Part I

Optics
Chapter 1

Introduction

Light is a form of radiant energy emitted from a luminous body and is the external physical cause which produces the sensation of sight. It is a form of electromagnetic waves travelling in free space with the speed of $3 \times 10^8$ m/s and with wavelengths ranging approximately from 400 to 800 nm ($1 \text{ nm} = 10^{-9}$ m). While interacting with matter, light sometimes behaves as a stream of particles or quanta of energy, called photons. The branch of physics dealing with light and its interaction with matter is known as optics. There are two branches of optics: geometrical optics and physical optics. In geometrical optics, the phenomena of reflection and refraction of light are treated on the basis of rectilinear propagation of light. Physical optics is concerned with the theories and nature of light, and seeks to explain the optical phenomena on the basis of these theories. We shall focus our attention first on geometrical optics, and then on physical optics.

1.1 SOME DEFINITIONS

(i) Source of Light: The bodies which emit light are called sources of light or luminous bodies. The bodies which have their own power of radiating light are known as self-luminous (or simply luminous) bodies. Examples of such bodies are the sun, a candle flame, a glowing electric lamp etc. The bodies which have no light of their own but are visible only by the light falling on them from other sources are said to be non-luminous bodies. The moon is a good example of a non-luminous body. The light sources which can be approximated as geometrical points are called point sources. Bigger sources are termed extended sources; such sources consist of innumerable point sources.

(ii) Optical Medium: A material through which the passage of light is considered, is called an optical medium. A medium may be transparent, translucent or opaque. A transparent medium is one through which light can pass easily. Examples are air, glass etc. A medium which allows light to pass through it partly is a translucent medium. Oil paper, ground glass etc. belong to this class. An opaque medium is that through which light cannot pass; e.g., wood, iron, stone, etc. Some opaque materials like gold, silver etc. become translucent when they are very thin. A medium is called homogeneous when its physical and chemical properties are the same at all points in it. When the properties vary from point to point, the medium is termed heterogeneous or inhomogeneous.

(iii) Ray of Light: The path along which light propagates is called a ray. Usually a ray is denoted by a straight line with an arrowhead in the direction of propagation. A collection of rays, usually starting from an
object, is referred to as the beam of light. A narrow beam is called a pencil of light. If the rays in a beam are parallel, we call it a parallel beam [Fig. 1.1 (a)]. If the rays in a beam proceed towards a point, it is called a convergent beam [Fig. 1.1 (b)]. In a divergent beam, the distance between any two rays gradually increases as the light proceeds [Fig. 1.1 (c)].

Fig. 1.1.

1.2 RECTILINEAR PROPAGATION OF LIGHT

In a homogeneous medium, light travels in straight lines. The most familiar illustrations of the rectilinear propagation of light are provided by (a) formation of inverted images in a pinhole camera and (b) formation of shadows.

(a) Pinhole Camera: A pinhole camera is a rectangular wooden box (C) having a very small hole (X) on the front face and a ground glass screen at the back. The interior of the box is painted black to prevent reflection of light. If a bright object (AB) is placed in front of the hole, an inverted image (A′B′) will appear on the ground glass (Fig. 1.2). This can be explained in the following manner. A ray of light from the point A travels along the straight line AX and falls on the glass plate at A′. Similarly, a ray from B passes through X and meets the plate at B′: A′ and B′ are respectively the images of A and B. Similarly, the rays from other points of AB produce the images of those points between A′ and B′. Thus an inverted representation (A′B′) of AB is obtained on the glass plate. In Fig. 1.2, MX and NX are the distances of the object AB and the image A′B′ respectively from the hole X. From the similar triangles ABX and A′B′X, we have \( \frac{AB}{A'B'} = \frac{AX}{A'X} \). Again from the similar trianglesAXM and A′XN we obtain \( \frac{AX}{A'X} = \frac{MX}{NX} \). It follows that \( \frac{A'B'}{AB} = \frac{NX}{MX} \), i.e.

\[
\frac{{\text{Image size}}}{\text{Object size}} = \frac{{\text{Distance of screen from aperture}}}{\text{Distance of object from aperture}} \quad (i)
\]

The ratio between the image size and the object size is called magnification. Equation (i) shows that image will be larger when the screen is removed further from the aperture. If the distance of the object from the hole is increased, the image becomes smaller.

When the aperture is small, the image has a sharp outline but its brightness is reduced. For very small apertures, however, diffraction occurs and the concepts of geometrical optics are no longer valid. For a large aperture, the image gets brighter but blurred. A big aperture is formed of many small apertures, each one of which produces an inverted image on the screen. These images partially overlap, making the outline indistinct. The shape of the image follows that of the object; it is not determined by the geometric shape of the aperture.
(b) Shadows: When an opaque obstacle is placed in the path of light from a point source, a dark region appears behind the obstacle. This dark region is called the shadow of the obstacle (Fig. 1.3). If a screen is placed behind the obstacle, the shadow falls on it. The shape of the shadow follows that the obstacle and its linear magnification is given by

\[
\text{Shadow size} = \frac{\text{Distance of screen from source}}{\text{Distance of obstacle from source}} \times \text{Obstacle size}
\]

In Fig. 1.3, \( S \) is the point source of light, \( AB \) is a spherical opaque body and \( P \) is the screen. No light from the source falls in the region \( XY \) of the screen, so that it is completely dark. \( XY \) is the shadow of \( AB \). The shadow is circular, the obstacle being spherical. As the distance between the obstacle and the screen is increased, the shadow becomes bigger.

