2 Refraction of Light

In vacuum, lights of different colours and wavelengths travel with the same speed but they travel with different speeds in different media. Light travels faster in air than in water or glass. The speed of light is 3×10^8 m s^{-1} in vacuum, $2{\cdot}25 \times 10^8$ m s^{-1} in water and 2×10^8 m s^{-1} in glass. A medium is said to be optically denser if it slows down the speed of light and it is said to be rarer if it increases the speed of light.

CONCEPT OF REFRACTION

When light travels from one transparent medium to another transparent medium, it bends from its original path. This phenomenon of bending of light is called refraction. Refraction (or bending of light) takes place at the surface of separation of the two media.

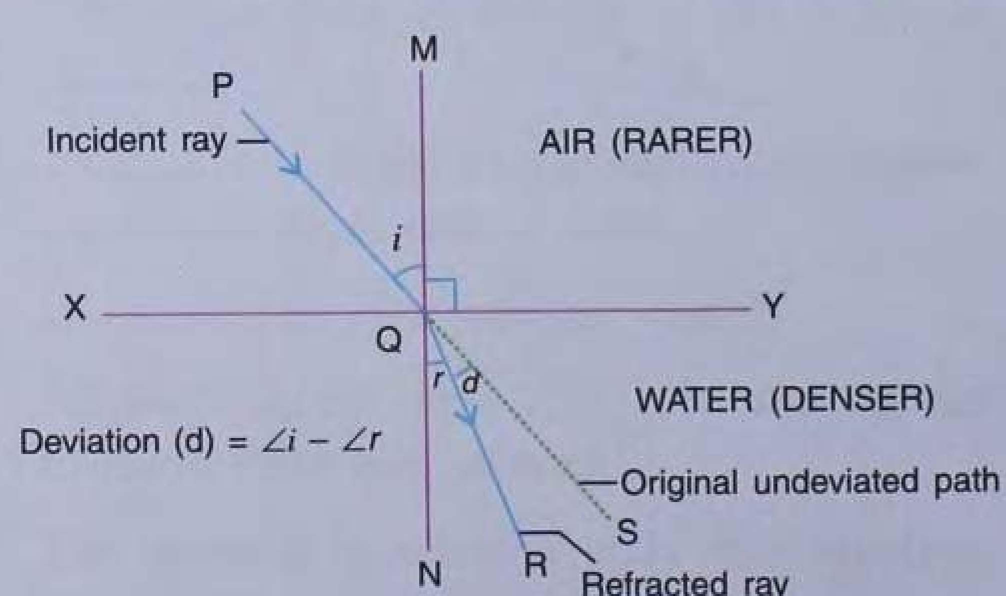


Fig. 2.1 (a)

Figure 2.1 (a) shows XY as the surface of separation between air and water media (water is denser than air). Let PQ be the incident ray which, at point Q, enters from air medium into water medium.

It is observed that as ray PQ enters from air to water, it does not follow the straight line path PQS but it bends along the path QR.

At point Q, a normal MN (*i.e.* perpendicular to surface XY) is drawn.

Thus, **angle PQM**, which is the angle between the incident ray PQ and normal MN, is called the **angle of incidence (i)** and **angle RQN**, which is the angle between the refracted ray QR and normal MN, is called the **angle of refraction (r)**. Angle SQR is the angle of deviation (d) of light from its own path.

In Fig. 2.1(a) when the ray of light is travelling from a rarer medium (air) to a denser medium (water), we find that the angle of refraction ∠RQN is smaller than the angle of incidence ∠PQM; hence, we conclude :

Whenever light travels from a rarer medium to a denser medium, it bends towards the normal.

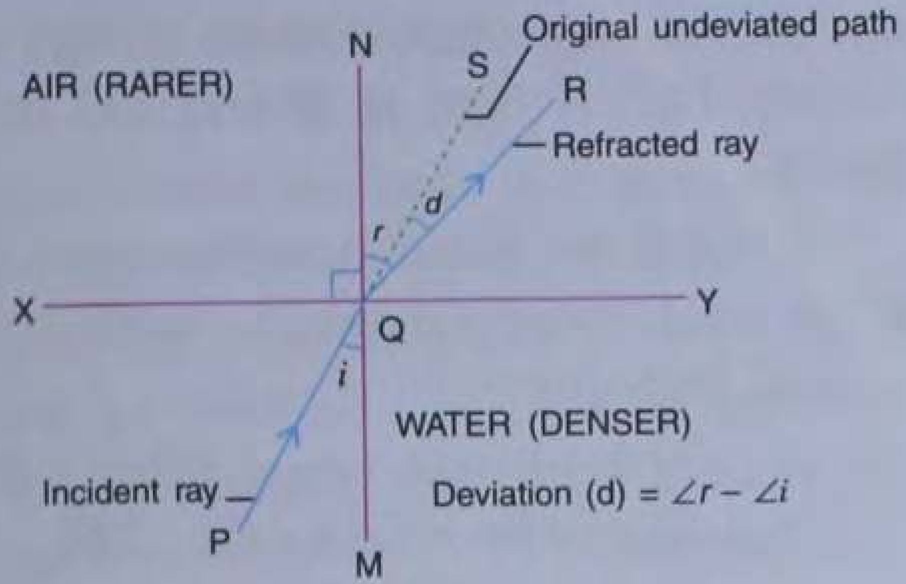


Fig. 2.1 (b)

Figure 2.1(b) given above shows an incident ray of light PQ which, at point Q, enters from a denser medium (water) to a rarer medium (air). It is observed that the refracted ray does not cover a straight path PQS but bends away from the normal MN as ray QR. The angle SQR is the angle of deviation (*d*) of light from its own path.

This clearly shows that the angle of refraction ∠RQN is greater than the angle of incidence ∠PQM. So, we conclude :

Whenever light travels from a denser medium to a rarer medium, it bends away from the normal.

Terms related to refraction of light :

1. **Incident ray :** The ray which falls on the surface of separation to enter into the other medium is known as the incident ray.

