Name: ____ Block: ________

PHYSICS: UNIT 6
WAVES, SOUND, AND LIGHT

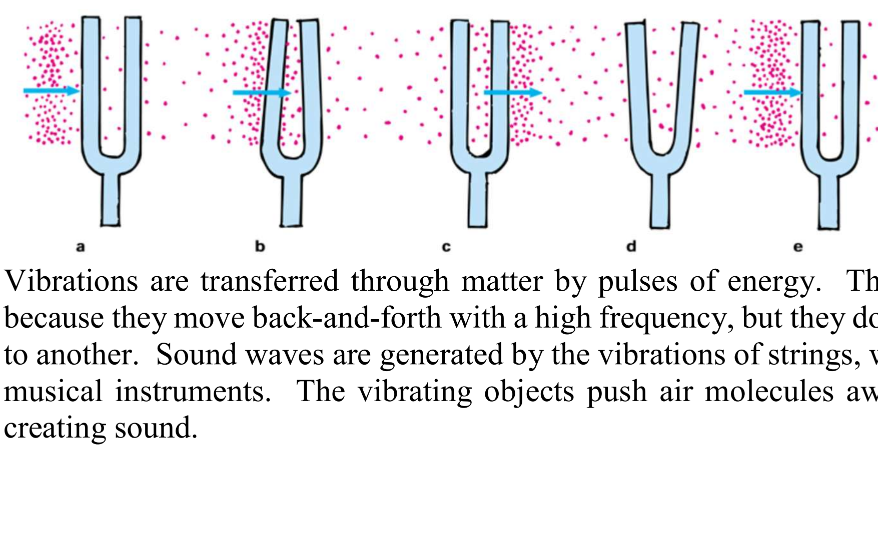
Part 1: PROPERTIES OF WAVES

Learning Targets

1. Students should be able to identify the parts of longitudinal waves, the parts of transverse waves, and the parts of standing waves.
2. Students can explain the difference between mechanical waves, standing waves, and electromagnetic waves in terms of media, speed, and how they are formed.
3. Students should be able to explain simple harmonic motion in contexts of vibrations, pendulums, oscillating springs, or other repetitious motions.
4. Students must understand that waves move energy away from a disturbance, but waves do not carry the matter or medium through which they pass.

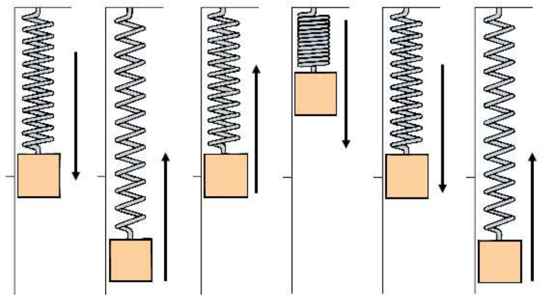
A. Simple harmonic motion

Simple harmonic motion refers to the repetitive back-and-forth motion of an object that has a defined period and a defined frequency. Objects that can be characterized as having simple harmonic motion includes vibrating objects, waves, swinging pendulums, and oscillating springs. The ***period*** is the amount of time it takes for the moving object or wave to complete ***one cycle*** (e.g., complete back-and-forth motion or up-and-down motion). The ***frequency*** is the number of cycles (complete back-and-forth motions) per second. Period and frequency are reciprocals of each other.



A ***vibration*** is a repetitive back-and-forth motion by a particle, molecule, or object around a fixed position. Vibrational kinetic energy is one form of kinetic energy.

Vibrations are transferred through matter by pulses of energy. The prongs on the tuning fork vibrate because they move back-and-forth with a high frequency, but they do not physically move from one place to another. Sound waves are generated by the vibrations of strings, wires, metal tubes, bells, and reeds in musical instruments. The vibrating objects push air molecules away from them, carrying energy and creating sound.



An ***oscillation*** is another type of simple harmonic motion. When an object oscillates, the object moves up and down repetitively. The springs to the left oscillate, or move up-and-down around their equilibrium positions. Just like vibrations, oscillating springs have a defined period and a defined frequency.

This unit focus on the properties of waves. A ***wave*** is a traveling disturbance that carries energy from one location to another. All waves move in straight lines outward and away from the source of a disturbance. Like the radiating circular ripples, the waves of water carry energy away from where a rock was dropped into the pond.

Waves can move as a *single pulse* or as a *continuous series of waves* (train of waves), carrying energy away from its source. A ***pulse*** is a single disturbance, wave, or ripple that moves outward from the point of disturbance. A train of waves are many waves emitted over and over again from a single source.

As waves travel through matter, they will temporarily displace the molecules or particles in matter up-and-down or side-to-side. ***Waves move the energy but they do not carry the matter with them*** longitudinally as they move through matter. Once the disturbance passes, the medium will return to its original state or position.

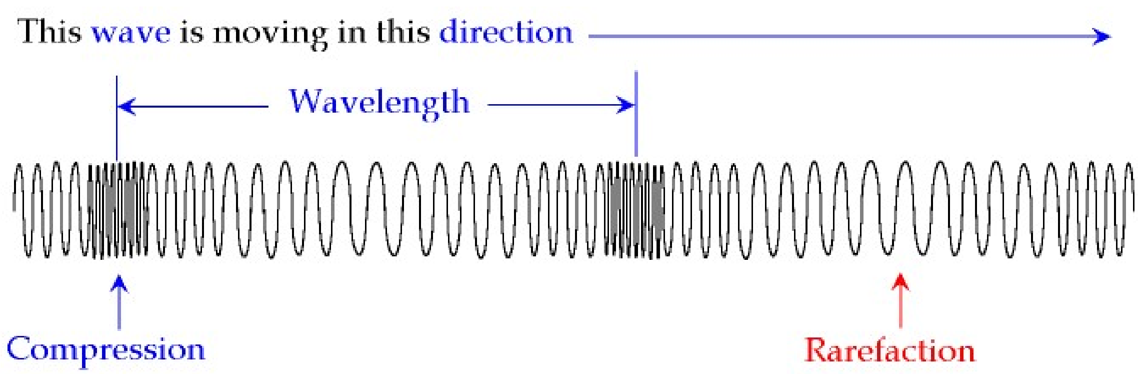
For example, ocean waves will move across the surface of the water creating crests (upper part of waves) and troughs (lower part of waves). The ocean surface is temporarily pushed up and down. The waves do not carry the ocean water with them as they move across the surface of the water. In the figure to the right, the duck is pushed up and down as the wave passes under it, however, the wave does not move the duck away from its current position. Waves carry the energy but do not carry the matter.

B. Mechanical waves

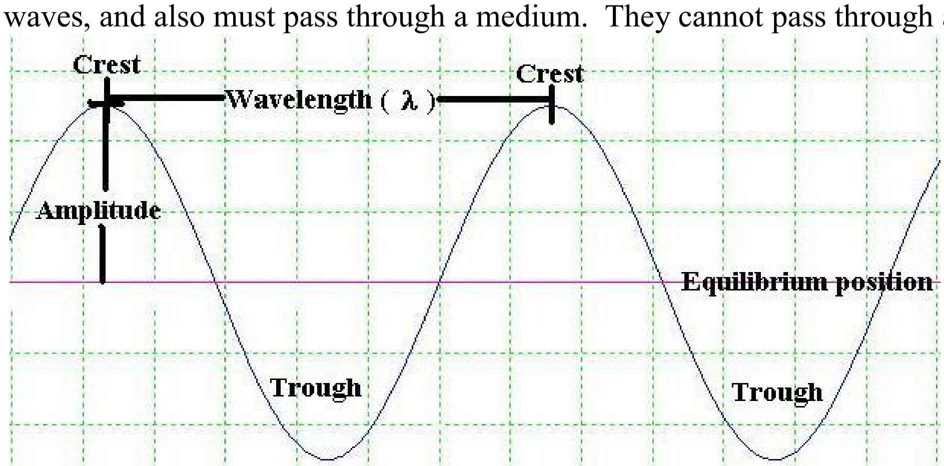
There are two classes of waves: Mechanical Waves and Electromagnetic Waves. Electromagnetic waves are the waves that form when light is emitted from a source, and will be discussed later.

Mechanical waves are waves that must pass through a medium that contains matter. Mechanical waves propagate, or travel, through solids, fluids, or gases. Mechanical waves cannot move through a vacuum, such as in space. As a mechanical wave passes through matter, the matter is temporarily deformed by the wave energy. All mechanical waves produce work. As the wave passes through the matter, the energy of the wave causes matter to move. Thus longitudinal waves, transverse waves, and standing waves perform work—work against resistance and mechanical work by pushing and pulling the molecules in the medium through which they pass. Waves transfer energy, but more or less, the matter returns to its original place after the wave passes through it. There are three types of mechanical waves: Longitudinal Waves, transverse waves, and standing waves.

