



YABELLO IFA BORU SPECIAL BOARDING SECONDARY SCHOOL

PHYSICS SHORT NOTE FOR GRADE 9

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UNIT: 8

WAVE MOTION AND SOUND

Introduction

- A **wave** is a disturbance or variation which travels through a medium from one region of space to another.
- Wave motion is the transfer of energy and momentum from one point of the medium to another point of the medium without actual transport of matter between two points.
- The medium through which the wave travels may experience some local oscillations as the wave passes, but the particles in the medium do not travel with the wave.
- The disturbance may take any of a number of shapes, from a finite width pulse to an infinitely long sine wave.
- Generally, wave is a moving disturbance in the direction of the energy level, which transfer energy and information from one point to another in space.

- For example, if you drop a piece of stone into a pond, the stone first disturbs the water at the point where it hits the water.
- However, shortly afterwards you can see expanding concentric circular patterns spreading on the water's surface.
- The spreading circular patterns are water waves that propagate starting from the initial point hits by the stone to all direction on the surface of the water.
- Sound, light, radio and television transmission, and Earthquakes are examples of wave phenomena.
- The concept of waves is very important in all branches of study in life. This unit will study different **types of waves**, their **characteristics** and **behavior** and some of their **uses**.
- It also study about some terms used to describe wave motion and common properties of waves like **reflection**, **refraction**, **diffraction** and **interference** of waves.

8.1 Wave propagation

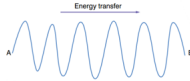
What are waves?

- A wave is defined as a continuous disturbance or a series of vibration that travel through a medium and transporting energy and momentum from one place to another place. A medium is a material through which the wave is travelling.
- All waves are transferring or transporting energy without the actual movement of the matter or the medium from one place to another. A wave does NOT carry matter with it. It just moves the matter as it goes through it.
- Light waves travelling out from a light source just like a light bulb transfer energy from the bulb to the surroundings or to your eye.
- Sound wave transfers energy from a speaker to your ear. When a wave transfer energy from one place to another there is no transfer of matter.

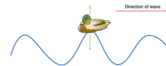
- That means the material the wave is travelling through does not move along with the wave propagation. In other words, when waves travel through water the water does not travel along with the wave.
- This can be seen by observing a duck sitting on the surface of the water or any object that floats on the surface of the water. As the water moves past the duck it just bobs up and down. The duck does not travel along with the wave.
- When the wave passes through the material medium the particles in the medium simply vibrate from side to side and they remain in their equilibrium position.
- The vibration could be up and down, left to right or any vibration, but the particles always move back and forth past their equilibrium position.
- The movement (travelling) of waves from source through the medium is referred to as **propagation** of wave.



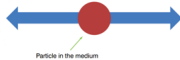
Rays of light travel out as waves from a light bulb.



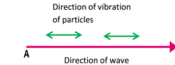
Waves transfer energy from A to B.



A duck floating on the water just moves up and down as the waves go past.

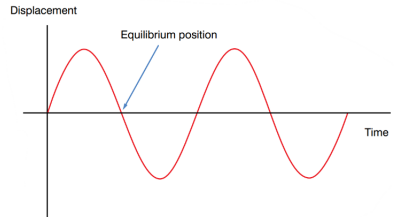


The particles vibrate back and forth past their equilibrium position.



The particles vibrate back and forth past their equilibrium position.

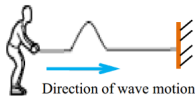
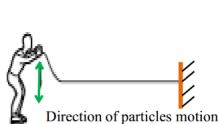
- If you plot a graph of the particle's displacement from its equilibrium position against time we will get a graph similar to Figure.



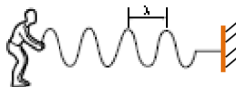
Particle's displacement against time

Wave pulses

- A pulse wave is a special non-periodic waveform that typically has one major crest. It is a single disturbance with a finite length. A pulse wave is often associated with a single sudden motion, impact, or even explosion. It usually has a sinusoidal shape, but in electronics there are also square and rectangular pulse waves. For example, if you shook the end of a rope once you would produce a wave pulse as shown below in Figure below. Here you can see that there are no repeated vibration but only one short pulse.



Simple wave pulse



A simple Continuous wave

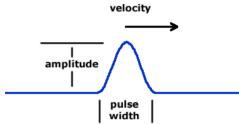
- As with other wave forms, a pulse has a **velocity** and **amplitude**. Since there is primarily only one crest, there is no frequency or true wavelength, although the width of the pulse relates to **wavelength**.
- The location of the rope before and after the pulse passes is the **equilibrium position**.
- The maximum magnitude of the displacement of the pulse from equilibrium is the **amplitude (A)**

Types of wave pulses

- As with regular waveforms, pulse waves can be compression or transverse.

i. Transverse pulse wave

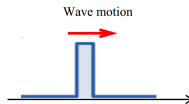
- An example of a simple crest pulse wave is seen at sporting events where groups of fans stand up and then sit down, creating the effect of a "wave" moving across the stadium. It is a transverse waveform.



- ii. **Compression pulse wave** A compression or longitudinal pulse wave can be seen with a slinky toy

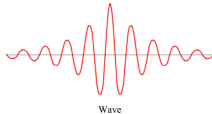


- iii. **Square pulse wave**



Wave packet

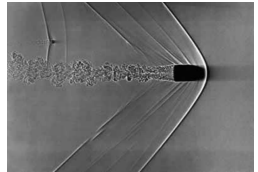
- When the pulse wave has sub-harmonic crests, it is called a wave packet.
- A drop of water into a pool creates the initial pulse wave, accompanied by a series of smaller wavelets in Figure



Water drop creates wave

Shock wave

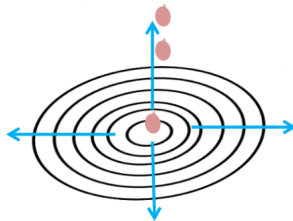
- A special type of pulse wave is a shock wave. When an aircraft travels faster than the speed of sound, it is preceded by a shock wave form of a pulse wave. The same is true with a bullet. The noise from an explosion, as well as thunder, is also a form of shock wave.



Continuous wave

- Consider a rope fixed at one end and move the other end of the rope up and down uniformly. When you move it up and down, you create a continuous motion in the particles of the medium that make up and down that rope. This is referred to as a **continuous wave**.
- A wave which travels continuously in a medium in the same direction without the change in its amplitude is called a **travelling wave** or a **progressive wave**.
- When a stone is dropped into a quiet pond, a set of circular patterns spread outward from the point of impact in even increasing radii. The size of each circular ripple grows at a constant rate. This is referred to as a continuous wave.
- A floating cork does not move forward when the ripples strike it but merely bobs up and down. To us, water waves look like hills of water travelling towards the shore of the pond. But the water itself is not travelling at all. The bobbing of the cork up and down shows that “something” is moving. But the cork does not move with that “something”.

- The same is true of the water itself. It does not travel a long distance with the ripples. It just moves locally up and down. That is first one part of the water surface moves upwards, then the next part and so on. The only thing that is transported through a long distance with the ripples is the energy. Notice that, because of the ripple a floating cork moves up and down. The rock is energized by the ripples. Hence, we can say the energy is transported by the ripples.



Circular pattern
of ripples

8.2 Classification of Waves

- Waves may be classified based on the way they are produced or on the basis of their ability or inability to transmit energy through a vacuum and according to the direction of vibration of the medium's particles relative to that of the energy transfer.

8.2.1 Classification of waves based on their production

- Based on their production or on the basis of their ability or inability to transmit energy through a vacuum, waves can be classified into two main groups.
 1. Mechanical waves
 2. Electromagnetic waves

Mechanical waves

- Mechanical waves characterized by the oscillatory motion of the particles of a material medium (solid, liquid and gas). They are produced by a physical disturbance of a material medium.
- Mechanical waves include water waves, sound waves, waves on springs or strings, Seismic waves, P-waves in earthquakes pressure wave and S-waves in earthquakes. They need material medium for their propagation or for transporting the energy from one location to another.
- They do not travel through vacuum and as a result they can't transport energy through vacuum. Sound waves are incapable of traveling through a vacuum.

Electromagnetic waves

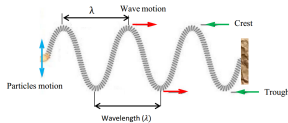
- Electromagnetic waves are characterized by the oscillation of magnetic and electric fields.
- They are capable of transmitting their energy through a vacuum. They are produced by the interaction or the vibration of magnetic and electric fields.
- Electromagnetic waves include Radio waves, Microwaves, Light waves, X-rays, Gamma-rays etc. They travel or propagate both through a material medium and vacuum.
- They do not need necessarily a material medium for their propagation. Light from the sun propagates through a vacuum and via the atmosphere and reaches the surface of the earth.
- This is because of the propagation of electromagnetic waves. Therefore, they transport energy both through vacuum and matter.
- All electromagnetic waves have the same speed in vacuum. That is $3 \times 10^8 \text{ m/s}$. But they have different wavelengths and frequencies.