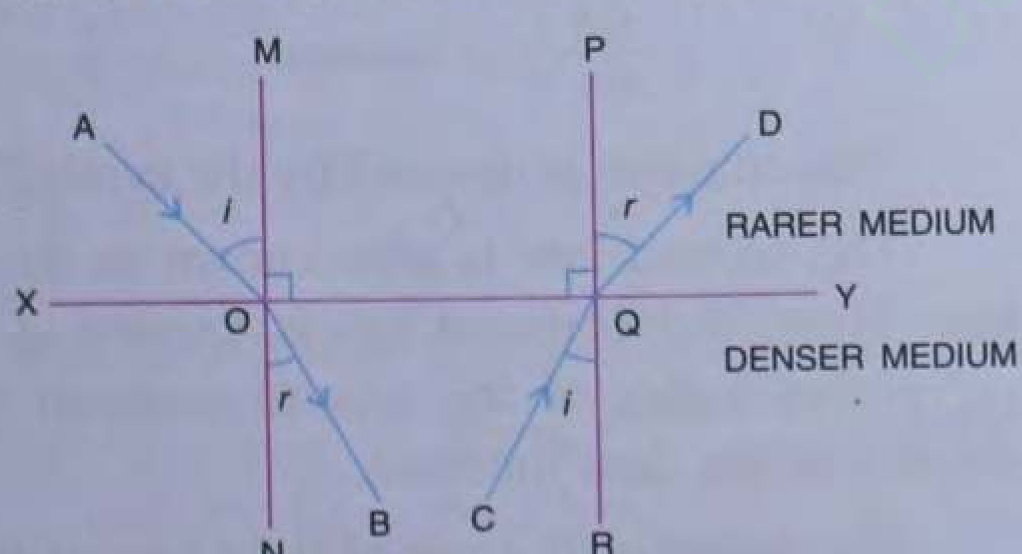


Fig. 2.2

In Fig. 2.2, given above, AO and CQ are the incident rays.

2. **Refracted ray :** The ray in the second medium obtained after refraction is known as the refracted ray. In Fig. 2.2, OB and QD are the refracted rays.
3. **Normal :** In Fig. 2.2, MN and PR are the normals. A normal is an imaginary straight line perpendicular to the refracting surface.
4. **Angle of incidence :** The angle between the incident ray and the normal at the point of incidence is known as the angle of incidence. It is generally represented by ∠*i*. In Fig. 2.2, ∠AOM and ∠CQR are the angles of incidence.
5. **Angle of refraction :** The angle between the refracted ray and the normal at the point of incidence is known as the angle of refraction. It is generally represented by ∠*r*. In Fig. 2.2, angles ∠BON and ∠PQD are the angles of refraction.

SOME SALIENT POINTS

1. When a ray of light passes obliquely from a rarer medium to a denser medium, it always bends towards the normal and the angle of refraction is smaller than the angle of incidence *i.e.* ∠*r* < ∠*i* (Fig. 2.3a).

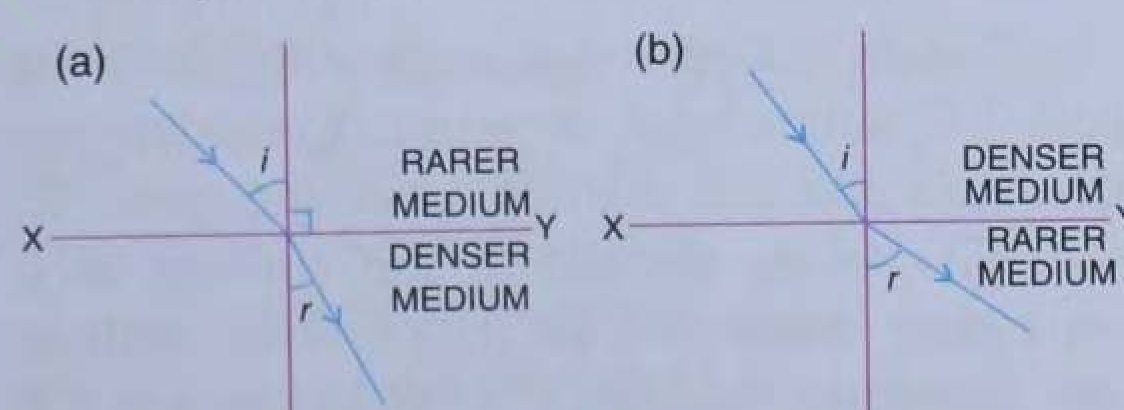


Fig. 2.3

2. When a ray of light passes obliquely from a denser medium to a rarer medium, it always bends away from the normal and the angle of refraction is greater than the angle of incidence *i.e.* ∠*r* > ∠*i* (Fig. 2.3b).

3. When a ray of light passes from one medium to another medium at right angle to the surface separating the two media, it does not bend *i.e.*, it goes in its original direction only (Fig. 2.4).

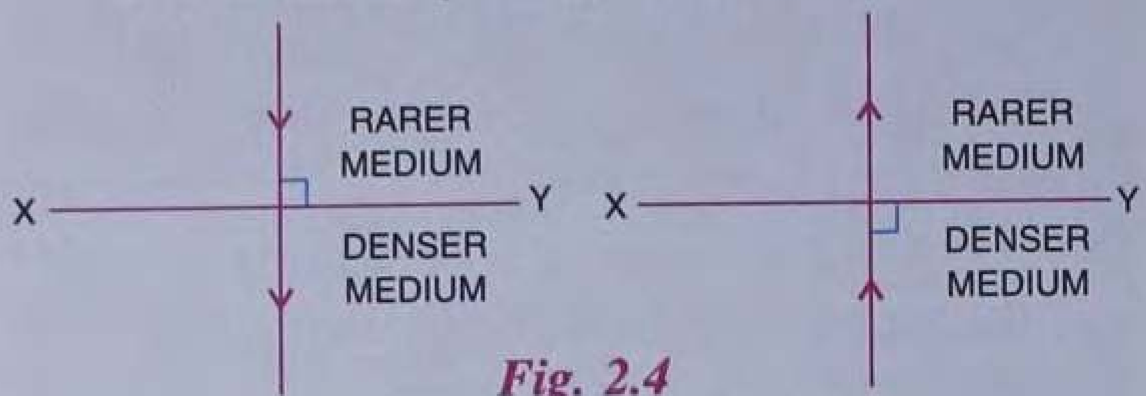


Fig. 2.4

In this case, the angle of incidence is zero and the angle of refraction is also zero *i.e.* $\angle i = 0$ and $\angle r = 0$.

