When two waves meet, they do **NOT** collide like normal matter.

Instead of colliding, waves add together as they interfere with each other and then continue traveling afterward as if they had never encountered each other.

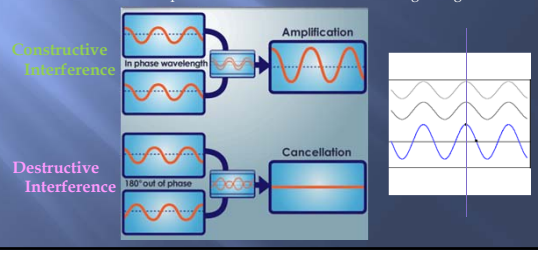


Wave Interactions

- **Wave Interference** – when two or more waves interact at the same point in space and time
  - **Spatial Interference**– A regularly spaced increase/decrease in wave amplitude due to waves of *equal or similar frequencies*
  - **Temporal Interference** –A regularly spaced increase/decrease in wave amplitude due to waves of *different frequencies*
  - **General Interference** – Random increase/decrease in wave amplitude due to waves of *arbitrary frequency*

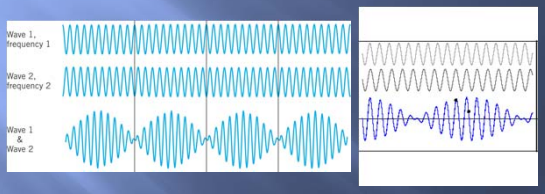
Wave Interactions

- **Spatial Interference**
  - **Constructive Interference** – combining waves to produce a new wave amplitude larger than of **ANY** of the original waves.
  - **Destructive Interference** – combining waves to produce a new wave with a smaller amplitude than **SOME** or **ALL** of the beginning waves



Wave Interactions

- **Temporal Interference (*Beats*)**



Beat Frequency (f_b) – number of pulses per sec

$$f_b = |f_2 - f_1|$$

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Example:

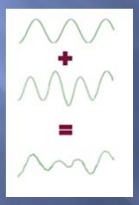
- Two frequencies arrive at a detector simultaneously. One has a frequency of 212 Hz and the second a frequency of 217 Hz. What is the beat frequency?
- What if the second frequency is 207 Hz instead of 217 Hz?

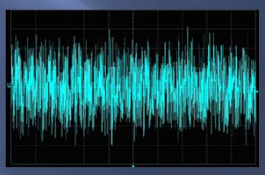
NOTE:

If the beat frequency gets too large, it may become undetectable and just recognized as a single, mixed frequency.

Wave Interactions

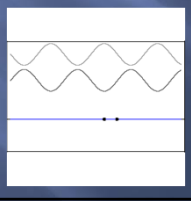
- **General Interference** (*Noise*)
  - Because the waves that are interfering have no similar characteristics, the resultant wave formed by superposition has NO *discernable pattern or behavior.*





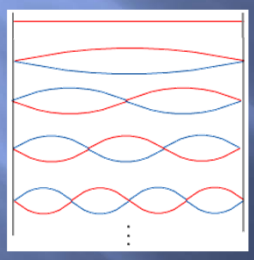
Wave Interactions

- **Standing Waves**
  - **An observed wave pattern that vibrates in place and does not appear to move left or right**
  - **Formed when two waves of identical frequency are traveling in opposite directions and interfere.**



Wave Interactions

- **Standing Waves on a finite string/spring**



Each standing wave pattern is one of the many *natural frequencies* of the string.

Notice
Standing waves ONLY contain a integer number of loops (1, 2, 3, 4 ….)

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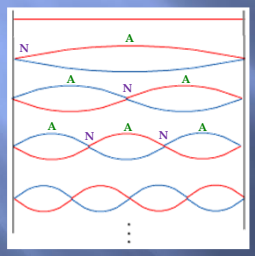
Wave Interactions

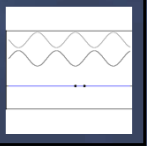
- **Nodes and Anti-Nodes**



Equilibrium Position

Nodes
Points on a standing wave that do not move
(zero amplitude)

Anti-Nodes
Points on a standing wave of maximum displacement
(max amplitude)

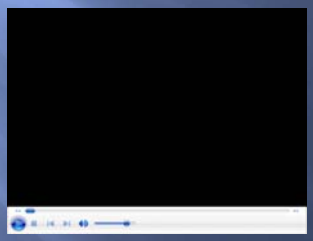


Wave Interactions

- **Every system or object has a unique set of natural frequencies based on:**
  - Medium
  - Material
  - Shape