8.2.2 Classification of waves based on the way they propagate

- Another way to categorize waves is on the basis of the direction of movement of the individual particles of the medium relative to the direction that the waves travel or that of the energy transfer.
- Categorizing waves on this basis leads to three known categories: transverse waves, longitudinal waves, and surface waves. They are
 1. Transvers wave
 2. Longitudinal wave
 3. Surface waves
- The two types of waves are illustrated by an example in which a coil spring fixed at one end and is held stretched out by a person.

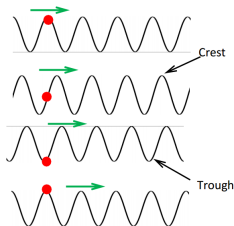
Transverse wave

- If the first person then shakes his end up and down or from side to side, a transverse wave will travel along the spring.
- In a transverse waves, the vibration or oscillation of the particles of the medium is perpendicular to the direction of the wave motion or the transfer of energy.
- Wave direction means the direction in which wave is travelling or the direction in which energy is propagating or transferring.
- Examples of transverse waves include vibrations on a string, light waves, S-wave in earthquakes, waves on the surface of deep water, radio waves and ripples on the surface of water are some examples of transverse waves.
- We can make a horizontal transverse wave by moving the slinky vertically up and down.



- All transverse waves comprise a series of crests (peaks) and troughs. Like ripples on pond, the crests travel outwards in the same direction as the wave motion.

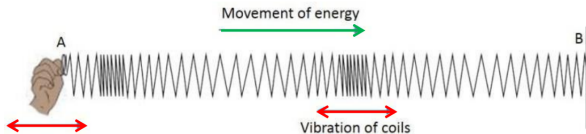
- The particles of the rope vibrate just move up and down past their equilibrium position while the energy transfers at right angles to this from left to right. This can be seen by the RED particle. There is no transfer of matter from left to right.



- **A crest** is a point on a wave where the particles of the medium have the maximum phase of vibration.
- **A trough** is point on a wave where the particles of the medium have the minimum phase of vibration.

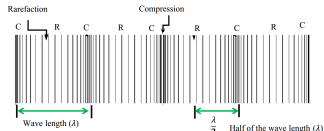
Longitudinal waves

- If the person holding one end pulls a few coils toward himself and releases them, a longitudinal wave will travel along the spring, with coils alternately being pressed closer together, then stretched apart, as the wave passes.
- A longitudinal wave is a wave in which particles of the medium move in a direction parallel to the direction that the wave moves or in the direction along the direction in which the energy of the wave is transporting. Suppose that a slinky is stretched out in a horizontal direction as shown in Figure below and then a pulse is introduced into the slinky on the left end by vibrating the first coil left and right.

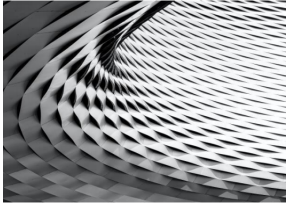


- Energy will begin to be transported through the slinky from left to right. As the energy is transported from left to right, the individual coils of the medium will be displaced leftwards and rightwards.
- In this case, the particles of the medium move parallel to the direction that the pulse moves.
- This type of wave is a longitudinal wave. Longitudinal waves are always characterized by particle motion being parallel to wave motion.
- Sound wave, Pressure waves, P- Wave in earthquakes, and Wave on a spring are some examples of longitudinal waves.
- Figure above shows a longitudinal wave moving along a stretched spring. The coils of the spring vibrate along the length of the spring, while energy travels along the same line, from A to B. Note that the spring itself does not move from A to B.

- Longitudinal wave can be expressed in terms of Compression and Rarefaction. The regions where the spring is compressed or the particles are pushed together are called **Compressions** whereas the regions where the spring is relaxed or the particles are more spread out are called **Rarefaction**.
- Compression and Rarefaction in longitudinal waves are equivalent to Crest and Trough in transverse waves respectively. If the longitudinal wave is travelling through a gas then compression can be thought of an area of higher pressure and a rarefaction can be an area of low pressure.
- The distance between two successive compressions or rarefactions equals to one wave length (λ). The distance between a compression and adjacent rarefaction is equal to half wave length ($\frac{1}{2}\lambda$)



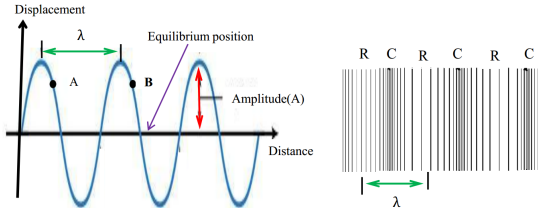
Surface wave

- A surface wave is a mechanical wave that propagates along the interface between differing media. A surface wave is a wave in which particles of the medium undergo a circular motion. Surface waves are neither longitudinal nor transverse.
- In longitudinal and transverse waves, all the particles in the entire bulk of the medium move in a parallel and a perpendicular direction (respectively) relative to the direction of energy transport. In a surface wave, it is only the particles at the surface of the medium that undergo the circular motion.
- The motion of particles tends to decrease as one proceeds further from the surface. In a surface wave, particles of the medium vibrate both up and down and back and forth, so they end up moving in a circle. A surface wave is combination of a transverse wave and a longitudinal wave.

8.3 Waves characteristics and behaviors

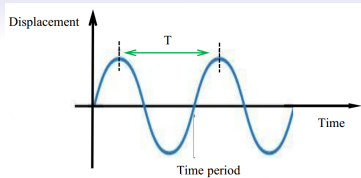
Waves characteristics

- All waves have commonly the following some characteristics. Consider the two commonly described wave types called Transverse and Longitudinal waves.



- **A wavelength (λ)** is the distance between two successive points on a wave or crest or trough that are in the same state of oscillation. For instance, points A and B in Figure, are the nearest or successive points that are both the same amount passed the maximum and therefore in the same state of oscillation.

- In a transverse wave, a wavelength is also defined as the distance between two successive crests or trough of the waves and as the distance between two successive compressions or rarefactions
- The distance between two successive crests or troughs is equal to one wave length (λ). The distance between a crest and adjacent trough is equal to half wave length($\frac{\lambda}{2}$)
- Generally, a wavelength is the distance of one complete wave cycle traveled in one period.
- **Amplitude (A):** The amplitude of a wave is the maximum displacement of any particle of the medium from its equilibrium position. It can be determined from displacement against distance graph of the wave motion shown in Figure.
- **The time period (T)** is the time taken for one complete wave to pass a given point or to make one complete wave or cycle. It is represented by a symbol T.



- It can be determined from the displacement-time graph of the particles motion. The length between two peaks or crests or troughs is equal to the time period.
- **The frequency (f)** is the number of complete waves passing a given point per second. This can be determined by the number of crests/troughs or compressions/rarefactions that pass a given point per second.
- The higher the frequency, the greater the number of the waves per second. Frequency is given the symbol ' f ' and is measured in hertz (Hz). A frequency of 10Hz would mean 10 waves per second. There are two important equations linking these terms. The first links frequency and time period.

$$\text{frequency} = \frac{\text{number of waves}}{\text{time taken}}$$

- If you consider a wave with a frequency of 8Hz, this would mean four waves passing a point per second. Each wave would therefore take 0.125second to pass the point. Therefore, the time period would be 0.125second. As a result the time period is the reciprocal of the frequency. The relationship between time period (T) and frequency (f) is

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

Example

- What is the time period of a wave with a frequency of 25Hz ?

Speed of waves

- The wave speed (v) is defined as the distance the wave travels or propagates in one second.

$$\text{wave speed} = \frac{\text{distance travelled}}{\text{time taken}}$$

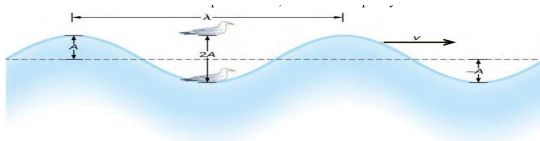
- Wave speed is related to both wavelength and wave frequency. Wavelength is the distance between two corresponding points on adjacent waves. Wave frequency is the number of waves that pass a fixed point in a given amount of time. This equation shows how the three factors are related.
- If a wave travels a distance of one wavelength (λ) in one period (T), then the wave speed is given by:

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

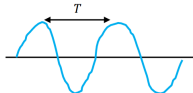
- The equation that related, wave speed, wavelength and frequency of the wave is known as wave equation. All waves have this equation.