EFFECTS OF REFRACTION :

1. *When a stick is dipped partially in water, it appears to be bent and short.*

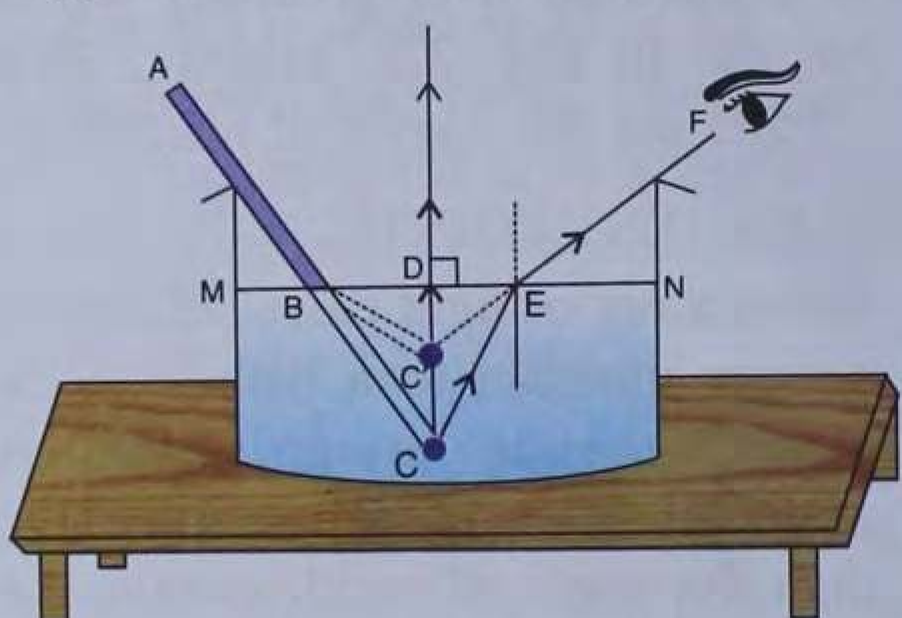


Fig. 2.5 A stick appears to be bent inside water

Figure 2.5 shows a stick ABC with its part BC submerged in water. Consider two rays CD and CE starting from the point C. Ray CD being normal to the surface MN, separating water and air, is refracted without any deviation (bending), whereas the ray CE falling obliquely on the surface MN bends away from the normal as refracted ray EF. When ray EF is produced backwards, it meets ray CD at point C′. Hence, C′ is the image (virtual image) of C which appears to be raised. Similarly, each point in part BC of the stick appears to be raised and finally, the part BC of the stick has its image as BC′. Clearly, BC′ is bent at B and BC′ is shorter than BC.

It must be noted here that only the part of the stick which is inside water appears to be bent and short.

2. *A coin kept in a vessel filled with water appears to be raised (Fig. 2.6).*

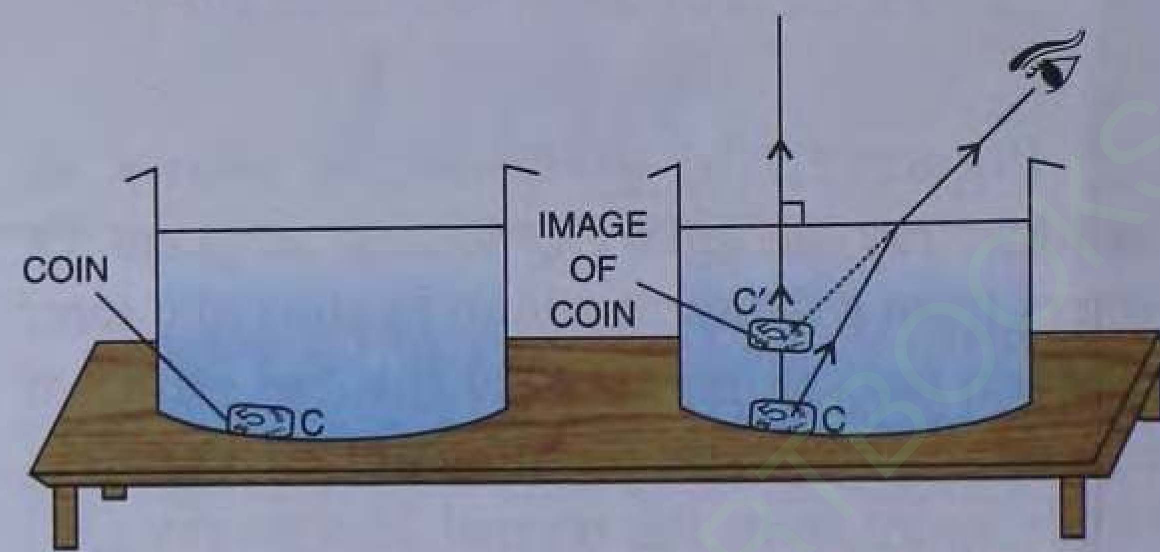


Fig. 2.6 A coin appears to be raised when kept at the bottom of a beaker, filled with water

LAWS OF REFRACTION

Refraction of light obeys the following two laws :

1. The incident ray, the normal at the point of incidence and the refracted ray, all lie in the same plane.
2. For a given pair of media and given colour of light, the ratio of the sine of angle of incidence to the sine of angle of refraction is a constant *i.e.*,

$$\frac{\sin i}{\sin r} = \text{constant}$$

This constant is denoted by the symbol 'μ'.

The second law is also known as **Snell's law**. Here, the constant (μ) is known as the **refractive index** of the second medium with respect to the first medium.

For example, if a ray of light travels from air to water, then the constant $\left(= \frac{\sin i}{\sin r}\right)$ is the refractive index of water with respect to air.

REFRACTION THROUGH A PARALLEL SIDED GLASS SLAB

You may trace the path of a refracted ray in a glass slab as shown in Fig. 2.7.

