

# Light and Optics

What are the concepts and principles related to light and optics?

How are the concepts of light and optics used to explain natural phenomena and applied in daily life?

Why are fibre optics and small lenses used in optical instrument technology?

## Let's Study

- 6.1 Refraction of Light
- 6.2 Total Internal Reflection
- 6.3 Image Formation by Lenses
- 6.4 Thin Lens Formula
- 6.5 Optical Instruments
- 6.6 Image Formation by Spherical Mirrors



Dew drops on grass can function as liquid magnifying lenses that form images of objects around them. The effect of light refraction is influenced by the size and shape of the dew drops.

The thickness of the human eye lens is controlled by cilia muscles so as to have different focal lengths to form images in the range of human vision. The concept of focal length adjustment is applied by scientists and engineers to invent liquid camera lens in smartphones. The focal length of the liquid lens can be adjusted using electric field in the electronic system of the smartphone. As such, one liquid lens can replace a set of lenses installed in the smartphone camera. The saving of space allows the overall thickness of smartphones to be reduced.

Video on liquid camera lens



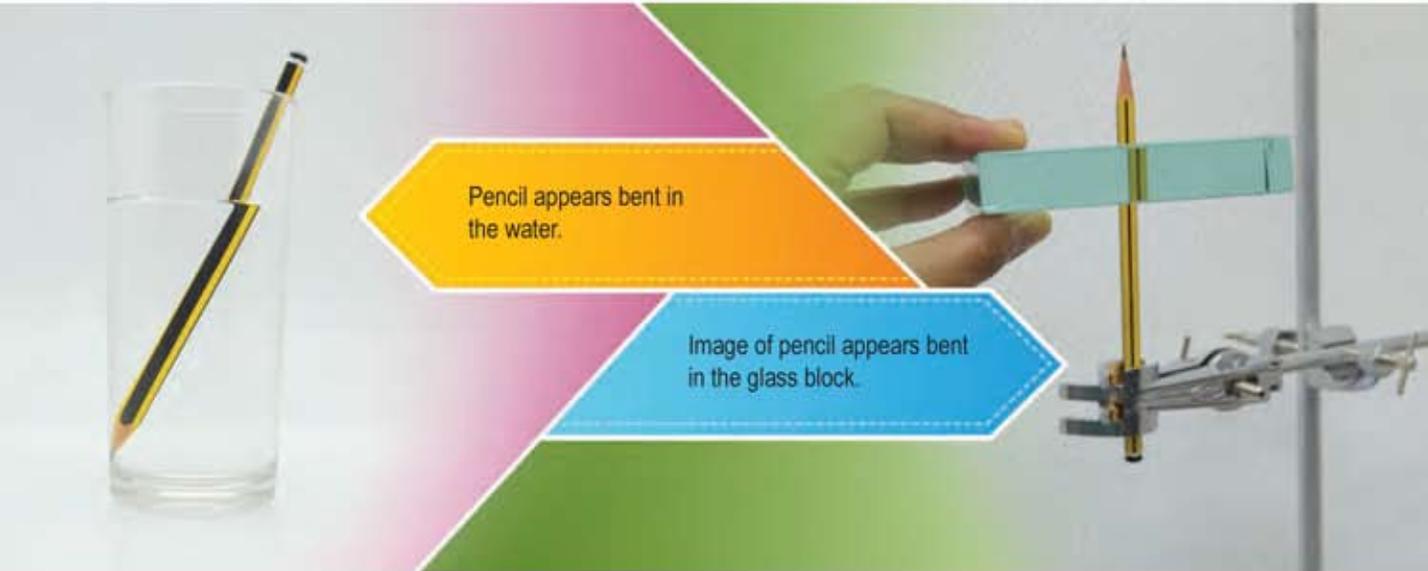
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Learning Standards and  
List of Formulae



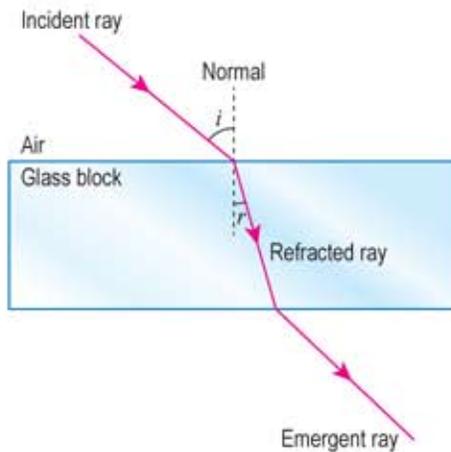
## 6.1 Refraction of Light

Observe Figure 6.1. What causes the phenomena?



*Figure 6.1 Phenomena of refraction of light*

These phenomena are known as **refraction of light**. They occur due to the change in velocity of light when travelling through mediums of different optical densities as shown in Figure 6.2.

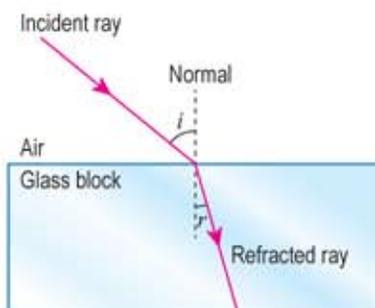


*Figure 6.2 Refraction of light*

### SMART INFO

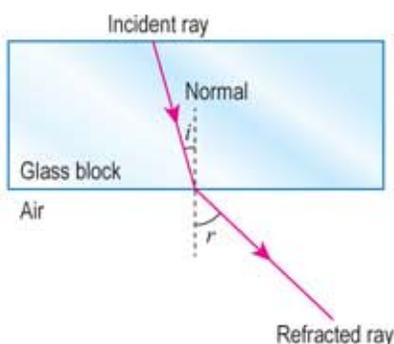
Optical density is not the same as density which is defined as mass per unit volume. For example, the density of oil is lower than that of water causing it to float on the surface of water. On the other hand, the optical density of oil is higher than the optical density of water.

Based on Figure 6.3, light rays bend towards the normal when light travels from a medium of low optical density (air) to a medium of high optical density (glass block). This is because the velocity of light decreases when light travels from an optically less dense medium to a denser medium. Due to this, the angle of refraction,  $r$  is smaller than the angle of incidence,  $i$ .



**Figure 6.3** Refraction of light from air to glass block ( $i > r$ )

Based on Figure 6.4, the light ray bends away from the normal when light travels from a medium of high optical density (glass block) to a medium of low optical density (air). This is because the velocity of light increases when light travels from an optically denser medium to a less dense medium. Due to this, the angle of refraction,  $r$  is bigger than the angle of incidence,  $i$ .



**Figure 6.4** Refraction of light from glass block to air ( $i < r$ )

### Refractive Index

Refractive index,  $n$  determines the degree to which light bends when travelling from vacuum to a medium. As such, we can define refractive index as the ratio of speed of light in vacuum to the speed of light in medium.

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

where  $c = 3.0 \times 10^8 \text{ m s}^{-1}$

### Info File

When optical density increases, value of refractive index,  $n$  will increase. Value of  $n$  is always more than or equal to 1. The value  $n$  depends on the wavelength,  $\lambda$  of the light used. Change in temperature can also change the value  $n$  of a medium.



