

CHAPTER 14

LIGHT



Student's learning outcomes (SLOs)

After studying this chapter, students will be able to:

- define and use the terms normal, angle of incidence, and angle of reflection.
- describe an experiment to find the position and characteristics of an optical image formed by a plane mirror (same size, same distance from mirror as object, and virtual).
- use the law of reflection to solve simple optical problems.
- apply the qualitative principle that a wave refracts towards the normal when it slows down while entering a medium and that it refracts away from the normal if it speeds up when it enters a new medium (in the case the angle of incidence is zero, then the waves continue parallel to the normal).
- define and use the refractive index from vacuum to a medium for light as c/v .
- define refractive index n as; $n = \sin i / \sin r$. Apply Snell's law; $n = \sin i / \sin r$, to solve simple problems.
- describe an experiment to show refraction of light by transparent blocks of different shapes.
- define the terms critical angle C and total internal reflection.
- derive the equation; $n = 1 / \sin C$.
- apply the equation; $n = 1 / \sin C$ to solve simple problems.
- describe experiments to show internal reflection and total internal reflection.
- evaluate and illustrate the use of optical fibres, particularly in telecommunications, stating the advantages of their use in each context.
- analyze the action of thin converging and thin diverging lenses on a parallel beam of light.

- define and use the terms focal length, principal axis, and principal focus (focal point).
- draw ray diagrams to illustrate the formation of real and virtual images of an object by a converging lens.
- differentiate between real and virtual images.
- define and calculate linear magnification (as the ratio of image length to object length; state and use the equation; linear magnification = image length / object length).
- describe the use of a single convex lens as a magnifying glass.
- describe the use of a single convex lens in various optical device applications (specifically in the case of a magnifying glass, a camera, projector, and a photographic enlarger). This includes drawing ray diagrams to show how each forms an image.
- explain the dispersion of light by a prism [including the detection of non-visible spectra by a thermometer].
- draw ray diagrams to show the formation of images in the normal eye, a short-sighted eye, and a long-sighted eye.
- describe the use of converging and diverging lenses to correct long-sightedness and short-sightedness.
- state that extreme gravity from interstellar objects like black holes can cause light to bend (from the perspective of the observer) in a way that is analogous to a simple lens [This is called 'gravitational lensing'].

Light is a form of energy that travels in the form of waves and allows us to see the world around us. In this chapter, we will explore how light reflects from mirrors, bends (refracts) when passing through different materials, and how lenses shape light to form images. Key topics include the angles of incidence, reflection, and refraction, as well as the difference between real and virtual images in everyday tools like cameras, microscopes, and eyeglasses. We will also learn how the human eye detects light and colour, and how lenses help to correct vision problems. In addition to this, the chapter will introduce advanced ideas such as gravitational lensing and how light is used in modern scientific and industrial technologies.

14.1 Reflection of Light

Reflection of light takes place when light hits a surface and bounces back instead of passing through it. This usually occurs on smooth and shiny surfaces, such as mirrors. The angle at which light strikes the surface (angle of incidence) is always equal to the angle at which it reflects (angle of reflection) (Fig. 14.1).

There are two types of reflection:

Regular/Specular Reflection : It takes place on smooth surfaces (like mirrors) where light reflects in one direction, forming a clear image.

Diffused/Irregular Reflection: It occurs on rough surfaces (like paper), where light scatters in different directions, so no clear image is seen.

Reflection is important for mirrors, periscopes, and optical devices, allowing us to see objects and form images.

Laws of Reflection

The reflection of light follows two basic laws:

First Law: The incident ray, the reflected ray, and the normal (a line drawn perpendicular to the surface at the point of reflection) all lie in the same plane.

Second Law: The angle of incidence (i) is always equal to the angle of reflection (r).

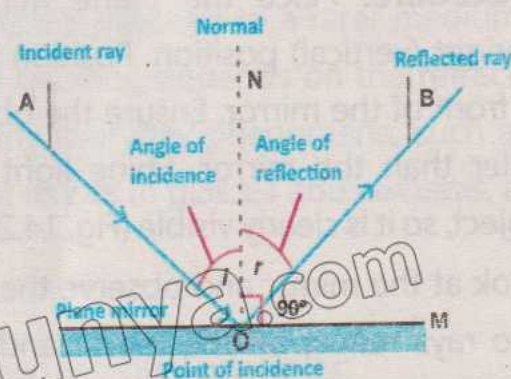
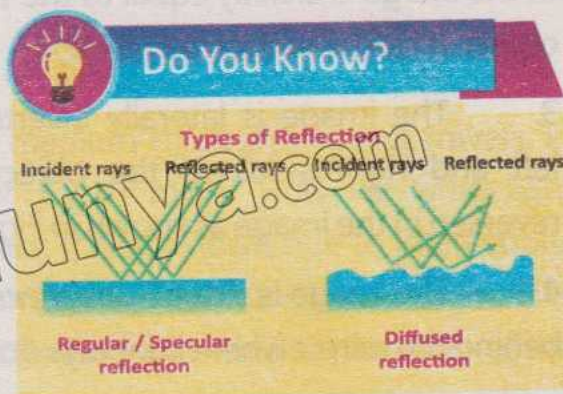


Fig. 14.1: Reflection of light



$$\angle i = \angle r \quad (14.1)$$

These laws apply to all reflective surfaces, such as mirrors and water, and help us to understand how light bounces back to form images.

Activity 14.1: Finding the Image Position in a Plane Mirror

Objective: To observe and understand the position and characteristics of the image formed by a plane mirror.

Materials Needed: A plane mirror, an object, a measuring tape, a light source, and a white paper.

Procedure: Place the plane mirror in an upright (vertical) position. Position the object in front of the mirror. Ensure the object is not taller than the mirror. Shine light onto the object, so it is clearly visible (Fig. 14.2).

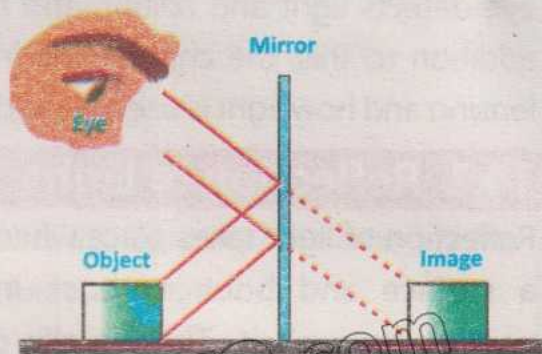


Fig. 14.2: Image formation by a plane mirror

Look at the mirror and observe the rays of light reflecting from the object. When two rays reflect off the mirror and reach the observer's eye, they appear to be coming from behind the mirror. By using a ruler and the law of reflection, we can draw the reflected rays on paper. Extend these reflected rays backward with dotted lines where they meet behind the mirror is the position of the image. This method shows the virtual image location.

There are four properties of an image formed by a plane mirror:

1. The image is erect – It appears upright, just like the object.

2. The image is of the same size – The size of the image is exactly equal to the size of the object. It can be written as: $d_i = d_o$.

3. The image is laterally inverted – The left and right sides of the object appear reversed in the image as shown in Fig. 14.3.