A ***longitudinal wave*** is a compression-expansion wave. As the wave moves through the medium, the molecules in the medium are temporarily compressed and expanded by the wave in a side-to-side motion—molecules are bunched up then pulled apart. The direction of the wave's energy is in the same direction as the wave moves. The regions of the medium where molecules or particles are temporarily compressed are called ***compressions*** or ***condensations***. The regions of the medium where molecules are temporarily expanded are called ***rarefactions***. ***Sound waves*** are examples of longitudinal waves. Sound travels through air (gas), water (liquid), and walls (solids), but sound cannot travel through space because space is a vacuum.

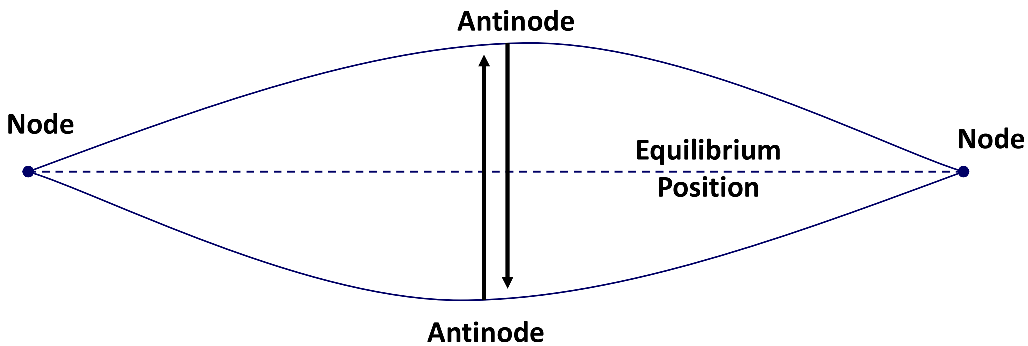


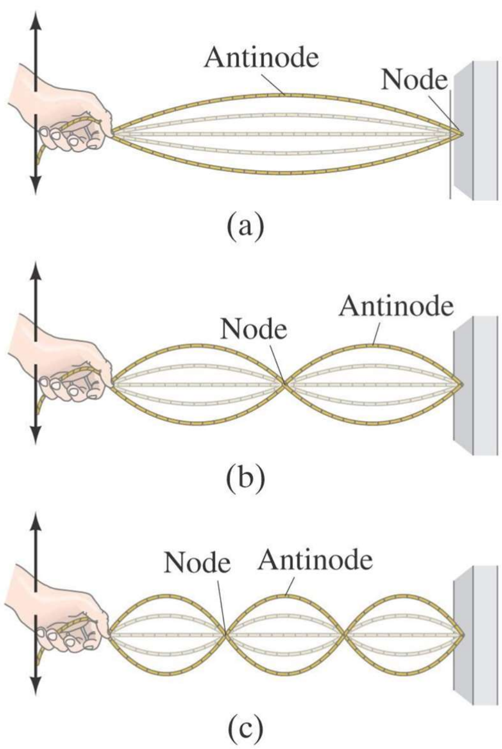
A ***transverse wave*** is a sinusoidal wave. Transverse mechanical waves cause the molecules in the medium to move up-and-down as the wave passes. The direction of the wave's energy is perpendicular to the direction as the wave moves. The regions of the transverse wave where the molecules are pushed up relative to the equilibrium position are called crests. The regions of the transverse wave where the molecules are pushed down relative to the equilibrium position are called troughs. Most transverse waves are mechanical waves, and also must pass through a medium. They cannot pass through a vacuum.



C. Standing waves

A ***standing wave*** is a wave that does not appear to translate laterally through the medium, it only appears to move back-or-forth or up-and-down. Standing waves tend to be formed when a taut string or wire that vibrates back and forth with a high frequency where the forward moving wave exactly overlaps, and is in phase, with the reflected. Standing waves produce the sound in stringed instruments and pianos. Standing waves have fixed points along the equilibrium position that appear not to move despite that the wire does move. These apparent fixed or motionless points are called ***nodes***. The moving arched parts of the wire or wave that appear to oscillate through the entire amplitude are called ***antinodes***. If a string is attached at the two ends to fixed points, a half-wavelength wave is generated—this would be the smallest possible standing wave (figure a).





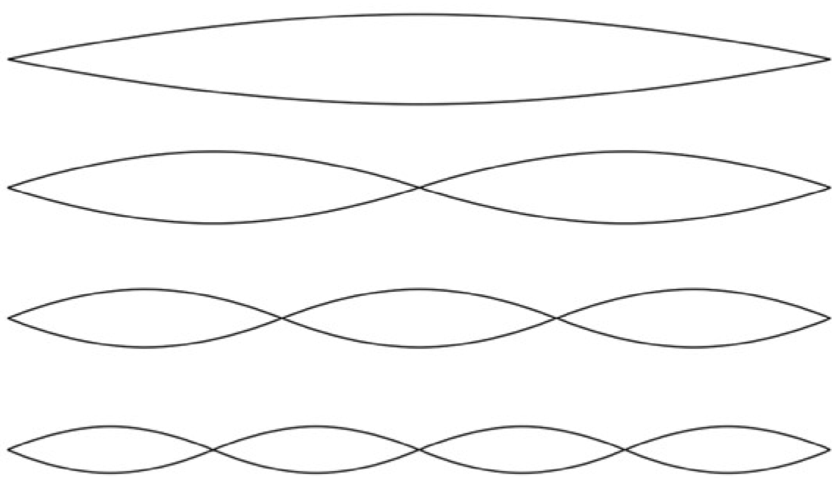
Standing waves are created when the frequency of the incident wave from the wave source exactly matches the frequency of the reflected wave, and they overlap.

In the image, the hand is creating the incident wave by quickly moving the wire up and down. The wave reflects off of the fixed end attached to the wall. The reflected wave moves the string from the wall back to the hand.

When the frequency of the incident and reflecting wave are identical, the standing wave is formed—as the wave is pushed forward, at the same time it is pushed backward crossing over each other at the same time.

The frequency of the vibration controls the number of nodes and antinodes on the wire. *The faster the vibration, the more nodes and antinodes are generated by the standing wave*. If a wire is vibrated slowly (lowest frequency), the standing wave that will be generated would have two end nodes and one antinode in between. This frequency will generate ½ wavelength, this would be the smallest possible standing wave called the ***first harmonic*** or ***fundamental frequency***. The fundamental frequency of a standing wave is the smallest possible frequency observed for the oscillation of a whole object. It is the lowermost vibration frequency that would generate a noise-less oscillation. In this case, the entire string is moving back and forth between two nodes. As the frequency of the oscillating string or standing wave increases, or the first harmonic. If the frequency was of the string's vibration was doubled, eventually there will be three nodes and two antinodes forming 1 wavelength, or the second harmonic.

If a string is attached at the two ends to fixed points (two nodes and one antinode), a half-wavelength wave is generated—additional nodes appear within the string or standing wave, producing two or more antinodes. These are overtones. **Overtones** are frequencies (must be multiples of the fundamental frequency) of a standing wave above the fundamental frequency. The diagram below shows four standing waves. The first standing wave represents the fundamental frequency. The second, third, and fourth waves represent the overtones because the standing wave has multiple antinodes oscillating simultaneously on the same wave. For wires with fixed ends, the number of nodes on the standing wave is equal to the number of antinodes + 1. For example, if a standing wave or string has one antinode, there will be two nodes. If a standing wave or oscillating string has two antinodes, there will be three nodes.



1st harmonic (fundamental frequency)
½ wavelength

2nd harmonic (1st overtone)
1 wavelength

3rd harmonic (2nd overtone)
3/2 wavelengths

4th harmonic (3rd overtone)
2 wavelengths

Each harmonic and overtone past the fundamental frequency forms at integer multiples of the fundamental frequency. If the fundamental frequency of a wave is 100 Hz, the 2nd harmonic would form at a frequency of 200 Hz, the 3rd harmonic would form at a frequency of 300 Hz, and etc… At frequencies between the harmonics, the wave forms will be noisy and will not form nodes and antinodes.

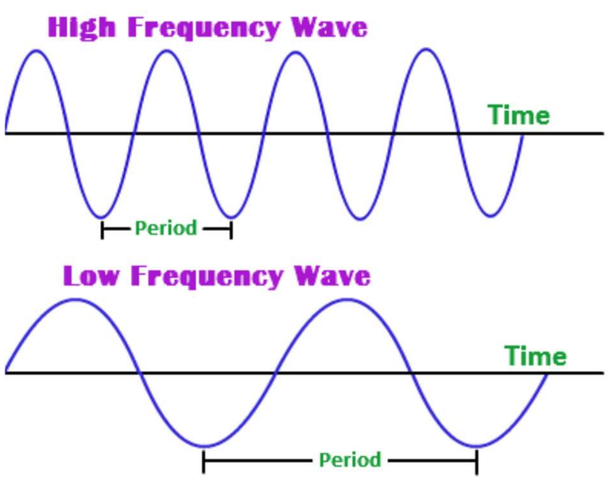
Part 2: QUANTIFYING PARAMETERS OF WAVES

Learning Targets

1. Students will calculate frequency, period, wavelength, wave speed, and number of cycles of longitudinal waves.
2. Students will understand the inverse relationship between frequency and period, and the inverse relationship between frequency and wavelength.
3. Students will predict the relative energy of waves based on the frequency and amplitude of the waves.
4. Students will estimate amplitude, wavelength, and period of transverse waves from graphs of waves.