On a white sheet of paper, place a glass slab. Mark its boundary as ABCD and then remove it. Now mark a point Q on the side AB. Draw a normal M_1N_1 passing through point Q and perpendicular to AB. Draw another line PQ such that $\angle PQM_1 = \angle i = 60°$. Fix two ordinary pins at P_1 and P_2 vertically on line PQ and place the glass slab back into its position ABCD. Look through the slab from the side CD. You will see the images of the pins P_1 and P_2. Now fix two more pins at P_3 and P_4 so that these pins and images of P_1 and P_2 are exactly in the same straight line. Remove the slab and all the pins. Encircle the dot marks left over by the pins. Join P_4 with P_3 and extend till it meets the side CD at point S. Join QS. $\angle SQN_1$ is the angle of refraction $\angle r$ corresponding to the angle of incidence $\angle PQM_1$. Draw another normal M_2N_2 passing through S and perpendicular to CD. Measure angle $\angle P_3SM_2$ (marked as $\angle e$ in the figure).

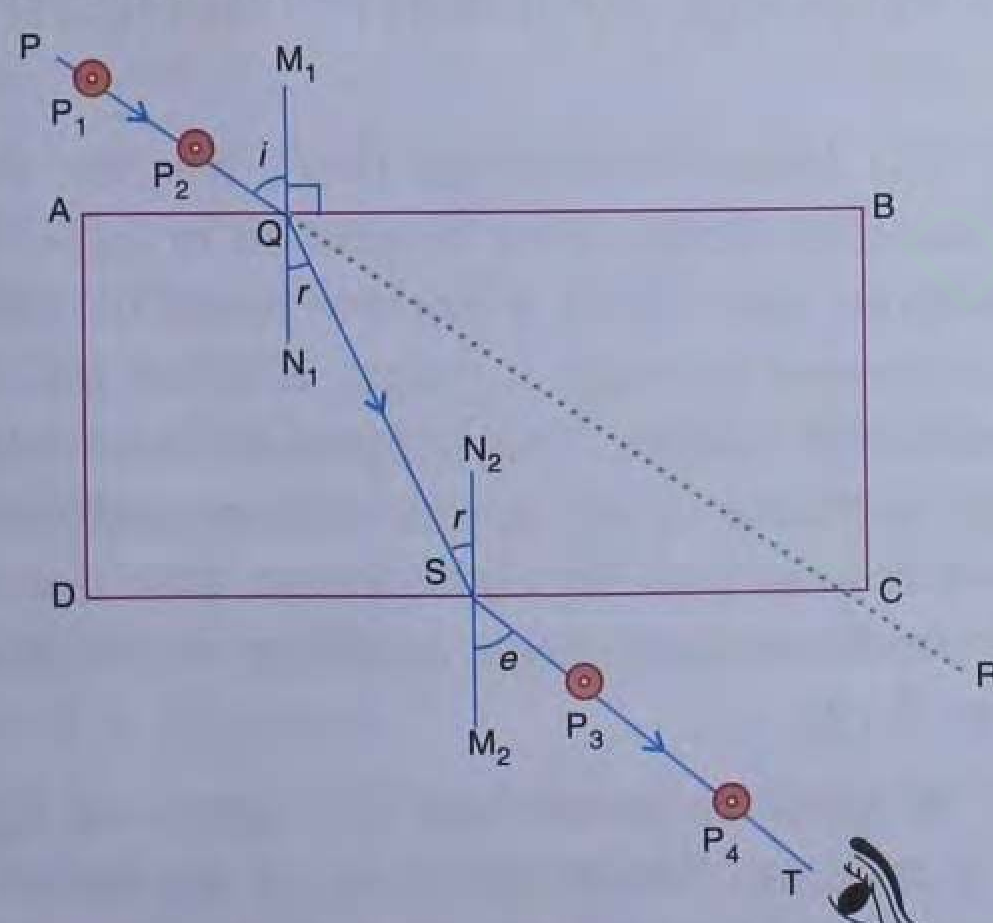


Fig. 2.7 Refraction through a glass-slab

You will find $\angle i = \angle e$. Here, $\angle e$ is known as the angle of emergence. Also, you will find that the incident ray PQ produced is parallel to the emergent ray ST (Fig. 2.7).

Thus, when a ray of light passes through a rectangular glass slab :

(i) the angle of emergence is equal to the angle of incidence *i.e.* $\angle e = \angle i$.

(ii) the emergent ray is parallel to the incident ray produced *i.e.*, ST is parallel to QR.

REFRACTION THROUGH A PRISM

A prism is a glass block with each cross-section as a triangle and each face as a rectangle as shown in Fig. 2.8.

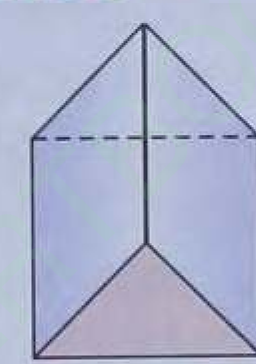


Fig. 2.8

The refraction of a light ray PQ through a glass prism is shown in Fig. 2.9 :

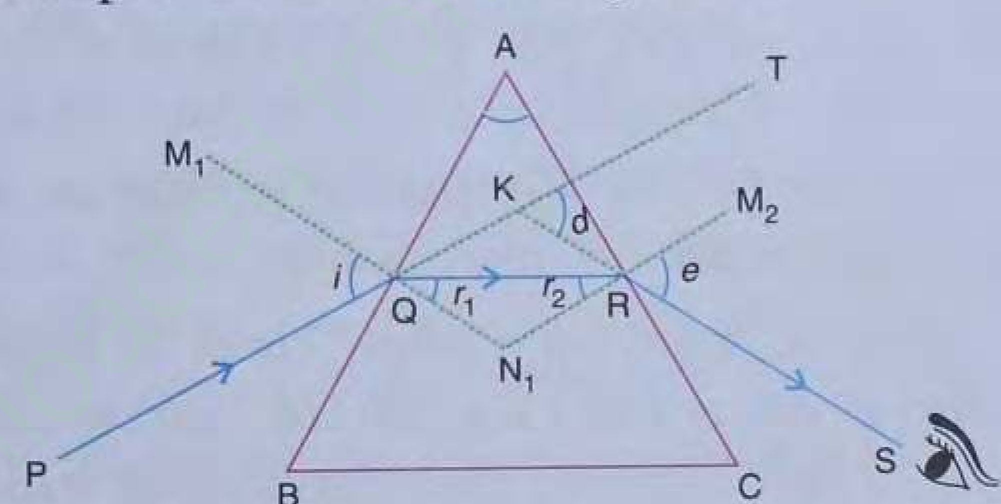


Fig. 2.9 Refraction through Prism

Here,
PQ = incident ray
QR = refracted ray
RS = emergent ray
$\angle i$ = incident angle
$\angle r_1$ = refracted angle at first face
$\angle r_2$ = incident angle at second face
$\angle e$ = angle of emergence
$\angle d$ = angle of deviation
$\angle A$ = angle of prism
M_1N_1 = Normal to the face AB at point Q
M_2N_1 = Normal to the face AC at point R.