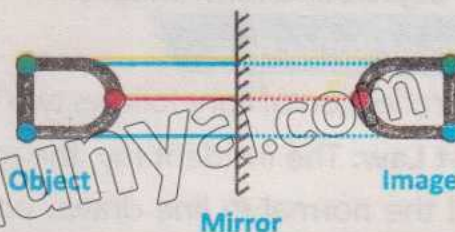


Fig. 14.3: Letter 'D' showing lateral inversion in a mirror

4. The image is virtual – It cannot be captured on a screen because it is formed behind the mirror where light rays do not actually meet.

14.2 Refraction of Light

Refraction of light occurs when light changes direction as it passes from one medium to another, such as from air to water or glass (Fig. 14.4). This happens because light travels at different speeds in different materials. When light moves from a rarer medium (air) to a denser medium (glass or water), it bends towards the normal. When it moves from a denser medium to a rarer medium, it bends away from the normal. The amount of bending depends on the refractive index of the medium. Refraction explains many everyday phenomena, such as a pencil appearing bent in water, the working of lenses in glasses and cameras, and the formation of rainbows.

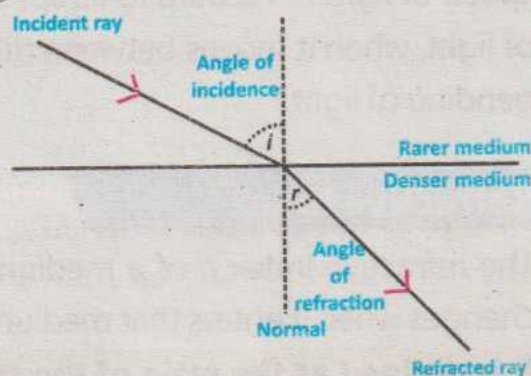


Fig. 14.4: Refraction of light

Laws of Refraction of Light

The bending of light during refraction follows two essential principles:

1. **First Law:** The incident ray, refracted ray, and the normal at the point where light enters a new medium all lie in the same plane.
2. **Second Law (Snell's Law):** The ratio of the sine of the angle of incidence i to the sine of the angle of refraction r remains constant for a specific pair of media.

$$\frac{\sin i}{\sin r} = n \quad \dots\dots\dots (14.2)$$

Here, n is the refractive index of the second medium relative to the first. The refractive index indicates how much light bends when entering a different medium.

Speed of Light in a Medium

The speed of light varies depending on the medium through which it travels. In vacuum, light moves at its maximum speed of $3 \times 10^8 \text{ m s}^{-1}$. However, when light passes through materials like air, water, or glass, it slows down due to interactions with medium particles. The denser the medium, the slower the speed of light. This change in speed is measured using the refractive index n , which is the ratio of the

speed of light in vacuum to its speed in a given medium. The variation in the speed of light, when it moves between different material, is what causes refraction, or the bending of light.

Refractive Index

The refractive index n of a medium is a measure of how much the speed of light changes when it enters that medium.

It is defined as the ratio of the speed of light in air or vacuum c to the speed of light in the given medium v :

$$\text{Refractive index} = \frac{\text{Speed of light in air}}{\text{Speed of light in a medium}}$$

$$\text{or } n = \frac{c}{v} \quad \dots\dots\dots (14.3)$$

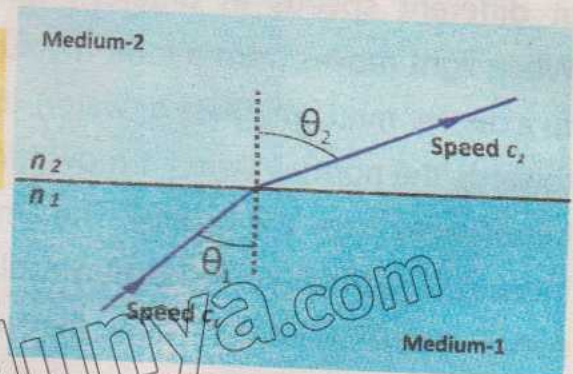


Fig. 14.5: Refraction of light at a boundary between two media

Figure 14.5 illustrates how a light ray changes direction when passing from medium-1 (with refractive index n_1 and speed c_1) to medium-2 (with refractive index n_2 and speed c_2). The angles θ_1 (angle of incidence) and θ_2 (angle of refraction) demonstrate how the light bends according to Snell's law due to the difference in refractive indices.

Example 14.1: A ray of light enters from air into water. The angle of incidence is 40° and the refractive index of water is 1.33. Find the angle of refraction.

Solution:

Given that; Angle of incidence $i = 40^\circ$

Refractive index of water $n = 1.33$

To Find; Angle of refraction $r = ?$

Using Snell's law:

$$\frac{\sin i}{\sin r} = n$$

Substituting the values:

$$1.33 \times \sin r = \sin 40^\circ$$

$$\sin r = \sin 40^\circ / 1.33$$

$$\sin r = 0.483$$

$$r = \sin^{-1}(0.483)$$

$$\text{or } r = 28.9^\circ$$

Hence, the angle of refraction is 28.9° .

Example 14.2: The refractive index of water is 1.33. What is the speed of light in water?

Solution:

Given that;

Refractive index of water $n = 1.33$

Speed of light in vacuum $c = 3 \times 10^8 \text{ m s}^{-1}$

To find;

Speed of light in water $v = ?$

Using the formula:

$$n = c / v$$

or

$$v = c / n$$

Substituting the values

$$v = (3 \times 10^8 \text{ m s}^{-1}) / 1.33$$

$$v = 2.26 \times 10^8 \text{ m s}^{-1}$$

For your information

Convex Mirror	Concave Mirror
The Focus lies behind the mirror	The focus is in front of the mirror
The focus is virtual as the rays of light after reflection appear to come from the focus.	The focus is real as the rays of light after reflection converge at the focus.



Do You Know?

Some sign conventions for mirrors are:

Quantity	When Positive (+)	When Negative (-)
Object distance p	Real object	Virtual object
Image distance q	Real image	Virtual image
Focal length f	Concave mirror	Convex mirror

Refraction Through Prism

A prism is a transparent optical object with at least two polished plane surfaces inclined towards each other. It is usually made of optical glass and is used to refract (bend) light. In the case of a triangular prism (Fig. 14.6), 60° angle each, the light passing through it does not emerge parallel to its original path but instead changes direction. When an incident ray (PE) strikes the prism at point E, it bends towards the normal N and travels inside the prism as refracted ray (EF). Inside the prism, the ray makes an angle of refraction r before reaching the second surface at point F. As it exits the prism, it bends again, forming an emergent ray (FS) at an angle e . The emergent ray (FS) is not parallel to the incident ray (PE) but is instead deviated by an angle D , known as the angle of deviation. This bending effect of light through a prism is widely used in optical instruments, spectrometry, and light dispersion experiments.