## Activity 6.1

ISS ICS

**Aim:** To compare refractive index of different mediums and relate the refractive index of a medium to its optical density

**Instructions:**

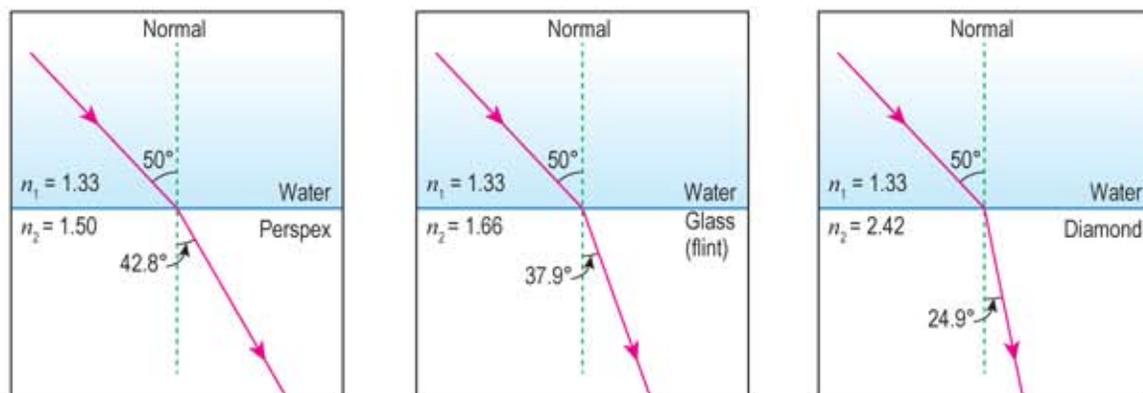
1. Work in groups.
2. Gather information from reading resources or websites regarding refractive index for several different mediums such as air, water, cooking oil, ice, glass, diamond and other mediums.
3. Discuss:
  - (a) The relationship between refractive index of the selected mediums and their optical densities.
  - (b) What are the physical factors that influence the value of refractive index of a medium?
  - (c) Which medium has the highest value of refractive index?
4. Present your findings.

### Snell's Law

Table 6.1 shows the refractive indices for several mediums. Figure 6.5 shows light rays travelling from water into three different mediums.

**Table 6.1** Refractive indices for several mediums

Medium	Refractive index
Vacuum and air	1.00
Olive oil	1.46
Perspex	1.50
Glass (crown)	1.52
Glass (flint)	1.66
Diamond	2.42



**Figure 6.5** Light rays travelling from water into three different mediums

Based on Figure 6.5, the value of  $n_1 \sin \theta_1$  is the same as  $n_2 \sin \theta_2$  for the three different mediums. According to the law of refraction of light, when light travels from one medium to another:

- The incident ray, refracted ray and normal meet at one point and are in the same plane.

- Snell's Law:  $n_1 \sin \theta_1 = n_2 \sin \theta_2$ , where  $n_1 =$  refractive index of medium 1  
 $n_2 =$  refractive index of medium 2  
 $\theta_1 =$  angle of incidence in medium 1  
 $\theta_2 =$  angle of refraction in medium 2

$$\frac{n_2}{n_1} = \frac{\sin \theta_1}{\sin \theta_2}$$

When medium 1 is air ( $n_1 = 1$ ) and medium 2,  $n_2 = n$   
 $n = \frac{\sin i}{\sin r}$   
*i* is the angle of incidence in air,  
*r* is the angle of refraction in medium 2

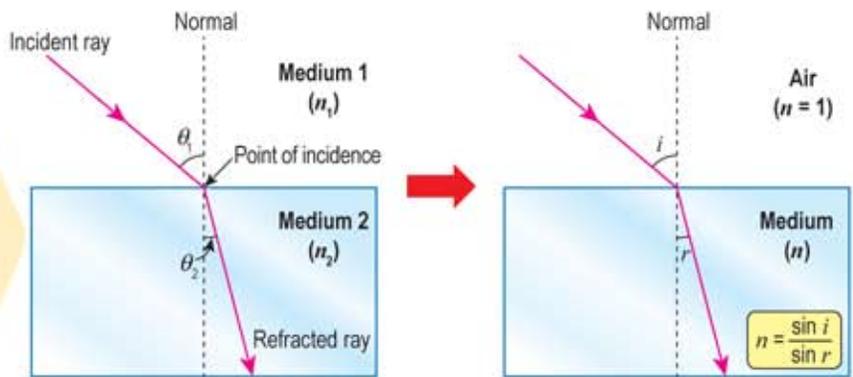


Figure 6.6 Law of refraction of light

Observe Figure 6.7. Why does light ray bend when entering a glass block?

Angle of refraction depends on the angle of incidence and the value of refractive index of the glass block.

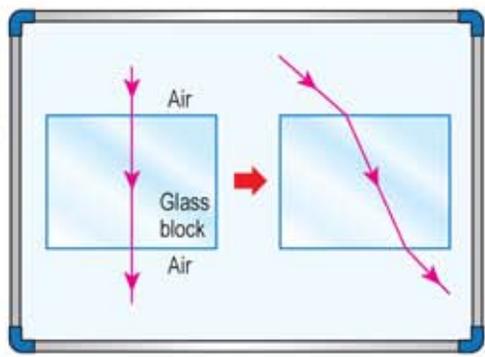


Figure 6.7 Bending of light ray



## Experiment

### 6.1

**Inference:** Angle of refraction depends on angle of incidence

**Hypothesis:** The larger the angle of incidence,  $i$ , the larger the angle of refraction,  $r$

**Aim:** To determine the refractive index of glass block

**Variables:**

- (a) Manipulated variable: Angle of incidence,  $i$
- (b) Responding variable: Angle of refraction,  $r$
- (c) Constant variable: Refractive index of glass block

**Apparatus:** Ray box with single slit, protractor and ruler

**Materials:** Glass block, white paper and pencil

**Procedure:**

1. Set up the apparatus on a piece of white paper (as shown in Figure 6.8).
2. Trace the outline of the glass block on the white paper and draw a normal line at point  $O$ .
3. Draw five lines at different angles of incidence,  $i = 20^\circ, 30^\circ, 40^\circ, 50^\circ$  and  $60^\circ$  using a protractor to represent five incident rays.
4. Direct the light ray from the ray box at angle of incidence,  $i = 20^\circ$ . Draw the emergent ray  $PQ$ .
5. Remove the glass block and draw the refracted ray  $OP$ . Measure the angle of refraction,  $r$  and record the reading in Table 6.2.
6. Put the glass block back in place. Repeat steps 4 and 5 with angle of incidence,  $i = 30^\circ, 40^\circ, 50^\circ$  and  $60^\circ$ .
7. Calculate the value of  $\sin i$  and  $\sin r$ . Record the values in Table 6.2.

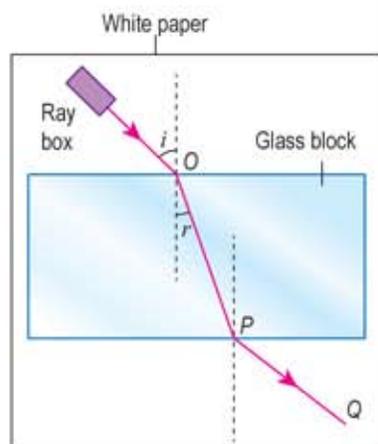


Figure 6.8

**Note:** This experiment can also be carried out using perspex.

**Results:**

Table 6.2

Angle of incidence, $i / ^\circ$	Angle of refraction, $r / ^\circ$	$\sin i$	$\sin r$
20			
30			
40			
50			
60			

**Analysis of data:**

1. Plot a graph of  $r$  against  $i$  and a graph of  $\sin i$  against  $\sin r$  on a different graph paper.
2. Calculate the gradient of the graph of  $\sin i$  against  $\sin r$ .
3. State the relationship between angle of incidence,  $i$  and angle of refraction,  $r$  when light moves from air into the glass block.

### Info File

If a laser pointer is used in this experiment, apparatus set up needs to be rearranged.

**Demonstration video on refraction of laser ray**



<http://bt.sasbadi.com/p4236>

**Conclusion:**

What conclusion can be made from this experiment?

Prepare a complete report for this experiment.

**Discussion:**

1. What is the value of refractive index of the glass block?
2. State one precaution that needs to be taken to increase the accuracy of readings in this experiment.

## Real Depth and Apparent Depth

Observe Figure 6.9. Why does the position of the image of the fish appear closer to the water surface?

This situation is caused by refraction of light. When light rays from the fish travel from water to air, light is refracted away from normal. This effect of refraction of light causes the image of the fish to be closer to the water surface as seen by an observer.