Wave Interactions

Ruben's Tube



Wave Interactions

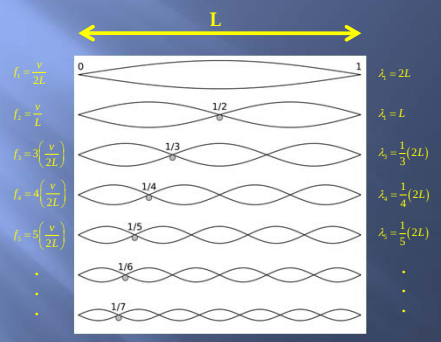
The frequency of a standing wave on a string can be found using:

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

n = number of loops (*anti-nodes*)
v = wave speed
L = length of string

The wavelength of a standing wave (*distance between anti-nodes*) can be found using:

$$\lambda_n = \frac{2L}{n} = \frac{1}{n}(2L)$$



NOTICE: $f_n = n\left(\frac{v}{2L}\right) = nf_1$

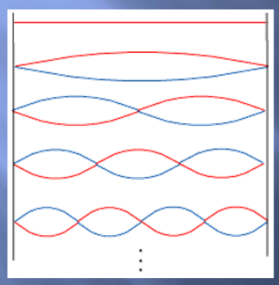
ANY set of standing waves that can be written as:

$f_n = nf_1$ using $f_1 = \frac{v}{2L}$

is called a **harmonic series**.

Each frequency, natural frequency or normal mode of the series is called a harmonic.

Wave Interactions



Equilibrium

Fundamental frequency (f_1)
(1st Harmonic)

2nd Harmonic (f_2)

3rd Harmonic (f_3)

4th Harmonic (f_4)

.
.
.

f_n = n^{th} harmonic

Example

A string has a fundamental frequency of 311 Hz. What is the frequency of the 7th Harmonic?

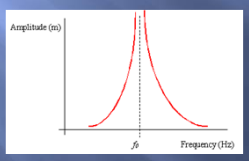
Example

A string is observed with 5 standing wave loops present vibrating at 120 Hz. The length of the string 2 *m*. What is the:

wavelength

wave speed

- Every standing wave or harmonic frequency requires a certain amount of energy in order to be produced.
- Adding energy to a system to cause it to vibrate in one of its many natural frequencies is called Resonance.
  - Thus, standing waves can also be called resonant frequencies



(energy)

DEMO
2 Tuning Forks

Controlled Resonance


Uncontrolled Resonance




Video

- Tacoma Narrows Bridge

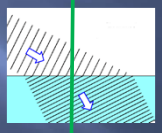
Interaction of Waves with Matter

- When waves encounter matter, a barrier or change in medium type, they can be:
  - Absorbed
    - Taken in by matter, resulting in temp increase or broken atomic or molecular bonds
  - Transmitted (Refraction)
    - Passes through
  - Reflected (Reflection)
    - Bounces back

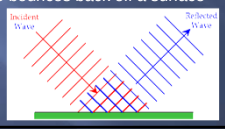
Interaction of Waves with Matter

- Refraction
  - The bending of a wave due to the wave moving from one type of medium into another.

Normal Line – an imaginary line draw perpendicular to a surface



- Reflection
  - When a wave bounces back off a surface

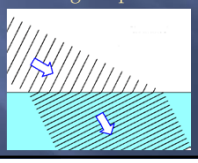


Interaction of Waves with Matter

- Refraction
  - The propagation of energy through a medium will depend on the properties of the medium

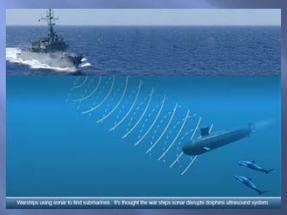
    Waves have different velocities in different media

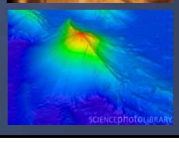
  - When a wave hits the boundary between 2 media at an oblique angle, one side changes speed sooner than the other causing the path to bend



Interaction of Waves with Matter

- Reflection
  - Reflected waves can be used to create images at the boundaries of media or detect objects within a media





Sound

- Sound Waves
  - Pressure (*longitudinal*) waves that we *perceive* through hearing
  - Can travel though **ANY** type of medium
  - Requirements for sound:
    - Energy Disturbance
    - Medium for Transmission
    - Detector /Receiver

- If a tree falls in the woods, does it make a sound?

- Can they hear you scream in space?

Sound

- Recall:
  - *Waves travel at different speeds in different media*
  - Speed of Sound in:
    - Air is **767 mph** (343 m/s) – about 1 mile every 5 sec
    - Helium is **2,074 mph** (927 m/s)
    - Water is **3,315 mph** (1,482 m/s)
    - Sea Water is **3,490 mph** (1,560 m/s)
    - Steel is **13,330 mph** (5,960m/s)
  - The speed of sound depends on the elasticity, density and temperature of the medium.