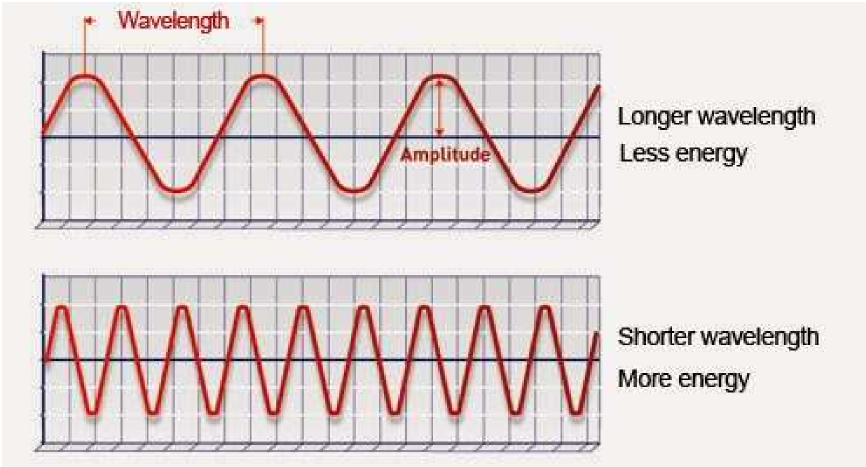
A. Frequency and Period

An ***oscillation*** or ***vibration*** is a repetitive back-and-forth motion. One ***cycle*** is defined as one complete back-and-forth motion of a vibration or of a wave. The time it takes to complete one cycle (one wave or one vibration) is called the ***period***. The frequency of a wave is defined as the number of waves, cycles, or vibrations created per second or passes a reference position per second. Frequency is reported in units of Hertz, abbreviated Hz. A **Hertz** is a number per second, (units of s in the denominator). Period is calculated as the reciprocal of frequency. Period is reported in units of seconds.



Frequency and period are reciprocals of each other. As one increases, the other decreases. If frequency of the wave is higher (more cycles per second), the time per wave is lesser—the time between adjacent waves becomes shorter and shorter (upper diagram). Conversely, if frequency of the wave is lower (lesser cycles per second), the time per wave is longer—the time between adjacent waves is greater (lower diagram).

- The greater the frequency (more waves, vibrations, or cycles per second), the shorter the period.
- The lower the frequency (less waves, vibrations, or cycles per second), the longer the period.



The energy of a wave is proportional to frequency. Higher frequency waves have more energy because there are more traveling pulses and disturbances per second. Lower frequency waves have lesser energy because there are less traveling pulses and disturbances per second.

- The greater the frequency, the greater the number of waves pushing through matter per second, the greater the energy (more kinetic energy and more heat).
- The lower the frequency, the fewer the number of waves pushing through matter per second, the lower the energy (lesser kinetic energy and lesser heat).

Calculating Frequency and Period

Frequency is calculated as the number of waves, cycles, or vibrations divided by the time. Time must be in seconds. Frequency is reported in Hertz (#/s). Frequency is also the reciprocal of period.

Period is calculated as the time divided by the number of waves, cycles, or vibrations. Time must be in seconds. Period is reported in seconds. Period is also the reciprocal of frequency.

$$f = \frac{\#waves}{t} \quad \text{or} \quad f = \frac{\#cycles}{t}$$

$$T = \frac{t}{\#waves} \quad \text{or} \quad T = \frac{t}{\#cycles}$$

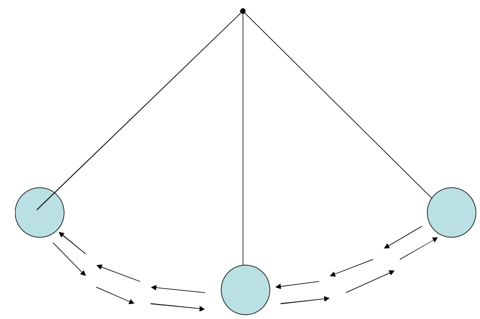
$$f = \frac{1}{T}$$

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

f = frequency (Hz)
t = time (s)
T = Period (s)

Illustrative example

A pendulum swings back and forth 10 times in 35 seconds. Calculate frequency and period.



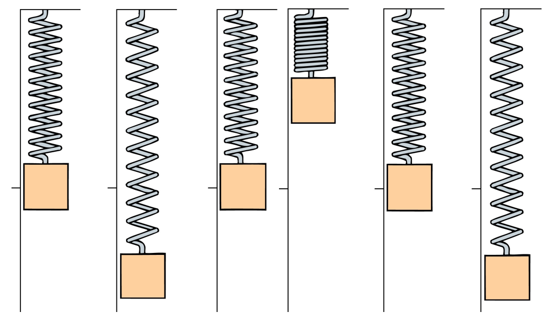
$$f = \frac{\#\,cycles}{t} = \frac{10}{35} = 0.286\Big/_{s} = 0.286\ Hz$$

$$T = \frac{1}{f} = \frac{1}{0.286} = 3.5\,s \quad \text{or} \quad T = \frac{t}{\#\,cycles} = \frac{35s}{10} = 3.5\,s$$

Illustrative example

A spring oscillates with a frequency of 2.5 Hz.

- Calculate the period of the spring's oscillation.
- Calculate how many back-and-forth cycles the pendulum will make in 1 minute.



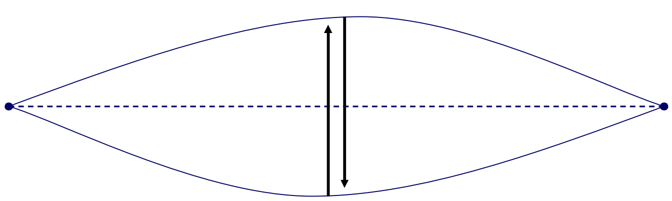
$$T = \frac{1}{f} = \frac{1}{2.5/s} = 0.40\,s$$

$$Cycles = f \cdot t = 2.5\Big/_{s} \cdot 60\,s = 150$$

Illustrative example

A guitar string vibrates at a rate of 42000 oscillations per minute.

- Calculate the frequency (f) of the guitar string in Hz.
- Calculate the period (T) of the vibration. (s)



$$f = \frac{cycles}{t} = \frac{42{,}000}{60\,\text{s}} = 700\Big/_{s} = 700\ Hz$$

$$T = \frac{1}{f} = \frac{1}{700} = 0.00143\,s \quad \text{or} \quad T = \frac{60s}{42{,}000} = 0.00143s$$

B. Amplitude

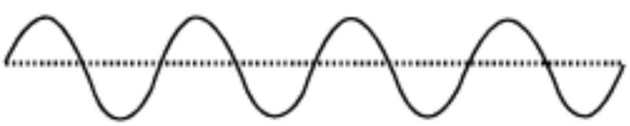
Amplitude is the maximum displacement of the wave from its equilibrium position. The ***equilibrium position*** is the "rest" position of the molecules in the medium if the wave was not passing through the medium. As a wave or disturbance passes through the medium, the equilibrium position is the mid-point position around which the vibration or wave moves.

Amplitude of Longitudinal Waves

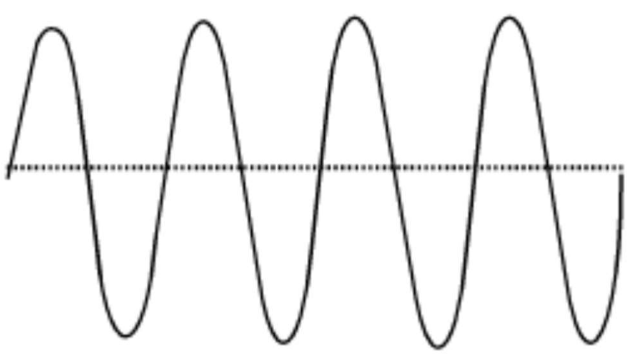
Lower amplitude longitudinal wave. The density of particles compressed in the compressions is small (fewer pushed together). The travelling wave has lesser pressure and lesser force because of the tenuous layer of particles.

Higher amplitude longitudinal wave. The density of particles compressed in the compression is greater (more pushed together). The travelling wave has more pressure and more force because of the dense layer of particles.