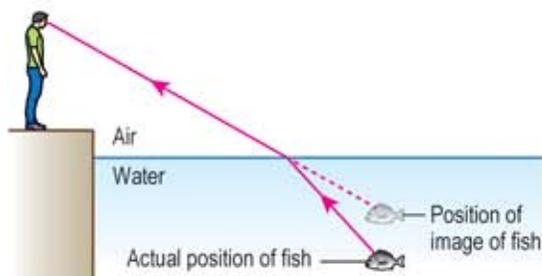


Figure 6.9 Effect of refraction of light



### Activity 6.2

ICS

**Aim:** To draw a ray diagram to show real depth,  $H$  and apparent depth,  $h$

Figure 6.10 shows a coin, placed under a glass block with a thickness of 8.0 cm. Ray  $OPQ$  is the path of light from the centre of the coin, to the eye of the observer. You are required to draw another light ray,  $OP'Q'$  from point  $O$  to the eye of the observer. You can download and print Figure 6.10 from the website given.

**Instructions:**

1. Work in pairs.
2. Draw lines  $QP$  and  $Q'P'$  and extend both lines into the glass block until they meet.
3. Mark the meeting point as point  $X$ .  $X$  is the apparent position of the centre of the coin, that is the image for point  $O$ .
4. Complete your ray diagram by drawing line  $OP'$ .
5. Measure:
  - (a) Real depth,  $H$ , which is the distance from  $O$  to the surface of the glass block.
  - (b) Apparent depth,  $h$ , which is the distance from  $X$  to the surface of the glass block.
6. Calculate the value of  $\frac{H}{h}$ . Compare the value of  $\frac{H}{h}$  with the refractive index of the glass block,  $n$ . Relate real depth,  $H$ , apparent depth,  $h$ , and refractive index of the glass block,  $n$ .

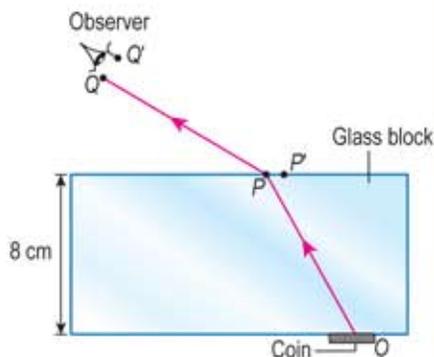


Figure 6.10

Download Figure 6.10



<http://bt.sasbadi.com/p4237>

Figure 6.11 shows that a diving instructor who is at the poolside sees the position of the diver closer to the water surface. Figure 6.12 shows a diver who is at the base of the pool sees his instructor further away from him. Can you explain these situations?

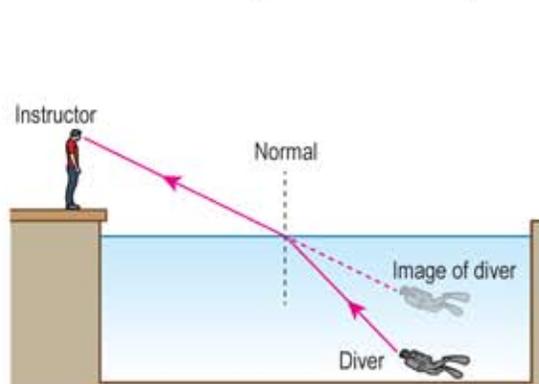


Figure 6.11 Position of image of diver from the viewing angle of instructor

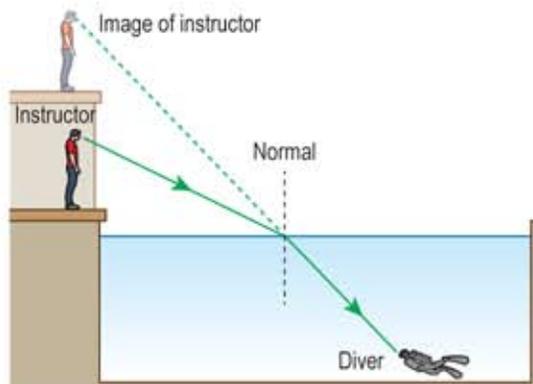


Figure 6.12 Position of image of instructor from the viewing angle of diver



## Experiment 6.2

**Inference:** Position of an image is influenced by position of object and refractive index of different mediums

**Hypothesis:** The greater the real depth of an object, the greater the apparent depth

**Aim:** To determine the refractive index of water using non-parallax method

**Variables:**

- (a) Manipulated variable: Real depth,  $H$
- (b) Responding variable: Apparent depth,  $h$
- (c) Constant variable: Refractive index of water,  $n$

**Apparatus:** 1 000 ml beaker, ruler and retort stand with two clamps

**Materials:** Cork, two pins, cellophane tape and water

**Procedure:**

1. Set up the apparatus as shown in Figure 6.13.

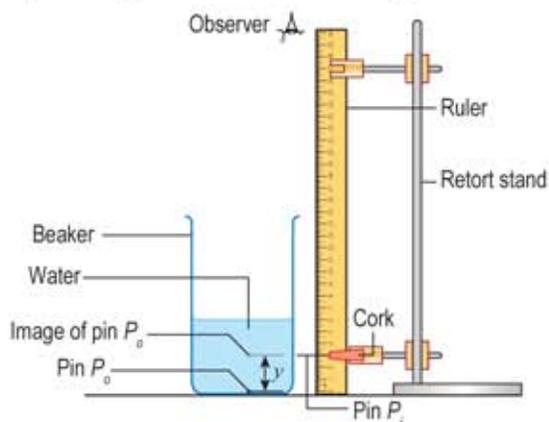


Figure 6.13

### Info File

Non-parallax method is an important method to determine position of image accurately in optical experiments.

- Stick a pin  $P_o$  with cellophane tape to the base of the beaker.
- Fill the beaker with water to a depth of 6.0 cm. This depth is real depth,  $H$ .
- Observe the image of pin  $P_o$  from above the water surface.
- Adjust the position of pin  $P_i$  vertically until it appears in line with the image of pin  $P_o$ . At this level, position of pin  $P_i$  is at the same level as the image of pin  $P_o$ .
- Measure the distance  $y$  between pin  $P_i$  and the base of the beaker. Record the reading in Table 6.3.
- Repeat this experiment with real depth,  $H = 7.0$  cm, 8.0 cm, 9.0 cm and 10.0 cm.

**Results:**

**Table 6.3**

Real depth, $H$ / cm	$y$ / cm	Apparent depth, $h$ / cm
6.0		
7.0		
8.0		
9.0		
10.0		

**Analysis of data:**

- Determine the value of apparent depth,  $h$  which is equal to the distance between pin  $P_i$  and the water surface using the formula,  $h = (H - y)$ .
- Plot a graph of  $H$  against  $h$ .
- Determine the gradient of the graph.
- Relate real depth, apparent depth and refractive index of water.
- State the value of refractive index of water.

**Conclusion:**

What conclusion can be made from this experiment?

**Prepare a complete report for this experiment.**

**Discussion:**

- If water is replaced by cooking oil in this experiment, what will happen to the gradient of the graph?
- State one precaution that needs to be taken to improve the accuracy of the results.
- Discuss the advantage of non-parallax method compared to the method used in Experiment 6.1 to determine the refractive index of a substance.

Based on the above experiment, the relationship between the refractive index of a medium,  $n$ , real depth,  $H$  and apparent depth,  $h$  is:

$$n = \frac{\text{real depth}}{\text{apparent depth}} = \frac{H}{h}$$

## Solving Problems Involving Refraction of Light

### Example 1

Figure 6.14 shows a light ray travelling from air into a plastic block at an angle of  $60^\circ$ . The refractive index of plastic is 1.49.

Calculate:

- angle of refraction,  $r$ .
- speed of light in plastic.

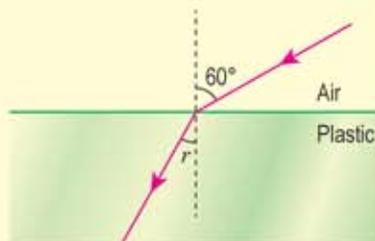


Figure 6.14

### Solution:

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

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

$$= \frac{\sin 60^\circ}{1.49}$$

$$r = \sin^{-1} \left( \frac{\sin 60^\circ}{1.49} \right)$$

$$= 35.54^\circ$$

$$(b) \quad n = \frac{c}{v}$$

$$v = \frac{c}{n}$$

$$= \frac{3.0 \times 10^8}{1.49}$$

$$= 2.01 \times 10^8 \text{ m s}^{-1}$$

### Example 2

When a coin inside a beaker containing a solution is observed, image of the coin is seen at a height equal to  $\frac{2}{7}$  of the depth of the solution. What is the refractive index of the solution?