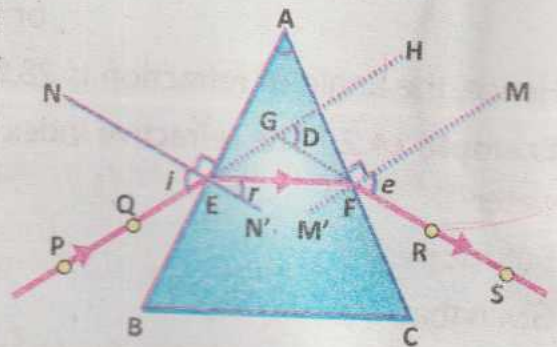


Fig. 14.6: Refraction through a triangular glass prism

Total Internal Reflection

When a light ray is incident at a boundary between two different media, it splits into two parts: one part reflects back into the original medium (reflected ray), and the other part passes into the second medium (transmitted or refracted ray), as shown in Fig. 14.7(a).

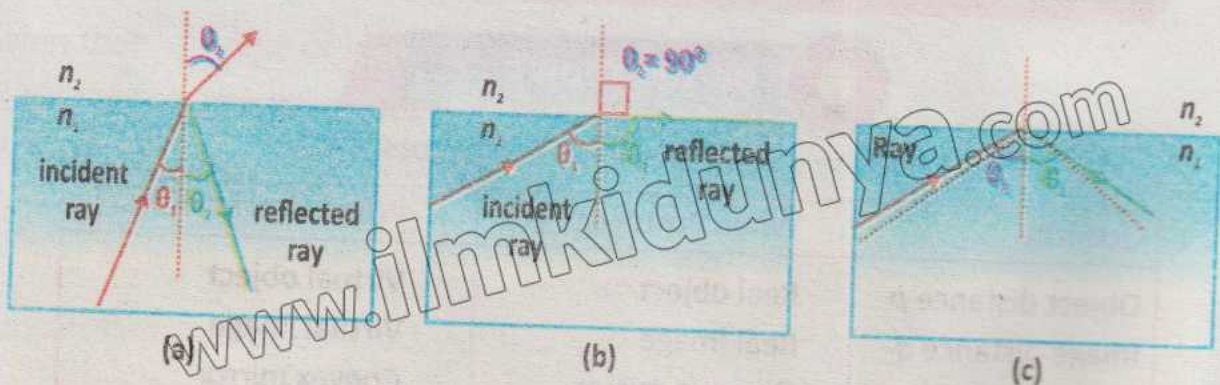


Fig. 14.7: Total internal reflection

If the angle of incidence increases then refraction angle also increases. The more the angle of incidence increases, the greater the angle of refraction becomes. At a particular angle, the refracted ray no longer enters the second medium but travels along the boundary. This angle is called the critical angle (Fig. 14.7-b), and is defined as:

The angle of incidence for which the angle of refraction is 90° is called the critical angle.

Now, if the angle of incidence is increased beyond the critical angle, the light ray does not refract at all. Instead, it reflects entirely back into the same medium. This phenomenon is called total internal reflection, as shown in Fig. 14.7(c).

Total internal reflection is the phenomenon of reflection of light ray back to the same medium when passing from denser medium to rarer medium in such a way that angle of incidence is greater than its critical angle.

The values of the refractive index, speed of light, and critical angle for different media are given in Table 14.1.

Table 14.1: Refractive index, speed of light, and critical angle for different media

Medium	Refractive Index	Speed of Light ($\times 10^8 \text{ m s}^{-1}$)	Critical Angle
Diamond	2.42	1.25	24.4°
Glass (flint)	1.66	1.81	37.0°
Glass (crown)	1.52	2.01	41.2°
Perspex	1.49	2.00	42.0°
Water	1.33	2.25	48.8°
Ice	1.31	2.30	49.8°
Air	1.00	2.99	88.6°
Vacuum	1.00	3.00	90.0°

Derivation of the formula for Total Internal Reflection

To derive a formula for total internal reflection, we start with Snell's law:

$$n_1 \sin i = n_2 \sin r \quad \text{..... (14.4)}$$

When total internal reflection occurs, the refracted angle becomes 90° . So, the equation becomes:

$$n_1 \sin i = n_2, \text{ because } \sin(90^\circ) = 1$$

Now, if ' i ' is the critical angle C , the formula becomes:

$$\sin C = n_2 / n_1 \quad \text{..... (14.5)}$$

To find the critical angle C , we rearrange it as:

$$C = \sin^{-1}(n_2 / n_1) \quad \text{..... (14.6)}$$

This only works when $n_1 > n_2$, meaning the light must travel from a denser medium to a rarer medium. If the second medium is air (where $n_2 = 1$), the equation becomes:

$$\sin C = 1 / n$$

From the above equation, the refractive index of the first material (denser medium) can be found as:

$$n = 1 / \sin C \quad \text{..... (14.7)}$$

This relation only holds true if the light is moving from a denser medium with refractive index n into air.

Experiment to Study Refraction

To understand how light bends (refracts) when it passes through different transparent materials, we can perform a simple experiment using blocks of different shapes right in our classroom or school laboratory (Fig. 14.8).

Aim of the Experiment

To observe how light refracts (bends) when it passes through a rectangular block, semi-circular block, and glass prism.

Materials Needed

Laser light, protractor, paper sheet, pencil, ruler, and Perspex blocks (rectangular, semi-circular, and prism-shaped).

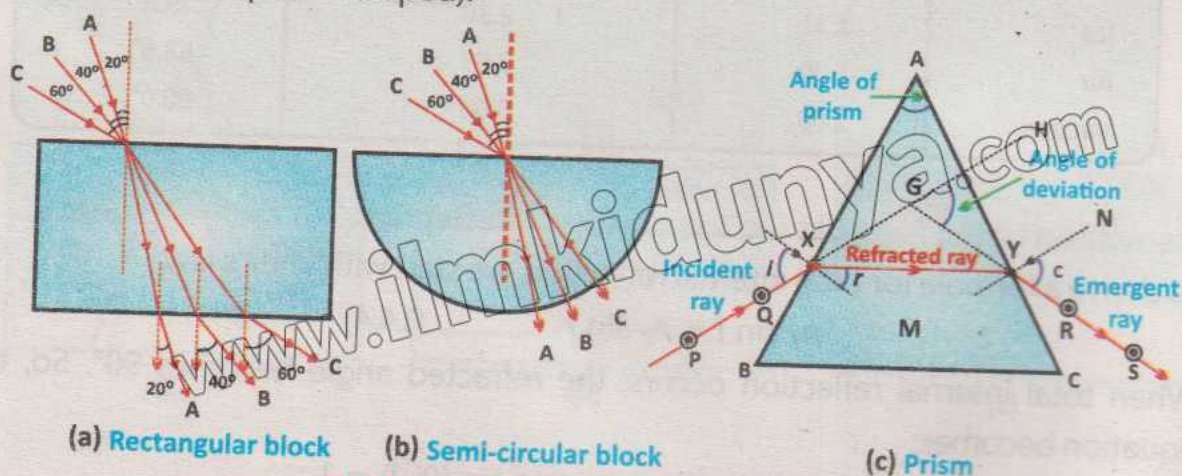


Fig.14.8: Experiment for refraction of light

Method of Experiment

Place the rectangular glass block on a sheet of paper and observe its result.