Amplitude of Transverse Waves

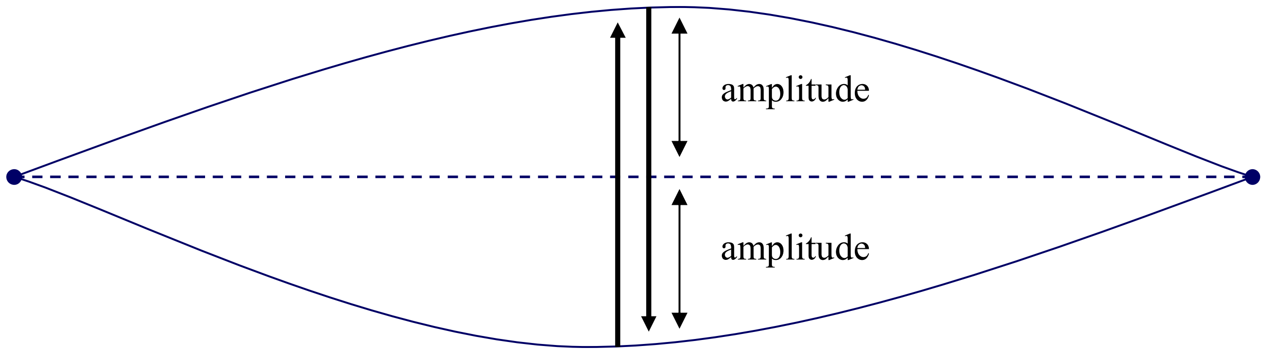


Lower amplitude transverse wave. The crests and troughs of the waves have small displacements from the equilibrium position. The matter through which it moves is pushed up and down with minimal displacement.



Higher amplitude transverse wave. The crests and troughs of the waves have larger displacements from the equilibrium position. The matter through which it moves is pushed up and down with greater displacement.

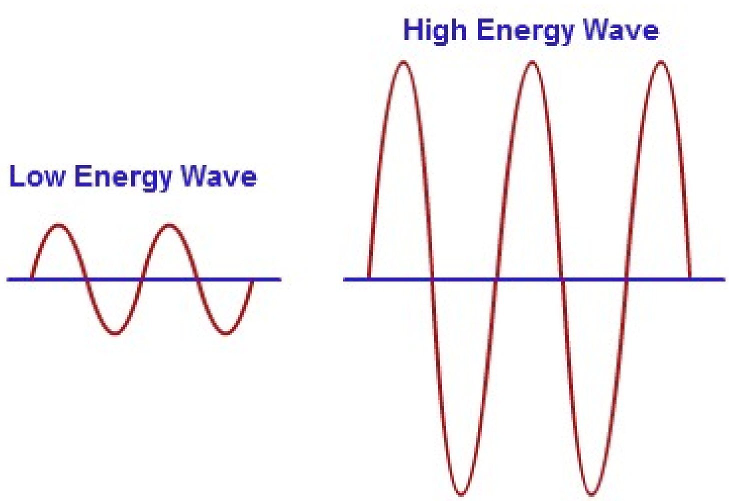
Amplitude of Standing Waves



For a standing wave, such as a plucked string, the equilibrium position is represented by the horizontal dashed line. The string vibrates up-and-down around the equilibrium position. The amplitude of the standing wave is the maximum displacement in the up direction or down direction of the string from the equilibrium position. If the string was plucked with a lot of force, the amplitude will be greater. If the string was plucked with weaker force, the amplitude will be lesser.

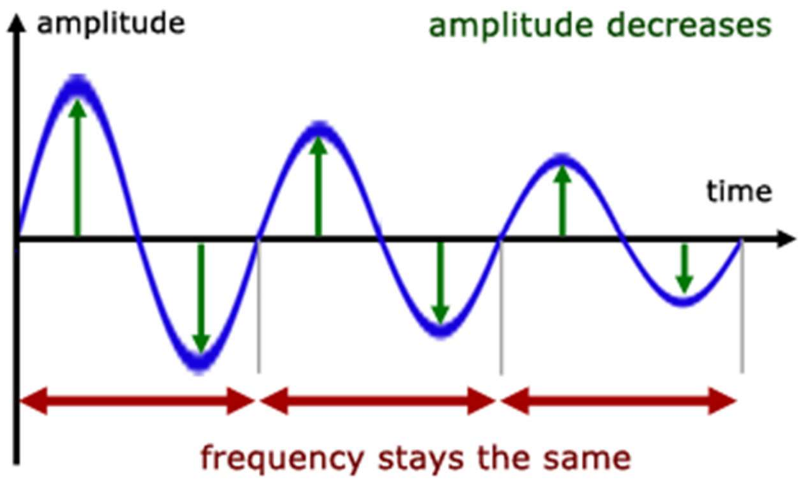
Amplitude and Wave Energy

As waves pass through media, the wave energy will temporarily displace the particles of the matter through which it passes—in other words, the wave is performing work on the particles in the media by moving the particles around. Particles are pushed up and down (transverse) or squeezed and expanded (longitudinal).



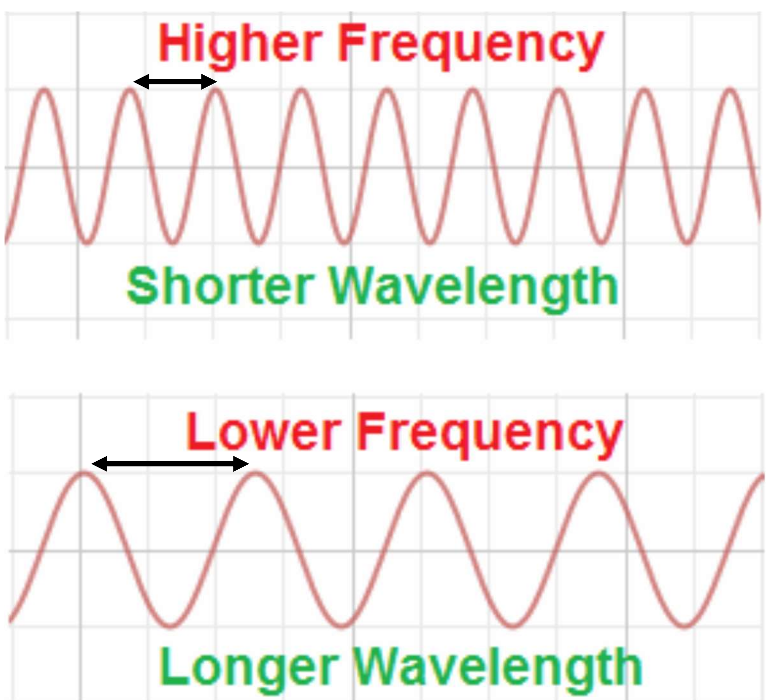
- ***The greater the amplitude***, the more work was done to move the medium molecules in the up-and-down direction, the greater the energy of the wave.
- ***The smaller the amplitude***, the lesser work was done to move the medium molecules in the up-and-down direction, the lesser the energy of the wave.

Damping is the gradual loss of amplitude of a propagating wave with time and distance after the initial disturbance. If allowed, amplitude will eventually reach zero as energy is slowly reduced by transforming the wave energy to heat by friction or by the wave "thinning" as it spreads out.



Amplitude of the wave decreases, however wave speed, wavelength, and frequency remain constant. Damping also affects standing waves. Eventually all vibrating strings on string instruments stop vibrating. Only the amplitude of the vibrating string decreases (affecting volume), however, the frequency remains constant (the same pitch).

C. Frequency and Wavelength



Wavelength is defined as the distance between two identical positions on two adjacent or consecutive waves. Wavelength could be crest-to-crest, trough-to-trough, equilibrium position to equilibrium position, compression-to-compression, or node-to-node.

In the diagrams, the wavelength is shown as crest-to-crest. The diagram to the left shows two different waves. The top wave is a "high frequency" wave with a shorter wavelength. The bottom wave is a "low frequency" wave with a longer wavelength.

There is an *inverse relationship* between frequency and wavelength.

- If a wave has a high frequency, the wavelength of the waves is shorter.
- If a wave has a low frequency, the wavelength of the waves is longer.

The relationship between frequency and wavelength is determined by the following series of equations that have been algebraically rearranged. The product of the frequency of the wave and the wavelength of the wave is always the wave speed. Wave speed is denoted by the letter c. This applies to the speed of sound, speed of light, or speed of seismic waves.

$$c = f \cdot \lambda \qquad f = \frac{c}{\lambda} \qquad \lambda = \frac{c}{f}$$

f = frequency (Hz)
c = wave speed (m/s)
λ = wavelength (m)

D. Wave Speed

Wave speed is the speed of the wave moving through a given medium. Treat wave speed like a normal speed—the wave moves a given distance per unit time. Wave speeds may be reported in units of m/s, km/hr, or km/s depending on the context of the wave. Wave speed is dependent on many factors, such as temperature and the medium through which the wave is moving. Wave speed is denoted by the letter c. This applies to the speed of sound, speed of light, or speed of seismic waves.

Waves peed is calculated two ways. First, wave speed is calculated as the distance moved by the wave per second (just like linear speed). Second, wave speed is also calculated as the product of frequency multiplied by wavelength.

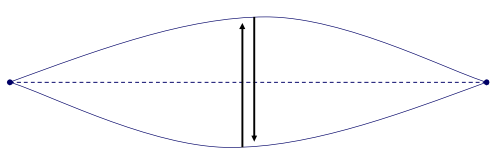
Wave speed: $c = \frac{d}{t}$ or $c = f \cdot \lambda$

c = wave speed (m/s)
d = distance traveled (m)
t = time (s)

Illustrative Example

A guitar string vibrates at a rate of 60000 oscillations per minute. The speed of sound in air at 20ºC is 343 m/s.

