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THIN LENSES

A lens is generally a transparent material with at least one curved surface. Lenses are usually made of glass, clear plastic or perspex. They are found in cameras, spectacles and even human eye. A lens works by refracting the light traversing it.

Types of Lenses

There are two types of lenses, namely, convex (converging) and concave (diverging) lenses. Convex lenses are thickest at the middle while concave lenses are thinnest at the middle. See figure 1.1 (a) and (b).

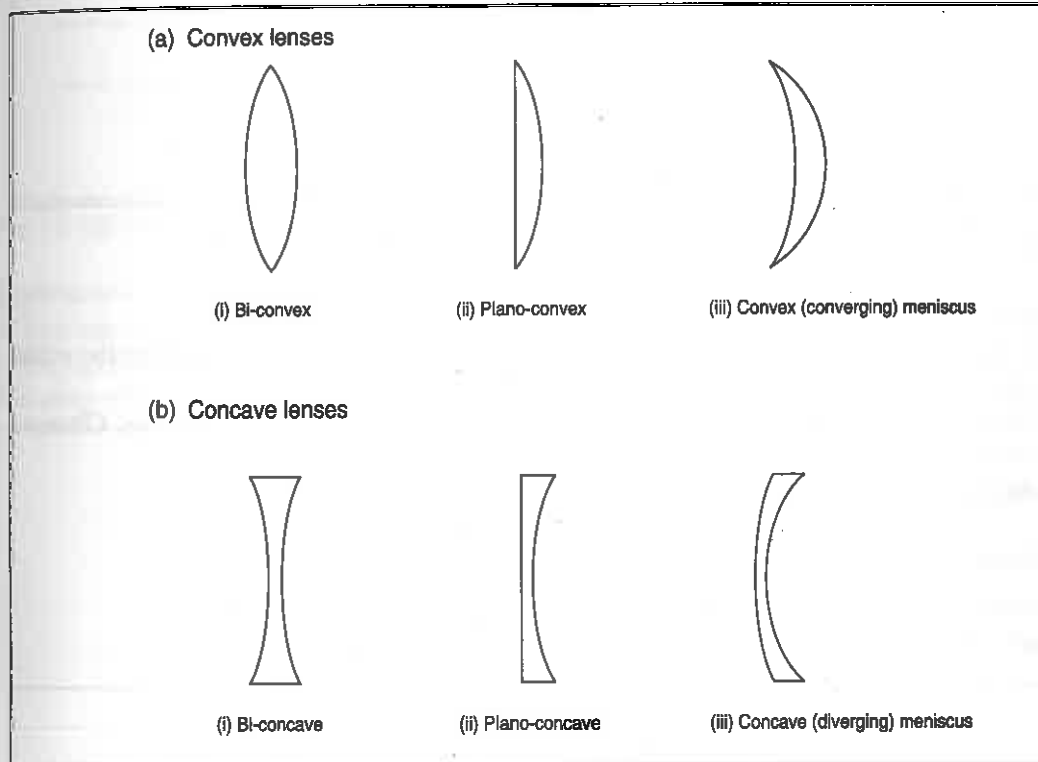


Fig. 1.1: Types of lenses

Effects of Lenses on Parallel Rays of Light

EXPERIMENT 1.1: To investigate the effect of lenses on parallel rays of light

(a) Using Rays from the Sun

Apparatus

Card with parallel slits, plane mirror, cylindrical bi-convex lens, white sheet of paper, cylindrical bi-concave lens.

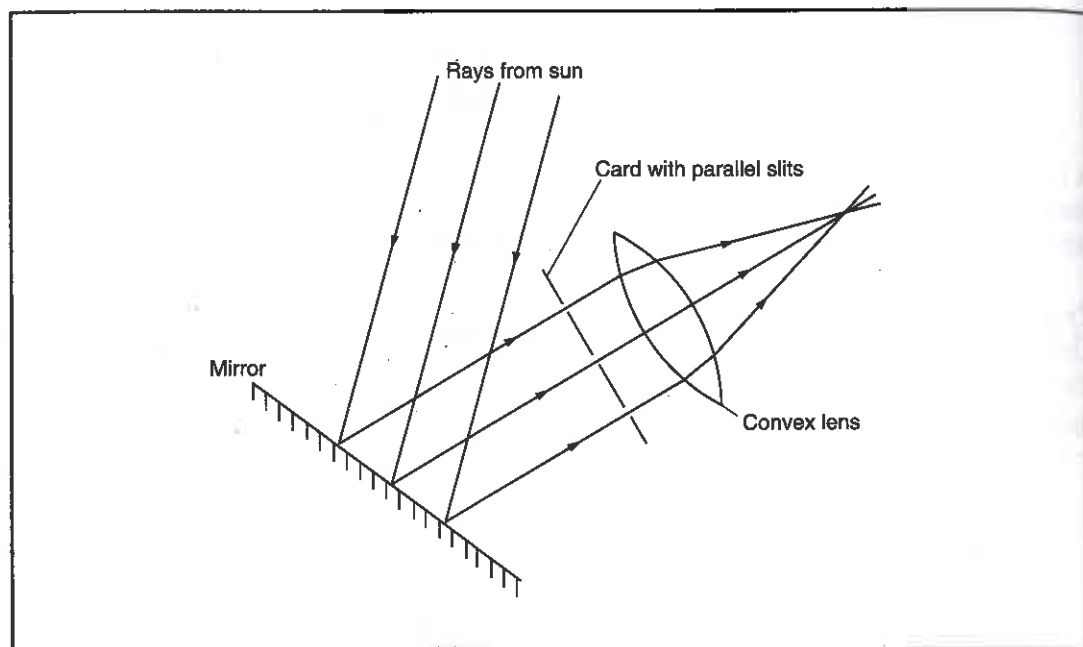


Fig 1.2: Effect of lenses on parallel rays of light

Procedure

- Using a plane mirror, direct a beam of sunlight onto the parallel slits placed on the white sheet of paper, as shown in figure 1.2.
- Place the bi-convex lens in the path of parallel beam obtained from the slits. Observe what happens to the rays.
- Repeat the procedure using bi-concave lens.

(b) Using Ray box**Apparatus**

Ray box, cylindrical lenses (convex and concave), white sheet of paper.

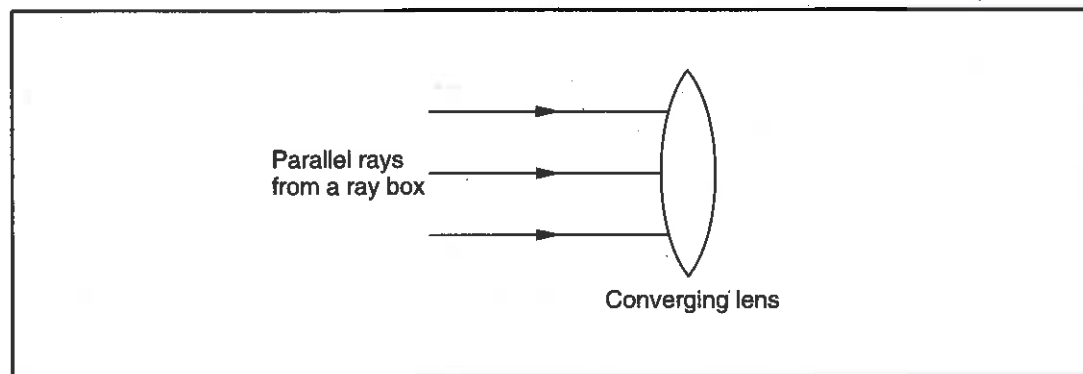


Fig. 1.3: Parallel rays of light towards convex lens

Procedure

- Direct a parallel beam of light from a ray box towards a convex lens, as shown in figure 1.3. Observe what happens to the rays on the white sheet of paper.
- Repeat the procedure with a concave lens.

Observation

When a convex lens is used, the rays are converged at a point on the paper and then diverge as they continue. When a concave lens is used, then rays diverge as if they were from a point in front of the lens, see figure 1.4 (a) and (b).

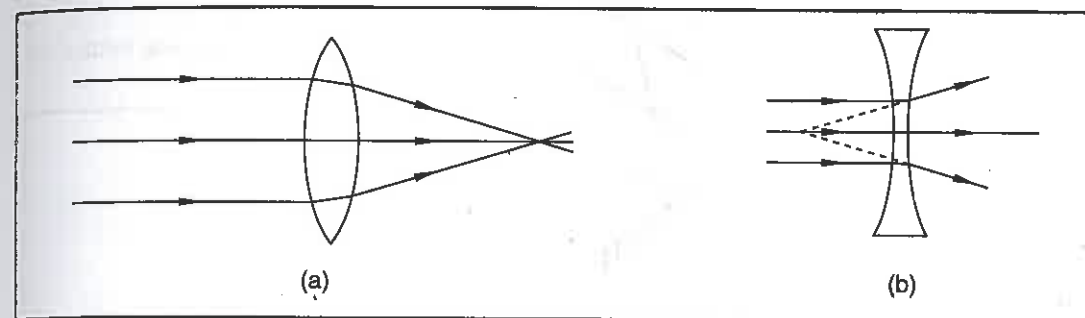


Fig. 1.4: Effect of lenses on parallel rays of light

Explanation

A lens can be considered as an assembly of prisms, as shown in figure 1.5 (a) and (b). Each prism refracts light as in the diagram. The mid-segment acts like a glass block (rectangular) and a ray of light incident normally passes on undeviated.

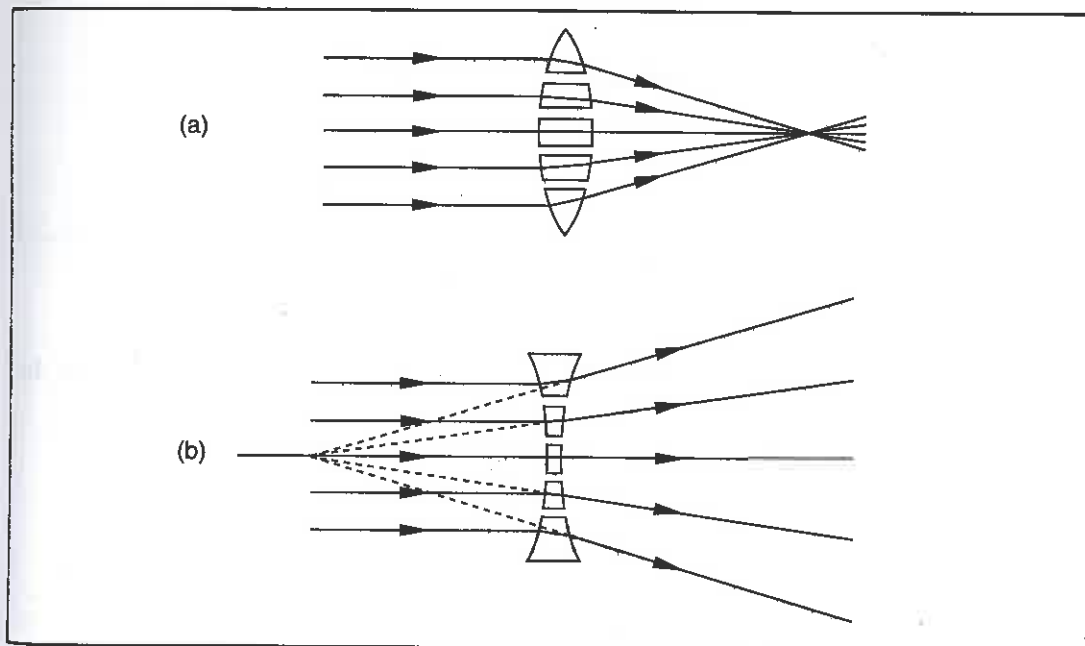


Fig. 1.5: Lenses as assembly of prisms

The diagrams explain why convex lenses have a converging effect and concave lenses a diverging effect.

The point of convergence or divergence is referred to as the **principal focus**. For a converging lens, the principal focus is real (actual rays converge at the point) while for a diverging lens, the principal focus is virtual (rays appear to come from the point).

Definitions of Terms

Centre of Curvature, C

The centre of curvature is the centre of the sphere of which the surface of the lens is part. Since a lens has two surfaces, it has two centres of curvature, see figure 1.6 (a) and (b).

In the case of plano-convex or plano-concave lens, the lens has only one centre of curvature, since the centre of the plane surface is at infinity.

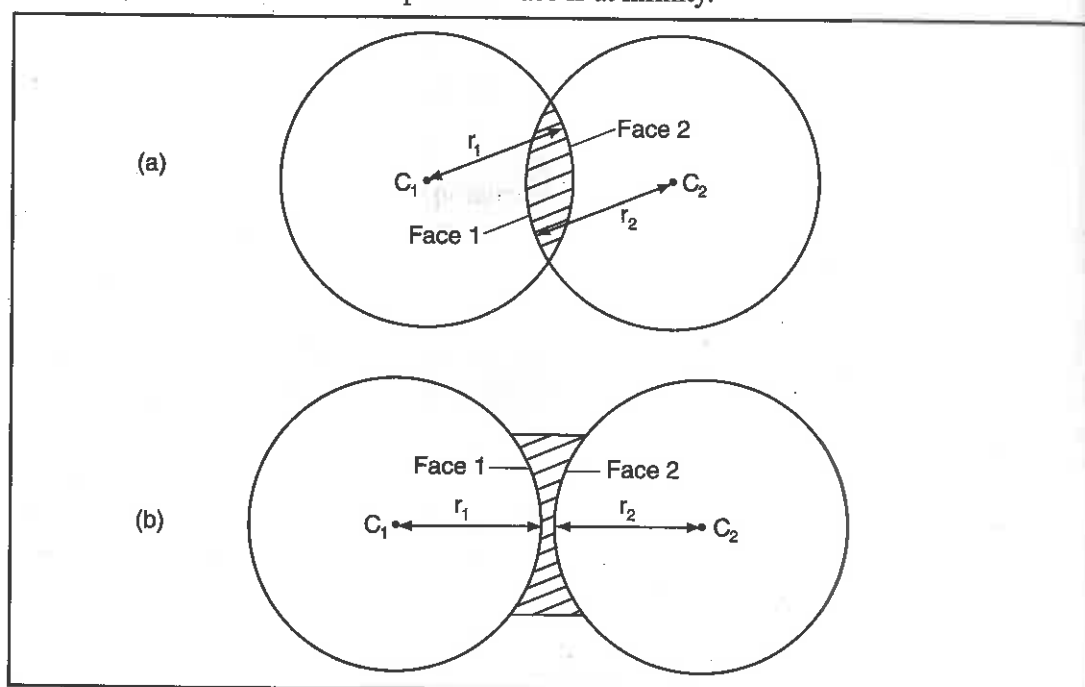


Fig. 1.6: Centres and radii of curvature

Radius of Curvature, r

The radius of curvature is the radius of the sphere of which the surface of the lens is part. In figure 1.6 (a) and (b), it is given by r_1 and r_2 .

Principal Axis

The principal axis is the imaginary line passing through the centres of curvatures.

Optical Centre, O

The optical centre is the point on the principal axis midway between the lens surfaces. Any ray of light through this point passes on undeviated.

Principal Focus, F

For a converging lens, the principal focus is the point on the principal axis to which rays parallel and close to the principal axis converge after refraction by the lens. For a diverging lens, it is that point on the principal axis from which rays parallel and close to the principal axis appear to diverge after refraction by the lens, see figure 1.7 (a) and (b).

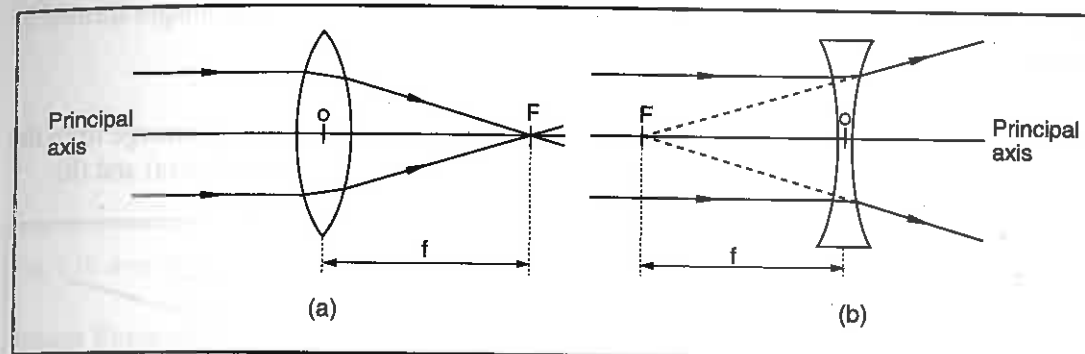


Fig. 1.7: Principal focus

F – Principal focus.

O – Optical centre.

f – Focal length.

A lens has two principal foci, one on either side. The principal focus of a converging lens is real while that of a diverging lens is virtual. Rays that are parallel and close to the principal axis or make very small angles with the principal axis are known as **paraxial rays**. Those rays parallel and far away from the principal axis are known as **marginal rays**.

Focal Length, f

The focal length is the distance between the optical centre and the principal focus. The focal length of a converging lens is real, while that of a diverging lens is virtual.

Focal Plane

Consider parallel rays of light, which are not parallel to the principal axis and incident to a lens as shown in figure 1.8 (a) and (b).

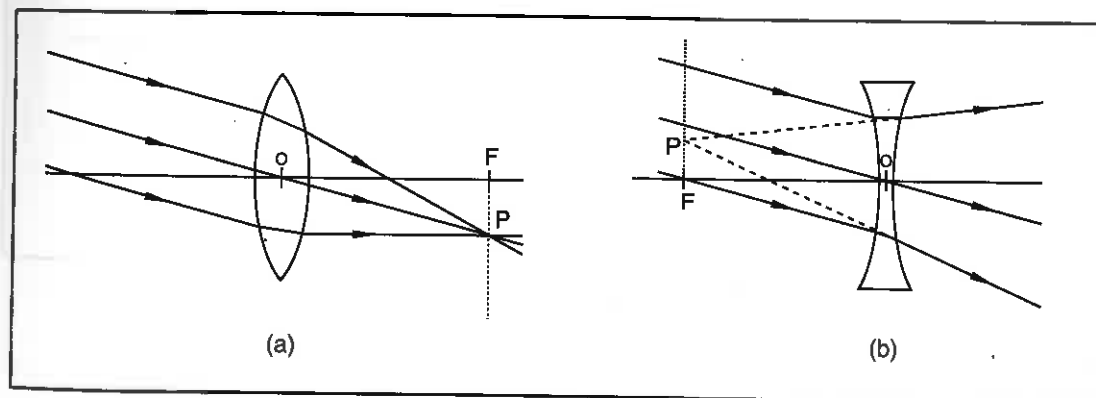


Fig. 1.8: Focal plane

After refraction by the lens, the rays converge at or appear to diverge from a point P on a plane perpendicular to the principal axis and passing through the principal focus F. This plane is called the **focal plane**.

Ray Diagrams

There are three important rays that are used in diagrams for the location of images formed by lenses:

(i) A Ray of Light Parallel to the Principal Axis

This ray passes through the principal focus (for a convex lens) or appears to emerge from the principal focus (for a concave lens) after refraction by the lens, see figure 1.9 (a) and (b).

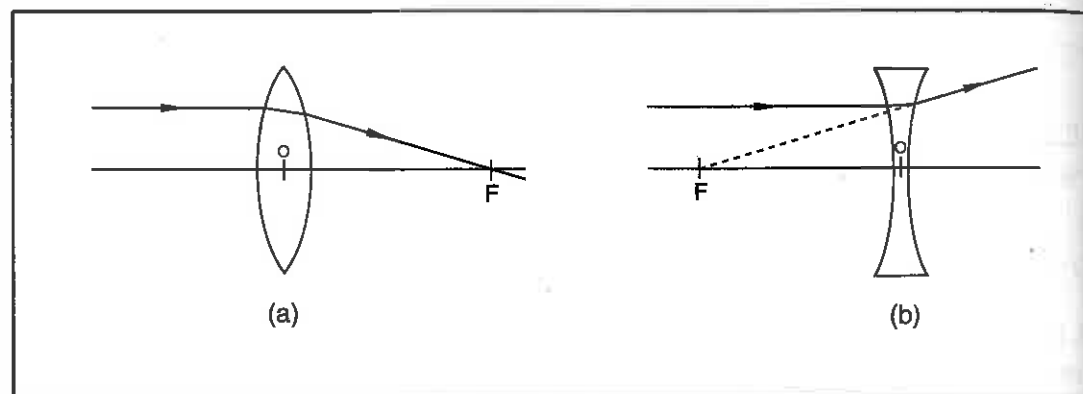


Fig 1.9: A ray of light parallel to principal axis

(ii) A Ray of Light Passing (or appearing to pass through) the Principal Focus F

This ray emerges parallel to the principal axis after refraction by the lens, see figure 1.10.

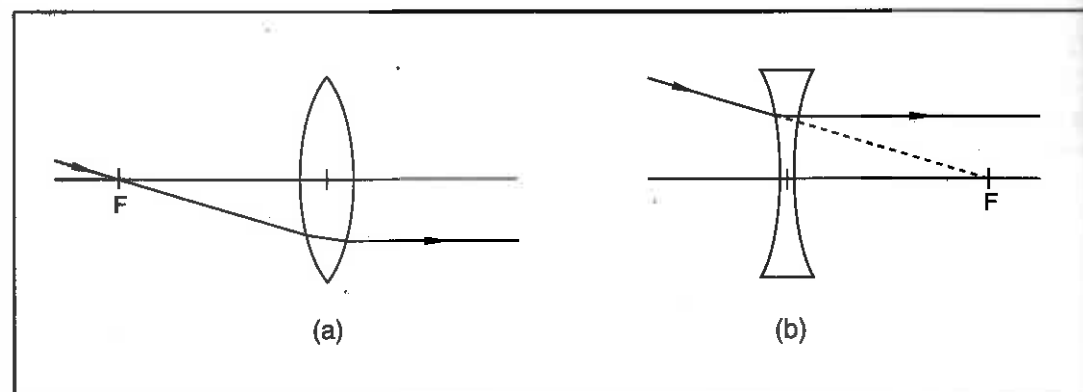


Fig 1.10: A ray of light through F (or appearing to pass through F)

(iii) A Ray of Light Through the Optical Centre

This ray passes on undeviated, see figure 1.11 (a) and (b).

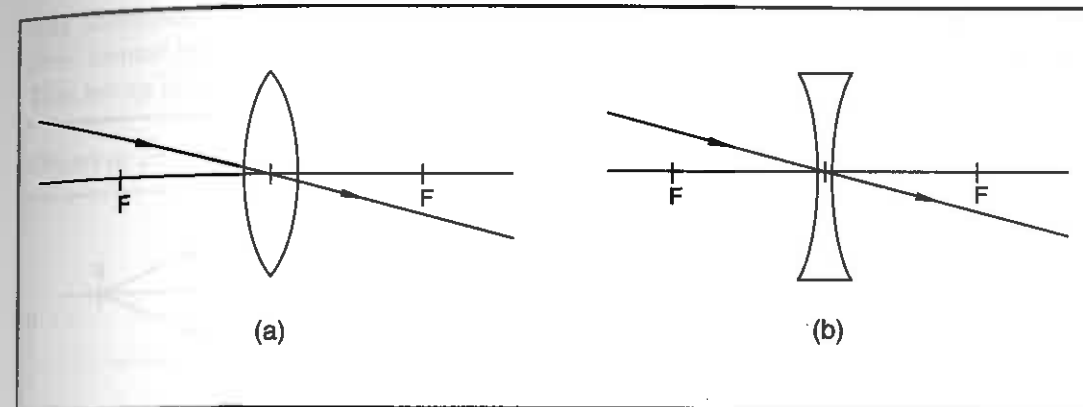


Fig. 1.11: A ray through the optical centre

Image Formation by Lenses

Ray diagrams can be used to locate images formed by lenses. It is important to note that:

- (i) real rays and real images are drawn in full lines.
- (ii) virtual rays and virtual images are drawn in broken lines.
- (iii) to locate the image, two (or three) rays from the tip of the object are drawn (these should be rays whose direction after refraction by the lens are known).

Where the rays (real or virtual) intersect after refraction by the lens gives the tip of the image. If the object stands and is perpendicular to the principal axis, the image will also be perpendicular to the principal axis. To complete the image, a line is drawn perpendicular to the principal axis from the tip of the image.

- (iv) should the foot of the object cross the principal axis, the method explained in (iii) above is used to get the foot of the image. The top is joined to the foot to get the image.
- (v) converging and diverging lenses are represented by the symbols shown in figure 1.12 (a) and (b) respectively.

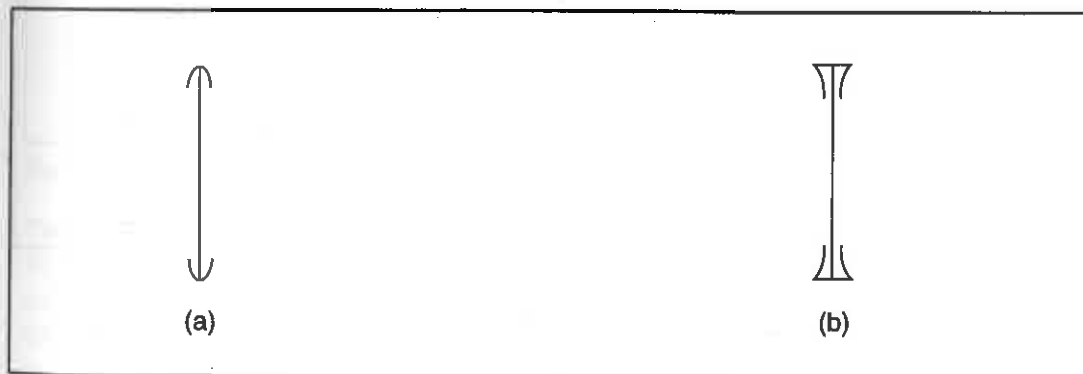


Fig. 1.12: Symbols used for lenses

Characteristics of Images formed by Lenses

Converging Lenses

Object at Infinity

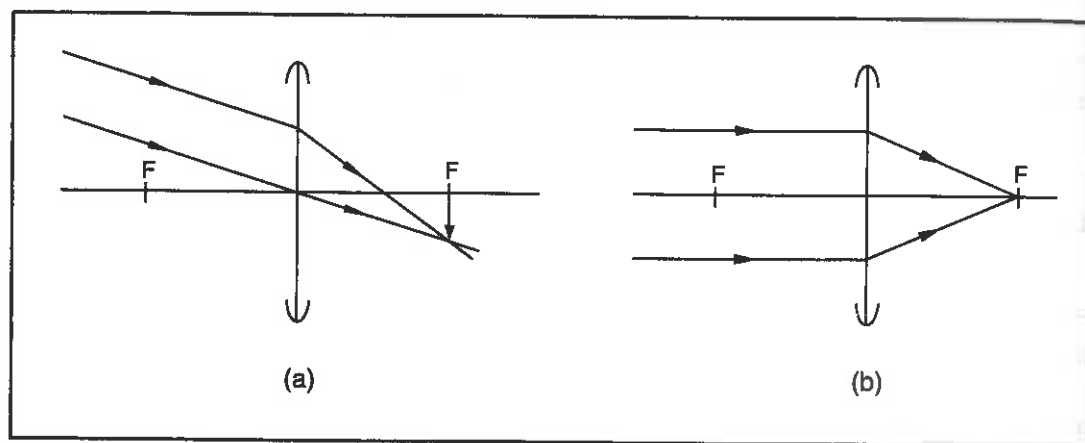


Fig. 1.13: Object at infinity

The parallel rays from the object converge after refraction by the lens. The image is:

- (i) real.
- (ii) inverted.
- (iii) diminished.
- (iv) formed at F .

This set-up is used in the objective lens of a telescope.

Object beyond $2F$

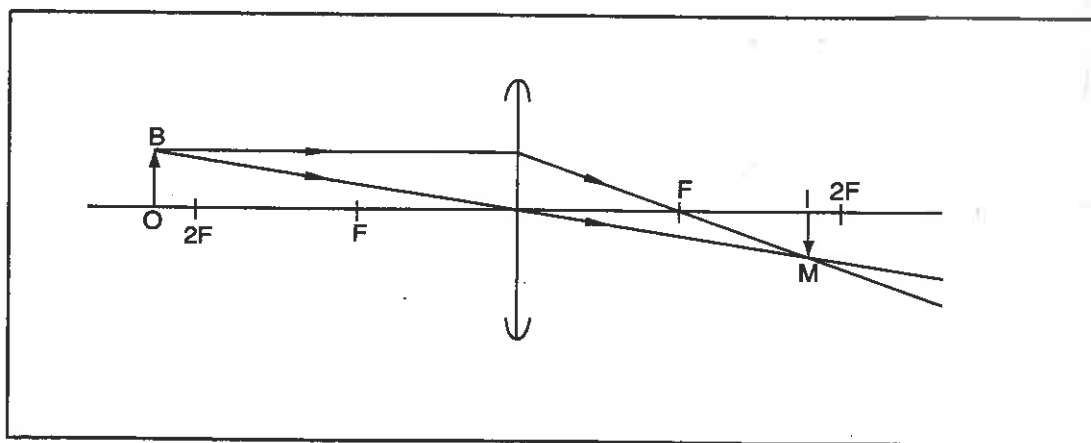


Fig. 1.14: Object beyond $2F$

- (i) real.
- (ii) inverted.

- (iii) diminished.
 - (iv) formed between F and $2F$, on the other side of the lens.
- This set-up is used in the camera and human eye.

Object at $2F$

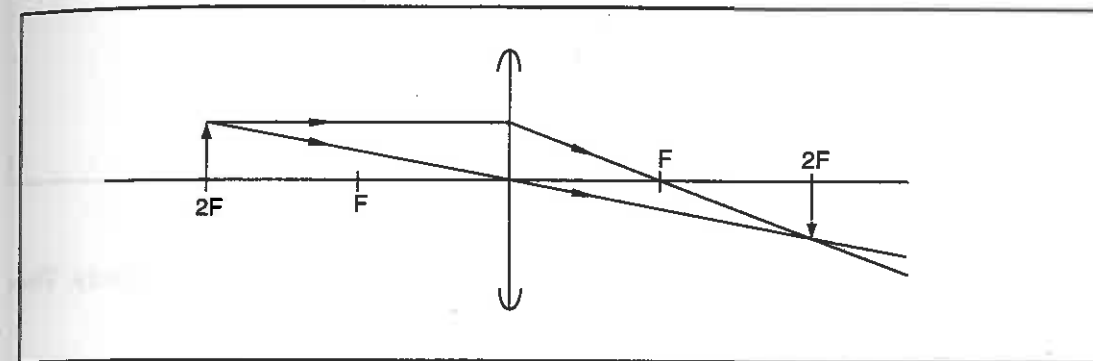


Fig. 1.15: Object at $2F$

The image is:

- (i) real.
- (ii) inverted.
- (iii) same size as the object.
- (iv) formed at $2F$, on the other side of the lens.

The set-up is used in the terrestrial telescope.

Object between F and $2F$

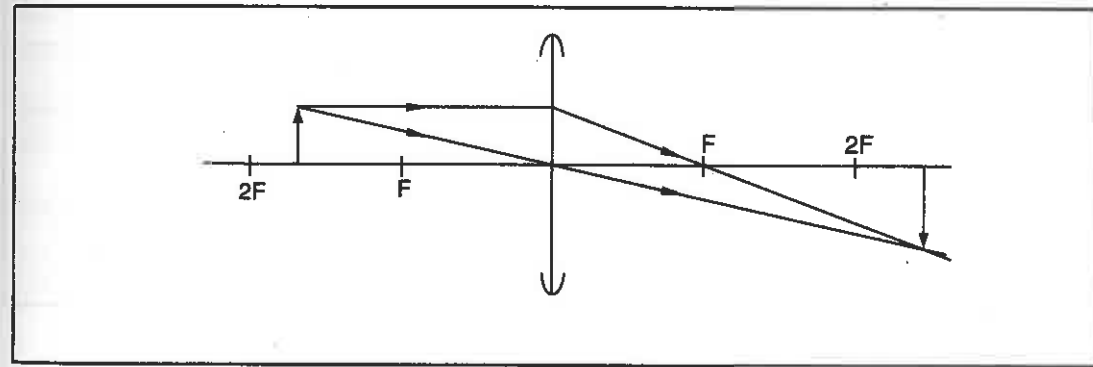
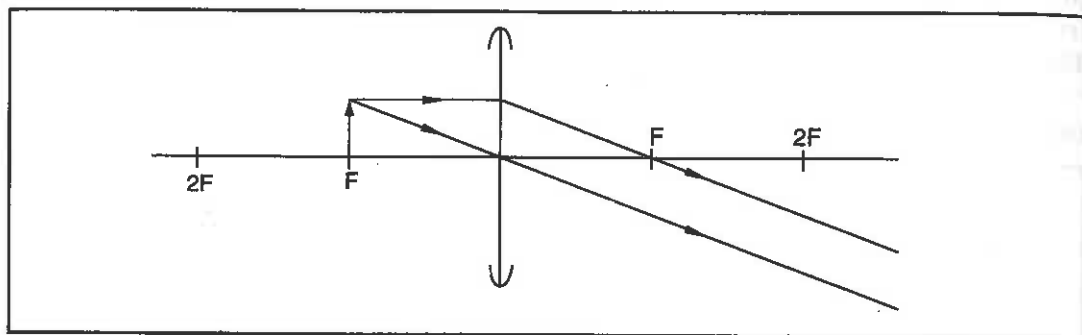


Fig. 1.16: Object between F and $2F$

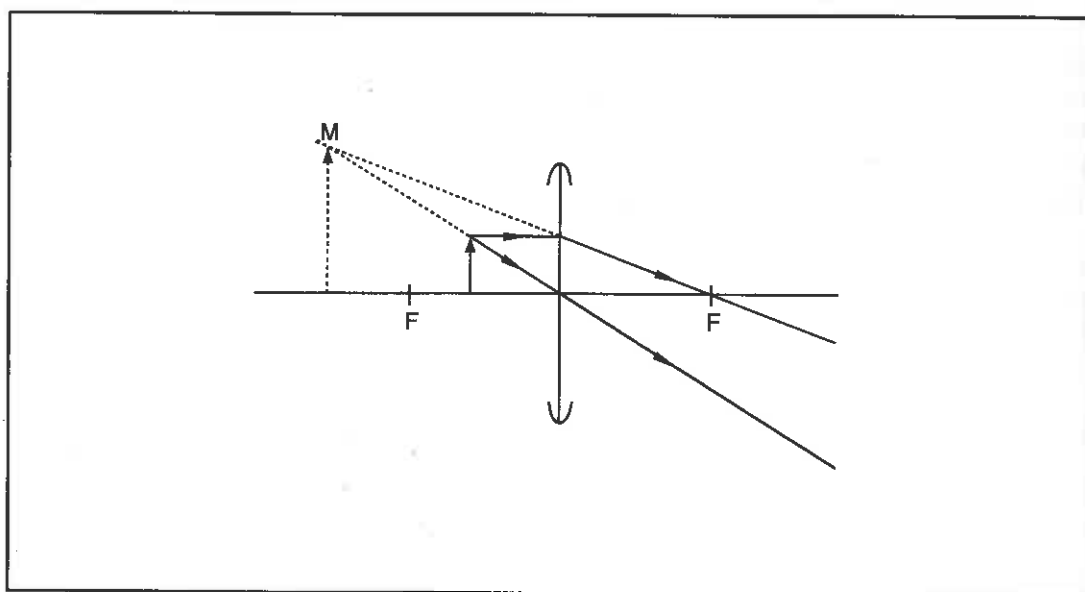
The image is:

- (i) real.
- (ii) inverted.
- (iii) magnified.
- (iv) formed beyond $2F$, on the other side of the lens.

This set-up is used in projectors, microscope objective and photographic enlarger.

Object at F Fig. 1.17: Object at F

The rays emerge parallel after refraction by the lens. The image is formed at infinity. This set-up is used in searchlights and spotlights.

Object between F and LensFig. 1.18: Object between F and lens

The rays diverge after refraction. If they are produced backwards, they meet at M . The image is :

- (i) virtual.
- (ii) erect.
- (iii) magnified.
- (iv) formed on the same side as object.

This set-up is used in magnifying glasses and the microscope.

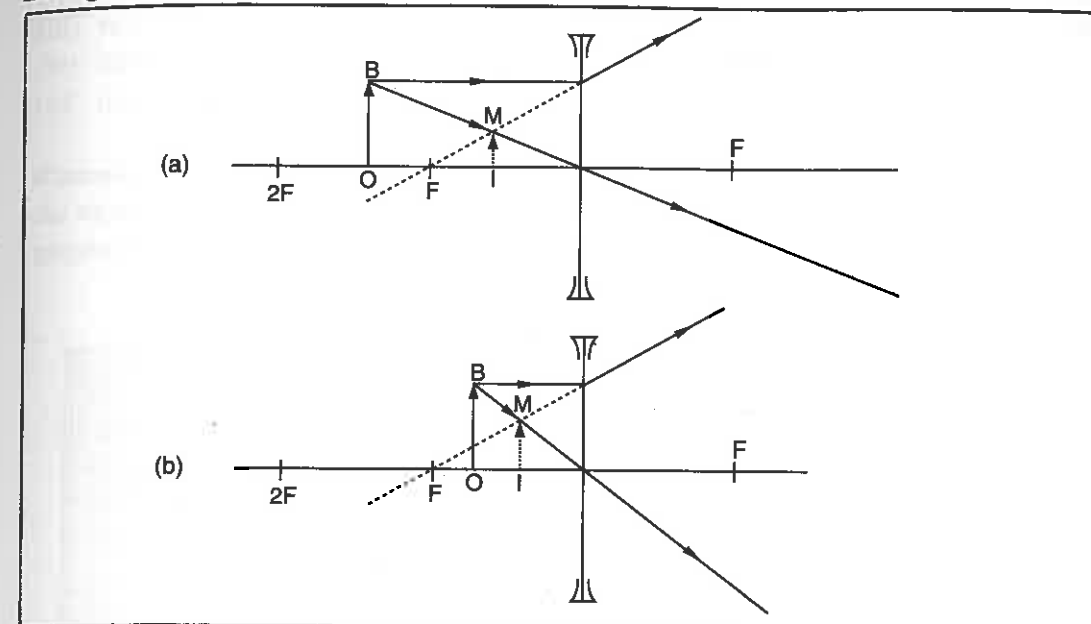
Diverging Lenses

Fig. 1.19: Formation of images by diverging lenses

For concave lenses, rays diverge after refraction. When produced backwards, they intersect at M , see figure 1.19. IM is the virtual image of OB . The image is always:

- (i) virtual.
- (ii) erect.
- (iii) diminished.

This set-up is used in spectacles (to correct short sightedness), in the peephole (since concave lenses have a large field of view), and as eyepiece in the Galilean telescope.

Linear Magnification

The linear magnification, m , is defined as the ratio of the height of image to the height of the object.

$$\text{Magnification, } m = \frac{\text{height of image}}{\text{height of object}}$$

Consider an object OB placed in front of a convex lens, as shown figure 1.20.

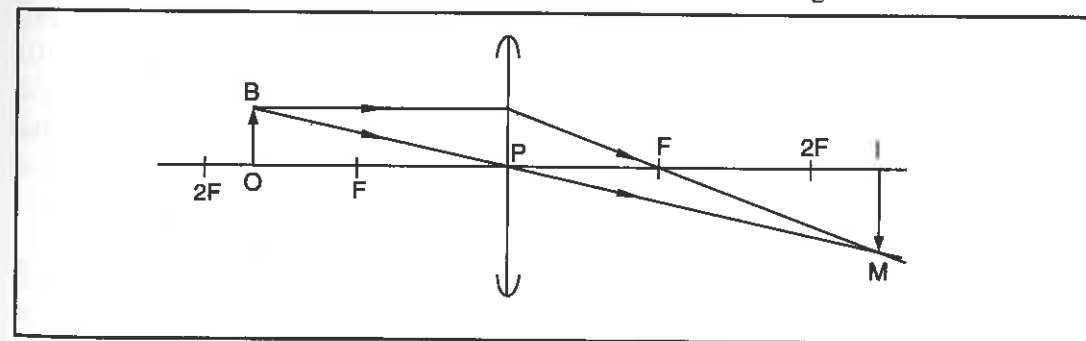


Fig. 1.20: Linear magnification

OB is the height of the object and IM the height of image. Let u be the object distance, PO , and v the image distance, PI .

The triangles POB and PIM are similar. Therefore;

$$\frac{IM}{OB} = \frac{PI}{PO}$$

$$\text{Thus, } \frac{\text{image height}}{\text{object height}} = \frac{\text{image distance}}{\text{object distance}}$$

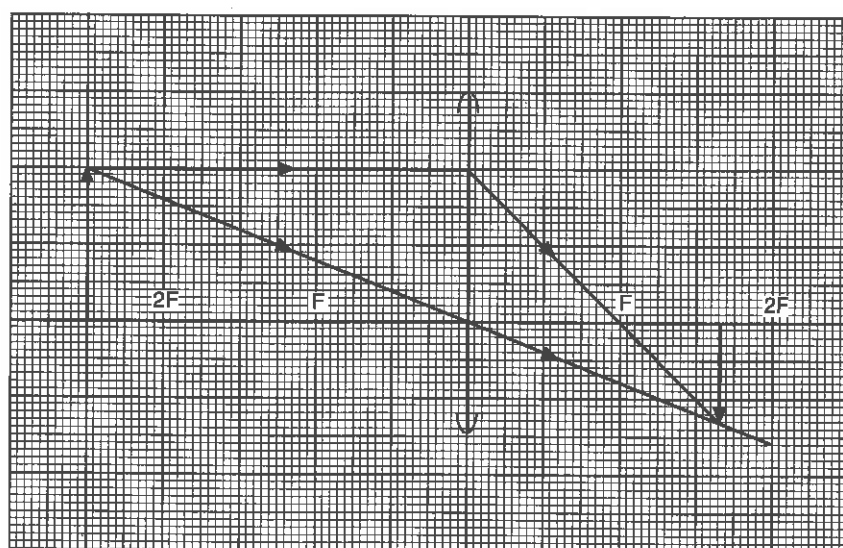
$$\text{Magnification, } m = \frac{\text{image distance}}{\text{object distance}}$$

$$m = \frac{v}{u}$$

Example 1

An object 10 cm high is placed 25 cm from a converging lens of focal length 10 cm. By scale drawing, find the position, size and nature of the image.

Solution



Scale:

Horizontal: 1 cm rep 5 cm.

Vertical: 1 cm rep 5 cm.

Fig 1.21

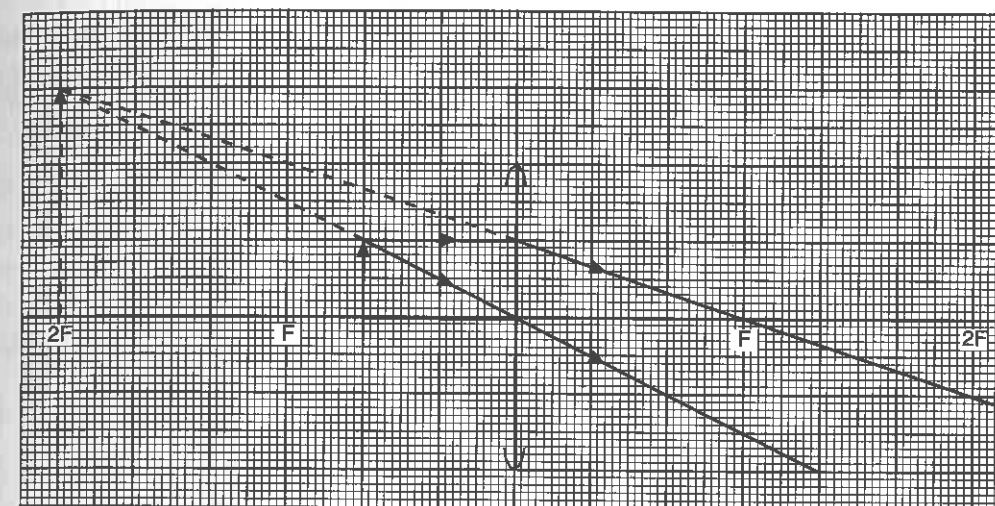
The image is:

- (i) 6.5 cm tall.

- (ii) 16.5 cm from the lens, on the opposite side of the lens.
- (iii) real.
- (iv) diminished.
- (v) inverted.

Example 2

An object 1 cm high is placed 2 cm from a converging lens of focal length 3 cm. Find, by graphical construction, the position, size and nature of the image.



Scale:

Horizontal: 1 cm rep 1 cm.

Vertical: 1 cm rep 1 cm.

Fig. 1.22

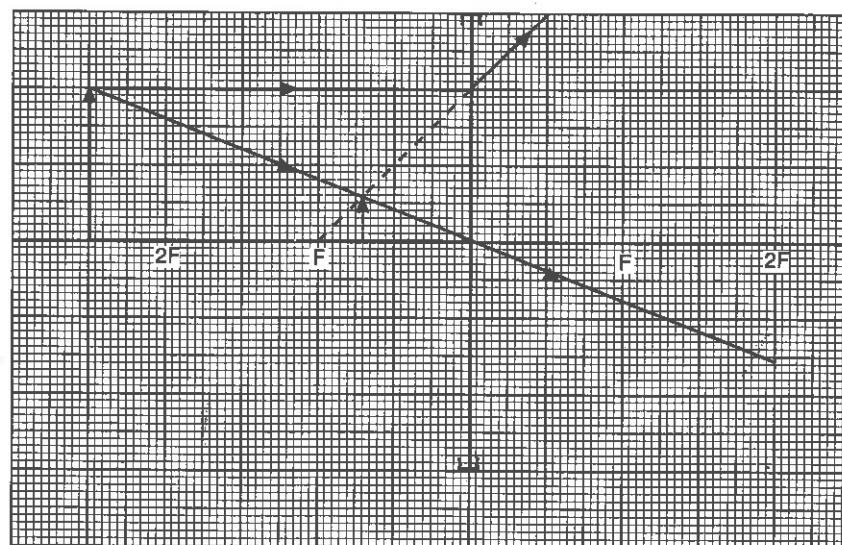
The image is:

- (i) 6 cm from the lens, on the same side as the object.
- (ii) 3 cm tall.
- (iii) virtual.
- (iv) erect.
- (v) magnified.

Example 3

An object 2 cm high is placed 5 cm from a diverging lens of focal length 2 cm. Find, by graphical construction, the position, size and nature of the image.

Solution



Scale:

Horizontal: 1 cm rep 1 cm.

Vertical: 1 cm rep 1 cm.

Fig. 1.23

The image is:

- (i) 1.4 cm from the lens, on the same side as the object.
- (ii) 0.6 cm tall.
- (iii) virtual.
- (iv) erect.
- (v) diminished.

The Lens Formula

Consider an image formed by a converging lens, as shown in the figure 1.24.

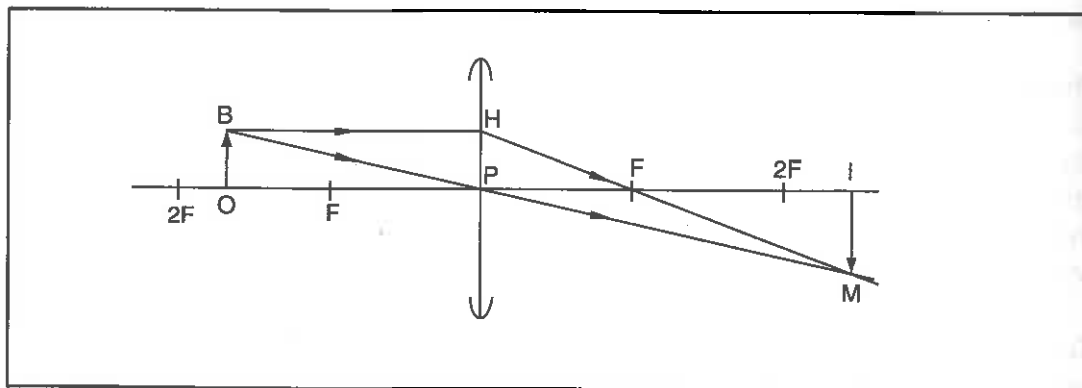


Fig. 1.24: Lens formula

In the figure, PO is the object distance, u, PI the image distance, v and PF the focal length, f.

OB = PH

Triangles POB and PIM are similar. Therefore;

$$\frac{OB}{IM} = \frac{PO}{PI} = \frac{u}{v} \dots\dots\dots (1)$$

Similarly, triangles PFH and IFM are similar. So;

$$\frac{PH}{IM} = \frac{PF}{IF} \dots\dots\dots (2)$$

But PF = f

IF = PI - PF

= v - f

Substituting these values in equation (2);

$$\frac{OB}{IM} = \frac{f}{v - f} \dots\dots\dots (3)$$

Combining equations (1) and (3);

$$\frac{u}{v} = \frac{f}{v - f}$$

$$uv - uf = vf$$

$$uv = vf + uf$$

$$uv = f(v + u)$$

$$\frac{uv}{f} = v + u$$

$$\frac{1}{f} = \frac{v+u}{uv} = \frac{v}{uv} + \frac{u}{uv}$$

$$\frac{1}{f} = \frac{1}{u} + \frac{1}{v}$$

This equation is known as the **lens formula** and holds for both converging and diverging lens.

Note:

When numerical values of f, u and v are substituted in the formula, their appropriate signs must also be included.

The sign convention of Real-is-positive is adopted here.

Example 4

An object is placed 15 cm in front of a convex lens of focal length 10 cm. Calculate the image distance and the magnification.

Solution

$$\frac{1}{f} = \frac{1}{u} + \frac{1}{v}$$

$$\frac{1}{10} = \frac{1}{15} + \frac{1}{v}$$

$$\frac{1}{v} = \frac{1}{10} - \frac{1}{15} = \frac{3-2}{30}$$

$$\frac{1}{v} = \frac{1}{30}$$

$$\Rightarrow v = 30 \text{ cm}$$

$$m = \frac{v}{u} = \frac{30}{15}$$

$$m = 2$$

Example 5

An object is placed 4 cm in front of a convex lens of focal length 6 cm. Find the position, nature and magnification of the image.

$$\frac{1}{f} = \frac{1}{u} + \frac{1}{v}$$

$$\frac{1}{6} = \frac{1}{4} + \frac{1}{v}$$

$$\frac{1}{v} = \frac{1}{6} - \frac{1}{4} = \frac{2-3}{12}$$

$$\frac{1}{v} = -\frac{1}{12} \text{ cm}$$

$v = -12 \text{ cm}$ (implying the image is virtual).

$$m = \frac{v}{u} = \frac{12}{4} = 3$$

The image is:

- (i) three times the size of the object.
- (ii) virtual.
- (iii) erect.
- (iv) 12 cm from the lens, on the same side as the object.

Example 6

A lens forms an image that is four times the size of the object on a screen. The distance between the object and the screen is 100 cm when the image is sharply focused.

- (a) State with reasons what type of lens was used.
- (b) Calculate the focal length of the lens.

Solution

- (a) The lens used was a converging one. This is because the image formed is real.

$$(b) \quad m = \frac{v}{u} = 4$$

$$v = 4u$$

$$u + v = 100$$

$$u + 4u = 100$$

$$5u = 100$$

$$u = 20 \text{ cm}$$

$$\therefore v = 80 \text{ cm}$$

$$\frac{1}{f} = \frac{1}{u} + \frac{1}{v}$$

$$\frac{1}{f} = \frac{1}{20} + \frac{1}{80} = \frac{5}{80}$$

$$\frac{1}{f} = \frac{1}{16}$$

$$f = 16 \text{ cm}$$

Example 7

An object of height 10 cm stands before a diverging lens of focal length 30 cm and at distance of 20 cm from the lens. Determine:

- (a) the image distance.
- (b) the height of the image.
- (c) the magnification.

Solution

$$(a) \quad \frac{1}{f} = \frac{1}{u} + \frac{1}{v}$$

$$f = -30 \text{ cm}$$

$$u = 20 \text{ cm}$$

$$\therefore -\frac{1}{30} = \frac{1}{20} + \frac{1}{v}$$

$$\frac{1}{v} = -\frac{1}{30} - \frac{1}{20} = -\frac{5}{60}$$

$$v = -12 \text{ cm}$$

Thus, the image is formed 12 cm from the lens and on the same side as the object. The negative sign implies that the image is virtual.

$$(b) \quad \text{Image height} = \frac{\text{image distance}}{\text{object distance}} \times \text{object height}$$

$$= \frac{12}{20} \times 10$$

$$= 6 \text{ cm}$$

$$(c) \quad m = \frac{v}{u}$$

$$= \frac{12}{20}$$

$$= 0.6$$

Thus, the image is diminished.