- Draw a straight line at one edge where the light will enter.
- Draw a normal (a straight perpendicular line) at the point where light will hit the block.
- Shine the laser light at an angle on the block along the drawn line.

Tidbit

Diamonds sparkle because they have a very high refractive index, causing multiple total internal reflections inside.

Experiment to study Total Internal Reflection

Aim of the Experiment

To study how total internal reflection of light occurs using a semi-circular glass block (Fig. 14.9).

Materials Needed

Light ray, protractor, paper, pencil, ruler, and a semi-circular Perspex (glass) block.

Brain Teaser

Place a pencil in a glass of water, it appears bent. What does this tell about the speed of light in water compared to air?

Figure 14.9 (a) demonstrates the refraction, while Fig. 14.9 (b) and Fig. 14.9 (c) illustrate the critical angle and total internal reflection respectively.

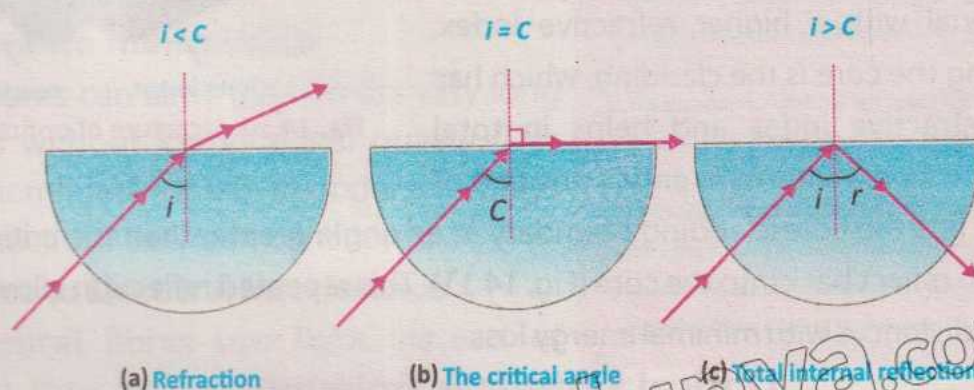


Fig. 14.9: Experiment for total internal reflection

Example 14.3: Find the value of critical angle for water (refracted angle = 90°). The refractive index of water is 1.33 and that of air is 1.

Solution:

Using Snell's law:

$$n_1 \sin i = n_2 \sin r$$

For the critical angle, the refracted angle $r = 90^\circ$ and $i = C$, so $\sin(90^\circ) = 1$
 $n \sin C = 1$

Rearranging for C:

$$C = \sin^{-1} (1 / n)$$

Substituting the values

$$C = \sin^{-1} (1 / 1.33)$$

$$C = \sin^{-1} (0.752)$$

$$C = 48.8^\circ$$

The critical angle for water is 48.8° .

14.3 Optical Fibre

Optical fibres use the principle of Total Internal Reflection (TIR) to transmit light efficiently over long distances. These fibres are widely used in the telecommunication industry due to their high speed and reliability.

An optical fibre consists of thin, hair-like strands made of glass or plastic (Fig. 14.10). It has two main parts: the **core** and the **cladding**. The core is the inner part that carries the light and is made of a material with a higher refractive index. Surrounding the core is the cladding, which has a lower refractive index and helps in total internal reflection. When light enters one end of the core, it hits the core-cladding boundary at an angle greater than the critical angle, causing it to reflect back into the core (Fig. 14.11). This repeated reflection allows light to travel long distances with minimal energy loss.

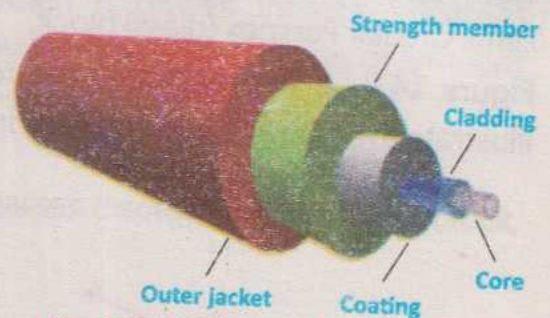


Fig. 14.10: Structure of optical fibre

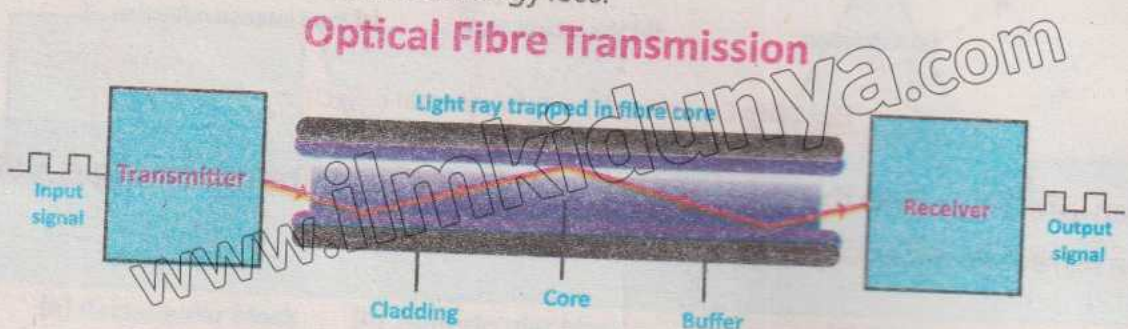


Fig. 14.11: Transmission of information through optical fibre

Advantages of Optical Fibres

Optical fibres are used in many areas of life, but their most common use is in modern telecommunications. Compared to traditional copper cables, optical fibres offer several key benefits:

High Bandwidth

Optical fibres can carry a much larger amount of data than copper wires. Bandwidth means how much data can be sent over a network per second. In today's world, where we need fast internet, optical fibres are the best choice because they support high-speed data transfer.

Low Power Consumption

They use less power than copper cables. Also, because they last longer and are more durable, they reduce the cost of repairs and maintenance.

Faster Speed

They send data using light pulses, which travel extremely fast almost at the speed of light. This allows data to move quickly from one place to another, faster than electrical signals in copper wires.

Long Distance Transmission

Optical fibres can carry data across very long distances without losing signal quality. This makes them ideal for use in undersea cables and connections between continents.

Resistance to Electrical Interference

Since optical fibres use light instead of electricity, they are not affected by electrical noise or interference. This is a big advantage over copper wires, which often face signal problems due to electrical disturbances.

14.4 Thin lenses

A lens is a transparent material with two surfaces, at least one of which is curved. It bends (refracts) light in a way that forms an image of an object. Lenses come in

Brain Teaser

Why can we use optical fibres to send data around bends and corners without much loss?

For Your Information



What is a Fibre Optic Cable?

Fibre optic cables are composed of very thin strand of extremely pure glass fibres.

- They transmit information using light from lasers or LEDs that is modulated with data or used in some cases as a light source.
- They have several thousand fibres that are insulated from one another by a protective jacket.
- Each fibre also has an internal cladding that bounces light inward to prevent signal loss.

different types and are widely used in optical devices such as cameras, eyeglasses, microscopes, telescopes, and projectors. They play an important role in correcting vision.

