Unit 6

Mechanical Oscillation and Sound Wave

6.1 Common Characteristics of Waves

What are waves?

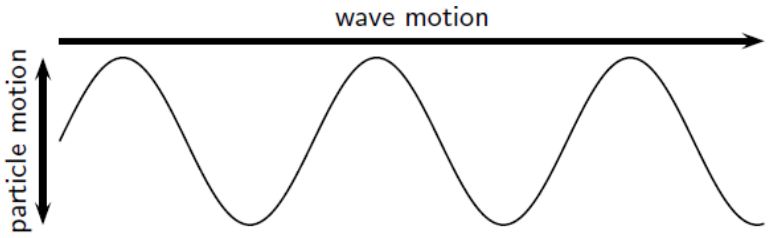
- A wave is a periodic, continuous disturbance that consists of a train of pulses.
- All waves transfer energy from one place to another.
- Waves may be invisible or visible.
- Sound, radio, TV wave etc are invisible.
- Water wave and waves on string (spring) are visible.
- **wave pulse** a wave with no repeated vibrations.
- **continuous wave** a wave with repeated vibrations

Types of wave

- Based on the direction of vibrations in relation to the direction of wave movement, there are two type of wave

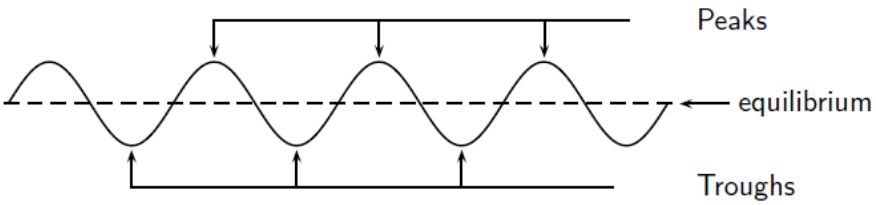
1. **Transverse wave**

- A transverse wave is a wave where the movement of the particles of the medium is perpendicular to the direction of propagation of the wave.



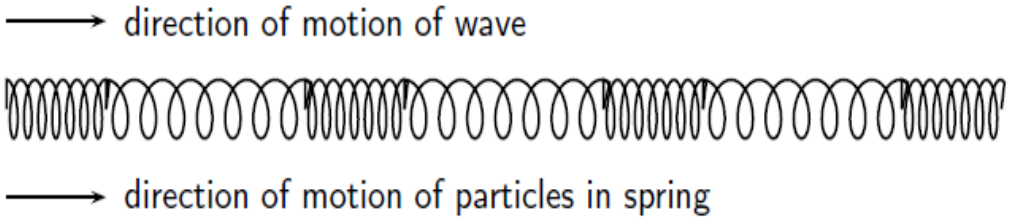
- Examples of transverse waves;
    - all electromagnetic waves (Light, radio waves, X-rays etc.)
    - S-waves in earthquakes
    - waves on strings
    - waves on the surface of deep water.
- All transverse waves comprise a series of **crests** (or **peaks**) and **troughs**.
- **A peak** is a point on the wave where the displacement of the medium is at a maximum.

- A **trough** is a point on the wave where the displacement of the medium is at a minimum.



2 Longitudinal

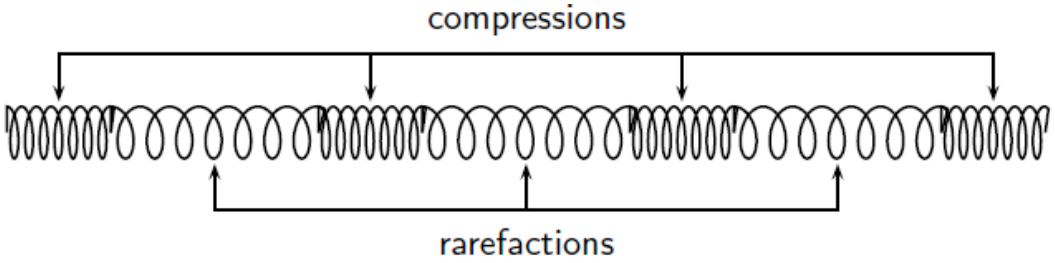
- A longitudinal wave is a wave where the particles in the medium move parallel to the direction of propagation of the wave.



