

Topic 2: Waves

1. Wave Properties and Propagation

Learning Outcomes:

- i. Describe wave motion in terms of transfer of energy from one position to another.
- ii. Define wave
- iii. Describe the way in which sound waves are produced and propagated in a medium.
- iv. Differentiate between transverse and longitudinal waves in terms of the movement of particles in the medium of transmission and the energy of the waves.
- v. Analyze/Interpret graphical representations of transverse and longitudinal waves.
- vi. Define the terms as related to a wave:
 - a. Amplitude/displacement
 - b. Wavelength
 - c. Frequency
 - d. Period
 - e. Speed/Velocity
- vii. Deduce from the definition of speed, frequency and wavelength, the equation $v = f\lambda$
- viii. Solve problems involving wave speed/velocity, frequency and wavelength.
- ix. Demonstrate the propagation of waves in water.
- x. Sketch and interpret diagrams involving wave fronts and rays.
- xi. Describe why the average displacement of vibration particles in a wave motion is zero.
- xii. Calculate speed of sound in various transporting media.
- xiii. Use the terms phase and phase difference with reference to behaviour of waves.

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Waves

Wave is a common term for a number of different ways in which energy is transferred:

- In electromagnetic waves, energy is transferred through vibrations of electric and magnetic fields.
- In sound waves, energy is transferred through vibration of air particles or particles of a solid through which the sound travels.
- In water waves, energy is transferred through the vibration of the water particles.

Wave refers to variation or disturbance of energy transfer through a medium from one point to another without the net movement of particles. Wave transfers energy differently depending on the type of media, such as water, sound, and magnet.

A wave is produced by some kind of disturbance that is associated with energy. When the wave travels, it carries that energy with it. Therefore, energy transportation is realized in a wave motion. When we watch surf waves coming into shore, it's easy to think that individual water particles are moving towards us, but that's not actually the case. The particles involved in waves move back and forth perpendicularly to the way the wave is going, but don't move significantly in the direction of the wave. The particles 'take part' in the wave by bumping into one another and transferring energy. This is why energy can be transferred, even though the average position of the particles doesn't change.

Transverse and Longitudinal Waves

A **transverse wave** is a wave in which particles of the medium move in a direction perpendicular to the direction that the wave moves. Suppose that a slinky is stretched out in a horizontal direction across the classroom and that a pulse is introduced into the slinky on the left end by vibrating the first coil up and down. 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 upwards and downwards. In this case, the particles of the medium move perpendicular to the direction that the pulse moves. This type of wave is a transverse wave. Transverse waves are always characterized by particle motion being perpendicular to wave motion.

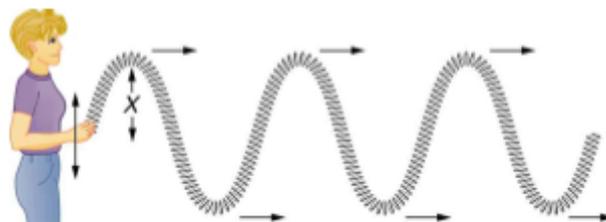


Figure 1.1: Transverse wave, the wave propagates horizontally, and the disturbance in the cord is in the vertical direction.

In contrast, **longitudinal wave** is a wave in which particles of the medium move in a direction parallel to the direction that the wave moves. Suppose that a slinky is stretched

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out in a horizontal direction across the classroom and that 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.

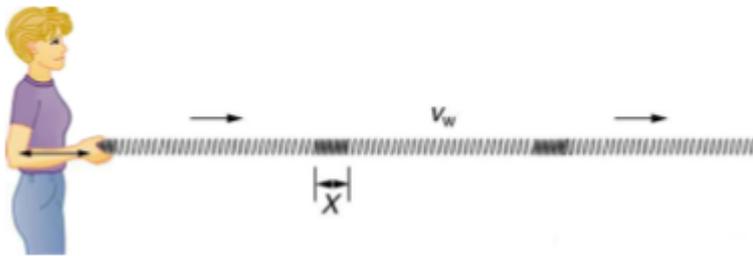


Figure 1.2: Longitudinal wave, the wave propagates horizontally, and the disturbance in the cord is also in the horizontal direction.

A **sound wave** traveling through air is a classic example of a longitudinal wave. As a sound wave moves from the lips of a speaker to the ear of a listener, particles of air vibrate back and forth in the same direction and the opposite direction of energy transport. Each individual particle pushes on its neighbouring particle so as to push it forward.