### Solution:

Based on Figure 6.15,

$$\text{Apparent depth, } h = H - \frac{2}{7} H$$

$$= \frac{5}{7} H$$

$$\text{Refractive index of solution, } n = \frac{H}{h}$$

$$= \frac{H}{\frac{5}{7} H}$$

$$= \frac{7}{5}$$

$$= 1.4$$

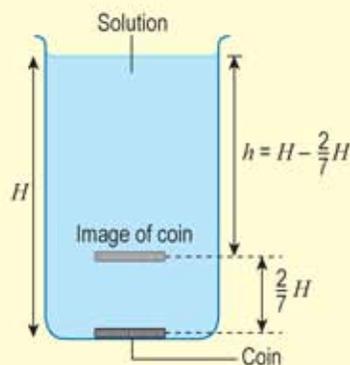


Figure 6.15

## Formative Practice 6.1

1. Figure 6.16 shows the path of light which travels from medium 1 to medium 2.

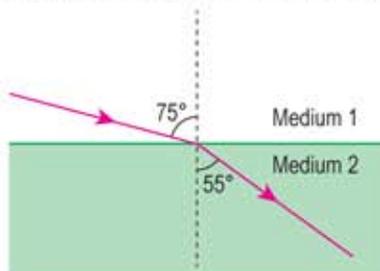


Figure 6.16

- Write an equation to relate the light that travels through the mediums.
  - Determine the refractive index for medium 2 if the speed of light in medium 1 is  $3.0 \times 10^8 \text{ m s}^{-1}$ .
  - What is the speed of light in medium 2?
2. Figure 6.17 shows a tank filled with oil to a height of 3 m. The oil has a refractive index of 1.38. What is the apparent depth of the tank as seen by the observer from above the tank?

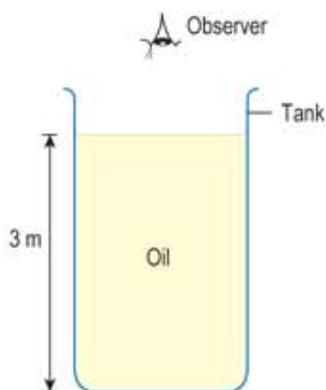


Figure 6.17

## 6.2 Total Internal Reflection

Photograph 6.1 shows a turtle below the surface of water. A reflected image of the turtle can be seen on the boundary of water and air. Why does this happen?

This phenomenon is known as **total internal reflection** of light. Total internal reflection only occurs when light travels from a medium of high optical density to a medium of low optical density.



Photograph 6.1 Phenomenon of total internal reflection



### Activity 6.3

**Aim:** To observe the phenomenon of total internal reflection and determine the critical angle of glass

**Apparatus:** Semi-circular glass block, ray box, power supply and protractor

**Material:** White paper

**Instructions:**

1. Draw a straight line  $AB$  and a perpendicular line  $PQ$  on a piece of white paper.
2. Set up the apparatus as shown in Figure 6.18. Point  $O$  is the centre of the semi-circular glass block.

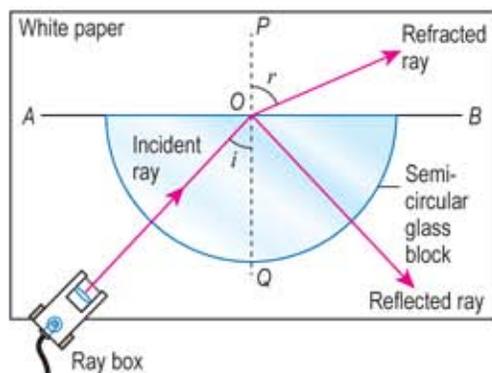


Figure 6.18

3. Switch on the ray box so that a ray of light is directed along  $QO$ . Observe the refracted ray in air.
4. Shift the ray box so that a ray of light is directed to point  $O$  with a small angle of incidence,  $i$ . Observe the refracted ray in air and the reflected ray in the semi-circular glass block.
5. Repeat step 4 with an increasingly bigger angle of incidence,  $i$  until it is almost  $90^\circ$ .
6. Adjust the position of the ray box so that the refracted ray travels along  $OB$ , that is angle of refraction,  $r = 90^\circ$ . Mark the path of the incident ray.

- Remove the glass block. Draw the incident ray and measure the angle of incidence. This angle of incidence is known as the critical angle of glass,  $c$ .
- Place the glass block back to its original position. Observe the refracted ray and reflected ray when:
  - angle of incidence is smaller than the critical angle, and
  - angle of incidence is larger than the critical angle.

**Discussion:**

- What is the critical angle of glass?
- Describe the propagation of light ray through the glass block when the angle of incidence is smaller than the critical angle.
- What happens to the light ray travelling through the glass block when
  - the angle of incidence is smaller than the critical angle?
  - the angle of incidence is larger than the critical angle?

Figure 6.19 shows light rays travelling from glass (high optical density) to air (low optical density) for three different angles of incidence.

① When the incident angle is less than the critical angle, the ray is refracted away from the normal. A weak reflected ray can also be detected.

② When the incident angle is the same as the critical angle, the refracted ray travels along the glass-air boundary. The reflected ray appears brighter.

③ When the incident angle is greater than the critical angle, there is no refracted ray. Total internal reflection happens.

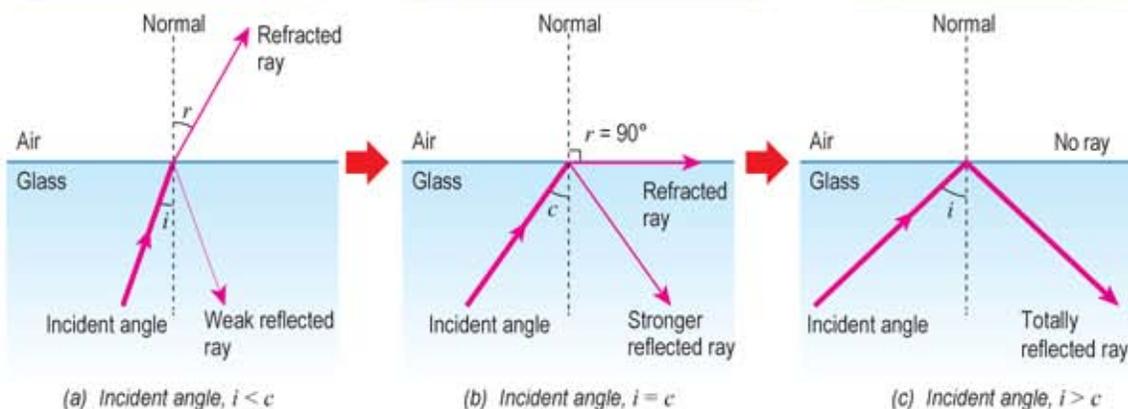


Figure 6.19 Light ray travelling from glass to air

The phenomenon of total internal reflection happens when light travels from a medium of high optical density to a medium of low optical density, with the angle of incidence larger than the critical angle. **Critical angle**,  $c$  is the angle of incidence in the medium of high optical density when the angle of refraction in the medium of lower optical density is equals to  $90^\circ$ . Does the critical angle of a medium depend on its refractive index?

**Aim:** To discuss the relationship between critical angle and refractive index

**Instructions:**

1. Work in pairs.
2. Study Figure 6.20 that shows a light ray travelling from glass to air with an angle of incidence,  $i$  equals to the critical angle,  $c$ .