Examples of longitudinal waves include:

- sound waves
- pressure waves
- waves forwards and backwards through a spring
- P-waves in earthquakes

- longitudinal waves have compressions and rarefactions.
- A **compression** is a region in a longitudinal wave where the particles are closer together.
- A **rarefaction** is a region in a longitudinal wave where the particles are further apart.



Classification of wave

- Depending whether a wave requires a material medium to propagate or not they are classified into two

1. **Mechanical waves**

- Requires a medium to travel through it.
- Can only travel in a material medium by setting the particles of the medium into motion as they transfer energy
- All mechanical waves could not travel through vacuum.
- A medium is the substance or material in which a wave will move.
- The medium does not create the wave and the medium is not the wave.
- Air is a medium for sound waves, water is a medium for water waves and rock is a medium for earthquakes

2. Electromagnetic wave (EM)

- Waves that comprise of electric and magnetic fields.
- Not require a medium to travel through.
- They are able to travel through a vacuum and when they travel through a medium there are no particles vibrations inside that medium.
- Light wave, radio and TV waves, microwaves, infrared, UV- rays and gamma rays are all EM waves

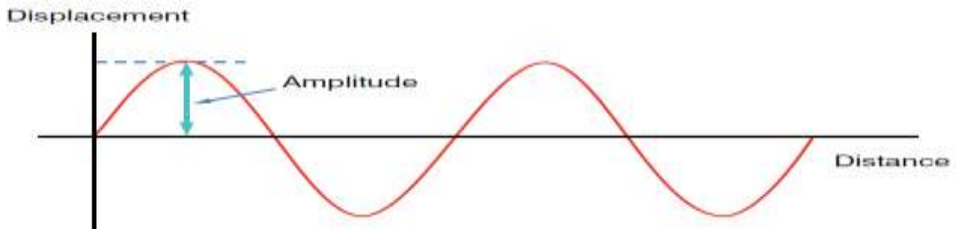
Waves characteristics

Rest position (Equilibrium position): Rest position is the undisturbed position of particles or fields when they are not vibrating.

Displacement: Displacement is the distance that a certain point in the medium has moved from its rest position.

Amplitude (a)

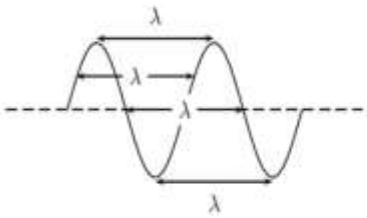
- The maximum displacement above or below from the equilibrium position.
- it's the maximum height of the wave.

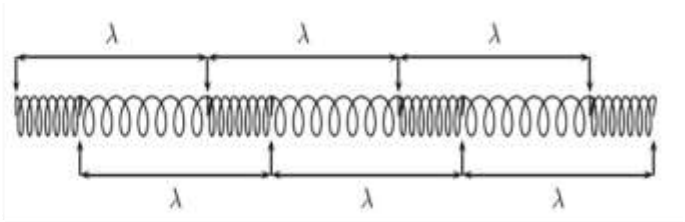


- Amplitude is given the symbol a (x_o). it is measured in metres (m).

Wavelength (λ)

- the distance the wave travels in one complete cycle or
- the distance between any two adjacent points that are in phase.





Transverse wave **longitudinal wave**

- Wavelength is given the symbol λ(lambda); this is the Greek letter l.
- As wavelength is a distance it is measured in metres (m).

Period (T)

- the time taken for a wave to make one complete vibration or
- The time taken for two successive peaks (or troughs)to pass a fixed point.
- Measured in seconds (s).

Frequency (f)

- the number of complete vibration performed in one second
- The frequency and the period are related to each other. As the period is the time taken for 1 peak to pass, then the number of peaks passing the point in 1 second is $1/T$. But this is the frequency.

  So $f = 1/T$
- Frequency is given the symbol f and is measured in hertz (Hz).

  $Hz = 1/s$ or s^{-1}

Wave speed (v)

- The distance the wave travels in one second.
- It's given the symbol v (c for electromagnetic waves) and it is measured in metres per second (m/s).

Wave equation

It relates wave speed, frequency and wavelength.