Types of Lenses

Lenses are classified based on how they bend light rays. A convex lens, also known as a converging lens, brings parallel light rays together at a point. It is thicker in the centre and thinner at the edges (Fig. 14.12). On the other hand, a concave lens, also called a diverging lens, causes parallel light rays to spread out. This lens is thinner in the centre and thicker at the edges (Fig. 14.13).

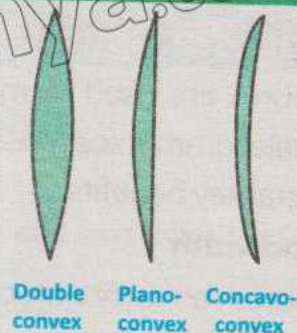


Fig. 14.12: Convex lenses

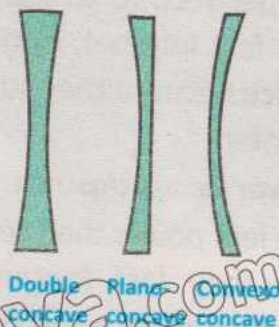


Fig. 14.13: Concave lenses

Important Terms Related to Lenses

To understand how lenses form images, it is important to learn some basic terms as illustrated in Fig. 14.14.

Focal Length

The focal length (f) is the distance from the lens (optical centre) to the principal focus, where light rays either meet (converge) or appear to spread out (diverge).

1. In converging lenses, focal length is positive and the rays meet at a point after passing through the lens.

2. In diverging lenses, focal length is negative and rays seem to spread out from a virtual point on the same side of the lens as the light source.

Principal Axis

This is a straight, imaginary line that passes through the centre of the lens. Light rays that travel along the principal axis do not bend or change direction when passing through the lens.

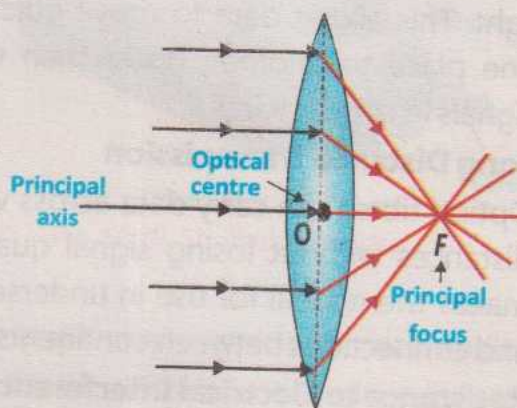


Fig. 14.14: Key terms of a lens

Principal Focus (Focal Point)

The principal focus is the point on principal axis where light rays that are parallel to the principal axis come together (in converging lenses) or appear to come from (in diverging lenses).

1. For a converging lens, the focus is on the opposite side of the incoming rays.
2. For a diverging lens, the focus is on the same side as the incoming rays and appears to be behind the lens.

Optical Centre

The optical centre is the geometrical middle point of the lens through which the principal axis passes. Light passing through this point does not bend. It is usually marked as O.

Centre of Curvature

Lenses are made from parts of a sphere. The centre of this imaginary sphere is called the center of curvature. It is generally located at twice the focal length from the lens.

Lens and Mirror Formula

The relationship between the focal length f , object distance p , and image distance q for both lenses and mirrors is expressed by the lens/mirror formula as:

$$\frac{1}{f} = \frac{1}{p} + \frac{1}{q} \quad \text{..... (14.8)}$$

This fundamental equation helps determine the position and nature of the image formed by a given optical system.

Action of Lenses on Parallel Rays

When a set of parallel light rays pass through a lens, they refract and show specific patterns based on the lens type. Depending on how they interact with the rays, lenses are grouped into converging and diverging lenses.

Refraction and Convergence for Convex lens

As the rays enter the lens, they bend towards the principal axis due to refraction. This bending takes place because of the lens's curved surfaces and its refractive index. After passing through the lens, all the rays meet at a common point on the principal axis this is known as the focal point.

Formation of Image

The type of image formed depends on the object's distance from the lens. Generally, a converging lens forms a real and inverted image, but if the object is very close to the lens, the image can be virtual and upright.

The ray behaviour for a converging lens is shown in Fig. 14.15.

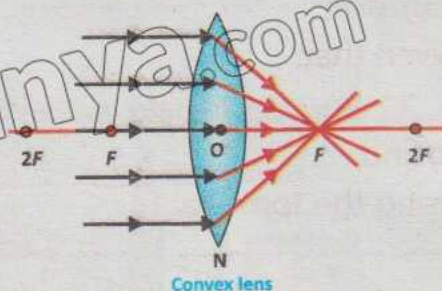


Fig. 14.15: Action of convex lens on parallel rays

Refraction and Divergence of Concave Lens

The rays are bent away from the principal axis. This bending gives the illusion that they originate from a point behind the lens, the virtual focus. This is a result of refraction through the curved surface of the lens.

Virtual Focal Point

In a diverging lens, the rays do not actually meet at a point. Instead, when extended backward, they appear to spread out from a common point on the same side of the lens. This is called a virtual focal point.

Formation of Image

When an object is placed far from a diverging lens (at infinity), the image formed is virtual, upright, and smaller than the actual object.

This behaviour of diverging lenses is illustrated in Fig. 14.16.

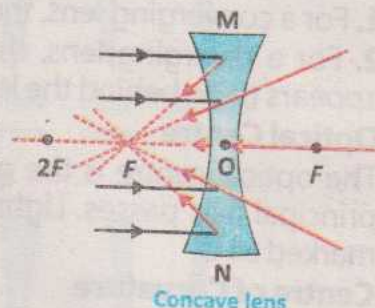


Fig. 14.16: Action of concave lens on parallel rays

Power of a Lens

The reciprocal of focal length (f) is called power of a lens.

It is given by the formula:

$$P = 1/f \quad \text{..... (14.9)}$$

The SI unit of power is diopter (D), where $1D = 1 \text{ m}^{-1}$. A convex lens has a positive focal length, so its power is positive.

A concave lens has a negative focal length, so its power is negative. Lenses with higher power bend light more strongly, and this concept is important in eyeglasses, microscopes, and optical instruments.

Example 14.4: A concave lens has a focal length of -25 cm. Find its power.

Solution:

Given that;

To find;

Using the formula:

$$f = -25 \text{ cm} = -0.25 \text{ m}$$

$$P = ?$$

$$P = 1/f$$

$$P = 1/(-0.25 \text{ m})$$

$$P = -4.0 \text{ D}$$

Do You Know?

The thicker lens bends the light more, so it has a greater **POWER** than the thin lens. This concept is important in eyeglasses, microscopes, and optical instruments.

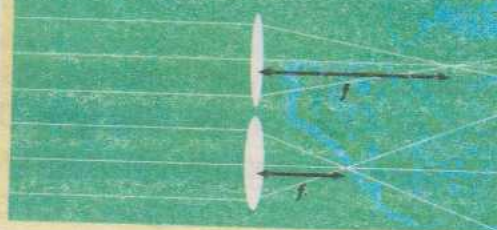


Image Formation by Thin Lenses

Unlike mirrors, which form images through reflection, lenses create images through refraction. This process can be understood using ray diagrams.