- Calculate the frequency (*f*) of the guitar string in Hz.
- Calculate the period (T) of the vibration. (s)
- Calculate the wavelength (λ) of the vibration. (m)



$$f = \frac{cycles}{t} = \frac{60{,}000}{60\text{ s}} = 1000\!\!\diagup_{s} = 1000\ Hz$$

$$T = \frac{1}{f} = \frac{1}{1000} = 0.001\,s \text{ or } T = \frac{60}{60{,}000} = 0.001s$$

$$\lambda = \frac{c}{f} = \frac{343\,m\!/\!s}{1000\!/\!s} = 0.343\ m$$

Illustrative Example

A horn emits a sound with a frequency of 6500 Hz. The speed of sound in air at 20ºC is 343 m/s.

- Calculate the period (T) of the sound waves emitted from the horn. (s)
- Calculate the wavelength (λ) of the sound waves. (m)

$$T = \frac{1}{f} = \frac{1}{6500/\text{s}} = 0.000154\,s$$

$$\lambda = \frac{c}{f} = \frac{343\,m/s}{6500/s} = 0.0.528m$$

Illustrative Example

A whale's song has a frequency of 400 Hz. The speed of sound passing through seawater at 10ºC is 1530 m/s.

- Calculate the period of the sound waves of the whale's song.
- Calculate the wavelength of the sound waves of the whale's song.

$$T = \frac{1}{f} = \frac{1}{400/s} = 0.0025\,s$$

$$\lambda = \frac{c}{f} = \frac{1530\,m/s}{400/s} = 3.83\,m$$

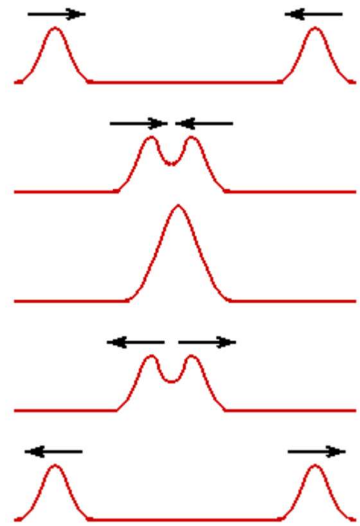
Part 3: SUPERPOSITION AND INTERFERENCE

Learning Targets

1. Students in their own words explain the difference between constructive interference and destructive interference, and in-phase and out-of-phase waves.
2. Students will draw the resultant wave by superimposing two transverse waves.
3. Students will predict the location of beats of a resultant wave when two waves of slightly different frequency overlap.
4. Students will understand that waves only interact at the position where they overlap, and waves will move away with their original properties (energy, amplitude, wave speed, and frequency) after the interaction.

The Principle of Superposition describes when two or more waves overlap or interact with each other to produce a resultant wave—the new wave that is formed by the superposition is the algebraic sum of the waves—in other words, add the waves together. The resultant wave's appearance, frequency, and amplitude depends on where each wave involved in the superposition is in its cycle when they collide or overlap. Superposition does not destroy or modify the energy, amplitude, wave speed, and frequency of the interfering waves or wave pulses. After the waves or pulses pass through each other at the point of interference, they continue to move away with the same energy, amplitude, wave speed, frequency, and direction as before they crossed.

If two different waves overlap and identical positions on the two waves align (e.g., crest aligns with crest, trough aligns with trough), the resulting effect is called ***constructive interference.*** Constructive interference between two or more overlapping waves will produce a resultant wave that has a greater positive amplitude that is the sum of the two interfering waves.



Constructive interference by two pulses. Two pulses that have amplitudes oriented in the same up direction cross paths. At the point of crossing, the pulses merge forming one larger wave pulse (the resultant) that is the sum of the amplitudes of the two individual wave pulses. After they superimpose, they move in the same direction with the same amplutide and wavespeed as before they crossed.

If two different waves overlap and non-identical positions align (e.g., crest aligns with equilibrium position; crest aligns with trough), the amplitude of the combined waves will be smaller than the amplitudes of the two overlapping individual waves. This is ***destructive interference***.

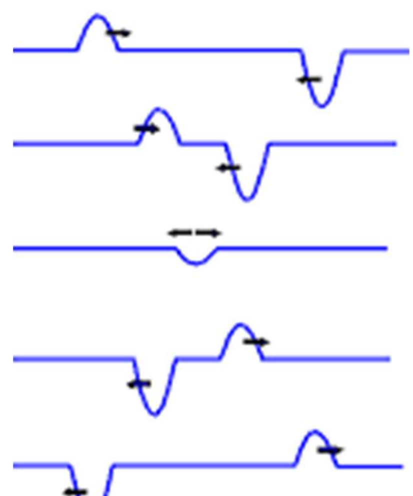
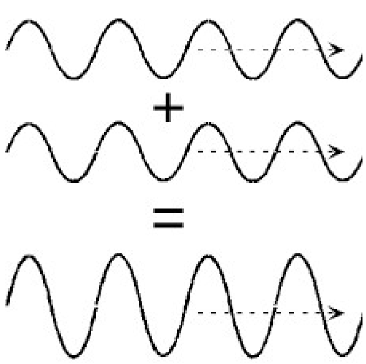


Figure 1(a)

Destructive interference by two pulses. Two pulses with their amplitudes in opposing directions (one up and one down) cross paths. At the point of crossing, the pulses merge to form the resultant wave. The resultant's amplitude is much smaller than the amplitudes of the two individual waves because as they cross they almost cancel each other out. After they superimpose, they move in the same direction with the same amplutide and wavespeed as before they crossed.

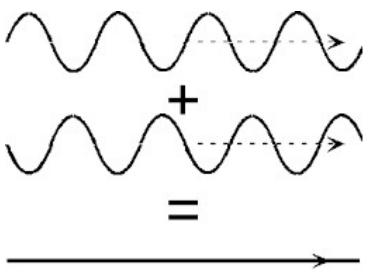
In Phase and Out-of-Phase

Superposition of two waves with same frequency In Phase



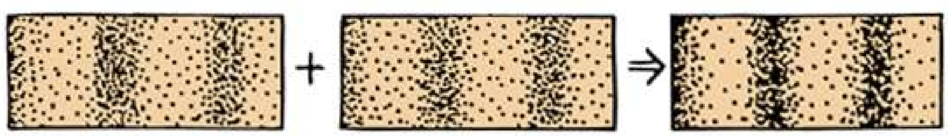
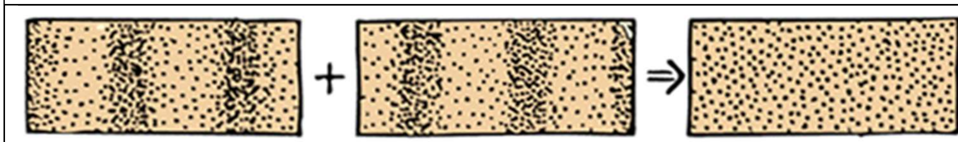
The diagram to the left shows what happens when two identical transverse waves that are exactly ***in phase*** and overlap with each other. Note that the crests align on the upper wave align with the crests on the lower wave, and the same for the troughs. During the superposition, the resultant wave (sum of the two individual waves) has an amplitude greater than the two waves' amplitudes—crests are higher and troughs are deeper. This is due to total ***constructive interference*** of the two waves being in phase.

Superposition of two waves with same frequency 180º Out of Phase

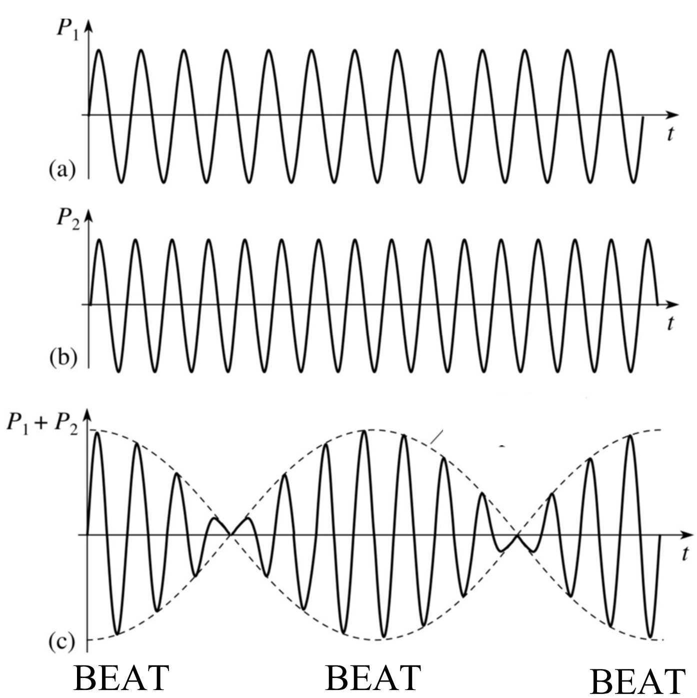


The diagram to the left shows two identical transverse waves that are exactly 180º ***out of phase*** and overlap with each other (upper and middle wave). Note that the crests on the upper wave exactly align with the troughs on the middle wave, and vice versa. During the superposition, the resulting wave (sum of the two individual waves, the bottom) is a flat line. The individual wave energies are cancelled out. This is due to the total ***destructive interference*** of the two identical waves being 180º out of phase.