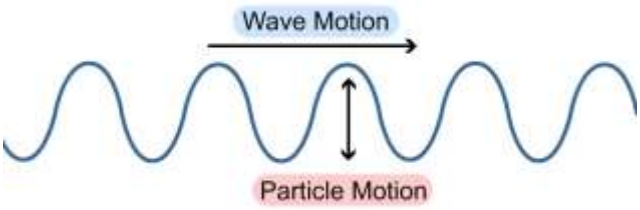
Wave speed = frequency × wavelength

$$v = f\lambda$$

6.2 String, Pendulum and Spring

String

The type of wave that occurs in a string is called a transverse wave. Imagine you are holding one end of a string, and the other end is secured and the string is pulled tight. Now, if you were to flick the string either up and down, a simple kind of wave called "pulse" is created. The pulse moves horizontally along the string while the particles of the string moves up and down at right angles to the horizontal motion of the pulse (wave). The act of flicking creates disturbance called wave which propagates along the string.



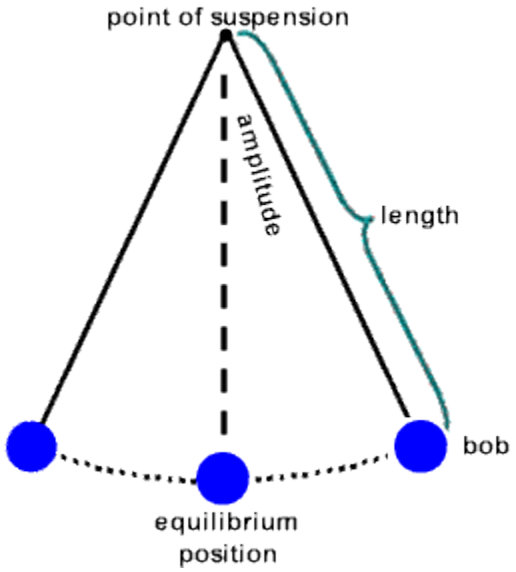
Pendulum,

- Body suspended from a fixed point so that it can swing back and forth under the influence of gravity.
- Pendulums are used to regulate the movement of clocks because the interval of time for each complete oscillation, called the period, is constant.
- The period of a simple pendulum depends only on its length and the acceleration due to gravity. It does not depend on the mass of the bob.

- The formula for the period T of a pendulum is

$$T = 2\pi \sqrt{l/g}$$

Where l is the length of the pendulum and g is the acceleration due to gravity.



Example

1. A playground swing is 3 meters long. What is the period of the swing? What is the frequency?
2. A pendulum is observed to complete 32 full cycles in 56 seconds.
    a. Calculate the period.
    b. Calculate the frequency.
    c. Calculate the length.
3. Find the length of a pendulum that has a period of 2.0 s.
4. Find the length of a pendulum that has a frequency of 0.80 Hz.
5. Find the length of a pendulum on earth that has a period of 2.0s.
6. The acceleration due to gravity on the moon is 1.6m/s2. How long of a pendulum would be required to have a period of 1.0 s?
7. A pendulum is 0.75 meters long and has a period of 4.17 seconds. Is this pendulum on the earth, moon, or mars? Do a calculation to prove your answer.

The simple spring

Suppose an object of mass m is attached to one end, while the other end of the spring is held fixed. The object has an equilibrium position, call it x = 0, and this is the position where the spring is neither stretched nor compressed. If the object is displaced away from x = 0 (either stretched or compressed) and released, it will undergo a to and fro motion about x = 0. This is another example of periodic motion. In this case, x is the distance by which the spring is either stretched or compressed and is measured from the equilibrium position.

If the object is displaced form x = 0, the spring pulls (or pushes) it back to the equilibrium position (x = 0). Thus, the spring produces a restoring force denoted by *Fres*. The restoring force (or the force exerted by the spring) is directly proportional to the displacement of the object from the equilibrium position x.