Experimentally, it is found that :

$$\angle i + \angle e = \angle A + \angle d.$$

It can easily be observed that when incident ray PQ gets refracted through face AB, it travels from a rarer medium (air) to a denser medium (glass). So, it bends towards the normal M_1N_1 as refracted ray QR. Now this ray QR works as the incident ray for face AC and is travelling from a denser medium (glass) to a rarer medium (air). So, it bends away from the normal M_2N_1 as emergent ray RS. The angle between the extended incident ray PQ and the emergent ray RS is the angle of deviation ($\angle d$).

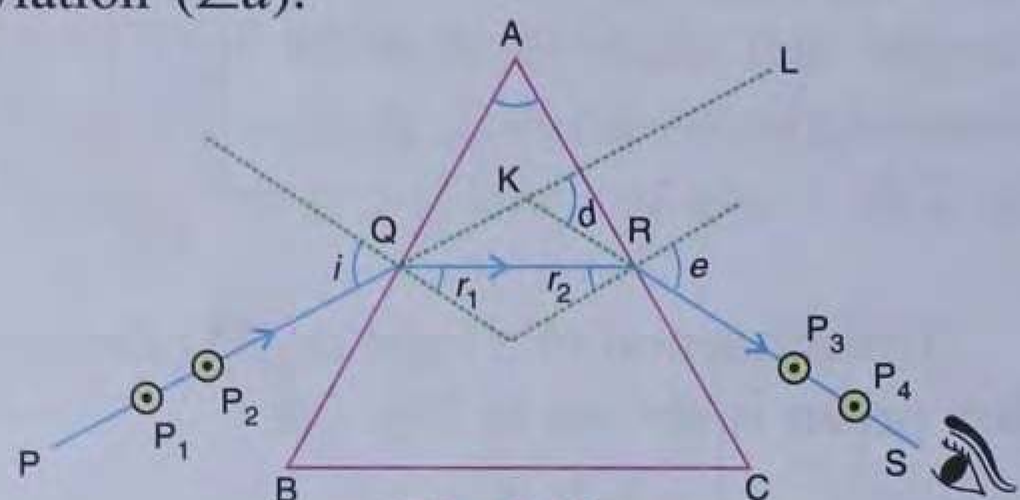


Fig. 2.10

Let us do a simple experiment to understand minimum deviation :

Place a prism on a white sheet of paper mounted on a drawing board. Draw the boundary ABC for the given prism and make an angle of 30° for angle of incidence 'i' as shown in figure 2.10. Place two pins P_1 and P_2 on the incident ray PQ. Now look through the other face AC of the prism and locate the images of pins P_1 and P_2. Place two more pins P_3 and P_4 so that these pins and images of P_1 and P_2 are all in a perfect straight line. Remove the prism and the pins. Encircle the dot marks left over by the pins. Extend the line PQ to L and then draw the line SR to extend it till it meets the line QL at K. Measure $\angle$LKS (or $\angle d$). Repeat the experiment for i = 35°, 40°, 45°, 50° and 55° and in each case find the corresponding values of $\angle d$. You will notice that as the angle of incidence ($\angle i$) increases, the value of $\angle d$ first decreases, acquires a minimum value and then increases again. The minimum value it acquires is called the angle of minimum deviation represented by (d_m). At the condition of minimum deviation we find that $\angle i = \angle e$, $\angle r_1 = \angle r_2$ and QR || BC

The graph drawn between i and d is as follows :

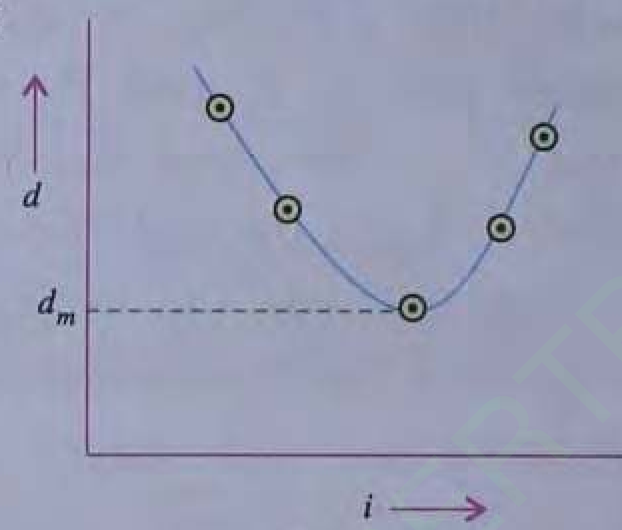


Fig. 2.11

The angle of minimum deviation depends on :

(1) Angle of prism

(2) Material of prism

(3) Angle of incidence

(4) Wavelength and colour of light used.

DISPERSION OF LIGHT THROUGH A PRISM

Sir Isaac Newton, in 1666, was the first Scientist to study about dispersion of light. He observed that, when a narrow beam of white light passes through a prism, it splits into its constituent colours. This happens because white light is made up of seven colours and when these colours pass through a prism, they deviate differently and so, move in different directions (Fig. 2.12).