Longitudinal waves are traveling disturbances of compressions (particles squeezed together into dense zones) and rarefactions (particles expanded apart into diffuse zones). Longitudinal waves, like sound waves, can also have interference as they superimpose. If longitudinal waves overlap with compressions in-phase with other compressions and rarefactions in-phase with other rarefactions, the density of the compressions will increase and the wave will increase in amplitude. If the waves are out-of-phase and compressions overlap with rarefactions, the density of the compressions decreases and the amplitude will decrease.

	In phase. Constructive interference. Denser compressions. Greater amplitude.
	Out-of-phase. Destructive interference. Diffuse compressions. Weaker amplitude

Superposition of two waves with slightly different frequencies



Wave #1 (slightly lower frequency)

Wave #2 (slightly higher frequency)

Resultant wave with beats (constructive interference, increased amplitude)

The diagram on the previous page shows what happens when two different transverse waves that have slightly different frequencies superimpose. The crests and troughs on the two waves have regions where they totally align (in phase), partially align (shifted out of phase), and are totally 180º out of phase. The resultant wave (lower) has intervals of increased amplitude intensity corresponding to the alignment of crest-to-crest and trough-to-trough, resulting in beats. **Beats** are created by periodic constructive interference between waves of different frequency. Conversely, the resultant wave also has intervals of reduced and zero amplitude (nodes) corresponding to the alignment of crest-to-trough. These intervals or signal or amplitude cancelling are created by destructive interference between waves where superimposing regions are out of phase.

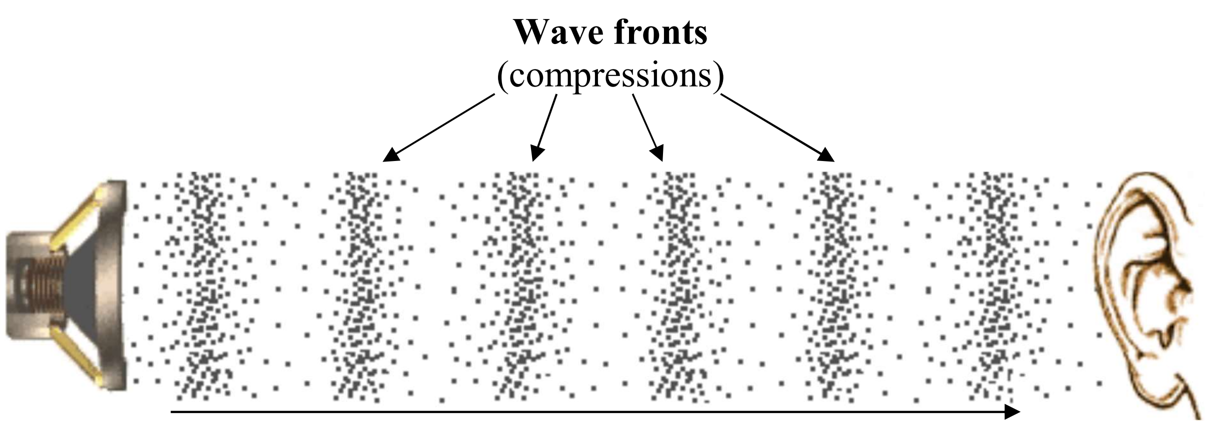
Part 4: SOUND AND SOUND WAVES

Learning Targets

1. Students will compare and contrast frequencies of sound in the audible range of human hearing, and be able to describe sound waves in the infrasonic and ultrasonic ranges.
2. Students will describe the physical nature of sound waves and how they move through a medium.
3. Students will compare and contrast the speed of sound through various media, such as through solids, liquids, and gases.
4. Students will characterize subsonic, transonic, and supersonic speeds, as well as how sonic booms are formed.
5. Students will describe how sound is made through vibrations.

A. Sound Waves

Acoustics is the field of science that describes the properties of sound. Vibrating objects like strings, reeds, and metals make sound. Sound is energy that moves as a traveling vibration in the form of ***longitudinal waves***. Like all ***mechanical waves***, sound waves propagate or travel through matter—solids, fluids, and gases—but cannot travel through a vacuum like space. The ***compressions*** of the sound wave are called ***wave fronts***.



Wave fronts are traveling pulses of higher pressure created when the molecules of the medium are bunched up—the compression part of the longitudinal wave. Wave fronts carry the energy of the sound wave. When the wave fronts impact the ear or sound detector, they carry the intensity of the sound and transmit the sound. The greater the number of molecules bunched up at the wave front, the thicker the wave front, the greater the amplitude and pressure of the wave, the louder the sound will be perceived. Conversely, the rarefactions or the regions between wave fronts where air molecules are spread out or expanded, carries little intensity of the sound.

B. Speed of Sound

The speed of sound is much lower than the speed of light. This can be observed during a thunderstorm. One always sees a lighting strike before hearing the thunder. Light travels through air at 300,000,000 m/s. In contrast, at 20ºC, sound travels through air at 343 m/s. Light travels ~872,000 times faster than sound. That is why during thunderstorms the lightning flash is always seen first, the sound of thunder follows seconds later. The two greatest factors affecting the speed of sound is density of the medium and the temperature of the medium through which sound travels.

Sound waves travel faster through denser materials and slower through lesser dense materials. This is true because sound travels as a longitudinal wave, a moving vibration. If molecules are closer together and packed in a tight configuration, the vibration and wave fronts can easily move from molecule to the next molecule, bunching them up easily.

- Sound waves travel fastest through dense solids.
- Sound waves travel slowest through gases.

Speed of Sound

Air 20ºC: 343 m/s
Ethanol 25ºC: 1270 m/s
Water 25ºC: 1500 m/s
Lead: 2160 m/s
Glass: 5100 m/s
Steel: 5900 m/s
Vacuum: 0 m/s

Sound travels faster through warmer air and slower through cooler air. This is true because sound waves are traveling wave fronts in a longitudinal wave. They have kinetic energy. If the material is warmer, the background kinetic energy of the air molecules is already greater. Thus, as the wave fronts pass through the material with the molecules of greater kinetic energy, the waves increase in velocity. If the wave passes through cooler materials with lesser molecular kinetic energy, the vibrations are passed through slower.

- Sound waves travel faster through warmer air.
- Sound waves travel slower through cooler air.

Speed of Sound in Air at different temperatures

Air 0ºC: 331 m/s
Air 10ºC: 337 m/s
Air 20ºC: 343 m/s
Air 30ºC: 349 m/s
Air 40ºC: 355 m/s

Calculating the Speed of Sound

The speed of sound in a medium, c, is equal to the distance that sound travels divided by the time of travel:

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

c = wave speed (m/s)
d = distance traveled (m)
t = time (s)

The speed of sound in air at a given temperature is calculated using the following equation

$$c_{(T)} = 331\, {}^{m}\!/\!_{s} + \left(0.6 \cdot T_C\right)$$

c_T = wave speed at a given temperature (m/s)
T_C = air temperature (ºC)

As T_C is greater (hotter), $C_{(T)}$ increases and sound travels faster.

Illustrative Example

A sound wave travels at 343 m/s through air. Calculate how far the wave travels in 1 minute.

$$d = c \cdot t$$
$$d = 343\, {}^{m}\!/\!_{s} \cdot 60\ s = 20{,}580\ m$$

In 1 minute, the sound waves travel 20,580 m (or 20.6 km).

Illustrative Example

A sound wave travels 340 m/s through air. How long does it take for the wave to travel 3 km (3000 m) ?

$$t = \frac{\Delta d}{c} = \frac{3000m}{340\, {}^{m}\!/\!_{s}} = 8.82\ s$$

The waves travel for 8.82 seconds over a distance of 3.0 km.

Illustrative Example

Calculate the speed of sound through air at -20ºC.

$$c_{(T)} = 343\, {}^{m}\!/\!_{s} + 0.60\left(T - 20^\circ C\right)$$
$$c_{(T)} = 343\, {}^{m}\!/\!_{s} + 0.60\left(-20 - 20^\circ C\right)$$
$$c_{(T)} = 319\, {}^{m}\!/\!_{s}$$

The speed of sound through air at -20ºC is 319 m/s.

Illustrative Example

Calculate the speed of sound through air at 40ºC.

$$c_{(T)} = 343\, {}^{m}\!/\!_{s} + 0.60\left(T - 20^\circ C\right)$$
$$c_{(T)} = 343\, {}^{m}\!/\!_{s} + 0.60\left(40 - 20^\circ C\right)$$
$$c_{(T)} = 355\, {}^{m}\!/\!_{s}$$

The speed of sound through air at 40ºC is 355 m/s.