Example:

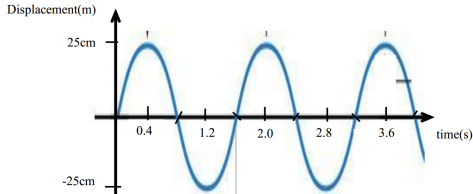
1. The frequency of a certain microwave in vacuum is 10^6 Hz.
 - a) What is the period of this wave?
 - b) What is the wavelength of this wave?
2. A duck floating on the water moves up and down as the wave on the water forms a transverse wave. If the duck takes 5 seconds to pass 11 crests, what is the frequency of the wave?



3. Consider the displacement-time graph of the transverse wave train shown in figure below. The distance between a crest and adjacent trough is 0.8cm . Find the wavelength of the wave.



4. Consider a transverse wave shown in figure below. Find the amplitude, the period and frequency of the wave.



5. The speed of a wave train shown in the figure below is 20m/s . What is the frequency of this wave?

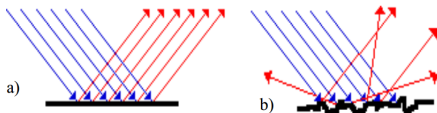
Wave's behaviors

- All types of waves behave in certain characteristics ways. They can undergo Reflection, Refraction, Diffraction, and Interference. These basic properties and define the behavior of all waves. These behaviors of waves can help us to understand how water waves interact with land and other waves.

Reflection

- All waves are known to undergo reflection or the bouncing off of an obstacle. Consider when light ray strikes the boundary between two media, such as air and glass, one or more of three things can happen. As illustrated in Fig8.27, some of the light incident on a glass surface is reflected, and some passes into the glass. The light enters the glass is partially absorbed and partially transmitted.
- The reflection might be either **Specular** or **Diffuse reflections**.

- Light reflection from smooth surfaces such as mirrors or a calm body of water is known as regular reflection or specular reflection. Reflection of light from rough surfaces or irregular boundaries such as clothing, paper, and the asphalt roadway leads to a type of reflection known as diffuse reflection.



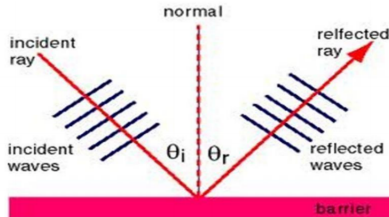
(a) Specular reflection, (b) Diffuse

- The diagram below depicts two beams of light incident upon a rough and a smooth surface. A light beam can be thought of as a bundle of individual light rays which are traveling parallel to each other. Each individual light ray of the bundle follows the law of reflection. If the bundle of light rays is incident upon a smooth surface, then the light rays reflect and remain concentrated in a bundle upon leaving the surface. On the other hand, if the surface is rough, the light rays will reflect and diffuse in many different directions.

- Reflection is a sudden change in the direction of propagation of a wave that strikes the boundary between two different media. It occurs when the waves bounce back to the first medium by changing its direction.
- Let us extend the discussion for regularly reflected light wave. Assume the incoming light ray makes an angle θ_i with the normal perpendicular to the surface.
- Then the reflected ray makes an angle θ_r with this normal and lies in the same plane as the incident ray and the normal. Under this case, the angle at which the wave approaches a flat reflecting surface is equal to the angle at which the wave leaves the surface. This characteristic is observed for all waves.

- **The law of reflection of waves**

1. The incident rays, reflected rays and the normal line all lie in the same plane.
2. The angle of incident ray is equal to the angle of reflected ray.
($\theta_i = \theta_r$)



Refraction

- Light travels in straight lines at a constant speed in a uniform medium. If the medium changes, the speed will also change and the light will travel in a straight line along a new path. The bending of light ray as it passes obliquely from one medium to another is known as Refraction.
- Refraction is the change in direction of propagation of a wave when the wave passes from one medium into another, and changes its speed. Therefore, light waves are refracted when crossing the boundary from one transparent medium into another because the speed of light is different in different media.
- The principle of refraction is illustrated in Figure 8.28 for light wave entering water from air. The angle θ_1 the incident beam makes with the normal to the surface is refracted to as the angle of incidence. The angle θ_2 between the refracted beam and the normal is called the angle of refraction.

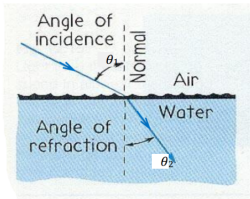


Figure Refraction of light ray

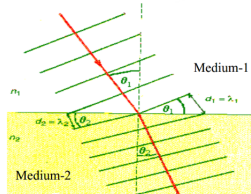


Figure Refraction of wave front.

- What happens to the waves as they pass into the glass and continue to travel through the water? The speed of light in glass or water is less than the speed of light in a vacuum or air. The speed of light in a given substance and in vacuum can be related by index of refraction.
- **Index of refraction** is the ratio of the velocity of light in vacuum(c) to the velocity of light in a particular medium.

$$\text{index of refraction} = \frac{\text{speed of light in vacuum}}{\text{speed of light in medium}} \implies n = \frac{c}{v}$$

- n : refractive index, it is a number which gives a measure of the refraction or “bending” of light when it travels from one medium to another.
- The speed of light in vacuum(air) is $c = 3 \times 10^8 m/s$
- In terms of wavelength, the speed of light in vacuum or air and in medium can be expressed as:

$$c = \lambda_{air} f \quad \text{and} \quad v = \lambda_m f$$

$$n = \frac{c}{v} = \frac{\lambda_{air} f}{\lambda_m f} = \frac{\lambda_{air}}{\lambda_m}$$

- We have seen that light slows down when passing into a medium of greater **optical density**. What happens to the wavelength of light entering a new medium? Since the frequency of the wave is the same in **medium-1** as it is in **medium-2**, but the speed reduced due to the decrease in its wavelength and from equation of wave, $v = \lambda f$, we have the following relations.

$$v_1 = \lambda_1 f \quad \text{and} \quad v_2 = \lambda_2 f$$

- Solve for f and equate them

$$f = \frac{v_1}{\lambda_1} \quad \text{and} \quad f = \frac{v_2}{\lambda_2} \implies \frac{v_1}{\lambda_1} = \frac{v_2}{\lambda_2} \implies \frac{v_1}{v_2} = \frac{\lambda_1}{\lambda_2}$$

- but we have $v_1 = \frac{c}{n_1}$ and $v_2 = \frac{c}{n_2}$ insert this in above equation, then we have got

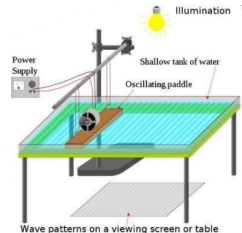
$$n_1 \lambda_1 = n_2 \lambda_2 \implies \frac{n_1}{n_2} = \frac{\lambda_2}{\lambda_1} \implies \frac{\lambda_1}{\lambda_2} = \frac{n_2}{n_1}$$

- Where n_1 and n_2 are refractive index of medium-1 and medium-2 respectively.

The ripple tank

- Refraction can also be shown using a ripple tank. In physics, a ripple tank is a shallow glass tank of water used to demonstrate the basic properties of waves. The ripple tank is used to generate water waves in laboratory.
- It is useful in demonstrating wave properties such as reflection and refraction. It consists of a shallow tray of water with a transparent base, a light source directly above the tray and a white screen beneath the tray to capture the image of the shadows formed when water waves spread across the tank as shown above.

- Straight waves can be set up by using a straight dipper, Figure; The ripple tank while circular waves can be formed by using a spherical dipper. Both dipper are vibrated up and down by a motor to generate water waves.



- The waves in the ripple tank are water waves, just like those generated by a stone in a pond. If we make these waves pass along the tank, and look at them through the glass side, they can be seen to have a general shape like that shown in Figure below.
- When light passes near the crests of the waves, these act as converging lenses, when it passes near the troughs these act as diverging lenses. Consequently, if the light passes through a series of waves, images of the waves are projected on the screen underneath the tank, and a series of alternate light and dark bands are seen.

- Ripples travel more slowly in shallower water than in deeper water, because they drag on the bottom. A shallow area can be created in the tank by placing a sheet of glass in the tank.

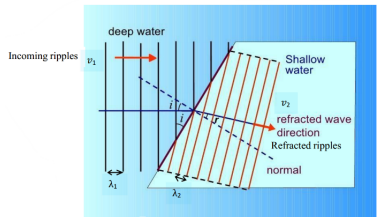


Figure Wave fronts change direction when their speed change

- Figure above shows the pattern that results when the boundary between the deep and shallow water is at an angle to the water front. The depth of water affects the speed the speed of these waves directly without having any things to do with the density of water. The deeper the water, the faster the waves travel, and so waves will reflect when they enter deeper or shallower water at an angle.
- Things to be notice:
 - The ripples change direction as they enter the shallower water.
 - The ripples are closer together in the shallower water and their wavelength and speed are decreased. ($\lambda_1 > \lambda_2$)
 - The frequency of the waves remains the same in both cases.
- Generally, water waves travel fastest when the medium is the deepest. So, if water eaves are passing from deep water to shallow water, they will slow down. This decreases in speed and also leads to a decrease in wavelength.