It must be noted here that speed of light in a medium (other than air or vacuum) is different for the light of different colours. Thus, the refractive index of the medium is

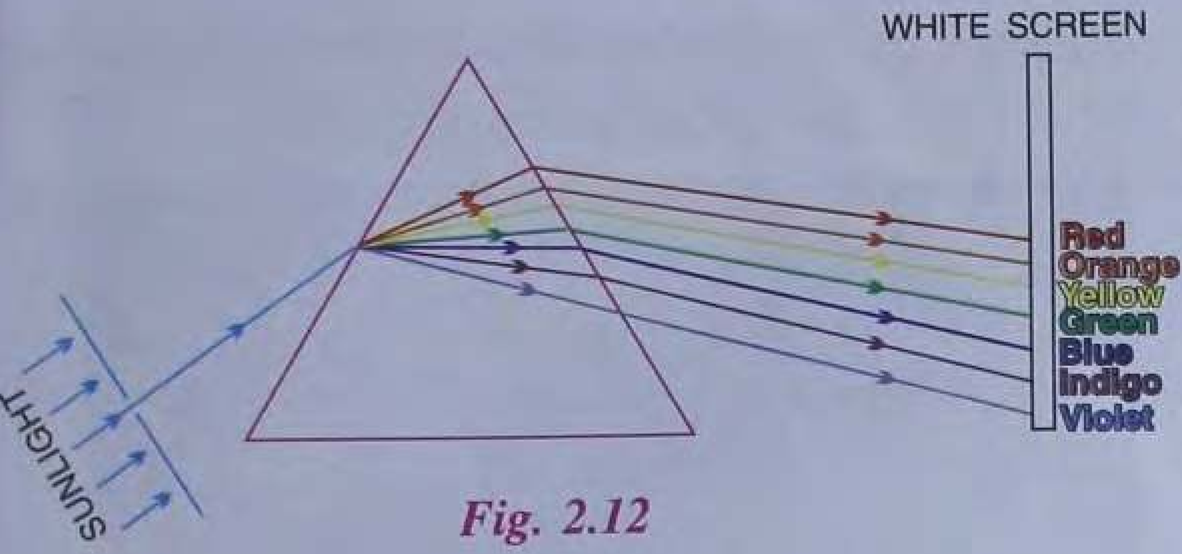


Fig. 2.12

different for the light of different colours due to which, they deviate from their paths differently.

The splitting (breaking-up) of white light into its constituent colours as it passes through a refracting medium (such as prism) is known as **dispersion**. The dispersion of white light into seven colours occurs because the lights of different colours bend through different angles while passing through a glass prism.

EXPERIMENT

Make a hole in a thick cardboard sheet to form a slit or use a hole in the window of your room. Through this hole, allow a narrow beam of light (sunlight) to pass through. When this narrow beam of sunlight passes through a prism and falls on a white screen, a band of colours is formed on the screen (see Fig. 2.12).

The band of colours on the screen resembles the seven colours of a rainbow and these seven colours from the base of the prism are in the order :

Violet (V), Indigo (I), Blue (B), Green (G), Yellow (Y), Orange (O) and Red (R). This order of colours can be read as VIBGYOR and the corresponding band is called a **spectrum**.

Spectrum is the band of seven colours obtained on a white screen when white light passes through a prism and splits into its constituent colours.

When a ray of white light passes through a prism, the red light travels the fastest and the violet light the slowest of all the seven colours. As a result the red light bends the least and the violet light bends the most, other colours lying in between.

The Rainbow

Rainbow is a spectacular example of dispersion of white light. Just after the rain, a large number of small droplets of water remain suspended in the air. Each drop acts like a small prism. When sunlight passes through these drops, it splits into seven colours. The dispersed light from a large number of drops forms a continuous band of seven colours; red on the outer side and violet on the inner side. This coloured band is called a rainbow. Thus, rainbow is produced due to the dispersion of white light by small raindrops suspended in the air after the rain.

It must be noted here that the prism does not produce or emit any colour. It only breaks the composite light into its constituent colours. Since white light is a mixture of seven colours (VIBGYOR), so a prism splits white light into these seven colours. This fact can easily be understood by the following experiment :

Take two identical prisms of the same material and place them as shown in Fig. 2.13.

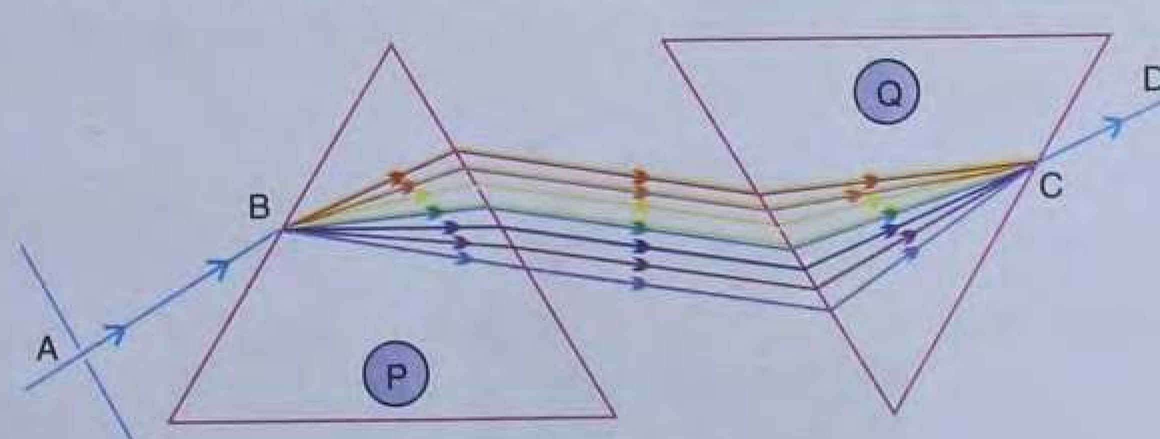


Fig. 2.13

Allow a narrow beam of light AB to pass through prism P and split into its constituent colours. On the other side of the prism P, the band of colours is allowed to fall on the identical inverted prism Q. The band of colours enter into prism Q and recombine to form a white light. This gives a narrow beam CD of white light. This experiment verifies that white light is a mixture of seven colours (VIBGYOR). It will also be observed that the rays AB and CD are parallel to each other *i.e.,* the combination of two identical prisms (Fig. 2.13) work as a rectangular glass block.

During sun rise and sunset, sun appears to be red in colour : During sunrise or sunset, light travels the largest distance through the atmosphere to reach the observer. As a result of scattering, the light loses violet, indigo, blue, green and yellow portions as their wavelengths are shorter than orange and red. Only red and orange reaches the observer's eye. Hence it appears to be red in colour.