C. How Fast?

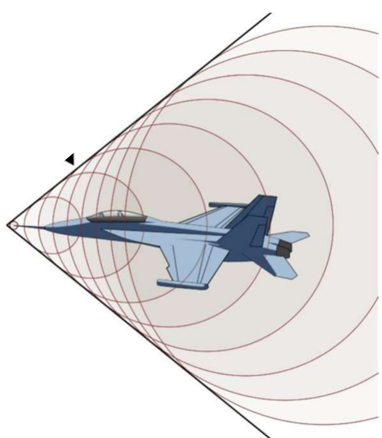
Objects that move at ***subsonic*** speeds are moving slower than the speed of sound. Objects that move at ***transonic*** speeds are moving at the speed of sound. Objects that move at ***supersonic*** speeds are moving at speeds 1-5 times greater than the speed of sound. Objects that move at ***hypersonic*** speeds are moving at speeds 5-times or greater than the speed of sound.

Subsonic	Transonic	Supersonic	Hypersonic
Mach < 1.0	Mach $= 1.0$	Mach > 1.0	Mach > 5.0

Conventional aircraft and ground vehicles

Military aircraft and missiles

Spacecraft

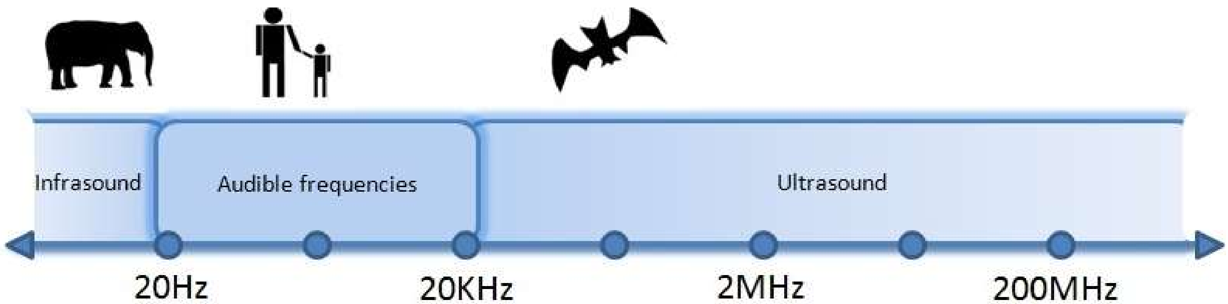


Mach numbers are the ratios of the objects speed divided by the speed of sound in air at 20ºC (v = ~0.34 km/s). Mach numbers are used to describe the relative flying speed of aircraft and spacecraft. For example, Mach 1 is transonic and Mach numbers greater than 1 are supersonic.

When aircraft "**break the sound barrier**" by achieving supersonic speeds (e.g., moving faster than the speed of sound), the wave fronts or compressions of the sound waves generated by the supersonic aircraft are being pushed together into a thicker and denser layer of air molecules at the nosecone of the aircraft. This powerful collection of wave fronts gets denser and denser, building up into the high pressure layer of air called the ***shockwave***. When the aircraft passes by, the shockwave emitted by the aircraft will create a power impact on the objects it hits and create a thunderous violent roar called the ***sonic boom***.

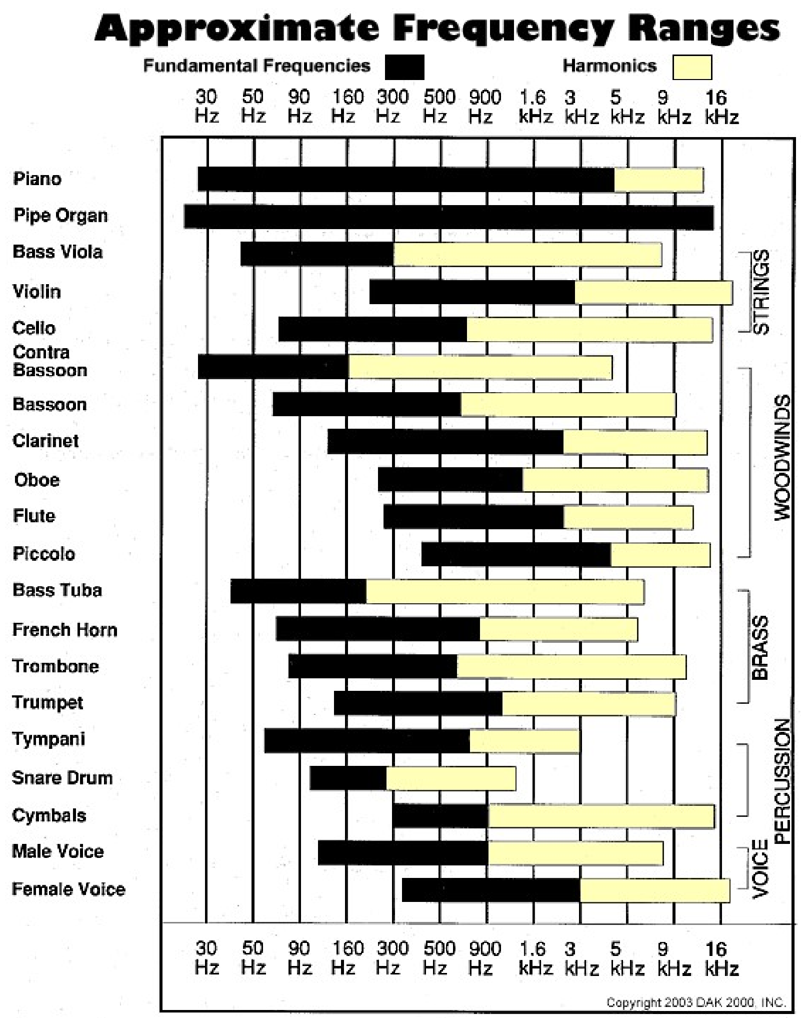
D. Frequency of Sound Waves

The ***audible range*** of typical human hearing is 20 Hz to 20,000 Hz. Most human ears can detect sound with frequencies in that range. Humans cannot hear or detect sound outside of that range. Most mammals can hear higher frequency sound. ***Infrasonic*** waves are sound waves that have frequencies below 20 Hz. ***Ultrasonic*** waves are sounds that have frequencies greater than 20,000 Hz. Some seismic waves, whale songs, and thunder are infrasonic. Bats and dolphins emit ultrasonic pulses for echolocation.



Frequency is the number of vibrations, waves, or cycles passing a given position per second. Wavelength is the distance between two identical positions on two consecutive waves. Remember, frequency is inversely proportional to wavelength. The higher the frequency, the shorter the wavelength; the lower the frequency, the longer the wavelength. The frequency of sound affects pitch.

Pitch is the quality of sound received by and interpreted by the human ear. If sound has lower frequency, the ear detects sound that is bass (low). If sound has a higher frequency, the sound is more shrill (high). A tuba produces low frequency sound (200-300 Hz) which has a more bass pitch. A trumpet produces a medium frequency sound (160-900 Hz). A flute produces a high frequency sound that has a more shrill pitch (300-2000 Hz). The sounds emitted by pianos encompass a very large range of frequency (30-4000 Hz).



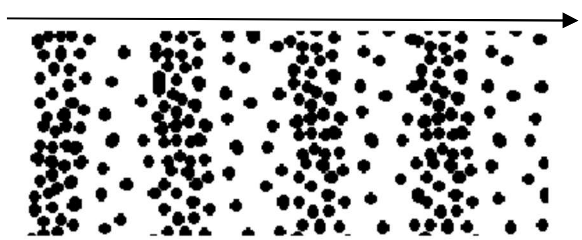
The relationship between frequency and wavelength of sound is determined by the following series of equations that have been algebraically rearranged. The product of the frequency of the wave and the wavelength of the wave is always the speed of sound (wave speed).

$$c = f \cdot \lambda \qquad f = \frac{c}{\lambda} \qquad \lambda = \frac{c}{f}$$

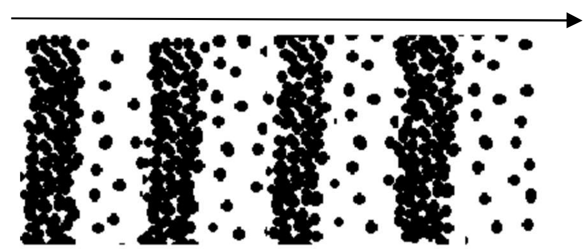
f = frequency (Hz)
c = wave speed (m/s)
λ = wavelength (m)

E. Volume and Intensity of Sound

Volume is the loudness of sound. ***Intensity*** is the power of sound energy at a given distance away from the sound emitting sources. The two are related. Volume is a function of the ***amplitude*** of the sound wave. The greater the air is compressed at the wave front, the more molecules bunched up in the condensation, the louder the volume will be.