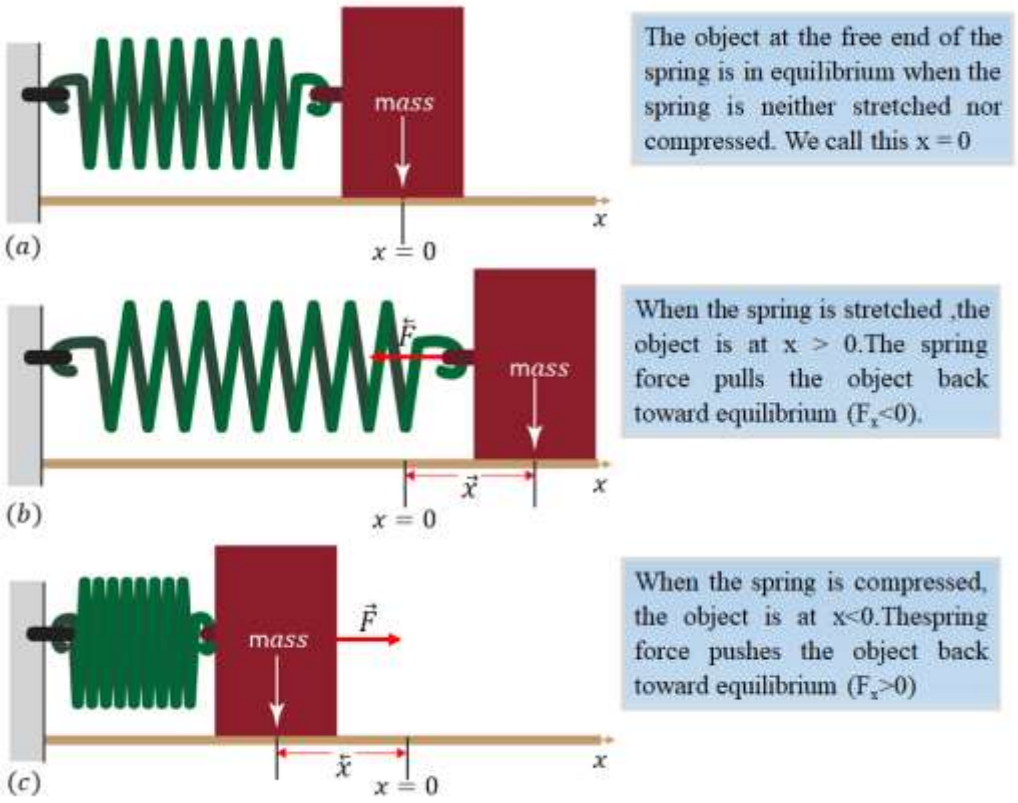
No matter which way the object is displaced from equilibrium, the spring force always acts to return the object to equilibrium.

Mathematically, $Fres = -kx$

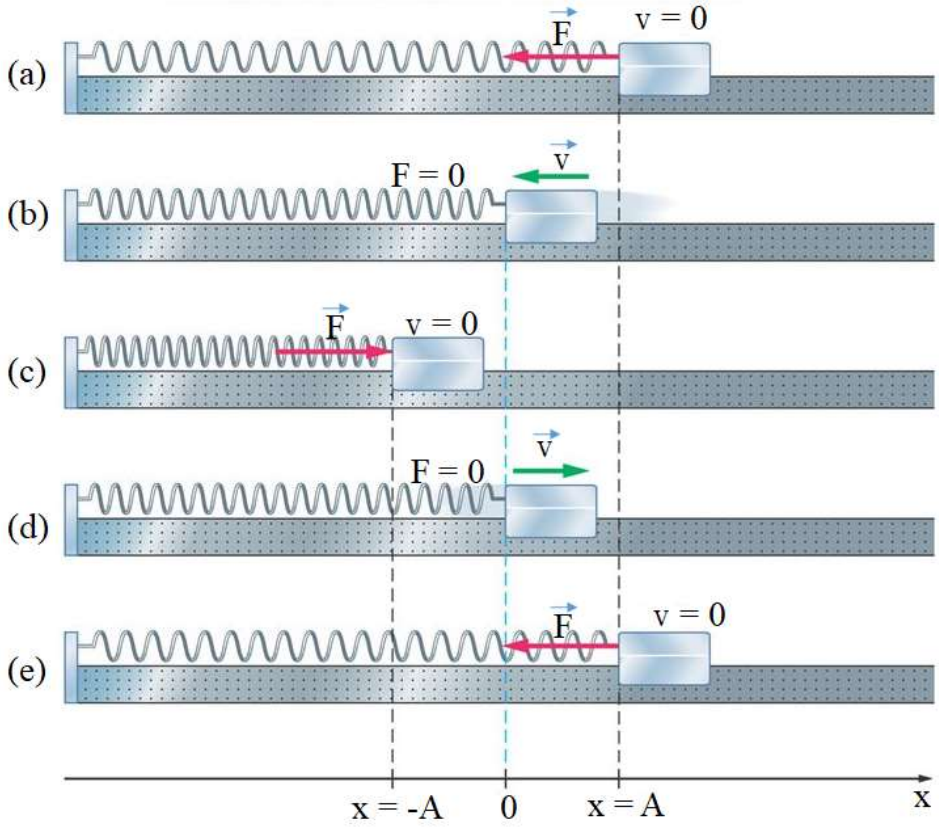
An oscillating object moves repeatedly one way and then in the opposite direction through its equilibrium position. The displacement of the object (i.e., distance and direction) from equilibrium continually changes during the motion.