Rules for Image Formation

For a convex lens, image formation follows three rules (Fig. 14.17).

1. A ray parallel to the principal axis passes through the focal point F after refraction from the lens (ray-1).
2. A ray passing through the optical centre of the lens continues straight without bending (ray-2).
3. A ray passing through the focal point after refraction from the lens, becomes parallel to the principal axis (ray-3).

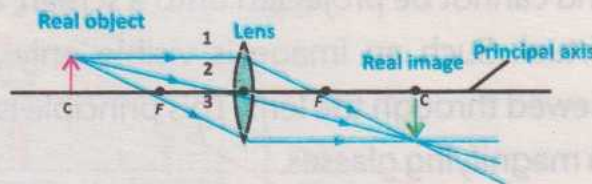


Fig. 14.17: Image formation by a convex lens

By tracing these rays, we can determine where and how an image is formed. The position, size, and nature of the image depend on where the object is placed in relation to the lens. These principles are important in devices like cameras, magnifying glasses, microscopes, and eyeglasses. The image formation by a convex lens for different positions is described in Table 14.2.

Tidbit

A convex lens can flip our image upside down, but when it is close to our eye (like in a magnifier), it stays upright and larger.

Table 14.2: Image formation by a convex lens

Position of the Object	Position of the Image	Size of the Image	Nature of the Image
At infinity	At F	Highly diminished	Real and inverted
Behind $2F$	Between F and $2F$	diminished	Real and inverted
At $2F$	At $2F$	Same as that of the object	Real and inverted
Between F and $2F$	Beyond $2F$	Enlarged	Real and inverted
At F	At infinity	Highly enlarged	Real and inverted
Between lens and F	Same side as the object	Enlarged	Virtual and erect

Formation of Real Image by a Converging Lens

A convex lens produces a real image when the object is placed beyond $2F$. As illustrated in Fig. 14.18, the image appears on the opposite side of the lens from where the object is located.

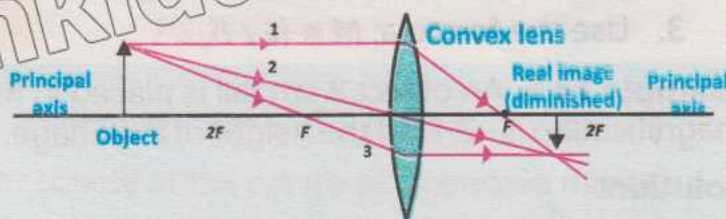


Fig. 14.18: Real image formation by a converging lens

Formation of a Virtual Image by a Converging Lens

For a convex lens to produce a magnified virtual image, the object should be placed within the focal length of the lens as illustrated in Fig. 14.19. In this arrangement, the image appears on the same side of the lens as the object. It is upright, larger in size, and cannot be projected onto a screen, as it is virtual. Such an image is visible only when viewed through the lens. This principle is used in magnifying glasses.

Brain Teaser

Why is the image in a plane mirror considered virtual, even though it looks real?

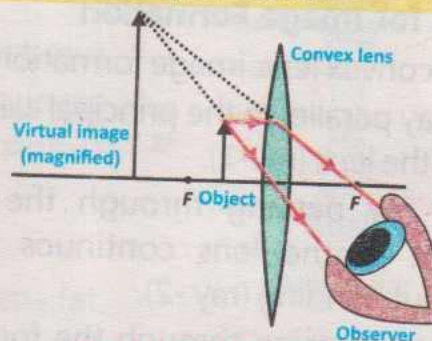


Fig. 14.19: Virtual image formation by a converging lens

Difference between real and virtual images

Real Image	Virtual Image
- Can be displayed or captured on a screen. - Always appears upside down (inverted). - Created when light rays actually meet after reflecting or refracting. - Result of actual light rays intersecting. - Can be displayed on a screen (like a wall or sensor).	- Cannot be projected or caught on a screen. - Always appears upright (erect). - Created when light rays only seem to meet, they do not actually converge. - Formed by the imaginary extension of diverging light rays.

Linear Magnification

Linear magnification is the ratio of the height (or length) of the image to the height (or length) of the object.

It indicates how much larger or smaller the image is compared to the object.

$$\text{Linear magnification} = \frac{\text{Image Height}}{\text{Object Height}}$$

or $M = h_i / h_o \dots\dots\dots (14.10)$

Steps to Calculate Linear Magnification

1. Measure the height of the object h_o .
2. Measure the height of the image h_i .
3. Use the formula; $M = h_i / h_o$.

Example 14.5: An object 8 cm tall is placed in front of a concave mirror. The linear magnification is +2. Find the height of the image.

Solution:

Given that;

$$h_o = 8 \text{ cm}; M = -2$$



Do You Know?

Facts About Magnifying Glass

Did you know that if your eyes can only focus to within about 15 cm in front of them? Anything closer will be blurry. If your eyes could focus you would not need magnifiers!



To find;

Using the formula:

$$h_i = ?$$

$$M = h_i / h_o \text{ or } h_i = M \times h_o$$

$$h_i = -2 \times 8 \text{ cm} = -16 \text{ cm}$$

The negative sign shows that the image is inverted and twice the size of the object.

14.5 Optical devices

Now we discuss applications of lenses in some optical devices such as magnifying glass, camera, slide projector and photograph enlarger.

1. The Magnifying Glass

A magnifying glass is a convex (converging) lens used to make objects appear larger. When an object is placed closer to the lens than its focal length ($p < f$), the refracted light rays do not meet but appear to come from a point behind the lens. This creates a virtual, upright, and magnified image, which cannot be projected on a screen (Fig. 14.20). This simple use of a convex lens is also known as a simple microscope.

2. Camera

A camera consists of a light-proof box with a convex lens at the front and a light-sensitive film or sensor at the back. The lens focuses light onto the film to capture an image. In a simple camera, the lens-film distance is fixed and equal to the focal length of the lens. The object is placed beyond $2F$, forming a real, inverted, and smaller (diminished) image on the film (Fig. 14.21).

3. Slide Projector

A slide projector works by projecting an enlarged image of a slide or film onto a screen (Fig. 14.22-a). It consists of: A light source at the centre of a concave mirror, which reflects light as parallel rays.

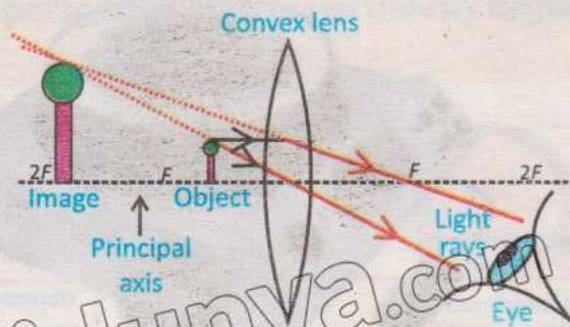


Fig. 14.20: Image formation by magnifying glass

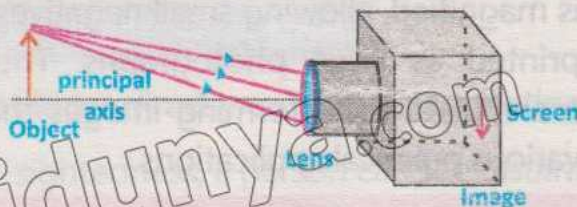


Fig. 14.21: Image formation by camera

A condenser lens system (two plane convex lenses) that evenly distributes light across the slide. A projection lens (convex lens) that creates a real, large, and inverted image on the screen. To ensure the image appears correctly, the slide must be placed upside down because the projection lens inverts the image. The slide is positioned between F and $2F$ to form a real, magnified, and inverted image on the screen (Fig.14.22-b).