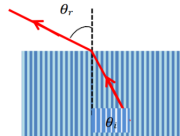
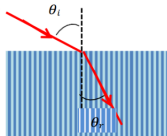
- The frequency and wavelength in each case are related to the velocity as follow:

$$v_1 = \lambda_1 f \quad \text{and} \quad v_2 = \lambda_2 f$$

- We know $\lambda_1 > \lambda_2$, it follows that $v_1 > v_2$ and the velocity of the wave is reduced when the depth of the water is smaller. Where λ_1 and λ_2 , and v_1 and v_2 are the wavelengths and velocities of the water wave in deeper and shallower water respectively. Take the ratio of the two velocities to show the relationship between waves velocity and wavelength.
- **Notice**
- Optical density is a property of a transparent material which is a measure of the speed of light through the material.
 - i. When light passes into a medium of greater optical density, the speed of the light is reduced.
 - ii. When light passes into a medium of smaller optical density, the speed of the light is increased.

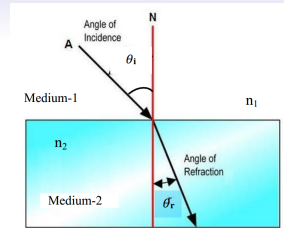
Law of refraction

1. The incident ray, the refracted ray, and the normal to the surface all lie in the same plane
2. The path of a ray refracted at the interface between two media is exactly reversible.



- **Snell's Law:** Snell's law gives the degree of refraction and relation among the angle of incidence, the angle of refraction and refractive indices of a given pair of media. We know that light experiences the refraction or bending when it travels from one medium to another medium. Snell's law predicts the degree of the bend. It is also known as the law of refraction.

- Snell's law is defined as **“The ratio of the sine of the angle of incidence to the sine of the angle of refraction is a constant, for the light of a given colour and for the given pair of media”**.



- Snell's law formula is expressed as:

$$\frac{\sin \theta_i}{\sin \theta_r} = \text{constant}$$

- This constant value is called the refractive index of the second medium with respect to the first medium (vacuum). If the boundary is with vacuum or air, the constant is the refractive index of the medium.
- Where; θ_i is the angle of incidence and θ_r is the angle of refraction

$$\frac{\sin \theta_i}{\sin \theta_r} = n$$

- If the light crosses a boundary between any two media, the Snell's law can be expressed in the form:

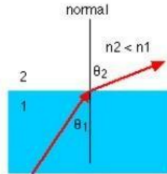
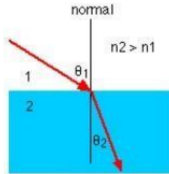
$$\frac{\sin \theta_i}{\sin \theta_r} = \frac{n_2}{n_1}$$

- Where n_1 and n_2 are the refractive index of medium-1 and medium-2 respectively, Since “n” is greater than one, irrespective the direction the light is travelling in you always put the sine of the larger angle on top.
- From previous discussion, we have seen that $n_1 = \frac{c}{v_1}$ and $n_2 = \frac{c}{v_2}$. Insert this into above equation:

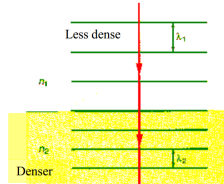
$$\frac{\sin \theta_i}{\sin \theta_r} = \frac{n_2}{n_1} = \frac{v_1}{v_2} = \frac{\lambda_1}{\lambda_2}$$

Refraction at Air-water and Water-Air interface

- When light ray travelling from less dense medium to denser medium such as at Air-water interface, the wave refracted **towards the normal**.
- When light ray travelling from denser medium to less dense medium such as at water-air interface, the wave refracted **away from the normal**.

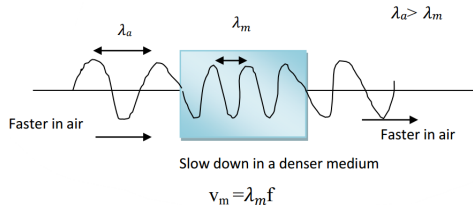


- When light ray travelling at right angle from optically denser/less dense medium to optically less dense/denser medium, the wave does not refract away. It travels straight forward but the wave's wavelength and velocity are changed. That is $\lambda_1 > \lambda_2$ and then $V_1 > V_2$



Example

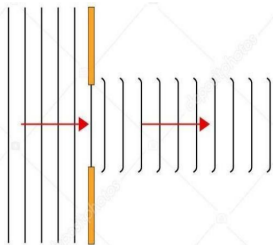
1. A red light of wave length 640nm passes from air into a glass plate of refractive index 1.5. What is the wavelength of the light inside the medium?



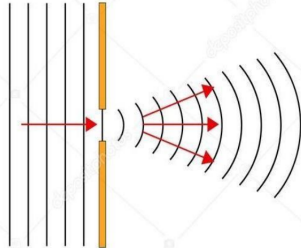
Diffraction

- When light waves pass through an aperture or past the edge of an obstacle, they always bend to some degree into the region not directly exposed to the light source. This phenomenon is called Diffraction.
- **Diffraction** is the spread out of the wave when the wave passes through gap or around an obstacle. Therefore, refraction is the ability of waves to bend around obstacles placed in their path.
- Diffraction is the slight bending of light as it passes around the edge of an object. The amount of bending depends on the relative size of the wavelength of light to the size of the opening. It occurs when the size of the aperture or obstacle is of the same order of magnitude as the wavelength of the incident wave. If the opening is much larger than the light's wavelength, the bending will be almost unnoticeable. However, if the two are closer in size or equal, the amount of bending is considerable, and easily seen with the naked eye.

- To understand this bending of waves, let us consider what happens when water strike a narrow opening when a plane waves the barrier? When the plane waves strike the barrier they are spreading out the region behind the gap. The amount of bending depends on the relative size of the wavelength of light to the size of the opening or gap. If the opening is much larger than the light's wavelength, the bending will be almost **unnoticeable**. However, if the two are closer in size or equal, the amount of bending is **considerable** and easily seen with the naked eye. That is the narrow gap is more effective than the wide one to demonstrate the diffraction of wave.
- The effect of diffraction is the greatest when the width of the gap is the same as the wavelength of the wave.



a) Wide gap



b) Narrow gap

Interference of waves

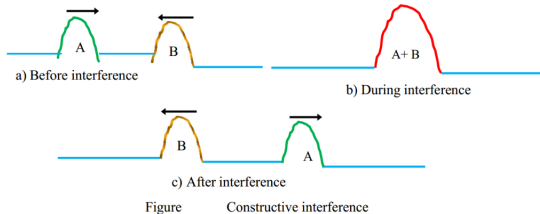
- What happens when two waves meet while they travel through the same medium? What effect will the meeting of the waves have upon the appearance of the medium? Will the two waves bounce off each other upon meeting or will the two waves pass through each other? These questions involving the meeting of two or more waves along the same medium pertain to the topic of wave interference.
- When two or more waves propagate through a single medium simultaneously, like for example radio waves through an antenna of a radio receiver they interfere or mix and you may not hear a clear sound, in fact to hear a clear sound the radio has to be turned. Such mixing of waves due to the simultaneous propagation of waves is known as Interference. When they interfere or mix they add up or cancel out each other based on superposition principle.
- The **superposition principle** states that when two or more waves overlap or interfere in space, the resultant disturbance is equal to the algebraic sum of the individual disturbances. This can be done by adding their amplitude algebraically. Superposition is the combination of two or more waves at the same location.

- There are two types of interferences such as **constructive interference** and **destructive interference**.
- To begin our exploration of wave interference, consider two pulses of the same amplitude traveling in different directions along the same medium.

I. **Constructive interference**

- Consider two sine pulses move towards each other. Constructive interference occurs whenever these waves come together so that they are in phase with each other. This means that their oscillations at a given point are in the same direction, the resulting amplitude at that point being much larger than the amplitude of an individual wave. For two waves of equal amplitude interfering constructively, the resulting amplitude is twice as large as the amplitude of an individual wave.
- For instance, for 100 waves of the same amplitude interfering constructively, the resulting amplitude is 100 times larger than the amplitude of an individual wave. Constructive interference then can produce a significant increase in amplitude.