The *collision* of particle #1 with its neighbour serves to restore particle #1 to its original position and displace particle #2 in a forward direction. This back-and-forth motion of particles in the direction of energy transport creates regions within the medium where the particles are pressed together and other regions where the particles are spread apart. Longitudinal waves can always be quickly identified by the presence of such regions. This process continues along the *chain* of particles until the sound wave reaches the ear of the listener.

Waves traveling through a solid medium can be either transverse waves or longitudinal waves. Yet waves traveling through the bulk of a fluid (such as a liquid or a gas) are always longitudinal waves. Transverse waves require a relatively rigid medium in order to transmit their energy. As one particle begins to move it must be able to exert a pull on its nearest neighbor. If the medium is not rigid as is the case with fluids, the particles will slide past each other. This sliding action that is characteristic of liquids and gases prevents one particle from displacing its neighbor in a direction perpendicular to the energy transport. It is for this reason that only longitudinal waves are observed moving through the bulk of liquids such as our oceans. Earthquakes are capable of producing both transverse and longitudinal waves that travel through the solid structures of the Earth.

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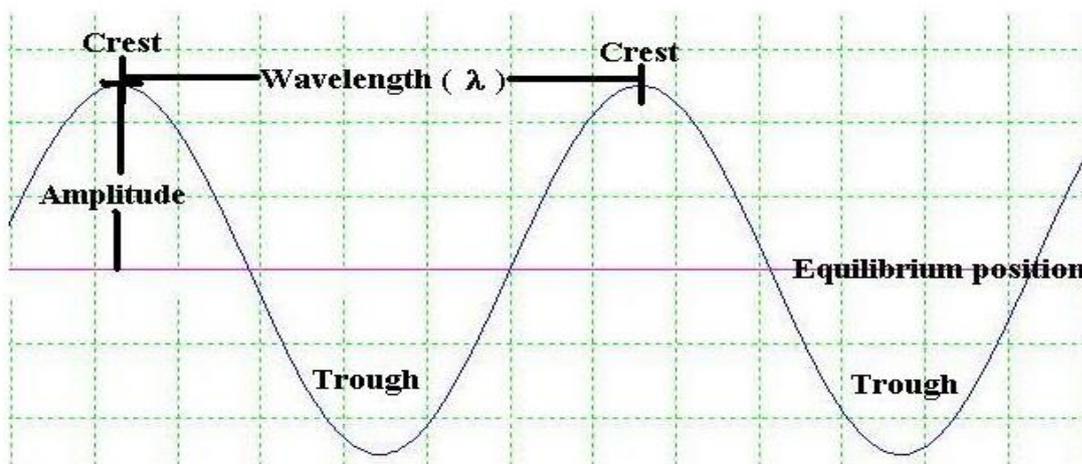
Waves can be described by a number of variables, included: *amplitude*, *wavelength*, *period* and *frequency*.

- The amplitude of a wave (A) is a measure of the magnitude of a disturbance in the medium during one wave cycle. In this exhibit, the amplitude of a wave will be the distance between the maximum displacement of the stick on the vertical direction and the equilibrium point (the point of zero displacement).
- The wavelength (λ) is the total distance travelled by the wave in one full cycle. In this case, the wavelength can be given by horizontal distance between repeating units of wave pattern.
- The period (T) is the amount of time it takes to complete one cycle.
- The frequency (f) is the number of cycles the wave completes in a given time, and is the inverse of the period.

$$f = 1/T, \text{ where } T \text{ is given in seconds (s) and } f \text{ in hertz (Hz).}$$

The frequency and wavelength are related by the velocity of wave:

$$v = \lambda f, \text{ where } \lambda \text{ is in meter (m) and } f \text{ is in Hz.}$$