Determination of the Focal Length of a Converging Lens

Different methods are used in the determination of focal lengths of lenses. The following experiments illustrate some of the methods used.

EXPERIMENT 1.2: To estimate the focal length of converging lens

By Focusing a Distant Object**Apparatus**

Metre rule, lens, a lens holder, screen.

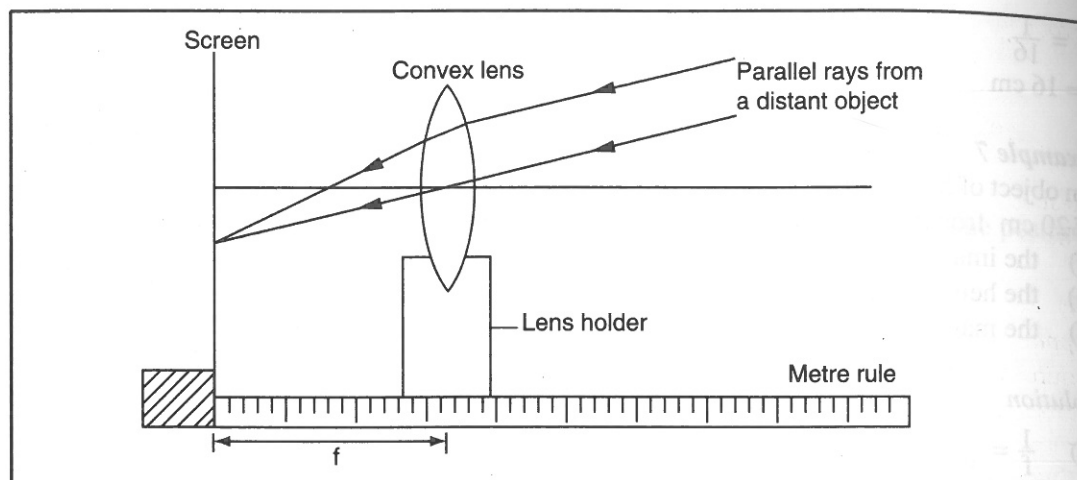


Fig. 1.25: Estimation of focal length

Procedure

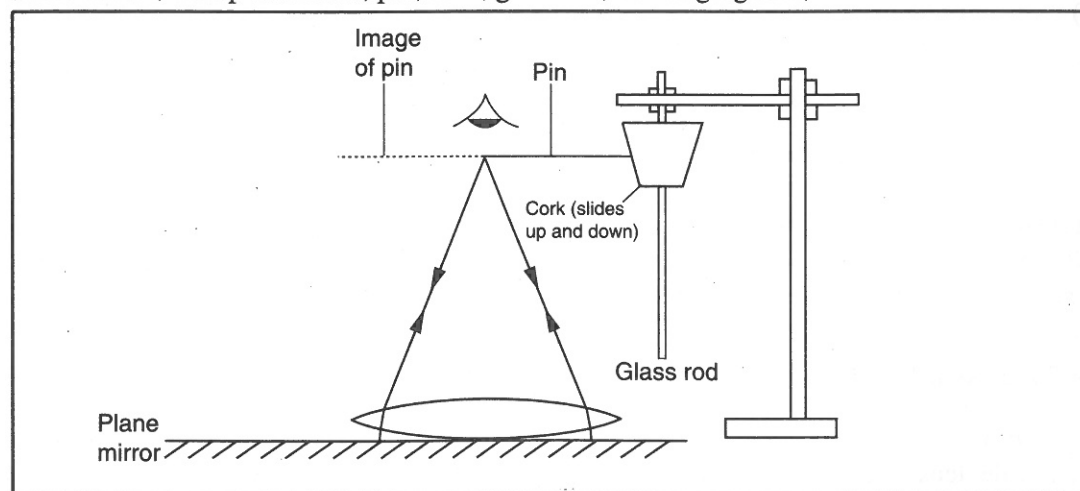
- Mount a convex lens on a lens holder and fix a metre rule on a bench using plasticine.
- Place a white screen at one end of the rule.
- Move the lens to and fro along the metre rule to focus clearly the image of a distant object, like a tree or window frame.
- Measure the distance between the lens and the screen.

The distance between the lens and the screen gives a rough estimate of the focal length of the lens. This is because parallel rays from infinity are converged at the focal point on the screen.

EXPERIMENT 1.3: To determine the focal length of a converging lens by plane mirror method

(a) No-parallax Method**Apparatus**

Plane mirror, clamp and stand, pin, cork, glass rod, converging lens, metre rule.

Fig. 1.26: Determination of f using no-parallax method**Procedure**

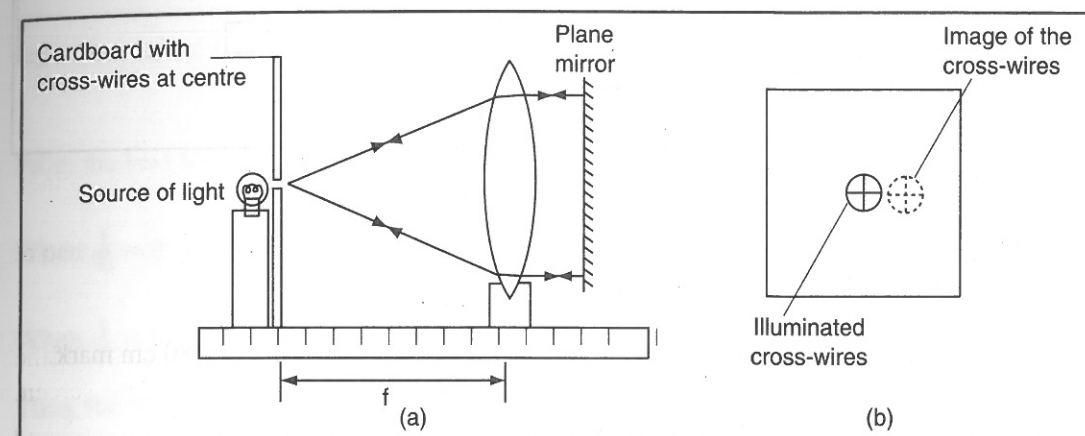
- Set up the apparatus as shown in figure 1.26
- Adjust the pin until there is no parallax between the object pin and its image.
- Measure the distance between the lens and the pin using a metre rule.

Result

The distance between the lens and the pin gives the focal length of the lens.

(b) Using an Illuminated Object**Apparatus**

Source of light, plane mirror, metre rule, lens mounted on a holder, cardboard with cross-wires at its centre.

Fig. 1.27: Determination of f using illuminated object**Procedure**

- Set the apparatus as shown in figure 1.27 (a). The illuminated object consists of cross-wires mounted on a circular hole in a cardboard.
- Move the object along the metre rule until a sharp image of the cross-wires is formed alongside the object cross-wires, as shown in figure 1.27 (b).
- Measure the length f using the metre rule. Repeat the process and find the average focal length.

Results

The length f gives the focal length of the lens.

Explanation

From (a) and (b), the rays from the object at the principal focus F are refracted and emerge parallel, striking the mirror normally. The plane mirror reflects them back parallel to the principal axis according to the principle of reversibility of light, forming an image at F .

EXPERIMENT 1.4: To determine the focal length of a convex lens using the lens formula method

Apparatus

Metre rule, lens on a lens holder, cardboard with cross-wires, screen, source of light.

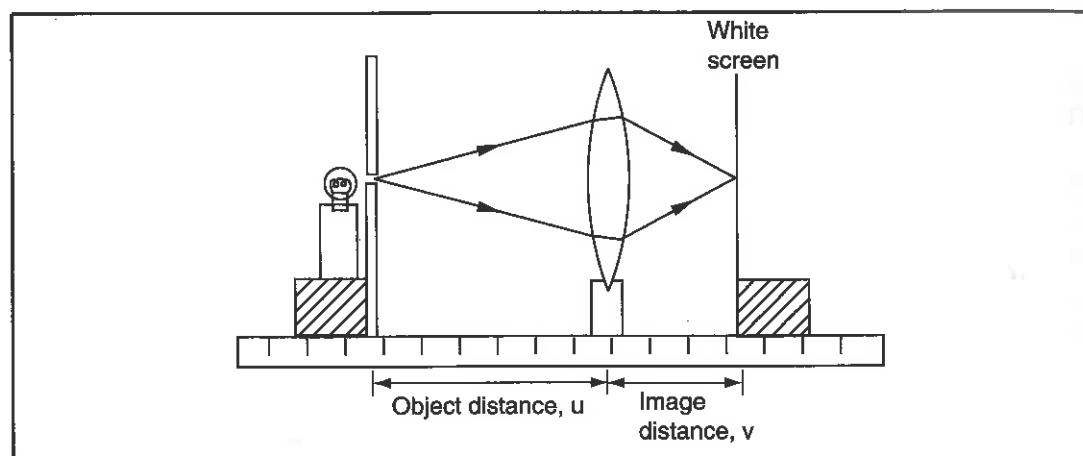


Fig. 1.28: Determination of f using formula method

Procedure

- Set up the apparatus as shown in figure 1.28.
- Place the object at zero centimetre mark.
- Set the object distance by placing the lens at a reasonable distance, say 80 cm mark.
- Adjust the screen until a sharp image is obtained.
- Determine the object and image distances u and v respectively.
- Reduce the object distance u by, say 5 cm, and obtain new values of u and v .
- Repeat the procedure to get different sets of values of u and v .
- Record your results as shown in table 1.1.

Table 1.1

Object distance u (cm)	Image distance v (cm)	$\frac{1}{u}$ (cm^{-1})	$\frac{1}{v}$ (cm^{-1})

- Use the table to plot a graph of $\frac{1}{v}$ against $\frac{1}{u}$.

Results and Explanations

Figure 1.29 shows the expected graph:

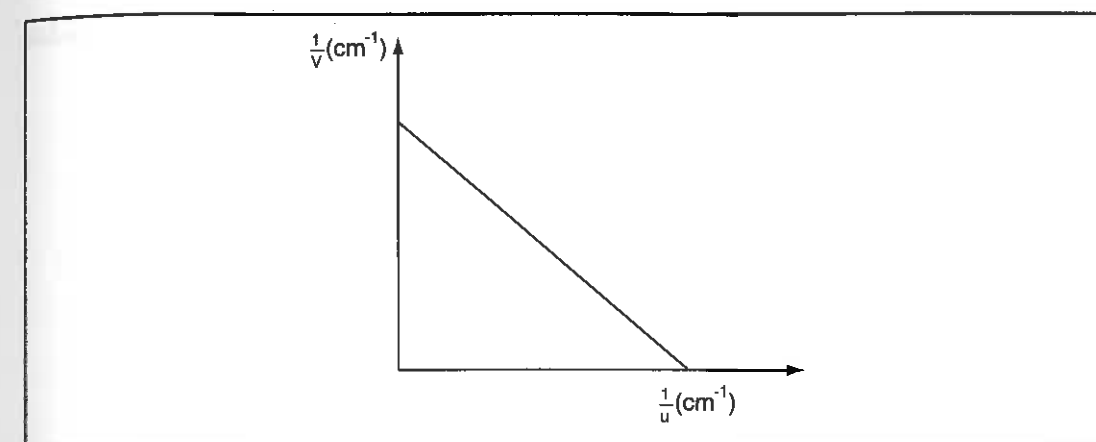


Fig. 1.29: Graph of $\frac{1}{v}$ against $\frac{1}{u}$

From the lens formula, $\frac{1}{f} = \frac{1}{u} + \frac{1}{v}$

When $\frac{1}{u} = 0$, then $\frac{1}{f} = \frac{1}{v}$

When $\frac{1}{v} = 0$, then $\frac{1}{f} = \frac{1}{u}$

Thus, the intercepts on the $\frac{1}{u}$ and $\frac{1}{v}$ axes are both equal to $\frac{1}{f}$. The value of f can therefore be determined.

Example 8

In an experiment to determine the focal length of a converging lens using the lens formula method, a student obtained the results shown in the table 1.2. Use the table to plot a graph of $\frac{1}{v}$ against $\frac{1}{u}$. Hence, determine the focal length of the lens.

Object distance u (cm)	Image distance v (cm)	$\frac{1}{u}$ (cm^{-1})	$\frac{1}{v}$ (cm^{-1})
20	60.0	0.050	0.017
25	37.5	0.040	0.027
30	30.0	0.033	0.033
35	26.3	0.029	0.038
40	24.0	0.025	0.042
45	22.5	0.022	0.044

Solution

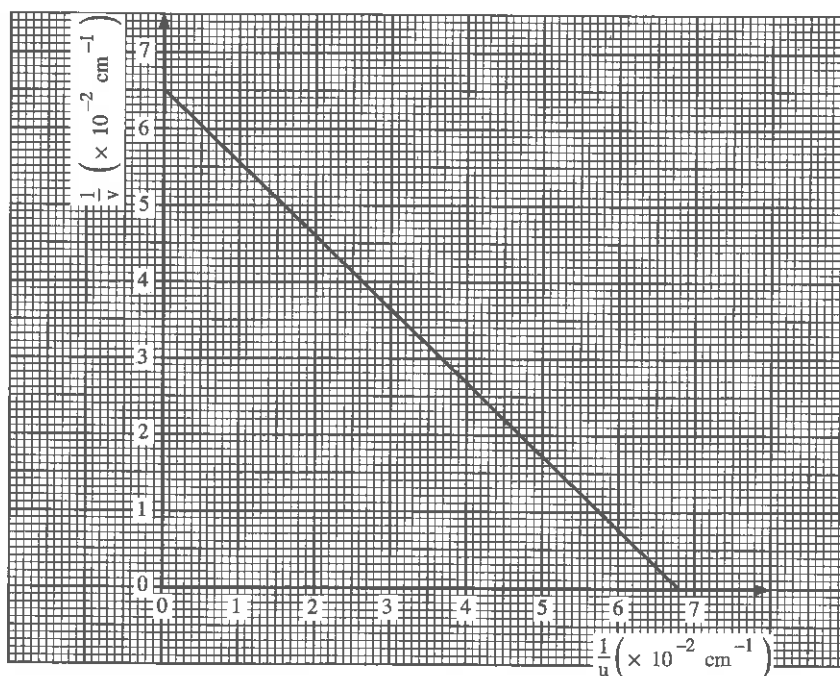


Fig. 1.30

Intercept on $\frac{1}{u}$ axis = $6.8 \times 10^{-2} \text{ cm}^{-1}$

$$\therefore \frac{1}{f} = 6.8 \times 10^{-2}$$

so, $f = 14.7 \text{ cm}$

Intercept on $\frac{1}{v}$ axis = $6.5 \times 10^{-2} \text{ cm}^{-1}$

$f = 15.4 \text{ cm}$

$$\begin{aligned} \text{Average focal length} &= \frac{14.7 + 15.4}{2} \\ &= 15.1 \text{ cm} \end{aligned}$$

Example 9

In an experiment to determine the focal length of a converging lens, several values of image distance v corresponding to different values of object distance u were determined and a graph of $(u + v)$ against uv plotted, as shown in figure 1.31. From the graph, calculate the focal length of the lens.

Solution

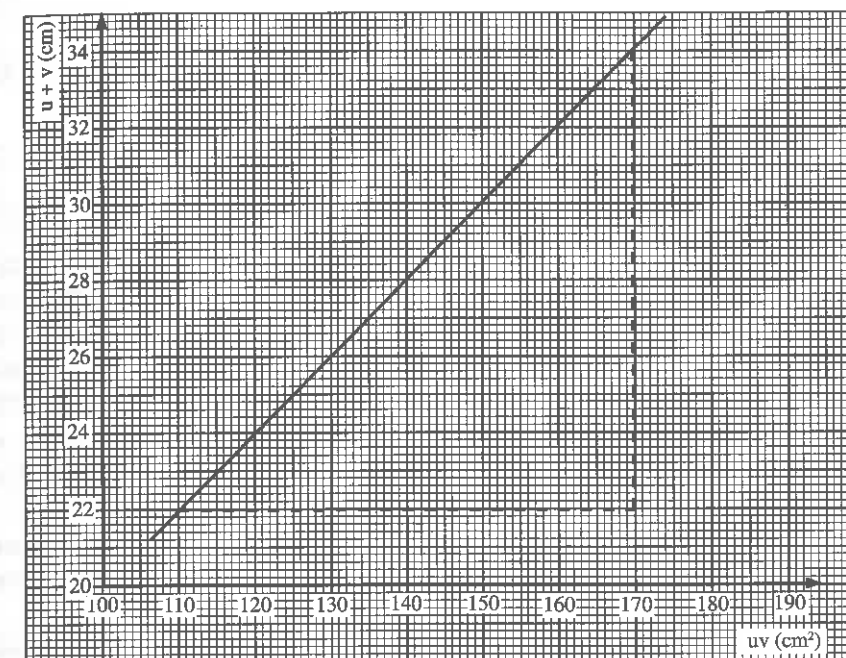


Fig. 1.31

$$\frac{1}{f} = \frac{1}{u} + \frac{1}{v}$$

$$\frac{1}{f} = \frac{u+v}{uv}$$

$$u+v = \frac{uv}{f}$$

Therefore, a graph of $(u + v)$ against uv is a straight line of slope $\frac{1}{f}$.

$$\begin{aligned} \text{From the graph, slope} &= \frac{34 - 22}{170 - 110} \\ &= \frac{12}{60} \\ &= \frac{1}{5} \end{aligned}$$

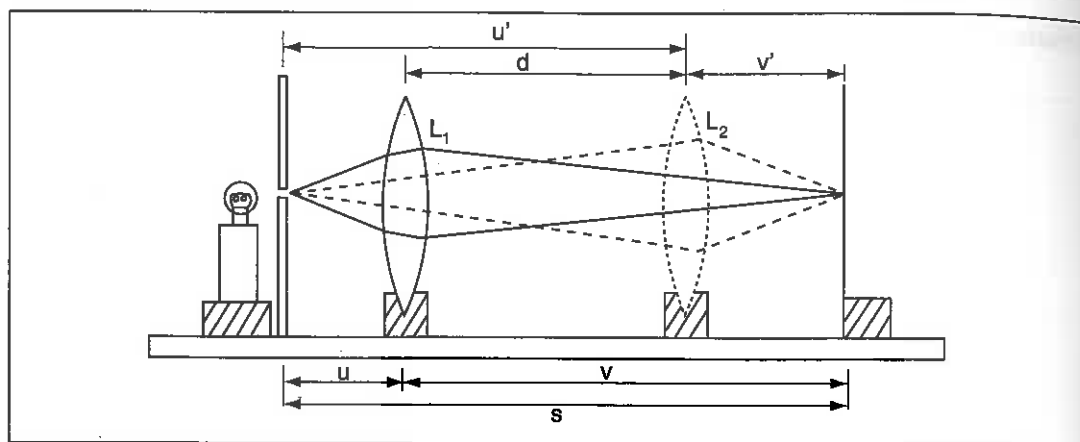
$$\text{Thus, } \frac{1}{f} = \frac{1}{5}$$

$$\therefore f = 5 \text{ cm}$$

EXPERIMENT 1.5: To determine the focal length of a converging lens by displacement method

Apparatus

Lens on a holder, screen, board with cross-wires, source of light, metre rule.

Fig. 1.32: Determination of f by displacement method**Procedure**

- Estimate the focal length of the lens by using a distant object.
- Set up the apparatus as shown in figure 1.32 (ensure that the distance between the object and the screen is equal to, or more than $4f$).
- Obtain the image of the illuminated object on the screen when the lens is at position L_1 .
- Without changing the position of the object on screen, move the lens to position L_2 , where another clear but diminished image is formed on the screen.
- Measure u and v for positions L_1 and the new distances u' and v' for position L_2 .
- Determine the displacement d .

Results and Calculations

Now, $s = u + v$ (1)

$d = u' - u$, or $d = v - v'$

But $u' = v$ and $v' = u$

Therefore, $d = v - u$ (2)

Adding (1) and (2);

$$2v = s + d$$

$$v = \frac{s + d}{2}$$

Subtracting (2) from (1);

$$2u = s - d$$

$$u = \frac{s - d}{2}$$

Substituting these values of u and v in the lens formula;

$$\frac{1}{f} = \frac{1}{\frac{s-d}{2}} + \frac{1}{\frac{s+d}{2}}$$

$$\frac{1}{f} = \frac{2}{s-d} + \frac{2}{s+d}$$

$$= \frac{2(s+d) + 2(s-d)}{(s-d)(s+d)}$$

$$= \frac{2s + 2d + 2s - 2d}{s^2 - d^2}$$

$$= \frac{4s}{s^2 - d^2}$$

$$\therefore f = \frac{s^2 - d^2}{4s}$$

Since s and d are known, f can be found.

This method is useful for measuring the focal length of a lens that is not accessible. From the above equation, $s^2 - d^2 = 4fs$. Thus, a graph of $(s^2 - d^2)$ against s is a straight line through the origin and of slope $4f$.

The experiment is performed by changing the distance between the object and the screen and then calculating the corresponding d . It is repeated for different values of s . The two positions L_1 and L_2 of the lens are known as conjugate points.

Relationship between Magnification and Focal Length

We have;

$$\frac{1}{f} = \frac{1}{u} + \frac{1}{v}$$

Multiplying both sides by v ;

$$\frac{v}{f} = \frac{v}{u} + \frac{1}{v}$$

But $\frac{v}{u} = \text{magnification, } m$.

Therefore, $\frac{v}{f} = m + 1$

Rearranging;

$$m = \frac{v}{f} - 1$$

Thus, a graph of m against v is a straight line of slope $\frac{1}{f}$.

Example 10

In an experiment to determine the focal length of a converging lens, the following readings were obtained:

Table 1.3

Image distance, v (cm)	13.3	15.0	16.7	20.0	30.0
Magnification, m	0.3	0.5	0.7	1.0	2.0

Plot a graph of m against v and determine the focal length of the lens from the graph.

Solution

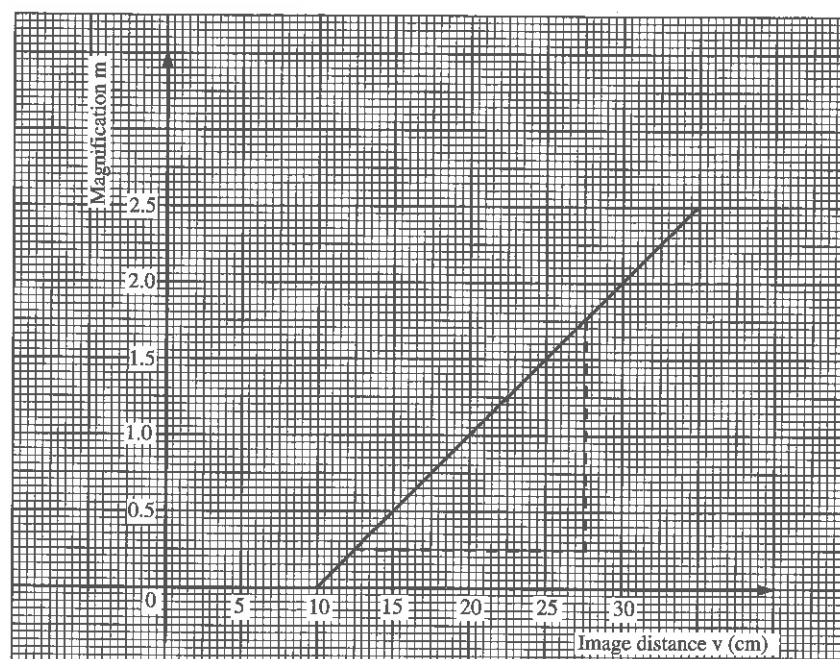


Fig. 1.33

Intercept on v-axis = focal length
= 10 cm

Slope of the graph = $\frac{1}{f}$

$$\therefore \frac{1}{f} = \frac{1.75 - 0.25}{27.5 - 12.5}$$

$$= \frac{1.50}{15.0}$$

So, $f = 10$ cm

The average focal length is 10 cm.

Power of a Lens

The power of lens is property of its focal length and is a measure of its refracting ability. The power of a lens is given by;

$$\text{Power} = \frac{1}{\text{focal length in metres}}$$

The unit of power is **dioptries (D)**. A lens of short focal length refracts light more than one of large focal length. Thus, a lens of small focal length is more powerful than that of larger focal length. Converging lenses have a positive power while diverging ones negative. For example, the power of a converging lens of focal length 10 cm is given by;

$$\text{Power} = \frac{1}{0.1}$$

$$= +10 \text{ D or simply } 10 \text{ D.}$$

That of diverging lens of the same focal length is given by;

$$\text{Power} = \frac{1}{-0.1}$$

$$= -10 \text{ D}$$

APPLICATIONS OF LENSES

Lenses have many uses, especially in optical instruments. Some optical instruments that use lenses are the magnifying glass, compound microscope and the human eye.

Simple Microscope or Magnifying Glass

When an object is placed between a convex lens and its principal focus, the image formed is virtual, erect and magnified. When used this way, the lens serves as a simple microscope or magnifying glass. Usually, a lens of short focal length (high power) is preferred. Figure 1.33 shows a simple microscope.

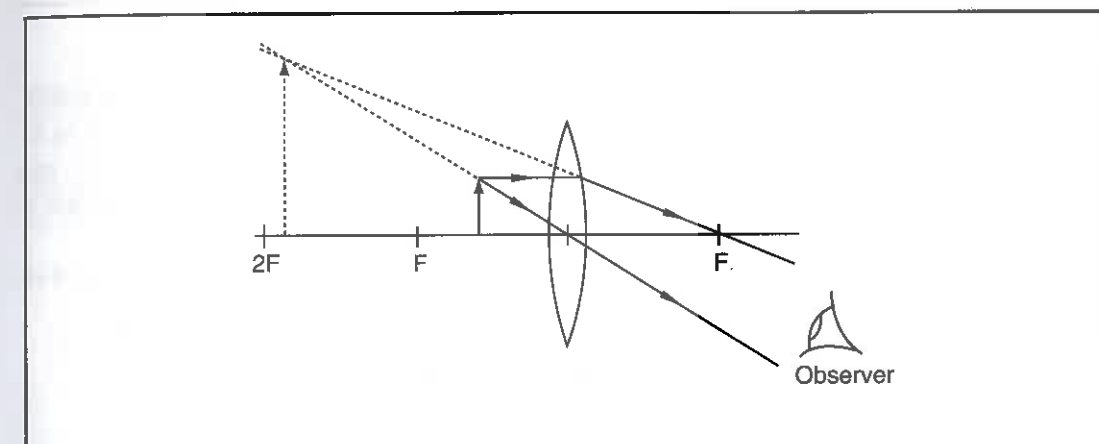


Fig. 1.34: Lens used as a magnifying glass

Compound Microscope

There are two cases under which a converging lens can produce magnified images, namely:

- (i) when the object is between F and 2F.
- (ii) when the object is between the lens and F.

A compound microscope combines the two. It consists of two converging lenses of short focal length. The lens next to the object is known as the **objective lens** and the one next to the eye is known as the **eyepiece** or **ocular**. The objective lens is of short focal length. The eyepiece is also of short focal length, but longer than that of the objective lens. Figure 1.34 shows the compound microscope.

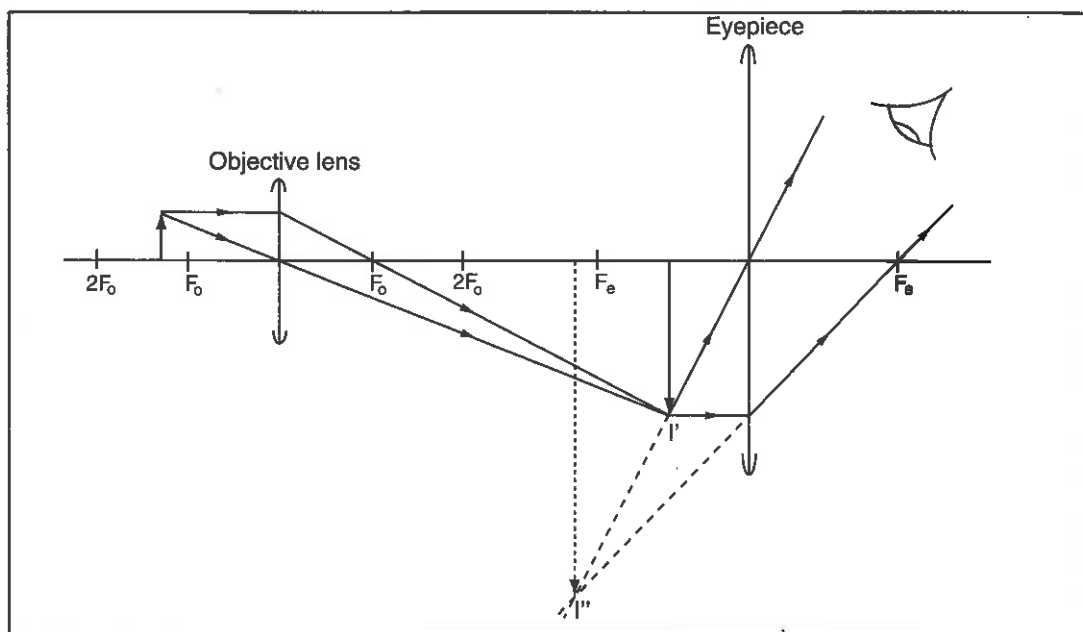


Fig. 1.35: A compound microscope in normal adjustment

The object to be viewed is placed between F_o and $2F_o$ of the objective lens so that a real, inverted and magnified image is formed. This image is in front of the eyepiece and acts as an object to it. The eyepiece is adjusted so that this image falls between its principal focus F_e and itself. This way, the eyepiece acts as a magnifying glass and produces a final image that is greatly magnified, as shown in the figure.

A compound microscope overcomes the limitations of a simple microscope by use of an objective lens with many lenses and an eyepiece with more than one lens.

Total Magnification produced by Compound Microscope

A compound microscope has two lenses and each magnifies, as shown in figure 1.34.

Magnification of objective lens, $m_o = \frac{v}{u}$, where v is the distance of first image from L_1 and u the object distance. Taking f_o as focal length of the objective lens, we have, from lens formula;

$$\frac{1}{u} + \frac{1}{v} = \frac{1}{f_o} \quad \dots\dots\dots (1)$$

Multiplying through by v ;

$$1 + \frac{v}{u} = \frac{v}{f_o} \quad \dots\dots\dots (2)$$

Substituting $m_o = \frac{v}{u}$;

$$1 + m_o = \frac{v}{f_o}$$

$$m_o = \frac{v}{f_o} - 1 \quad \dots\dots\dots (3)$$

Likewise, $m_e = \frac{D}{f_e} - 1$, where D is the distance of I' from the eyepiece. The total magnification

is a product of m_o and m_e ;

$$\text{Total magnification} = \left(\frac{D}{f_e} - 1\right) \left(\frac{v}{f_o} - 1\right)$$

Example 11

A compound microscope with objective lens L_1 of focal length 0.8 cm and an eyepiece lens L_2 of focal length 2.5 cm is shown in figure 1.35. An object O is placed in front of the objective lens at a distance u_1 of 1.2 cm. The system forms a final image I_2 at a distance of 10 cm from L_2 . Determine the distance of separation of lenses L_1 and L_2 .

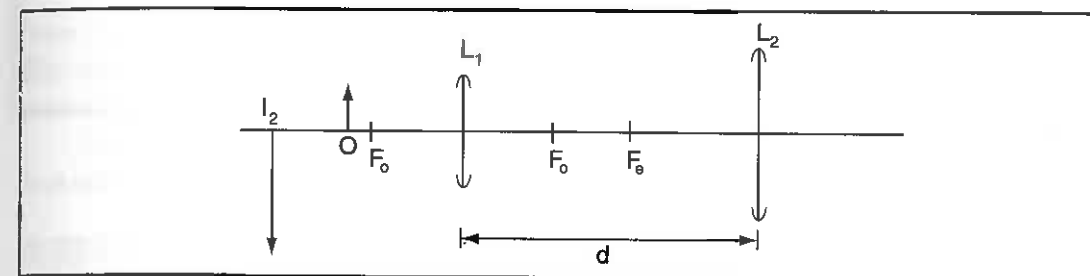


Fig. 1.36

Solution

The first image I_1 is formed between L_1 and L_2 . From lens formula;

$$\begin{aligned} \frac{1}{v} &= \frac{1}{f} - \frac{1}{u} \\ &= \frac{1}{0.8} - \frac{1}{1.2} \end{aligned}$$

So, $v = 2.4$ cm

But $d = v + u_2$

$$\begin{aligned} \text{Hence, } u_2 &= d - v \\ &= d - 2.4 \end{aligned}$$

Again;

$$\begin{aligned} \frac{1}{d - 2.4} &= \frac{1}{2.5} - \frac{1}{10} \\ &= \frac{3}{10} \end{aligned}$$

$$\therefore d - 2.4 = 3.33$$

$$d = 5.733 \text{ cm}$$

Hence, separation distance is 5.733 cm.

The Human Eye

The human eye is a natural optical instrument. Its main features are shown in figure 1.36.

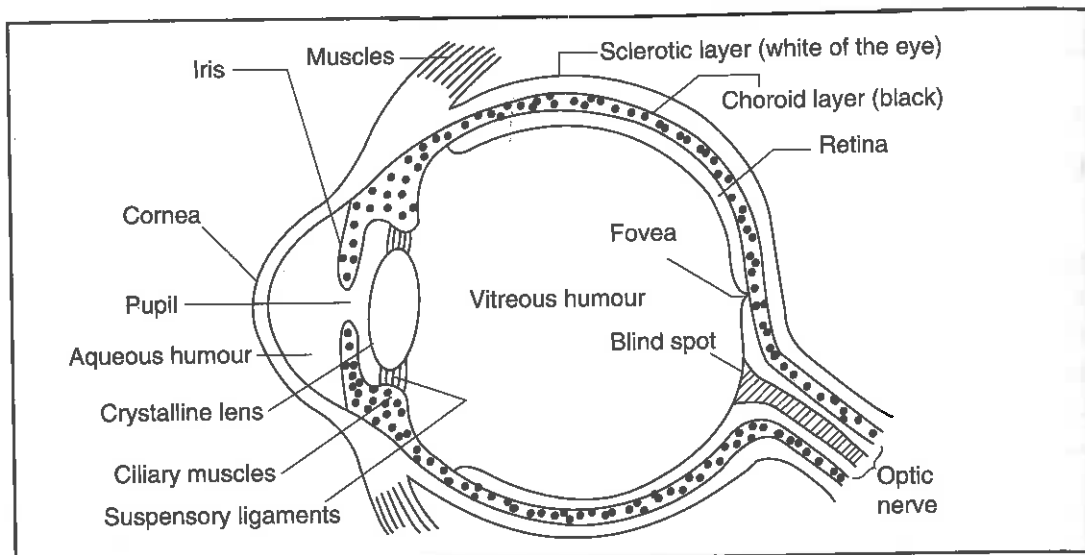


Fig. 1.37: The human eye

Sclerotic Layer

This is a hard shell that encloses the eye and is white. The front part of the sclerotic layer is transparent and spherical. It is called the cornea. Most of the bending of light entering the eye occurs at the cornea.

Aqueous Humour

This is clear liquid between the cornea and the lens. It helps the eye to maintain its shape.

Iris

This is the colouring of the eye. It has an opening known as the pupil, through which light enters the eye. The iris controls the amount of light entering the eye by changing the size of the pupil.

Crystalline Lens

This is a converging lens. It can change its focal length by action of the ciliary muscles for fine focusing. This is achieved by the muscles either contracting or relaxing.

Vitreous Humour

This is a transparent jelly-like substance filling another chamber between the lens and the retina.

Retina

This is where images are formed. It is made of cells that are sensitive to light.

Fovea

This is central part of the retina. The eye exhibits best details and colour vision at this place.

Blind Spot

This contains cells that are not light-sensitive.

Ciliary Muscles

These are muscles on which the lens is suspended inside the eye. They control the shape of the lens by either contracting or relaxing.

Relaxation of the muscles enables the lens to increase its focal length, hence focus distant objects. Contractions on the other hand reduce tension in the lens, making it have a shorter, focal length, thus focusing near objects.

This fine adjustment to accommodate images of objects at different distances on the retina by the lens is called **accommodation**.

Near Point

The closest point which the normal eye can focus clearly is called the **near point**. For the normal eye, it is 25 cm. This distance is also known as the least distance of distinct vision.

The farthest point which can be seen clearly by an unaided eye is called the **far point**. It is at infinity for the normal eye.

Defects of Vision**Short Sight (Myopia)**

In this defect, the eye can only see clearly near objects but not ones that are far away. Rays from a near object are clearly focused on the retina whereas those from a distant object are focused in front of the retina. Hence, objects appear blurred, see figure 1.37 (a) and (b).

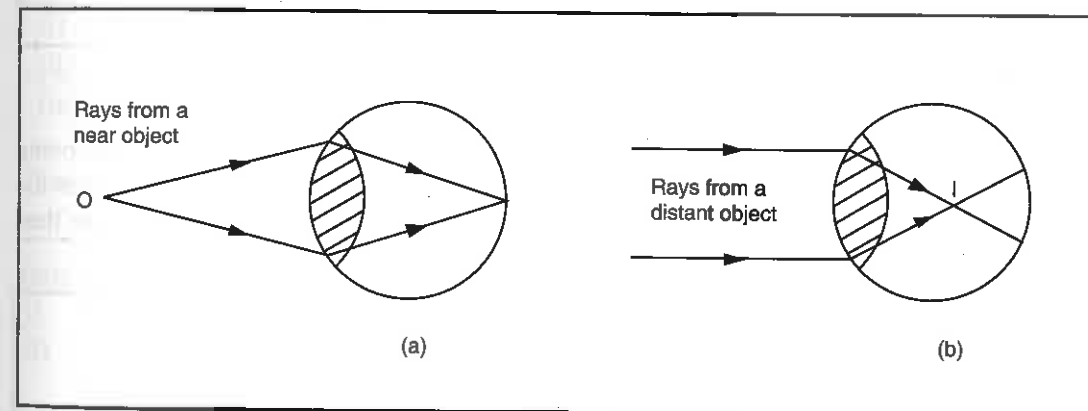


Fig. 1.38: Short sightedness

The cause of this defect is either the eye lens having a short focal length or the eyeball being too long. Diverging lenses are used to correct short sightedness. They cause the parallel rays to diverge and appear as if they are coming from O, as shown in figure 1.38. These rays are then brought to focus on the retina.

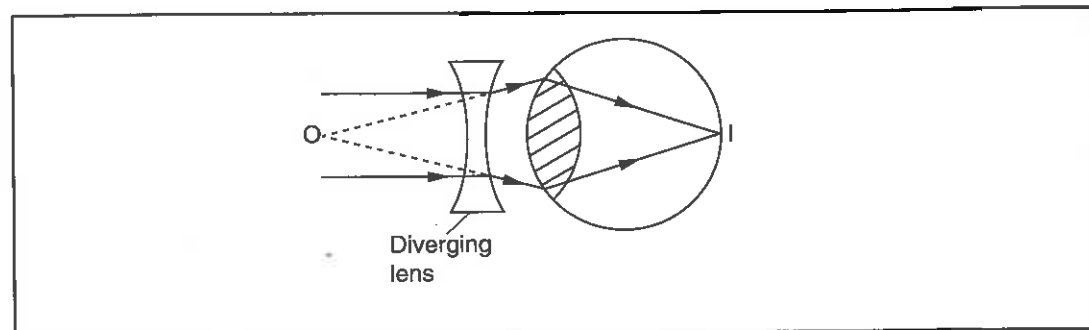


Fig. 1.39: Correcting short sightedness

Long Sight (Hypermetropia)

In this defect, the eye can see distant objects clearly, but not near ones. Images of near objects are formed behind the retina and hence appear blurred. Those of distant objects are focused on the retina, as shown in figure 1.39.

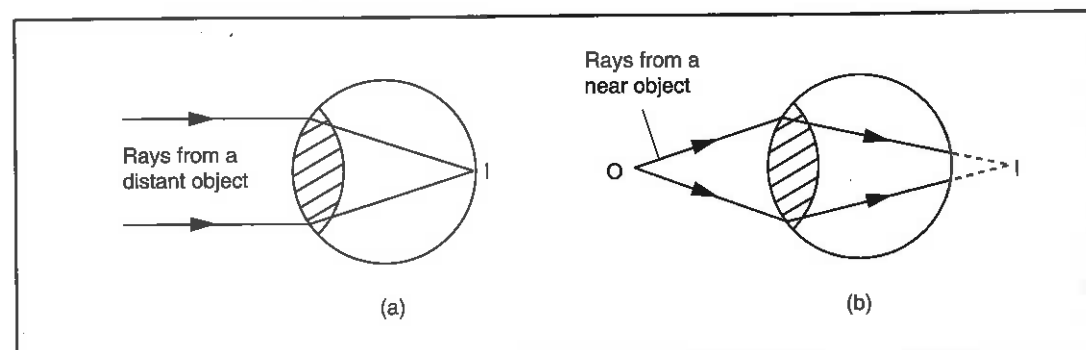


Fig. 1.40: Long sightedness

The cause of this defect is either the focal length of the lens being too long or the eyeball being too short. The defect is corrected by using converging lenses. The lens slightly converges the rays before they reach the eye, see figure 1.41. The rays appearing to come from O are then brought to focus on the retina.

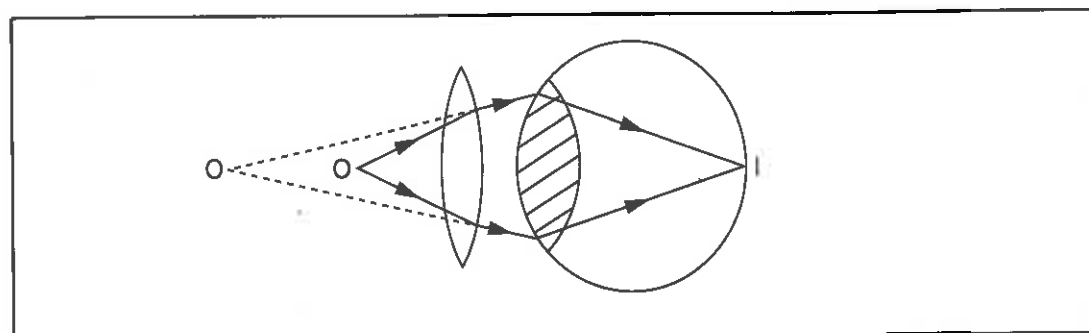


Fig. 1.41: Correcting long sightedness

The Camera

A camera is an instrument used for taking photographs. It consists of a light-tight box blackened on the inside, a system of lenses, a shutter and photographic film for receiving the image, see figure 1.41.

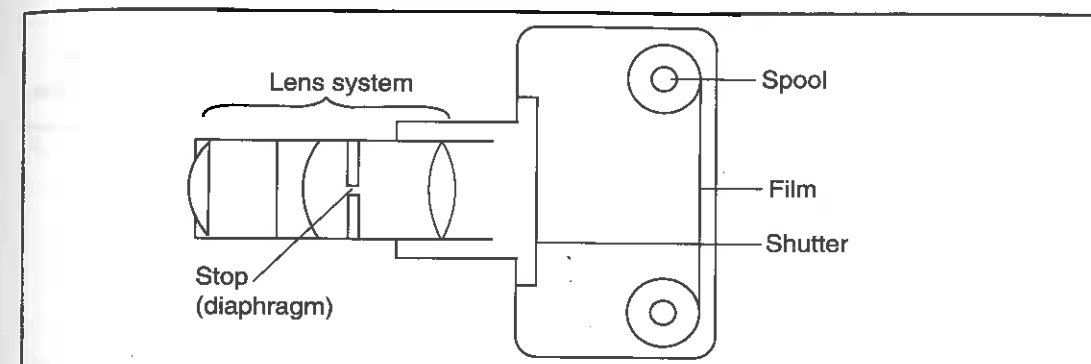


Fig. 1.42: Camera

The lens focuses light from an object to form an image of the object on the film. Focusing is done by adjusting the distance between the lens and the film or moving the camera away from or towards the object. The stop is an adjustable aperture that controls the amount of light entering the camera. The shutter allows light to reach the film only for a precise period when the camera is operated. The inside is blackened to absorb any stray light.

Similarities between the eye and the camera

Eye	Camera
(i) The eye has a crystalline convex lens.	The camera has a convex lens.
(ii) The choroid layer of the eye is black.	The camera box is painted black inside.
(iii) The eye has the retina, where images are formed.	The camera has a light-sensitive film, where images are formed.
(iv) The iris controls the amount of light entering the eye.	The diaphragm controls the amount of light entering the camera.

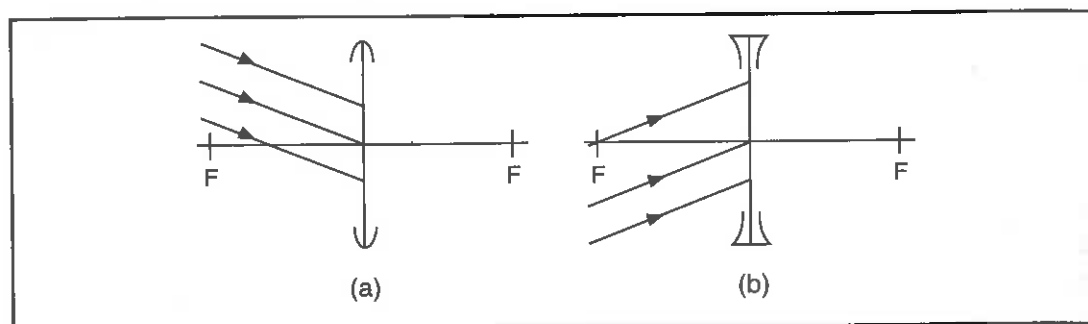
Differences

- (i) The focal length of the eye lens is variable while that of a camera is fixed.
- (ii) Cameras (with zoom lens) have variable image distance while the eye has a constant image distance.
- (iii) Only one photograph can be taken at a time when the shutter of the camera opens. The eye is always open to form constantly changing pictures.

Revision Exercise 1

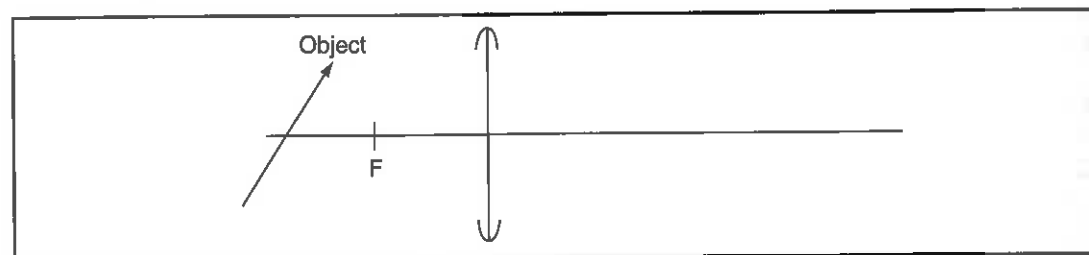
1. (a) Define the following terms:
 - (i) Focal length.
 - (ii) Radius of curvature.
 - (iii) Linear magnification.

- (b) With the aid of a diagram, describe an experiment to determine the focal length of a convex lens.
2. (a) Distinguish between real and virtual image.
 (b) A lens may be used as a magnifying glass.
 (i) Name the type of lens used in this way.
 (ii) With the aid of a ray diagram, show the position of the image in this case.
3. The figures below show parallel beams of light incident on a convex and concave lens.



Complete the ray diagrams to show the emergent beam in each case.

4. The figure below shows an object placed in front of a convex lens.



Complete the ray diagram to show the position of the image.

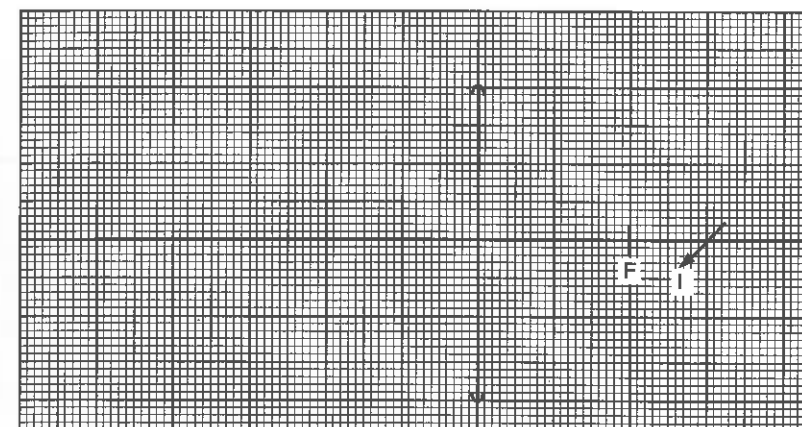
5. A concave lens has a focal length of 12 cm. By use of accurate scale drawing, locate the position of an image of an object placed at each of the following distances from the lens:
 (a) 10 cm.
 (b) 30 cm.
 State the nature of the image formed in each case.
6. An object 15 cm high is placed 30 cm from a convex lens of focal length 12 cm. By scale drawing, find:
 (a) the position of the image formed.
 (b) magnification of the image.
 (c) the height of the image.
7. A convex lens forms an image five times the size of the object on a screen. If the distance between the object and the screen is 120 cm, determine:
 (a) the object and image distance.
 (b) focal length of the lens.

8. The table below shows values of object distance u and corresponding value of image distances v for a convex lens:

Object distance u (cm)	10	15	20	25	30	35
Image distance v (cm)	40.0	17.1	13.3	11.8	10.9	10.4

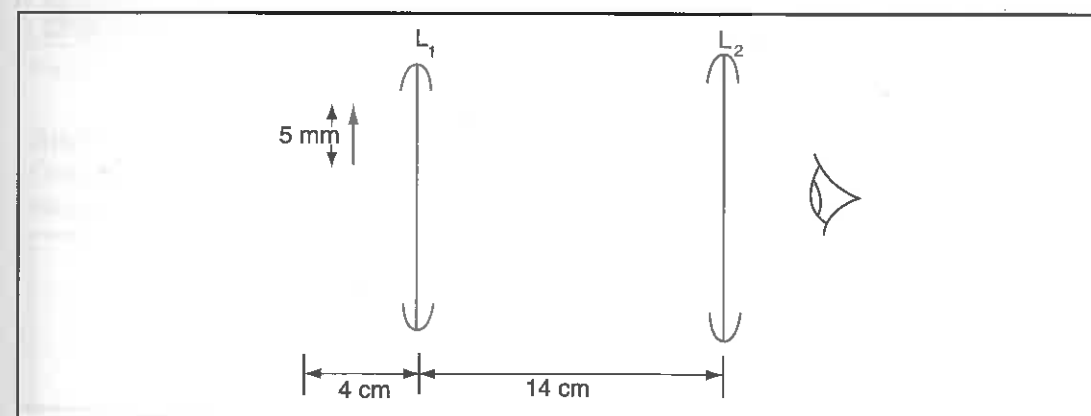
Plot a suitable graph and from the graph determine the focal length of the lens.

9. The figure below shows a real image I formed by a convex lens:



On the same grid, construct a ray diagram to locate the position of the object.

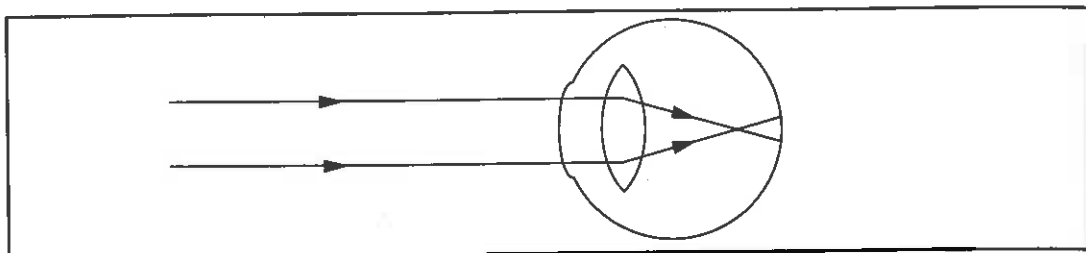
10. The figure below shows two convex lenses L_1 and L_2 placed 14 cm apart. The focal length of L_1 is 2.5 cm and that of L_2 is 4.5 cm. An object 5 mm tall is placed 4 cm from the lens L_1 . An observer positions his eye as shown.