In one full cycle after being released from a non-equilibrium position, the displacement of the object:

- decreases as it returns to equilibrium
- reverses and increases as it moves away from equilibrium in the opposite direction
- decreases as it returns to equilibrium
- increases as it moves away from equilibrium towards its starting position.



Now, suppose the cart is released from rest at the location x = A. As indicated in Figure 6.6, the spring exerts a force on the cart to the left, causing the cart to accelerate toward the equilibrium position. When the cart reaches x = 0, the net force acting on it is zero. Its speed is not zero at this point, however, and so it continues to move to the left. As the cart compresses the spring, it experiences a force to the right, causing it to decelerate and finally comes to rest at x = -A. The spring continues to exert a force to the right; thus, the cart immediately begins to move to the right until it comes to rest again at x = A, completing one oscillation in the time T.



The period of an object of mass m attached to a spring of spring constant k is given by

$$T = 2\pi\sqrt{\frac{m}{k}}$$

Where, m is the mass of the object and k is the spring constant of the spring. It can be seen that the period only depends on the mass and the spring constant (or stiffness) of the spring.

Periodic motion, in physics, motion repeated in equal intervals of time. For example, a bouncing ball, a swing in motion, the Earth in its orbit around the Sun, and a water wave.

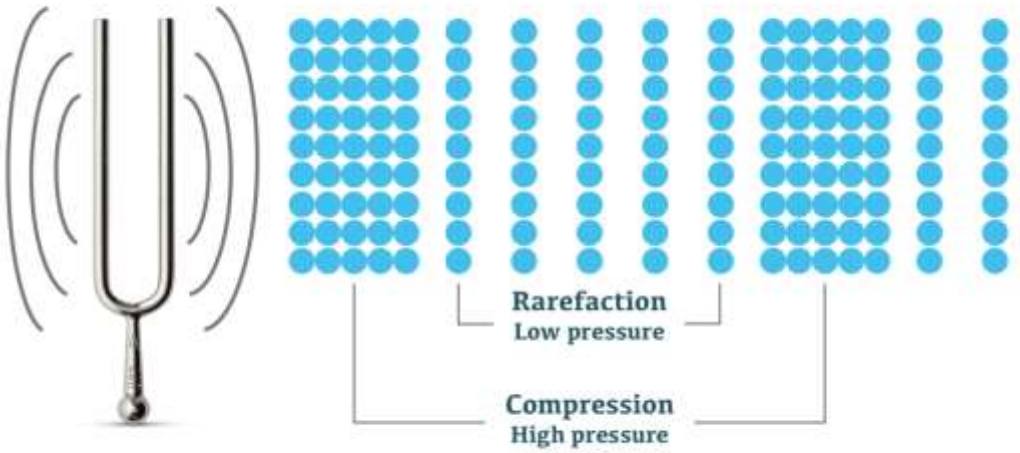
6.4 Sound Waves

Sound is produced when an object vibrates, creating a pressure wave. This pressure wave causes particles in the surrounding medium (air, water, or solid) to have vibrational motion. As the particles vibrate, they move nearby particles, transmitting the sound further through the medium. The human ear detects sound waves when vibrating air particles vibrate small parts within the ear. The human ear can hear frequencies from 20 to 20 000 Hz.

Every source of sound is in a state of vibration.

Production and Propagation of Sound

A sound wave is the pattern of disturbance caused by the energy travelling away from the source of the sound. Sound waves are longitudinal waves. This means that the propagation of vibration of particles is parallel to the energy wave propagation direction. When the atoms are set in vibration they move back and forth. This continuous back and forth motion results in a high-pressure and a low-pressure region in the medium. These high- pressure and low-pressure regions are termed compressions and rarefactions, respectively. These regions are transported to the surrounding medium resulting in the sound waves travelling from one medium to another.