Sound

- The Speed of Sound in Air

$v_s = 331\,\frac{m}{s} + 0.61T$ $\qquad$ $v_s = 1086.9\,\frac{ft}{s} + 1.83T$

Temperature (°C)	Speed of Sound (*m*/s)	Speed of Sound (*mph*)
50	362	810
20	343*	767
0	331	740
-20	319	714
-50	300	671

* SI default value at STP

Example

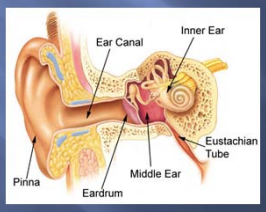
A sound wave with a frequency of 492 Hz is observed at 30 °C. Find:

- the speed of the wave
- it's wavelength
- the time it takes the wave to travel 1 mile (1609 *m*)

Human Hearing

Ears are sound wave detectors that are sensitive to a small range of sound frequencies:

- Infrasonic range f < 20 Hz
- Sonic (Audible) range: 20 Hz <f< 20,000 Hz
- Ultrasonic range f > 20,000 Hz



Human Hearing

Example

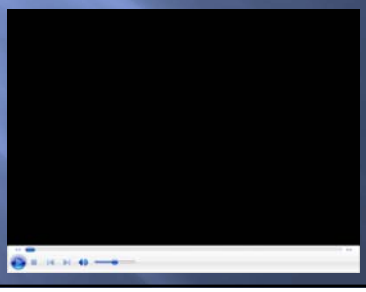
What are the wavelengths corresponding to the highest and lowest frequencies humans can hear?

Assume $v_s = 343\ m/s$

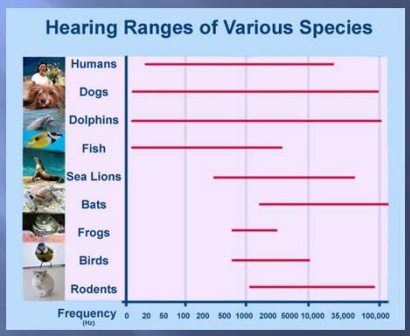
Human Hearing

Example

Hearing Test – How high a frequency can you hear?



Animal Hearing



Sound Terms

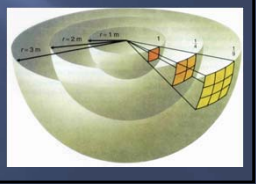
- Pitch *(frequency)*
  The ***perceived*** highness/lowness of a sound wave
  - High Pitch = High Frequency
  - Low Pitch = Low Frequency
- On average, Humans can only produce sounds vocally in the range:
  80 Hz – 1,100 Hz
  - **Guinness Records**
    - Lowest Note: Roger Menees (F#-6 – 0.393 Hz) 2010
    - Highest Note: Adam Lopez (C#8 – 4435 Hz) 2005
      Georgia Brown (C10 – 25104 Hz) 2006

Sound Terms

- Loudness
  The ***perceived*** intensity (energy) of a sound wave
- Intensity (I) – the amount of energy the wave carries per second per meter squared
  intensity = Watts / m^2

Because sound originates from a point source and spreads in 3 dimensions, the loss of intensity with distance from the source depends on the geometry

$I \propto 1/r^2$



Sound Terms

- Loudness
  - Human ears can hear over an intensity range of 10^{12}
    - **Decibels** - a logarithmic scale rather than a linear scale for measuring sound intensity:

$$I(dB) = 10 \log\left[\frac{I}{I_o}\right]$$

w/ $I_o = 1 \times 10^{-12}$ W/m^2
(*Threshold of hearing*)

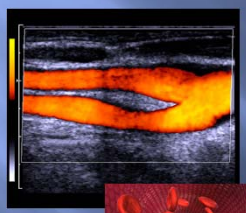
NOTE
It takes 10 times the intensity to sound twice as loud (*increase by* 10 *dB*)

Sound Effects

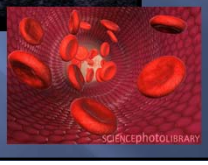
- Doppler Effect
  - The ***perceived*** shift in frequency of sound due to the motion of the sound emitter and/or detector

Sound Effects

- Uses of Sound Wave Properties



Noise Cancellation
(*Superposition*)



Blood Flow Speed
(*Doppler Effect*)

Auto-Focus
(*Reflection*)

Sound Effects

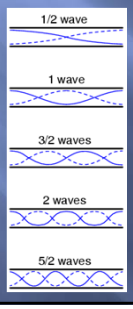
- Standing Sound Waves
  - Standing sound waves can be produced in any object that is classified as an:
    - Open Pipe – A pipe that is open at both ends