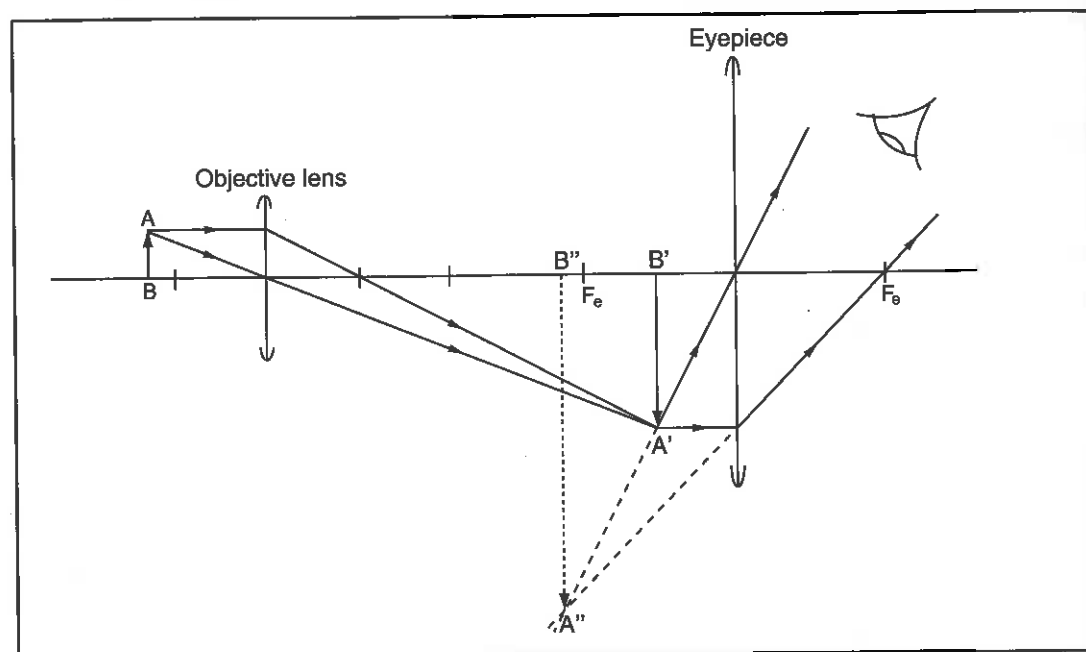
Construct an accurate ray diagram to show the position of the final image as seen by the observer.

11. A photographer focuses his camera on an object 2 m from the lens. Given that the focal length of the lens and the height of the film are 10 cm and 4 cm respectively, determine the:

- (a) image distance.
 (b) linear magnification of the image.
 (c) maximum height of the object, if its image is to fit on the film.
12. A defective eye focuses a distant object as shown in the figure below.
- (a) State the defect.
 (b) Suggest a suitable lens to correct the defect.



- (c) Draw a suitable diagram to show the correction of the defect.
13. The figure below shows a compound microscope with the objective and eyepiece lenses having a focal length 0.8 cm and 2.5 cm respectively. The objective lens forms an image $A'B'$ at a distance of 16 cm from it. The eye positioned close to the eyepiece views the virtual image $A''B''$, at a distance of 25 cm.



Calculate the total magnification.

14. (a) An eye has a far point of 5.0 m and a normal near point. Determine the focal length of the lens used to correct the defect.
 (b) A long-sighted individual has a far point at infinity and a near point of 400 mm away. Determine the focal length of a suitable correcting lens.

UNIFORM CIRCULAR MOTION

Cases of bodies moving in circular paths abound in our day to day experiences. These include the merry-go-round, turntable, a wheel turning round the axle and a stone whirled at the end of a string. Other examples are the earth and other planets revolving round the sun in their orbits and a motorist or cyclist moving along a curved path. The motion of such bodies is described as circular motion. When the speed of a body moving in a circular path is constant, the body is said to be moving with uniform circular motion.



Fig 2.1: Merry-go-round

Angular Displacement

Consider a particle moving along the arc from A to B shown in figure 2.2. The radius OA sweeps through an angle θ .

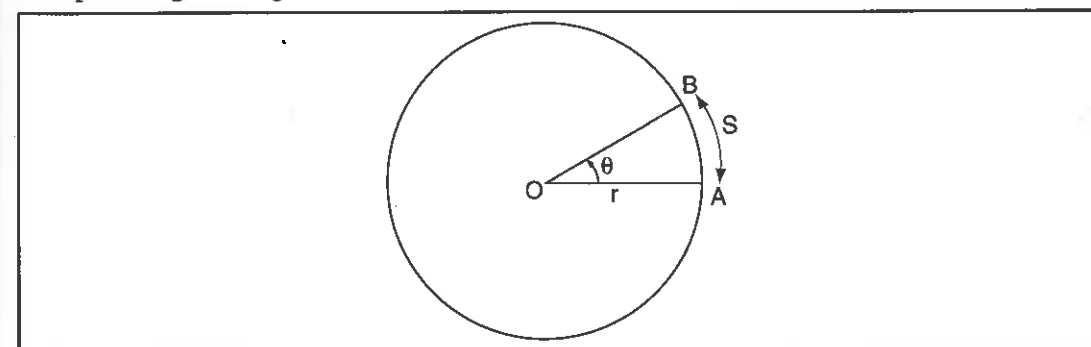


Fig. 2.2: A particle moving along an arc

The arc AB represents the distance, S , while the angle subtended by arc AB is the angular displacement. In circular motion, the angles are measured in radians, θ° .

$$\begin{aligned}\text{The angle } (\theta) \text{ in radians} &= \frac{\text{arc length AB } (S)}{\text{radius OA } (r)} \\ &= \frac{S}{r}\end{aligned}$$

when $S = r$, then, $\theta = 1$ radian.

A radian is defined as an angle subtended at the centre of a circle by an arc length equal to the radius of the circle. In radians, the angle θ subtended by the circumference at the centre of a circle of radius r is given by;

$$\begin{aligned}\theta &= \frac{\text{circumference}}{\text{radius}} \\ &= \frac{2\pi r}{r} \\ &= 2\pi\end{aligned}$$

But in degrees, this angle is 360°

$$\therefore 2\pi \text{ radians} = 360^\circ$$

Angular Velocity

Angular velocity is defined as the rate of change of angular displacement with time and is denoted by the Greek letter ω (read as omega).

$$\text{Angular velocity} = \frac{\text{change in angular displacement}}{\text{time change}}$$

$$\text{That is, } \omega = \frac{\Delta\theta}{\Delta t}$$

Angular velocity is expressed in radians per second (rads^{-1}). By dividing both sides of the

equation $\theta = \frac{S}{r}$ by t , the equation becomes;

$$\frac{\theta}{t} = \frac{S}{rt}$$

Using small changes, we have;

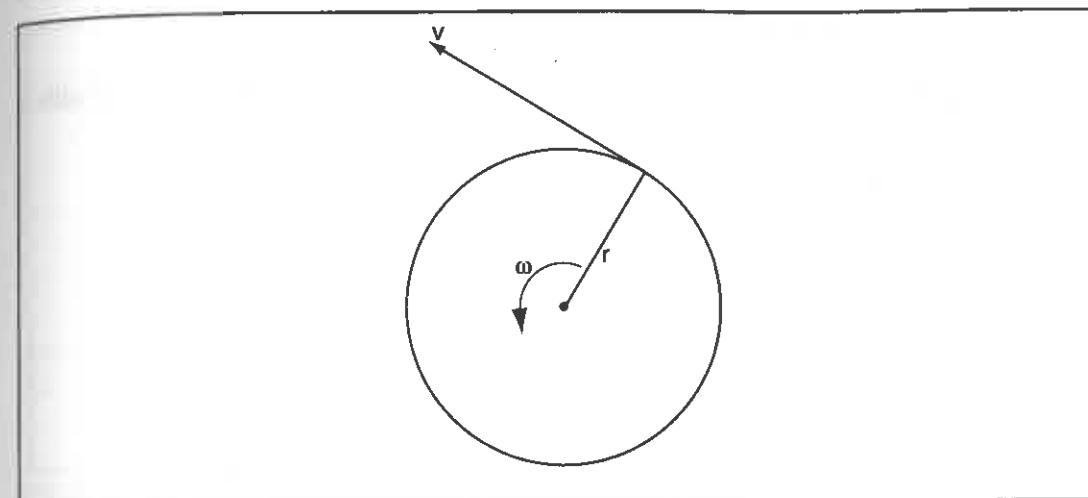
$$\frac{\Delta\theta}{\Delta t} = \frac{\Delta S}{r\Delta t}$$

But $\frac{\Delta\theta}{\Delta t} = \omega$ and $\frac{\Delta S}{r\Delta t} = \frac{v}{r}$, where v is the linear velocity.

$$\text{So, } \omega = \frac{v}{r}$$

Thus, $v = r\omega$

Any object in circular motion has both linear velocity (ms^{-1}) and angular velocity (rads^{-1}), as shown in figure 2.3.

Fig.2.3: Angular velocity (ω) and linear velocity (v)

The time taken to make one complete revolution is called the period (T) and is given by;

$$\begin{aligned}T &= \frac{\text{circumference}}{\text{speed}} \\ &= \frac{2\pi r}{\omega r} \\ &= \frac{2\pi}{\omega}\end{aligned}$$

$$\text{Also, } T = \frac{2\pi r}{v}, \text{ since } \omega = \frac{v}{r}$$

$$\text{Since } T = \frac{1}{f} \text{ and } \omega = \frac{2\pi}{T}, \omega = 2\pi f, \text{ where } f \text{ is the frequency of rotation.}$$

Example 1

A turntable rotates at a rate of 45 rev/min. What is its angular velocity in rads^{-1} ?

Solution

Angle turned in 1 rev = 2π rads

Angle turned in 45 rev = $2\pi \times 45$ rad

$$\begin{aligned}\therefore \omega &= \frac{2\pi \times 45}{60} \text{ rad s}^{-1} \\ &= 1.5\pi \text{ rads}^{-1} \\ &= 4.71 \text{ rads}^{-1}\end{aligned}$$

Example 2

- (a) A model car moves round a circular track of radius 0.4 m at 2 revolutions per second. What is its:
- period T ?

- (ii) angular velocity ω ?
 (iii) speed v ?
 (b) Find the angular velocity and the frequency of the motion of the car if it moves with a uniform speed of 2 ms^{-1} in a circle of radius 0.2 m . (Take $\pi = 3.142$)

Solution

- (a) (i) Period T is the time for one revolution.

$$\begin{aligned} T &= \frac{1}{f} \\ &= \frac{1}{2} \\ &= 0.5 \text{ s} \end{aligned}$$

$$\begin{aligned} \text{(ii) } \omega &= \frac{2\pi}{T} \\ &= \frac{2\pi}{0.5} \\ &= 4\pi \text{ rads}^{-1} \\ &= 12.57 \text{ rads}^{-1} \end{aligned}$$

$$\begin{aligned} \text{(iii) Speed } v &= r\omega \\ &= 0.4 \times 4\pi \\ &= 1.6\pi \\ &= 5.027 \text{ ms}^{-1} \end{aligned}$$

- (b) From $v = r\omega$

$$\begin{aligned} \omega &= \frac{v}{r} \\ &= \frac{2}{0.2} \\ &= 10 \text{ rads}^{-1} \end{aligned}$$

$$\text{But } \omega = 2\pi f$$

$$\begin{aligned} \therefore f &= \frac{\omega}{2\pi} \\ &= \frac{10}{2\pi} \\ &= 1.591 \text{ Hz} \end{aligned}$$

Centripetal Acceleration

If a stone is tied to one end of a string and whirled horizontally at a constant speed, it describes a circular path of constant radius, see figure 2.4 (a).

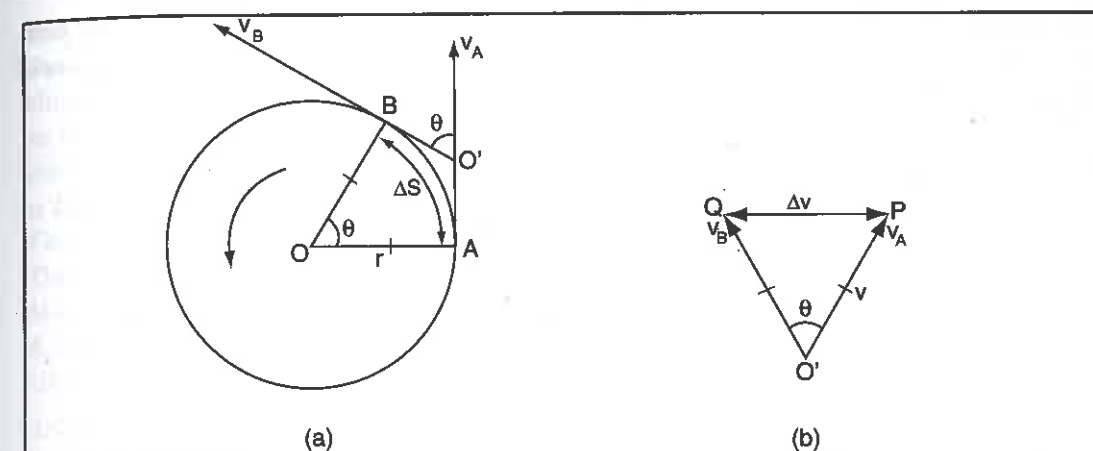


Fig. 2.4: A body moving in circular motion with constant speed

Consider A and B, two close points on the circumference as in figure 2.4 (a). The velocities of the body at A and B are v_A and v_B respectively. These velocities are tangential to the circular path. The magnitudes of v_A and v_B are equal, but they are in different directions. Since velocity is a vector quantity, this change in direction from A to B implies a change in velocity. Consequently, the change in velocity v from A to B over the time interval Δt is the acceleration of the body.

According to Newton's second law, the body must experience a net force. It can be shown that this force is directed towards the centre of the circle. The acceleration of the body is in the direction of the net force and hence towards the centre. This acceleration is referred to as **centripetal acceleration**. Although we talk of the body moving with a constant speed, the fact that the instantaneous velocities are changing every time implies that the body is accelerating.

Referring to figure 2.4 (a) and (b), where θ is a small angle, the arc length ΔS is approximately equal to the chord AB. The triangles OAB and OPQ are similar, and;

$$\frac{AB}{PQ} = \frac{OA}{O'P}$$

Thus, $\frac{\Delta S}{\Delta v} = \frac{r}{v} \dots \dots \dots (1)$

$$\Delta v = \frac{\Delta S \cdot v}{r} \dots \dots \dots (2)$$

$$\text{Since } \Delta S = \Delta t \cdot v;$$

$$\Delta v = \frac{v^2}{r} \cdot \Delta t$$

Dividing through by Δt ;

$$\frac{\Delta v}{\Delta t} = \frac{v^2}{r}$$

$$\text{But } v = r\omega$$

$$\therefore a = \frac{v^2}{r} = r\omega^2$$

The centripetal acceleration is directed towards the centre along the radius of the circular path. The term 'centripetal' is used to indicate that the acceleration is directed towards the centre of the circle.

Example 3

A point on the rim of a wheel has a velocity of 5.6 ms^{-1} . If the rim has a radius of 0.4 m , calculate:

- the angular velocity of the point.
- its centripetal acceleration.

Solution

$$(a) \quad v = r\omega$$

$$\omega = \frac{v}{r}$$

$$= \frac{5.6}{0.4}$$

$$= 14 \text{ rads}^{-1}$$

$$(b) \quad a = \frac{v^2}{r}$$

$$= \frac{5.6^2}{0.4}$$

$$= 78.4 \text{ ms}^{-2}$$

Alternatively;

$$a = r\omega^2$$

$$= 0.4 \times 14 \times 14$$

$$= 78.4 \text{ ms}^{-2}$$

Centripetal Force

If a stone is tied to one end of a string and whirled horizontally with constant speed, it describes a circular path of constant radius. To maintain the stone in the circular path, there must be a force acting on it, as shown in figure 2.5.

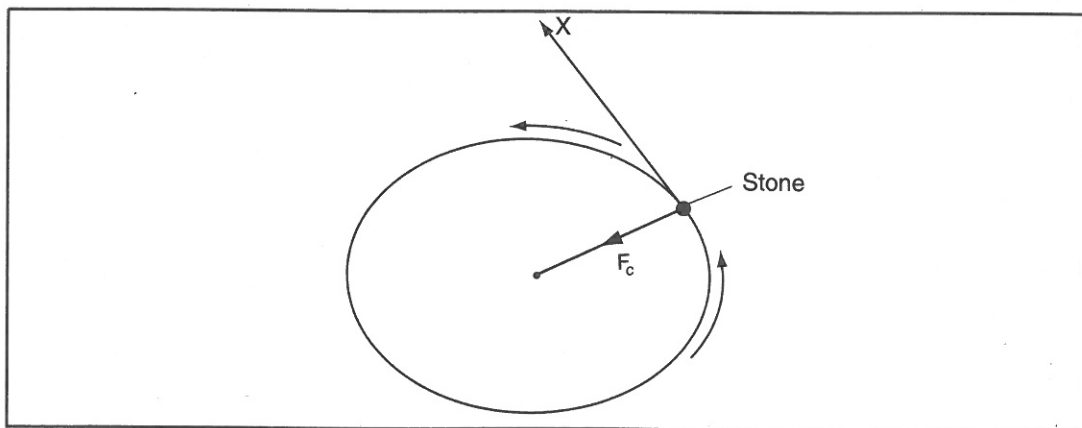


Fig. 2.5: A stone moving in a circular path

The force acting on the stone is referred to as **centripetal force** and is directed towards the centre of the circle. If the string is suddenly released the stone will fly off tangentially along X direction, as shown in the figure. This indicates that some force is required to maintain an object in circular motion. A heavier stone will require a larger centripetal force to keep it moving in a circular path if the radius of the circle and the speed are constant.

Factors Affecting Centripetal Force

The centripetal force needed to make an object describe a circular path depends on the following:

Mass of the object

A heavier stone in figure 2.5 will require a larger centripetal force to keep it moving in the circular path.

Angular velocity of the object

Increasing the rate of whirling requires a higher centripetal force.

Radius of the path

A shorter string will require a larger centripetal force.

These factors can be investigated using the apparatus shown in figure 2.6.

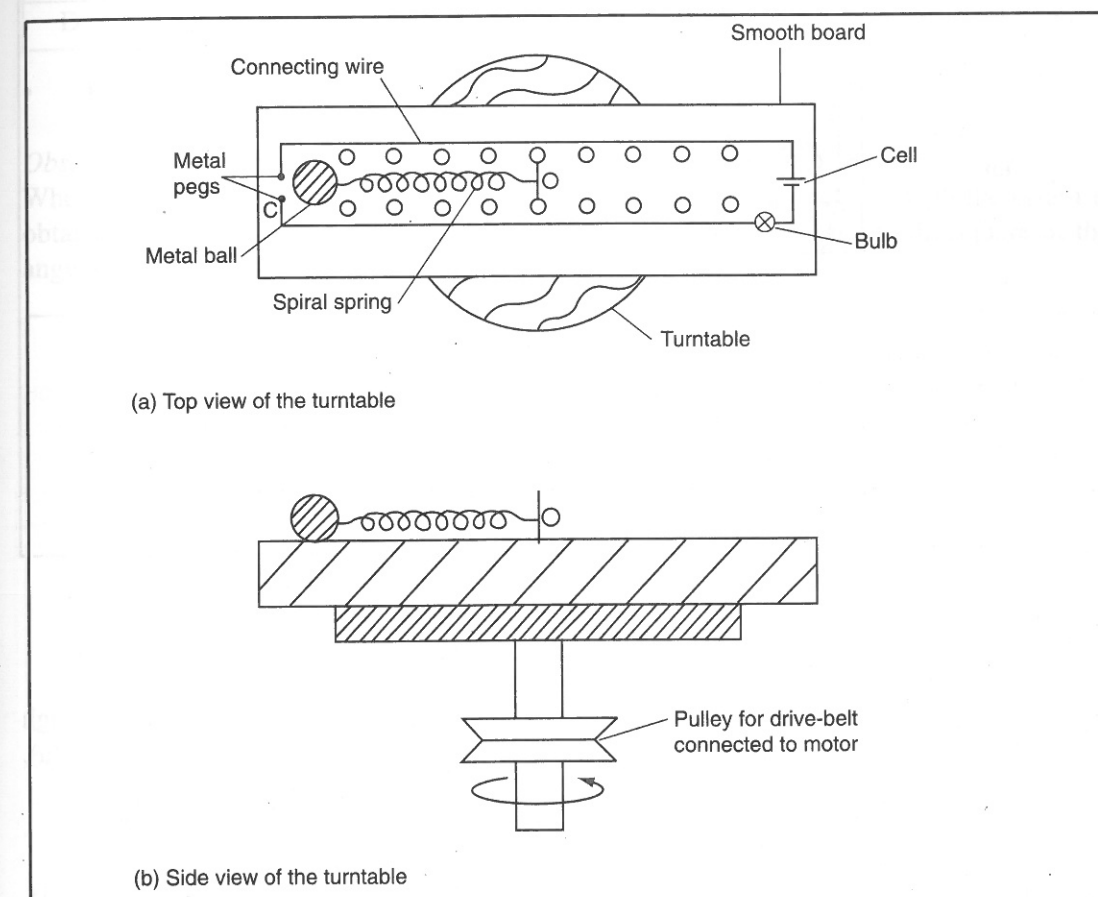


Fig. 2.6: Turntable

EXPERIMENT 2.1: To investigate the relationship between the centripetal force (F) and the angular velocity (ω), keeping radius of rotation constant

Apparatus

Metal pegs, turntable connected to a motor, source of electricity, bulb, clock, variable resistor dry cell, metal ball connected to a string.

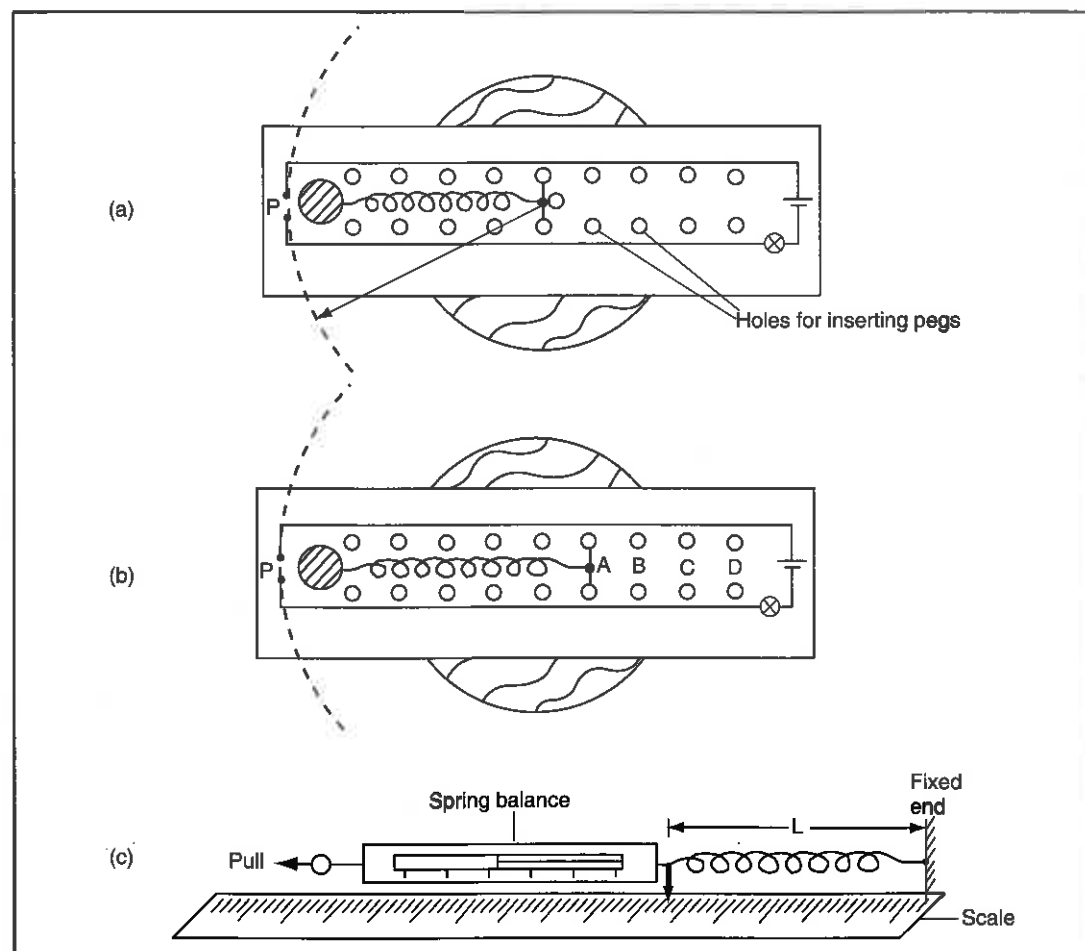


Fig. 2.7

Procedure

- Fix the metal pegs at a distance r from the centre O of the turntable.
- Increase the speed of rotation of the turntable gradually by increasing the current through the motor, until the metal ball makes contact at P for the bulb to light, see figure 2.7 (a).
- Record the time t for 20 revolutions and calculate the period T (where $T = \frac{t}{20}$).
- Change the force by moving the pegs from O to A , as shown in figure 2.7 (b).
- Increase the speed of the turntable gradually as was done previously until the bulb lights. Record the time for 20 revolutions and work out T .

- Measure and record the length AP .
- Repeat the experiment with pegs at B , C and D and obtain the measurements as before.
- Obtain the forces corresponding to OP , AP , BP , e.t.c, as shown in figure 2.7 (c).
- Stretch the string to the corresponding measured lengths, L , and read off the forces from the spring balance in Newtons, as shown in figure 2.7 (c).
- Record your results in table 2.1.

Table 2.1

Position of pegs	L (cm)	Time for 20 revolutions t (s)	$T = \frac{t}{20}$ (s)	$\omega = \frac{2\pi}{T} \text{ rad s}^{-1}$	$\omega^2 (\text{rad}^2 \text{s}^{-2})$	F (N)
O						
A						
B						
C						
D						

- Plot a graph of F against ω^2 .

Observation

When a graph of force F is plotted against ω^2 , a straight line passing through the origin is obtained. This shows that the centripetal force is directly proportional to the square of the angular velocity ($F \propto \omega^2$), see figure 2.8.

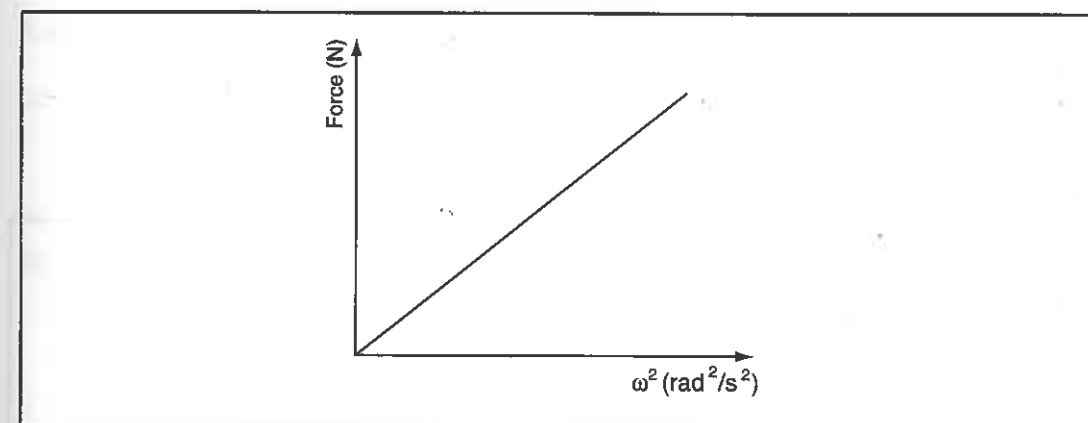


Fig.2.8: Graph of F against ω^2

EXPERIMENT 2.2: To investigate the variation of speed with radius, keeping force constant

Apparatus

Same as in experiment 2.1.

Procedure

- Set the apparatus as in experiment 2.1. The force is made constant by keeping the length of the spring constant.
- Measure and record r_1 , the length OP.
- Increase the speed of the motor gradually until the bulb lights.
- Time 20 revolutions and calculate the period T .
- Determine the speed of rotation using the relation $v = \frac{2\pi r}{T}$
- Displace the ball and the metallic pegs by the same margin x to the right, as shown in figure 2.9 (this keeps the length of the spring constant and reduces the radius of the ball from the centre of rotation).

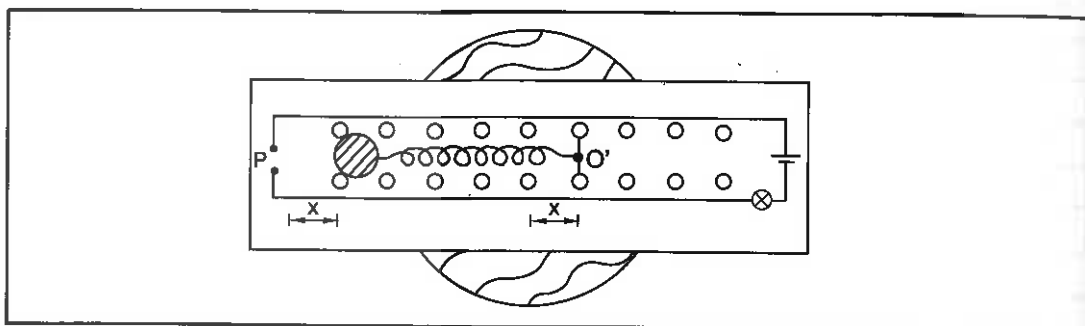
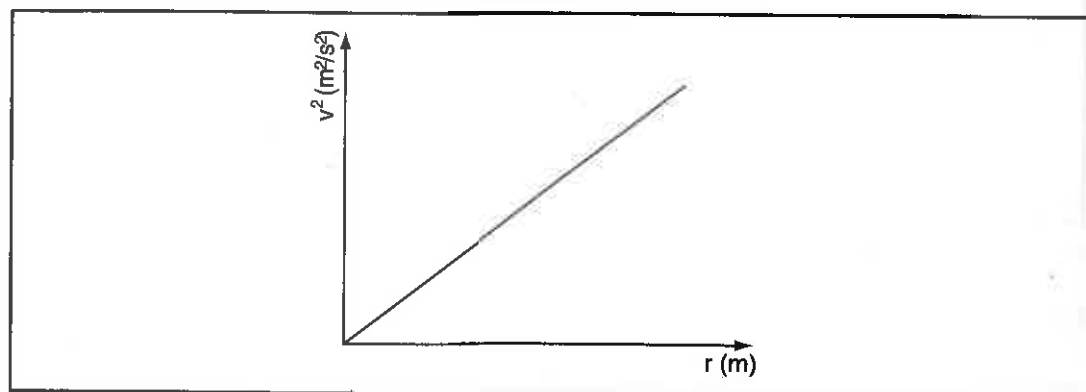


Fig. 2.9

- Again increase the speed of the motor until the bulb just lights.
- Record time for 20 revolutions.
- Calculate T and measure the new radius r^2 . Compute the new speed as before.
- Repeat the experiment for other values of r and record your results.
- Plot a graph of v^2 against r .

Observation

A graph of v^2 against r is a straight line passing through the origin, see figure 2.10.

Fig. 2.10: Graph of v^2 against r **Results and Calculation**

From the experimental results, it can be concluded that the centripetal force required to keep an object in a circular path increases with:

- an increase in the mass m of the body.
- an increase in the speed v of the object.
- a decrease in the radius r of the circular path.

$$\text{Hence, } F \propto \frac{mv^2}{r}$$

$$F = k \frac{mv^2}{r}$$

$$\text{So, } F = \frac{mv^2}{r}, \text{ where } k = 1.$$

$$\text{Since } v = r\omega, F = mr\omega^2$$

$$\text{Also, } a = \frac{v^2}{r}$$

$$\therefore F = ma \text{ (Newton's second law).}$$

Example 4

A body having a mass of 0.5 kg is tied to a string and whirled in a horizontal circle of radius 2 m with a speed of 3.16 ms^{-1} . Calculate:

- the centripetal acceleration.
- the tension in the string.

Solution

$$(a) \quad a = \frac{v^2}{r}$$

$$= \frac{3.16 \times 3.16}{2}$$

$$= 4.99 \text{ ms}^{-2}$$

- The centripetal force is provided by the tension in the string.

$$\begin{aligned} T &= F = \frac{mv^2}{r} = ma \\ &= 0.5 \times 4.99 \\ &= 2.50 \text{ N} \end{aligned}$$

Case Examples of Circular Motion**A Car Rounding a Level Circular Bend**

When a car travelling with uniform speed passes a level circular path, it experiences a centripetal force, see figure 2.11 (a).

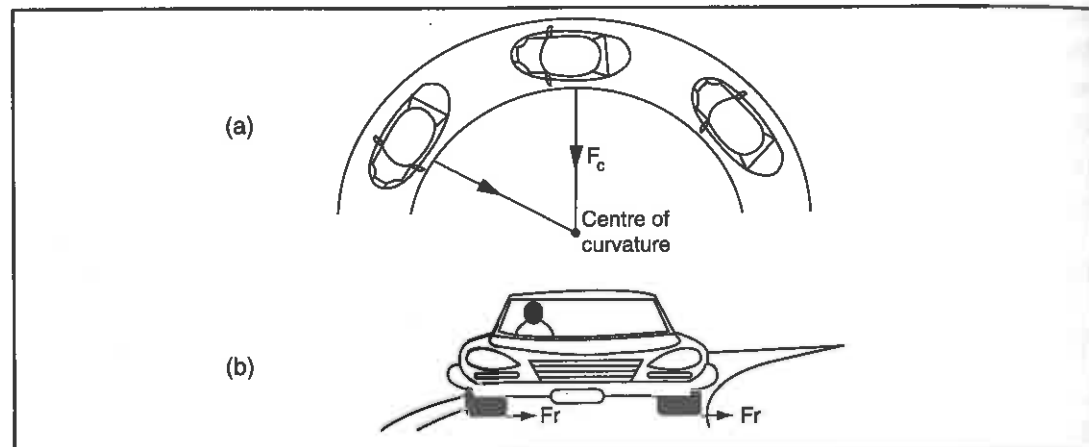


Fig. 2.11: A car on horizontal bend

The frictional force between the tyres and the road provides the centripetal force. The centripetal force is always directed towards the centre of the curvature, see figure 2.11 (b).

Thus, $F_r = F_c$, where F_r is the frictional and F_c the centripetal force.

Therefore, $F_r = \frac{mv^2}{r}$

If the road is slippery, the frictional force may not be sufficient to provide the centripetal force. As a result, skidding may occur. To prevent skidding, the car should not exceed a certain speed limit referred to as the **critical speed**, which depends on the radius of the bend. One may successfully negotiate a bend on a flat level road at a higher critical speed if the radius of the bend is big.

Other factors may also come in, such as the condition of the car tyres and the nature of the road surface. New car tyres and a rough road surface are necessary for sufficient frictional force to be produced.

Banked Track

Sports cars can negotiate corners at extremely high speeds without running the risk of skidding or overturning. This is made possible by gradually raising the road from the inner side of the bend, so that the track attains a saucer-like shape. The road is then said to be **banked**, see figure 2.12.

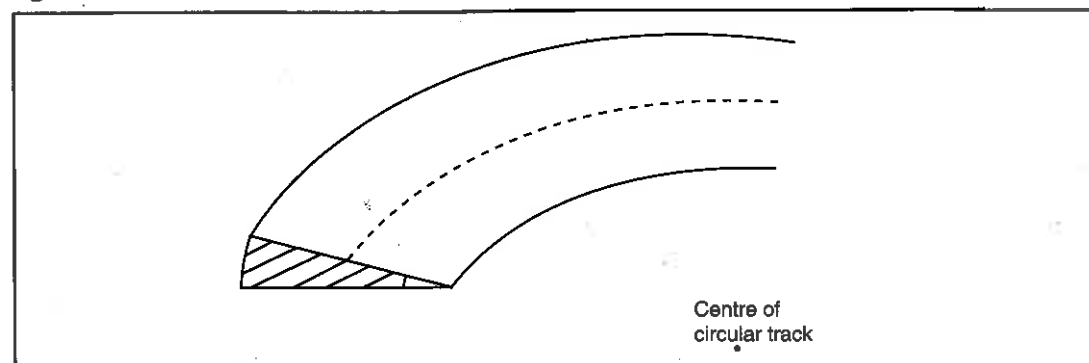


Fig. 2.12: Saucer-like track

In the case of the flat level road, the centripetal force is provided by the frictional force between the tyres and the road surface. In a banked road, the banking angle is such that the centripetal force acting on the car comes from the reaction R of the road, see figure 2.13.

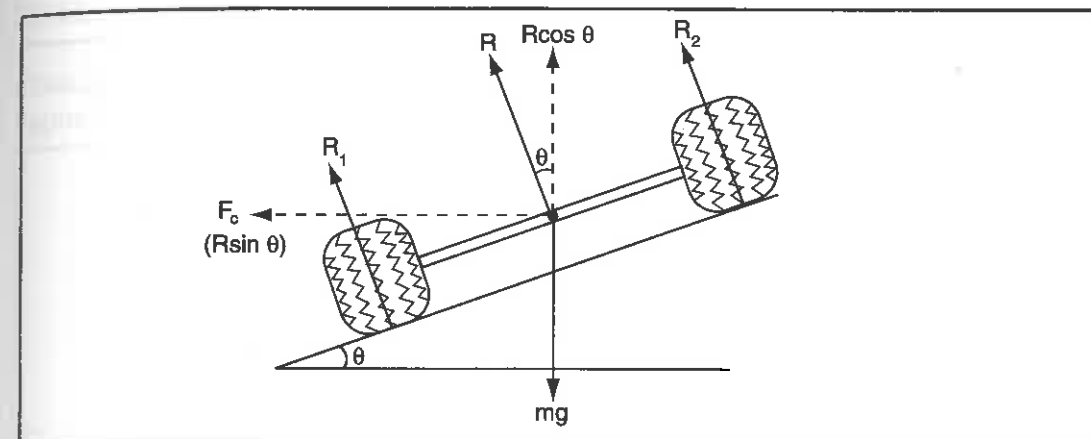


Fig. 2.13: A car on a banked track

Consider a car mass m and travelling round a bend of radius r with speed v . The bend is banked at an angle θ . It can be shown that;

- (i) $F_c = R \sin \theta$, and,
- (ii) $mg = R \cos \theta$

Hence, $\tan \theta = \frac{v^2}{rg}$

For a given banking angle θ , the critical speed can be obtained from the equation $v = \sqrt{rg \tan \theta}$.

In general, the critical speed depend on radius r and banking angle θ .

Aircraft Banking

An aircraft turns in the air at extremely high speed without overturning. This is made possible by the aeroplane gradually lowering a wing on one side and raising the other, see figure 2.14.

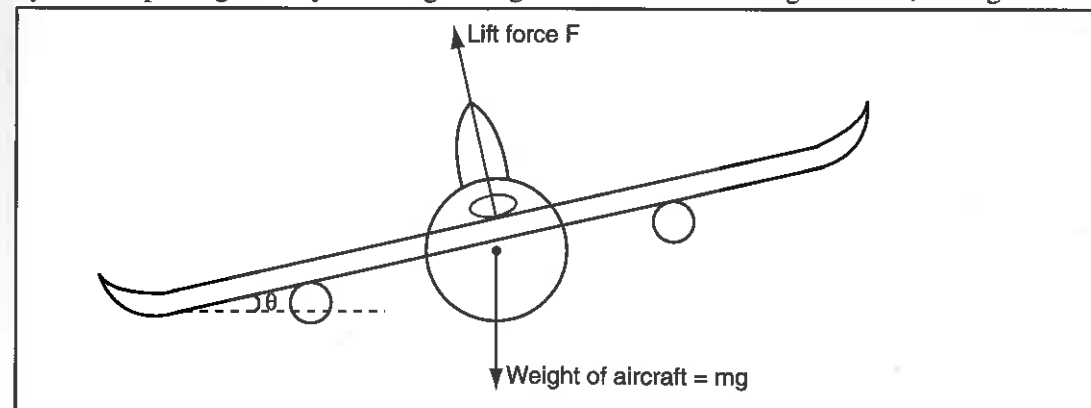


Fig. 2.14: An aircraft banking to provide centripetal force

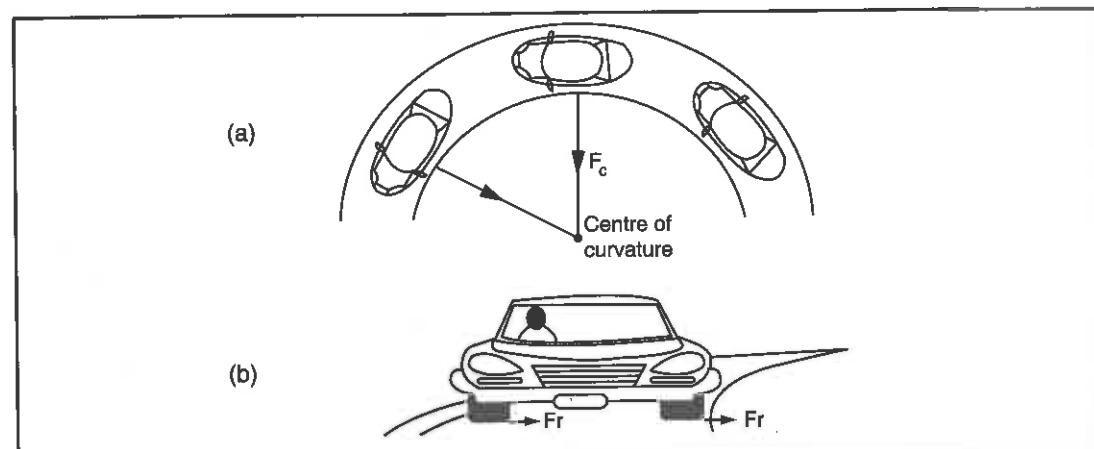


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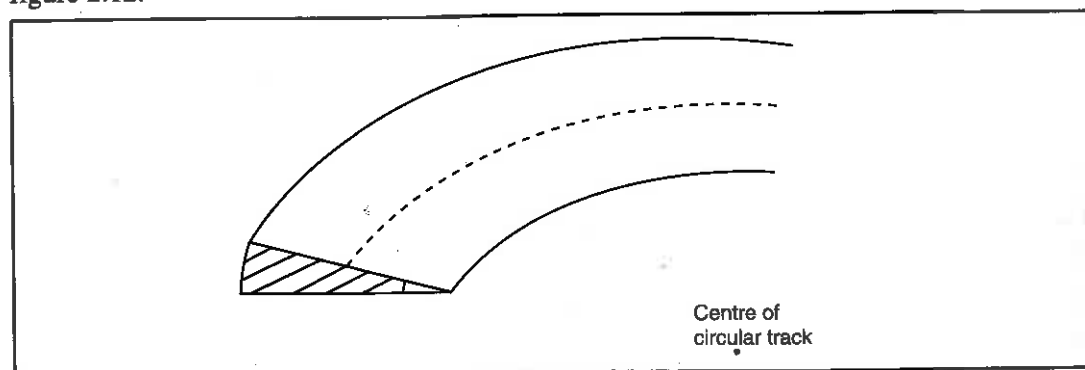


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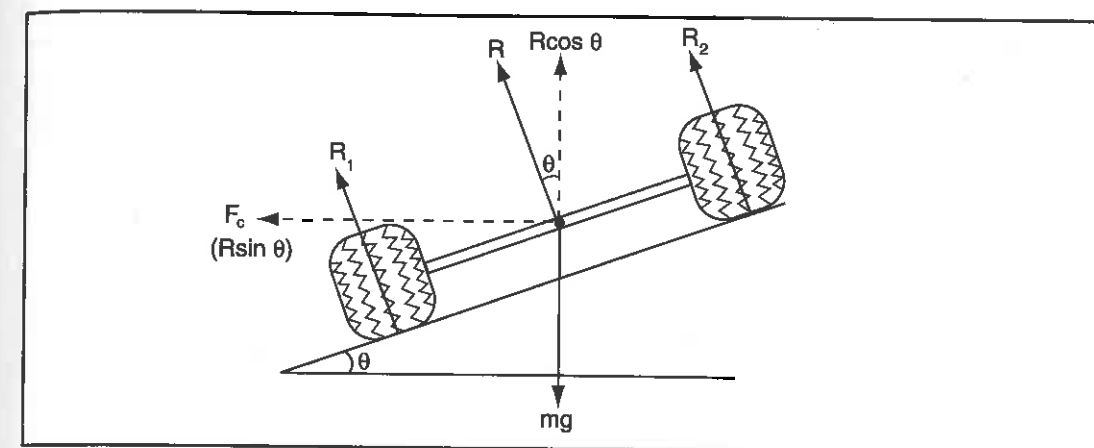


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Hence, $\tan \theta = \frac{v^2}{rg}$

For a given banking angle θ , the critical speed can be obtained from the equation $v = \sqrt{rg \tan \theta}$.

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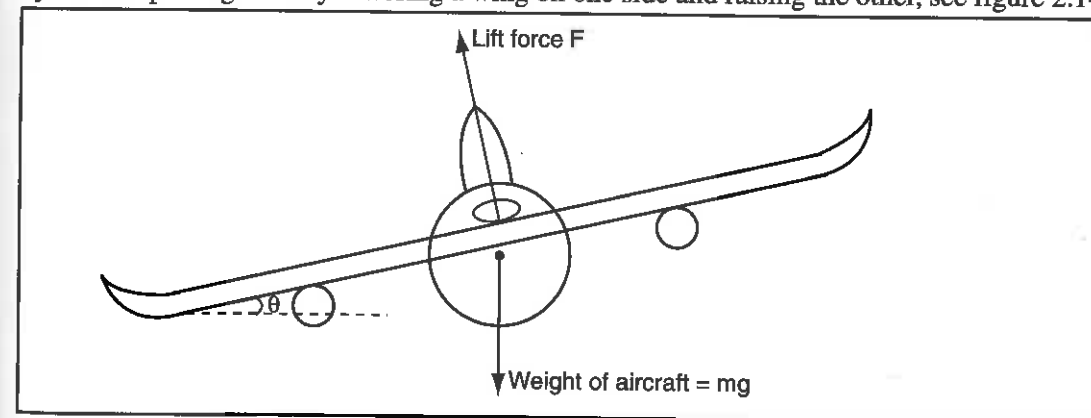


Fig. 2.14: An aircraft banking to provide centripetal force

A cyclist Moving Round a Circular Track

Figure 2.15 (a) shows a cyclist turning round a curved corner. The forces acting on the cyclist are his weight and the normal reaction R . The frictional force F provides the centripetal force, which is directed towards the centre.

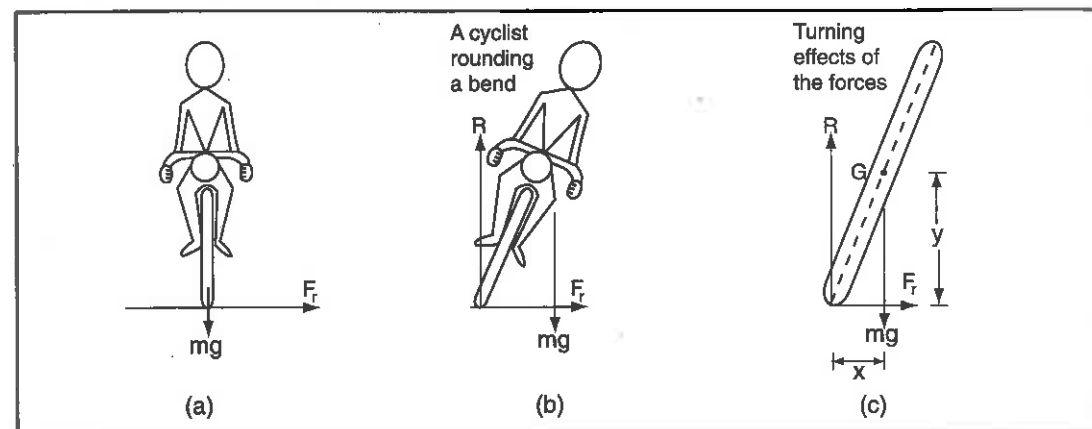


Fig. 2.15: A cyclist on a circular track

The centripetal force is unbalanced and this causes centripetal acceleration. If the frictional force is not sufficient to provide the centripetal force, the cyclist skids.

In order to overcome the problem of skidding, it is common practice for the cyclist to lean inwards, see figure 2.15 (b). By so doing, the normal reaction and the frictional forces produce the turning effects in the clockwise and the anticlockwise directions respectively, see figure 2.15 (c).

For no skidding to occur, taking moments about the centre of gravity G ;

$$F_r y = R x$$

$$\text{But } R = mg$$

$$\text{So, } F_r y = mg x$$

$$\frac{F_r}{mg} = \frac{x}{y}$$

$$\tan \theta = \frac{x}{y}$$

$$\text{Hence, } \tan \theta = \frac{F_r}{mg}$$

$$\text{But } F_r = \frac{mv^2}{r}$$

$$\therefore \tan \theta = \frac{mv^2}{rmg}$$

$$= \frac{v^2}{rg}$$

$$\text{From } \tan \theta = \frac{F_r}{mg}$$

$$F_r = mg \tan \theta$$

Since $F_r = \mu mg$, where μ is the coefficient of friction;

$$mg \tan \theta = \mu mg$$

$$\text{So, } \tan \theta = \mu$$

Skidding therefore occurs when $\tan \theta > \mu$

Conical Pendulum

Figure 2.16 shows a ball moving in a horizontal circle and the forces acting on it.

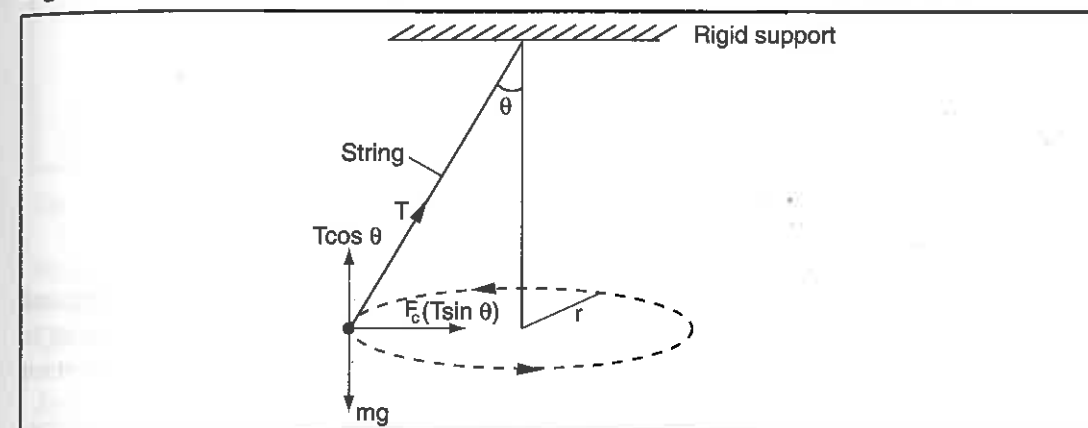


Fig. 2.16: A body moving in a horizontal circle

When the angular velocity ω increases, the ball rises. Hence, the angle θ also increases. The working of the mechanical speed governor and merry-go-round lean heavily on this behaviour.

Motion in a Vertical Circle

Figure 2.17 (a) shows a ball of mass m tied to one end of a string and moving with uniform speed in a vertical circle of radius r .