Sound carries energy and loses its energy as it travels. So, the further the sound travels, the more energy it loses and the quieter the sound becomes. Our ears are designed by nature to pick up sound transmitted through different materials.

Speed of sound

The speed of sound waves in a medium depends on the compressibility and density of the medium. This means that sound has different speed in different media. Sound moves most quickly through solids, because its molecules are densely packed together. This enables sound waves to rapidly transfer vibrations from one molecule to another. Sound moves similarly through water, but its velocity is over four times faster than it is in air. The velocity of sound waves moving through air can be further reduced by high wind speeds that dissipate the sound wave's energy.

Table 6.1: Speed of sound in various materials.

S. No	Material	Speed of sound in m/s
1	Air (0^oC)	331
2	Air (20^oC)	343
3	Sea water (25^oC)	1533
4	Water (25^oC)	1493
5	Iron	5950
6	Lead	1960
7	Rubber	1600

The speed of sound in air is about 331 m/s at 0 ^0C. The speed of sound in air, v at any temperature *Tc* can be calculated as

$$v = 331m/s\sqrt{1 + \frac{T_c}{273}}$$

Or

$$v = 331m/s + \frac{0.6m/s}{^\circ c} \times T_c$$

Where 331m/s is the speed of sound at 0 ^0C and *Tc* is the air temperature in degree Celsius. The speed of sound in liquids and solids is not affected significantly by the change in temperature, but affected by their body structure.

Activities

1. What is the speed of sound in air at 20 ^0C?
2. Sound travels along a steel rod of length 4m in a time of 0.0008 s. What is the speed of sound in the steel?
3. Calculate the speed of sound in air at 30 ^{0}C.

Reflection, Refraction, Diffraction and Interference of Sound

i. **Reflection of Sound**

Sound reflection occur when sound waves bounce back from the surface of a solid or liquid. Many fascinating phenomena, such as echo and reverberation, are caused by sound reflection.

When a sound hits a hard surface, it bounces back to its source. This type of sound reflection is known as an echo. Soft materials absorb and muffle sound, whereas hard surfaces reflect it.

If the frequency of the sound wave is low, it will not be reflected.

Echo

- Sound, like all waves, is able to reflect off surfaces.
- A reflection of sound is called an echo.
- Matter can in solid, liquid and gas state but from these state the best echo is obtain in solid state like metal sheets and stone.
- If the sound produced is in an enclosed space it may produce a number of echoes. This sound is building up than slowly decaying away. This is called reverberation.

Application of Echo (reflection of sound)

- ❖ To determine the velocity of sound in air.
- ❖ To determine the depth of an ocean (sea).
- ✓ The depths of oceans are determined using a device called sonar.
- ✓ Sonar makes underwater sound waves, which travels to the bottom of the sea. This wave is then reflected off the seabed and returns to the ship. The time for the sound wave to return back to the ship(echo time) is measured. By use of the speed V of sound in sea water, we can then determine the depth of the sea(ocean) using the equation

$$S = {}^{vt}/_{2}$$

ii. **Refraction of Sound**

Refraction is the bending of waves when they enter a medium where their speed is different.

Sound waves travel outward in straight lines from their source until something interferes with their path. When sound changes mediums (enters a different material) at an angle other that 90 degrees, it is bent from its original direction. This change in angle of direction is called refraction.

The speed of sound is greater in hot air than it is in cold air. This is because the molecules of air are moving faster and the vibrations of the sound wave can therefore be transmitted faster.

This means that when sound travels from hot air to cold air or from cold air to hot air it will refract.

You can notice this on a hot day or a cold night.