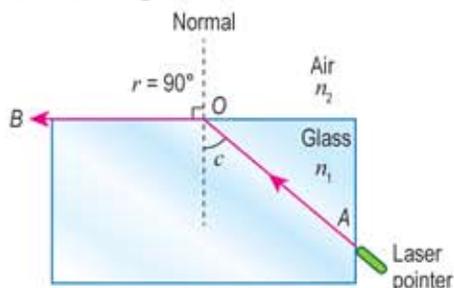


Figure 6.20 Relationship between critical angle and refractive index

3. Discuss and complete the following statements.
  - (a) Snell's Law for light ray travelling from glass to air is:

$n_1 \sin \theta_1 = n_2 \sin \theta_2$ , where  $n_1 =$  refractive index of \_\_\_\_\_  
 $n_2 =$  refractive index of \_\_\_\_\_  
 $\theta_1 =$  angle of incidence in \_\_\_\_\_  
 $\theta_2 =$  angle of refraction in \_\_\_\_\_

- (b) Value  $\theta_1 = c$ ,  $\theta_2 =$  \_\_\_\_\_ and  $n_2 =$  \_\_\_\_\_.  
 With this,  $n_1 \sin$  \_\_\_\_\_  $= n_2 \sin$  \_\_\_\_\_.

$$n_1 = \frac{1}{\square}$$

In general, the relationship between the critical angle,  $c$  and the refractive index,  $n$  for a medium in air is  $n = \frac{1}{\sin c}$ . If the refractive index of diamond is 2.42, then the critical angle for diamond can be calculated as follows:

$$\begin{aligned} \sin c &= \frac{1}{2.42} \\ &= 0.4132 \\ c &= \sin^{-1}(0.4132) \\ &= 24.4^\circ \end{aligned}$$

Critical angle for diamond,  $c$  is  $24.4^\circ$ .

Critical angle for a medium depends on the optical density of the medium. The higher the refractive index of a medium, the smaller the critical angle of the medium.

## Natural Phenomena and Applications of Total Internal Reflection in Daily Life



*Photograph 6.2 Night view of the River of Life and Blue Pool, Jamek Mosque, Kuala Lumpur*

The beauty of decorative lamps shown in Photograph 6.2 is due to total internal reflection. Can you state other phenomena involving total internal reflection?



### Activity 6.5

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ICS

**Aim:** To gather information and discuss natural phenomena which involve total internal reflection

**Instructions:**

1. Work in groups.
2. Gather information from various reading resources and websites regarding:
  - (a) natural phenomena which involve total internal reflection.
  - (b) applications of total internal reflection in daily life.
3. Present your findings in the form of a mind map.

## Activity 6.6

**Aim:** To observe the phenomenon of total internal reflection in a water stream

**Apparatus:** 1.5 litre plastic bottle, plastic basin, laser pointer, wooden block and retort stand

**Materials:** Water and cellophane tape

### Instructions:

1. Punch a hole at the side of a plastic bottle. Then, seal the hole with cellophane tape.
2. Set up the apparatus as shown in Figure 6.21(a).

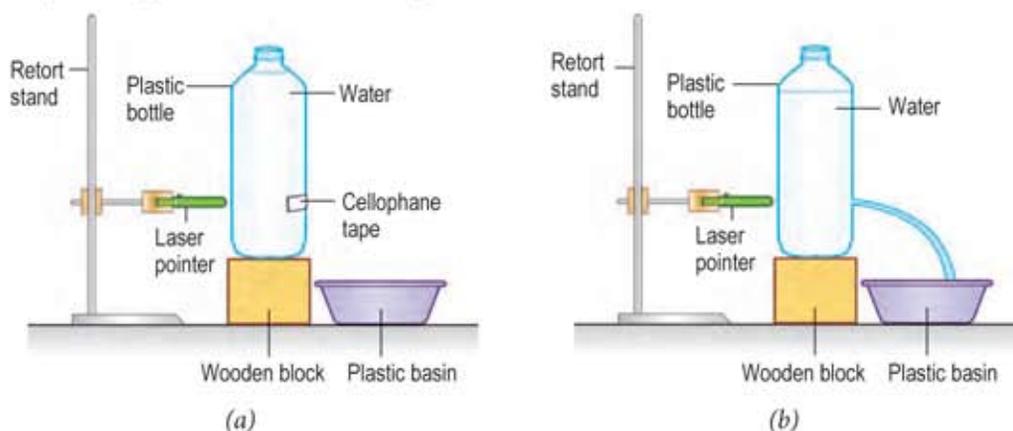


Figure 6.21

3. Carry out this activity in a dark room for clearer observation.
4. Remove the cellophane tape so that water flows out from the hole into the basin.
5. Direct the laser beam towards the hole as shown in Figure 6.21(b). Observe the colour of the water stream.
6. Record your observations.

### Discussion:

What will happen if the water stream is replaced by an oil stream?

Demonstration video on total internal reflection



<http://bt.sasbadi.com/p4246>

**Note:** This activity can also be carried out using an optical fibre kit.

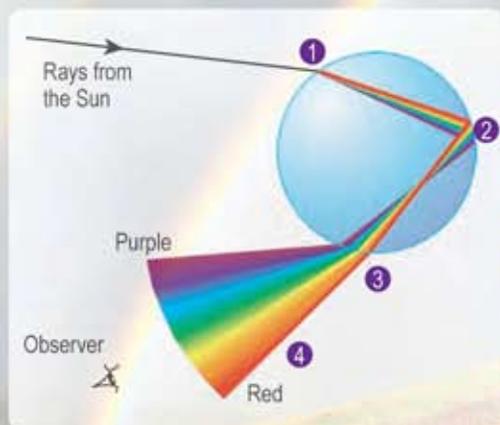
Based on Activity 6.6, a laser beam which enters the water stream experiences repeated total internal reflection until it comes out from the end of the water stream. This situation shows that the water stream acts as a light pipe to guide the laser beam from one end to another end.

If the water stream is replaced by an oil stream, light beams will experience total internal reflection even more times. This is because the refractive index of oil is higher than the refractive index of water. The critical angle of oil is smaller than the critical angle of water.

## Natural Phenomena that Involve Total Internal Reflection

### Formation of rainbow

Formation of rainbow is a phenomenon caused by refraction, dispersion and total internal reflection when light passes through water droplets in the air. Figure 6.22 shows the formation of rainbow.



- 1 When white light from the Sun enters water droplets, the light experiences refraction and disperses into different colours.
- 2 All these different colours experience total internal reflection on the surface of the water droplets.
- 3 Light rays reflected experience refraction and dispersion again when moving from water to air.
- 4 Colours of the rainbow are seen by the observer.

Figure 6.22 Formation of rainbow

### Mirage

On a hot and bright day, a car driver sees the blurry image of a puddle of water on the surface of the road ahead. When he gets nearer to the puddle of water, he discovers that the puddle of water does not actually exist. This natural phenomenon is known as **mirage** which is caused by refraction and total internal reflection of light. Figure 6.23 shows the process of formation of mirage.

- 1 Layers of air above the road have different optical densities. The layer of air just above the road surface is hotter than the upper layers. The layer of hot air has smaller optical density than cold air.
- 2 Light which travels from the upper layer to the lower layer are gradually refracted away from the normal. When the angle of incidence is greater than the critical angle of air, total internal reflection occurs.
- 3 Reflected light rays are then gradually refracted towards the normal and reach the eyes of the observer. The observer will see the image of a cloud as a puddle of water on the road surface.