Transverse Wave

Figure 1.3: Graphical Transverse Wave

Longitudinal Waves

- Longitudinal waves show areas of **compressions** and **rarefactions**

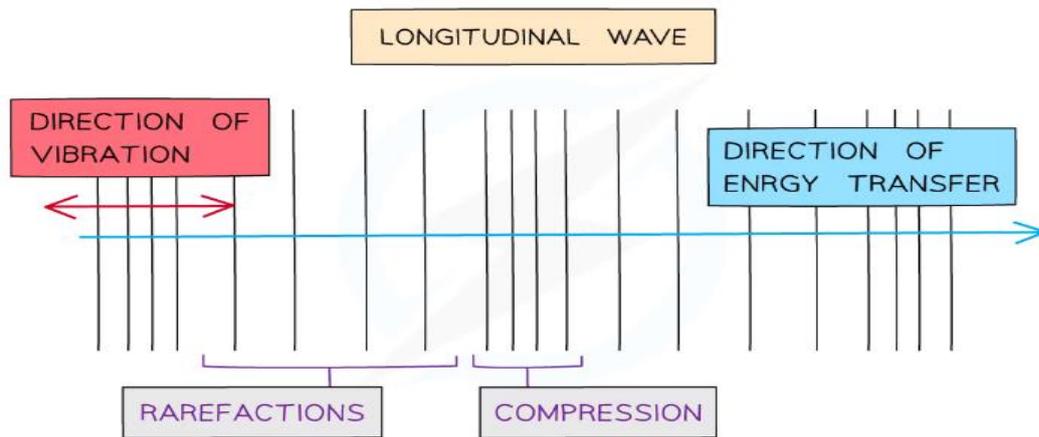


Figure 1.4: Graphical Longitudinal Wave

- The **compressions** are areas of high pressure due to particles being close together.
- The **rarefactions** are areas of low pressure due to the particles spread further apart
- The direction of energy transfer is **parallel** to the direction of vibration of the particles in the wave

Wave with Wavefronts

So far, we've pictured waves using only an oscillating sine function. For one-dimensional waves this was adequate, but for two- or higher dimensional waves this representation becomes difficult, and so we introduce the idea of *wavefronts* and *rays*. Let us start by thinking of dropping a stone in water and letting the ripples propagate outward. Some time later, the ripples appear as shown on the figure below on the left. In this figure, parts of the wave are obscured by other waves and it is generally difficult to draw and visualize interactions between waves like this.

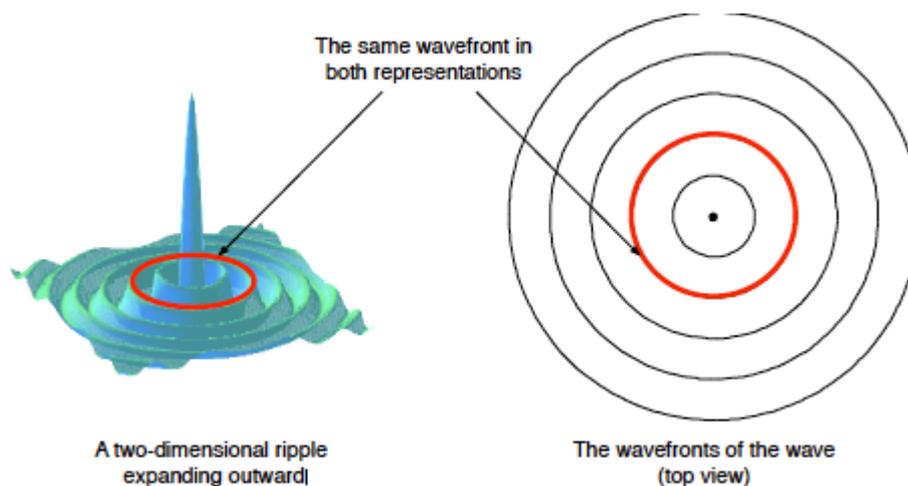


Figure 1.5: Wavefront

These limitations make it a difficult to use representation, so we adopt a more useful representation that omits a few details. One such representation is

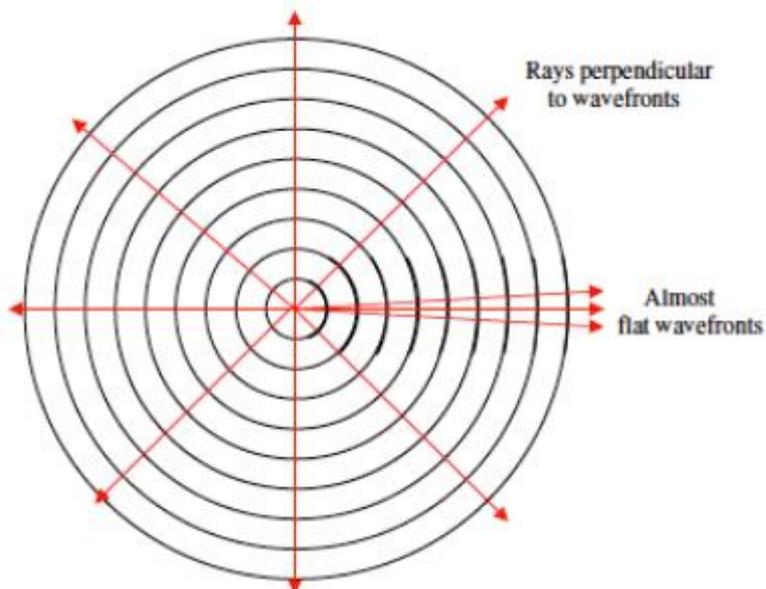
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the **wavefront** representation in which we choose to only draw one part of the waves. The figure above and on the right is a wavefront representation of the picture on the left where we've chosen only to show the peaks of the waves. Because we know the wave is oscillating up and down, and traveling outward, you should have a reasonable idea of what the wave is doing just by looking at the picture of the wavefronts.