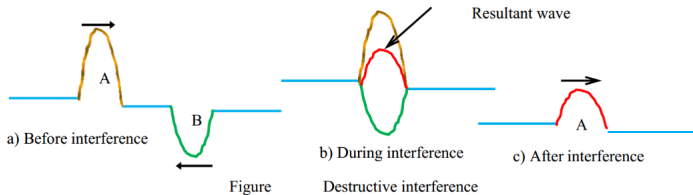
- The following diagram shows two pulses of equal amplitude coming together, interfering constructively and then continuing to travel as if they'd never encountered each other.



- Completely constructive interference occurs when the two waves are superimposed in phase. In the above figures the two waves A and B are **in phase**.
- In the diagram, the individual sine pulses are drawn in green and yellow and the resulting wave is drawn in red. Another way to think of constructive interference is in terms of peaks (crest) and troughs; when waves are interfering constructively, all the crests line up with the crests and the troughs line up with the troughs. In constructive interference, the amplitudes of the two waves add together resulting in a higher wave at the point they meet.

II. Destructive interference

- Destructive interference is the second type of interference that occurs at any location along the medium where the two interfering waves have amplitude in the opposite direction. The size of the amplitude of the resultant pulse or wave can be obtained by algebraic sum of the individual amplitude. In destructive interference, the two waves cancel out resulting in lower amplitude at the point they meet.



- If the interfering pulses have the same maximum amplitude and opposite directions, then the resulting wave is completely destroyed. No resultant wave is obtained; the graph will be a horizontal straight line. Completely destructive interference occurs when two identical waves are superimposed exactly **out of phase**. That is, when the crest of the first wave falls exactly on the trough of the second wave or if the two points on each point are out of phase by 180° .



Figure Completely destructive interference

- In general, whenever a number of waves come together the interference will not be completely constructive or completely destructive, but somewhere in between. It usually requires just the right conditions to get interference that is completely constructive or completely destructive as discussed above.

Interference of ripples

- The interference of two sets of periodic and concentric waves with the same frequency produces an interesting pattern in a ripple tank. The diagram at the right shows an interference pattern produced by two periodic disturbances.
- This can be shown clearly in the diagram shown in Figure (b) below.
- The crests are denoted by the violet lines and the troughs are denoted by the dotted red lines.
- Thus, constructive interference occurs wherever a violet line meets with a violet line or a dotted red line meets with a dotted red line; this type of interference results in the formation of an antinode. The **Antinodes** are denoted by a blue dot.
- Destructive interference occurs wherever a violet line meets with a dotted red line; this type of interference results in the formation of a Node. The **Nodes** are denoted by a green dot.

- At the top of the photograph, Figure (a), it is clearly seen regions where the ripples are cancelling out (destructively interfere) and the region where constructively interfere.
- There are two ways to do this.
 1. Use two vibrating dippers to produce two set of circular ripples. Where the ripples overlap, they produce a characteristic pattern (Figure (a)). At some points, the ripples add together (interfere constructively) to produce a large effect. In between them, they cancel out (interfere destructively) so that the surface of the water is unperturbed.
 2. Alternatively, use a straight vibrating source to produce parallel ripples. Direct these at a barrier with two gaps; the ripples pass through the gaps and diffract into the space beyond. Here, they overlap to produce interference pattern similar to the one shown in the photograph.

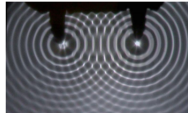


Figure The two vibrating balls produce sets of ripples that overlap with each other.

(a)

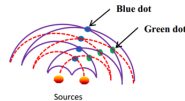
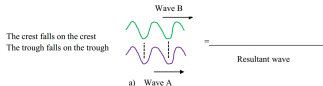


Figure Circular pattern of interference

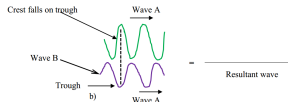
(b)

Exercise

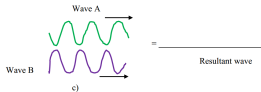
1. Constructive and destructive interferences can be occurred when the two waves overlap and their crests/ troughs fall to crests/ troughs to obtain increased amplitude and their crests/ troughs to trough/crests to give reduced amplitude. Sketch the resulting wave on the space given the right side of the component waves.
 - a. When the amplitude of wave A and wave B is 5cm.



- b. When the amplitude of wave A is 9cm and that of B is 5cm.



- c. When the two components waves A and B are out of phase by 180° and have equal amplitude of 5cm.



8.4 Sound waves

- Sound and music are parts of our everyday sensory experience. Just as humans have eyes for the detection of light and color, so we are equipped with ears for the detection of sound.
- We seldom take the time to consider the characteristics and behaviors of sound and the mechanisms by which sounds are produced, propagated, and detected.
- Sound is a wave that is created by vibrating objects and propagated through a material medium from one location to another.
- In this section, we will investigate the nature, properties and behaviors of sound waves.

8.4.1 Production and propagation of sound waves

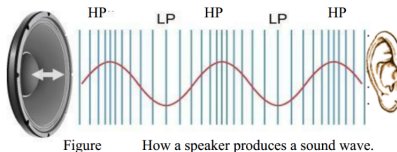
- I. **Production of sound waves:** Sound waves are longitudinal mechanical waves and produced by oscillation or vibration of particles of the medium and audibly perceived through a sense of hearing.
- Sound waves are a series of **compressions** and **rarefactions** and we can see this by conducting a very simple experiment. To study the production of sound consider a tuning fork and a loud speaker. A tuning fork is a metal object consisting of two tines capable of vibrating if struck by a rubber hammer or mallet.
- When the tuning fork is struck, the prongs of the fork begin to vibrate. Each time the prong vibrates, a new sound wave is produced. The movement of the speed of sound waves depends on the medium by which the sound waves travel. When the tuning fork strikes, you can hear the sound.

- Thus we have produced the sound by striking the **tuning forks**.



- A speaker produces a sound wave by oscillating a cone, producing vibrations in the surrounding air molecules. This shows that the vibrations are parallel to the direction of wave motion. As the speaker oscillates back and forth, it transfers energy to the air. This situation is creating slightly higher and lower local pressures. These compressions (high-pressure regions) and rarefactions (low-pressure regions) move out as longitudinal pressure waves having the same frequency as the speaker. This process continues creating a longitudinal wave as shown in figure below.

LP = Lower pressure or Rarefaction and HP = Higher pressure or Compression

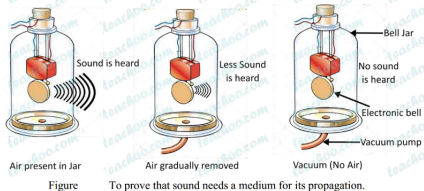


- Other examples are, when you speak your vocal cords in your throat vibrate as the air is pushed over them. Different musical instruments produce sound by making a part of the instrument vibrate. The disturbance created by the vibrating string and soundboard of a guitar or violin, or the vibrating diaphragm of a radio speaker. When this produced sound travels through the air it creates high and low pressure points, or waves. As the same time your ears can detect the waves and you perceive this as sound.

II. Propagation of Sound waves: Whenever you make a call, you can hear the voice of your friend even though he/she is at a great distance. The mean through which your sound is transmitted is called as the medium. The waves consist of particles of the medium through which it travels. A sound is an energy that is transmitted in the form of sound waves. When the objects vibrate, the air surrounding it vibrates and sound waves are carried. If there is no medium, then vibrations in an object will not travel through it. This is the mechanism for the propagation of sound.

- Therefore, a sound wave needs a material medium for its propagation and transporting energy. It travels through solids, liquids and gases. It does not travel in vacuum. The creation and propagation of sound waves are often demonstrated in class through the use of a tuning fork. As the tines of the tuning forks vibrate back and forth, they begin to disturb surrounding air molecules. These disturbances are passed on to adjacent air molecules by the mechanism of particle interaction.
- Sound wave is a mechanical wave. You have discussed in the previous section as mechanical waves cannot travel through a vacuum. The same is also true for sound waves. This feature of sound waves is often demonstrated in Physics class using a ringing bell in “a Bell jar Experiment”.
- The experiment is done by suspending an electrical bell in the bell jar as Figure below; As the air is pumped out of the sealed bell jar using a vacuum pump, the sound from the bell jar gradually diminishes. Once air is removed from the jar, the sound of the ringing bell can no longer be heard because of the vacuum inside the jar.

Bell Jar Experiment



- The clapper is seen striking the bell; but the sound that it produces cannot be heard because there are no particles inside of the jar to transport the disturbance through the vacuum. This demonstrates that the sound wave cannot travel through vacuum.

Audible and Inaudible Sounds

- Sound is a form of energy that is produced by vibrating bodies. But do we hear the sound of every vibrating body? The answer is NO. We have two types of sound: audible sounds and inaudible sounds. These sounds are categorized on the basis of their frequency ranges.

i. **Audible sounds**

- The human ear can easily detect frequencies between 20 Hz and 20 kHz. Hence, sound waves with frequency ranging from 20 Hz to 20 kHz is known as audible sound. The human ear is sensitive to every minute pressure difference in the air if they are in the audible frequency range. This varies from person to person and factors such as age and exposure to loud music dramatically changes this range. As we grow older and are exposed to sound for a longer period of time, our ears get damaged and the upper limit of audible frequencies decreases. For a normal middle-aged adult person, the highest frequency which they can hear clearly is 12-14 kilohertz.