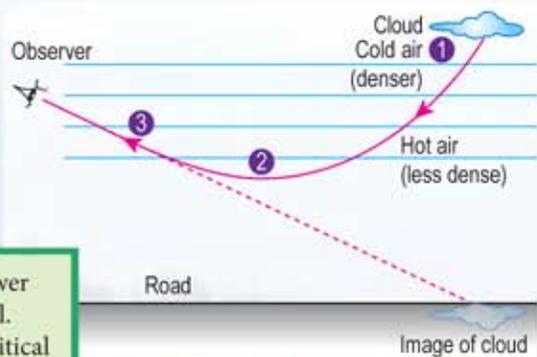
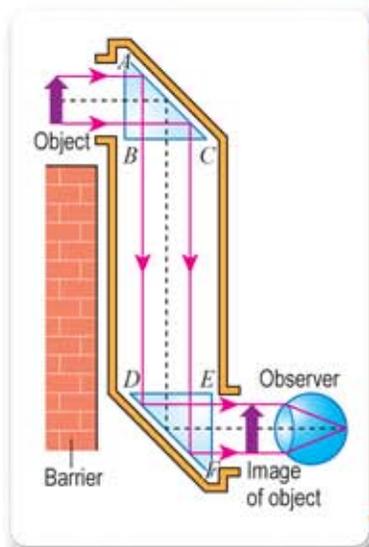


Figure 6.23 Formation of mirage

## Applications of Total Internal Reflection in Daily Life

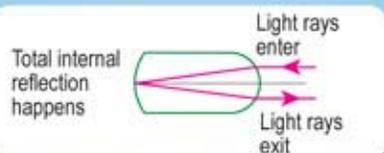
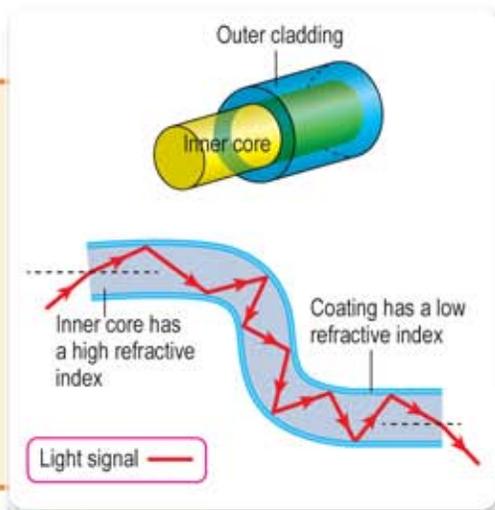


### Prism periscope

- Used to see objects behind a barrier.
- Made up of two right angle prisms fitted at both ends of a long tube.
- Light rays from an object travel along the normal to the side  $AB$  of the upper prism (pass through the opening of the periscope). The light rays reach side  $AC$  without refraction. The angle of incidence is  $45^\circ$  and is larger than the critical angle of the prism, which is  $42^\circ$ . Therefore, total internal reflection happens at side  $AC$  and the light rays are reflected downwards.
- The reflected light rays travel downwards along the normal to side  $DE$  of the lower prism.
- Once again, the reflected light rays experience total internal reflection at side  $DF$ . Finally, the reflected light rays emerge from side  $EF$  without refraction and enter the eyes of observer. The image formed is upright and of the same size as the object.

### Optical fibre

- Widely used in the fields of telecommunication and medicine.
- Made from pure glass or plastic fibres.
- Inner core which has a high refractive index is surrounded by a layer of cladding with a low refractive index.
- Light signals enter one end of the optic fibre and experience total internal reflection continuously in the inner core until they reach the other end. As such, signals can be sent rapidly without disturbances from electric signals.



### Cat's eye reflector

- Used for the purpose of safety for road users at night.
- Light rays from car headlights enter the reflector and experience total internal reflection on the back surface of the reflector.

### CAREER INFO

Doctors use endoscope to examine the internal organs. Engineers use fibre optics to examine the interior of complex machines. Communication experts use fibre optics for sending data speedily.

Figure 6.24 Applications of total internal reflection in daily life

## Solving Problems Involving Total Internal Reflection

## Example 1

Figure 6.25 shows a light ray travelling from air to a prism with refractive index of 1.49.

- Calculate the critical angle of the prism.
- Complete the path of the light ray until it exits the prism.

## Solution:

$$\begin{aligned} \text{(a)} \quad \sin c &= \frac{1}{n} \\ &= \frac{1}{1.49} \\ c &= \sin^{-1}\left(\frac{1}{1.49}\right) \\ &= 42.2^\circ \end{aligned}$$

Critical angle of prism,  $c$  is  $42.2^\circ$ .



Figure 6.25

(b)

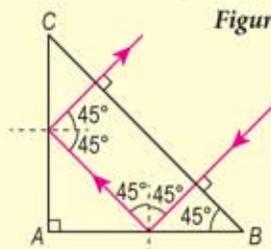


Figure 6.26

In Figure 6.26, angle of incidence ( $i = 45^\circ$ ) is larger than critical angle ( $c = 42.2^\circ$ ) at the sides  $AB$  and  $AC$ . Total internal reflection happens and light ray emerges from the side of  $BC$  along its normal.

## Example 2

Figure 6.27 shows the path of light ray travelling through optical fibre from end  $A$  to end  $B$ .

- Explain the change in direction of the light ray at points  $Q$ ,  $R$ ,  $S$ ,  $T$  and  $U$ .
- If the refractive index of the optical fibre is 1.51, determine the value of angle  $x$ .
- Why must the material of optical fibres be of high optical purity?

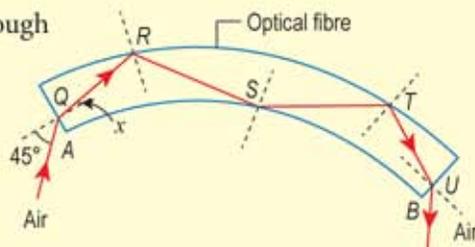


Figure 6.27

## Solution:

- At point  $Q$ , refracted light bends towards the normal. At points  $R$ ,  $S$  and  $T$ , total internal reflection happens. At point  $U$ , refracted light bends away from normal.

$$\begin{aligned} \text{(b)} \quad n_1 \sin \theta_1 &= n_2 \sin \theta_2 \\ 1 \times \sin 45^\circ &= 1.51 \sin x \\ \sin x &= 1 \times \frac{\sin 45^\circ}{1.51} \\ &= 0.468 \\ x &= \sin^{-1}(0.468) \\ &= 27.9^\circ \end{aligned}$$

- High purity material allows the critical angle along the fibre optic to be consistent. All signals which enter the fibre will experience total internal reflection.

1. Figure 6.28 shows the path of light which travels from air to a prism.

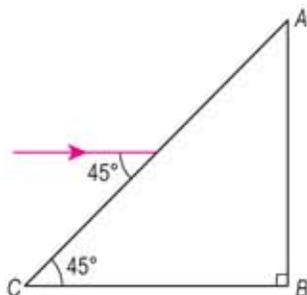


Figure 6.28

- (a) Determine the angle of refraction of light ray in the prism. The refractive index of the prism is 1.50.
- (b) Will the light ray experience total internal reflection at the side  $AB$  of the prism? Explain your answer. 🧠
2. Figure 6.29 shows a fine optical fibre made up of inner core which has a high refractive index surrounded by cladding material of a low refractive index.

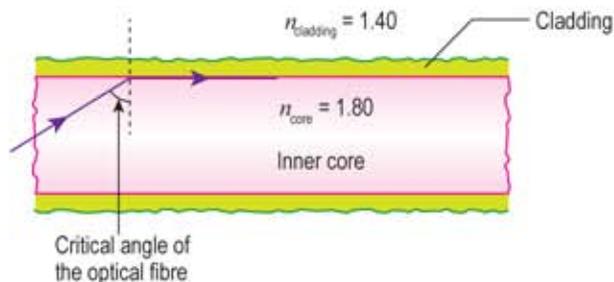
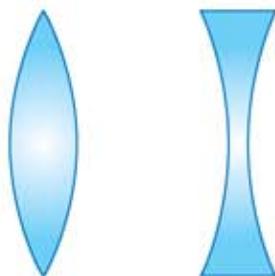


Figure 6.29

- (a) Determine the critical angle of the optical fibre.
- (b) What is the advantage of fine optical fibre? 🧠

## 6.3 Image Formation by Lenses

Lens is a piece of transparent material such as glass, perspex or plastic which has two surfaces with at least one surface curved. There are two main types of lenses, convex lens and concave lens as shown in Figure 6.30.