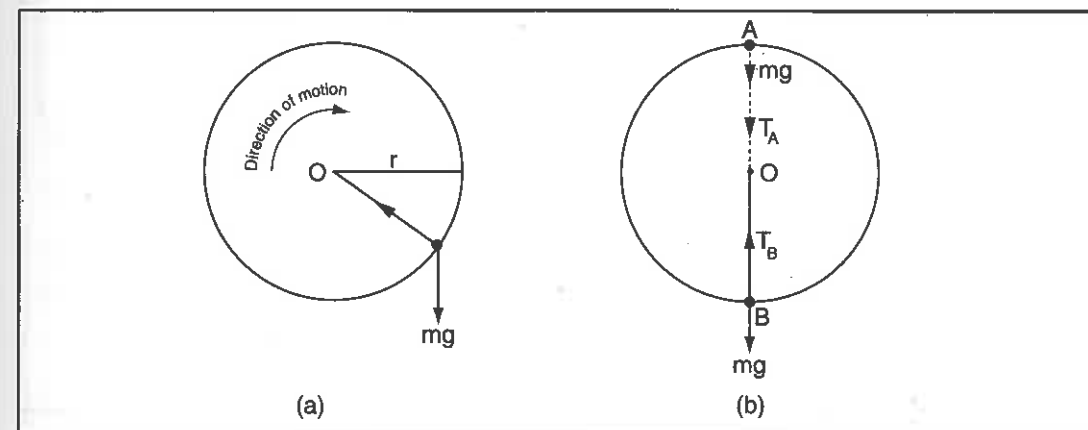


Fig. 2.17: A ball moving in vertical motion

The forces acting on the ball at any instant are its weight mg , which acts vertically downwards and the tension T , which is always directed towards the centre of circle. The tension in the string changes in magnitude at different positions of the ball.

When the ball is at position A in figure 2.17 (b), the tension T_A and the weight mg provide the centripetal force.

$$\frac{mv^2}{r} = T_A + mg \quad (1)$$

When the ball is at B, which is the lowest point of the path, it is acted upon by the tensional force T_B and its weight mg . The centripetal force is therefore provided by the resultant force ($T_B - mg$);

$$\frac{mv^2}{r} = T_B - mg \quad (2)$$

Re-arranging equations (1) and (2);

$$T_A = \frac{mv^2}{r} - mg \quad (3)$$

$$T_B = \frac{mv^2}{r} + mg \quad (4)$$

From equations (3) and (4), it is evident that $T_B > T_A$.

The tension in the string is therefore maximum when the object is at the lowest point and the string is most likely to snap at this position. Also clear from above is that the tension is minimum when the object is at the highest point of the circle. It is at this position that a certain minimum speed must be maintained in order to keep the string taut.

For minimum velocity, $T_A = 0$

$$\frac{mv^2}{r} - mg = 0$$

$$\therefore v_{\min} = \sqrt{rg}$$

Practical examples of motion in a vertical plane are:

- (i) a bucket of water whirled in a vertical circle without the water spilling, see figure 2.18.

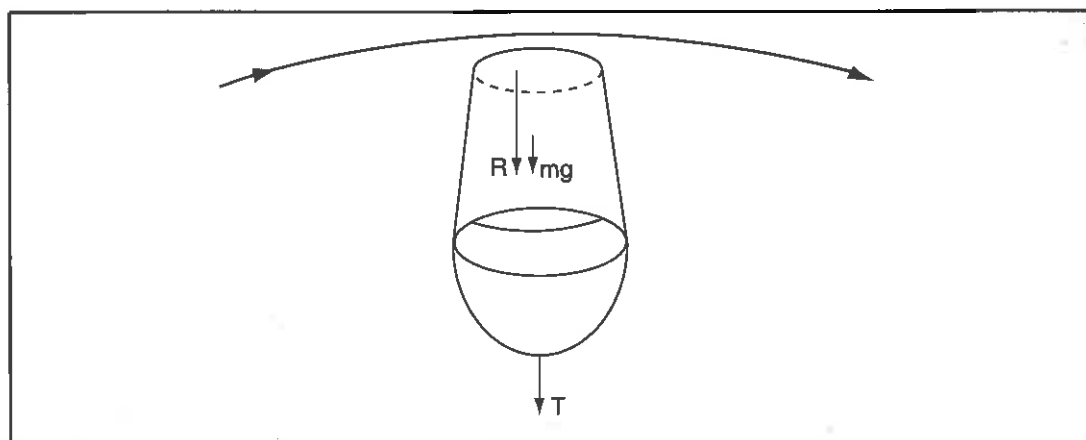


Fig. 2.18: A bucket containing water being whirled in a circle

- (ii) a pilot not strapped to his seat in a 'loop the loop' manoeuvre without falling off.
 (c) a ball bearing 'looping the loop' on a curtain rail lying in a vertical plane.
 (d) a toy car on a 'loop the loop' track, see figure 2.19.

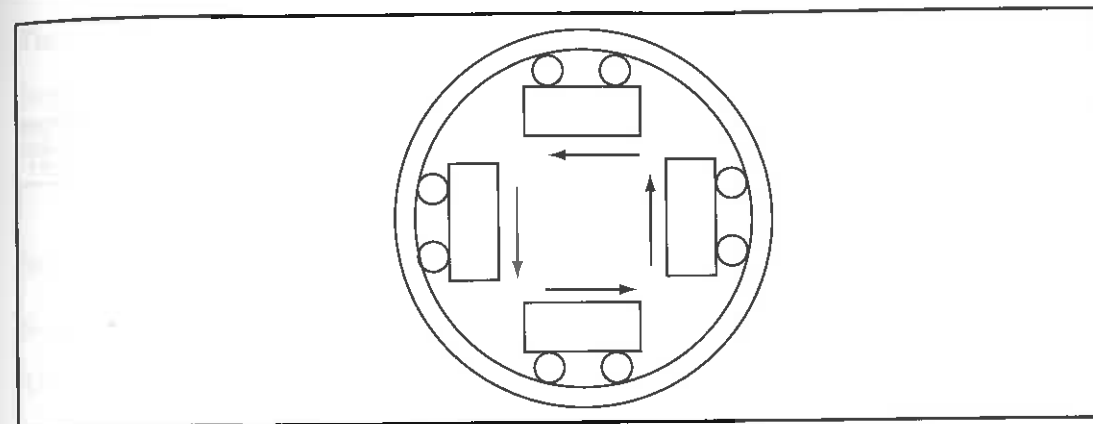


Fig. 2.19: A toy car on a 'loop the loop' track

Example 5

A car travels over a lumpback bridge of radius of curvature 40 m. Calculate the maximum speed of the car if its wheels are to stay in contact with the bridge. Assume g is 10 ms^{-2} .

Solution

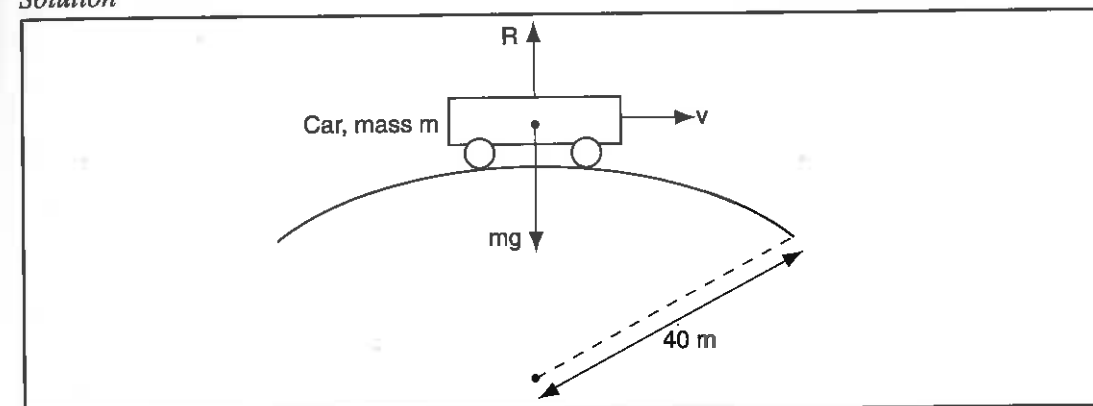


Fig. 2.20

$$mg - R = \frac{mv^2}{r}$$

As v increases, R must decrease, since mg is constant. In the limiting case, when the wheels are just about to leave the ground, $R = 0$.

$$\therefore mg = \frac{mv^2}{r}$$

For maximum speed, $v^2 = rg$

$$\therefore v = \sqrt{rg}$$

Since $r = 40 \text{ m}$ and $g = 10$;

$$\therefore v = \sqrt{40 \times 10}$$

$$v = 20 \text{ ms}^{-1}$$

Applications of Circular Motion

Centrifuges

A centrifuge is used for separating particles in suspension in liquids or liquids of different densities. It consists of small metal container tubes which can be rotated in a circle, as in figure 2.21.

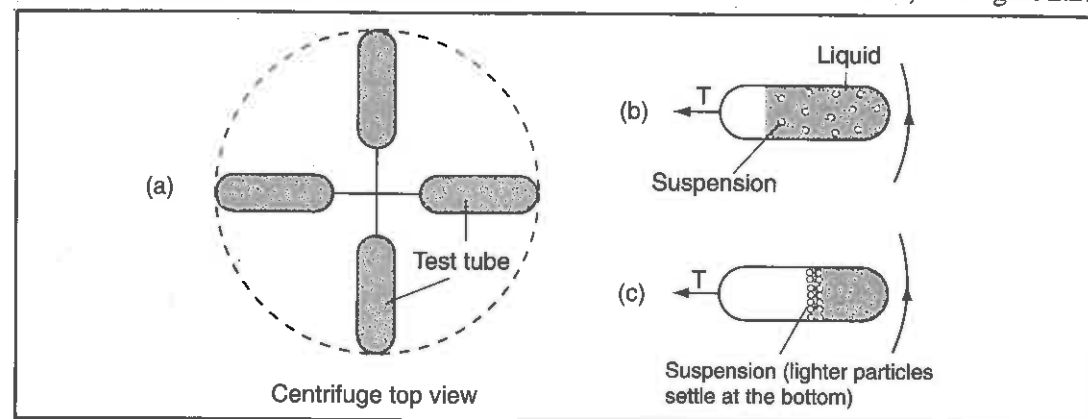


Fig. 2.21: Centrifuge

The pressure difference created at a distance r from the centre of rotation exerts a force, which then provides the centripetal force. For lighter particles, the centripetal force would be too great according to the relation $F = m\omega^2 r$, and r would thus become smaller. The less dense particle is thus drawn inwards towards the centre of rotation, see figure 2.21 (b) and (c).

If the particles have a mass m and the liquid mass m_1 , the net force which provides the centripetal force required to make the particles move towards the centre is given by;

$$F = (m - m_1) r\omega^2$$

Satellites

When two bodies of mass m_1 and m_2 are at a distance r apart, they experience a mutual force of attraction given by;

$$F = \frac{Gm_1m_2}{r^2}, \text{ where } G \text{ is a constant called the universal gravitational constant. The expression}$$

is called **Newton's law of universal gravitation**.

Consider a satellite of mass m set in an orbit of radius r round the earth as in figure 2.22.

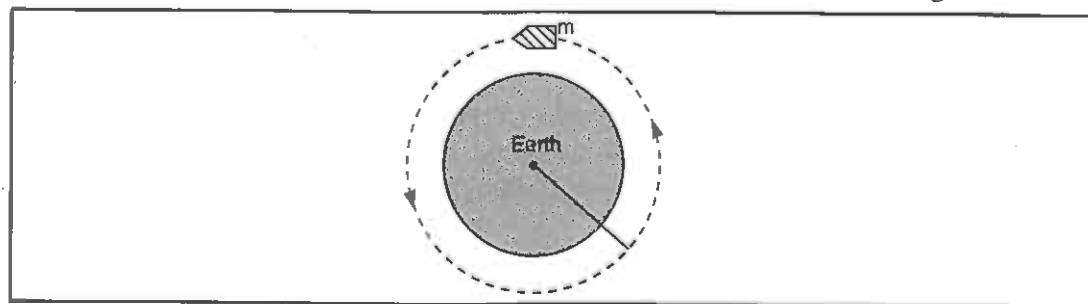


Fig. 2.22: Satellite orbiting the earth

The gravitational force of attraction between the satellite and the earth provides the centripetal force. Thus, $\frac{mv^2}{r} = \frac{GMm}{r^2}$, where m is mass of satellite, M the mass of the earth and v the velocity of the satellite.

$$\therefore v^2 = \frac{GM}{r}$$

$$\text{So, } v = \sqrt{\frac{GM}{r}}$$

$$\text{Hence, } v \propto \frac{1}{\sqrt{r}}$$

This shows that the velocity of a satellite increases with decrease in the radius of its orbit.

A satellite will appear stationary to an observer at a particular point on the earth if its periodic time (time taken to complete one revolution) is equal to that of the earth. Such satellites are said to be in a **parking orbit**, and are used in weather forecast and telecommunications.

Speed Governor

The principle of the conical pendulum is used in the operation of speed governors. Figure 2.23 shows a speed governor used in a steam engine.

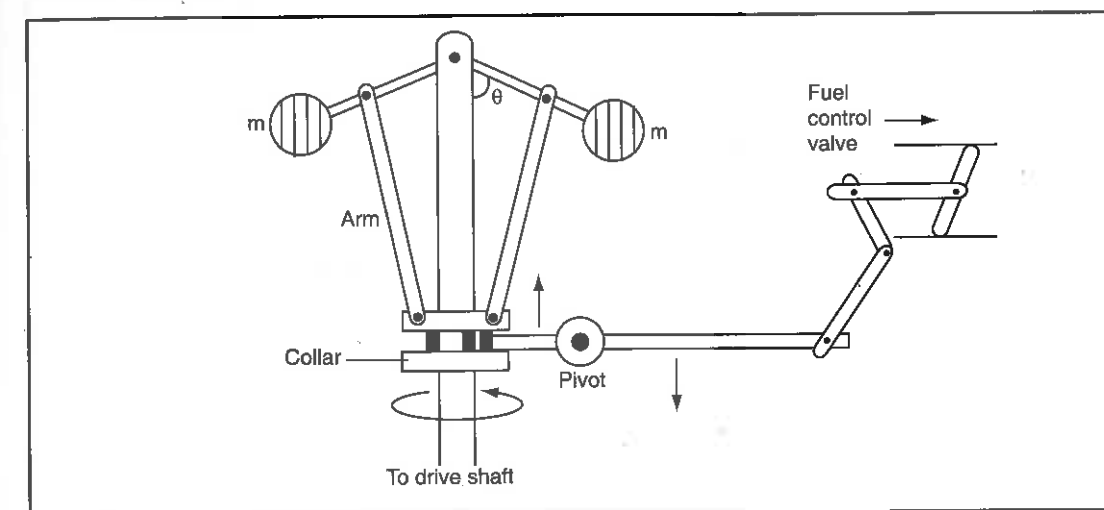


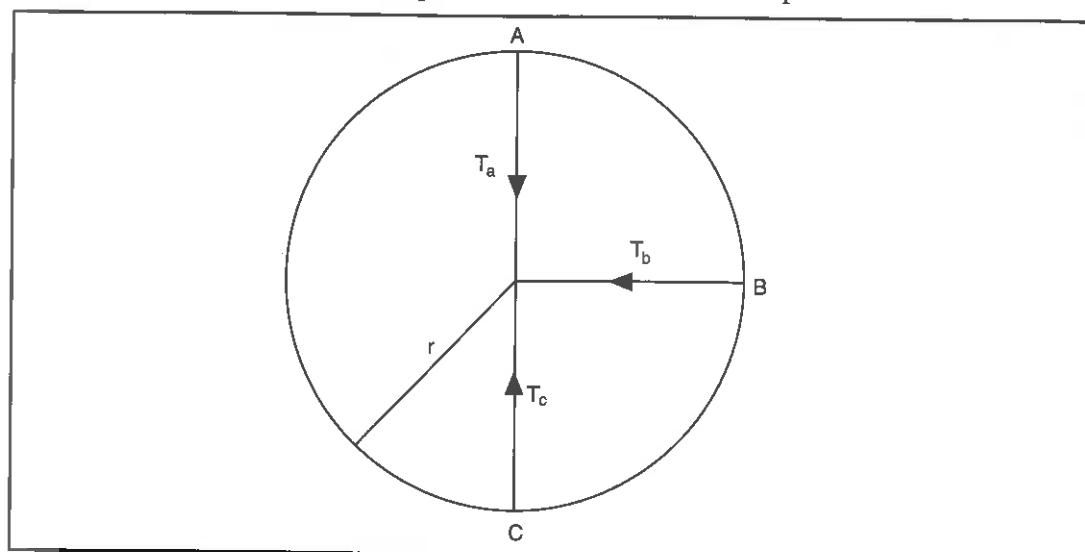
Fig. 2.23: Speed governor

As the masses marked m rotate with an increasing angular velocity, the vertical angle θ increases. The collar is then moved by the arms which in turn pull the lever up. The lever is connected to a steam valve which regulates the flow of steam. The axis of the governor is connected to a drive shaft of the engine which turns it. By controlling the rate of flow of steam or fuel, the speed of the engine can be controlled.

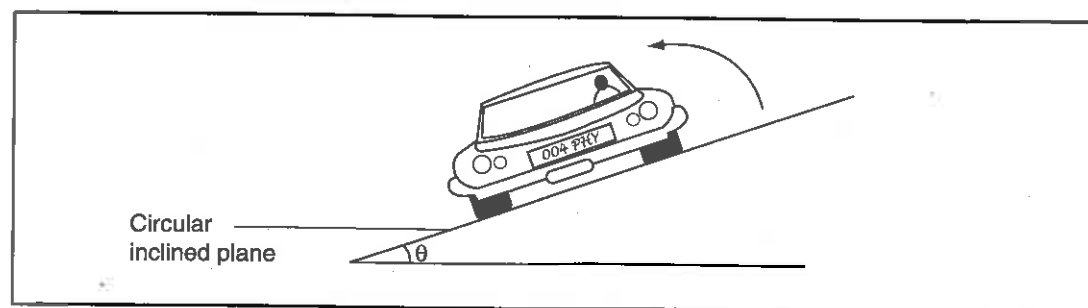
Revision Exercise 2

1. In circular motion, there is acceleration, yet the speed is constant. Explain.
2. Explain how a centrifuge may be used to separate cream from milk.

3. An astronaut in orbit round the earth may feel weightless even when the earth's gravitational field still acts on him. Explain.
4. (a) Distinguish between angular and linear velocity.
 (b) How is the centripetal force different from any other force?
 (c) A stone is whirled with uniform speed in horizontal circle having radius of 10 cm. It takes the stone 10 seconds to describe an arc of length 4 cm. Calculate:
 (i) the angular velocity ω .
 (ii) linear velocity v of the stone.
 (iii) the periodic time T .
5. The figure shows a path of a particle in a circle in a vertical plane:



- (a) Write down an expression showing the relationship between the tensional forces T_a , T_b and T_c in order of their increasing magnitude.
 (b) What contributes to the centripetal force at the positions marked A, B and C?
6. (a) State a condition necessary for a body travelling on a banked road not to skid.
 (b) A car is moving in an unbanked circular path. Sketch a diagram of the motion and show the forces acting on the car. State what provides the centripetal force.
7. (a) To avoid skidding and overturning, roads are usually banked. What do you understand by the term 'banking'?
 (b) Copy the diagram shown and indicate all the forces acting on the car.



8. A pilot in a jet plane 'loops the loop' in a vertical circle with a diameter of 0.8 km at constant speed of 260 kmh^{-1} . If the mass of the pilot is 75 kg:
 (a) sketch a graph showing the magnitude of the forces acting on him in a complete loop.
 (b) calculate the minimum speed the pilot must maintain for him not to fall off at the top of the loop.
9. A bob having a mass of 1 kg is moving in uniform circular path in a vertical plane having a radius of 1 m. It is whirled with a frequency of 2 cycles per second.
 (a) Calculate:
 (i) the tension in the supporting string when the bob is at the topmost part of the circle.
 (ii) the tension when the bob is at the bottom of the circle.
 (b) at what position of the object is the string likely to break?
10. A child whirls a stone of mass 0.5 kg in a vertical circle on the end of a string 40 cm long. At the lowest point of the circle, the velocity of the stone is 3 ms^{-1} . Calculate the tension on the string at this point.
11. A mass of 1.5 kg moves in a circular path with a constant speed of 3 ms^{-1} on a horizontal frictionless surface. The mass is held to the circular path by a light cord 2.4 m long that has one end fixed and the other end attached to the mass. Calculate the tension in the cord.
12. A cord 2.8 m long has a breaking strength of 600 N. One end of the cord is fixed and a 2 kg mass attached to the free end moves in a horizontal circular path on a frictionless level surface. What is the maximum speed if the cord is not to break?

FLOATING AND SINKING

A steel ferry floats on water although steel is denser than water, see figure 3.1. When a cork is immersed in water and then released, it immediately rises to the surface. It is easier to lift a heavy stone when it is immersed in water than when it is in air.



Fig. 3.1: Ferry crossing a creek

These observations show that there is always an upward force acting on a floating object or one immersed in a liquid. This upward force is referred to as **upthrust**. Thus, a body when partially or fully immersed in a liquid appears lighter than it actually is. This apparent loss in weight is equivalent to the upthrust force.

EXPERIMENT 3.1: To investigate the relationship between upthrust and weight of fluid displaced

Apparatus

Spring calibrated in newtons, object, e.g., stone, string, Eureka can, beaker.

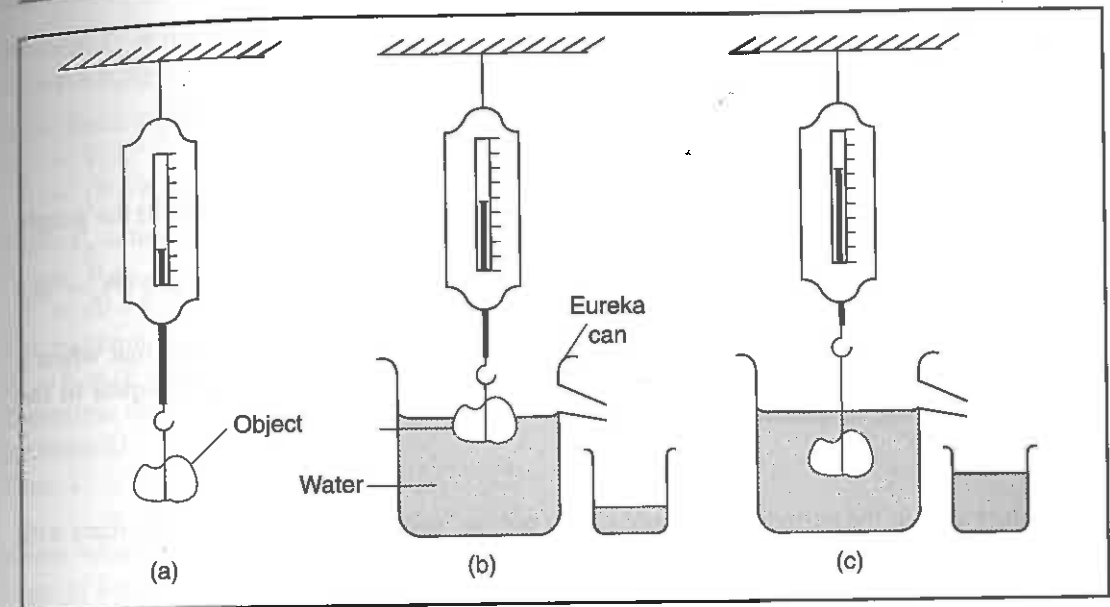


Fig. 3.2: Demonstration of upthrust

Procedure

- Tie the object with the string, then suspend it on the spring balance, as in figure 3.2 (a).
- Record the weight of the object in air.
- Fill the Eureka can with water until it flows out freely through the spout. Leave the can in that position.
- Weigh the empty beaker (a beam balance may be used and the mass converted to weight).
- Put the beaker in position under the spout and then partially immerse the object into the water, as shown in figure 3.2 (b). Wait until the dripping stops, then weigh the beaker plus the contents.
- Record the weight of the partially immersed object.
- Remove the object from the water.
- Repeat the experiment with the object totally immersed, see figure 3.2 (c).

Results and Calculation

Weight of object in air = W_1

Weight of object when partially immersed in water = W_2

Weight of empty beaker = W_3

Weight of beaker + water displaced (object partially immersed) = W_4

Weight of object when totally immersed in water = W_5

Weight of beaker + water displaced (object totally immersed) = W_6

Object partially immersed

Apparent loss in weight = $W_1 - W_2$

Weight of water displaced = $W_4 - W_3$

Object totally immersed

Apparent loss in weight = $W_1 - W_5$

Weight of water displaced = $W_6 - W_3$

Observation and Conclusion

When the object is partially immersed, the apparent loss in weight ($W_1 - W_2$) equals the weight of water displaced ($W_4 - W_3$).

Similarly, when the object is totally immersed, the apparent loss in weight ($W_1 - W_5$) equals the weight of water displaced ($W_6 - W_3$).

The results above are a verification of Archimedes' principle which states that **when a body is partially or totally immersed in a fluid, it experiences an upthrust equal to the weight of the fluid displaced.**

Note:

The object used in the experiment should not be porous, soluble and or one that can react with the liquid used.

Cause of Upthrust

Consider a cylindrical solid of cross-sectional area A , totally immersed in a fluid of density ρ , as shown in figure 3.3.

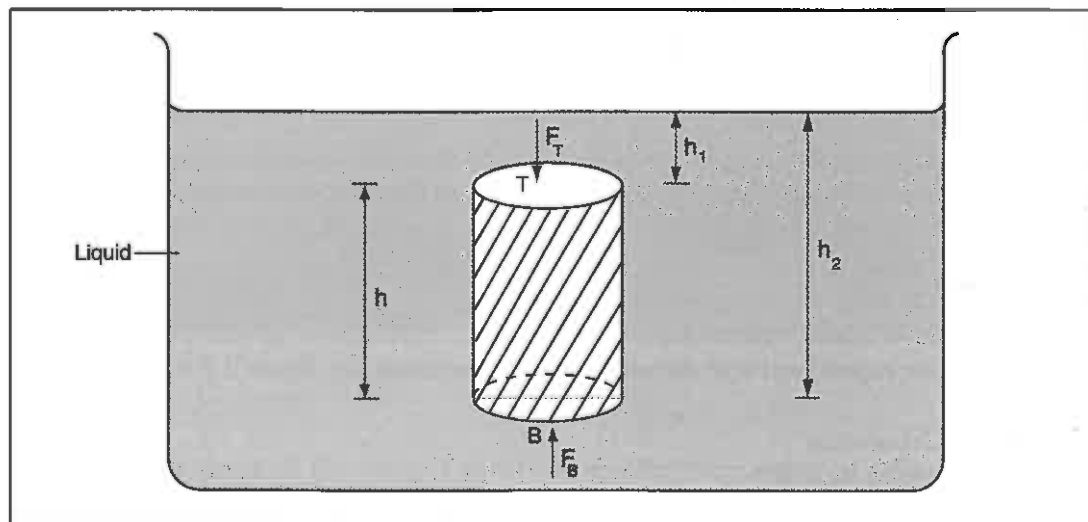


Fig. 3.3: Pressure and upthrust

Since pressure in liquids increases with depth, pressure of the liquid at the top T of the solid is less than that at the bottom B .

Pressure of a liquid at a given depth acts equally in all directions. Hence, pressure on the sides of the solid cancel out. If P is the atmospheric pressure, pressure P_T at the top of the solid is given by;

$$P_T = P + h_1 \rho g$$

Pressure P_B at the bottom of the solid;

$$P_B = P + h_2 \rho g$$

Since force = pressure $\times$ area, force F_T acting on top of the object is given by;

$$\begin{aligned} F_T &= P_T A \\ &= (P + h_1 \rho g) A \end{aligned}$$

Force F_B acting on the bottom of the solid;

$$\begin{aligned} F_B &= P_B A \\ &= (P + h_2 \rho g) A \end{aligned}$$

The resultant upward force on the cylinder is given by;

$$F_B - F_T = (P + h_2 \rho g) A - (P + h_1 \rho g) A$$

Therefore, the resultant upward force is $h \rho g A$, where $h = h_2 - h_1$. This resultant force is the upthrust, U .

$$\text{Thus, } U = h A \rho g$$

$$= V \rho g$$

where volume V of liquid displaced by the solid is given by, $V = Ah$.

Mass of liquid displaced = $A h \rho$

Weight of fluid displaced = $A h \rho g$

Upthrust is therefore, equal to the weight of liquid displaced. The magnitude of the upthrust depends on the volume of the fluid displaced and its density.

Upthrust in Gases

Like liquids, gases exert upthrust on objects in them. The upthrust in air is small owing to its low density (about 1.3 kgm^{-3}), but sufficient to make balloons filled with hydrogen (density about 0.09 kgm^{-3}) or helium (about 0.18 kgm^{-3}) rise.

Consider the balloon in figure 3.4 (a). If it is inflated with air to a certain volume, the weight of air in the balloon plus its fabric is greater than the weight of air displaced by the balloon, since the volume of air in the balloon is nearly equal to the volume of air displaced. Upthrust on the balloon due to the air is thus less than the weight. The balloon stays on the ground due to the downward resultant force, $W - U$.

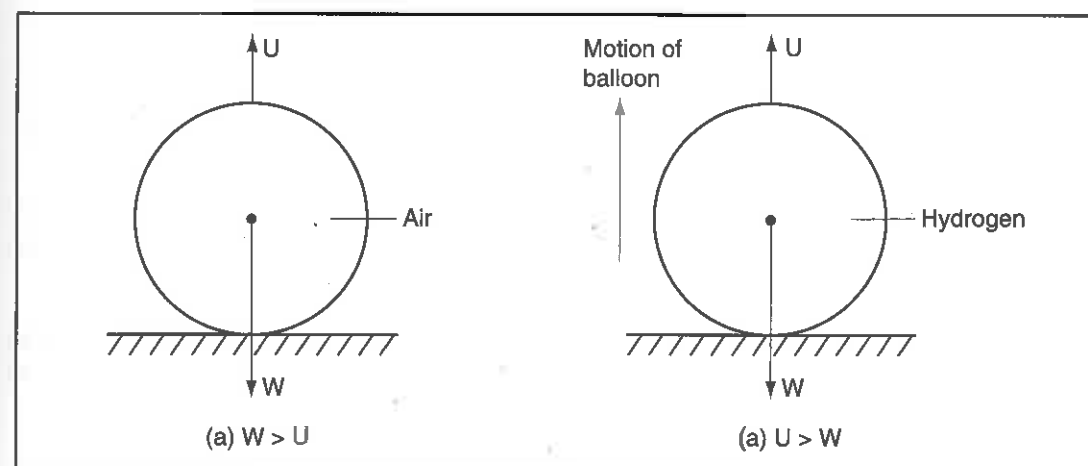


Fig. 3.4: Upthrust in air

If the balloon is filled with a gas which is less dense than air, such as hydrogen or helium, the weight of the gas plus the balloon fabric is less than the weight of air displaced by the balloon. In this case, the upthrust U exerted by the air on the balloon is greater than the weight W of the inflated balloon. The resultant upward force $U - W$ lifts the balloon upwards, see figure 3.4 (b).

Example 1

A solid sphere of radius 3 cm and made of material of density 2.6 gcm^{-3} is fully immersed in a liquid of density 0.8 gcm^{-3} . Determine the apparent weight of the sphere.

Solution

Let density of the sphere be ρ_1 and that of the liquid ρ_2 .

Volume of the sphere = $\frac{4}{3}\pi r^3$, where r is its radius.

Mass of the sphere = $\frac{4}{3}\pi r^3 \rho_1$

Weight of sphere in air = $\frac{4}{3}\pi r^3 \rho_1 g$

Volume of a liquid displaced by the sphere = $\frac{4}{3}\pi r^3$

Mass of the liquid = $\frac{4}{3}\pi r^3 \rho_2$

Weight of liquid displaced = $\frac{4}{3}\pi r^3 \rho_2 g$

Weight of liquid displaced equals upthrust,

$\therefore$ Upthrust on the sphere = $\frac{4}{3}\pi r^3 \rho_2 g$

Apparent weight of the sphere = weight in air – upthrust

$$\frac{4}{3}\pi r^3 \rho_1 g - \frac{4}{3}\pi r^3 \rho_2 g = \frac{4}{3}\pi r^3 g (\rho_1 - \rho_2)$$

Since $r = 3 \text{ cm}$ ($3 \times 10^{-2} \text{ m}$), $\rho_1 = 2.6 \text{ gcm}^{-3}$ ($2\,600 \text{ kgm}^{-3}$) and $\rho_2 = 0.8 \text{ gcm}^{-3}$ (800 kgm^{-3});

$$\begin{aligned} \text{Apparent weight} &= \frac{4}{3} \times 3.142 \times (3.0 \times 10^{-2})^3 \times 10 \times (2\,600 - 800) \\ &= 2.04 \text{ N} \end{aligned}$$

Example 2

A cylinder of length 5 cm and uniform cross section area 50.24 cm^2 is suspended from a spring balance and totally immersed in water. If the density of the material of the cylinder is 1.25 gcm^{-3} , determine:

- the upthrust on the cylinder.
- the reading on the spring balance (Take $g = 10 \text{ ms}^{-2}$ and density of water as $1\,000 \text{ kgm}^{-3}$)

Solution

$$\begin{aligned} \text{(a) Volume of the cylinder} &= (5 \times 50.24 \times 10^{-6}) \text{ m}^3 \\ &= 2.51 \times 10^{-4} \text{ m}^3 \end{aligned}$$

Volume of water displaced by the cylinder = $2.51 \times 10^{-4} \text{ m}^3$

$$\begin{aligned} \text{Weight of water displaced} &= (2.51 \times 10^{-4} \times 1\,000 \times 10) \\ &= 2.51 \text{ N} \end{aligned}$$

But weight of water displaced = upthrust on cylinder.

Therefore, upthrust = 2.51 N

$$\begin{aligned} \text{(b) Mass of the cylinder} &= 2.51 \times 10^{-4} \times 1\,250 \\ &= 3.14 \times 10^{-1} \text{ kg} \end{aligned}$$

$$\begin{aligned} \text{Weight of the cylinder} &= 3.14 \times 10^{-1} \times 10 \\ &= 3.14 \text{ N} \end{aligned}$$

$$\begin{aligned} \text{Apparent weight} &= \text{real weight} - \text{upthrust} \\ &= 3.14 - 2.51 \\ &= 0.63 \text{ N} \end{aligned}$$

This is the reading on the spring balance.

Example 3

A stone weighs 2.0 N in air and 1.2 N when totally immersed in water. Calculate:

- the volume of the stone.
 - the density of the stone.
- (Take $g = 10 \text{ N kg}^{-1}$)

Solution

$$\begin{aligned} \text{(a) Upthrust} &= \text{weight in air} - \text{apparent weight} \\ &= (2.0 - 1.2) \text{ N} \\ &= 0.8 \text{ N} \end{aligned}$$

Upthrust = weight of water displaced by the stone.

Weight of water displaced = 0.8 N

$$\begin{aligned} \text{Mass of water displaced} &= \frac{0.8}{10} \\ &= 0.08 \text{ kg} \end{aligned}$$

Since density of water = $1\,000 \text{ kgm}^{-3}$,

$$\begin{aligned} \text{Volume of the water displaced} &= \frac{0.08}{1\,000} \text{ m}^3 \\ &= 8.0 \times 10^{-5} \text{ m}^3 \end{aligned}$$

Volume of stone = $8 \times 10^{-5} \text{ m}^3$

$$\begin{aligned} \text{(b) Mass of the stone} &= \frac{2.0}{10} \\ &= 0.2 \text{ kg} \end{aligned}$$

$$\begin{aligned} \text{Density of the stone} &= \frac{\text{mass of stone}}{\text{volume of stone}} \\ &= \frac{0.2 \text{ kg}}{8.0 \times 10^{-5} \text{ m}^3} \\ &= 2\,500 \text{ kgm}^{-3} \end{aligned}$$

Example 4

A meteorological balloon has a volume of 36 m^3 and is filled with helium of density 0.18 kgm^{-3} . If the weight of its fabric is 120 N , calculate the maximum load which the balloon can lift. (Take density of air as 1.3 kgm^{-3})

Solution

Volume of air displaced by the balloon = 36 m^3 .

Mass of air displaced by the balloon = $(36 \times 1.3) \text{ kg}$

Weight of air displaced = $36 \times 1.3 \times 10$
 $= 468 \text{ N}$

Weight of air displaced = upthrust
 $= 468 \text{ N}$

Mass of helium in the balloon = $(36 \times 1.8 \times 10^{-1}) \text{ kg}$

Weight of helium in the balloon = $(36 \times 1.8 \times 10^{-1} \times 10)$
 $= 64.8 \text{ N}$

Weight inflated balloon = $(64.8 + 120) \text{ N}$
 $= 184.8 \text{ N}$

Upthrust = maximum load + weight of inflated balloon

Maximum load = upthrust – weight of balloon
 $= 468 - 184.8$
 $= 283.2 \text{ N}$

Law of Flotation

EXPERIMENT 3.2: To investigate the upthrust on a floating object

Apparatus

Measuring cylinder, water, test-tube, sand, weighing balance.

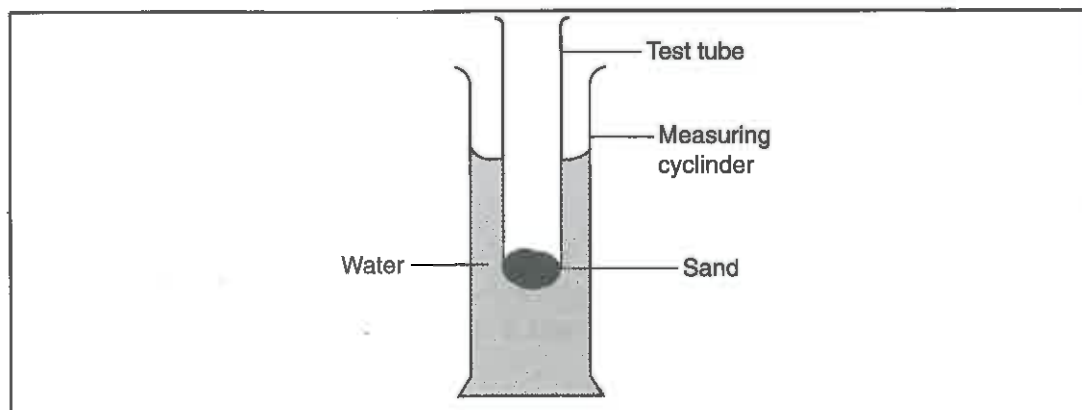


Fig. 3.5: Investigating upthrust on a floating object

Procedure

- Half-fill the measuring cylinder with water and record the level.
- Place a clean dry test tube into the cylinder and add some sand to it so that it floats upright, see figure 3.5. Record the new water level.
- Determine the volume of water displaced.
- Remove the test tube from the cylinder, dry it and determine its weight.
- Repeat the experiment four times, adding a little more sand each time. Record the results in table 3.1.

Table 3.1

Weight of sand and test-tube (N)	Volume of displaced water (cm^3)	Mass of displaced water (kg)	Weight of displaced water (N)

Observation

It is observed that:

- the test tube sinks deeper with each addition of sand.
- the weight of the test tube and its contents is equal to the weight of water displaced.

Conclusion

A floating object displaces its own weight of the fluid in which it floats. This is the law of flotation. It should be noted that the law is a special case of Archimedes' principle.

Example 5

A boat of mass $1\,000 \text{ kg}$ floats on fresh water. If the boat enters sea water, determine the load that must be added to it so that it displaces the same volume of water as before. (Take density of fresh water as $1\,000 \text{ kgm}^{-3}$ and density of sea water as $1\,030 \text{ kgm}^{-3}$)

Solution

Weight of the boat = $1\,000 \times 10$
 $= 10\,000 \text{ N}$

By the law of flotation;

Weight of fresh water displaced = weight of the boat
 $= 10\,000 \text{ N}$

Mass of fresh water displaced = $\frac{10\,000}{10}$
 $= 1\,000 \text{ kg}$

Volume of fresh water displaced = $\frac{1\,000}{1\,000}$
 $= 1 \text{ m}^3$

Volume of sea water displaced on addition of load = 1 m^3

Mass of sea water displaced = $1 \times 1\,030$
 $= 1\,030 \text{ kg}$

Weight of sea water displaced = $(1\,030 \times 10)$
 $= 10\,300 \text{ N}$

Extra load required = weight of sea water displaced – weight of fresh water displaced
 $= 10\,300 - 10\,000$
 $= 300 \text{ N}$

Example 6

A balloon of volume 6.0 m^3 is filled with hydrogen of density 0.09 kgm^{-3} and floats in air of density 1.3 kgm^{-3} . Calculate the weight of the fabric of the balloon.

Solution

Mass of hydrogen in the balloon = 6.0×0.09
 $= 0.54 \text{ kg}$

Weight of hydrogen = 0.54×10
 $= 5.4 \text{ N}$

Let W be the weight of the fabric of the balloon.

Total weight of the inflated balloon = $(5.4 + W) \text{ N}$

Volume of air displaced by the balloon = 6.0 m^3

Mass of air displaced = 6.0×1.3
 $= 7.8 \text{ kg}$

Weight of the air displaced = 7.8×10
 $= 78 \text{ N}$

By the law of flotation, $5.4 + W = 78$

$W = 78 - 5.4$
 $= 72.6 \text{ N}$

Example 7

A cube of side 4 cm weighs 1.12 N in air. Calculate:

- its apparent weight when immersed in a liquid of density 0.79 gcm^{-3} .
- the density of the material of the cube.

Solution

(a) Volume of the cube = $4 \times 4 \times 4 \times 10^{-6}$
 $= 6.4 \times 10^{-5} \text{ m}^3$

Volume of a liquid displaced by the cube = $6.4 \times 10^{-5} \text{ m}^3$

Mass of liquid displaced = $(6.4 \times 10^{-5} \times 7.90 \times 10^2)$
 $= 5.06 \times 10^{-2} \text{ kg}$

$\therefore$ Weight of a liquid displaced = $5.06 \times 10^{-2} \times 10$
 $= 5.06 \times 10^{-1} \text{ N}$

But weight of liquid displaced = upthrust on cube

$\therefore$ Apparent weight = $1.12 - 0.506$
 $= 6.14 \times 10^{-1} \text{ N}$

(b) Weight of the cube = 1.12 N

$\therefore$ Mass of the cube = $\frac{1.12}{10}$

$= 1.12 \times 10^{-1} \text{ kg}$

Volume of the cube = $6.4 \times 10^{-5} \text{ m}^3$

Density of the cube = $\frac{1.12 \times 10^{-1}}{6.4 \times 10^{-5}}$
 $= 1.75 \times 10^3 \text{ kgm}^{-3}$

Example 8

A model ferry boat 50 cm long and 20 cm wide floats in fresh water. If the ferry sinks 6 cm as a result of loading, calculate the load on the block.

Solution

Volume of water displaced as a result of loading = $6 \times 50 \times 20 \times 10^{-6}$
 $= 6 \times 10^{-3} \text{ m}^3$

Mass of water displaced = $6 \times 10^{-3} \times 1000$
 $= 6 \text{ kg}$

Weight of water displaced = 6×10
 $= 60 \text{ N}$

Extra load on the model = weight of extra water displaced
 $= 60 \text{ N}$

Example 9

A balloon has a volume 100 m^3 . If the weight of the balloon fabric is negligible, determine the maximum load it can lift when filled with hydrogen. (Take density of air = 1.2 kgm^{-3} , density of hydrogen = 0.09 kgm^{-3})

Solution

Volume of hydrogen in the balloon = 100 m^3

Mass of hydrogen = 100×0.09
 $= 9.0 \text{ kg}$

Weight of hydrogen = $(9.0 \times 10^1) \text{ N}$

Volume of air displaced by the balloon = 100 m^3

Mass of air displaced = $(100 \times 1.2) \text{ kg}$

Weight of air displaced = $1.2 \times 10^2 \times 10$
 $= 1.2 \times 10^3 \text{ N}$

But upthrust = weight of air displaced

Upthrust on the balloon = $1.2 \times 10^3 \text{ N}$

Maximum load possible = upthrust – weight of hydrogen in the balloon
 $= 1.2 \times 10^3 - 9.0 \times 10^1$
 $= 1.11 \times 10^3 \text{ N}$

Example 10

The wooden block in figure 3.6 floats in two liquids X and Y. Given that the densities of X and Y are 1 gcm^{-3} and 0.8 gcm^{-3} respectively, determine:

- (a) the mass of the block.
(b) the density of the block.

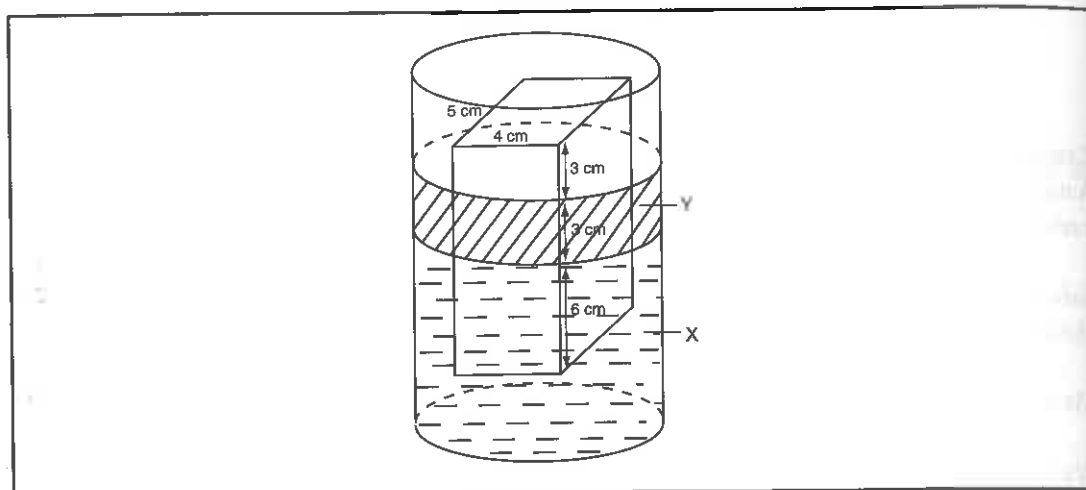


Fig. 3.6

Solution

- (a) Volume V of liquid Y displaced $= 5 \times 4 \times 3 \times 10^{-6} \text{ m}^3$
 $= 6 \times 10^{-5} \text{ m}^3$

$$\begin{aligned}\text{Upthrust} &= \rho Vg \\ &= 800 \times 6 \times 10^{-5} \times 10 \\ &= 0.48 \text{ N}\end{aligned}$$

$$\begin{aligned}\text{Volume } V \text{ of liquid X displaced} &= 5 \times 4 \times 6 \times 10^{-6} \text{ m}^3 \\ &= 1.2 \times 10^{-4} \text{ m}^3\end{aligned}$$

$$\begin{aligned}\text{Upthrust} &= \rho Vg \\ &= 1000 \times 1.2 \times 10^{-4} \times 10 \\ &= 1.2 \text{ N}\end{aligned}$$

$$\begin{aligned}\text{Total upthrust on block} &= 0.48 + 1.2 \\ &= 1.68 \text{ N}\end{aligned}$$

The block is floating, hence weight of block equals total upthrust.

$$\therefore \text{Weight of block} = 1.68 \text{ N}$$

$$\begin{aligned}\text{Mass of block} &= \frac{1.68}{10} \\ &= 0.168 \text{ kg}\end{aligned}$$

- (b) Volume of block $= 5 \times 4 \times 12 \times 10^{-6} \text{ m}^3$
 $= 2.4 \times 10^{-4} \text{ m}^3$

$$\text{Density} = \frac{\text{mass}}{\text{volume}}$$

$$\begin{aligned}&= \frac{0.168}{2.4 \times 10^{-4}} \\ &= 700 \text{ kgm}^{-3}\end{aligned}$$

Upthrust and Relative Density

Archimedes' principle can be used to determine relative densities of both solids and liquids.

Relative Density of a Solid

By definition;

$$\text{relative density of a solid} = \frac{\text{mass of the solid}}{\text{mass of equal volume of water}}$$

Since mass is directly proportional to weight, the relative density can also be expressed as;

$$\begin{aligned}\text{relative density of a solid} &= \frac{\text{weight of solid}}{\text{weight of equal volume of water}} \\ &= \frac{\text{weight of solid}}{\text{weight of water displaced by solid}}\end{aligned}$$

But, weight of water displaced by solid = upthrust

$$\therefore \text{Relative density of a solid} = \frac{\text{weight of solid}}{\text{upthrust in water}}$$

To determine the relative density of a solid, the solid is weighed in air and then totally immersed in water. The upthrust is calculated and relative density determined from the formula above.

Relative Density of a Liquid

To determine relative density of a liquid using the Archimedes' principle, three measurements are taken:

- Weight W_1 of a solid in air.
- Weight W_2 of the solid when totally immersed in water.
- Weight W_3 of the solid when totally immersed in a liquid whose relative density is to be determined.

By definition;

$$\begin{aligned}\text{relative density of the liquid} &= \frac{\text{mass of liquid}}{\text{mass of equal volume of water}} \\ &= \frac{\text{weight of liquid}}{\text{weight of equal volume of water}}\end{aligned}$$

Since the same solid is used in both the liquid and the water, the volume of water displaced equals volume of liquid displaced. Thus;

weight of liquid displaced by solid = upthrust in liquid, and;

weight of water displaced by solid = upthrust in water

$$\text{Relative density of the liquid} = \frac{\text{upthrust in the liquid}}{\text{upthrust in water}}$$

$$\text{Upthrust in the liquid} = W_1 - W_3$$

$$\text{Upthrust in water} = W_1 - W_2$$

$$\text{Relative density of the liquid} = \frac{W_1 - W_3}{W_1 - W_2}$$

Example 11

A solid mass 0.8 kg suspended by a string is totally immersed in water. If the tension in the string is 4.8 N, calculate:

- the volume of the solid.
- the relative density of the solid.

Solution

$$\begin{aligned} \text{(a) Weight of the solid} &= (0.8 \times 10) \text{ N} \\ &= 8.0 \text{ N} \end{aligned}$$

$$\text{Apparent weight of the solid} = 4.8 \text{ N}$$

$$\begin{aligned} \text{Upthrust} &= (8.0 - 4.8) \text{ N} \\ &= 3.2 \text{ N} \end{aligned}$$

But upthrust = weight of water displaced.

$$\text{Weight of the water displaced} = 3.2 \text{ N}$$

$$\begin{aligned} \text{Mass of water displaced} &= \frac{3.2}{10} \text{ g} \\ &= 0.32 \text{ kg} \end{aligned}$$

$$\begin{aligned} \text{Volume of water displaced} &= \frac{0.32}{1000} \\ &= 3.2 \times 10^{-4} \text{ m}^3 \end{aligned}$$

Volume of water displaced = volume of the solid

$$\text{Volume of the solid} = 3.2 \times 10^{-4} \text{ m}^3$$

$$\begin{aligned} \text{(b) Relative density of the solid} &= \frac{\text{weight of the solid}}{\text{upthrust in water}} \\ &= \frac{8.0}{3.2} \\ &= 2.5 \end{aligned}$$

Example 12

In an experiment with a metal cube, the following results were obtained:

Weight of the cube in air = 0.5 N

Weight of the cube when completely immersed in water = 0.44 N

Weight of the cube when completely immersed in oil = 0.46 N

Calculate the relative density of the oil.

Solution

$$\text{Relative density of the oil} = \frac{\text{upthrust in oil}}{\text{upthrust in water}}$$

$$\begin{aligned} &= \frac{0.5 - 0.46}{0.5 - 0.44} \\ &= \frac{4.0 \times 10^{-2}}{6.0 \times 10^{-2}} \\ &= 0.667 \end{aligned}$$

Archimedes Principle and Moments

Relative densities of solids and liquids can also be determined by use of a balanced lever.

Solids

EXPERIMENT 3.3: To determine the relative density of a solid using upthrust and moments

Apparatus

Metre rule suspended from a clamp, solid S, metal block W, water in a beaker.