- Table below shows the audible range of some animals.

Animals	Approximate audible range (Hz)
Human	20-20,000
Bat	10-200,000
Dog	15-40,000
Dolphin	120-110,000

ii. Inaudible sounds

- Human ear cannot detect sound frequencies less than 20 vibrations per second i.e. 20 Hz. So any sound below this frequency will be inaudible sound for humans. In the high-frequency range, the human ear cannot detect frequencies above 20,000 vibrations per second (20 kHz) and the amplitude of the wave would be dependent on the loudness of the sound. So the frequencies below 20 Hz and above 20 kHz come under the category of inaudible frequencies. The low-frequency sound which the human ear cannot detect is also known as infrasonic sound. Whereas the higher range inaudible frequency is also known as **ultrasonic sound**.

- Some animals like dogs have the ability to hear sounds having frequencies higher than 20 kHz. The police department uses whistles with frequencies higher than 20 kHz so that the dogs can listen to it. Inaudible frequencies are helpful for many purposes. These are used in many fields like research and medicine. The ultrasound equipment is used for tracking and studying many medical problems works at frequencies above 20 kHz.

iii. **The speed of sound in different materials**

- We know that the particles of a medium are disturbed when a sound wave passes along it, and that compressions and rarefactions occur. It travels through all materials such as through solids, liquids and gases. But the degree of transmission of sound is different for different media.
- The speed of sound varies greatly depending upon the medium it is traveling through. The speed of sound in a medium is determined by a combination of the medium's rigidity (or compressibility in gases) and its density. The more rigid (or less compressible) the medium is, the faster the speed of sound. The greater the density of a medium is, the slower the speed of sound.

- The speed of sound in air is low, because air is compressible. Since liquids and solids are relatively rigid and very difficult to compress them, the speed of sound in such media is generally greater than in gases.
- In general, sound travels faster through solids than liquids and faster through liquids than gases, although there are exceptions.
- For example, the speed of sound through water is around five times faster than in air and in metals like iron or steel it is about 15 times faster than in air.
- What is the reason? Sound travels faster in liquids than in gases because molecules are more tightly packed. Sound travels fastest through solids. This is because molecules in a solid medium are much closer together than those in a liquid or gas, allowing sound waves to travel more quickly through it.

- Table below shows the speed of sound in various media. Since temperature affects density, the speed of sound varies with the temperature of the medium, through which it's traveling to some media.

Medium	v_w (m/s)
Gases at 0 °C	
Air	331
Carbon dioxide	259
Oxygen	317
Helium	972
Hydrogen	1290

<i>Liquids at 25 °C</i>	
Methyl alcohol	1140
Mercury	1450
Water, fresh	1490
Sea water	1530

<i>Solids (longitudinal or bulk)</i>	
Vulcanized rubber	54
Polyethylene	920
Copper	3560
Glass, Pyrex	5640
Lead	1320
Aluminum	5100
Steel	5130

The speed of sound in air

- When sound waves travel through gases it would be a little more complex due to the motion and density the gases. The density of the gases varies with temperature. Therefore, the speed of sound in air varies with the temperature of the air. When the gas is at a higher temperature, the average kinetic energy of the particles is higher. This means on average the particles are moving faster.
- It depends on the temperature of the medium. For a given medium, sound has a slower speed at lower temperatures. The faster the particles are moving, the faster the speed of sound through the gas.
- This can be seen in table. Experiment and theory show that the speed of sound “ v ” in air increases approximately by 0.6m/s for every degree Celsius rise in temperature. So it depends on the temperature of the air.

Air temperature (°C)	Speed (m/s)
-20	319
-10	325
0	331
10	337
20	343
30	349

- Generally, the speed of sound traveling through air depends on the temperature of the medium and the relationship between the speed of sound and temperature is given by

$$v = 331m/s + 0.6(\Delta T_C) \quad \text{or} \quad v = 331m/s \sqrt{\frac{T_k}{273K}}$$

- Where; $v_0 = 331m/s$ is the speed of sound in air at 0°C at sea level, ΔT_C is the temperature of the air during this time and T_k is the absolute temperature (in Kelvin).

Example

- 1 What is the speed of sound in air at temperature of 60°C ?

$$v = 331\text{m/s} + 0.6\text{m/s}(60) = 331\text{m/s} + 36\text{m/s} = 367\text{m/s}$$

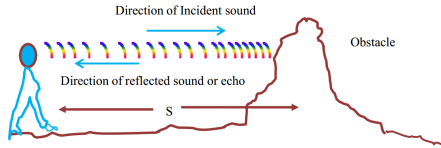
OR

$$v = 331\text{m/s}\sqrt{\frac{333\text{k}}{273\text{k}}} = 331\text{m/s}\sqrt{1.23} = 331\text{m/s}(1.11) = 367\text{m/s}$$

Reflection of sound

- Sound waves, like other waves, show the property of reflection. They are reflected by surfaces such as walls or by other obstacles. For example, if you stand in front of a mountain or a hill or near a big building at some distance and clap your hand, you will hear a reflection of the claps in a certain time later.
- This reflection of sound wave is called **Echo**. An echo is a single reflection of a sound wave off a distance surface. Reverberation is the reflection of sound waves created by the superposition of such echoes. The human ear can distinguish an echo that comes 0.1second after the emission of the original sound. If the time between hearing the original sound and the echo is less than 0.1sec, the original sound appears to be prolonged, this is called Reverberation.

- An **echo** can only be heard by humans when the distance between the source of the sound and the reflecting body is about 17m and the speed sound in air during this time is about 340m/s, keeping that the temperature of sound is constant. The reflection of sound waves back to the person shouting is an example of an Echo
- If the reflecting surface is “s” distance from the source and “t” is the time taken by the observer to hear echo, the velocity of sound v can be calculated as follow



$$\text{speed} = \frac{\text{Distance for the two trip}}{\text{total time}} \implies v = \frac{2s}{t}$$

1. A boy standing 400m away from a hill claps his hand loudly. If he hears the echoes of his clap 2second later, what will be the speed of the sound in air? What was the temperature of the day during that time?

$$v = \frac{2s}{t} = \frac{2(400m)}{2s} = 400m/s$$

$$v = 331m/s + 0.6(T_c)$$

$$400m/s = 331m/s + 0.6(T_c)$$

$$69m/s = 0.6T_c$$

$$T_c = 115^0C$$

Application of Echoes

- Echoes have different applications. The following are some examples of the applications of echoes.
- To determine the speed of sound in air, to determine the depth of the sea or ocean, for medical diagnosis. for echolocation, for blind person in finding their way, for find oil (mineral) underground etc.

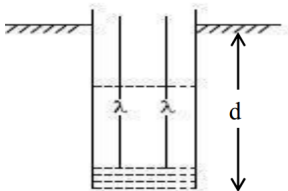
i. **Determination of the depth of a well:**

- Depth of water surface of a well can be very easily determined by means of echo. When a sound is produced at the mouth of the well, it is reflected from its water surface heard in the form of an Echo. The time between the production of sound and the hearing of echo is determined by means of a stopwatch.
- Let, depth of well is h the time difference between the production of sound and hearing of echo is t Speed of sound is v .

- Now the distance traveled by reflected sound to the listener is $2h$ and therefore,

$$2d = V_{xt} \implies d = (V_{xt})/2$$

- If the depth of the well is less than 16.6m, it will not be possible to perform this experiment as it is based on echo. In the same way, this method can also be used to find mineral substances on earth.



ii. Flying of the bat

- Bat flies using the echo of sound as it cannot see. Bat can produce and hear an ultrasonic sound.
- We cannot hear ultrasonic sound. Most bat echolocation occurs beyond the range of human hearing.
- Humans can hear from 20 Hz to 20 kHz depending on age. Bats produce ultrasonic sounds, which mean that the sounds exist at frequencies higher than humans can hear. Bat calls can range from 9 kHz to 200 kHz. They spread this sound forward which reflects back to the bats from a reflector Since bats cannot see from their eyes, so they use the method of echolocation to situate their ways.
- Therefore, Bats can understand from the reflected sound if there is an object before it.

- They hunt their prey using this technique. If the sound does not reflect back them, they can understand that there is open space and they fly that way. Sometimes the bat fails to detect the position of wires of electric lines and flies through the parallel wires and gets stuck and becomes dead as soon as the positive and negative electric lines get connected with its body. This is why sometimes bats are found hanging dead from electric lines.