Occasionally we shall draw wavefronts for the peaks and troughs in different colours so that we can superpose them, recalling that peak-and-peak or trough-and-trough interference is *constructive*, while peak-and-trough interference is *destructive*.

Wave with Rays

We can simplify representing a wave in a different way; consider only the direction that a particular piece of the wave is traveling. We can join these directions and trace out a path of a particular piece of a wave. These paths are called **rays**, and are always perpendicular to the wavefronts. Examples of rays are shown in the figure below as arrows.



Notice that we can draw whichever rays are convenient to use; in the above example, we drew many rays going in all directions. On the right, we concentrated the rays in the part where we discussed the wavefronts looking flat so we can discuss one more important quality of rays: when you are a far distance from the source of the wave, the rays are approximately parallel. The extra rays do not indicate that there is more energy in that part of the wave.

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Activity 2.1

1. Define wave.
2. Describe wave motion in terms of transfer of energy from one position to another.
3. Describe the way in which sound waves are produced and propagated in a medium.
4. Differentiate between transverse and longitudinal waves in terms of the movement of particles in the medium of transmission and the energy of the waves.
5. Define the terms as related to a wave:
 - a. Amplitude/displacement
 - b. Wavelength
 - c. Frequency
 - d. Period
 - e. Speed/Velocity
6. Wind gusts create ripples on the ocean that have a wavelength of 5.00 cm and propagate at 2.00 m/s. Calculate their frequency?
7. Calculate the wavelength of the waves you create in a swimming pool if you splash your hand at a rate of 2.00 Hz and the waves propagate at 0.800 m/s?
8. Scouts at a camp shake the rope bridge they have just crossed and observe the wave crests to be 8.00 m apart. If they shake it the bridge twice per second, calculate the propagation speed of the waves?
9. Sketch and interpret diagrams involving wave fronts and rays.

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2. The Wave Nature of Light

Learning Outcomes:

- i. Explain the relationship between reflection and refraction of light.
- ii. Describe the properties of electromagnetic waves.
- iii. Describe the relationship between amount of refraction and frequency.
- iv. Discuss the failure of corpuscular light model.
- v. Explain the dual nature of light.

Wave behaviour

Waves display several basic phenomena. In reflection, a wave encounters an obstacle and is reflected back. In refraction, a wave bends when it enters a medium through which it has a different speed. In diffraction, waves bend when they pass around small obstacles and spread out when they pass through small openings. In interference, when two waves meet, they can interfere constructively, creating a wave with larger amplitude than the original waves, or destructively, creating a wave with a smaller (or even zero) amplitude.

Reflection

When waves hit a boundary and are reflected, the angle of incidence equals the angle of reflection. The angle of incidence is the angle between the direction of motion of the wave and a line drawn perpendicular to the reflecting boundary.

Refraction

The speed of a wave depends on the properties of the medium through which it travels. For example, sound travels much faster through water than through air. When a wave enters at an angle a medium through which its speed would be slower, the wave is bent toward the perpendicular. When a wave enters at an angle a medium in which its speed would be increased, the opposite effect happens. With light, this change can be expressed by using Snell's law of refraction.

Reflection and refraction

All waves will reflect and refract in the right circumstances. The reflection and refraction of light explains how people see images and optical illusions.

Refraction of light rays

Different materials have different densities. Light waves may change direction at the boundary between two transparent materials. Refraction is the change in direction of a wave at such a boundary.

It is important to be able to draw ray diagrams to show the refraction of a wave at a boundary.