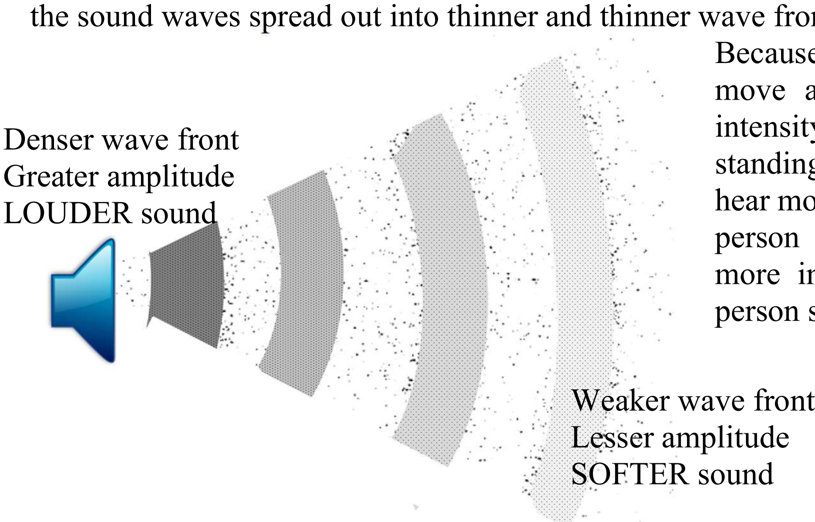


Softer sound and lower volume. The wave fronts have lesser amplitude—the wave fronts have lower density of air molecules.



Louder sound and higher volume. The wave fronts have greater amplitude—the wave fronts have higher density of air molecules.

The intensity of sound is greatest and volume the loudest near to the sound emitting source and volume decreases with increasing distance away from the source. As sound waves move away from the source, the sound waves spread out into thinner and thinner wave fronts.



Because of the thinning out of the waves as they move away from the source, the volume and intensity of the sound decreases. A person standing 1 meter in front of a music speaker will hear more intense sound and louder volume than a person standing 10 meters away, who will hear more intense sound and louder volume than a person standing 50 meters away.

Sound intensity is measured in ***decibels*** (ten-bels). ***Decibels*** is a base-10 logarithmic scale of measure that characterizes the intensity of sound. Each step interval of 10 on the Decibel system represents a 10-times increase in sound energy intercepted by the ear. For example, a whisper carries 10-times the sound energy of a watch ticking whereas tapping the foot is 1000-times the sound energy of a watch ticking.

Decibel	Loudness	Object
0	Threshold of hearing	
10	Very faint	Watch ticking
20	Very faint	Whisper
30	Faint	Quiet conversation
40	Faint	Tapping foot
50	Moderate	Normal Conversation
60	Moderate	Normal car engine
70	Loud	Rock music on radio
80	Loud	Alarm clock
90	Very loud	Machines in factory
100	Very loud	Lawn mower
110	Deafening	Train locomotive
120	Deafening	Plane taking off

How to calculate sound intensity in decibel units:

$$dB = 10 \cdot \log \frac{I_i}{I_o}$$

I_i = Intensity of sound (Watts/m^2)
I_0 = Intensity of sound at the threshold of human hearing (Watts/m^2)
$I_0 = 1.00\text{x}10^{-12}$ Watts/m^2

Part 5: THE DOPPLER EFFECT

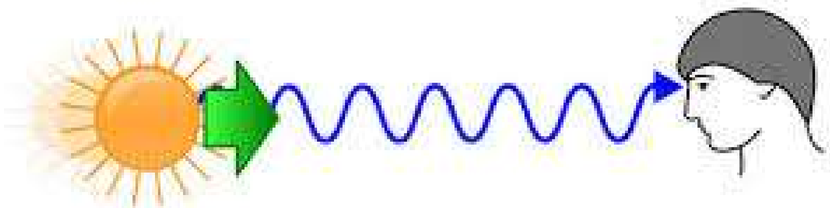
Learning Target

- Students will describe in their own words the concepts of redshift, blueshift, and Doppler effect.
- Students should be able to describe or predict how the observed frequency/pitch will change if a sound emitting object is approaching or receding from the observer.

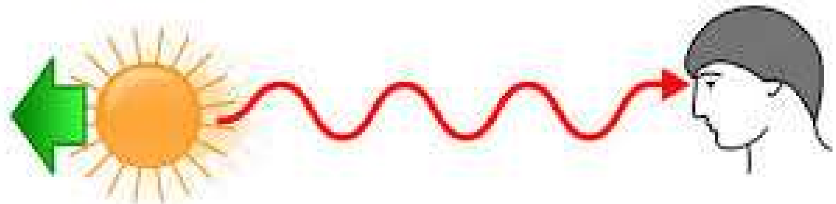
The ***Doppler effect*** is the *observed change in wave frequency* measured by an observer (e.g., pitch of sound, wavelength of light waves) that is produced by a moving object relative to the observer. If you have ever listened to a train or a fire engine while standing next to the railroad tracks or the road, you probably have heard the characteristic change in sound attributed to the Doppler effect. The Doppler effect is most notable with sound waves, however, it also applies to light waves. The object that emits the waves (light or sound) emits them with the same frequency regardless of its motion. When a moving object such as a car or train is producing sound, such as a whistle of a siren or the hum of a motor, the sound at the source is at constant frequency that never changes. It is the observer that notices changes in the frequency of the waves because of the direction that object moves.

A ***redshift*** is the observed decrease of frequency and increase in wavelength that is caused when wave emitting objects movie away from the observer. A ***blueshift*** is the observed increase of frequency and decrease in wavelength that is caused when the wave emitting objects move toward the observer.

Blueshift: higher frequency, and shorter wavelength because moving toward the observer.



Redshift: lower frequency and longer wavelength because moving away from the observer.

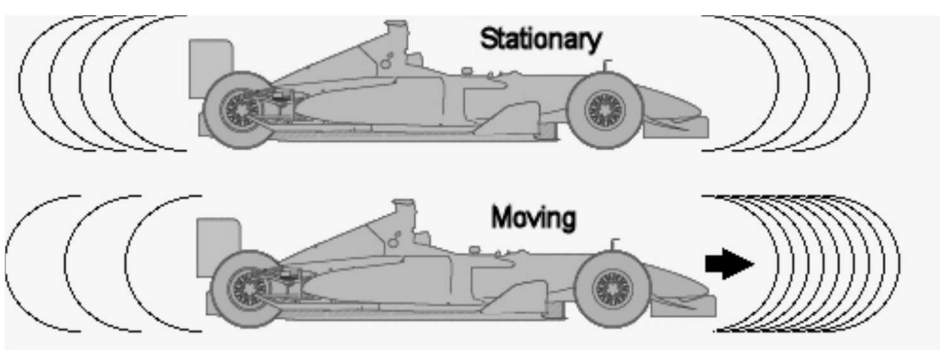


As the object moves, the sound or light waves become condensed in front of the moving object (frequency appears to increase, a blueshift) and become extended behind the moving object (frequency appears to decrease, a redshift) as the waves are being emitted. If you were standing in front of the object and it moved toward you, the sound you hear would be shriller with a higher pitch, or visible light would appear slightly greater in wavelength (redder). If you were standing behind the object and it moved away from you, the sound you hear would be more bass with a lower pitch, or visible light would appear slightly shorter in wavelength (bluer).

Illustrative example

The frequency of sound waves emitted by the race car is the same regardless if the car is stationary or moving. When the car is moving forward, the wave fronts in front of the moving car are closer together because as the sound waves are emitted, the car moves in the same direction as they move. An observer standing in front of the car as the car approaches him would hear the "blueshift" or higher pitch of the car's engine. The wave fronts behind the moving car are spaced farther apart because they move away from the car in the direction opposite of the car's motion. An observer standing behind the car as it moves away would hear the "redshift" or lower pitch of the car's engine.

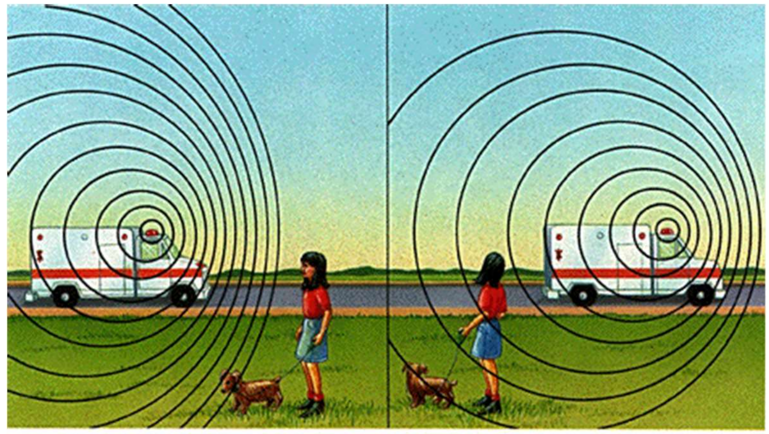
Lower pitch "redshift"



Higher pitch "blueshift"

Illustrative Example

As the ambulance moves toward the girl (observer), the siren will appear to have a higher pitch and frequency (a blueshift) because the wave fronts are closer together. As the ambulance moves away from the girl, the siren will appear to have a lower pitch and frequency (a redshift) because the wave fronts are farther apart. At the instant where the ambulance is immediately beside her, she will hear the truel pitch and frequency of the siren.



Higher pitch "blueshift"

Lower pitch "redshift"