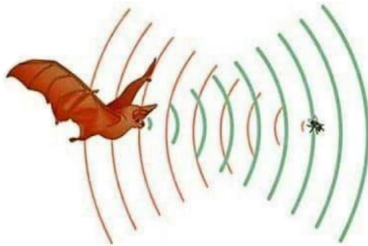


Figure Flying of the bat

iii. Echo-depth sounding

- Ships emit or transmit water sound waves under to the bottom of a sea and measure the time interval for the reflected wave or echo to return to the receiver. The device used for this purpose is called SONAR (Sound Navigation and Ranging).
- A sonar device sends out a sound and mechanically calculates the distance of an object. Using this technique the depth of the sea can be determined. By knowing the velocity of sound and measuring the time it takes to hear the echo, you can estimate the distance of the object. Echo is used in **SONAR**(SOund NAvigation and Ranging) to find the depth of seas or distance of submarines.
- Submarines use sonar to find objects under the water, including other submarines.

- The principle used here is the fact that time taken for the sound to reach the obstacle from the source is equal to the time is taken for it to return. It also helps to estimate the distance between two hills or mountains.

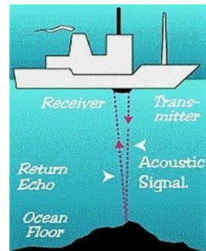


Figure Finding the depth of the sea using sonar.

Example

- The speed of sound in water is about 1500m/s . A sound wave sent to the bottom of the sea from the SONAR returns back to the device 4sec later. What was the depth of the sea at this location?

$$d = \frac{vt}{2} = \frac{1500\text{m/s} \times 4\text{s}}{2} = 3000\text{m} = 3\text{km}$$

iv. Medical Uses:

- Echo is used by doctors in a technique called **echocardiography** in which ultrasonic waves are made to reflect from various parts of the hearts and from an image of the heart. Doctors used this occurrence in cardiography, sonogram and many other medical diagnoses. It is also used in medical procedures to assess for blockages in the heart for example.
- An echocardiogram (echo) is a graphic outline of the heart's movement. During an echo test, **ultrasound** (high-frequency sound waves) from a hand-held wand placed on your chest provides pictures of the heart's valves and chambers and helps the sonographer evaluate the pumping action of the heart.

- Ultrasound is also used in pre-natal scanning. Here the ultrasound travels into the womb and reflects off the unborn baby. This sound is harmless (unlike using X-rays) and allows doctors to monitor the progress of the developing baby.



Figure *Using ultrasound to
monitor a baby*

v. **Other application of Echoes**

- Ultrasound is also used to detect flaws in metals and even to help people park their cars! In each case it is the reflection and refraction of the sound that makes the job possible.
- Blind people can be helped to “see” with Ultrasonic “torches”. The torches bounce ultrasonic wave off nearby objects. They produce a high sound which increases in frequency as objects get nearer to torch.
- Geologists looking for oil sometimes send vibrations down into the earth by using vibrations or explosions. Such vibrations are called Seismic waves. The waves are reflected back to the surface from the various layers of rock deep down in the ground. The time taken for the reflected waves to reach different point on the surface is recorded using special sensors. In this way, geologists find out the depth, shape and spacing of the underground rock.

Characteristics of sound

- Sound can be characterized by the following important terms such as, the loudness, pitch and quality(timbre).

i. **Loudness:**

- Loudness is audible strength of sound which depend on the amplitude of the sound wave.
- a. Based on the amplitude of a sound wave, we can determine the loudness of the sound. When the amplitude is high, it will produce a sound that is loud and when the amplitude is low, it will produce a sound that is soft.
- b. Loudness is proportional to the square of the amplitude of the vibration. This means that if the amplitude is doubled, the loudness increases four times.
- Generally, when we pluck a string of the guitar it starts vibrating with low amplitude and if we apply more energy by plucking more strongly, the string will vibrate with the greater amplitude and produce a loud sound.

ii. Pitch:

- Pitch is a characteristic of sound wave which distinguishes a sharp or a high-pitched sound from a grave or dull sound. Pitch is the quality of sound which makes some sounds seems "higher" or "lower" than others. It is determined by the number of vibrations produced during a given time period. The vibration rate of a sound is called its frequency and then it depends upon frequency.
- The higher the frequency of the sound waves is, the higher their pitch.
- a. Pitch denotes the shrillness or flatness of a sound. Sound can be high or low.
- b. We can identify a female and male voice without seeing them. A woman's voice generally has a high pitch than a man's voice. This is because the frequency of a woman's voice is higher.

iii. Timbre (Quality):

- Timbre is the quality of sound which allows us to distinguish between different sound sources producing sound at the same pitch and loudness. The vibration of sound waves is quite complex; most sounds vibrate at several frequencies simultaneously. The additional frequencies are called **overtones** or **harmonics**. The relative strength of these overtones helps to determine a sound's timbre.
- **The difference between pitch and timbre**
- **Pitch** allows us to hear intonation in a language and notes in a melody.
- **Timbre** allows us to distinguish the vowels and consonants that make up words, as well as the unique sound qualities of different musical instruments. Combinations of pitch and timbre enable us to identify a speaker's voice or a piece of music.

Sound Intensity and Distance

- The amount of energy that is transported past a given area of the medium per unit of time is known as the intensity of the sound wave. We know Sound carries energy. The amount of energy carried by sound waves depends on how much energy is given to the vibrating body. The intensity of sound depends on different factors. Such as it is:
 - directly proportional to the square of the amplitude of vibrations ($I \propto A$).
 - inversely proportional to the square of the distance between the source and the observer($I \propto \frac{1}{R^2}$).
 - directly proportional to the density of the medium ($I \propto \rho$).
 - directly proportional to the surface area of the vibrating body($I \propto a$)
 - directly proportional to the square of the frequency of the source ($I \propto f^2$).
 - directly proportional to the motion or speed of the particles of the medium ($I \propto v$).

- Generally, they combine together to give a good understanding about the intensity of sound as follow:

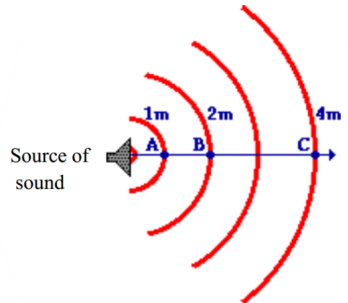
$$I = v\rho\pi^2A^2f^2$$

- Where f is the frequency of the wave, A is the amplitude of the sound wave, ρ is the density of the sound wave (air), f is the frequency of the sound wave and v is the speed of sound. If the amplitude of vibration of a sound is small, The energy carried by the wave is also small.
- If the amplitude of the vibrating body that produces the sound is large, the energy carried by the sound wave is also larger. The greater the amplitude of vibrations of the particles of the medium is, the greater the rate at which energy is transported through it, and the more intense that the sound wave is. It also depends on the frequency of the sound wave. The higher the frequency is the larger the amount of energy carried by the sound wave. In order to understand the energy carried by the wave, it is useful to introduce the concept of intensity.

- The intensity of a sound wave is defined as the rate of flow of energy through a given unit area perpendicular to the direction of the wave propagate. Energy per unit time is power, and then intensity is defined as the energy/time/area or:

$$\text{Intensity} = \frac{\text{Energy}}{\text{time} \times \text{Area}} = \frac{\text{Power}}{\text{Area}} \Rightarrow I = \frac{P}{a}$$

- The SI-units for expressing the intensity of a sound wave is Watts per square meter (W/m^2) When a sound wave carries energy through a medium the intensity of the sound wave decreases with increasing a distance from the source.



Figure

Intensity of sound

- The decrease in intensity with increasing distance is explained by the fact that the wave is spreading out over a circular (2- dimensions) or spherical (3- dimensions) surface and thus the energy of the sound wave is being distributed over a greater surface area.
- The diagram at the right shows that the sound wave in a 2-dimensional medium is spreading out in space over a circular pattern. Since energy is conserved and the area through which this energy is transported is increasing, the intensity must decrease.
- The mathematical relationship between intensity and distance is sometimes referred to as an inverse square relationship as mentioned above. So if the distance from the source is doubled increased by a factor of 2, then the intensity is quartered or decreased by a factor of 4.
- Similarly, if the distance from the source is quadrupled, then the intensity is decreased by a factor of 16. Applied to Figure above the intensity at point B is one-fourth the intensity as point A and the intensity at point C is one-sixteenth the intensity at point A.