For an extended source of light, the shadow of an obstacle can be divided into two regions. The central completely dark region is called the umbra, while the partially dark region around the umbra is termed the penumbra. No ray from the source can enter the umbra, but rays from some parts of the source can reach the penumbra. The extents of the umbra and penumbra depend on the relative shapes of the source and the obstacle, and the distance between them.
its darkness reduces continuously. At a very remote position of the screen the shadow becomes too diffused to be distinguished from the wholly lighted regions. That is why birds or aeroplanes flying high up in the air do not seem to cast their shadows on the earth’s surface in the sun.

When the source of light and the opaque body are equal in size, the umbra at all distances will have the same cross-sectional area surrounded by a diverging penumbra.

**Eclipses.** Solar and lunar eclipses can be explained from the principle of the formation of shadows.

The **solar eclipse** takes place at a new moon, when the moon comes between the sun and the earth. Since the source of light, i.e., the sun is much larger than the obstacle, i.e., the moon, the situation of Fig. 1.5(a) holds. In the position $P_1$ of the earth surface, no portion of the sun is visible from the region $DE$. So, in the region $DE$, the eclipse is **total**. When seen from the regions $CD$ or $EF$, the eclipse is **partial** since only a part of the sun’s disc is visible. As the moon is much smaller than the earth and the orbits of both are elliptic, the distance of the earth from the sun and the moon vary. Hence the earth may sometimes lie beyond the apex of the umbral cone. The position $P_1$ of the earth’s surface fits this situation. When seen from the region $MN$ of the earth’s surface, a narrow ring from the edge of the sun’s disc will be visible round the central dark moon [Fig. 1.5(b)]. The eclipse is then called **annular**.

The **lunar eclipse** occurs at a full moon, when the earth lies between the sun and the moon. When the moon is completely within the umbra of the earth’s shadow, i.e. in the region $DE$ of Fig. 1.5(a), **total eclipse** takes place. When the moon is partly in the umbra $DE$ and partly in the penumbra $CD$ or $EF$ [Fig. 1.5(a)], the eclipse is **partial**. When the moon lies **completely** in the penumbra outside the umbra, no eclipse is observed, but the brightness of the moon diminishes. As the moon has to pass through the penumbra before entering into the umbra and leaving it, the moon appears to be dull before and after the eclipse. Outside the penumbra, the moon regains its brightness. Annular eclipse does not occur for the moon since size of the earth is such that the apex of its umbral cone is always well beyond the orbit of the moon.

The orbital planes of the earth and the moon make with each other an angle of about $5^\circ$. So, the sun, the earth and the moon are not in the same plane at all new moons or full moons. Thus the solar eclipse does not take place at every new moon, neither does the lunar eclipse at every full moon.

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**EXAMPLES**

1. A man of height 1.6 m stands at a distance of 2.4 m from a roadside lamp. If the length of the shadow of the man cast on the road is 1.2 m, determine the height of the lamp post.

   **Ans.** In Fig. 1.6, $NO$ is the shadow of the man $MN$ and $LA$ is the lamp post. From the similar triangles $LAO$ and $MNO$, we have

   \[
   \frac{LA}{MN} = \frac{AO}{NO}
   \]

   or,

   \[
   \frac{LA}{1.6} = \frac{(2.4 + 1.2)}{1.2}
   \]

   or,

   \[
   LA = 1.6 \times 3 = 4.8 \text{ m}.
   \]
2. A man stands on the top of a vertical tower of height 20 m. Neglecting the height of the man, determine how far of the earth’s surface the man can see. What property of light would you use in your calculation? (WBJEE 1982)

**Ans.** Let \( R \) (in meter) be the radius of the earth \( E \) and \( AX \) the given tower (Fig. 1.7). The man can see up to the point \( C \) of the earth’s surface where \( C \) is the point of contact of the tangent \( AC \) drawn from \( A \) to the earth. Given, \( AX = h = 20 \) m. From the right-angled triangle \( ABC \), we get

\[
AB^2 = AC^2 + BC^2 \quad \text{or,} \quad (h + R)^2 = AC^2 + R^2
\]

or,

\[
AC^2 = h^2 + R^2 + 2hR - R^2 = h^2 + 2hR
\]

or,

\[
AC = (h^2 + 2hR)^{1/2} \approx (2hR)^{1/2} \quad \text{[since} \ h \ll R]\]

or,

\[
AC = \sqrt{4hR} \text{ m}
\]

In our calculations we have used the property that light travels in straight lines.