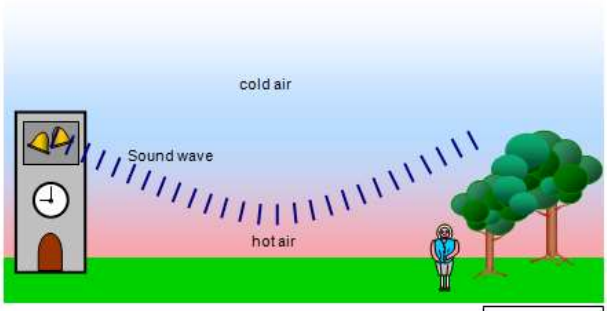


Figure 1

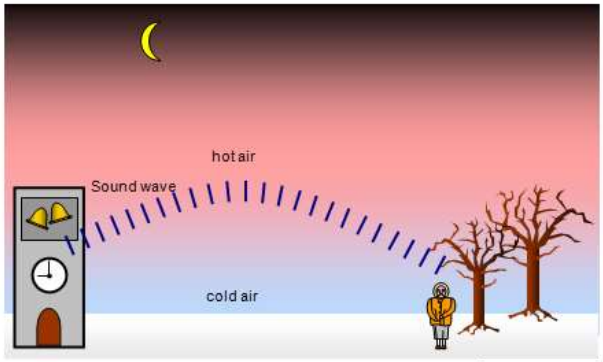


Figure 2

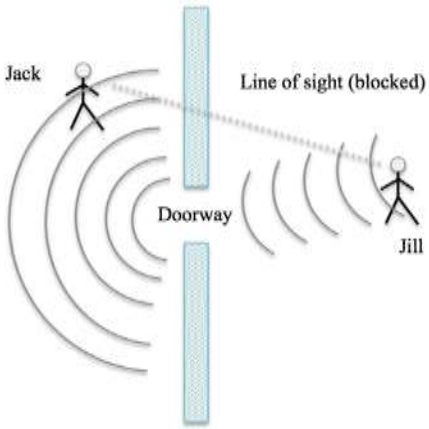
On a hot day the air near the ground is hot so the sound wave bends upwards from the hot air into the cold air (Figure 1).

On a cold night the air near the ground is cold and so the sound wave bends downwards. (Figure 2) This is why you can sometimes hear sounds from a long way away if the night air is cold.

iii. Diffraction of sound

Sound wave also changes its direction, for example, around corners or door openings allowing us to hear others who are speaking to us from adjacent rooms.

Such a change in the direction of sound wave as it passes through an opening or around a barrier in its path is known as **diffraction.**



Superposition of Waves

When two or more waves pass through a single point at the same time the resultant instantaneous displacement at that point is the sum of the displacements that would be created separately by each wave, taking signs in to account. This principle is said to be the **superposition principle**.

Superposition is also known as Interference. Interference can be either constructive or destructive depending on the phase between the interfering waves.

Two waves are said to be in phase when corresponding points of each wave reach maximum or minimum displacements at the same time. When two periodic waves with the same frequency and wavelength travel in the same direction in phase, their resultant wave is more amplified and we can say that the two waves interfere constructively.

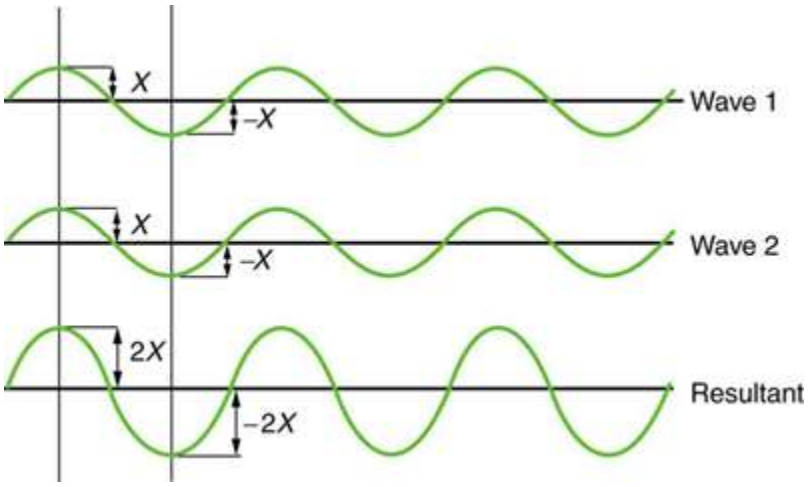


Figure: Constructive interference of two identical waves produces one with twice the amplitude, but the same wavelength.

If two periodic waves with the same frequency and wavelength travel in the same direction, but out of phase, the resulting wave is diminished (or may be zero) in amplitude. In such a case the two waves interfere destructively.