Fig. 14.22: (a) Slide projector (b) Ray diagram of slide projector

4. Photograph Enlarger

A photograph enlarger works similarly to a slide projector but is used to enlarge photographic negatives onto photographic paper (Fig. 14.23). The negative (object) is placed between F and $2F$, forming a real, inverted, and enlarged image on the paper. The convex lens ensures that the final image is magnified, allowing small negatives to be printed as large photographs. These optical devices use convex lenses to manipulate light, forming images that are magnified, reduced, or projected for various practical applications.

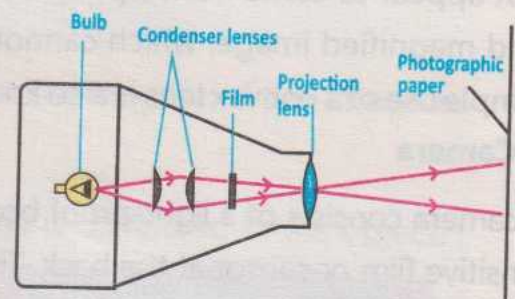


Fig. 14.23: Diagram of photograph enlarger

14.6 Image Formation in a Normal Eye

In a healthy eye, light rays from an object pass through the cornea and lens, and are focused directly onto the retina, forming a sharp and clear image. As shown in Fig. 14.24, rays from

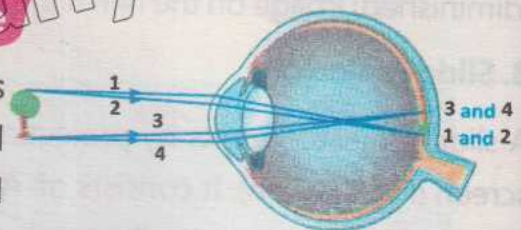


Fig. 14.24: Image formation by eye

the top and bottom of the object converge at specific points on the retina, allowing us to see a clear image. This process is similar to how a convex lens forms a real image.

Short-Sightedness (Myopia) and Its Correction

The closest distance from the eye where we can see things clearly is called near point. For a normal person, it is about 25 cm.

Short-sightedness is a condition where a person can clearly see nearby objects but struggles to see distant ones.

This occurs when the eye lens bends light rays too strongly, causing the image to form in front of the retina instead of on it (Fig. 14.25-a). As a result, distant objects look blurry. To correct this, concave lenses are used in glasses or contact lenses. A



Fig. 14.25: Short-sightedness or myopia

concave lens spreads out the light rays before they enter the eye, helping the eye's natural lens to focus them correctly on the retina (Fig. 14.25-b).

Causes of Short-Sightedness (Myopia)

There are two main causes of short-sightedness:

1. **Lens too strong:** The eye lens becomes too curved, focusing light in front of the retina.
2. **Eyeball too large:** The distance between the cornea and retina increases, so the focused image falls short of the retina.

Long-Sightedness (Hypermetropia) and Its Correction

In a normal eye, light rays from nearby objects focus directly on the retina, creating a clear image (Fig. 14.26-a). However, in long-sightedness, a person can see distant objects clearly, but nearby objects appear blurry. This happens when the eye lens is too weak or the eyeball is too small, so the light rays from near objects are not bent enough. As a result, the rays focus behind the retina instead of on it (Fig. 14.26-b).

To correct this, convex lenses are used in glasses or contact lenses. A convex lens

bends the light rays more before they enter the eye, helping them focus directly on the retina (Fig. 14.26-c).

Causes of Long-Sightedness

There are two main causes:

1. Lens too weak: The lens does not bend the light rays enough.
2. Eyeball too small: The retina is too close to the lens.

In both cases, the image is formed behind the retina, making close-up vision blurry.

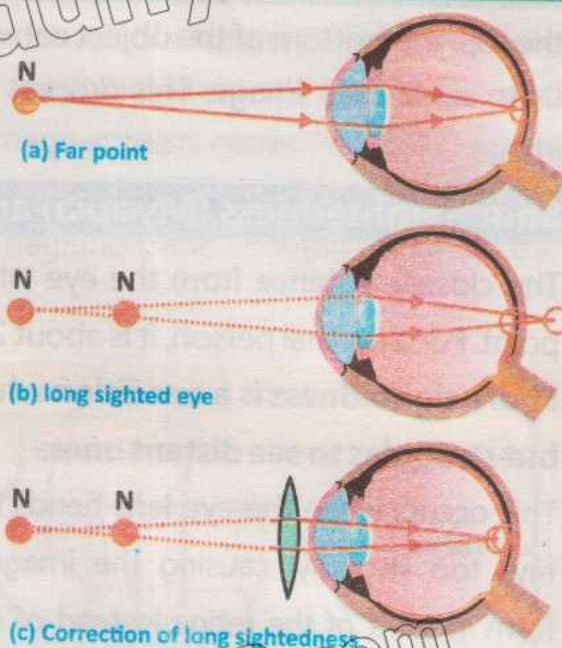


Fig. 14.26: Long-sightedness

14.7 Gravitational Lens and Acoustic Lens

Gravitational Lensing

Gravitational lensing occurs when the strong gravitational field of a massive object, like a black hole or galaxy, bends the path of light travelling near it. Just like an optical lens bends and focuses light, a massive celestial body acts as a "gravitational lens", altering the path of light from a distant object such as a star or galaxy. This effect can cause the distant object to appear magnified, distorted, or even duplicated, creating multiple images (Fig. 14.27). Gravitational lensing is a valuable tool in astronomy. It helps scientists study distant galaxies, dark matter, and the structure of the universe, providing insights into objects that are otherwise too far to observe directly.



Fig.14.27: Diagram of gravitational lens

Acoustic Lenses

Acoustic lenses are special devices designed to focus or spread sound waves, similar to how optical lenses control light. These lenses are made from materials

with different acoustic properties and are shaped to redirect and focus sound waves. They can concentrate sound into a narrow beam or spread it over a wider area, improving sound clarity and control (Fig. 14.28). These lenses can focus sound to a specific point (like a microphone or sensor), or diverge sound to spread it over a wider area.

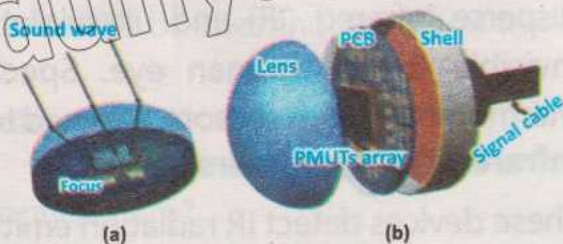


Fig. 14.28: Diagram of acoustic lens

Acoustic lenses are widely used in:

1. Medical imaging (e.g., ultrasound) to improve scanning accuracy.
2. SONAR systems to detect underwater objects.
3. Noise control to focus or reduce sound in specific areas.