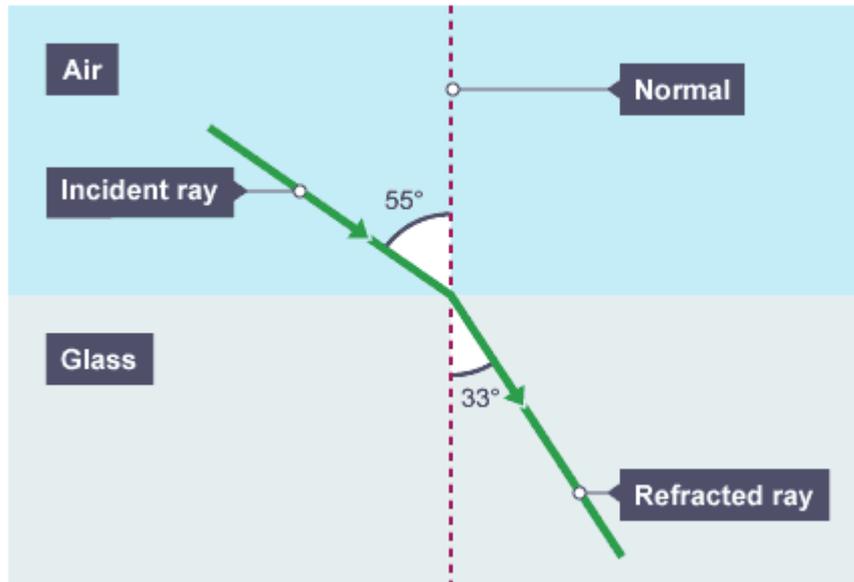


Figure 2.1: A ray diagram showing refraction of light at the boundary between air and glass

Refraction can cause optical illusions as the light waves appear to come from a different position to their actual source.

Refraction of water waves

Water waves will change direction at a boundary between deep and shallow water.