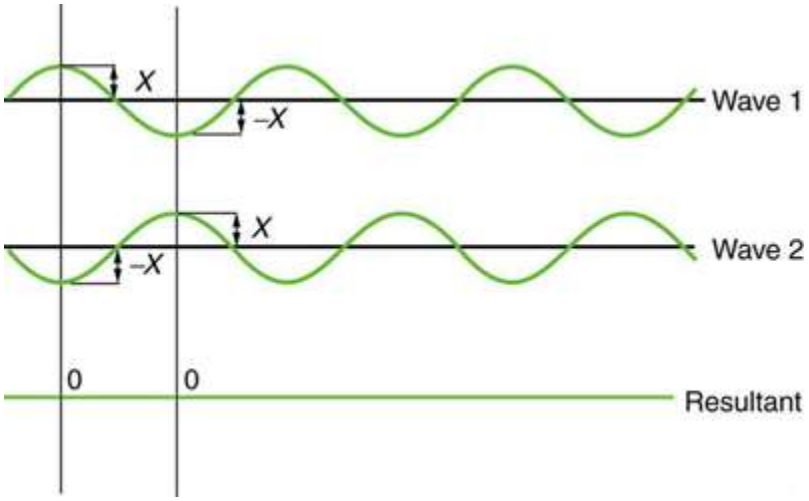


Figure: Destructive interference of two identical waves produces zero amplitude, or complete cancellation.

Standing Waves

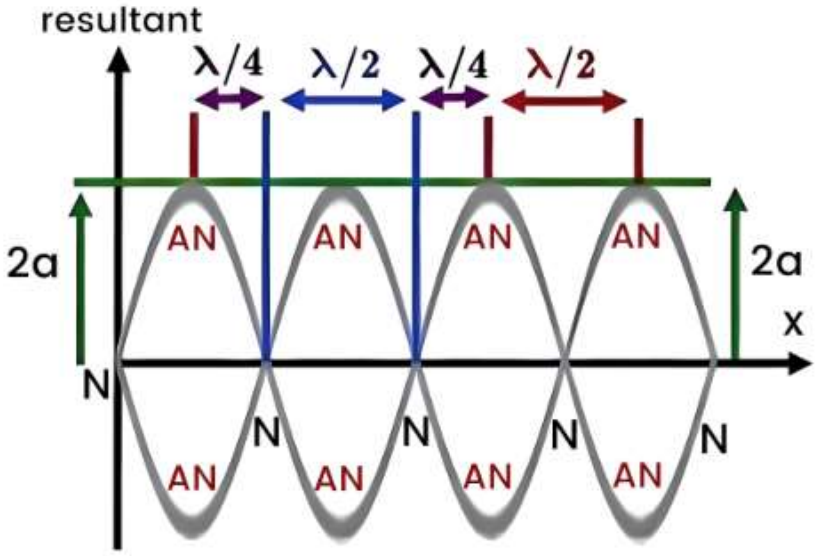
The superposition of two identical waves travelling in opposite directions in the same medium gives standing (stationary) wave.

A standing wave is one that oscillates with time, but remains fixed in its location. It is in this sense that the wave is said to be "standing."

The positions in the medium at which maximum displacement occurs are called antinodes (A) and those positions with zero displacement are called nodes (N).

Note that:

- The distance between adjacent antinodes is equal to $\frac{\lambda}{2}$
- The distance between adjacent nodes is equal to $\frac{\lambda}{2}$.
- The distance between a node and an adjacent antinode is $\frac{\lambda}{4}$.



Characteristics of a Sound Wave

- The basic properties of sound are: pitch, loudness and tone.

- **Pitch** highness or lowness of a sound, which depends on the frequency of the sound wave. A higher frequency sound has a higher pitch, and a lower frequency sound has a lower pitch.

- **Loudness** the audible strength of a sound, which depends on the amplitude of the sound wave. Larger amplitude means a louder sound, and smaller amplitude means a softer sound.

  The loudness of a sound is measured in decibel (dB).

  Exposure to elevated sound that may lead to adverse effects in humans or other living organisms is called sound pollution. Some of the adverse effects include hypertension, hearing loss, sleep disturbances, etc. A noise becomes harmful when it exceeds 75 dB and painful above 120 dB.

- **Tone** is a measure of the quality of the sound wave. Quality does not mean good or bad, it just refers to the difference in sound.

  The quality (timbre) of the sound heard depends on the pattern of the incoming vibrations, i.e. the shape of the sound wave.

  The more irregular the vibrations, the more jagged is the shape of the sound wave and the harsher is the sound heard.