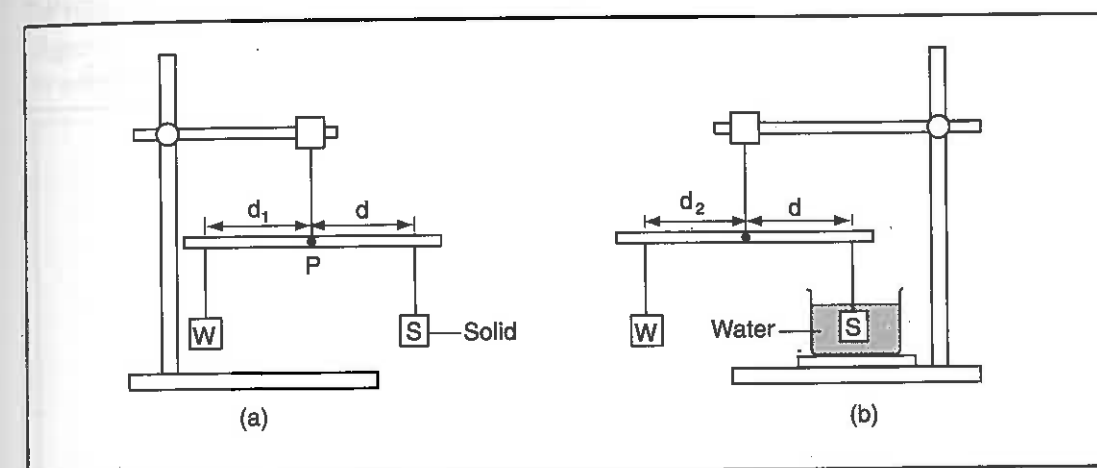


Fig. 3.7: Relative density using moments

Procedure

- Suspend the metre rule so that it balances at its centre of gravity.
- Suspend the solid S at a distance $d = 30 \text{ cm}$, then suspend and adjust the position of W such that the rule is balanced, see figure 3.7 (a). Record distance d_1 of W from point of suspension in table 3.2.
- While maintaining the distance d , immerse solid S completely in water, then adjust the position of W to balance the metre rule again, see figure 3.7 (b). Record the new distance d_2 for the metal block W in the table.
- Remove the beaker of water so that the solid S hangs freely in air.
- Increase the distance d in figure 3.7 (a) to a new value, say 35 cm, and repeat the procedure above.
- Repeat for four other values of d and complete table 3.2.

Table 3.2

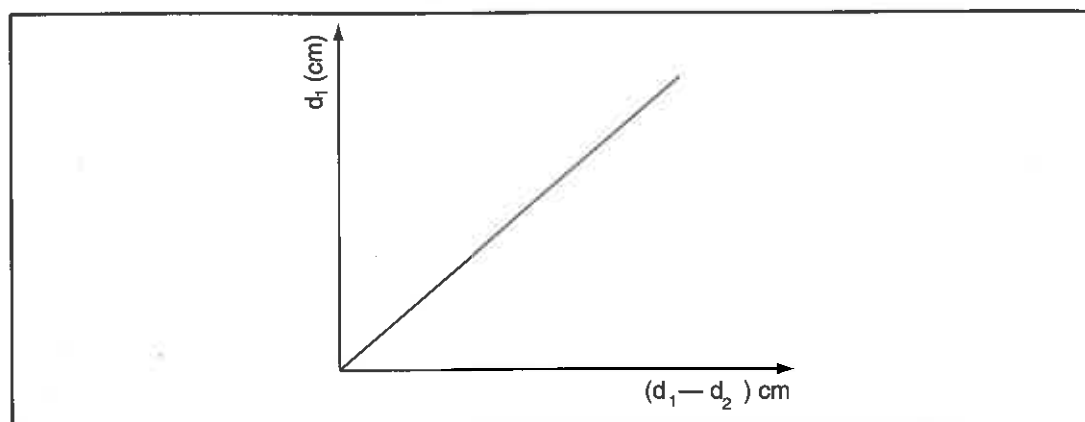
Distance of S in air, d (cm)	Distance of S in water, d_1 (cm)	Distance of W, d_2 (cm)	$d_1 - d_2$ (cm)
30			
35			
40			
45			
50			

- Plot a graph of d_1 against $(d_1 - d_2)$ and determine its slope.

Observation

Each time the solid S is immersed in water, the distance d_1 must be adjusted to a smaller distance d_2 for the metre rule to balance again.

The graph of d_1 against $(d_1 - d_2)$ is a straight line through the origin, see figure 3.8.

Fig. 3.8: Graph of d_1 against $(d_1 - d_2)$ **Calculation**

From the principle of moments;

$$Wd_1 = W_A d, \text{ where } W_A \text{ is the weight of solid S in air} \dots\dots\dots (1)$$

$$Wd_2 = W_w d, \text{ where } W_w \text{ is the weight of the solid in water} \dots\dots\dots (2)$$

From (1) and (2);

$$W_A = \frac{Wd_1}{d}, \text{ and;}$$

$$W_w = \frac{Wd_2}{d}$$

$$\begin{aligned} \text{Now, relative density of solid} &= \frac{W_A}{W_A - W_w} \\ &= \frac{\frac{Wd_1}{d}}{\frac{Wd_1}{d} - \frac{Wd_2}{d}} \\ &= \frac{d_1}{d_1 - d_2} \end{aligned}$$

Thus, the slope of the graph of d_1 versus $(d_1 - d_2)$ represents the relative density of the solid.

Liquids

To determine the relative density of a liquid, a similar approach to that used in the determination of relative density of a solid is followed. In addition to measurements made in the set-up in figure 3.7, the distance d_3 , at which the lever balances when the solid is immersed in the liquid, is noted, see figure 3.9.

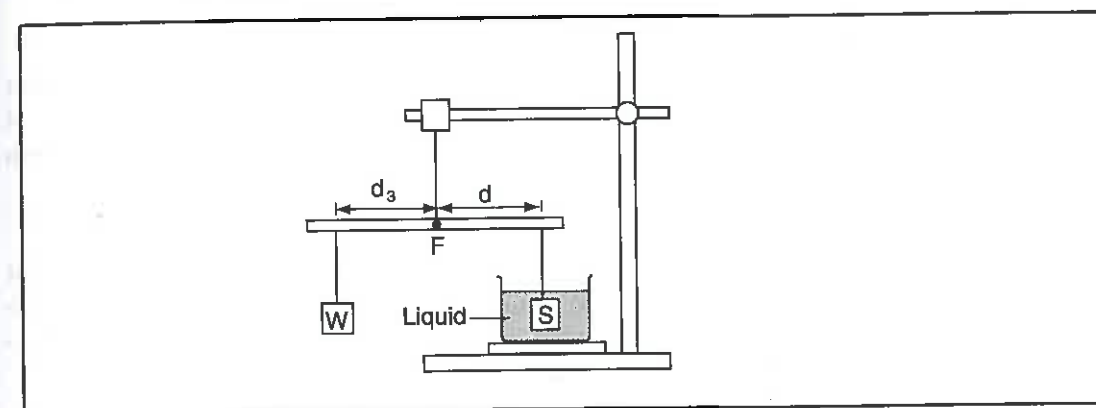


Fig. 3.9: Relative density of a liquid using moments

From the figure;

$$Wd_3 = W_L d, \text{ where } W_L \text{ is the apparent weight of the solid in the liquid.}$$

$$W_L = \frac{Wd_3}{d} \dots\dots\dots (3)$$

$$\begin{aligned} \text{Upthrust in water} &= W_A - W_w \\ &= \frac{Wd_1}{d} - \frac{Wd_2}{d} \\ &= \frac{W}{d} (d_1 - d_2) \end{aligned}$$

$$\text{Upthrust in liquid} = W_A - W_L$$

$$= \frac{Wd_1}{d} - \frac{Wd_3}{d}$$

$$= \frac{W}{d} (d_1 - d_3)$$

Relative density of the liquid = $\frac{\text{upthrust in liquid}}{\text{upthrust in water}}$

$$= \frac{\frac{W}{d} (d_1 - d_3)}{\frac{W}{d} (d_1 - d_2)}$$

$$= \frac{d_1 - d_3}{d_1 - d_2}$$

Note:

When this method is used to determine relative density of a solid or liquid, measurements of masses or weights are not required.

Applications of Archimedes' Principle and Relative Density

The Hydrometer

The densities or relative densities of liquids can be determined directly by use of an instrument called hydrometer, which uses the law of flotation in its operation. To determine density of liquids, a hydrometer tube designed for that purpose is required. Figure 3.10 shows one form of a modern hydrometer. The main features of this instrument are:

Wide bulb containing air

The bulb is made wide so that it can displace a large volume of liquid that provides a sufficient upthrust to keep the hydrometer floating. The volume of the bulb determines the density range to be measured by the hydrometer. Lead shot is waxed or glued to the bottom of the bulb to make the hydrometer float upright.

A narrow graduated hollow stem

The narrower the stem, the more sensitive it is.

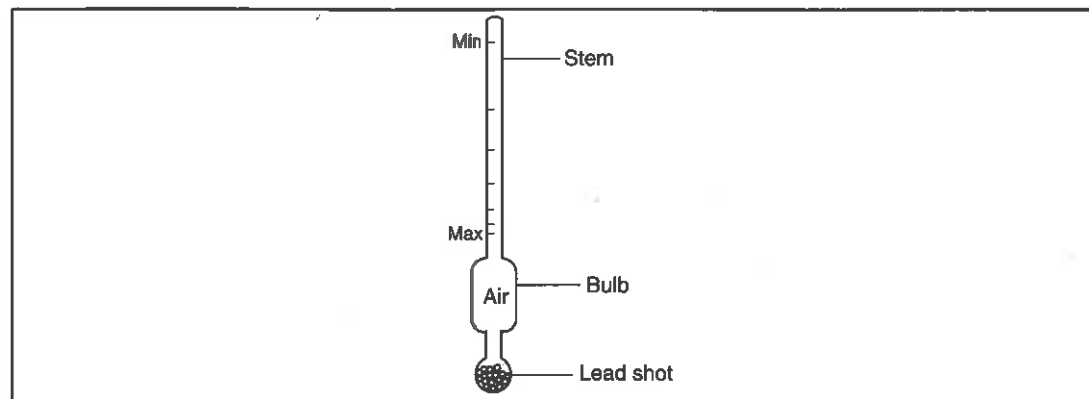


Fig. 3.10: Practical hydrometer

Some hydrometers are made for special purposes. One such hydrometer, called the lactometer, with a range of $1.015 - 1.045 \text{ g cm}^{-3}$, is used to measure density of milk. A brewer's hydrometer is used to measure relative density of beer, from which sugar and alcohol content can be inferred. Figure 3.11 shows a hydrometer used for measuring the density battery acid.

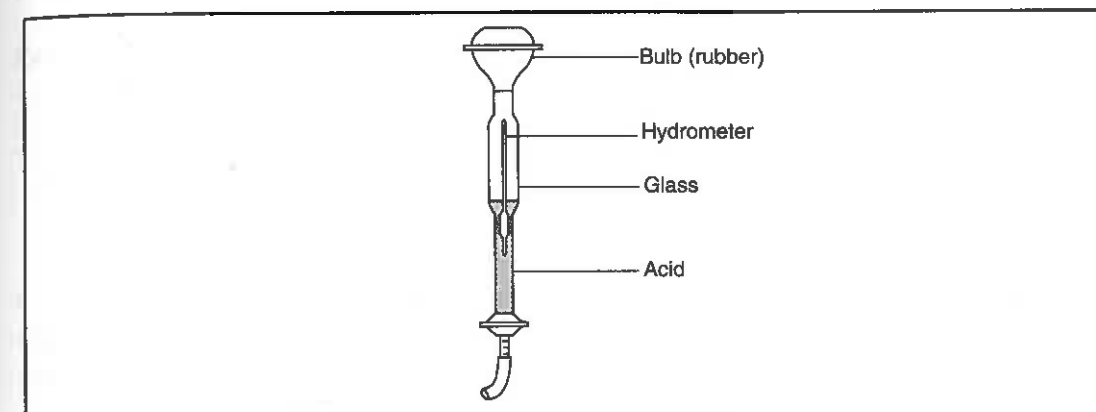


Fig. 3.11: A battery acid hydrometer

If the bulb is squeezed and released, the battery acid is drawn into the glass tube. The density of the acid is read from the floating hydrometer.

Example 12

A hydrometer of mass 20 g floats in oil of density 0.8 g cm^{-3} , with 5 cm of its stem above the oil. If the cross sectional area of the stem is 0.4 cm^2 , calculate:

- the total volume of the hydrometer.
- length of its stem out of water, if it floats in water (density of water = 1 g cm^{-3}).

Solution

$$(a) \text{ Volume of oil displaced} = \frac{20}{0.8}$$

$$= 25 \text{ cm}^3$$

This is the volume of hydrometer immersed in oil.

$$\text{Volume of part of hydrometer above oil} = 5 \text{ cm} \times 0.4 \text{ cm}^2$$

$$= 2.0 \text{ cm}^3$$

$$\therefore \text{Total volume of hydrometer} = 25 + 2.0$$

$$= 27 \text{ cm}^3$$

$$(b) \text{ Mass of hydrometer} = 2 \times 10^{-2} \text{ kg}$$

$$\text{Weight of hydrometer} = 2.0 \times 10^{-1} \text{ N}$$

$$\text{Weight of water displaced} = 2.0 \times 10^{-1} \text{ N}$$

$$\text{Mass of water displaced} = \frac{2.0 \times 10^{-1}}{10}$$

$$= 2.0 \times 10^{-2} \text{ kg}$$

$$= 20 \text{ g}$$

$$\begin{aligned}\text{Volume of water displaced} &= \frac{20 \text{ g}}{1 \text{ g cm}^{-3}} \\ &= 20 \text{ cm}^3\end{aligned}$$

But, this is volume of part of hydrometer immersed in water.

$$\begin{aligned}\therefore \text{Volume of part of hydrometer above water} &= 27 - 20 \\ &= 7 \text{ cm}^3\end{aligned}$$

$$\begin{aligned}\text{Length of stem out of water} &= \frac{\text{volume}}{\text{area}} \\ &= \frac{7}{0.4} \\ &= 17.5 \text{ cm}\end{aligned}$$

Example 13

A glass tube of uniform diameter 2.4 cm is weighted to float vertically in a liquid. The length of tube immersed in the liquid is 14 cm. If the density of the liquid is 1.2 g cm^{-3} , find the mass of the tube and its contents.

Solution

$$\begin{aligned}\text{Area of cross section of the tube} &= \pi r^2 \\ &= 3.142 \times (1.2)^2 \\ &= 4.52 \text{ cm}^2\end{aligned}$$

$$\begin{aligned}\text{Volume of liquid displaced by the tube} &= 4.52 \times 14 \\ &= 63.3 \text{ cm}^3\end{aligned}$$

$$\begin{aligned}\text{Mass of liquid displaced by the tube} &= 63.3 \times 1.2 \\ &= 75.96 \text{ g}\end{aligned}$$

$$\therefore \text{Mass of tube and contents} = 0.076 \text{ kg}$$

Balloons

Balloons used for meteorological investigations are filled with a gas of low density, such as hydrogen or helium.

Due to the low density of the gas, the weight of air displaced by the balloons is greater than weight of the gas in the balloon plus the balloon fabric. When released, the balloon therefore rises upwards. It gains altitude and at some height where the density of air is less than that at the ground, the upthrust on the balloon is equal to its weight. Resultant force on the balloon is zero and the balloon stops rising, but may drift sideways in the direction of wind.

Ships

Since steel is denser than water, solid steel will sink in water. However, a ship which is made of steel is hollow and the volume of water displaced is large. The upthrust exerted by the water on the ship is thus large. Like other floating bodies, the ship sinks to some level so that the weight of water displaced (upthrust) is equal to its weight. When the ship is loaded, it sinks more into the water.

Submarines

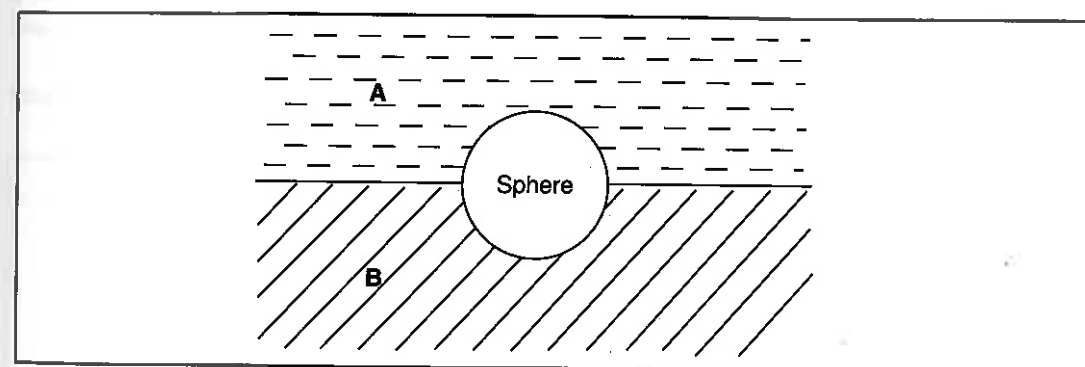
A submarine is designed so that it can float or sink below the surface of water. It is fitted with large flotation tanks which can be filled with water or air, hence varying its weight. If the

submarine is required to sink, the tanks are filled with water. The weight of the submarine thus becomes greater than the upthrust due to the water on it.

When the submarine is required to float, compressed air is forced into the flotation tanks, driving the water out. Its weight becomes less than upthrust on it, making it rise to the surface.

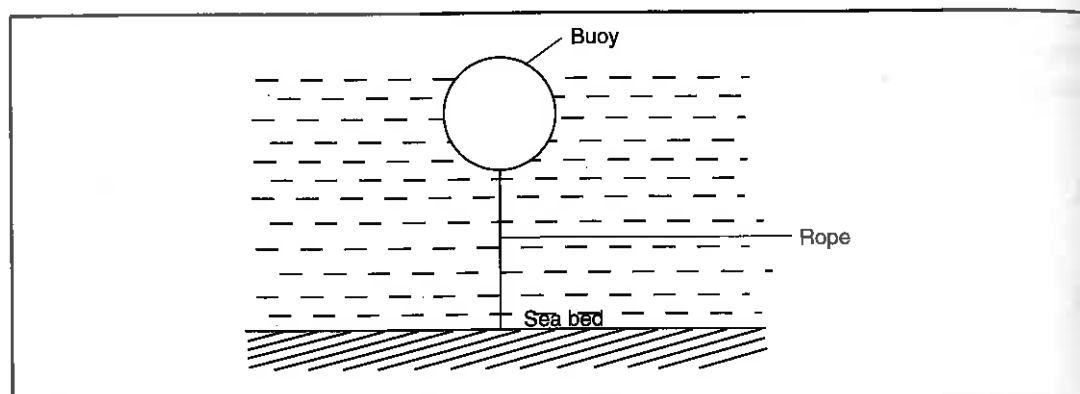
Revision Exercise 3

- State Archimedes' principle and describe an experiment to verify it.
- Explain why the narrow stem of a hydrometer provides greater sensitivity than a wide one.
- A glass block of weight 0.75 N is suspended by a string in water. If the block is completely immersed and the tension in the string is 0.45 N, find:
 - the upthrust on the block.
 - its density.
- A solid of density 2.5 g cm^{-3} is weighed in air and then when completely immersed in water in a measuring cylinder. The level of water in the cylinder rises from 40 cm^3 to 80 cm^3 . Determine:
 - the volume of the solid.
 - its apparent weight.
- A balloon of volume 10 m^3 filled with hydrogen floats in the atmosphere. If the mass of balloon fabric is 10.3 kg, calculate the density of the surrounding air. (Take density of hydrogen 0.09 g cm^{-3})
- A glass tube has a uniform cross-sectional area of 4.52 cm^2 . It is weighted and floated in a liquid. The length of the tube immersed in the liquid is 16 cm. If the mass of the tube and its contents is 80.0 g, determine the density of the liquid.
- The figure shows a sphere of radius 3 cm floating between two liquids A and B, so that half of it is in A. If the densities of liquids A and B are 0.8 g cm^{-3} and 1.0 g cm^{-3} respectively, determine the mass of the sphere.



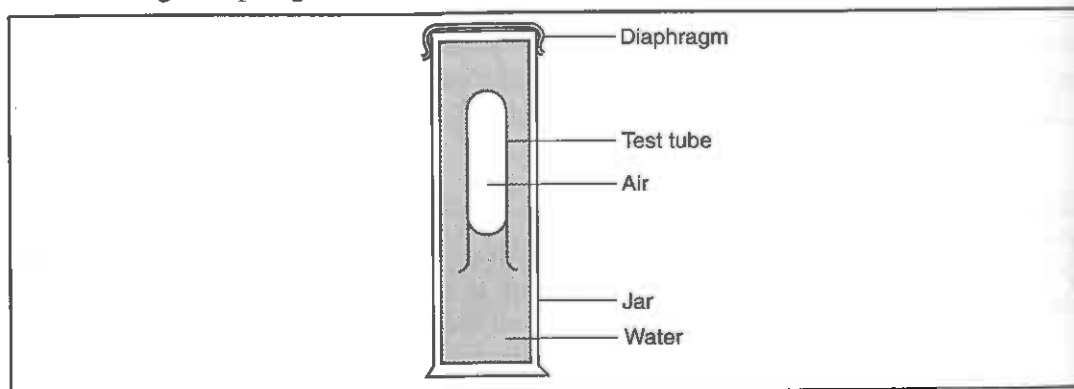
- State the law of flotation and describe an experiment to verify it.
- A block of length 15 cm and uniform cross-sectional area 9 cm^2 is suspended from a spring balance and completely immersed in oil of density 0.8 g cm^{-3} . Given that the density of material of the block is 1.25 g cm^{-3} , determine:
 - the mass of the block.
 - the reading of the spring balance.
 - the reading of the spring balance if the block was half immersed in the oil.

10. A cube of volume 0.15 m^3 and density 800 kgm^{-3} is placed in a liquid of density 1200 kgm^{-3} .
- Determine:
 - the fraction of the volume of the cube immersed in the liquid.
 - the weight that must be placed on the cube so that its top surface is on the same level as the liquid surface.
 - Explain what will happen if the cube is placed in oil of density 800 kgm^{-3} .
11. Explain how a submarine can be made to:
- float in water.
 - sink in water.
12. A spherical buoy of diameter 0.4 m and mass 20 kg is connected to a rope tied to a sea bed so that $\frac{3}{4}$ of its volume is below the surface, as shown in the figure below.



Assuming as the weight of the rope is negligible, calculate the tension in it. (Take density of sea water 1030 kgm^{-3})

13. Determine the minimum volume of copper that must be attached to a cork of mass 25 g so that the two will just submerge in water. (Take relative density of copper as 9.0 and that of cork 0.25)
14. A test tube containing some water and air is made to float inside a glass jar full of water and a tight diaphragm fixed at its mouth as shown in the figure below.



If the diaphragm is pressed downwards, the test tube moves to the bottom of the jar. Explain this observation.

ELECTROMAGNETIC SPECTRUM

Electromagnetic waves are transverse waves which result from oscillating electric and magnetic fields at right angles to each other, as shown in figure 4.1.

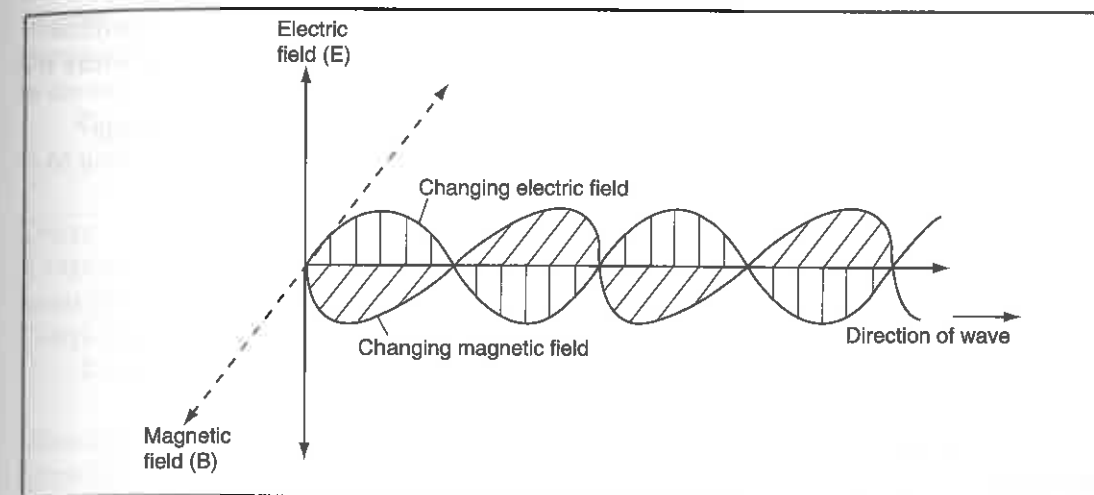


Fig. 4.1: Electromagnetic wave

Light, radio, X-rays, ultraviolet, infrared and gamma rays are electromagnetic waves. When these waves are arranged in order of wavelengths or frequencies, they form the **electromagnetic spectrum**. The wavelengths range from about $1 \times 10^6 \text{ m}$ to $1 \times 10^{-14} \text{ m}$, as shown in figure 4.2.

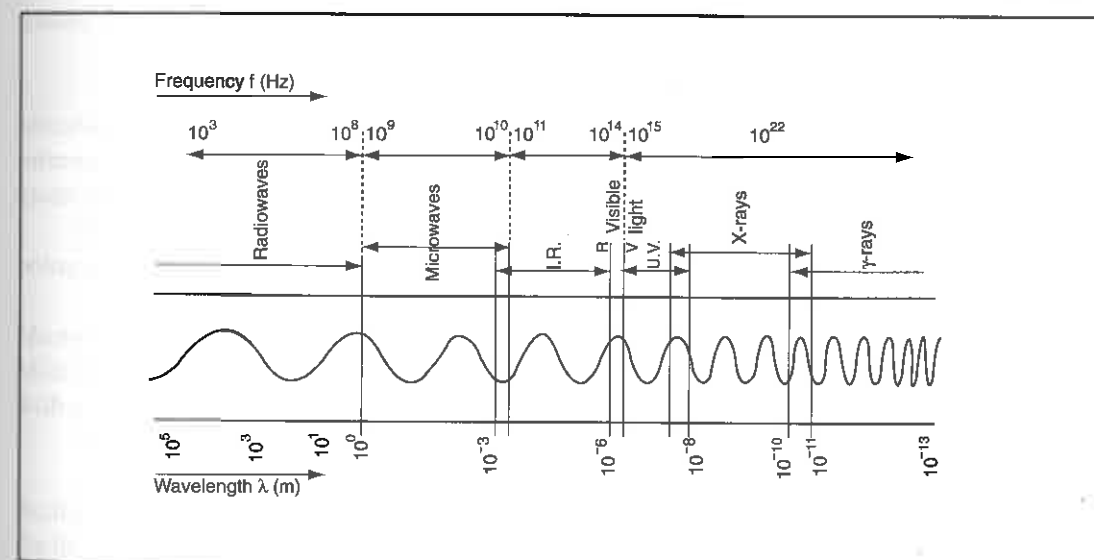


Fig. 4.2: Electromagnetic spectrum

Properties of Electromagnetic Waves

Although some electromagnetic waves differ greatly in their wavelengths and effects, they all have the following properties:

- (i) They travel through space (vacuum) with the speed of light ($3 \times 10^8 \text{ ms}^{-1}$).
- (ii) They do not require a medium for transmission.
- (iii) They are transverse waves in nature.
- (iv) They undergo interference, reflection, diffraction, refraction and polarisation effects.
- (v) They possess energy in different amounts, according to the relation $E = hf$, where h is planck's constant ($6.63 \times 10^{-34} \text{ Js}$) and f the frequency of the wave.
- (vii) They carry no charge, hence they are not affected by electric or magnetic fields.

Example 1

Green light has a wavelength of $5 \times 10^{-7} \text{ m}$. Calculate the energy it emits.

Solution

$$v = f\lambda$$

$$f = \frac{3 \times 10^8}{5 \times 10^{-7}}$$

$$= 6 \times 10^{14} \text{ Hz}$$

$$E = hf$$

$$= 6.63 \times 10^{-34} \times 6 \times 10^{14}$$

$$= 3.978 \times 10^{-19} \text{ J}$$

Example 2

A radio station is transmitting at a frequency of 15.42 MHz. Calculate the wavelength of the transmission.

Solution

$$\text{Given } c = f\lambda$$

$$= \frac{3.0 \times 10^8}{1.542 \times 10^7}$$

$$= 19.46 \text{ m}$$

Example 3

An X-ray machine produces radiation of wavelength of $1.0 \times 10^{-11} \text{ m}$. Calculate:

- (a) the frequency of the radiation.
- (b) its energy content.

Solution

$$(a) \text{ Given } c = f\lambda$$

$$f = \frac{c}{\lambda}$$

$$f = \frac{3.0 \times 10^8}{1.0 \times 10^{-11}}$$

$$= 3.0 \times 10^{19} \text{ Hz}$$

- (b) Energy content is given by;

$$E = hf$$

$$= 6.63 \times 10^{-34} \times 3.0 \times 10^{19}$$

$$= 1.989 \times 10^{-14} \text{ J}$$

Production and Detection of Electromagnetic Waves**Gamma Rays (γ -rays)**

Gamma rays are emitted by radioactive substances. This results from energy changes occurring in the nuclei of the radioactive atoms.

Gamma radiation is detected by photographic plates and radiation detectors, e.g., the G-M tube (discussed elsewhere in this book).

X-rays

X-rays are produced in X-ray tubes. This occurs due to electron transition between the energy levels of heavy elements, usually excited by electron bombardment. It can also be argued that X-rays originate from the action of a beam of fast-moving electrons hitting a metal target.

X-rays are detected by using a fluorescent screen or photographic film.

Ultraviolet Radiation

Ultraviolet radiation is produced by the sun, sparks and mercury vapour lamps, due to large energy changes in the electrons of an atom.

It is detected by photographic films, photocells, fluorescent materials (e.g., quinine sulphate) and paper lightly smeared with vaseline.

Visible Light

The sun is the major source of visible light. Other sources include hot objects, lamps and laser beams. Common detectors are the eye, photographic film and the photocell.

Infrared Radiation

Infrared radiation is produced as a result of small energy changes of an electron in an atom or molecular vibrations. It is produced by the sun, fires or any hot body.

Infrared radiation is detected by the heating effect produced on the skin, a thermopile, bolometer and thermometer with blackened bulb.

Microwaves

Microwaves are produced by special vacuum tubes called magnetrons in microwave ovens or with a maser.

Microwaves are detected by crystal detectors or solid state diodes.

Radio Waves

Radio waves have the longest wavelength within the electromagnetic spectrum. They are produced by oscillating electrical circuits and transmitted through antennae (aerials).

Radio waves are detected by resonant circuits in radio receivers with diodes and earphones.

Applications of Electromagnetic Waves

The applications of a given electromagnetic radiation depends on its special properties.

Gamma Radiation

Gamma rays have very high energy content, hence have high penetrating power. When supplied in correct quantities, the radiation can be used in:

- (i) medicine, for sterilising medical equipment, killing cancerous and other malignant growths in the body.
- (ii) industries, to detect flaws in metals.

X-Rays

X-rays have high penetrating power. The radiation is for this reason applied in medicine for photography (radiography) to identify the nature of such internal body structures as the bone, see figure 4.3. X-rays are therefore used to locate bone fracture or foreign objects such as an accidentally swallowed pin or a bullet lodged in the body.



Fig. 4.3: X-ray photograph of human bone

Other uses of X-rays include:

- (i) Cancer therapy, since the radiation is capable of killing malignant tissue.
- (ii) Controlling pests and germs by irradiation.
- (iii) Crystallography, to study crystal lattice. They are also used to detect flaws in metals and forgeries in art.

Ultraviolet Radiation

Ultraviolet radiation is easily stopped by glass. The radiation is used in spectroscopy and mineral analysis. It is also used to detect forgeries.

When ultraviolet radiation is absorbed by fluorescent materials, the materials fluoresce. Therefore, the materials are mixed with washing powders so as to make clean clothes brighter due to fluorescence when they are exposed to ultraviolet radiation in sunlight.

In medicine, ultraviolet radiation is used to kill bacteria, in skin treatment and also as a source of vitamin D.

In food technology, the radiation is used to detect the freshness of an egg. In industry, it is used with photocells.

Visible Light

Visible light is easily refracted by clear media such as glass and the eye lens.

It enables the eye to see, it is used in ordinary photography, optical fibres and **laser** (light amplification by the stimulated emission of radiation) beams.

Infrared Radiation

Infrared radiation causes heating effect. Therefore, it is used in cooking, heating and drying. In agriculture, it is used to warm greenhouses. Infrared radiation is also used in infrared photography and heat-seeking missiles.

Radio Waves

Radio waves have varying ranges of wavelengths, which make their applications wide, especially in communication.

Medium and short wavelength radio waves are used in radio transmission signals. Amplitude modulation (AM) radio transmission have a longer range because of the reflection by the ionosphere see, figure 4.4. Television and frequency modulation (FM) radio transmissions are received at a shorter wavelength than normal radio broadcasts. Very high frequency (VHF) transmissions (used in TV and FM radio) are transmitted over short distances and received directly from the transmission, as shown in the figure.

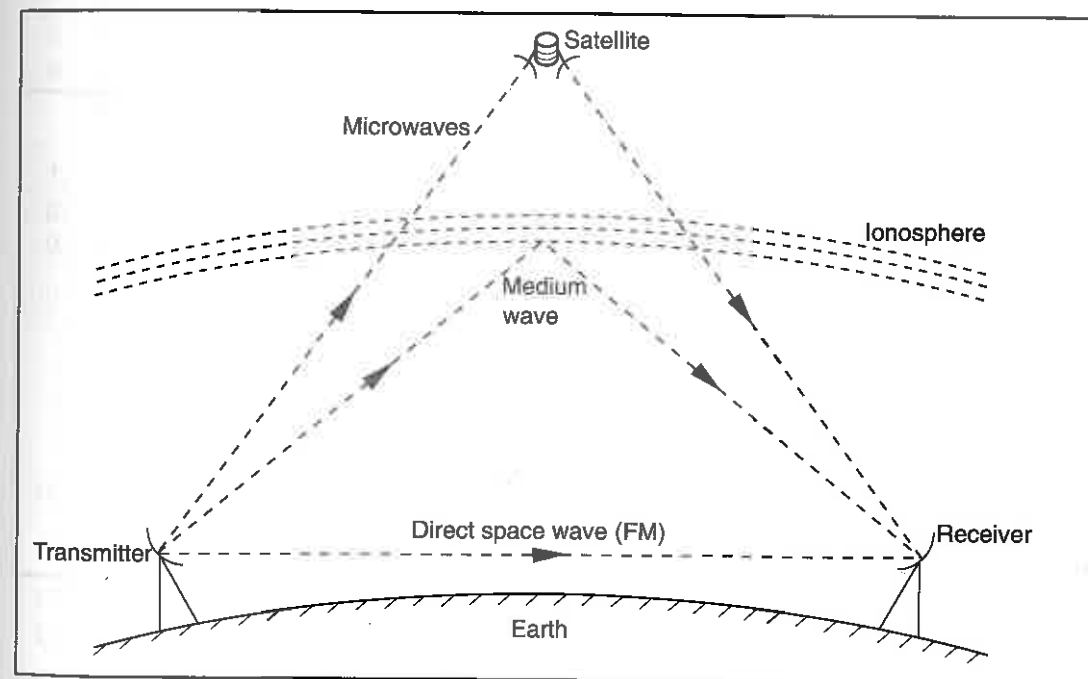


Fig. 4.4: Transmission of radiowaves

Microwaves, which have much shorter wavelengths, are used for **radar** (radio detection and ranging) communication, see figure 4.5. This communication is useful in locating the positions of aeroplanes and ships.

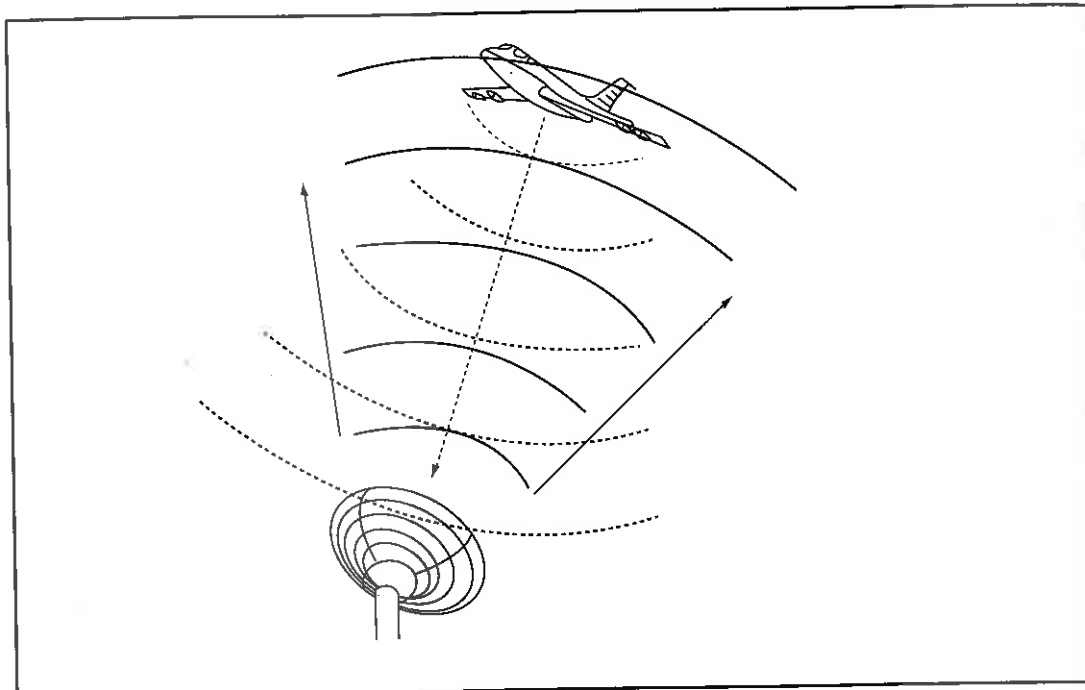


Fig. 4.5: Radio detection and ranging (radar)

Microwaves are also used for cooking, see figure 4.6.

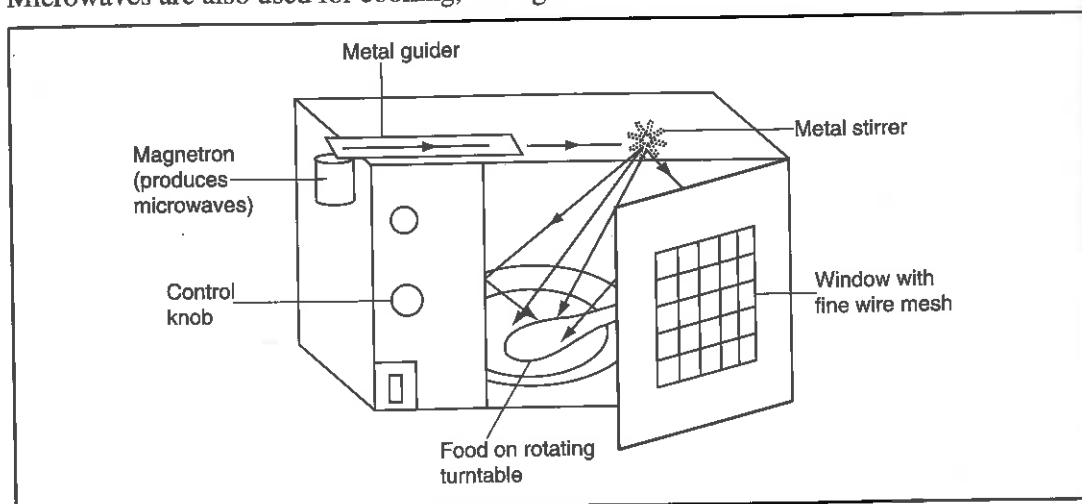


Fig. 4.6: Microwave cooker

The magnetron produces microwaves at a frequency of about 2 500 MHz. These waves are directed to a rotating metal stirrer, which reflects them to different parts of the oven.

In the oven, food is placed on a turntable, where it absorbs the waves evenly. The waves heat up the water and fat molecules in the food, hence cooking it. The wire mesh on the door reflects the microwaves back inside. The device is switched off before opening the door.

Hazards of some Electromagnetic Waves

The penetrating power of electromagnetic waves can cause damage when not controlled.

Ultraviolet rays, X-rays and γ -rays carry high energy and when absorbed into the body in large doses, may cause damage to the body cells, skin burn or affect the eyes. This widespread damage of cells may be fatal. There are also delayed effects of radiation such as cancer, leukaemia and hereditary defects in children. The Chernobyl disaster in the Ukraine (1986) is one of the examples in recent times. Many lives have been lost due to the radiations resulting from the nuclear reactor explosion.

The dangers posed by the above radiations can be minimised by reducing the dosage by shielding, keeping safe distance from sources and minimising exposure time.

Revision Exercise 4

Where necessary, take $c = 3.0 \times 10^8 \text{ ms}^{-1}$, $h = 6.63 \times 10^{-34} \text{ Js}$

- Distinguish between a bolometer and a thermopile.
 - Explain why a blackened bulb can be used to detect infrared radiation.
- State four properties of electromagnetic waves.
 - Describe how ultraviolet light can be detected.
- Arrange the following radiations in order of their wavelengths: infrared, blue light, ultraviolet, radio waves, X-rays.
- A radio transmitter produces waves of frequency $1.0 \times 10^8 \text{ Hz}$. Calculate the wavelength of the signal.
- Calculate the wavelength of green light, of frequency $5.0 \times 10^{14} \text{ Hz}$ in air.
- State two uses of X-rays.
 - Distinguish between X-rays and γ -rays.
 - Why are gamma rays more dangerous than X-rays?
- Differentiate between infrared and ultraviolet radiation.
- Why is sound not an electromagnetic wave?
- Name one radiation of the electromagnetic spectrum which has a higher frequency than the visible light. Describe:
 - how it is produced.
 - how it is detected.
 - its unique properties.
 - its applications.
 - the dangers of the radiation.
- Which part of the electromagnetic spectrum plays a major role in the greenhouse phenomenon?
 - Describe the changes the radiation above undergoes when incident on a greenhouse.
- State a property of electromagnetic wave on which the operation of radar system is based.
- Your radio is tuned into a radio station 144 km away.
 - How long does it take the signal to reach your receiver?
 - If the signal has frequency of 980 kHz, how many wavelengths is the station away from your receiver?

ELECTROMAGNETIC INDUCTION

In Book Two, it was observed that an electric current flowing through a conductor has an associated magnetic field. The converse is true – a changing magnetic field can, under suitable conditions, induce current in an electric conductor. This phenomenon is known as **electromagnetic induction** and was discovered by Michael Faraday. It has led to cheap large scale production of electrical energy in power stations.

Induced Electromotive Force (EMF)

EXPERIMENT 5.1: To investigate the conditions necessary for electromagnetic induction

Using a Straight Conductor

Apparatus

Thick electric conductor, U-shaped magnet, galvanometer, connecting wires.

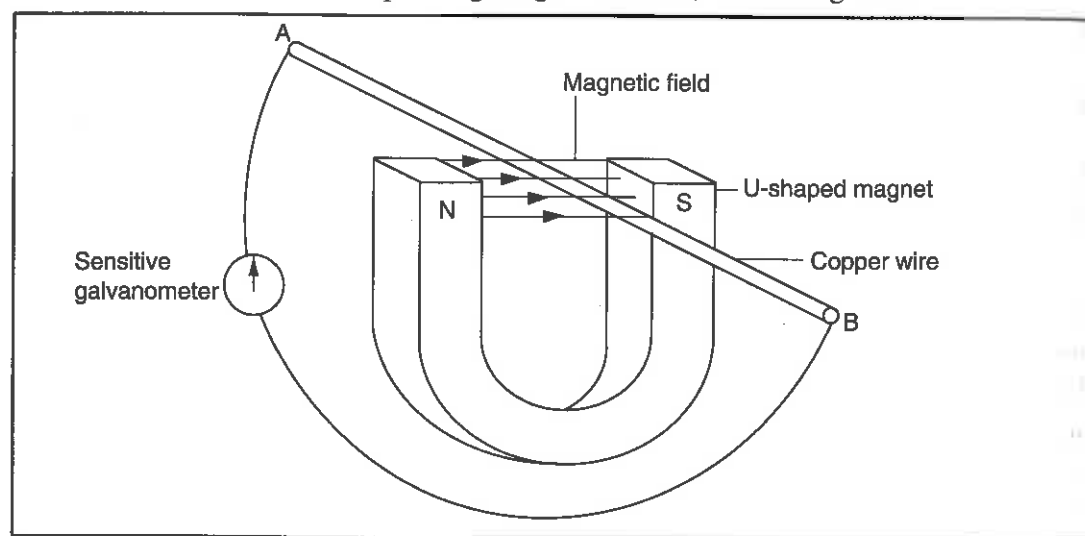


Fig. 5.1: Inducing e.m.f. in a straight conductor

Procedure

- Set up the apparatus as shown in figure 5.1.
- Observe the effect on the galvanometer when the conductor AB is:
 - (i) moved vertically downwards between the poles of the magnet.
 - (ii) moved vertically upwards between the poles of the magnet.
 - (iii) held stationary between the poles of the magnet.
 - (iv) moved parallel to the direction of the magnetic field.
 - (v) moved to cut the field at angles of, say, 30° and 60°.
 - (vi) held stationary and the magnet moved upwards, then downwards.

Observations

The galvanometer deflects when the conductor AB cuts the magnetic field lines. There is no flow of current when there is no relative motion between the conductor and the magnetic field. The magnitude of the induced current increases with the angle θ at which the conductor cuts the field, being maximum when θ is 90° and zero when θ is 0° (moving parallel to the magnetic field). The direction of deflection reverses when the direction of motion is reversed.

When the magnetic field is moved while the conductor remains stationary, the same observations are made.

Using a Coil

Apparatus

Coil, galvanometer, magnet.

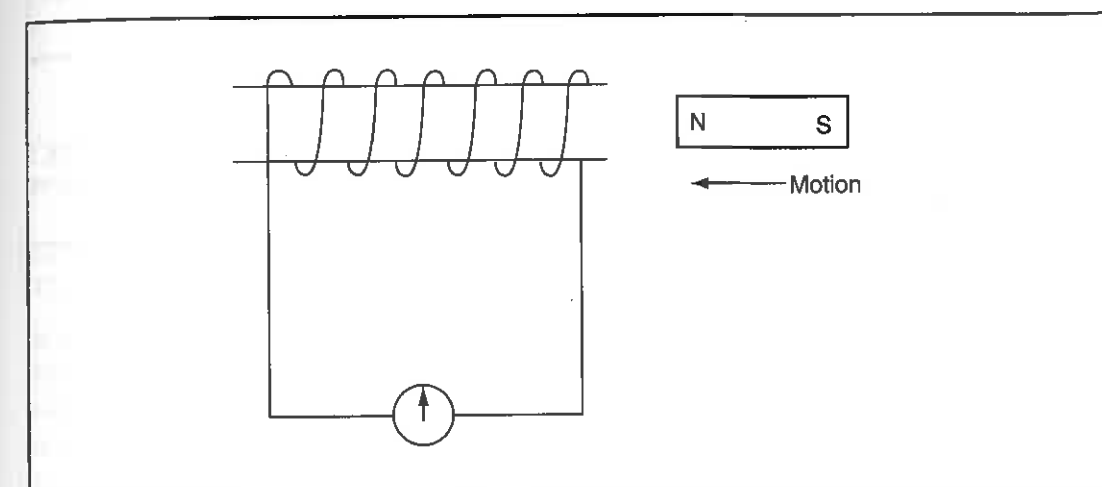


Fig. 5.2: Inducing e.m.f. in a coil

Procedure

- Set the apparatus as shown in figure 5.2.
- Observe the effect on the galvanometer when:
 - (i) the magnet is moved into the coil at a steady speed.
 - (ii) the magnet is moved out of the coil at a steady speed.
 - (iii) the magnet is held stationary in the coil.
 - (iv) the coil is moved to the stationary magnet.
 - (v) the coil is moved away from the stationary magnet.
 - (vi) the magnet is held stationary in the stationary coil.

Observation

The pointer of the galvanometer deflects in one direction when the magnet is moved into the coil and in the opposite direction when the magnet is moved out of the coil. The same observations are made when the coil is moved while the magnet is stationary.

No deflection is observed when there is no relative motion between the coil and magnetic field.

Explanation

Figure 5.3 shows how electrons entering a magnetic field are deviated as a result of force whose direction is given by Fleming's left-hand rule.

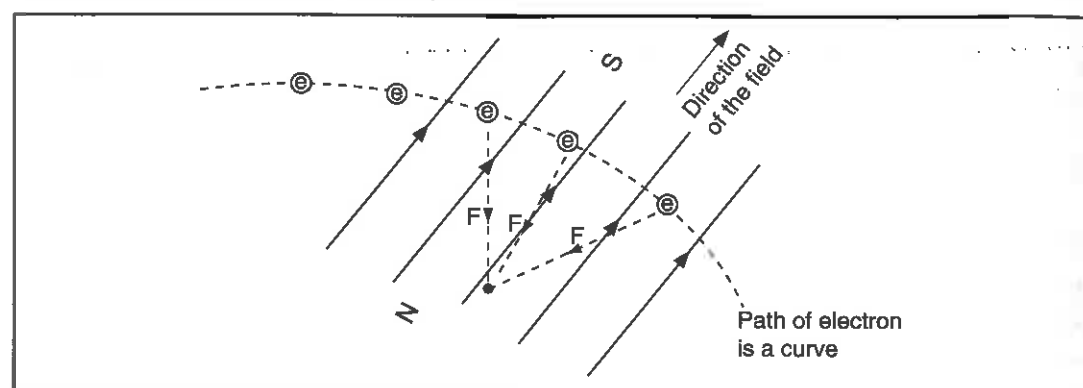


Fig. 5.3: Force on electrons in a magnetic field

Consider a conductor AB cutting a magnetic field, as shown in figure 5.4. Applying Fleming's left-hand rule, the electrons in the conductor experience a force that compels them to move from point A to B. This constitutes a conventional current in the opposite direction.

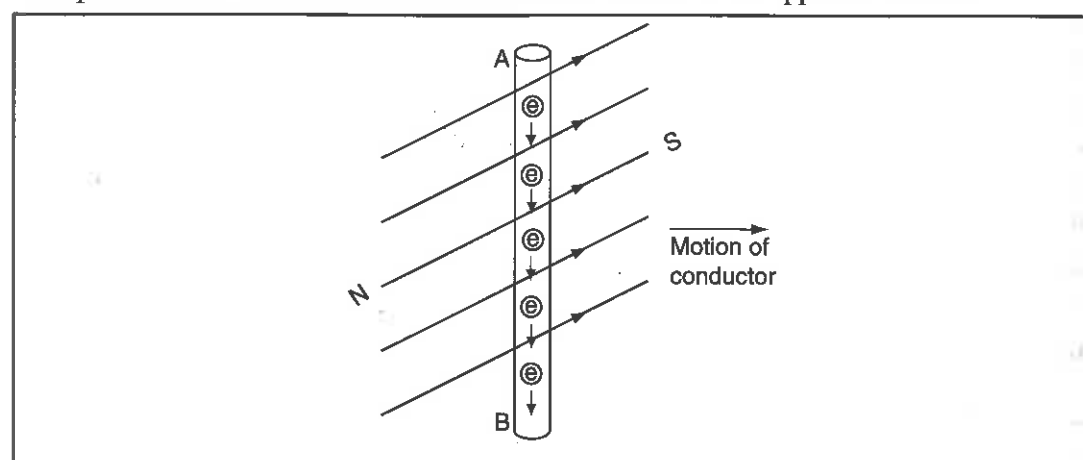


Fig. 5.4: Induced current in a conductor

Conclusion

From the above experiments, it is clear that whenever there is relative motion between a magnetic field and conductor, an induced current resulting from an induced e.m.f. flows in the conductor.

Factors Affecting the Magnitude of Induced E.m.f

EXPERIMENT 5.2: To investigate relationship between the rate of change of magnetic flux and induced e.m.f.

Apparatus

A coil of at least 50 turns, sensitive galvanometer, magnet.

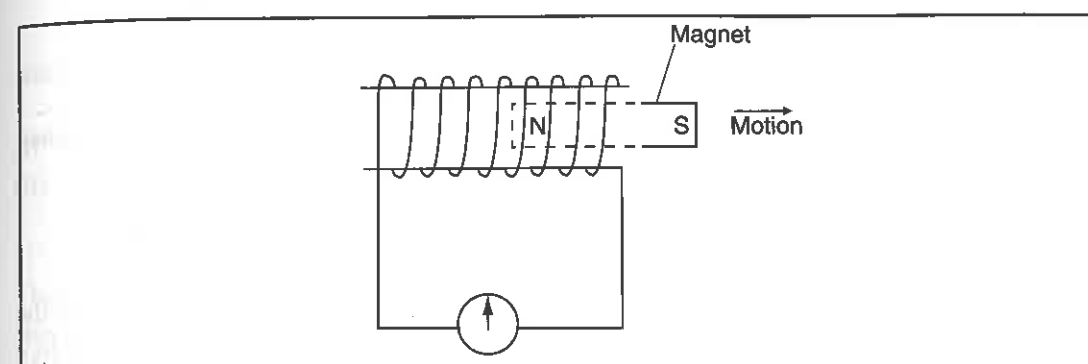


Fig. 5.5: Rate of change of flux

Procedure

- Insert the magnet into the coil.
- Note the maximum deflection of the galvanometer when the magnet is withdrawn from the coil :
 - (iii) very fast.
 - (iv) with moderate speed.
 - (v) very slowly.