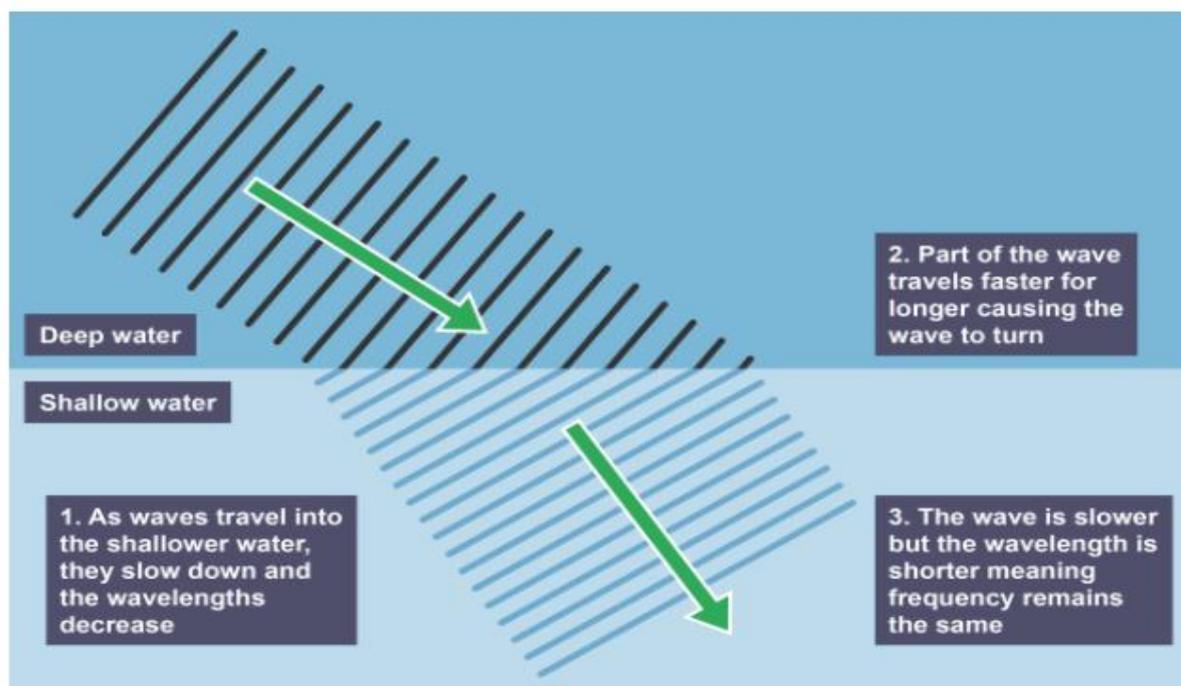


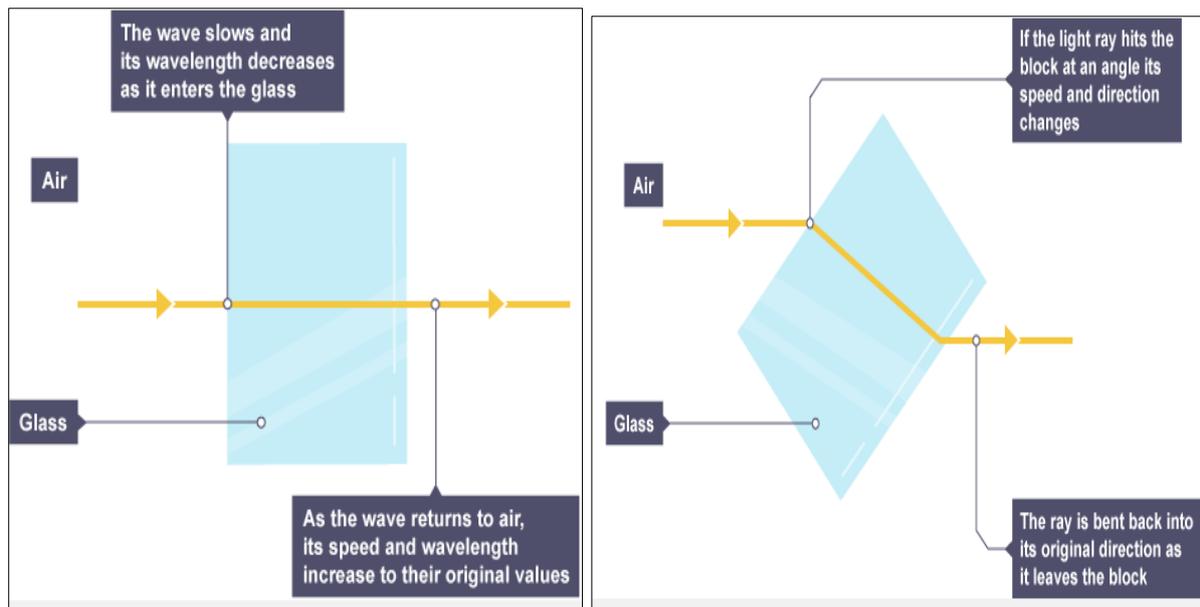
Figure 2.2: The waves slow down as they enter the shallow water which causes the wavelengths to shorten.

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The density of a material affects the speed that a wave will be transmitted through it. In general, the denser the transparent material, the more slowly light travels through it.

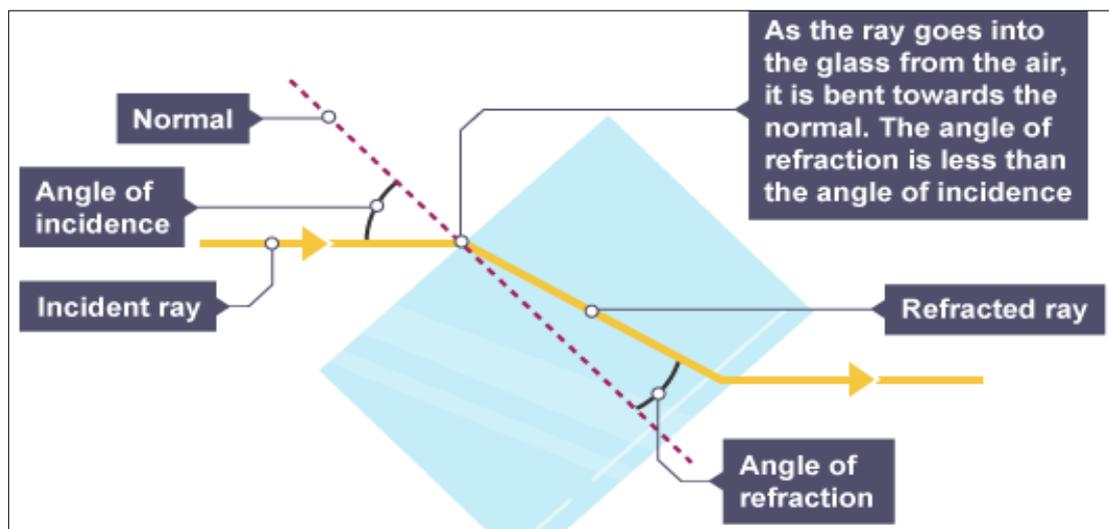
Glass is denser than air, so a light ray passing from air into glass slows down. If the ray meets the boundary at an angle to the normal, it bends towards the normal.

The reverse is also true. A light ray speeds up as it passes from glass into air, and bends away from the normal by the same angle.



a.

b.



c.