Newton's Colour Disc

Newton demonstrated by his colour disc, the recombination of seven colours to produce white light. He took a circular cardboard disc and divided it into seven sectors. He painted all the seven colours (violet, indigo, blue, green, yellow, orange and red) of white light on this disc in order as shown in Fig. 2.14. The disc appeared white when it was rotated at a high speed.

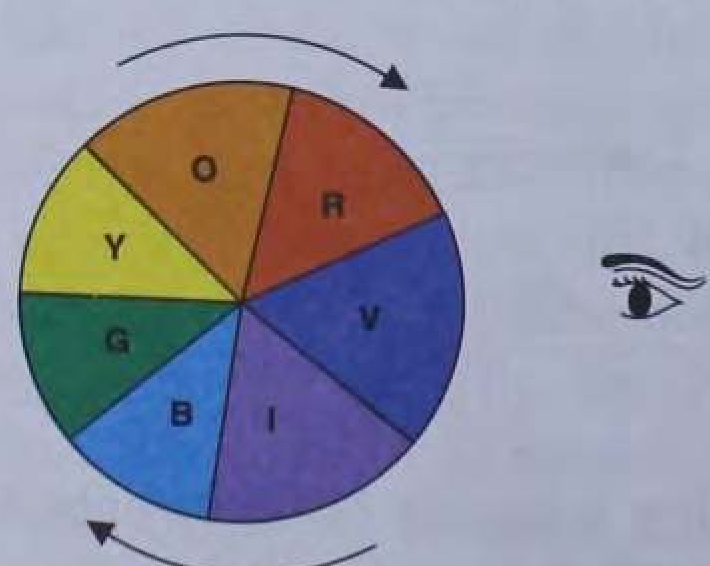


Fig. 2.14 Newton's colour disc

Newton thus proved that recombination of seven colours gives white colour.

Why do we use red colour light for the danger signal : Since the red colour light has the maximum wavelength therefore it scatters the least and the probability of reaching this light to the observer is the most. This is the reason why we use red colour light as a danger signal.

ACTIVITY 1

Take a cardboard of 12 cm × 12 cm and paste white paper on either side of it. Draw a pigeon on one side. Draw a cage on the other side. The cage should be bigger than the pigeon. Now hang the cardboard with a string from the middle portion. Rotate the cardboard slowly. You will see the pigeon and the cage separately, when it comes in front of your eyes. Now rotate the cardboard very fast.

Observe what happens ?

You will notice that suddenly the pigeon appears to be inside the cage. This is due to persistence of vision.

When an image is formed on the retina it lasts only for a period of 1/16 to 1/20 of a second. This is called persistence of vision. If another object is brought in front of the eyes within this period the image of the new object will overlap with the previous image and we shall see both the images together. This is exactly what happens when you rotate the cardboard very fast. The image of the pigeon and the cage appear together and we see that the pigeon is inside the cage.

ACTIVITY 2

Aim — To view the spectrum using a mirror.

Materials required — A plane mirror, transparent containers, sheet of white paper.

Procedure — Take a long plane mirror. Place it in a transparent container. Fill about three-fourth of the container with water. Place this container along with the mirror facing the sun near a window. Adjust the direction of the mirror by moving the container so that the reflected sunlight falls on its (container's) wall. Fix a sheet of white paper on the wall.

You will see a beautiful and colourful spectrum (like an inverted rainbow) on the white paper. Get a sharp spectrum by shifting the container. How does this happen ?

A prism is formed by the combination of water and mirror. This breaks up the light into its constituent colours. This is called the dispersion of light.

RECAPITULATION

- Refraction is the phenomenon by virtue of which when light travels from one medium to another medium of different optical density, it changes its direction.
- When light travels from a rarer to a denser medium, it bends towards the normal and when it travels from a denser to a rarer medium, it bends away from the normal.
- The ray of light incident perpendicular to the surface separating two media does not suffer any deviation *i.e.* it goes in the same direction.
- Refraction takes place only at the surface separating two media.
- The transparent medium, in which the speed of light is more, is rarer.
- When a ray of light passes through a glass block, the emergent ray is parallel to the incident ray *i.e.* the direction of incident ray is same as the direction of emergent ray. In other words, the ray passing through the glass block is not deviated but is displaced from its path.
- When a ray of light passes through a prism, it always deviates towards the base of the prism.
- A beam of light passing through a prism splits into its constituent colours. For this reason, when a ray of white light passes through a prism, it splits into its seven constituent colours (VIBGYOR).
- The splitting of white light into its constituent colours is called dispersion of light.
- Prism gives no colour to any light but it simply splits the light into its constituent colours.

TEST YOURSELF

A. Short Answer Questions

1. State whether the following statements are *true* or *false*. Rewrite the false statements correctly.

   (a) Light travels at a lower speed in water than in air.

   (b) Light travels in a straight line.

   (c) Light travels in a straight line path while passing through different media.

   (d) The angle formed between the normal and the refracted ray is known as the angle of incidence.

   (e) At the point of incidence, a line drawn at right angles to the surface, separating the two media, is called the normal.

(f) Images are formed in a mirror due to refraction.

2. Fill in the blanks :

(a) Sensation of sight is produced by ....

(b) Light is a form of ....

(c) Light travels in a straight line. This property of light is known as .... of light.

(d) Between water and glass, ... is the optically denser medium.

(e) A band of seven colours formed by the dispersion of white light is called.................

(f) A rainbow is formed when tiny drops of water suspended in the air act as ....

3. Tick the appropriate answer :

(a) The speed of light in air or vacuum is

(i) 3×10^8 m/s (ii) $2{\cdot}25 \times 10^8$ m/s

(iii) 332 m/s (iv) $2{\cdot}8 \times 10^8$ m/s

(b) A ray of light moving from an optically rarer to a denser medium

(i) bends away from the normal.

(ii) bends towards the normal.

(iii) remains undeviated.

(iv) none of these.

(c) The angle between the normal and refracted ray is called

(i) angle of deviation.

(ii) angle of incidence.

(iii) angle of refraction.

(iv) none of these.