    - Closed Pipe – A pipe that is open at one end

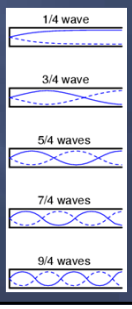
Sound Effects

- In order to produce standing sound waves, you must have anti-nodes at the open ends

Open Pipe



Closed Pipe



Sound Effects

- Open Pipe

Open at Both Ends	Harmonic	Wavelength λ	Frequency f
1st Harmonic	1st	$2L$	f_1
2nd Harmonic	2nd	L	$2f_1$
3rd Harmonic	3rd	$2L/3$	$3f_1$

Odd and Even Harmonics

$$f_n = \frac{nv}{2L} \qquad n = 1, 2, 3, 4 \ldots$$

DEMOS - Tuning Forks & Open Pipes
- Shell Horn

Sound Effects

- Closed Pipe

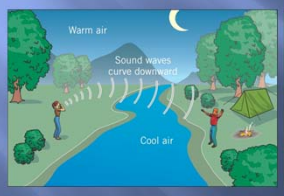
Closed at One End	Harmonic	Wavelength λ	Frequency f
1st Harmonic	1st	$4L$	f_1
3rd Harmonic	3rd	$4L/3$	$3f_1$
5th Harmonic	5th	$4L/5$	$5f_1$
	Odd Harmonics		

$$f_n = \frac{nv}{4L} \qquad n = 1, 3, 5, 7 \ldots$$

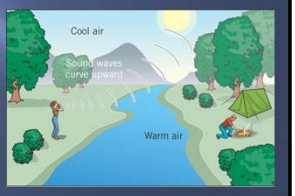
DEMOS - Bottle
- Bottle Music

Why does sound carry farther at night than during the day? REFRACTION

As waves pass though media of different densities, they will always bend toward the denser medium



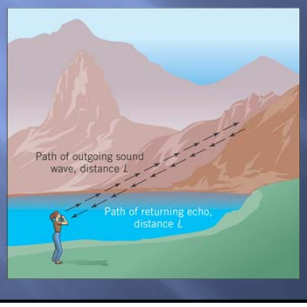
At night, cooler air is near the surface



During the day, warmer air is near the surface

What causes an echo? REFLECTION

An echo is a sound wave that bounces off a rigid wall back to the emitter



Distance to object

$$L = v_s\left(\frac{t}{2}\right)$$

w/ t = time until echo is heard

Breaking the Sound Barrier

- Chuck Yeager – first man to fly faster than the speed of sound
- Andy Green – first man to drive a land vehicle faster than the speed of sound.

October 14, 1947 –
in X1 "Glamorous Glennis"

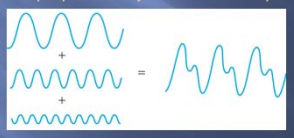
October 15, 1997 –
in SuperSonic Car
"Thrust SSC"
763 MPH

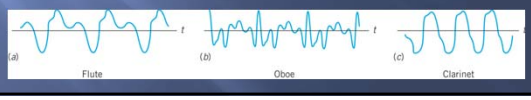
Music

- Music is a *human interpretation* of a series of simultaneous and organized sounds, **often** pleasing to the listener/performer
- The sounds produced in music are a direct result of superposition
  - *From a single source or from many*

Music

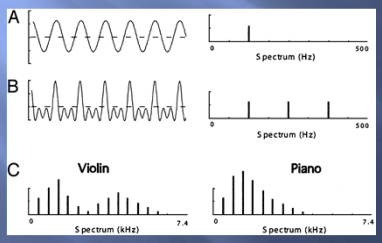
- How can a single source or a group play/sing the same *frequency* (*note*), yet it sound different?
  - *Timbre* (*Musicians*)
  - *Different Superposition of Harmonic Frequencies* (*Science*)





Music

- Can you determine what harmonics go into a specific tone or timbre? YES!
  - *Process is called Fourier Analysis*



Pure Tone (125 Hz)

Mixture of 3 Harmonics (125 Hz, 250 Hz, 375 Hz)

A_3 (440 Hz)

Music

- *Synthesizers*

- *Impressionists*

John Madden

Frank Caliendo

Other Mechanical Waves

- Seismic Waves – waves caused by the release of energy due to earthquakes composed of
  - ***Body Waves***
    - P - primary waves
    - S - secondary waves
  - ***Surface Waves***
    - L - Love waves
    - R – Rayleigh waves

Then [Jesus] got up and rebuked the winds and the waves, and it was completely calm. The [disciples] were amazed and asked, "What kind of man is this? Even the winds and the waves obey Him!"

Matthew 8:26-27