Figure 2.3: a - c, A useful way of remembering the speed and direction changes of light during refraction is 'FAST': Faster - Away / Slower - Towards

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Wave speed, frequency and wavelength in refraction

For a given frequency of light, the wavelength is proportional to the wave speed:

$$\text{wave speed} = \text{frequency} \times \text{wavelength}$$

So, if a wave slows down, its wavelength will decrease. The effect of this can be shown using wave front diagrams, like the one below. The diagram shows that as a wave travels into a denser medium, such as water, it slows down and the wavelength decreases. Although the wave slows down, its frequency remains the same, due to the fact that its wavelength is shorter.

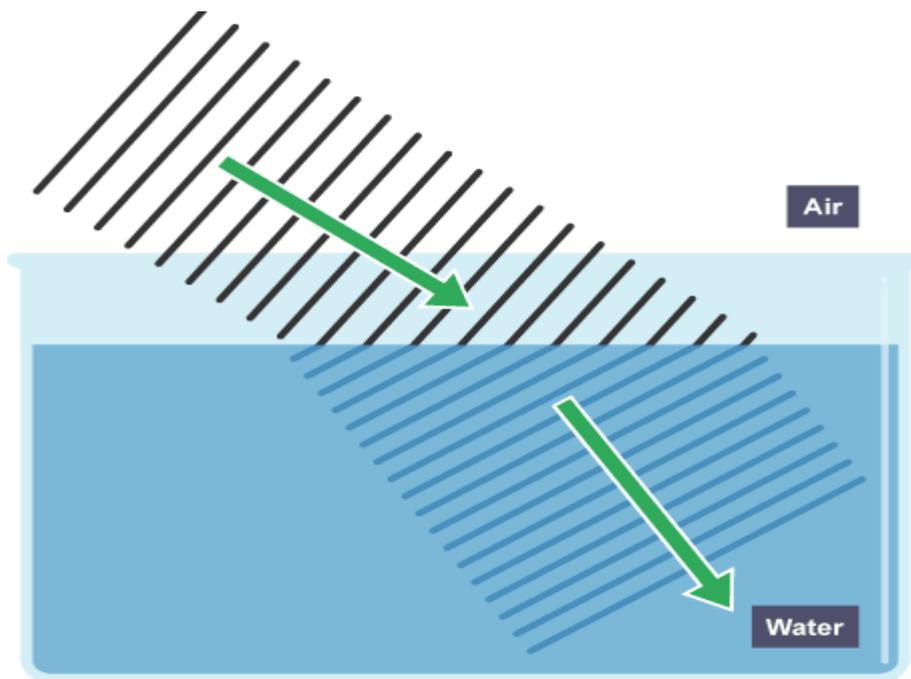


Figure 2.4: When waves travel from one medium to another the frequency never changes.

1. As waves travel into the denser medium, they slow down and wavelength decreases.
2. Part of the wave travels faster for longer causing the wave to turn.
3. The wave is slower but the wavelength is shorter meaning frequency remains the same.

Properties of Electromagnetic Waves

Electromagnetic waves consist of two waves oscillating perpendicular to each other. One is the oscillating electric field and the other one is an oscillating magnetic field. The direction of propagation of the wave is perpendicular to the electric field and the magnetic field. They are transverse waves and do not require a material medium for propagation. They travel at the speed of light which is 3×10^8 m/s.

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- Electromagnetic waves are transverse in nature.
- They propagate by varying electric fields and magnetic fields, such that these two fields are at right angles to each other and at a right angle with the direction of propagation of the wave.
- Electromagnetic waves travel with a constant velocity in vacuum. The speed of the waves is 3×10^8 m/s.
- Electromagnetic waves are non-mechanical waves. They do not require any material medium for propagation.
- They obey the equation $c = f\lambda$. Here, f is the frequency in Hertz and λ is the wavelength in metres. The product of wavelength and frequency is equal to a constant c , the speed of light which is equal to 3×10^8 m/s. From this relation between wavelength, frequency and speed of light we can understand that the electromagnetic waves will travel with the speed of light regardless of wavelength and frequency.
- The oscillating electric field and magnetic field are in the same phase. The ratio of the amplitudes of the electric field and the magnetic field is equal to the velocity of the wave.

Corpuscular Theory

The corpuscular theory states that light is made up of tiny particles called 'corpuscles' (little particles) that always travel in a straight line.