Observation

The faster the magnet is withdrawn from the coil, the greater the induced e.m.f.

Explanation

Magnetic flux ϕ (the strength of magnetic field threading a given area) changes when the magnet is withdrawn from the coil. A faster withdrawal gives rise to a higher rate of change in magnetic flux linking the coil, which in turn gives an increased induced e.m.f.

EXPERIMENT 5.3: To investigate the relationship between the strength of the magnetic field B and induced e.m.f.

Apparatus

U-shaped electromagnet, variable resistor, wire PQ, galvanometer, ammeter.

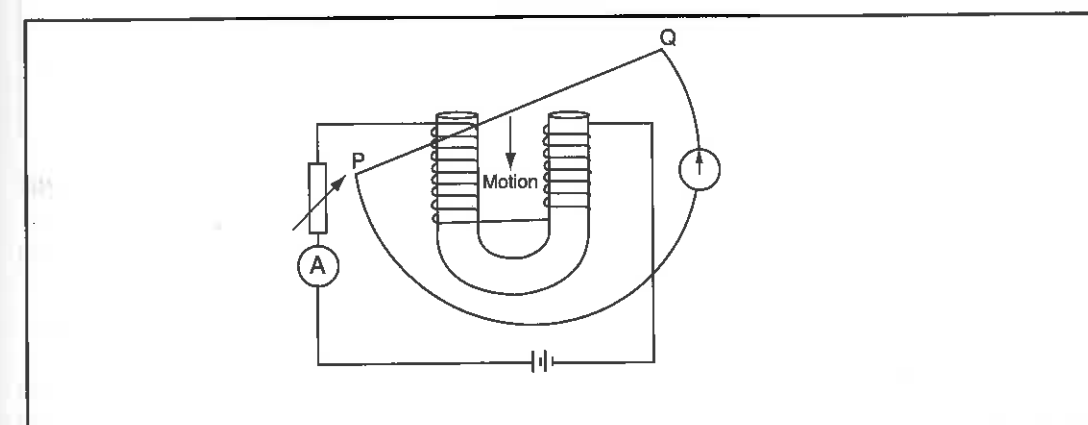


Fig. 5.6: Strength of magnetic field

Procedure

- Set the apparatus as shown in figure 5.6
- Adjust the variable resistor so that minimum current flows.
- Move wire PQ in a direction perpendicular to the magnetic field of the electromagnet. Note the maximum deflection on the galvanometer.
- Repeat the experiment for higher values of current (stronger field).

Observation

Whenever current through the ammeter is increased, a greater deflection is obtained on the galvanometer when the wire PQ cuts the field. Since a higher current in the coil leads to a stronger electromagnet hence a stronger magnetic field, it follows that the stronger the magnetic field, the higher the induced e.m.f.

EXPERIMENT 5.4: To investigate the relationship between the number of turns in a coil and the induced e.m.f.

Apparatus

Insulated copper wire, sensitive galvanometer, magnet, connecting wires.

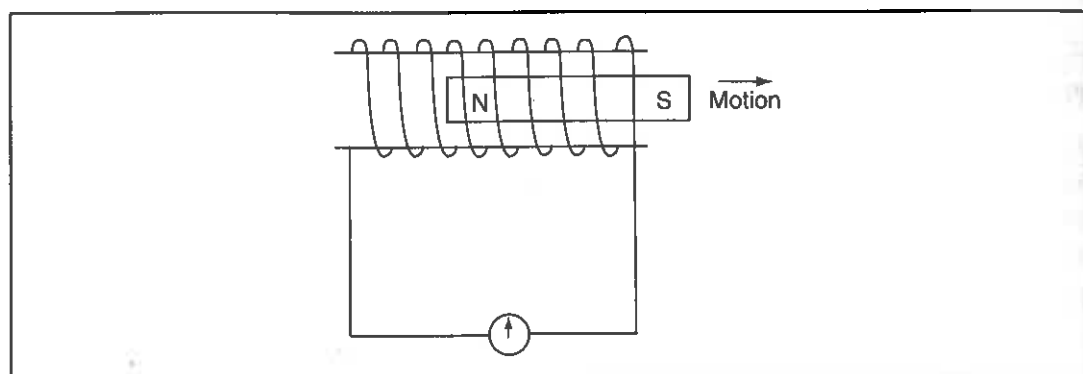


Fig. 5.7: Number of turns of the coil

Procedure

- Make a solenoid of, say, 60 turns.
- Connect the solenoid to the galvanometer.
- Insert a magnet into the coil, as shown in figure 5.7.
- Withdraw the magnet from the coil at a steady speed and note the maximum reading of the galvanometer.
- Repeat the experiment with the same steady speed as before, but this time with the coil having 50, 40, 30 and 20 turns.

Observation and Explanation

Each time the number of turns of the coil is decreased, a lower deflection of the maximum reading of the galvanometer is noted. This indicates a reduction in the induced current and therefore the magnitude of the e.m.f. induced in the coil.

There is an induced e.m.f. in each turn of the coil. The overall e.m.f. is proportional to number of turns.

From experiments 5.2, 5.3 and 5.4, it follows that:

- an e.m.f. is induced in a circuit whenever the magnetic flux linking it changes.
- the magnitude of the induced e.m.f. increases with:
 - the rate of change of the flux linkage.
 - the number of turns of the coil.

These observations can be summed up in **Faraday's law of electromagnetic induction**, which states that **the magnitude of the induced e.m.f. is directly proportional to the rate of change of magnetic flux linkage.**

Lenz's Law

Induced current produces a magnetic field whose effect can be used to predict the direction of the current.

EXPERIMENT 5.5: To determine the direction of the induced current in a coil

Apparatus

Variable resistor, sensitive centre-zero galvanometer, connecting wires, coil, magnet, switch.

- To establish the direction of the galvanometer deflection with respect to the direction of flow of current

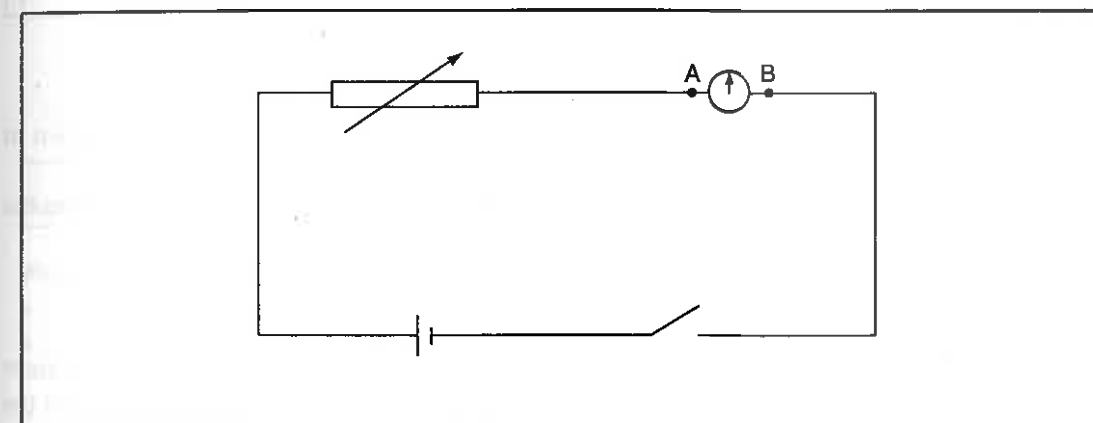


Fig. 5.8: Direction of current

Procedure

- Set the circuit as shown in figure 5.8.
- Adjust the variable resistor to a high value in order to limit the current through the sensitive galvanometer.
- Close the switch and note the deflection of the galvanometer when current flows from A to B.

Observation

If the deflection is to the right when the current is switched on, then the current enters the galvanometer through terminal A, which may be marked positive and leaves through terminal B, which is negative.

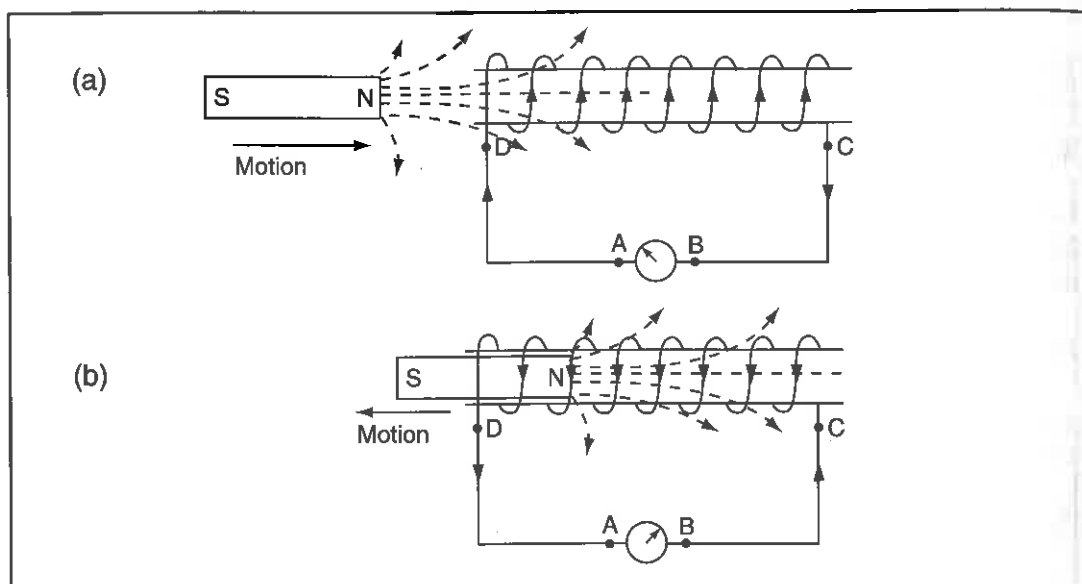
(b) To investigate the direction of induced current

Fig. 5.9: Direction of induced current in a coil

Procedure

- Connect the marked galvanometer used in Experiment 5.5 (a) to the coil, as shown in figure 5.9 (a).
- Move the north pole of the magnet into the coil as shown in figure 5.9 (a) and note the direction of the deflection.
- Move the north pole away from the coil and again note the direction of deflection.

Observation

It is observed that when the north pole of the magnet is moved towards the coil, the pointer deflects to the left, showing that the induced current flows in the direction DCBA. When the north pole of the magnet is moved away from the coil, the pointer deflects to the right, showing that the current flows in the direction DABC.

Explanation

As the north pole of the magnet is moved towards the coil, the induced current flows in the coil, forming an electromagnet with a north pole at the end nearest the in-coming magnet. This opposes the movement of the magnet.

When the magnet is moved away, the induced current in the coil flows in such a way that a south pole is formed at the end of the coil nearest to the receding magnet. This again opposes the movement of the magnet, see figure 5.9 (a) and (b).

Conclusion

The direction of the induced e.m.f. is such that the induced current which it causes to flow produces a magnetic effect that opposes the change producing it. This is Lenz's law.

Lenz's law is an example of the principle of conservation of energy. The mechanical energy of a moving magnet inside the coil is converted to the electrical energy as the induced current. The person pushing the magnet towards the coil must exert force to do work against repulsion of the induced pole of the coil magnet in order for induced current to flow.

EXPERIMENT 5.6: To determine the direction of induced current in a straight conductor**Apparatus**

U-shaped magnet, thick wire AB, marked centre-zero galvanometer.

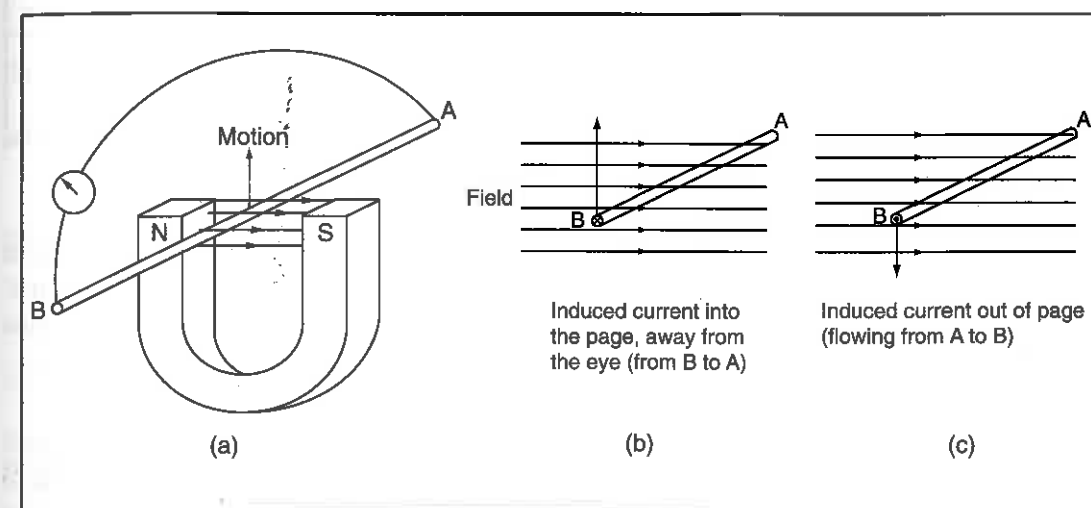


Fig. 5.10: Direction of induced current in a straight conductor

Procedure

- Arrange the apparatus as shown in figure 5.10 (a).
- Move the wire AB up, perpendicular to the magnetic field and note the direction of the induced current.
- Move the wire downward perpendicular to the magnetic field and again note the direction of current.

Observation

When the wire is moved upwards, the induced current flows from B to A, see figure 5.10 (b). When the wire is moved downwards, the current flows from A to B, see figure 5.10 (c).

Fleming's Right-hand Rule

The direction of induced current in a wire can be determined using Fleming's right-hand rule. It states that **if the thumb and the first two fingers of the right hand are held mutually at**

right angles with the first finger pointing in the direction field, the thumb pointing in the direction of motion, then the second finger points in the direction of the induced current, see figure 5.11 (a).

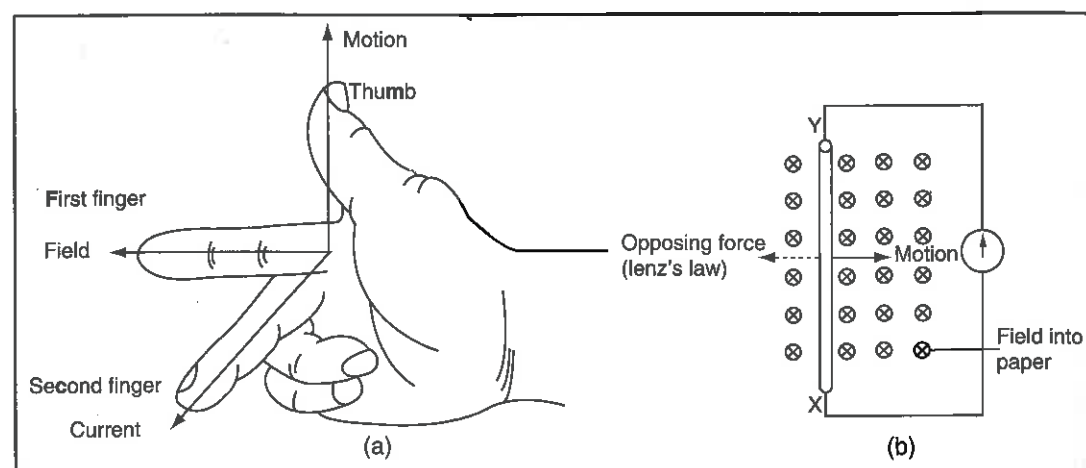


Fig. 5.11: Fleming's right-hand rule

Fleming's right-hand rule, also known as the **dynamo rule** is in agreement with Lenz's law. In figure 5.11 (b), Fleming's right-hand rule predicts that the induced current flows from X to Y. Fleming's left-hand rule confirms current to be consistent with Lenz's law; the current must flow from X to Y to produce a force to the left opposing the motion to the right.

Example 1

A square loop of a conductor is pulled at a steady speed across a uniform magnetic field, as shown in figure 5.12.

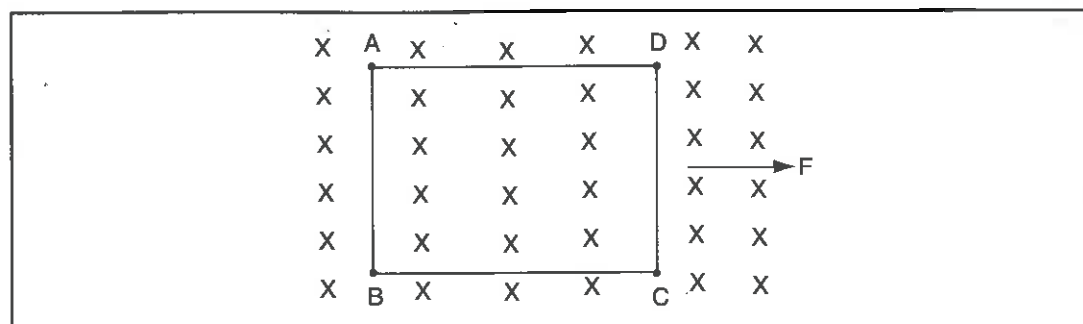


Fig. 5.12

- Determine in the figure the direction of induced current in the sides AB, AD, CD and BC, if any.
- Explain what happens when:
 - all the sides are moving in the uniform field and state the potential difference across points AB.
 - the side CD leaves the field.

- Suggest why in the absence of friction, more force is required to keep the coil moving at a steady speed when side CD leaves the field.

Solution

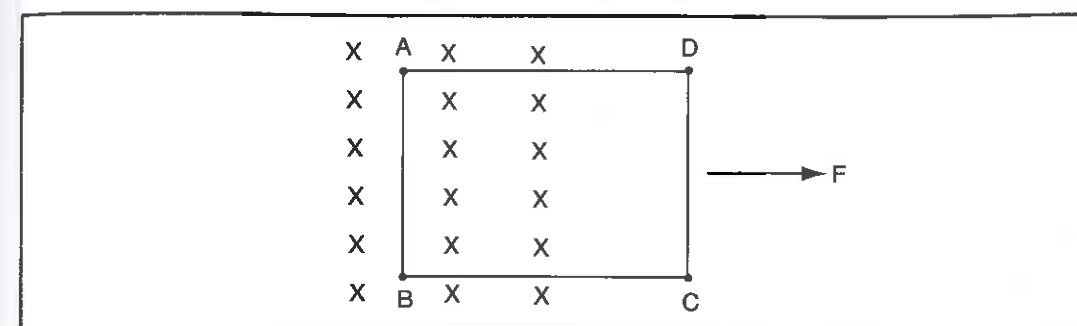


Fig. 5.13

- Sides AD and BC have no induced e.m.f. and hence no induced current, since they are not cutting the magnetic field. Sides AB and CD cut the magnetic field, causing current to flow from B to A in AB and C to D in CD.
- The currents in AB and CD are equal in magnitude and oppose each other. The resultant potential difference across the points A and B is zero.
 - Induced e.m.f. in AB which sets up a current that takes the path ADCB. There is no induced current side CD.
- The flow of current in AB creates a force that tends to oppose the motion.

Example 2

In figure 5.14, the current in conductor AB is increased with time. Explain the direction of current in the loop placed near the wire.

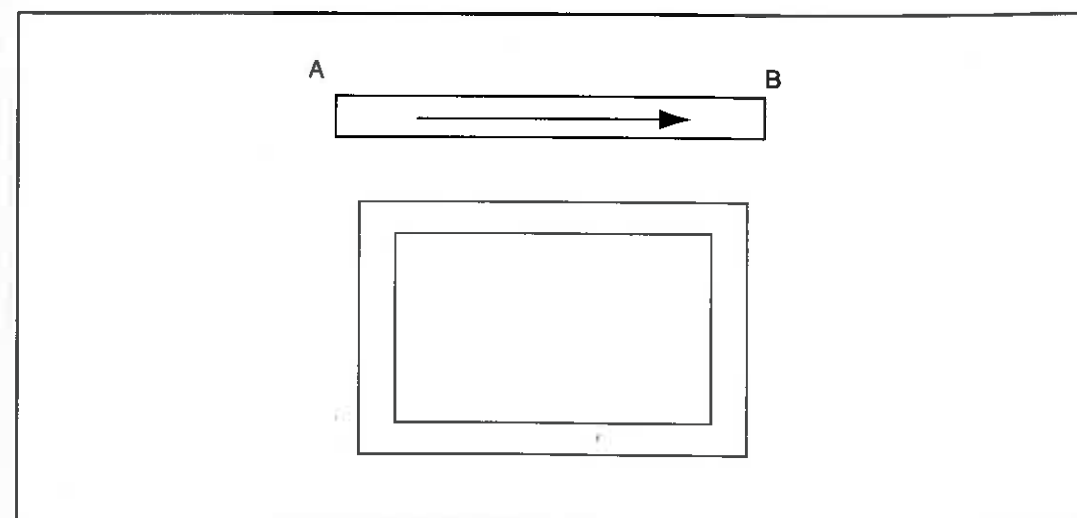


Fig. 5.14

Solution

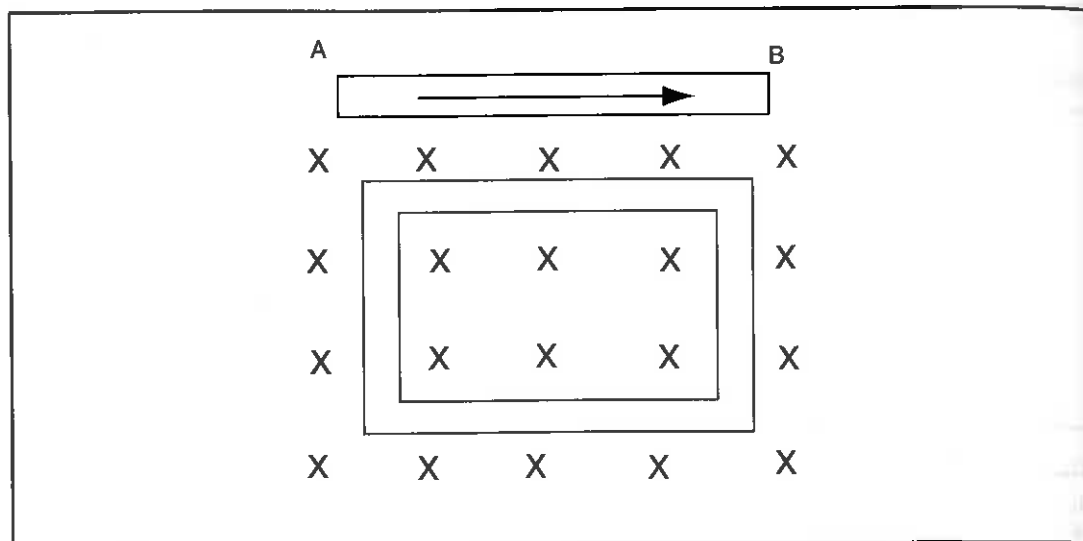


Fig. 5.15

The flow of current in the loop is anticlockwise, see figure 5.15. The wire AB has concentric magnetic field set up due to the current flowing through it. Applying the right hand grip rule, this field is directed into the paper. Since the field is changing, it induces an e.m.f. in the loop. This in turn sets up a current flow in the anticlockwise direction, in order to set up a field that tends to oppose the changing magnetic field due to the current flowing in AB.

Example 3

ABC in figure 5.16 is a section of a single coil of a wire. Movement of the magnet causes the current to flow as shown. In what direction is the magnet moving?

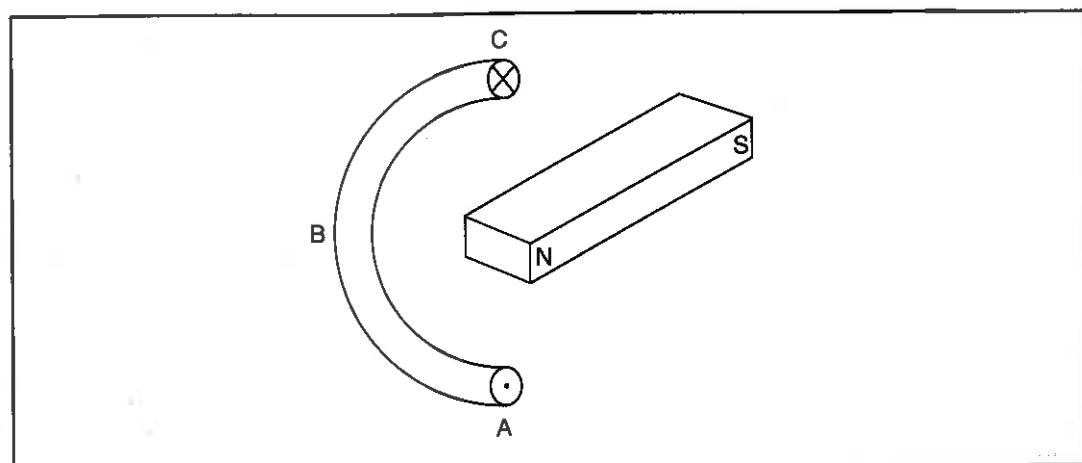


Fig. 5.16

Solution

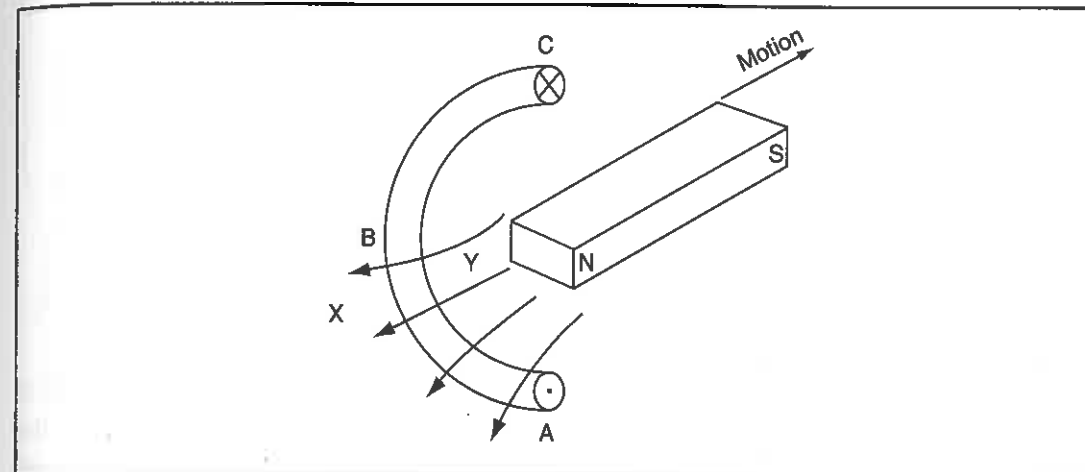


Fig. 5.17

The current in the loop creates the magnetic field shown in figure 5.17. Side X is the north pole while Y is south pole. By Lenz's law, the magnet must be moving away from Y, so that the motion is opposed by the magnetic effect of the current in the loop.

Mutual Induction

Mutual induction is said to occur when a changing current in one coil induces a current in another placed close to it. The changing magnetic flux in the first coil (primary coil) links with the second coil (secondary coil), inducing an e.m.f. in it.

EXPERIMENT 5.7: To demonstrate mutual induction**Apparatus**

Two coils P and S, galvanometer, battery, a.c. power source, switch, rheostat, connecting wires.

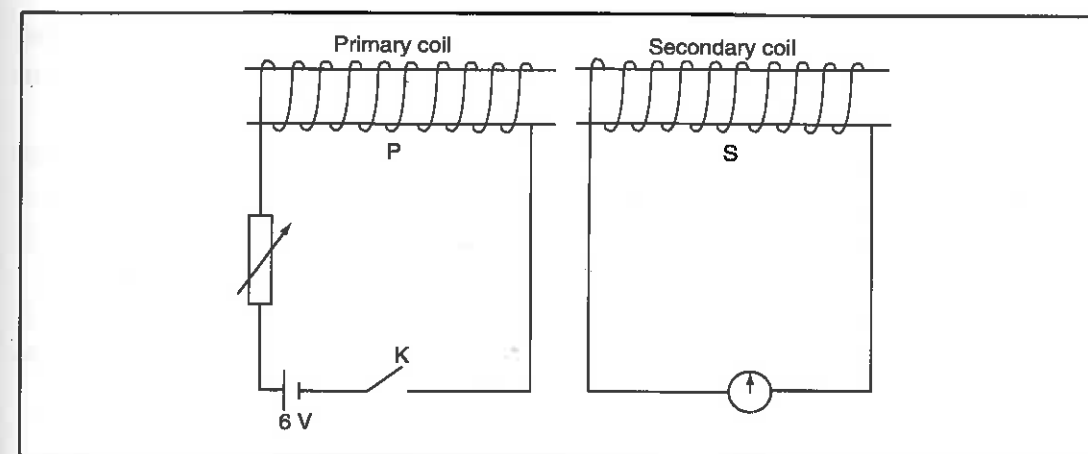


Fig. 5.18: Mutual induction

Procedure

- Set the apparatus as shown in the figure 5.18.
- Note the deflection on the galvanometer:
 - (i) on closing the switch.
 - (ii) on opening the switch.
 - (iii) when, with the switch closed, the current is increased.
 - (iv) when, with the switch closed, the current is decreased.
 - (v) The d.c. source is replaced by an a.c. one.

Observation

When K is closed, the pointer deflects in one direction, then comes back to zero. When K is opened, the pointer deflects to the opposite direction and falls back to zero. Increasing the primary current causes a deflection while decreasing it causes a deflection in the opposite direction.

When the d.c. is replaced by an a.c. source, the pointer vibrates about point zero.

Explanation

When K is closed, the current in the primary increases from zero to a maximum value within a very short time. The magnetic flux in the primary coil linking with the secondary coil increases from zero to a maximum value in the same interval of time, inducing an e.m.f. in the secondary. Current then flows, hence the deflection of the galvanometer. The induced e.m.f. in the secondary coil is momentary because once the current in the primary builds up to its maximum value, there is no further change in magnetic flux in the primary.

When K is opened, the current in the primary takes a very short time to fall from maximum value to zero. The magnetic flux in the primary linking with secondary turns also falls from maximum value to zero, inducing an e.m.f. in the secondary coil.

The induced e.m.f. in the secondary is much higher when current in primary is switched off than when it is switched on, because the current in the circuit takes a much shorter time to die off than build up.

When the current is increased continuously, the magnetic flux in the primary which links with the secondary also increases, causing an e.m.f. to be induced in the secondary. When current in the primary is decreased continuously, an e.m.f. is induced in the secondary due to the decreasing magnetic flux of the primary linking with the secondary.

Figure 5.19 (a) shows the direction of induced current when the primary current is increasing while 5.19 (b) shows the direction of the induced current when the current in the primary coil is decreasing. This can be verified by Lenz's law.

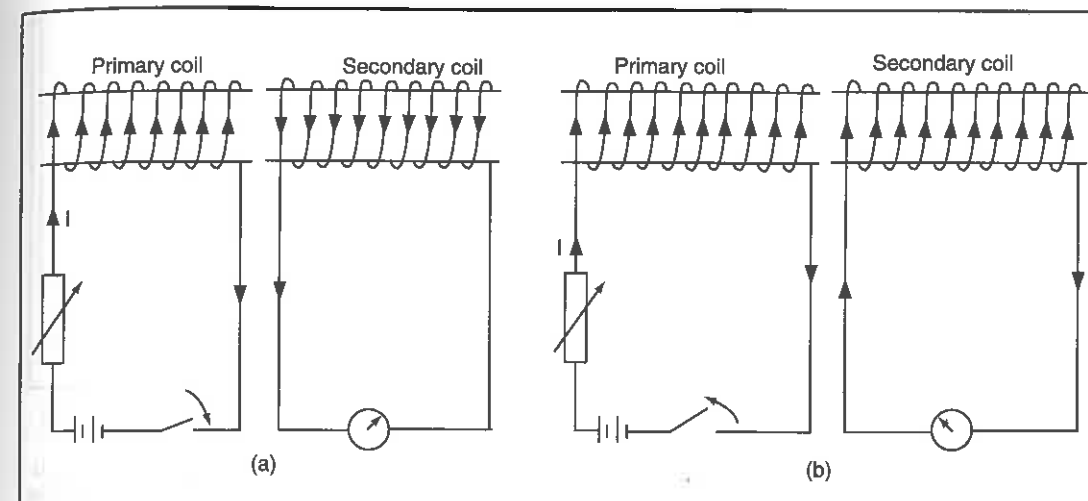


Fig. 5.19: Direction of induced current

The induced e.m.f. in the secondary can be increased by winding the primary and secondary coils on a soft iron rod, as shown in figure 5.20. This is because the soft iron concentrates the magnetic flux in both coils.

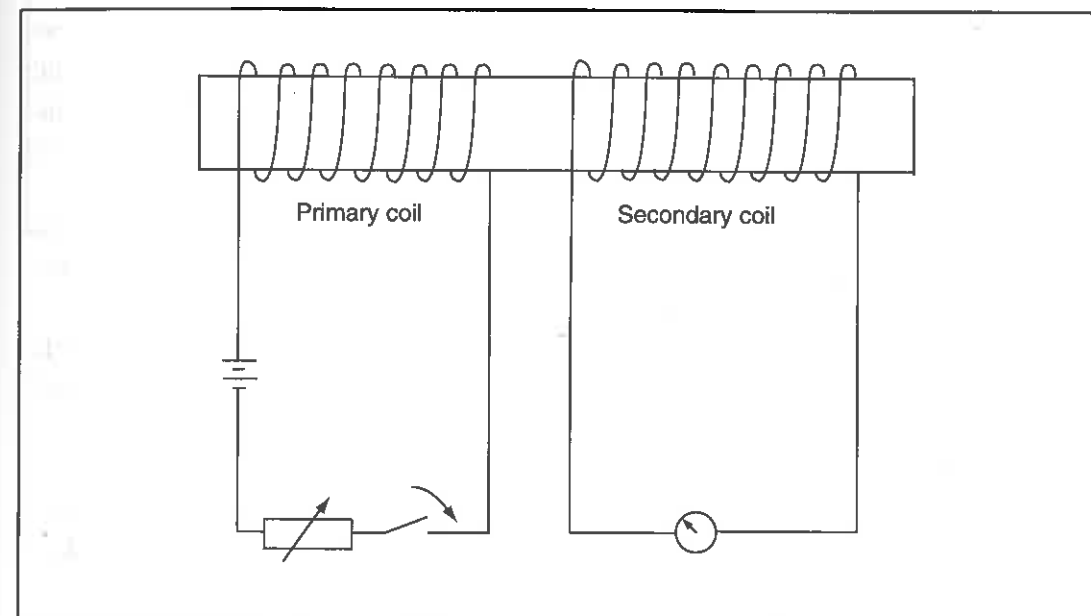


Fig. 5.20: Increasing induced e.m.f. by using soft rod

The induced e.m.f. can be increased further by winding both primary and secondary coils on a soft iron ring, as shown in figure 5.21. The ring enables all the magnetic flux of the primary to form concentric loops within it, thus reaching the secondary coil.

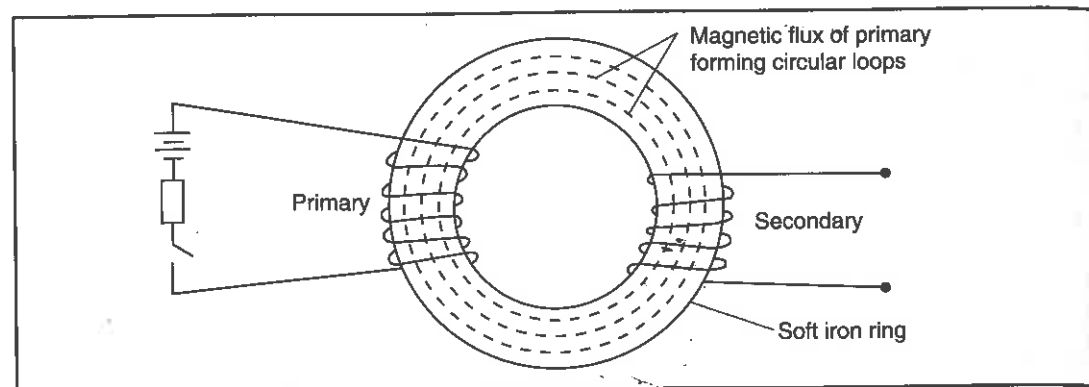


Fig. 5.21: Increasing induced e.m.f. by using a soft iron ring

The induced e.m.f. can generally be increased by having more turns in the secondary coil, as shown in figure 5.22.

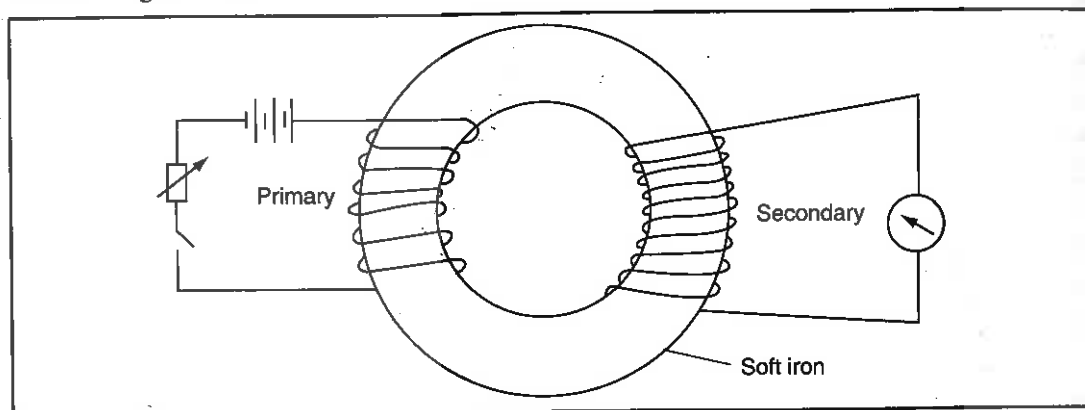


Fig. 5.22: Number of turns

The e.m.f. is induced in each turn of the secondary coil since the magnetic flux of the primary coils links with each. The total induced e.m.f. is the sum of the e.m.f. induced in the individual turns. Hence, the more the number of turns in the secondary coil, the higher the induced e.m.f.

APPLICATIONS OF ELECTROMAGNETIC INDUCTION

Electromagnetic induction is applied in many areas. Some of these are:

- (i) transformer.
- (ii) moving-coil microphone.
- (iii) induction coil.

Transformers

A transformer transfers electrical energy from one circuit to another by mutual induction. It consists of a primary coil, where an alternating current is fed and a secondary coil forming the output. The coils are wound on a common soft iron core, see figure 5.23.

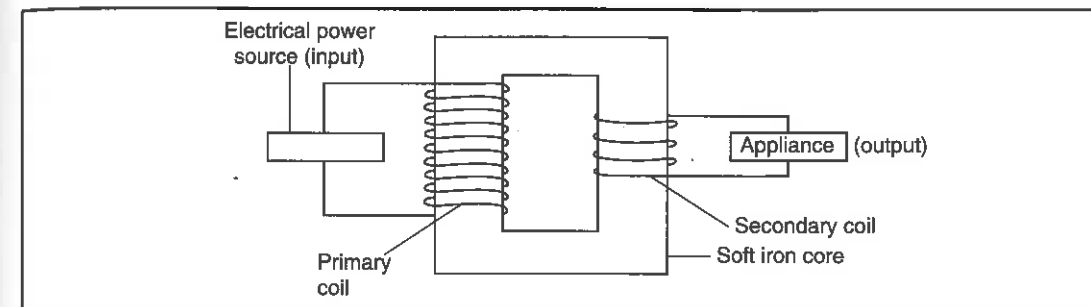


Fig. 5.23: Transformer

EXPERIMENT 5.10: To determine the variation of secondary e.m.f. with the number of turns

Apparatus

Long insulated copper wire, soft iron rod, low frequency a.c. source, a.c. voltmeter, switch, bulb.

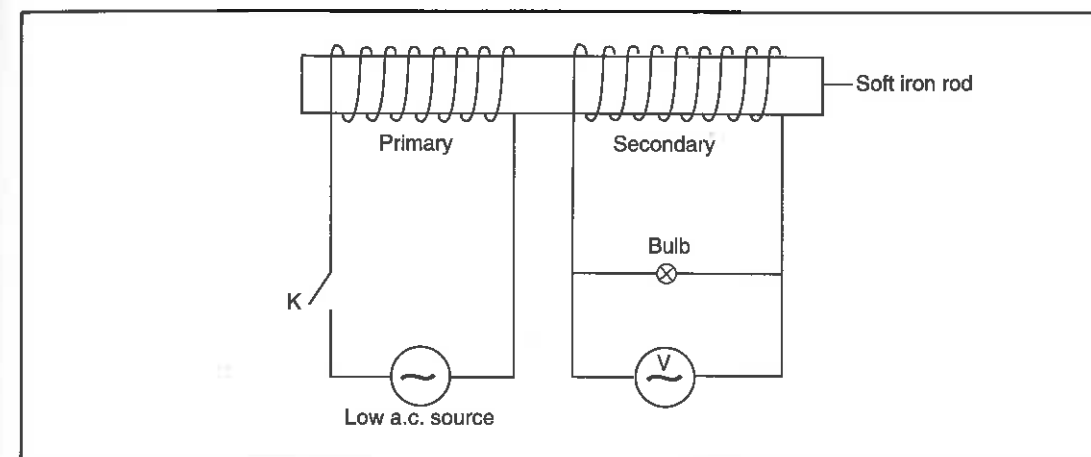


Fig. 5.24: A simple transformer

Procedure

- Using an insulated wire, wind a primary coil of 20 turns on a soft iron rod.
- Using another insulated copper wire, wind a secondary coil of 10 turns on the same soft iron rod. The coils should be wound closely together.
- Connect the primary coil to a low alternating voltage source and the secondary to a bulb and voltmeter, as shown in figure 5.24.
- Close switch K.
- Take the reading of the voltmeter and note the brightness of the bulb.
- Repeat the experiment and observe what happens to secondary e.m.f. when the number of turns of the secondary coil is increased.

Observation

The secondary voltage increases when the number of turns in the secondary coil is increased.

Explanation

When an alternating current flows in the primary coil, it produces an alternating magnetic flux which links with the turns of the secondary coil, inducing an e.m.f. in the secondary coil. The magnitude of induced e.m.f. increases with the number of turns of the secondary, because an e.m.f. is induced in each turn.

Step-down Transformer

Figure 5.25 (a) and (b) shows a step-down transformer and its circuit symbol. It has more turns in the primary coil (N_p) than in the secondary coil (N_s).

Note:

$\frac{N_s}{N_p} = n$ is referred to as the turns ratio.

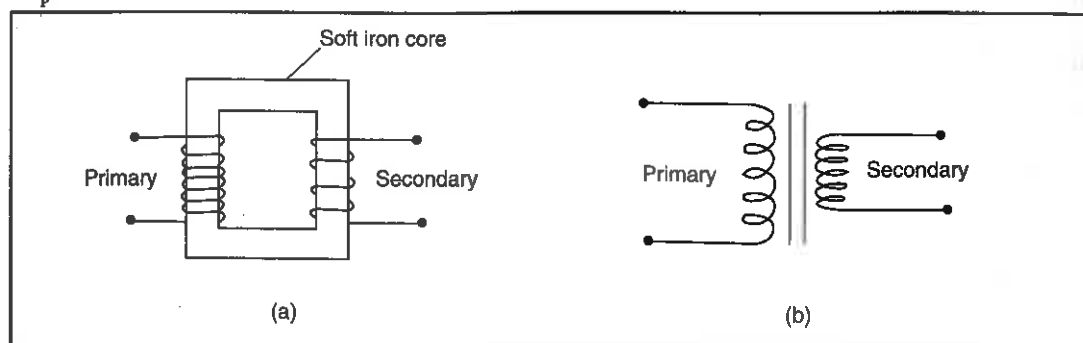


Fig. 5.25: Step-down transformer

The turns ratio for a step-down transformer is less than 1. Consequently, the changing magnetic flux in the primary induces a relatively smaller secondary voltage V_s than the primary voltage V_p . Thus, V_p is greater than V_s .

Step-up Transformer

Figure 5.26 shows the step-up transformer and its circuit symbol. It has more turns on the secondary coil than that of the primary, i.e., N_s is greater than N_p . The turns ratio is greater than 1 and the secondary (output) voltage V_s is greater than the primary (input) voltage.

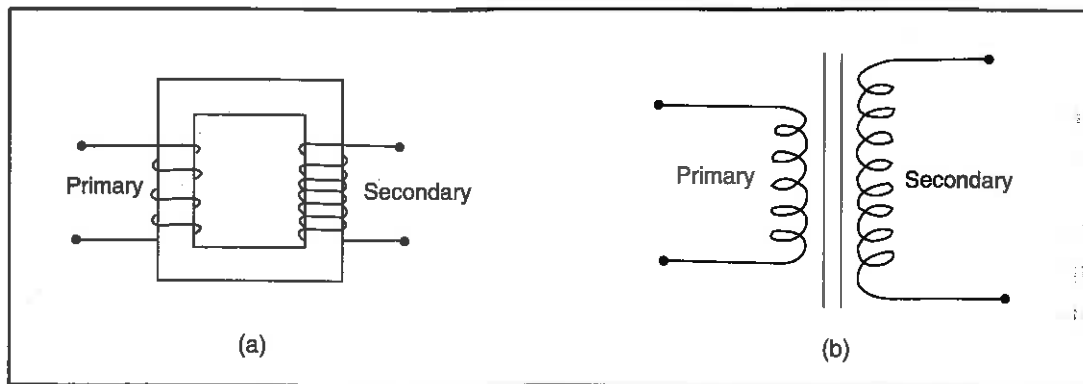


Fig. 5.26: Step-up transformer

Useful Transformer Equations

Experiments show that;

$$\frac{\text{secondary voltage}}{\text{primary voltage}} = \frac{\text{number of secondary turns}}{\text{number of primary turns}}$$

$$\frac{V_s}{V_p} = \frac{N_s}{N_p}$$

This equation is referred to as the **turns rule** and assumes that the coils have negligible resistance.

Since, electrical power = current x voltage;

$$\begin{aligned} \text{Power input} &= \text{primary current} \times \text{primary voltage} \\ &= I_p \times V_p \end{aligned}$$

$$\begin{aligned} \text{Power output} &= \text{secondary current} \times \text{secondary voltage} \\ &= I_s \times V_s \end{aligned}$$

$$\begin{aligned} \text{Efficiency (\%)} &= \frac{\text{power output}}{\text{power input}} \times 100 \\ &= \frac{V_s \times I_s}{V_p \times I_p} \times 100 \end{aligned}$$

For an ideal transformer (with no energy loss), the efficiency is 100%. Thus;

$$I_p \times V_p = I_s \times V_s$$

$$\text{Therefore, } \frac{V_s}{V_p} = \frac{I_p}{I_s} = \frac{N_s}{N_p} = n$$

Note:

In a step-down transformer, secondary current I_s is greater than the primary current I_p , while in a step-up transformer, the primary current I_p is greater than the secondary current I_s .

Energy Losses in a Transformer

There are four main causes of energy loss in a transformer, namely:

Flux Leakage

All the magnetic flux produced by the primary may not link up with the secondary coil, hence reducing e.m.f. induced in the secondary.

Flux leakage is reduced by efficient design of the transformers to ensure maximum flux linkage. Two commonly used designs have their coils wound as shown in figure 5.27 (a) and (b).

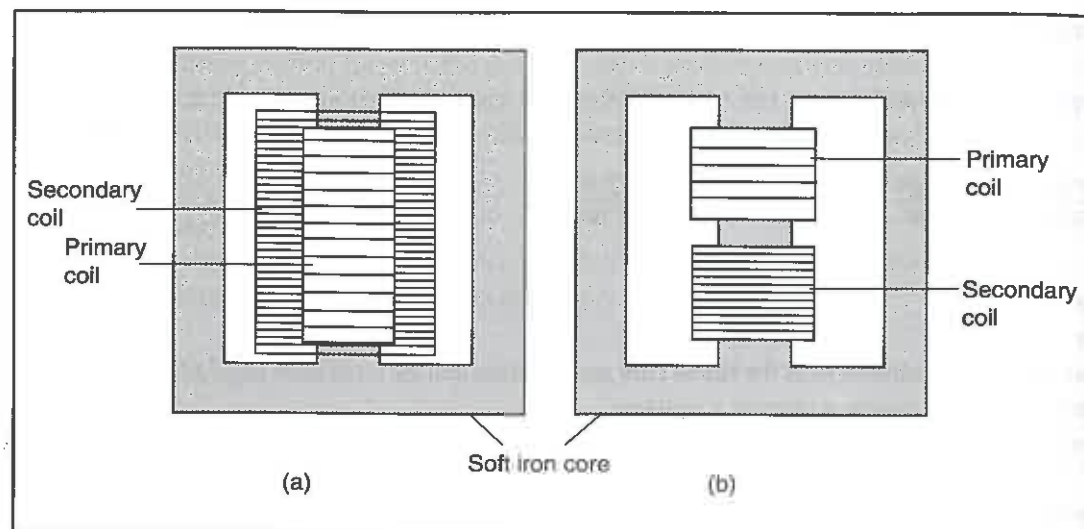


Fig. 5.27: Efficient designs of transformers

In figure 5.27 (a), the secondary coil is wound over the primary coil while in figure 5.27 (b), the coils are wound next to each other on a common core.

Resistance of Coils (Copper Losses)

Heat is generated in the coils when the current flows through them. This is because of the resistance of the wire making up the coils.

Thick copper wires (low resistance) are used in the secondary coils of a step-down transformer and the primary coils of step-up transformers to reduce this heating effect.

Eddy Currents in the Core

The alternating magnetic flux in the soft iron core cuts the very soft iron core, inducing an e.m.f. in it, which in turn sets up what is known as **eddy currents** to flow in the core. These eddy currents are sufficiently large to generate heat. In addition, the eddy currents have an associated flux that tends to oppose the flux changes in the primary. These effects reduce the power transfer to the secondary.

To reduce eddy currents, the core is **laminated**, that is, made of thin sheets of insulated soft iron plates. The current induced in each sheet is very small, causing minimal heating effect.

Hysteresis Loss

Some energy is lost in form of heat in magnetising and demagnetising the core every time the current reverses. This energy loss is called **hysteresis loss**.

Hysteresis loss is minimised by using a core of a soft magnetic material which magnetise and demagnetise easily, e.g., soft iron.

Practical Transformers

Heat is always generated in transformers despite the above measures. The heat generated in small transformers used in domestic appliances is low and therefore air is sufficient to cool

them. Large transformers used in power stations and along mains transmitting lines have a lot of heat generated in them and are cooled by oil, which does not easily evaporate. A well-designed transformer can have efficiency of up to 99 %.

Example 4

A transformer is to be used to provide power to a 12 V lamp from an a.c. mains supply of 240 V. Find the number of turns of the secondary coil if the primary coil has 1 000 turns.

Solution

$$\frac{V_s}{V_p} = \frac{N_s}{N_p}$$

$$\frac{12}{240} = \frac{N_s}{1\,000}$$

$$N_s = \frac{12}{240} \times 1\,000$$

$$N_s = 50 \text{ turns}$$

Example 5

A student designed a transformer to supply a current of 10 A at a potential difference of 60 V to a motor from an a.c. mains supply of 240 V. If the efficiency of the transformer is 80 %, calculate:

- the power supplied to the transformer.
- the current in the primary coil.