(a) Convex lens (b) Concave lens

Figure 6.30 Types of lenses

Lenses



<http://bt.sasbadi.com/p4251>



### Activity 6.7

**Aim:** To show convex lens as converging lens and concave lens as diverging lens

**Apparatus:** Convex lens, concave lens, ray box, power supply, three slit plate, pencil and ruler

**Material:** White paper

**Instructions:**

1. Set up the apparatus as shown in Figure 6.31.

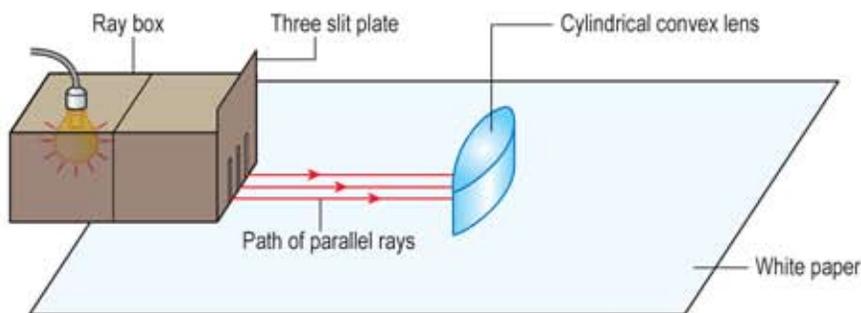


Figure 6.31

2. Trace the shape of the convex lens on white paper.
3. Direct three parallel rays of light from the ray box towards the convex lens. Observe the beams of light after passing through the convex lens and record your observations.
4. Make two marks on each path of light before and after passing through the lens. Remove the convex lens and draw a ray diagram for the paths of light.
5. Measure the distance between the centre of the lens,  $P$  and the point of focus,  $F$  of the three paths of light. Record your reading.
6. Repeat steps 2 to 4 by replacing the convex lens with a concave lens.



## Focal Length for Convex Lens

Convex lenses of different thickness have different focal lengths.

### Activity 6.8

**Aim:** To observe real image and estimate focal length of a convex lens using distant object

**Apparatus:** Convex lens, metre rule, lens holder and white screen

**Instructions:**

1. Set up the apparatus as shown in Figure 6.32.
2. Place the convex lens on the lens holder and position it towards an open window.

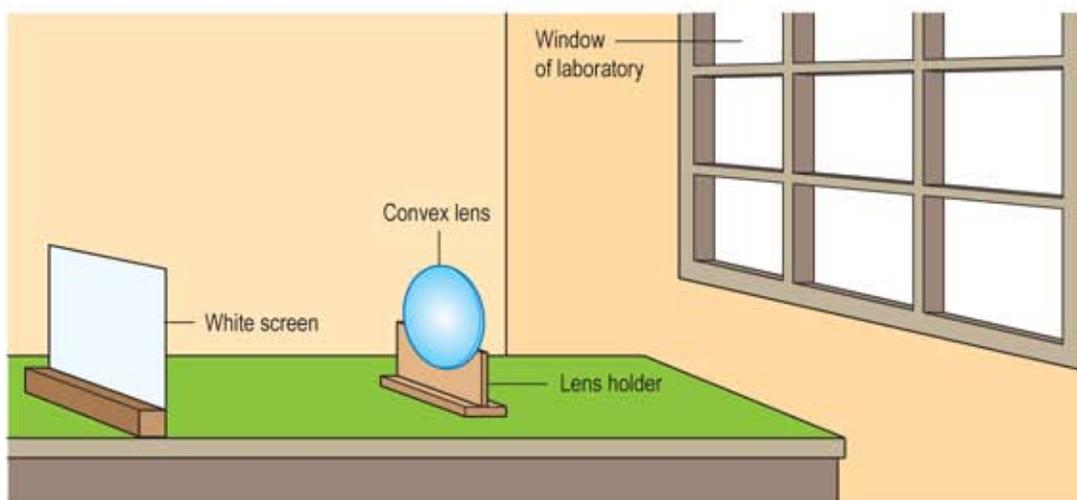


Figure 6.32

3. Place the white screen behind the lens and adjust its position closer or further from the lens until a sharp image is formed on the screen.
4. Measure the focal length of the lens, that is the distance between optical centre of the convex lens and the screen. Record your reading.

**Discussion:**

Why is the activity above not suitable to be used to estimate the focal length of a concave lens?

## Position and Characteristics of Images Formed by Lenses

Ray diagrams can be used to determine the position and characteristics of images formed by convex lens and concave lens. There are three rays used in the construction of a ray diagram (See Table 6.6).

**Table 6.6** Rays used in the drawing of a ray diagram

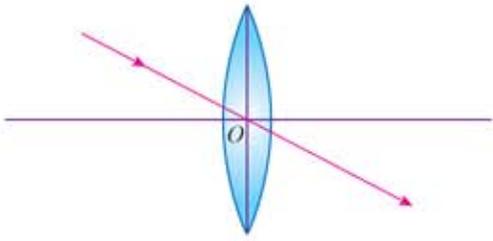
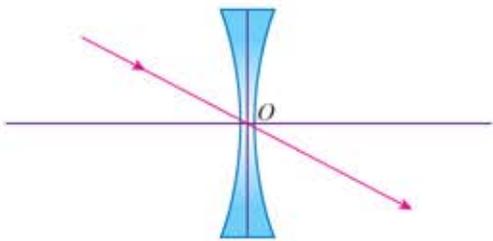
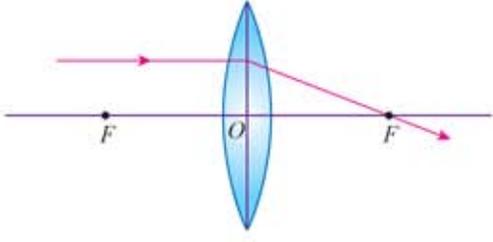
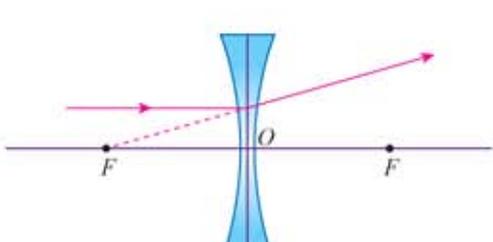
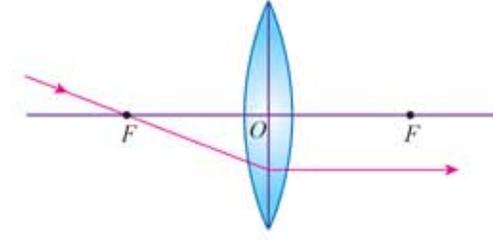
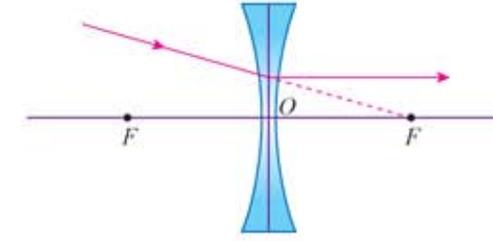
Convex Lens	Concave Lens
<p>1. Ray which passes through the optical centre travels in a straight line through the optical centre without being refracted.</p> 	<p>1. Ray which passes through the optical centre travels in a straight line through the optical centre without being refracted.</p> 
<p>2. Ray which is parallel to the principal axis is refracted and passes through the focal point, <math>F</math>.</p> 	<p>2. Ray which is parallel to the principal axis is refracted and appears to come from focal point, <math>F</math>.</p> 
<p>3. Ray which passes through the focal point, <math>F</math> is refracted parallel to the principal axis.</p> 	<p>3. Ray which travels towards focal point, <math>F</math> is refracted parallel to the principal axis.</p> 

Table 6.7 and Table 6.8 show ray diagrams as well as characteristics of images for convex lens and concave lens respectively.