Light is a form of energy that travels from one place to another place at high velocity. Various scientists have attempted to explain the nature of light. However, the first scientific attempt to explain the nature of light was made by Sir Isaac Newton. In the 17th century, two different theories about the nature of light were proposed; these theories were the 'wave theory' and 'corpuscular theory'.

The '**Corpuscular theory**' of light was proposed by Newton in 1704. In this theory, he successfully explained the nature of light.

The corpuscular theory is the simplest theory of light in which light is assumed as the tiny particles called 'corpuscles'. The corpuscular theory is often referred to as particle theory or Newton's theory of light.

Newton's Corpuscular Theory Statement

According to the Newton's corpuscular theory:

- Light is made up of tiny particles called 'corpuscles' having negligible mass.
- These particles (corpuscles) are perfectly elastic.
- The corpuscles are emitted from the luminous sources such as Sun, candle, electric lamp etc.
- The tiny particles (corpuscles) always travel in a straight line in all directions.

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- Each particle (corpuscle) carries kinetic energy with it while moving.
- The corpuscles travel at high velocity.
- The corpuscles (light) would travel faster in the denser medium than in rarer medium. But later this is proved wrong. We know that light travels faster in the rarer medium than in denser medium.
- When the particles (corpuscles) fall on the retina of the eye, they produce an image of the object or sensation of vision.
- The corpuscles can be of different sizes. The different colors of light are due to the different sizes of the corpuscles.

Corpuscular theory example

The corpuscular theory could be easily understood with a simple example.

- Take a rubber ball.
- Stand before a wall.
- Throw the ball in such a way that it hits the wall normally.
- You will observe that the ball bounces and returns along the same path.
- Now, throw the ball in such a way that it makes a certain angle with the surface of the wall.
- You will observe that the ball bounces and goes away from the surface of the wall making an equal angle with respect to the normal drawn at the point of incidence.

These observations show that the rubber ball obeys the laws of reflection. Just like the rubber ball, when corpuscles hit the surface, they are reflected back in the same path or reflect at an equal angle with respect to the normal drawn at the point of incidence.

The corpuscles of light behave like the rubber balls.

Failures of Newton's corpuscular theory

- Newton assumed that light travels faster in the denser medium than in the rarer medium which has been proved wrong.
- The assumption that the different colors of light are due to the differences in the sizes of corpuscles has no justification.
- Newton assumed that reflection of light is due to the repulsion between the corpuscles and reflecting surface while refraction of light is due to the attraction between the corpuscles and refracting surface. Thus, a medium could either attract or repel the corpuscles of light. But later this statement was proved wrong. We all know that glass partially reflects and partially refracts light. How could then glass attract and repel the corpuscles of light simultaneously.

Dual Nature of Light

Light has a dual nature:

1. Sometimes it behaves like a particle (called a photon), which explains how light travels in straight lines

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2. Sometimes it behaves like a wave, which explains how light bends (or diffracts) around an object.

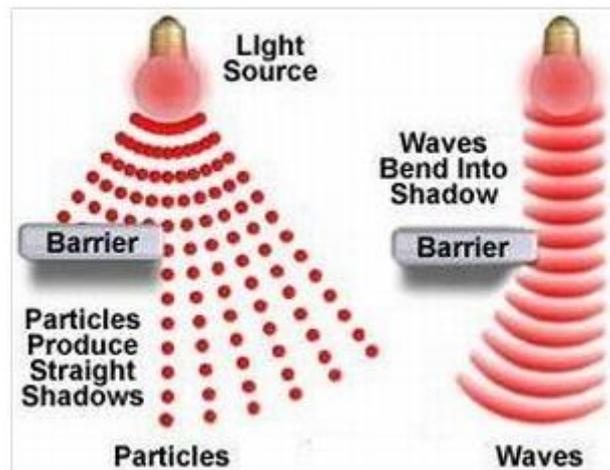


Figure 2.5: The dual nature of light is accepted and the current nature of light.

The properties of light can be summarized into two groups with its dual nature

Particle properties

- 1) Travels in straight lines
- 2) Reflection (changes direction)
- 3) Refraction (bends, in going from one material to another)

Wave properties

- 1) Interference (waves "superpose" and pass right through each other)
- 2) Diffraction (waves "spill over" the edges of their obstructions)
- 3) Polarization (eliminating one of light's "fields")

Activity 2.3

1. Explain the relationship between reflection and refraction of light.
2. Describe the properties of electromagnetic waves.
3. Describe the relationship between amount of refraction and frequency.
4. Discuss the failure of corpuscular light model.
5. Explain the dual nature of light.