Solution

$$\begin{aligned} \text{(a) Efficiency} &= \frac{\text{power output}}{\text{power input}} \times 100 \\ &= \frac{V_s \times I_s}{V_p \times I_p} \times 100 \end{aligned}$$

$$80 = \frac{60 \times 10 \times 100}{\text{power input}}$$

$$\begin{aligned} \text{Power input} &= \frac{60 \times 10 \times 100}{80} \\ &= 750 \text{ W} \end{aligned}$$

$$\text{(b) } 240 \times I_p = 750 \text{ W}$$

$$\begin{aligned} I_p &= \frac{750}{240} \\ &= 3.13 \text{ A} \end{aligned}$$

Example 6

Figure 5.28 shows a model power transmission system consisting of a power generator, a step-up transformer, transmission cables and a step-down transformer.

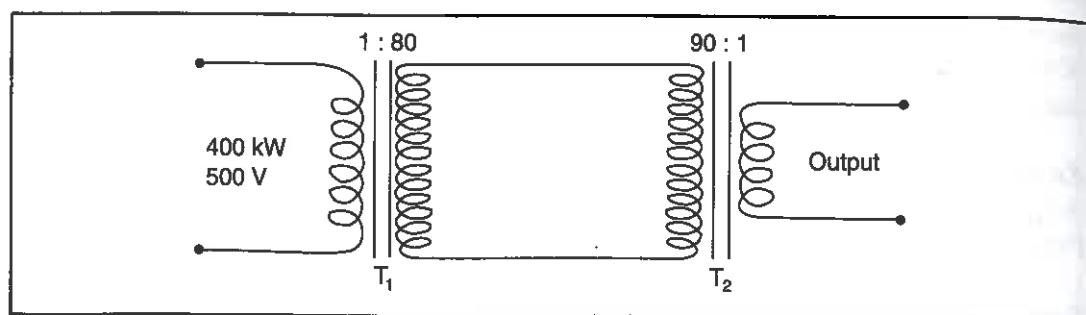


Fig. 5.28

The generator produces 400 kW at 500 V, which is fed into transformer T_1 , whose ratio of primary to secondary turns is 1 : 80. The power is then transmitted through cables whose total resistance is $200\ \Omega$ to a step-down transformer T_2 . Given that the efficiency of T_1 is 100 % and that of T_2 is 95 %, calculate:

- the current through the primary of T_1 .
- the voltage across the secondary of T_1 .
- the voltage across the primary of T_2 .
- the maximum power output of T_2 .

Solution

- (a) Power input = primary current $\times$ primary voltage

$$P = V_p \times I_p$$

$$I_p = \frac{P}{V_p}$$

$$I_p = \frac{400 \times 10^3}{500} = 800\text{ A}$$

(b) $\frac{V_s}{V_p} = \frac{N_s}{N_p}$

$$\frac{V_s}{V_p} = \frac{80}{1}$$

$$\begin{aligned} V_s &= 80 V_p \\ \therefore V_s &= 80 \times 500 \\ &= 40\,000\text{ V} \\ &= 40\text{ kV} \end{aligned}$$

- (c) Since T_1 is 100 % efficient;
power input = power output

$$400 \times 10^3 = V_s \times I_s$$

$$\text{But } V_s = 40\,000\text{ V}$$

$$\begin{aligned} \text{So, } I_s &= \frac{400 \times 10^3}{40\,000} \\ &= 10\text{ A} \end{aligned}$$

Current through the secondary coil of T_1 and the transmission cables is 10 A. Voltage lost during transmission is obtained from $V = IR$;

$$V = 10 \times 200$$

$$= 2\,000\text{ V}$$

$$\begin{aligned} \text{Voltage across primary of } T_2 &= \text{voltage across secondary of } T_1 - \text{voltage lost during transmission} \\ &= 40\,000 - 2\,000 \\ &= 38\,000 \end{aligned}$$

$$\begin{aligned} \text{(d) Power fed into } T_2 &= \text{voltage across primary of } T_2 \times \text{current through primary } T_2 \\ &= 38\,000 \times 10 \\ &= 380\,000\text{ W} \\ &= 380\text{ kW} \end{aligned}$$

Since T_2 is 95 % efficient;

$$\frac{95}{100} = \frac{\text{power output}}{\text{power input}}$$

$$\therefore \text{Power output} = \frac{95}{100} \times \text{power input}$$

$$= \frac{95}{100} \times 380 \times 10^3$$

$$= 3.61 \times 10^5\text{ W}$$

$$= 361\text{ kW}$$

Moving-coil Microphone

The moving-coil microphone is another important application of electromagnetic induction. Figure 5.29 shows the microphone and its typical current output.

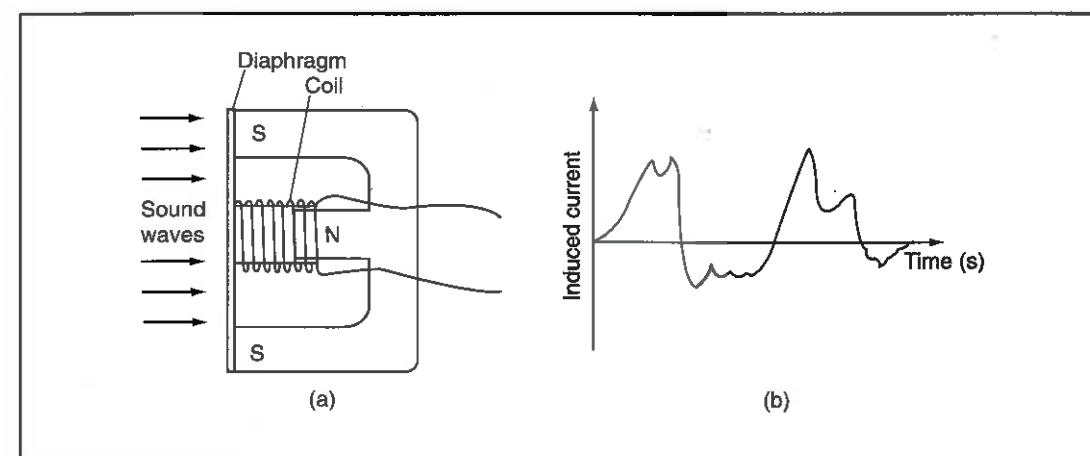


Fig. 5.29: Moving-coil microphone

A coil is wound on a cylindrical former connected to a diaphragm and placed between the poles of a pot of magnet, as shown in figure 5.29 (a). Sound waves from a source set the diaphragm in vibration, causing the coil to move to and fro, cutting the magnetic field. The field is radial so that the motion of the coil is perpendicular to it for maximum flux linkage. Induced e.m.f. of varying magnitude sets up varying current in the coil. An amplifier is used to increase the amplitude of this current before being fed into the loudspeaker to be converted back to sound.

The Induction Coil

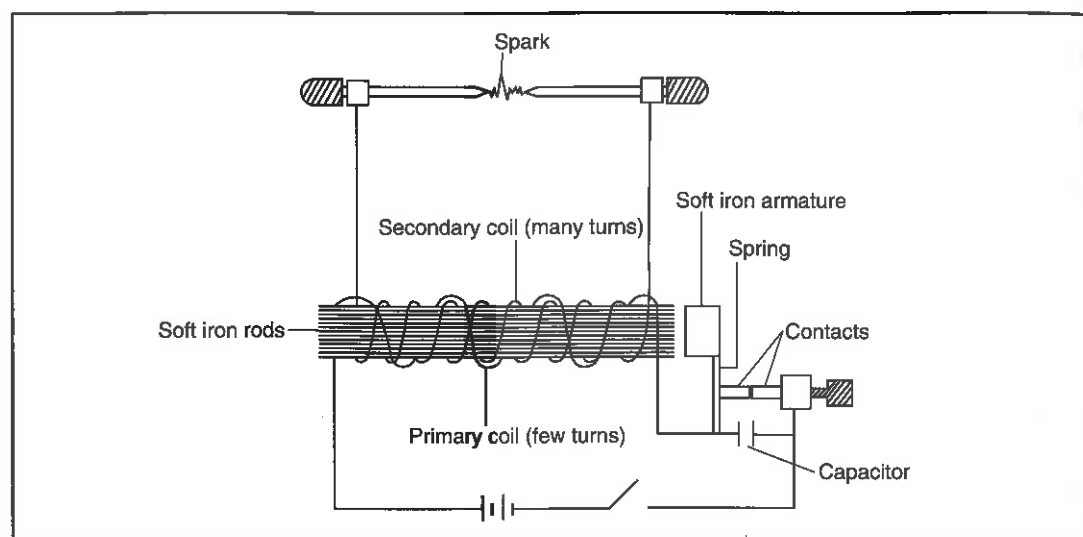


Fig. 5.30: Induction coil

The induction coil shown in figure 5.30 consists of few turns of thick insulated copper wire and a secondary coil of many turns of thin insulated copper wire, both wound on a soft iron core. The primary coil is connected to a direct current (d.c.) source of low voltage. When the switch is closed, the soft iron core becomes magnetised due to the current in the primary coil and attracts the soft iron armature. The moving armature opens the contacts and cuts off the primary current, rapidly reducing the magnetic field to zero. This in turn induces a large e.m.f. in the secondary coil by mutual induction. Meanwhile, the spring pulls the armature back to make contact once again for the current to flow in the primary coil. The process repeats itself.

The switching on and off of the primary current is thus continuous and so is the changing magnetic flux. The induced e.m.f. in the secondary coil is much higher when primary current is switched off than when it is switched on. This is because the current takes longer time to increase from zero to a maximum than to decrease from maximum to zero. Sparking may also occur at the contacts due to magnetic field of the primary cutting the primary coil and fulfilling the Lenz's law to keep primary current flowing. A capacitor connected across the contacts minimises the sparking and causes the primary current and hence magnetic flux to decay to zero. This, in addition to many turns in the secondary coil, increases the magnitude of the induced e.m.f. in the secondary. Sparks then jump across the gap between the ends of the secondary coil and can be used to ignite petrol-air mixture in a car engine.

Alternating Current (a.c.) Generator (Alternator)

A generator converts mechanical energy into electrical energy. Figure 5.31 shows a simple generator having rectangular, curved permanent magnetic poles, two slip-rings and carbon (graphite) brushes.

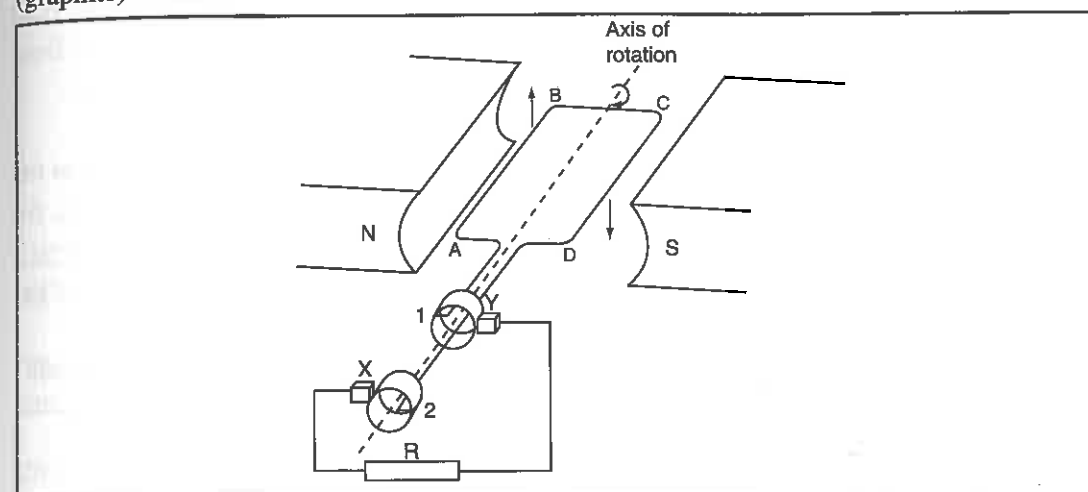


Fig. 5.31: Alternating current generator

The poles of the magnet are curved so that the magnetic field is radial. Current enters and leaves the coil through the brushes, which press against slip-rings. The brushes are made of carbon (graphite) which, apart from being a good conductor, is also slippery and acts as a lubricant.

Consider the coil being rotated in clockwise direction and just passing the horizontal position as in figure 5.31. The side AB of the coil is moving up while the other side (CD) is moving downwards. The two sides are cutting the field perpendicularly and thus maximum e.m.f. (E_0) is induced.

Applying Fleming's right-hand rule, the flow of current is in direction $A \rightarrow B \rightarrow C \rightarrow D$. This current flows through the external circuit via the slip-ring 2 and brush X. Brush Y and slip-ring 1 then complete the circuit. Brush X is thus **positive** terminal while Y is **negative**. As the coil rotates from the horizontal to the vertical position, the angle at which the sides of the coil cut the magnetic field reduces from 90° to 0° . Consequently, the induced e.m.f. reduces from the maximum value E_0 to zero, see figure 5.32.

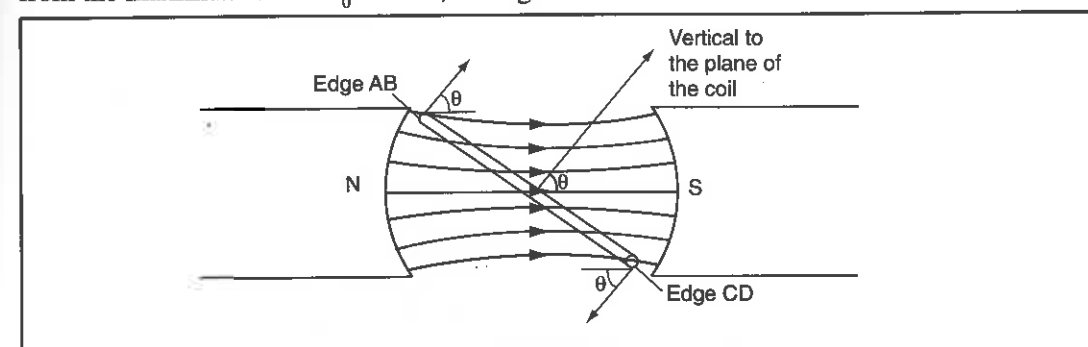


Fig. 5.32: Rotating coil in a magnetic field

Note that when the coil is rotating past the vertical position, the sides AB and CD at that instant move parallel to the field. The sides of the coil thus do not cut the magnetic field and induced e.m.f. is zero. When the coil rotates past the vertical position, side AB moves downwards as side CD moves upwards. The angle θ at which the sides of the coil cut the magnetic field increases from 0° to 90° when the coil is horizontal. The induced e.m.f. thus increases from zero to maximum value E_0 . Notice that the path of current flow in the coil reverses, i.e., $D \rightarrow C \rightarrow B \rightarrow A$. Brush Y now becomes **positive** and X **negative**.

As the coil rotates further to complete one revolution, the angle at which its sides cut the magnet field reduces from 90° to 0° . The e.m.f. in the coil reduces from E_0 to zero. Thus, for one cycle, an alternating e.m.f. E is induced in the coil. The magnitude of this e.m.f. obeys a sinusoidal equation, $E = E_0 \sin \theta$, where E_0 is the maximum e.m.f. and θ the inclination of the plane of the coil to the vertical.

Figure 5.33 shows the variation of induced e.m.f. with time for one revolution of the coil.

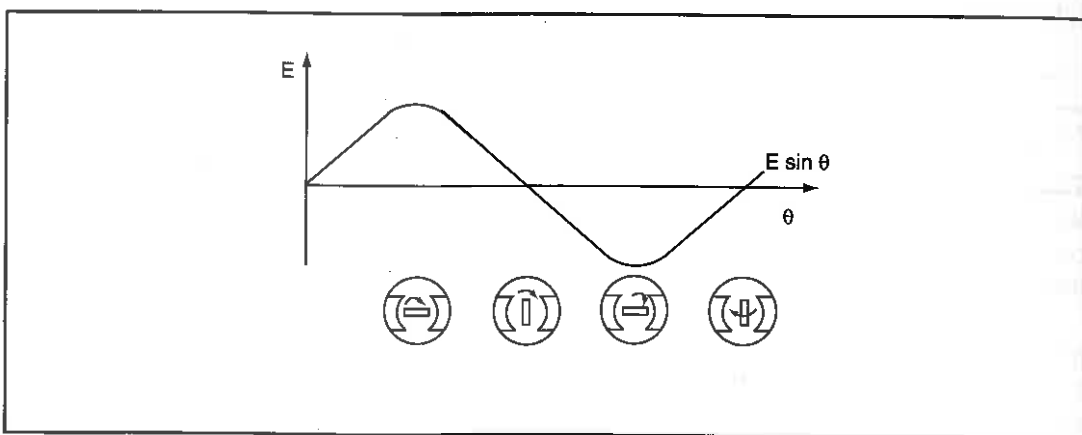


Fig. 5.33: Graph of induced e.m.f. against θ for an a.c. generator

By Ohm's law, $I = \frac{E}{R}$, where R is the resistance of the circuit.

If I is the current in the coil at any instant, then;

$$I = \frac{E}{R}$$

$$= \frac{E_0}{R} \sin \theta$$

If I_0 is the maximum value of I , then $I_0 = \frac{E_0}{R}$ and $I = I_0 \sin \theta$

The graph of the induced current I against the angle of inclination θ is similar to that of induced e.m.f. E against θ , as shown in figure 5.34.

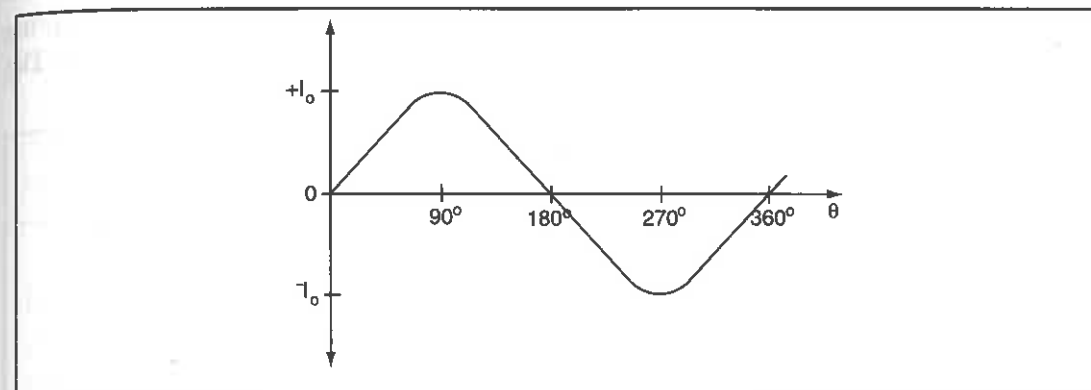


Fig. 5.34: Graph of I against θ (a.c. generator)

The frequency of the alternating current (a.c.) is the number of revolutions made by the coil in one second. The a.c. from the mains in Kenya has frequency of 50 Hz.

Direct Current (d.c.) Generator

A d.c. generator differs from an a.c. generator in that it has a split-ring (commutator) while an a.c. generator has slip-rings, see figure 5.35.

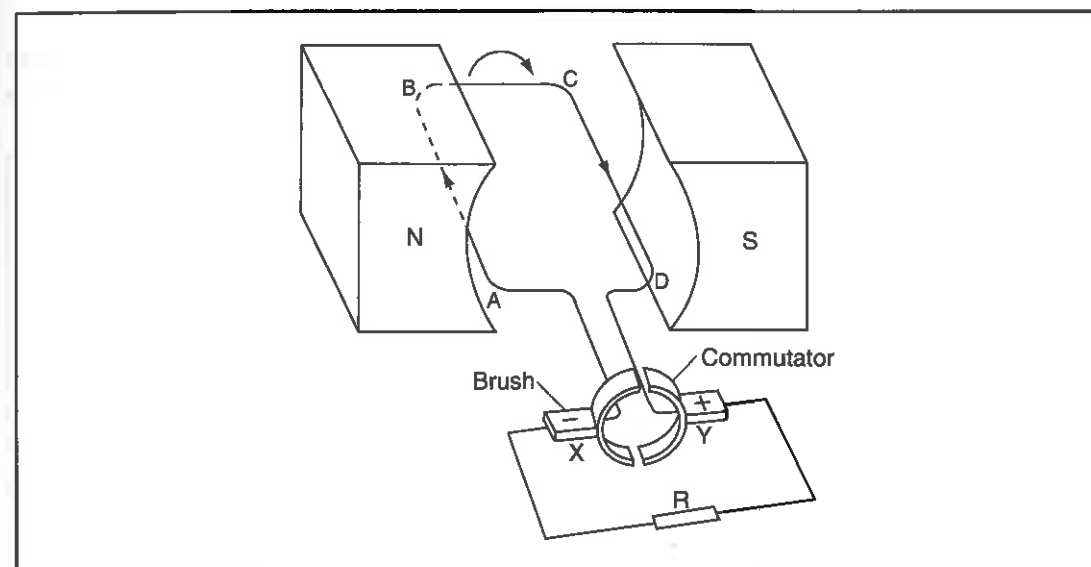


Fig. 5.35

As the coil rotates into the vertical position from the horizontal position with the side AB moving up, the induced e.m.f. and current through resistor R decreases from a maximum value to zero. The polarity of brush Y is positive and X negative.

When the coil is in vertical position, the e.m.f. is zero. The brushes touch the gaps within the commutator. When the vertical position is passed, the half-rings exchange brushes since

the induced currents AB and CD change direction, but the direction of current through the external resistor R remains the same. Brush Y therefore remains positive and X negative. The output of a d.c. generator is shown in figure 5.36.

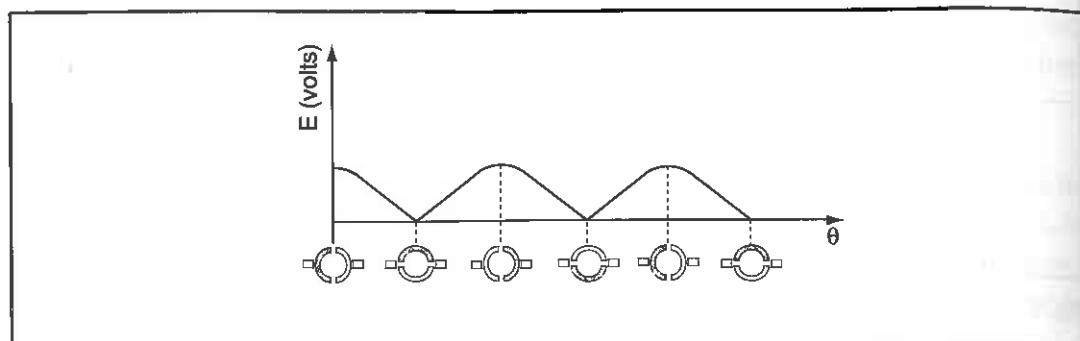


Fig. 5.36: Output of d.c. generator

Note:

The induced e.m.f. or current for both a.c. and d.c. generator can be increased by:

- (i) increasing the speed of rotation of the coil.
- (ii) increasing the number of turns of the coil.
- (iii) increasing the strength of the magnetic field.
- (iv) winding the coil on a laminated soft iron core

In some generators such as the bicycle dynamo, see figure 5.37, the coil remains stationary while the magnet rotates. The advantage of such generators is that there are no brushes which get worn out.

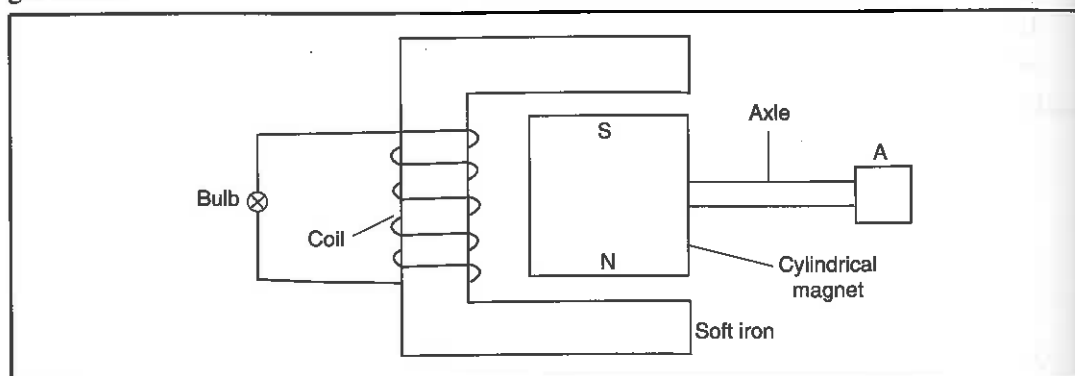
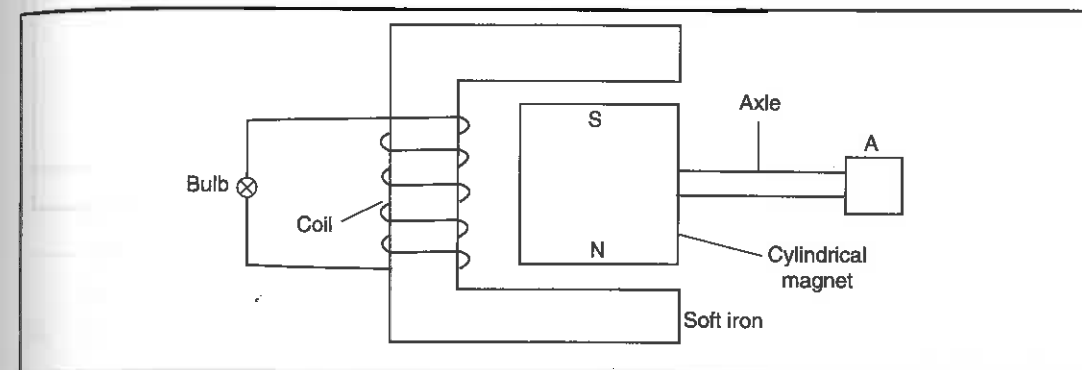


Fig. 5.37: Bicycle dynamo

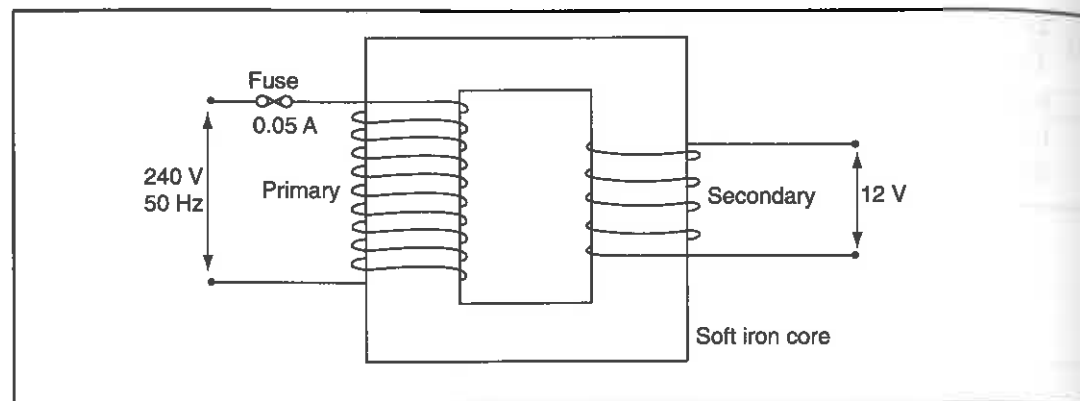
Revision Exercise 5

1. (a) State the factors that determine the magnitude of an induced e.m.f. in a conductor.
(b) How does each of the factors above affect the induced e.m.f.?
2. State the laws of electromagnetic induction.
3. With the aid of a diagram, explain how a simple d.c. generator works.
4. (a) State the various ways in which power is lost from a transformer.
(b) Explain how each loss above is minimised.

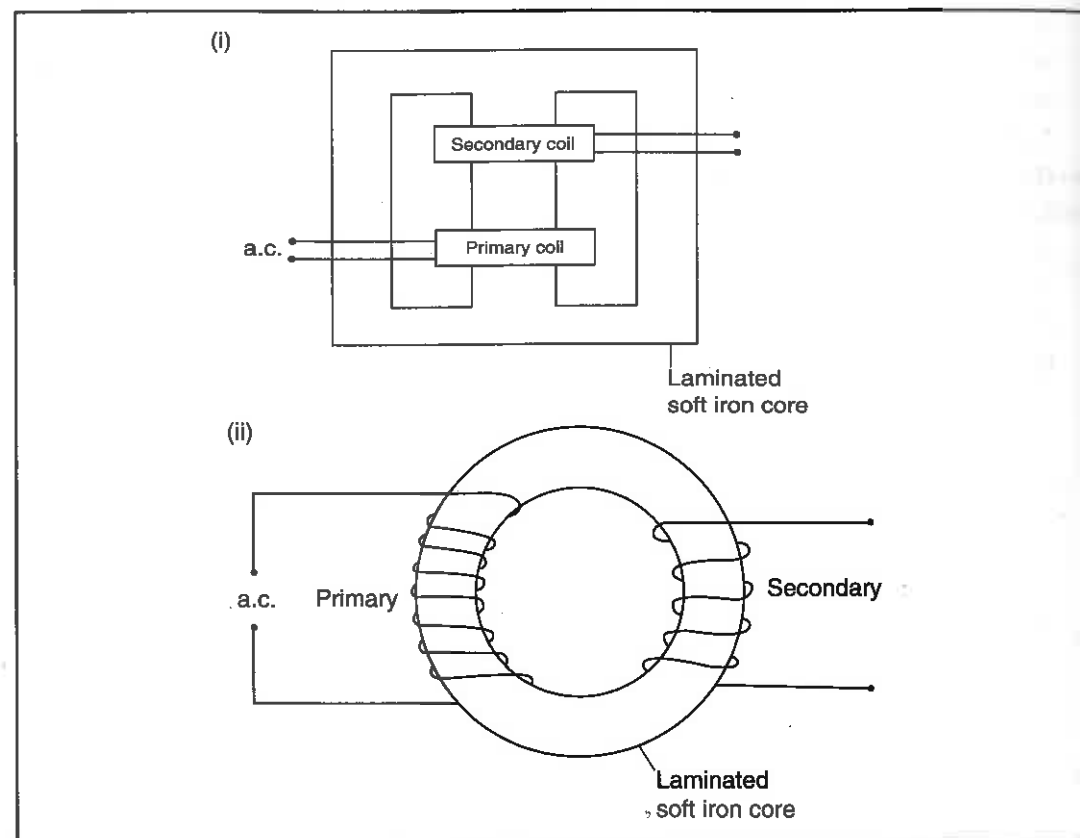
5. Describe how a moving coil microphone works.
6. The figure below shows a diagram of a bicycle dynamo. Wheel A is connected by an axle to a permanent cylindrical magnet and is rotated by the bicycle tyre.
(a) Explain why the bulb lights.
(b) If you were riding the bicycle, what would you do to make the bulb brighter?



7. A power station has an output of 33 kΩ at potential difference of 5 kV. A transformer with a primary coil of 2 000 turns is used to step up the voltage to 132 kV for transmission along a grid. Assuming that there are no power losses in the transformer, calculate the:
(a) current in the primary coil.
(b) number of turns of the secondary coil.
(c) current in the secondary coil.
8. A power station has an output of 10 kW at a p.d. of 500 V. The voltage is stepped up to 15 kV by transformer T_1 for transmission along a grid of resistance 3 kΩ and then stepped down to p.d. of 240 V by transformer T_2 at the end of the grid for use in a school.
(a) Given that the efficiency of T_1 is 95% and that of T_2 90%, find:
(i) the power output of T_1 .
(ii) the current in the grid.
(iii) the power loss in the grid.
(iv) the input voltage of T_2 .
(v) the maximum power and current available for use in the school.
(b) Why is it necessary to step up the voltage at the power station?
9. A transformer is used to provide a potential difference 100 kV to an X-ray tube from a 250 V a.c. mains supply. A current of 100 mA flows in the X-ray tube and the transformer is 100% efficient.
(a) Calculate:
(i) the ratio of number of turns of the secondary to the number of turns of the primary.
(ii) the current in primary coil.
(b) State, giving reasons, which of the coils of the transformer is thicker.
10. The figure shows a demonstration transformer intended to step down a 240 V mains supply to 12 V a.c.

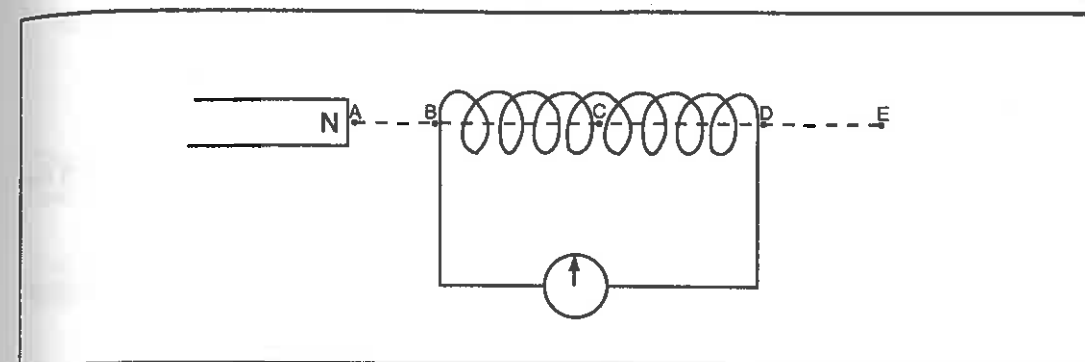


- (a) (i) What is the maximum secondary current that would be drawn from the transformer, assuming 80% efficiency?
 (ii) What is the frequency of the secondary voltage?
 (b) The two transformers below are more efficient than the one above.

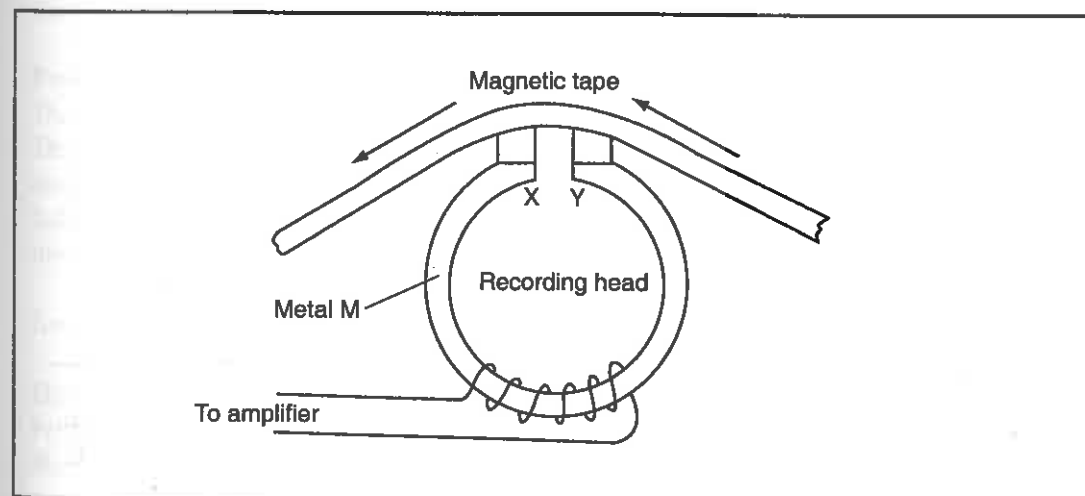


Explain why each of these designs is more efficient than the demonstration transformer.

11. A magnet is moved with uniform speed through the coil from point A to point E, as shown in the figure below.

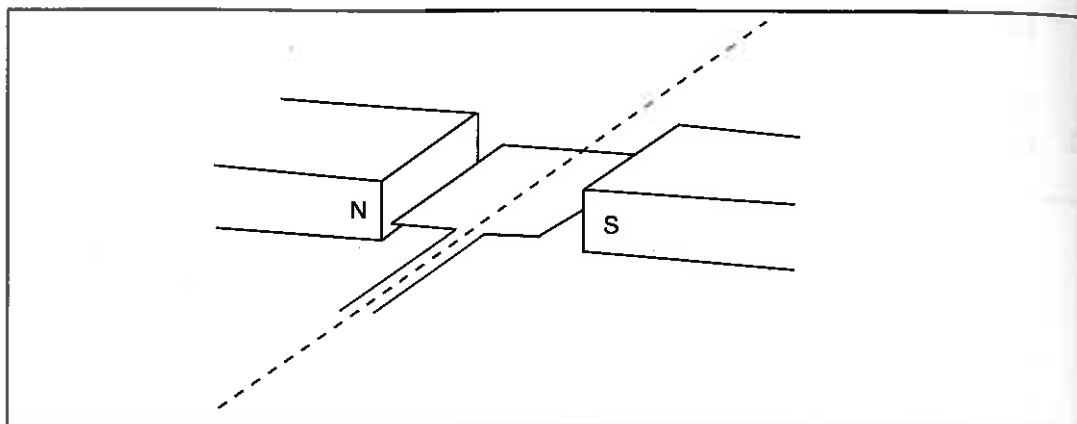


- (a) Draw sketch graph of readings of galvanometer against positions of the magnet as it moves from point A to E.
 (b) Explain why the galvanometer records the readings obtained.
 12. (a) A student designed a transformer to provide power to an electric bell marked 24 W 6 V from a mains supply 240 V. He wound coils 50 turns and N turns on an iron ring. When he connected the coil of 50 turns to the bell and the N turns coil to the a.c. source, he found out that the transformer was only 60% efficient. Find:
 (i) the value of N .
 (ii) the power in the primary coil.
 (b) How can the efficiency of the transformer be increased?
 (c) After re-designing the transformer, the efficiency increased to 80%. Determine the:
 (i) power supplied to the primary.
 (ii) voltage across primary coil.
 (iii) current in the primary coil.
 (d) Explain why it is wrong and sometimes dangerous to connect a transformer to a d.c. source.
 13. The figure below shows the recording head of a tape recorder:



Recording is done by magnetising the tape using different strengths of the magnetic field. During play back:

- (a)
 - (i) how is varying magnetic field produced on the head?
 - (ii) what material is suitable for metal M?
 - (iii) explain why there is a gap between X and Y and indicate the point at which the tape is magnetised.
 - (b) Using a sketch, explain how a loudspeaker may be used as a microphone.
14. With the aid of a diagram, explain how a continuous electrical spark can be produced across a gap.
15. The diagram below shows an incomplete simple a.c. generator.



- (a) Complete the diagram, including the connection to an appliance to which the generator is supplying power. The coil is rotated with a uniform angular velocity about its axis.
- (b) Draw a graph of power in the appliance against the angle the coil makes with the magnetic field.
- (c) What modifications would you make on the generator if the appliance requires:
 - (i) uniform power?
 - (ii) current in one direction only?

Chapter Six

MAINS ELECTRICITY

Electrical appliances such as heaters and heavy duty electric motors require a lot of electrical energy for their operation. An economical source of electrical energy is mains electricity.

Mains electricity is produced in large quantities by large generators at power stations that are located very far from the consumers. The power generated is then transmitted to the consumers through overhead transmission lines (cables).

Sources of Mains Electricity

The main sources of mains electricity are:

- (i) water in high dams.
- (ii) geothermal energy.
- (iii) coal or diesel.
- (iv) wind.
- (v) tidal waves in the seas.
- (vi) nuclear energy.

The type of power generation chosen for a given location depends on the most abundant source of energy available in that area. Hydro-electric power stations are for example located near large rivers, where the potential energy of water in a high dam when converted to kinetic energy is used to rotate water turbines connected to generators. These turbines rotate large coils in magnetic fields to produce electrical energy.

In coal, geothermal and nuclear power stations, water is heated into steam under very high pressure. This steam is then used to rotate steam turbines, which in turn rotate coils in a magnetic field to produce electricity. These power stations may cause environmental hazards. For example, coal is responsible for much air pollution while nuclear power stations may produce emissions from the radioactive materials.

The kinetic energy of a rotating flywheel of a thermal (diesel) engine is converted to electrical energy by direct coupling to a generator.

Power Transmission

The Grid System

The electricity generated at a power station is transmitted to consumers such as factories, institutions and homes by overhead or underground cables. All power stations in a country are linked together by cables and the power then distributed to the consumers. This ensures that the power is available to consumers even when one of the power stations is shut down.

This system of power cables connecting all the stations in a country to each other and finally to the consumers is called the national grid system.

High Voltage Transmission

Power stations generate electricity, usually a.c., at between 11 kV and 25 kV. This voltage is then stepped-up to between 132 kV and 400 kV for transmission. The electrical power is

usually transmitted over long distance to substations, which are located near towns, where the voltage is stepped down to 11 kV, see figure 6.1. The power is then transmitted at this low but still higher voltage to consumers, where it may be further stepped down to appropriate values for domestic and other uses. In Kenya domestic appliances normally operate at 240 V.

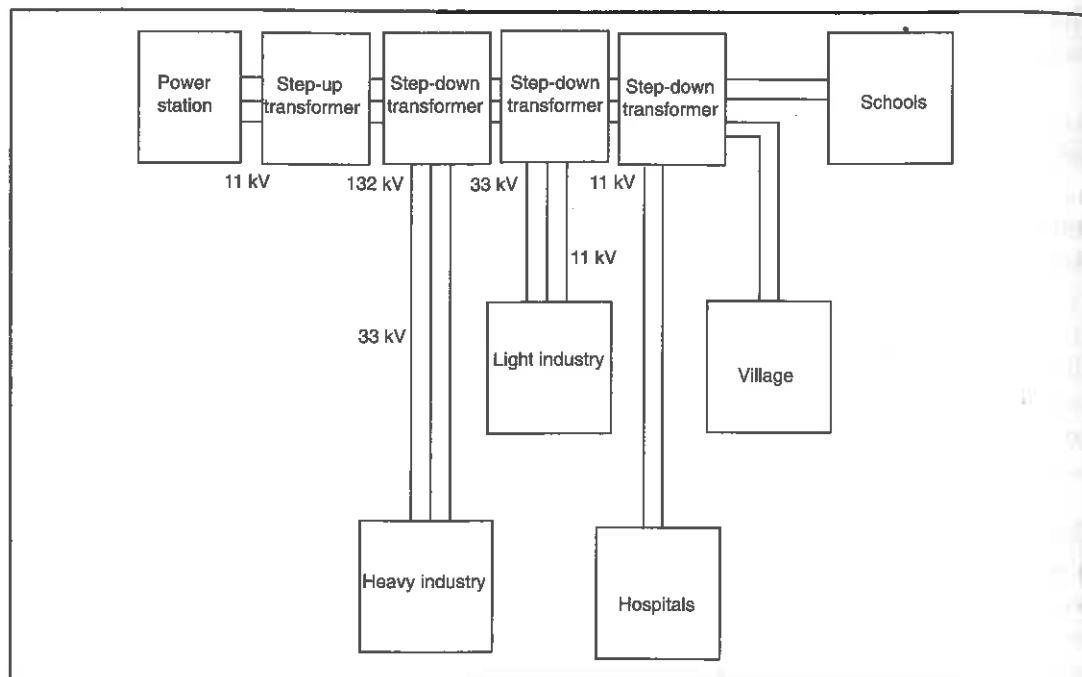


Fig. 6.1: Power transmission

Dangers of High Voltage Transmission

The dangers of high voltage transmission are:

- the risk of electric shock in case poles collapse or cables hang too low.
- the risk of fire on nearby structures and vegetation when the cables get too close.
- the harmful effects of strong electric field.

Power Losses During Transmission

Power dissipated in a circuit is given by $P = VI$.

But, $V = IR$ (Ohm's law)

Thus, $P = I^2R$, where I , V and R are current, voltage and resistance respectively.

This means that for a given resistance in a circuit, when the current is high, the power loss is large and when the current is low, the power loss is small. Power loss in transmission cables is therefore low when it is transmitted at high voltage and low current.

The output voltage from a power station is therefore stepped up for long distance transmission in order to minimise power loss in transmission cables. Since long distances are involved, transmission cables are thick and are made of materials which are good conductors of electricity, to minimise resistance. Aluminum is preferred because it is a good conductor, light and cheaply available.

Note:

It is impossible to step-up or step-down steady d.c. voltages.

Example 1

The resistance of a length of power transmitting cable is 10Ω and is used to transmit 11 kV at a current of 1 A. If this voltage is stepped-up to 16 kV by a transformer, determine the power loss.

Solution

Assuming the transformer is 100 % efficient;

Power input = power output

$$V_p I_p = V_s I_s$$

$$11\,000 \times 1 = 160\,000 \times I_s$$

$$\therefore I_s = \frac{11\,000}{160\,000}$$

$$= 0.069 \text{ A}$$

$$\text{Power loss} = I^2 R$$

$$= (0.069)^2 \times 10$$

$$= 0.048 \text{ W}$$

Note:

If the power is transmitted at 11 kV and current 1 A;

$$\text{Power loss} = I^2 R$$

$$= (1)^2 \times 10$$

$$= 10 \text{ W}$$

This shows that when the voltage is stepped up from 11 000 V to 160 000 V, the power loss is reduced by over 200 times.

Example 2

A generator produces 660 kW at a voltage of 10 kV. The voltage is stepped up to 132 kV and the power transmitted through cables of resistance 200Ω to a step-down transformer in a sub-station. Assuming that both transformers are 100 % efficient:

(a) calculate:

- the current produced by the generator.
- the current that flows through the transmission cables.
- the voltage drop across the transmission cables.
- the power lost during transmission.
- the power that reaches the sub-station.

(b) repeat (a) (i) to (v), but this time with the 10 kV stepped up only 20 kV instead of 132 kV for transmission.

Solution

(a) (i) Power input = $V_p \times I_p$

$$I_p = \frac{P}{V_p}$$

$$= \frac{660 \times 10^3}{10 \times 10^3}$$

$$= 66 \text{ A}$$

- (ii) At the step-up transformer;
power input = power output (since efficiency is 100%)

$$V_p I_p = V_s I_s$$

$$10 \times 10^3 \times 66 = 132 \times 10^3 \times I_s$$

$$I_s = \frac{10 \times 10^3 \times 66}{132 \times 10^3}$$

$$= 5 \text{ A}$$

- (iii) $V = IR$
 $= 5 \times 200$
 $= 1000 \text{ V}$

- (iv) $P = I^2 R$
 $= 5 \times 5 \times 200$
 $= 5000 \text{ W}$
 $= 5 \text{ kW}$

- (v) (Power at sub-station) = (power generated) – (power lost during transmission)
 $= 660 - 5$
 $= 655 \text{ kW}$

- (b) (i) $P = V_p \times I_p$

$$I_p = \frac{660 \times 10^3}{10 \times 10^3}$$

$$= 66 \text{ A}$$

- (ii) $I_s = \frac{V_p I_p}{V_s}$

$$= \frac{10 \times 10^3 \times 66}{20 \times 10^3}$$

$$= 33 \text{ A}$$

- (iii) $V = IR$
 $= 33 \times 200$
 $= 6600 \text{ V}$

- (iv) $P = I^2 R$
 $= 33 \times 33 \times 200$
 $= 217800 \text{ W}$
 $= 217.8 \text{ kW}$

- (v) (Power at sub-station) = (power generated) – (power lost during transmission)
 $= 660 - 217.8$
 $= 442.2 \text{ kW}$

Domestic Wiring

For domestic consumption, electrical power is usually supplied at 240 V. This is obtained from a local transformer sub-station, where the voltage from the national grid has been stepped down from 11 000 V to 240 V.

From the transformer, power is brought to the house through a two-wire cable, one of which is earthed at the transformer. The earthed one is called the **neutral** cable and is at zero potential while the other is known as the **live**. The cable goes through the electrical company fuse box, where the live wire is connected to a 60 A or higher fuse value. The cable is then connected to the power meter where the energy consumed is registered. From the metre, the cable passes on to the consumer's fuse box (or unit), see figure 6.2.

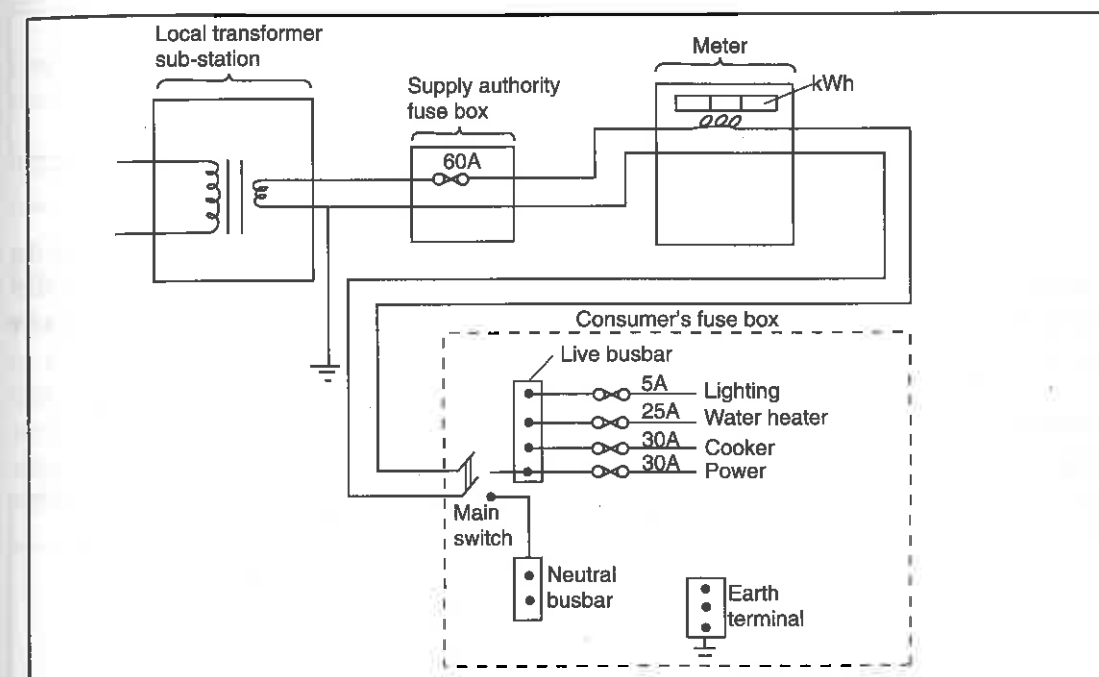


Fig. 6.2: The consumer fuse box

The consumer fuse box contains the following :

The main switch

This is double-pole switch which disconnects both the live and the neutral wires simultaneously, thereby disabling all the circuits in the house when necessary.

The live busbar

This is a brass bar connected to the live wire through the main switch. The live wire of each circuit is connected to it through a fuse.

Neutral busbar

This is a brass bar to which all the neutral wires of such circuits are connected.

Earth terminal

The terminal may be a busbar or a part of the fuse box, if it is metallic. Whichever case, the

terminal is earthed either through water piping or through a thick copper bar buried deep in the earth. Figure 6.2 illustrates the stages through which the power is delivered to the consumer's fuse box (consumer unit).

Fuses and Circuit Breakers

Fuses are used to safeguard against excess currents in a circuit. They are made of a short thin wire (an alloy of copper and tin) and have low melting point. When the current exceeds the fuse rating, the fuse wire gets very hot and melts, hence disconnecting the circuit. This reduces the risk of fire or damage to the electrical appliances. Figure 6.3 shows a fuse and its circuit symbol. As a safety measure, proper fuse wire must be used to replace a blown out fuse.

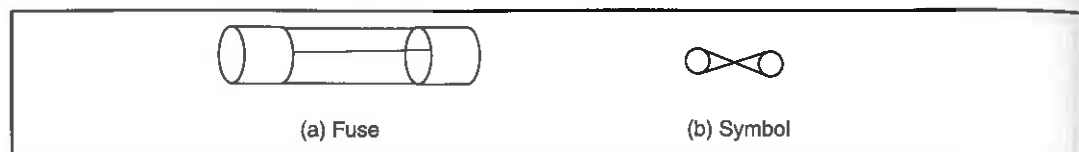


Fig. 6.3: Fuse and its circuit symbol

The circuit breaker, discussed in Book Two, is commonly used in the fuse box instead of the wire fuse. This is because it breaks the circuit instantaneously, whereas the wire fuse takes time to melt. It is reset for use again once the fault has been corrected, as opposed to the wire fuse which has to be replaced.

Distribution of Power From the Consumer Unit

Figure 6.4 shows a typical house wiring system.