(d) The property of splitting of white light into its seven constituent colours is known as :

(i) spectrum (ii) refractive index

(iii) reflection (iv) dispersion.

(e) For a white light, the colour which deviates the least is

(i) violet (ii) red

(iii) orange (iv) none of these.

(f) Rainbows are formed due to

(i) reflection of light.

(ii) refraction of light.

(iii) dispersion of light.

(iv) rectilinear propagation of light.

4. Differentiate between :

(a) Reflection of light and refraction of light.

(b) Angle of incidence and angle of refraction.

(c) Incident ray and refracted ray.

(d) Light travelling in air and light travelling in water.

5. (a) What do you mean by dispersion of light ?

(b) What do you mean by spectrum ?

(c) Draw a diagram to show the dispersion of white light through a prism.

6. Define the following :

(a) Spectrum (b) Dispersion of white light

B. Long Answer Questions

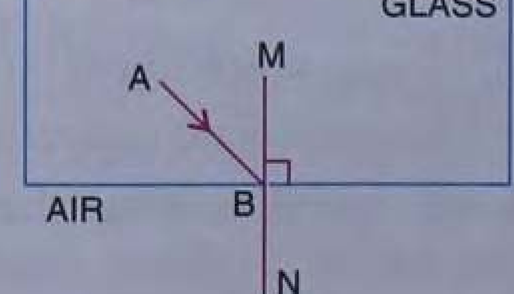
1. Draw a ray diagram to show that a rod partly dipped in water appears to be bent at the surface of the water.

2. Draw a neat labelled ray diagram to show the path of a light ray through a prism. Show all the angles clearly in the diagram.

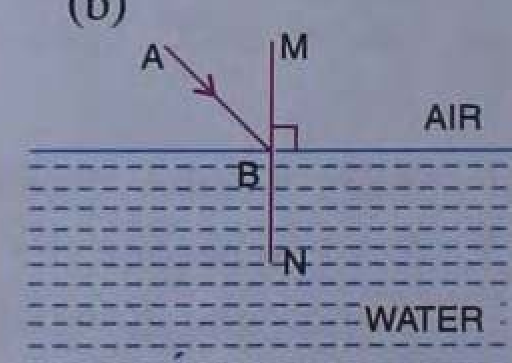
3. A ray of light falls normally on the surface separating two media. Write the measure of the corresponding angle of incidence.

4. In each case, given below, AB is the incident ray of light falling on the surface separating two media and MN is the normal at point B. Draw for each diagram, the corresponding refracted ray.

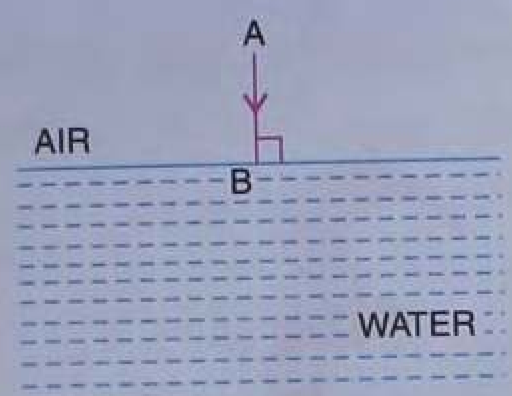
(a)



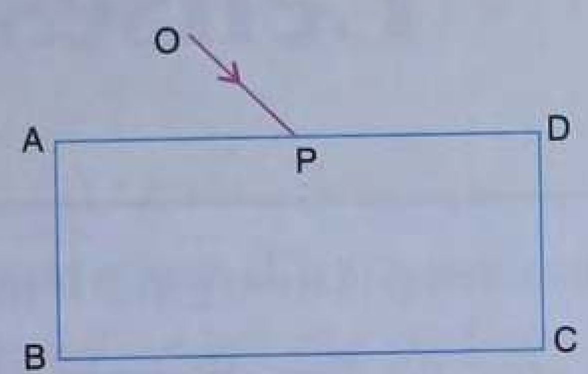
(b)



(c)



5. The following diagram shows a light ray OP falling on point P of a rectangular glass slab ABCD.

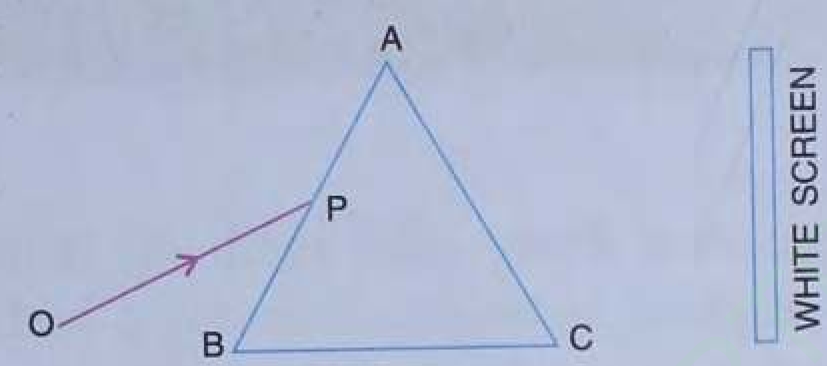


Complete the ray diagram till the ray emerges out of the glass slab. On the diagram, clearly label the incident ray, the refracted ray and the emergent ray. Also, mark the angle of incidence, angle of refraction and angle of emergence. Is there any relation between the angle of incidence and the angle of emergence ? If so, write the relation.

6. Explain Newton's colour disc. Which colour will be seen when Newton's colour disc is rotated with a high speed ?

7. A band of seven colours are obtained when white light, after passing through a prism, falls on a screen. What are these colours ?

8. The following diagram shows a ray OP of white light falling on a prism ABC.



Complete the diagram till the ray, after passing through the prism, falls on the white screen.

Projects and Activities

1. On a sunny day, connect a hose pipe to an outdoor tap and turn on the water. Adjust the flow so that the nozzle gives off a fine spray. Holding the hose in your hand, rotate your body until the sunlight streaming through the mist forms a beautiful rainbow.
2. Visit a laughing gallery in a science centre or a science park or a village mela. You will find some large mirrors there. You can see your distorted and funny images in these mirrors. Try to find out the kind of mirrors used there.