Table 6.7 Formation of image by convex lens

Object position	Ray diagram	Image position	Characteristics of image
Object at infinity		<ul style="list-style-type: none"> <li>Image distance: <math>v = f</math></li> <li>Image at <math>F</math></li> </ul>	<ul style="list-style-type: none"> <li>Real</li> <li>Inverted</li> <li>Diminished</li> </ul>
Object $O$ beyond $2F$ ( $u > 2f$ )		<ul style="list-style-type: none"> <li>Image distance: <math>f &lt; v &lt; 2f</math></li> <li>Image between <math>F</math> and <math>2F</math></li> </ul>	<ul style="list-style-type: none"> <li>Real</li> <li>Inverted</li> <li>Diminished</li> </ul>
Object $O$ at $2F$ ( $u = 2f$ )		<ul style="list-style-type: none"> <li>Image distance: <math>v = 2f</math></li> <li>Image at <math>2F</math></li> </ul>	<ul style="list-style-type: none"> <li>Real</li> <li>Inverted</li> <li>Same size as object</li> </ul>
Object $O$ between $F$ and $2F$ ( $f < u < 2f$ )		<ul style="list-style-type: none"> <li>Image distance: <math>v &gt; 2f</math></li> <li>Image beyond <math>2F</math></li> </ul>	<ul style="list-style-type: none"> <li>Real</li> <li>Inverted</li> <li>Magnified</li> </ul>
Object $O$ at $F$ ( $u = f$ )		<ul style="list-style-type: none"> <li>Image at infinity</li> </ul>	<ul style="list-style-type: none"> <li>Virtual</li> <li>Upright</li> <li>Magnified</li> </ul>
Object $O$ between $F$ and optical centre ( $u < f$ )		<ul style="list-style-type: none"> <li>Image distance: <math>v &gt; u</math></li> </ul>	<ul style="list-style-type: none"> <li>Virtual</li> <li>Upright</li> <li>Magnified</li> </ul>

## Activity 6.9

**Aim:** To determine the position and characteristics of images formed by convex lens and concave lens for different object distances

**Apparatus:** Convex lens ( $f = 10$  cm), concave lens ( $f = -10$  cm), ray box with transparent paper marked with an arrow as object, power supply, lens holder, white screen and metre rule

**Material:** Graph paper

### A Convex lens

**Instructions:**

1. Set up the apparatus as shown in Figure 6.33.

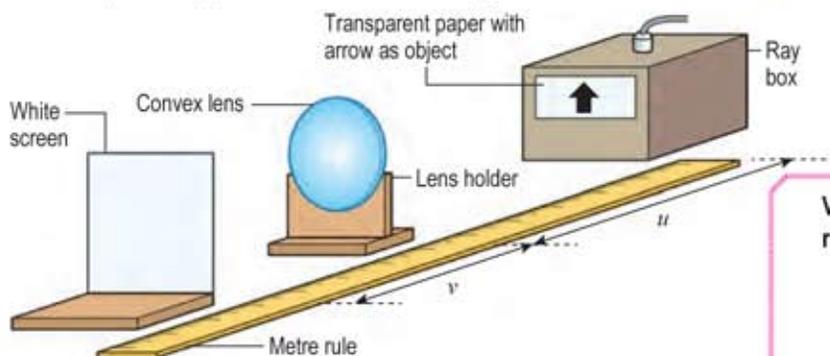


Figure 6.33

Download table



<http://bt.sasbadi.com/p4255a>

Video on steps to draw ray diagram



<http://bt.sasbadi.com/p4255b>

2. Place the convex lens so that its object distance,  $u = 30.0$  cm, that is  $u > 2f$ . Adjust the position of the screen until a sharp image of the arrow is formed on the screen.
3. Observe the image formed on the screen and record its characteristics in a table. You can download and print the table from the website given.
4. Choose a suitable scale and draw the ray diagram for convex lens of  $f = 10.0$  cm and  $u = 30.0$  cm on a piece of graph paper. You can scan the QR code given for steps to draw complete ray diagrams.
5. Determine the position of image and record it in the table downloaded.
6. Repeat steps 2 to 5 for object distance  $u = 20.0$  cm,  $15.0$  cm and  $8.0$  cm.

### B Concave lens

**Instructions:**

1. Hold the concave lens at object distance,  $u = 20.0$  cm,  $15.0$  cm and  $10.0$  cm in front of your eyes and look at the writing in your Physics textbook through the concave lens. Record the characteristics of the images you see in the table downloaded.
2. Draw the ray diagrams for concave lens of  $f = -10.0$  cm with  $u = 20.0$  cm,  $15.0$  cm and  $10.0$  cm on a piece of graph paper.

**Discussion:**

1. State the positions of convex lens which form real image and virtual image.
2. What are the common characteristics for real images formed by a convex lens?
3. What are the characteristics of images formed by a concave lens?

Table 6.8 Formation of image by concave lens

Object position	Ray diagram	Image position	Characteristics of image
Object $O$ beyond $2F$ ( $u > 2f$ )		<ul style="list-style-type: none"> <li>Between optical centre and focal point</li> <li>Image distance: <math>v &lt; f</math></li> </ul>	<ul style="list-style-type: none"> <li>Virtual</li> <li>Upright</li> <li>Diminished</li> </ul>
Object $O$ between $F$ and optical centre ( $u < f$ )		<ul style="list-style-type: none"> <li>Between optical centre and focal point</li> <li>Image distance: <math>v &lt; f</math></li> </ul>	<ul style="list-style-type: none"> <li>Virtual</li> <li>Upright</li> <li>Diminished</li> </ul>

### Linear Magnification

Observe Photograph 6.3. When an object is seen through a magnifying glass at a distance less than its focal length, the image formed is magnified. The size of the image formed by a convex lens depends on the position of the object.



Photograph 6.3 Image magnified through a magnifying glass



### Activity 6.10

ICS

**Aim:** To generate ideas on magnification of image with the help of ray diagrams

**Instructions:**

1. Work in pairs.
2. Visit the websites given on the simulation of magnification using convex lens.
3. Choose a suitable object height. Begin with this object at a position far from the convex lens.
4. Move the object slowly closer to the lens. Observe how the position and size of the image change.
5. Sketch ray diagrams for the following situations:
  - (a) Image size smaller than object size.
  - (b) Image size larger than object size.

**Discussion:**

1. Which position of the convex lens forms
  - (a) a magnified image?
  - (b) a diminished image?
2. What is the relationship between image height, object height, image distance and object distance?

**Simulation of magnification of image**



<http://bt.sasbadi.com/p4257a>



<http://bt.sasbadi.com/p4257b>

Activity 6.10 shows that image size formed by a lens depends on the position of the object from the centre of the lens. Comparison between image size and object size is made based on the ratio of image height to object height. This ratio is known as **linear magnification,  $m$** .

$$\text{Linear magnification, } m = \frac{\text{image height, } h_i}{\text{object height, } h_o}$$

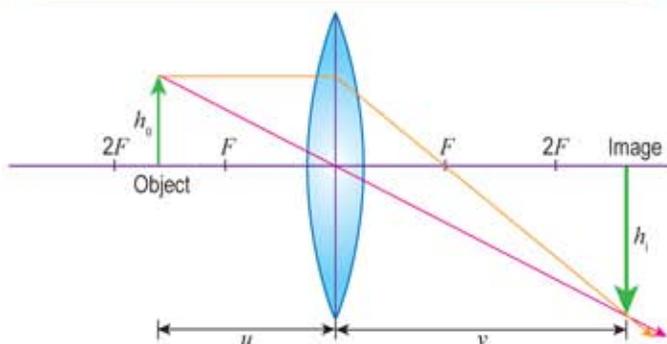


Figure 6.34 Formation of image by convex lens

Based on Figure 6.34, ratio of image height to object height is also the same as the ratio of image distance to object distance.

$$\text{Linear magnification, } m = \frac{\text{image distance, } v}{\text{object distance, } u}$$

As such, linear magnification can be formulated as,

$$m = \frac{h_i}{h_o} = \frac{v}{u}, \text{ where } \begin{array}{l} h_i = \text{image height} \\ h_o = \text{object height} \\ v = \text{image distance} \\ u = \text{object distance} \end{array}$$

### Info File

Linear magnification,  $m$  does not have a unit.

$m < 1$	Image diminished
$m = 1$	Image same size as object
$m > 1$	Image magnified

## Formative Practice 6.3

Figure 6.35 shows an image seen through a convex lens with focal length of 10 cm.

1. What are the characteristics of the image?
2. Draw a ray diagram to show how the image in the figure is formed. 🍷
3. Suggest a suitable position to place the object to produce an inverted image. 🍷

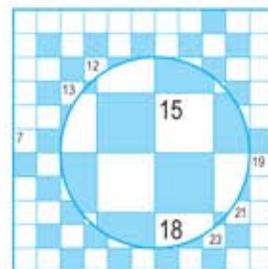


Figure 6.35