Both gravitational and acoustic lenses demonstrate how the principles of wave manipulation apply to both light and sound, playing an important role in astronomy, medicine, and technology.

14.8 Dispersion of Light by Prism

A prism is an optical object typically made of glass with triangular and rectangular sides. It bends light passing through it due to refraction. Since visible light consists of a range of wavelengths, and refraction depends on wavelength, different wavelengths bend at different angles, causing dispersion.

The splitting of white light into its seven constituent colours when passing through a prism is called dispersion of light.

When white light enters a prism, it slows down and bends toward the normal. Each colour has a unique wavelength, and as light travels through the prism, each wavelength refracts at a different angle. Shorter wavelengths (violet, blue) bend more than longer wavelengths (red, orange). As a result, the light exiting the prism separates into seven distinct colours: red, orange, yellow, green, blue, indigo, and violet forming the visible light spectrum (Fig. 14.29).

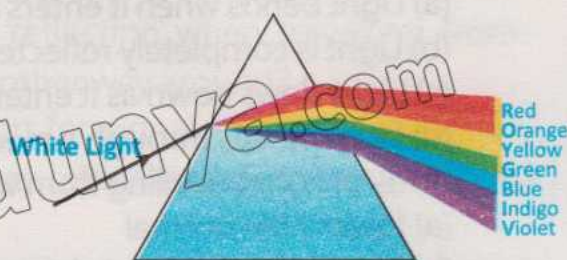


Fig. 14.29: Dispersion of light by prism

Beyond the visible spectrum, prisms can also

disperse infrared (IR) and ultraviolet (UV) light, though these wavelengths are invisible to the human eye. Special detection methods, such as infrared thermometers with sensors, are used to measure these wavelengths.

Infrared Thermometers

These devices detect IR radiation emitted by objects, which correlates with their temperature. When dispersed light from a prism reaches an IR thermometer, it can measure both visible and infrared light. By analyzing the intensity of IR radiation, the thermometer determines the temperature of the emitting object. This technology allows for non-contact temperature measurement, such as checking human body temperature (Fig. 14.30).



Fig. 14. 30: Infrared thermometer

EXERCISE

A. Multiple Choice Questions

Tick (✓) the correct answer.

- 14.1 What type of image is always formed by a convex mirror?
(a) Real and inverted (b) Virtual and diminished
(c) Real and magnified (d) Virtual and magnified
- 14.2 The optical device which uses a convex lens to magnify an object by creating a virtual image:
(a) camera (b) microscope
(c) magnifying glass (d) slide projector
- 14.3 Which statement best describes the phenomenon of total internal reflection?
(a) Light bends when it enters a new medium
(b) Light is completely reflected at the boundary of two media
(c) Light slows down as it enters a denser medium
(d) Light passes through a medium without changing direction
- 14.4 A ray of light travelling from water to air bends:
(a) toward the normal
(b) away from the normal
(c) at 90° to the normal
(d) parallel to the normal

- 14.5 The optical device which works on the principle of inverting an image for projection is:
(a) magnifying glass (b) photograph Enlarger
(c) slide projector (d) plane mirror
- 14.6 What happens to light when it enters an optical fibre?
(a) It is absorbed by the fibre
(b) It undergoes total internal reflection
(c) It gets refracted at every point
(d) It travels in a straight line without deviation
- 14.7 Which of the following phenomenon explains why a pencil appears bent when partially immersed in water?
(a) Reflection (b) Diffraction (c) Refraction (d) Interference

B. Short Answer Questions

- 14.1 What happens when light passes from air to water?
14.2 Define refractive index. What is the refractive index of air and water?
14.3 What is the principle behind optical fibres?
14.4 Describe briefly how a convex lens forms a real or virtual image.
14.5 How does the power of a lens relate to its focal length?
14.6 Write Snell's law and define the terms used in the equation.

C. Constructed Response Questions

- 14.1 When a pencil is partially dipped in water, it appears bent or broken. What principle of light explains this phenomenon, and how does it relate to changes in speed?
- 14.2 Why can a prism separate white light into its component colours while a plane glass slab cannot, even though both cause refraction?
- 14.3 Why does light undergo total internal reflection when travelling from water to air at a certain angle but not the other way around?
- 14.4 Optical fibres use total internal reflection for signal transmission. What would happen if the cladding had a higher refractive index than the core, and why?
- 14.5 A person uses a magnifying glass to read small print. What must be the relationship between the object distance and the focal length of the lens for the image to be upright and magnified?

D. Comprehensive Questions

- 14.1 Explain the terms, normal, angle of incidence and angle of reflection in the context of light reflection. Provide a diagram to illustrate these terms.
- 14.2 Define the terms critical angle and total internal reflection. Explain the conditions required for total internal reflection to occur.
- 14.3 Derive the equation; $(n = 1 / \sin C)$ for the refractive index in terms of the critical angle C . Include all steps and assumptions.
- 14.4 Describe the structure of an optical fibre. Write its any two advantages.
- 14.5 What is long-sightedness? Discuss its causes.

E. Numerical Problems

- 14.1 The speed of light in water is $2.25 \times 10^8 \text{ m s}^{-1}$. Calculate the refractive index of water. **[Ans: 1.33]**
- 14.2 A light ray in air ($n_1=1.0$) strikes a glass surface ($n_2=1.5$) at an angle of incidence 30° . Find the angle of refraction inside the glass. **[Ans: 19.5°]**
- 14.3 A beam of light in air hits a glass slab at an incidence angle of 40° . Find the angle of refraction inside the glass. **[Ans: 25°]**
- 14.4 A ray of light travels from air into an unknown liquid. The angle of incidence in air is 45° and the angle of refraction in the liquid is 30° . Calculate the refractive index of the liquid. **[Ans: 1.41]**
- 14.5 A ray of light passes from air into a liquid. The angle of incidence in air is 50° , and the angle of refraction inside the liquid is 32° . The speed of sound in air is 340 m s^{-1} and in the same liquid is 1500 m s^{-1} . Calculate: (a) the refractive index of the liquid (b) the speed of light in the liquid. **[Ans: (a) 1.45, (b) $2.08 \times 10^8 \text{ m s}^{-1}$]**
- 14.6 Light travels inside a glass block of refractive index $n = 1.6$. It strikes the glass-air boundary. Calculate the critical angle for total internal reflection. **[Ans: 38.68°]**
- 14.7 An object is placed 15.0 cm in front of a convex mirror, forming a virtual image 7.5 cm behind the mirror. What is the focal length of the mirror? **[Ans: -15 cm]**
- 14.8 An object 30 cm tall is located 10.5 cm from a concave mirror with focal length 16 cm . (a) Where is the image located? (b) How high is it? **[Ans: (a) -30.6 cm (b) 87.3 cm]**
- 14.9 An object is placed at 30 cm to the left of a concave lens with focal length -15 cm . Find the image distance and describe the image. **[Ans: -30 cm , image is virtual and upright formed on the same side of the object]**