3. An image, 6 cm high, is produced in a pinhole camera for a tower at a certain distance from the camera. If the camera is moved farther by 10 metre along the same straight line from the tower, the height of the image becomes 4 cm. What is the height of the tower? (length of the camera box = 20 cm)

**(WBHS 1985)**

**Ans.** Refer to Fig. 1.2. We have

\[
\frac{\text{Image size}}{\text{Object size}} = \frac{\text{distance of screen from aperture}}{\text{distance of object from aperture}}
\]

If the height of the tower is \( h \) metre and its distance from the aperture is \( x \) metre, we have in the first case

\[
\frac{6 \text{ cm}}{100h \text{ cm}} = \frac{20 \text{ cm}}{100x \text{ cm}} \quad \text{or,} \quad \frac{x}{h} = \frac{10}{3}
\]
In the second case, \( x \) is replaced by \((x + 10)\) metre and the image size becomes 4 cm. Therefore,

\[
\frac{4 \text{ cm}}{100h \text{ cm}} = \frac{20 \text{ cm}}{100(x + 10) \text{ cm}}
\]

or,

\[
\frac{x + 10}{h} = 5 \quad \text{or}, \quad \frac{x}{h} + \frac{10}{h} = 5
\]

or,

\[
\frac{10}{h} = 5 - \frac{x}{h} = 5 - \frac{10}{3} = \frac{5}{3} \quad \text{or} \quad h = 6 \text{ m}
\]

4. On a new moon, a man on earth sees the annular eclipse of the sun. How far above the earth’s surface must he rise to be able to just see the total eclipse of the sun? (Diameters of the sun and the moon are respectively \(8.6 \times 10^5\) mile and \(2 \times 10^3\) mile. Distances of the sun and the moon from the position of the man on earth are respectively \(93 \times 10^6\) mile and \(2.4 \times 10^5\) mile). (WBJEE 1975)

**Ans.** Refer to Fig. 1.8. Here \(SS_1\) is the sun, \(MN\) the moon, and \(E\) the earth. From the point \(X\) the man sees the annular eclipse. From \(X’\), total eclipse is seen, so that \(XX’\) is the required height (= \(h\) mile, say). From the similar triangles \(SOX’\) and \(MO_1X’\), we get

\[
\frac{SO}{MO_1} = \frac{OX’}{O_1X’}
\]

or,

\[
\frac{8.6 \times 10^5}{2 \times 10^3} = \frac{(93 \times 10^6 - h)}{(2.4 \times 10^5 - h)}
\]

whence

\[
h = 2.38 \times 10^4 \text{ mile.}
\]

**QUESTIONS**

1. Prove by means of a suitable experiment that light propagates in straight lines in a homogeneous medium.

2. With a diagram explain the working principle of a pinhole camera. What conclusions do you derive by experimenting with this camera? How does the image change when (i) the size of the pinhole is increased and (ii) the distance of the screen from the hole is increased?

3. Distinguish between umbra and penumbra. ‘When an aeroplane flies close to the ground, its shadow is cast on the ground. But when the aeroplane is high above no shadow is visible’.—Explain.
4. Explain how solar and lunar eclipses occur. Why don’t eclipses occur at every full moon or every new moon? ‘Annular eclipse occurs for the sun but not for the moon’.—Why?

PROBLEMS

1. A pinhole camera is used to produce an image of an object of height 1 metre placed at a distance of 3 metre from the pinhole. If the distance of the screen from the aperture is 24 cm, find the height of the image. What is the diameter of the image of a point of the object if the diameter of the pinhole is 0.025 cm?
   (Ans. 8 cm, 0.027 cm)

2. An incandescent filament of length 2 inch is placed vertically at a horizontal distance of 1 ft from an erect opaque object of height 6 inch. The shadow is produced on a vertical screen placed at a distance of 1 ft from the opaque body. Find the height of the shadow and that of the umbra.
   (Ans. 1 ft 2 in, 10 in)

3. The sun makes the same angle at a point as that made by a circular coin placed at a distance of 3 metre from that point. What is the size of the image of the coin produced by sunlight on a screen placed parallel to the coin at a distance of 1.5 metre from the coin?
   (Ans. Half the size of the coin)

4. A candle flame 3 cm long is positioned 6 cm from the centre of an opaque sphere of diameter 3 cm. A screen is located at a distance of 6 cm from the centre of the sphere to receive the shadow. Determine the height of the shadow and the height of the umbra. If the position of the screen is changed what will be its effect on the height of the umbra?
   (Ans. 9 cm, 3 cm, No change)

5. A luminous disc is of diameter 20 cm and has its centre at O. In front of it with centre at O’ is an opaque disc of diameter 2 cm. A man has his eye at O” on OO’ produced. OO’ is perpendicular to the plane of both the discs and OO” = 200 cm and O’O” = 50 cm. Find the area of the luminous disc visible to the eye. If the eye approaches O”, at a certain position the disc is just completely invisible. Find this position of the eye. Explain how this example serves as a model for a natural phenomenon.
   (Ans. 235.5 cm², 22.2 cm, annular eclipse of the sun)