- Since the intensity-distance relationship is an inverse relationship, an increase in one quantity corresponds to a decrease in the other quantity. And since the intensity-distance relationship is an inverse square relationship, whatever factor by which the distance is increased, the intensity is decreased by a factor equal to the square of the distance change factor.
- The intensity of sound also depends on the square of the amplitude of the vibrating source. This means if the amplitude is doubled while keeping the other factors constant, the intensity will be four times greater than its former value.
- As the sound waves propagate farther out into the surrounding air, the amplitude of vibration of the air molecules becomes smaller and smaller since the power of the source of the sound wave is constant.
- In a uniform medium, the intensity of a sound wave at a point is inversely proportional to the square of the distance between the source of the sound and the point of interest.
- Since sound wave spreads out in the surrounding air in a spherical pattern, at a given distance “R” from the source the intensity of sound is by:

$$I = \frac{P}{a} = \frac{P}{4\pi R^2}$$

- Where P is the constant power of the source and a is the area of a sphere around the source. $a = 4\pi R^2$.
- Consider any two points, like A, B and C, in Figure above. The intensity of sound at A and B can be determined as:

$$I_A = \frac{P}{4\pi R_A^2} \quad \text{and} \quad I_B = \frac{P}{4\pi R_B^2}$$

- P is constant for both points, $P = I_A 4\pi R_A^2$ and $P = I_B 4\pi R_B^2$

$$I_A 4\pi R_A^2 = I_B 4\pi R_B^2 \implies I_A R_A^2 = I_B R_B^2$$

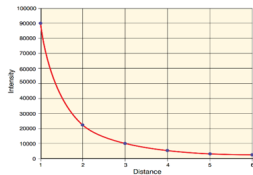
- Generally, for any two points 1 and 2 around the source, the intensity of sound can be expressed as:

$$I_1 R_1^2 = I_2 R_2^2 \implies \frac{I_1}{I_2} = \frac{R_2^2}{R_1^2} \implies \frac{I_2}{I_1} = \frac{R_1^2}{R_2^2}$$

- The sample data in the table below illustrate the inverse square relationship between power and distance. A graph showing how intensity varies with distance from source.

Point	Distance	Intensity
A	1m	160units
B	2m	40units
C	3m	17.8 units
D	4m	10units

(a)



(b)

Example

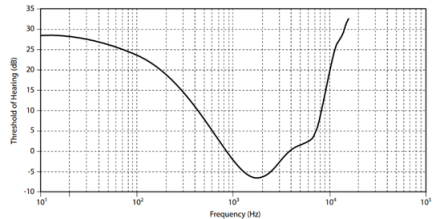
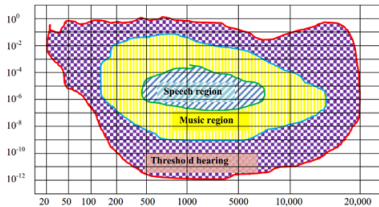
- The Intensity of sound produced from a certain source is found to be $10^{-3} W/m^2$ at 5cm away from the source.
 - What will be the intensity of the same sound at distance of 15cm?
 - What power is delivered by the source to its surroundings?

Intensity and Loudness of sound

- Humans are equipped with very sensitive ears capable of detecting sound waves of extremely low intensity. Intensity and loudness of sound are two different terms.
- **Intensity** is the amount of sound energy passing each second through a given unit area while loudness is a measure of the response of the ear to the intensity of sound.
- **Loudness** is a subjective sensation. That is it depends on the sensitivity of listener's ear. Usually a sound of higher intensity is louder. A sound louder for one person may not be louder for the other even they have the same intensity. Intensity is objective quantity.
- It is independent of sensitivity of the human ear but depends on sound's rate of energy or powers. The curve in Figure below shows the range of audibility of sound for the normal or average human ear. It gives the relation among frequency, intensity and hearing.

- All intensities below the line indicating the threshold of hearing are not sufficient enough to produce the sensation of hearing. Also intensities above the threshold of pain produce the sensation of pain rather than hearing. Therefore, the sensation of hearing is produced only in the region of intensity and frequency bounded by the curves of the **threshold of hearing** and **threshold of feeling or pain**.
- The faintest sound that the normal human ear can detect has an intensity of $1 \times 10^{-12} \text{ W/m}^2$.
- This intensity is known as the threshold of hearing. The most intense sound that the human ear can safely detect without suffering any physical damage is more than one billion times more intense than the threshold of hearing.
- This loudest sound that normal human ear can tolerate is called **threshold of pain**. Its intensity is about 1 W/m^2 .

- The frequency of the region of maximum sensitivity for the normal or average ear lies between 2000Hz to 4000Hz.



Intensity Level in Decibels

- Although an increase in the intensity of sound may cause the sound to seem louder, the loudness of a sound is not directly proportional to its intensity. For example, a sound must be 10 times more intense before it seems twice as loud.
- It must be 100 times as intense before it seems three times as loud, and so on. Therefore the loudness of this relation is not related directly instated it is a logarithmic relation. The loudness of a sound or the intensity level of a sound relates the intensity of any given sound to the intensity at the threshold of hearing. It is measured in decibels (dB).
- A decibel (dB) is a logarithmic unit used to measure sound level. The scale for measuring intensity is the **decibel scale**.

- The intensity level of the threshold of hearing ($10^{-12} W/m^2$) is assigned a sound level of 0 decibels(0 dB).
- A sound that is 10 times more intense ($10^{-11} W/m^2$) is assigned a sound level of 10 dB.
- A sound that is 10x10 or 100 times more intense ($10^{-10} W/m^2$) is assigned a sound level of 20 dB.
- A sound that is 10x10x10 or 1000 times more intense ($10^{-9} W/m^2$) is assigned a sound level of 30dB.
- A sound that is 10x10x10x10 or 10000 times more intense ($10^{-8} W/m^2$) is assigned a sound level of 40 dB.

Intensity(W/m^2)

$$I_0 = 10^{-12}$$

$$I_1 = 10^1 I_0 = 10^{-11}$$

$$I_1 = 10^2 I_0 = 10^{-10}$$

$$I_1 = 10^3 I_0 = 10^{-9}$$

$$I_1 = 10^4 I_0 = 10^{-8}$$

$$I_1 = 10^n I_0 = 10^{-12+n}$$

Intensity(bB)

$$0dB$$

$$10 \times 1 = 10dB$$

$$10 \times 2 = 20dB$$

$$10 \times 3 = 30dB$$

$$10 \times 4 = 40dB$$

$$10 \times n = n * 10dB$$

- Observe that this scale is based on powers of 10^n . If one sound is 10^n times more intense than another sound, then it has a sound level that is 10^n more decibels than the less intense sound.
- The Table below lists some common sounds with an estimate of their intensity and decibel level.
- Sound intensity level is not the same as intensity. Because β is defined in terms of a ratio, it is a unit less quantity telling you the level of the sound relative to a fixed standard (10^{-12} W/m^2).
- The intensity level or sound level measured in Decibels (dB). The units of decibels (dB) are used to indicate this ratio is multiplied by 10 in its definition. The **bell** is named for **Alexander Graham Bell**, the inventor of the telephone.

- Intensity level(dB) is defined as the Common logarithm or base 10 logarithm.

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

- Where; $I_0 = 10^{-12}$ is the intensity of threshold hearing and I is the intensity of a given sound. The units of decibels (dB) are used to indicate this ratio is multiplied by 10 in its definition.

Type of sound	Intensity I (W/m^2)	Sound intensity level β (dB)
Threshold of hearing at 1000 Hz	1×10^{-12}	0
Rustle of leaves	1×10^{-11}	10
Whisper at 1m distance	1×10^{-10}	20
Quiet home	1×10^{-9}	30
Average home	1×10^{-8}	40
Average office, soft music	1×10^{-7}	50
Normal conversation	1×10^{-6}	60
Noisy office, busy traffic	1×10^{-5}	70
Loud radio, classroom lecture	1×10^{-4}	80
Inside a heavy truck; damage from prolonged exposure	1×10^{-3}	90
Noisy factory, siren at 30 m; damage from 8 h per day exposure	1×10^{-2}	100
Damage from 30 min per day exposure	1×10^{-1}	110
Loud rock concert, pneumatic chipper at 2 m; threshold of pain	1	120
Jet airplane at 30 m; severe pain, damage in seconds	1×10^2	140
Bursting of eardrum	1×10^4	160

Example

1. Compute the intensity level (dB) of sound whose intensity is:
a) at the pain threshold. b) $1 \times 10^{-11} \text{ W/m}^2$
2. What sound intensity level in dB is produced by earphones that create an intensity of 110^{-2} W/m^2 ?
3. The sound level in a room may be 50 dB. What will be the intensity level of a sound that is twice as loud as a 50 dB?
4. Calculate the intensity of a wave propagating with the power of 20 KW. The area of the cross-section of the surface is 2.510^3 square meters.
5. The sound level in heavy truck may be 90 dB. What will be the intensity level of a sound that is one-third as loud as a 90 dB?

THE END