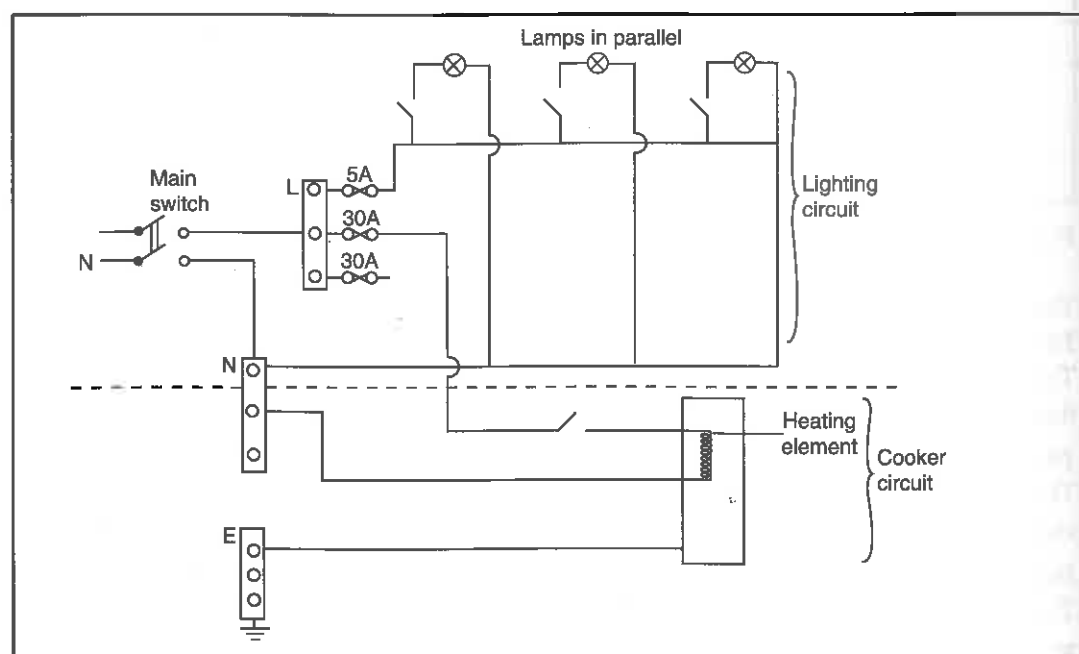


Fig. 6.4: Domestic wiring

Each component of the above circuit has a wire running from the live busbar through an appropriate fuse or circuit breaker and a return wire running from the neutral busbar to the output terminal. Except for the lighting circuit, other circuits have an earth connection running from the earth terminal to the outlet socket. Appliances that require earthing are automatically earthed through the sockets, making them safe to handle. When such appliances are not earthed, there is always danger of electric shock.

The Lighting Circuit

In the lighting circuit, the lamps are connected in parallel so that they operate at the same mains voltage and can be operated independently. The switches are on the live line for safety.

If a switch were on the neutral line, the live wire would still be at the mains potential even when the switch was off. This would cause an electric shock when one handles any conductor linked to the live wire.

Since the lighting circuit carries a small current, the wire used is relatively thinner than those for other circuits. In an ordinary house, power for the lighting is supplied through 5 A fuse, since each lamp takes only a small current.

The Two-way Switch Circuit

This is a circuit in which a lamp can be operated by any one of two switches. It can be put on by one switch and put off by the other, and vice versa. The arrangement is convenient in lighting of a staircase and corridors. A switch at the bottom of the staircase can be used to put on the light, which can then be put off when one gets to the top of the staircase. Similarly, a lamp can be put on by a switch at the door of a room and put off by another switch at the other end of the room. Figure 6.5 illustrates the wiring of a two-way switch circuit.

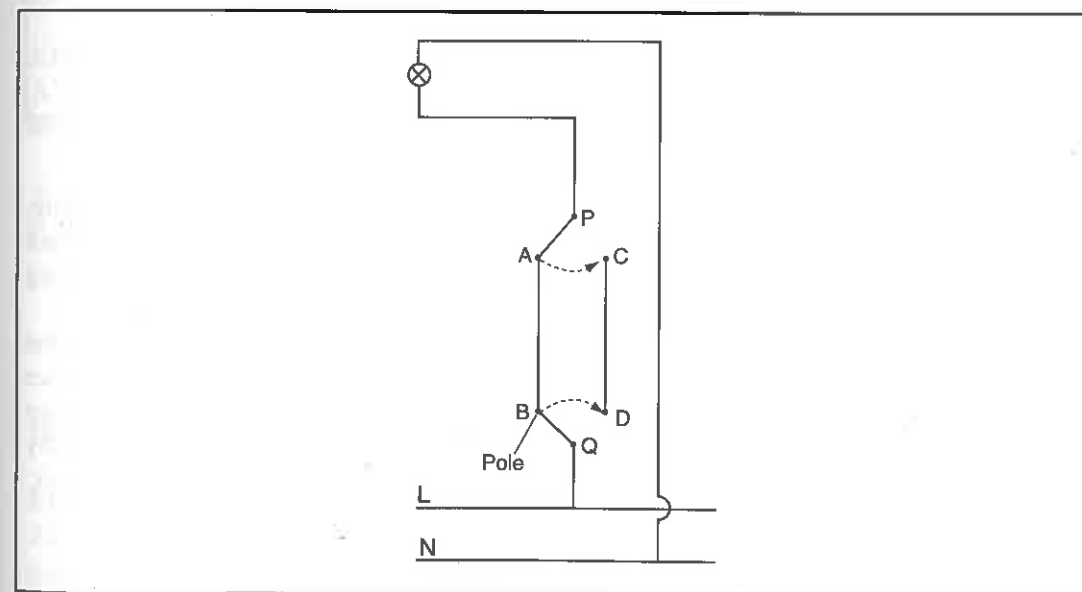


Fig. 6.5: Two-way switch

When the contact is made at poles A and B as shown, the bulb lights. The same is true when contact is made at C and D.

To put off the bulbs at point P, the switch is made to make contact at C, while the contact at point Q is at B. To put on again the bulb at point Q, the switch is made to make contact at D, while the contact at point P is still at C.

The Cooker Circuit

The cooker and water heater are usually supplied with their own circuits. These circuits are earthed and their wires are relatively thicker than those for the lighting circuits, since they carry large currents.

The Ring Mains Circuit

In this circuit, a cable containing the three wires, live, neutral and earth, forms a loop as shown in figure 6.6.

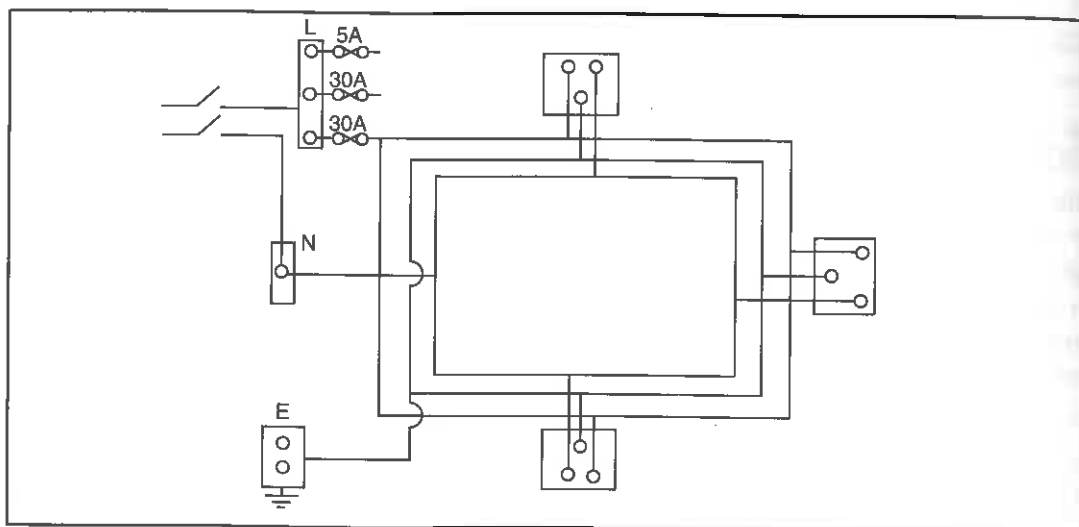


Fig. 6.6: Ring mains circuit

The power for the sockets in the various rooms is tapped at convenient points from the loop. The loop arrangement of the cable enables a double path for the current. The loop arrangement also effectively increases the thickness of the wires used. This reduces the risk of overloading the circuit when several sockets are in use.

Appliances using the ring mains circuit are provided with a third wire connected to the casing. From the power socket, this third wire links with the earth terminal at the consumer unit through the ring mains circuit earth wire. If the live wire accidentally touches the casing making it live, a large current will flow through the earth wire and the fuse will blow, thereby cutting off the current. Anyone handling the appliance would thus be safe from imminent shock.

A Three-pin Plug

The insulation on the three leads on a power circuit appliance are coloured distinctly so that they link correctly when connected to the power circuit. The live lead is coloured red or brown. The neutral is coloured blue or black while the earth is coloured green or green with yellow stripes.

A three-pin plug has the letters L, N and E marked against the live, neutral and earth pins respectively. The three leads from the appliance are connected to three pins at the plug as shown in figure 6.7 (a). The three-pin plug connects the appliance to a power source through the socket, shown in figure 6.7 (b).

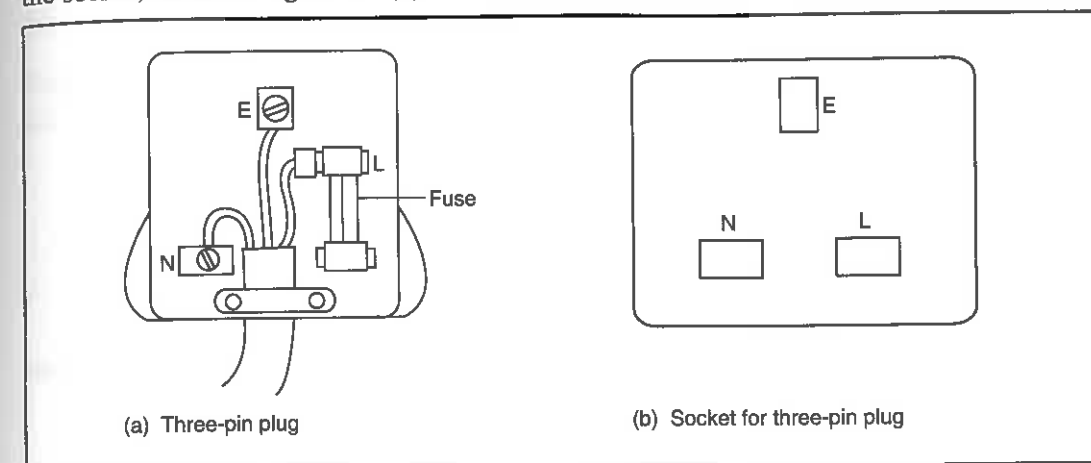


Fig. 6.7: Three-pin plug and socket outlet

A fuse is used in the plug to safeguard the appliance from damage due to excessive current in the circuit. The rating of the fuse used depends on the operating current of the appliance. The value of the chosen fuse should always be slightly above the value of the operating current of the appliance. The common values are 2 A, 5 A and 13 A.

For an appliance operating at 4 A, the most appropriate fuse would be the 5 A one while the 13 A fuse would be suitable for an appliance operating at 11 A.

Example 3

A house has a lighting circuit operated from the 240 V mains. Ten bulbs rated at 100 W 240 V are switched on at the same time. What is the most suitable fuse for this circuit?

Solution

$$P = VI$$

$$I = \frac{10P}{V}$$

$$= \frac{10 \times 100}{240}$$

$$= 4.16 \text{ A}$$

Hence, the suitable face for the circuit is a 5 A fuse

Electrical Energy Consumption and Costing

The Kilowatt-hour (kWh)

Commercial companies charge for electrical energy supplied to consumers. The amount of energy used by the consumer depends on the power rating of the appliances used and the time for which they have been in use.

Energy = power $\times$ time

The S.I. unit of energy is the joule. This unit is too small for measuring the large amounts of electrical energy used in homes. The unit for costing of electrical energy is the kilowatt-hour (kWh). The kilowatt-hour is the electrical energy spent in 1 hour at the rate of $1\,000\text{ Js}^{-1}$ (watts).

Recall;

$$1\text{ watt} = 1\text{ Js}^{-1}$$

$$1\text{ kilowatt} = 1\,000\text{ Js}^{-1} \\ = 1\,000\text{ W}$$

Total energy spent = power $\times$ time

$$\therefore 1\text{ kilowatt-hour} = 1\,000\text{ Js}^{-1} \times 1\text{ hour} \\ = 1\,000\text{ Js}^{-1} \times (60 \times 60)\text{ s} \\ = 3.6 \times 10^6\text{ J (3.6 MJ)}$$

Example 4

A consumer has the following appliances operating in his house for the times indicated in one day:

Appliance	Time
Two 40 W bulbs	30 min
One 500 W fridge	10 hrs
Four 75 W bulbs	3 hrs
One 3 kW electrical heater	45 min
One 100 W television	5 hrs

Calculate:

- the total power of the appliances used.
- the total electrical power consumed in kWh in 30 days, assuming that the power consumption per day is the same.

Solution

$$(a) \text{ Total power} = (2 \times 40) + (1 \times 500) + (4 \times 75) + (1 \times 3000) + (1 \times 100) \\ = 3\,980\text{ W}$$

- Total energy consumed in one day equals sum of energy consumed by each appliance.

$$\text{Two 40 W bulbs for 30 minutes: } 2 \times \frac{40}{1\,000} \times \frac{30}{60} = 0.04\text{ kWh}$$

$$\text{One 500 W fridge for 10 hours: } 1 \times \frac{500}{1\,000} \times 10 = 5\text{ kWh}$$

$$\text{Four 75 W bulbs for 3 hours: } 4 \times \frac{75}{1\,000} \times 3 = 0.90\text{ kWh}$$

$$\text{One 3 kW heater for 45 minutes: } 1 \times 3 \times \frac{45}{60} = 2.25\text{ kWh}$$

$$\text{One 100 W television for 5 hours: } 1 \times \frac{100}{1\,000} \times 5 = 0.50\text{ kWh}$$

$$\text{Total energy consumed in one day} = 8.69\text{ kWh}$$

$$\text{Hence, the electrical energy used in 30 days} = 8.69 \times 30 \\ = 260.7\text{ kWh}$$

Example 5

A house has five rooms with 240 W, 60 W bulbs. If the bulbs are switched on from 7.00 p.m. to 10.30 p.m.:

- calculate the power consumed per day in kilowatt-hours.
- find the cost per week for lighting these rooms at Ksh 6.70 per unit.

Solution

$$(a) \text{ Energy spent per second} = 60\text{ W} \times 5 \\ = 300\text{ W} \\ = 300\text{ Js}^{-1}$$

$$\text{Energy spent per evening} = 300 \times 3.5 \times 60 \times 60$$

$$\text{Energy spent in 7 days} = 300 \times 3.5 \times 60 \times 60 \times 7$$

$$\text{Number of kilowatt-hours per week} = \frac{300 \times 60 \times 60 \times 3.5 \times 7}{3.6 \times 10^6} \\ = 7.35\text{ kWh}$$

Alternatively;

$$\text{Power consumed by five 60 W bulbs} = 60 \times 5 \\ = 300\text{ W} \\ = 0.3\text{ kW}$$

$$\text{Power consumed per day} = 0.3 \times 3.5 \\ = 1.05\text{ kWh}$$

$$(b) \text{ Power consumed in 7 days} = 1.05 \times 7 \\ = 7.35\text{ kWh}$$

$$\text{Cost per week} = \text{No. of kilowatt-hours} \times \text{cost per kWh} \\ = 7.35 \times 6.70 \\ = \text{sh. } 49.25$$

Example 6

An immersion heater rated 3 000 W is used continuously for 45 min per hour per day. Calculate the cost per week at Ksh 6.70 per unit.

$$\text{Number of kW} = \frac{3\,000}{1\,000} \\ = 3.0\text{ kW}$$

$$\text{Number of kWh per day} = 3.0\text{ kW} \times \frac{3}{4} \times 1 \times 24$$

$$\text{Number of kWh per week} = 3.0 \times \frac{3}{4} \times 24 \times 7 \\ = 378\text{ kWh}$$

$$\text{Cost per week} = 378 \times 6.70 \\ = \text{sh. } 2\,532.60$$

Example 7

27 kg of water in a metal cylinder of heat capacity $9\,000\text{ JK}^{-1}$ is heated from 20°C to 90°C using an immersion heater rated 1.8 kW, 240 V. Assuming that no heat is lost to the surroundings and the immersion heater works at its correct voltage, find:

- the current flowing through the heater.

- (b) the time taken to heat the water from 20 °C to 90 °C.
 (c) the cost of heating the water from 20 °C to 90 °C, if electricity cost sh. 6.70 per unit.
 (Take specific heat capacity of water $c = 4.2 \text{ kJkg}^{-1} \text{ K}^{-1}$)

Solution

(a) $P = VI$

$$1\,800 = 240 \times I$$

$$\therefore I = \frac{1\,800}{240}$$

$$= 7.5 \text{ A}$$

(b) Total heat supplied = total heat gained

So, $P \times t = m_w c_w \theta + C_c \theta$, where P is the power of the heater, m_w the mass of the water, c_w specific heat capacity of the water, C_c the heat capacity of the cylinder and θ the change in temperature.

$$1\,800 \times t = 27 \times 4\,200 \times 70 + 9\,000 \times 70$$

$$= 7\,938\,000 + 630\,000$$

$$= 8\,568\,000 \text{ J}$$

$$\therefore t = \frac{8\,568\,000}{1\,800}$$

$$= 4\,760 \text{ sec}$$

$$\text{Time taken to heat the water in hours} = \frac{4\,760}{3\,600}$$

$$= 1.32 \text{ hrs}$$

$$\therefore \text{Electricity consumed in kWh} = 1.8 \times 1.32$$

$$= 2.376 \text{ kWh}$$

$$\text{Thus, the cost of electricity} = \text{rate} \times \text{units}$$

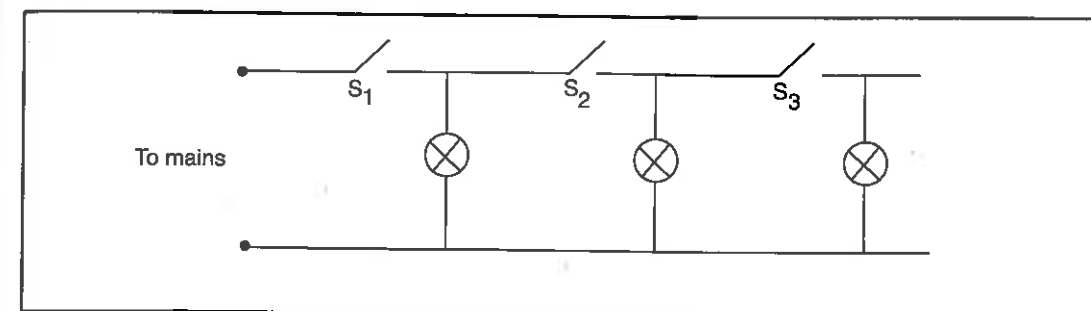
$$= 6.70 \times 2.376$$

$$= \text{sh. } 15.92$$

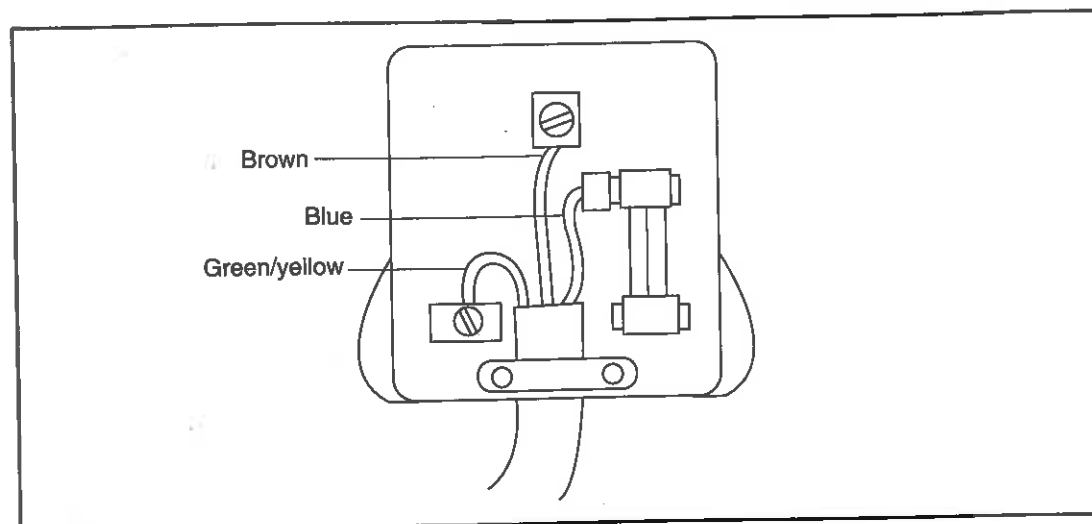
Revision Exercise 6

- Why are power transmission wires carrying power from the generating stations to long distance consumers referred to as the national grid?
 - Explain why long distance power transmission is done at a very high voltage.
 - How are the high voltages required during power transmission attained?
 - Draw block diagram of a power transmission line from the generating station to the final consumer, showing the values of the voltages suitable at each stage:
- A generator which produces 150 kW is connected to a factory by a cable which has a total resistance of 7.5Ω .
 - Find the potential difference at which the generator produces power if the maximum current in the cable is 10 A.
 - Determine the maximum power available to the factory.
- In what form is energy lost in a cable during transmission?
 - Calculate the power lost in a 100 km cable which has a resistance of $2.0 \times 10^{-3} \Omega$ per metre in the transmission of 100 kilowatts through it at:
 - 10 kV.
 - 33 kV.

- Describe briefly the features of a domestic electric wiring system which help to make the system safe, making clear the advantage of each feature.
 - A 75 W lamp and 1.5 kW water heater are connected in turn to a 240 V supply. Calculate:
 - the current which flows through each appliance.
 - the resistance of each appliance when in use.
 - Explain the difference you would expect to find between the wiring used to connect the bulb and the water heater to the mains supply.
- The figure below shows an attempt to supply each of the three lamps L_1 , L_2 and L_3 with a switch.



- Explain exhaustively why this is a poor connection.
 - Re-draw the diagram to show the best positioning for the switches.
 - Why is (b) above considered the best arrangement?
- What is the use of a fuse in an electric circuit?
 - How is the choice of the right fuse for a particular appliance made?
 - Explain why it is not advisable to use 10 A fuse for a hair drier rated at a 2.5 kW, 240 V.
 - If a hairdresser intending to use 7 A fuse for the device (c) above sought your advice, what would you tell her and why?
 - With the aid of a circuit diagram, explain how two-way switch works.
 - Where would this kind of switch be useful in a house?
 - Suppose in your home there are the following appliances, a cooker (6 kW), a kettle (2.4 kW) and a television (120 W). What fuse would be required for each appliance? Show how you arrived at your answers (mains potential is 240 V). Fuses available are 35 A, 30 A, 15 A, 13 A, 10 A, 3 A and 1 A.
 - A generator produces 100 kW which is transmitted through a cable of resistance 5 ohms. If the potential difference produced is 5 000 V:
 - what current is transmitted?
 - what power is received by the consumer?
 - The figure below shows a connection to the three-pin plug.



- (a) Identify the mistakes in this wiring.
 - (b) What would happen if this plug was connected to the mains of the socket?
 - (c) Why is the earth pin normally longer than the other two pins?
11. The cost of electricity in a region is sh. 6.70 per kWh.
- (a) What would be the total monthly consumption for a household that uses the following appliances:
 - (i) a 1.5 kW water heater for 1 hour per day,
 - (ii) a 100 W light bulb for 30 days at 12 hours per day, and,
 - (iii) a fan of resistance 24 ohms connected to a 240 V supply for 30 days at 2 hours per day?
 - (b) The above connection was made by the household in one month. Find the total monthly bill for this household if, in addition to the energy consumed, the power company charges each consumer:
 - (i) a monthly standing charge of sh. 150.00.
 - (ii) a fuel cost levy of 50 cents per kWh consumed.
 - (iii) a foreign exchange levy of 40 cts per kWh.
 - (iv) a value added tax of 16 % of the monthly energy consumption.

CATHODE RAYS AND CATHODE RAY TUBE

When a metal is heated to very high temperature, electrons may be emitted from its surface. This is because the electrons gain enough energy to enable them to break loose from the force of attraction of the nuclei. The process of emission of electrons due to heat energy is referred to as **thermionic emission**.

Thermionic Emission

The circuit in figure 7.1 can be used to demonstrate thermionic emission. The evacuated glass bulb has a cathode, which is made of a mixture of metal oxides (barium and strontium oxides) of low work function (discussed in chapter nine) and an anode on the other end.

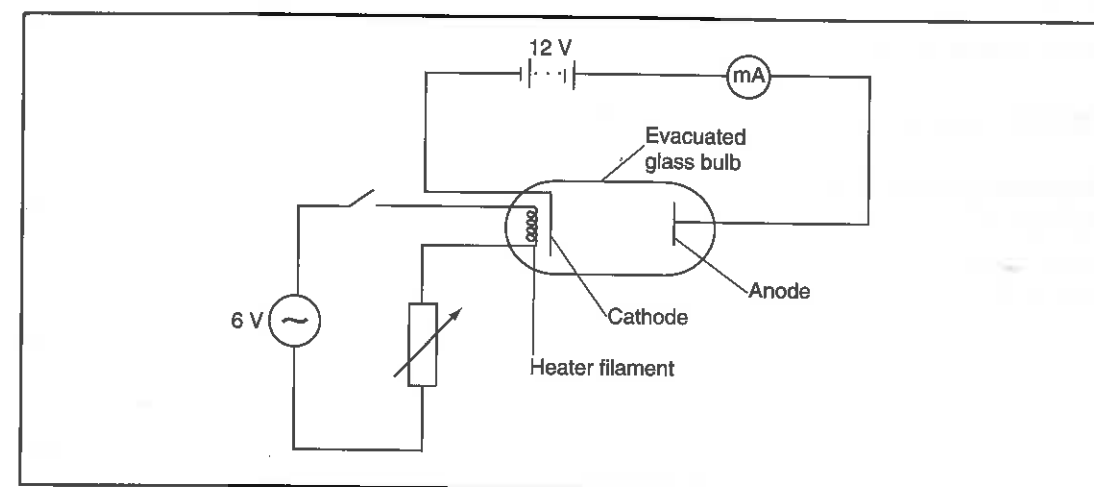


Fig. 7.1: Thermionic emission

A low voltage of about 6 V drives a current through the heater filament, which in turn heats the cathode.

Before the heater current is switched on, no current is registered. When the heater circuit is switched on and the current gradually increased, some current is now registered in the milliammeter. The hot cathode emits electrons, which are attracted by the anode, thus completing the gap between the electrodes.

Production of Cathode Rays

Cathode rays are streams of electrons moving from the cathode to the anode. They are produced in a cathode ray tube (CRT). The electrons produced at the cathode by thermionic emission are accelerated towards the fluorescent screen by an anode, which is connected to the positive terminal of an extra high tension (EHT) source, see figure 7.2. The tube is evacuated to prevent electrons from interacting with any particles before reacting the screen.

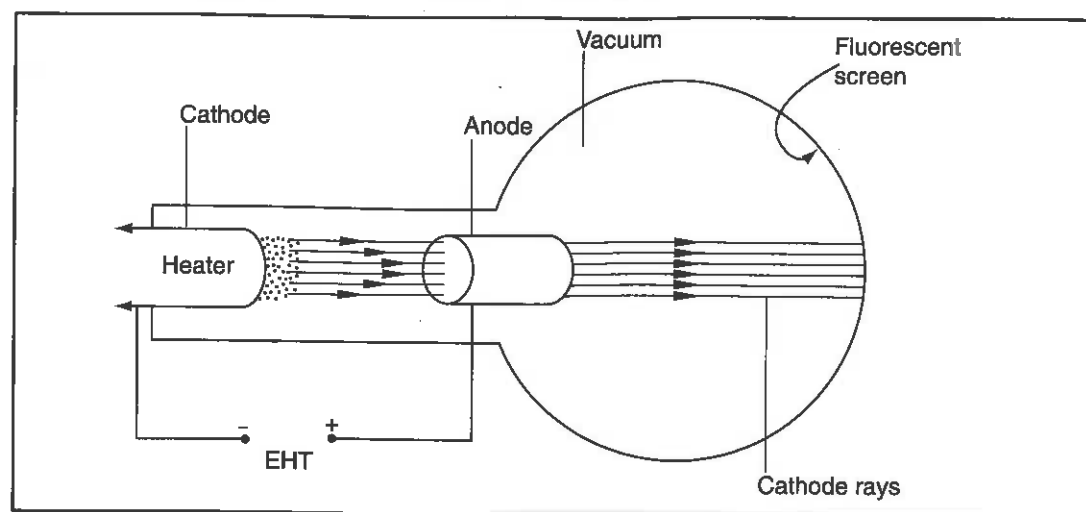


Fig. 7.2: Cathode ray tube

When the cathode rays hit the screen, it glows.

Properties of Cathode Rays

They travel in straight lines

Figure 7.3 shows an opaque object (Maltese cross) placed between the screen and the cathode in the path of the cathode rays. A sharp shadow of the object is cast on the screen.

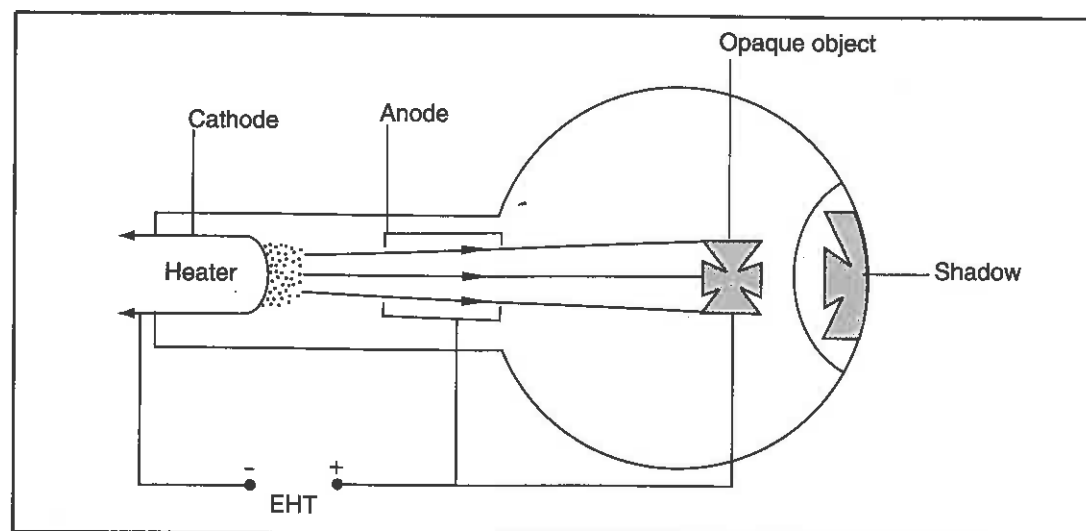


Fig. 7.3: Formation of shadow with cathode rays

They cause certain substances to glow or fluoresce

When an electron beam hits phosphor, e.g., zinc sulphide screen, it glows.

They are charged

They are deflected by both magnetic and electric fields. In figure 7.4 (a), the cathode ray tube is placed in an electric field.

The cathode rays are deflected towards the positive plate. This shows that they are negatively charged. In figure 7.4 (b), the cathode rays are made to pass through a magnetic field. The deflection is determined by Fleming's left-hand rule and confirms further that they are negatively charged.

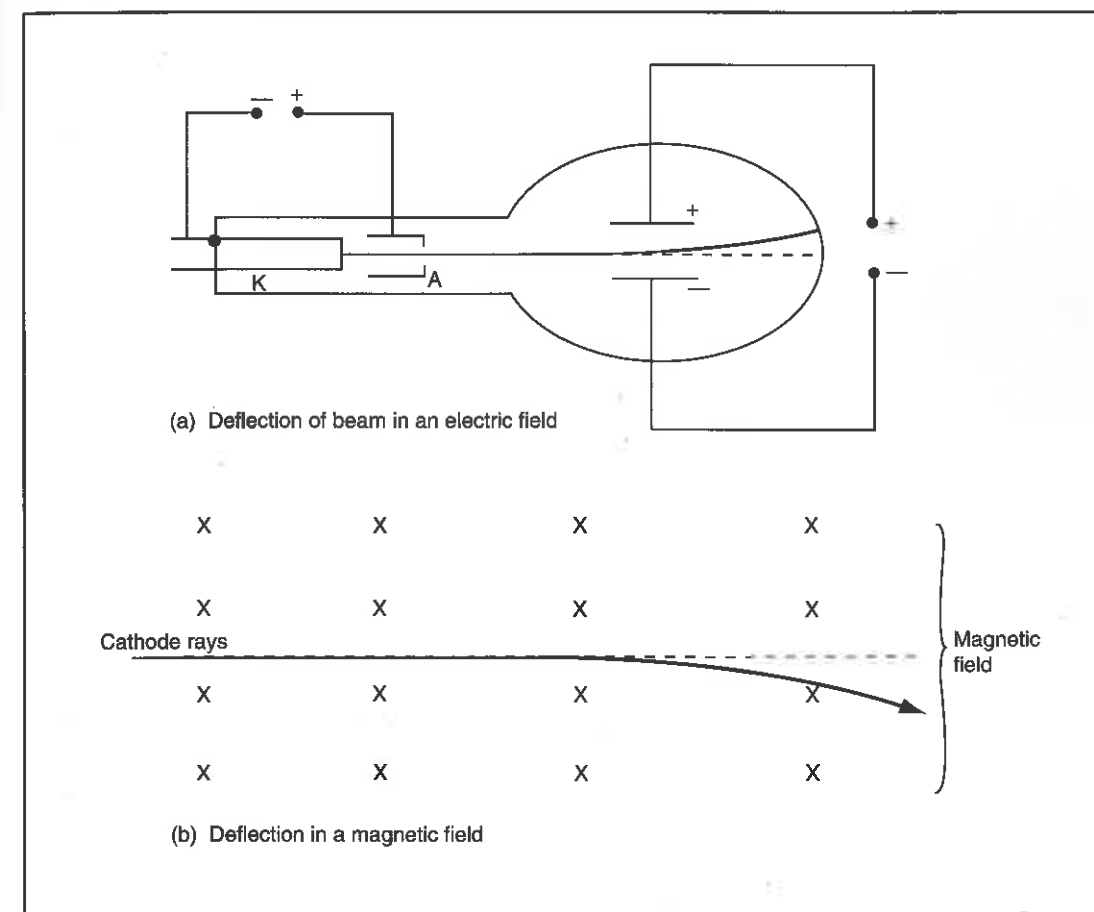


Fig. 7.4: Deflection in electric and magnetic fields

They possess kinetic energy

They can produce X-rays when suddenly stopped by a metal target

The above properties confirm that cathode rays are actually a stream of fast moving electrons.

Cathode Ray Oscilloscope

The cathode ray oscilloscope (CRO) is a development of the cathode ray tube.

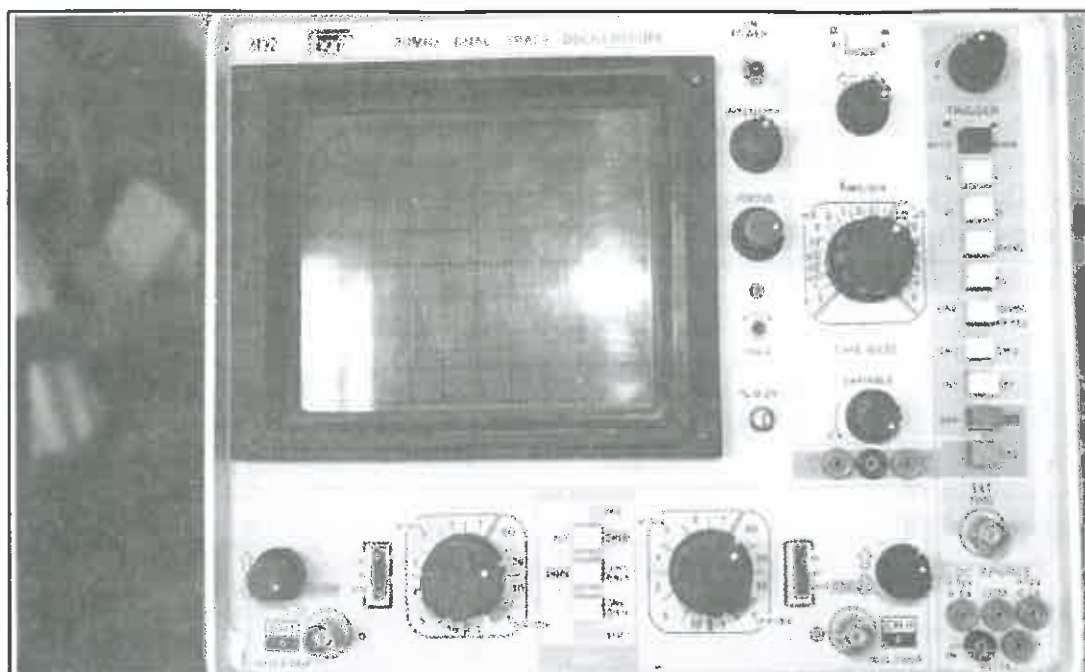


Fig. 7.5: Cathode ray oscilloscope

It consists of the following parts:

- (i) The electron gun.
 - (ii) A system of plates for deflecting the electron beam.
 - (iii) An evacuated strong glass envelope.
 - (iv) A fluorescent screen at one end of the glass envelope.
- Figure 7.6 shows the main parts of the cathode ray oscilloscope.

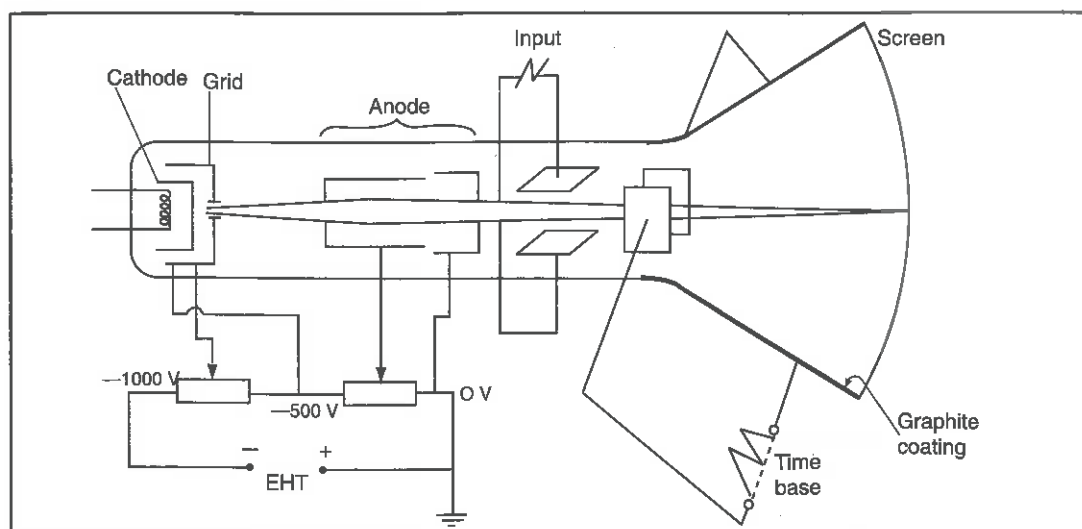


Fig. 7.6: Parts of the cathode ray oscilloscope

The Electron Gun

The purpose of the gun is to supply electrons, accelerate them towards the screen and focus the beam to a point on the screen.

It consists of a heated cathode, a grid to control the rate of flow of electrons and anodes to accelerate and focus the electron beam. Each of the parts is maintained at a d.c. potential from EHT source and a potential divider, as shown in figure 7.7.

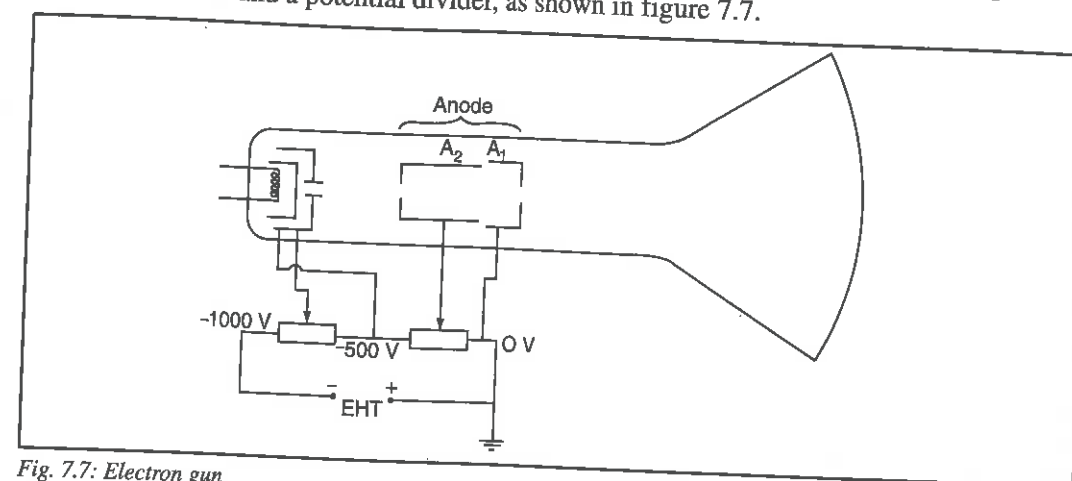


Fig. 7.7: Electron gun

The cathode is coated with oxides of thorium or strontium, preferred for their low work function. The anodes consist of cylinders and discs maintained at high positive potential relative to the cathode. They therefore attract the emitted electrons and eventually direct them to the screen.

Focusing the Beam

Anodes A_2 and A_1 are at different potentials, that of A_1 being higher. There is therefore an electric field between them. The direction of this field is such as to converge the diverging beam from the cathode as it leaves the aperture of anode A_1 , as illustrated in figure 7.8.

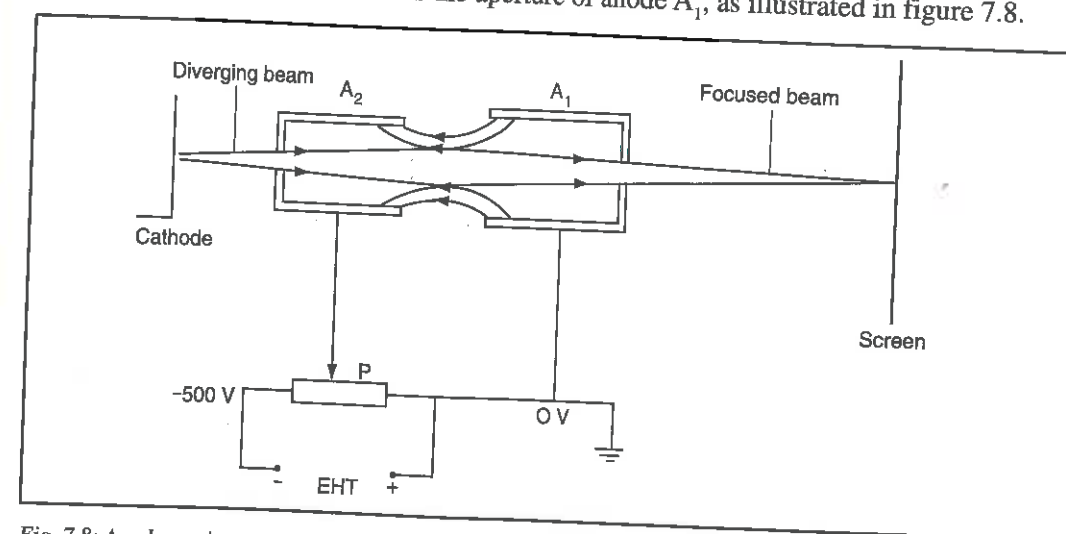


Fig. 7.8: Anodes acting as an electronic lens

The greater the potential difference between the anodes A_1 and A_2 , the greater the electric field intensity and therefore the greater the degree of focusing. This p.d. can be varied at P to produce the desired degree of focusing. This potential divider is the focusing knob on the control panel.

The Grid

The cathode is surrounded by a hollow cylinder, the grid, which has a small hole at the end, see figure 7.6. This cylinder is at a small negative potential relative to the cathode. It is used to control the intensity of the beam in that when the grid is made less negative, more electrons cross over and when made more negative, the number of electrons crossing over to the screen is cut down. The grid therefore controls the intensity of the beam and hence the brightness of the spot on the screen. The brightness knob controls a potential divider, which varies the p.d. between the grid and the cathode.

Deflection System

Vertical Deflection

Figure 7.9 shows the effect of electric field on the beam. When the beam passes between uncharged horizontal plates, it strikes the screen at A. The beam is therefore not deflected. When the switch is closed, the plates become charged and the beam is attracted towards the positive plate Y_2 . It is deflected to hit the screen at B.

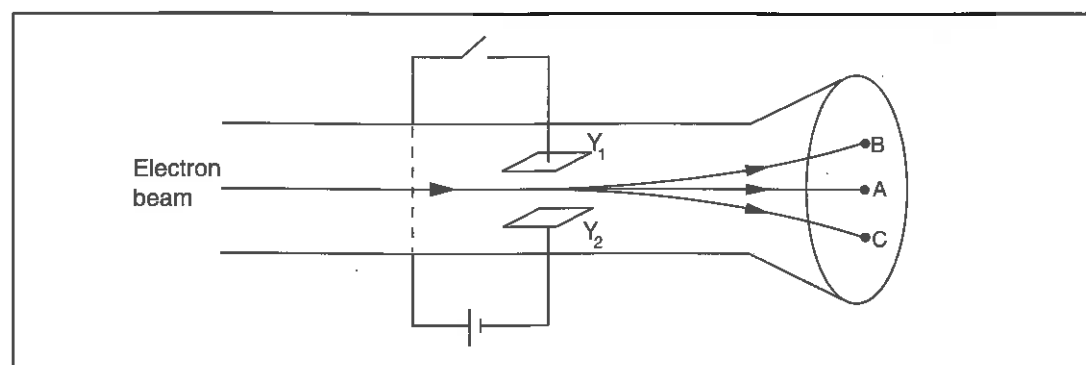


Fig. 7.9: Vertical deflection

If the polarity of the plates is reversed, the spot will shift to C through A. If the reversals of the polarity are sustained, the spot will shift from B to C and back at the frequency of the reversals. With an alternating voltage, the spot moves up and down in accordance with the instantaneous voltage at the frequency of the a.c. If the frequency is high enough, a vertical line is observed rather than moving spot, due to persistence of vision. Since the plates cause deflection in the vertical direction, they are called Y-plates.

The signal is fed in through the Y input terminal.

Horizontal Deflection

When plates are arranged as in figure 7.10, the beam of electrons is deflected horizontally across the screen from point M to N and back, as the polarities are reversed. Since the deflection is horizontal, the plates are referred to as X-plates.

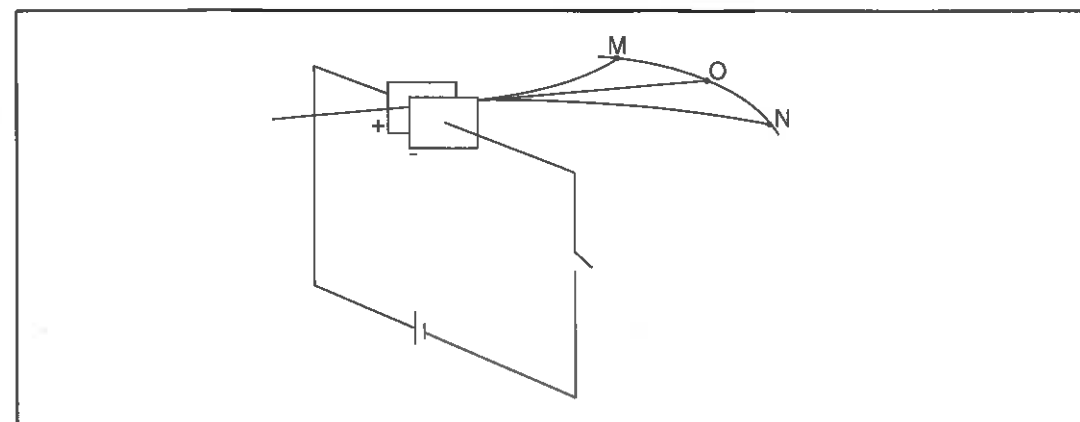


Fig. 7.10: Horizontal deflection

In the CRO, a voltage varying as in figure 7.11 is applied to the X-plates from a special circuit known as the **time base**.

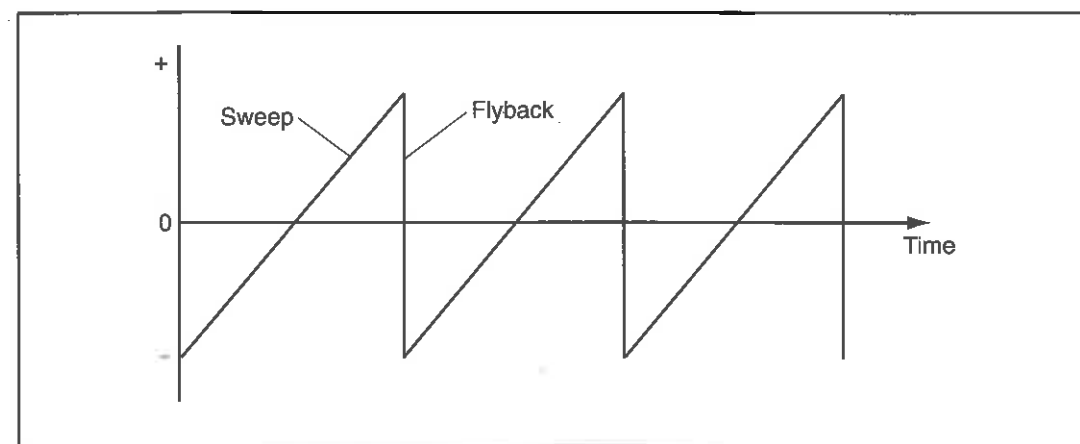


Fig. 7.11: The time base circuit

The voltage increases uniformly to a peak (sweep) and then drops suddenly (flyback). As the voltage rises, the spot moves horizontally at a uniform speed until the peak voltage is reached. The time base voltage then drops suddenly to a maximum negative value, this causing the spot to fly back to the starting point at the other end of the screen. The voltage builds up again and the process is repeated in subsequent cycles.

The sweep of the spot across the screen can be adjusted using the **time base control** knob which operates the frequency of the time base voltage. The higher the frequency, the shorter the time of sweep. Typical values are 10 ms/cm and 100 ms/cm.

When the time of sweep is long (low time base frequency), the spot moves slowly across the screen, see figure 7.12 (a). The eye can follow the spot as it crosses the screen. If the frequency is now raised to reduce time of sweep to, say 10 ms/cm, the movement of the spot gives a permanent trace of a horizontal line across the screen, see figure 7.12 (b).

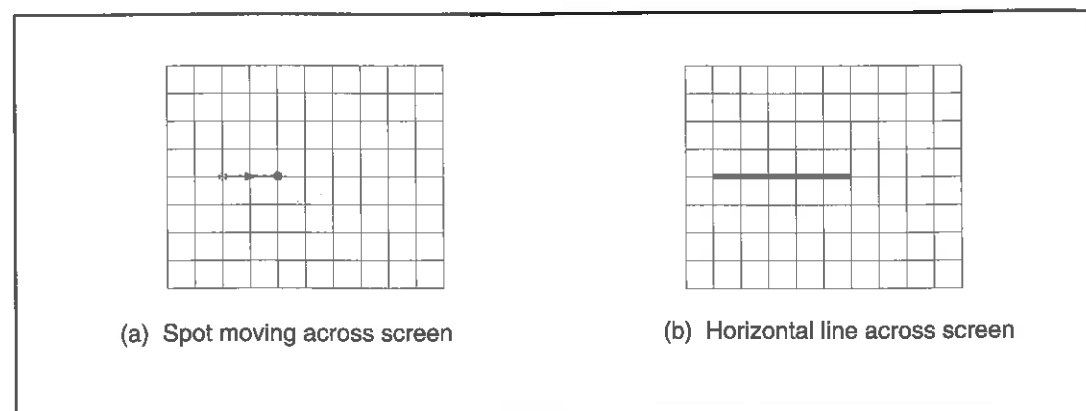


Fig. 7.12: Settings of the time base

Simultaneous application of the input voltage at the Y-plates and the time base voltage leads to the movement of the spot on the screen in two dimensions, producing two-dimensional image of the input voltage on the screen. Figure 7.13 shows the image formed on the screen when an a.c. signal is applied across the Y-plates with the time base on.

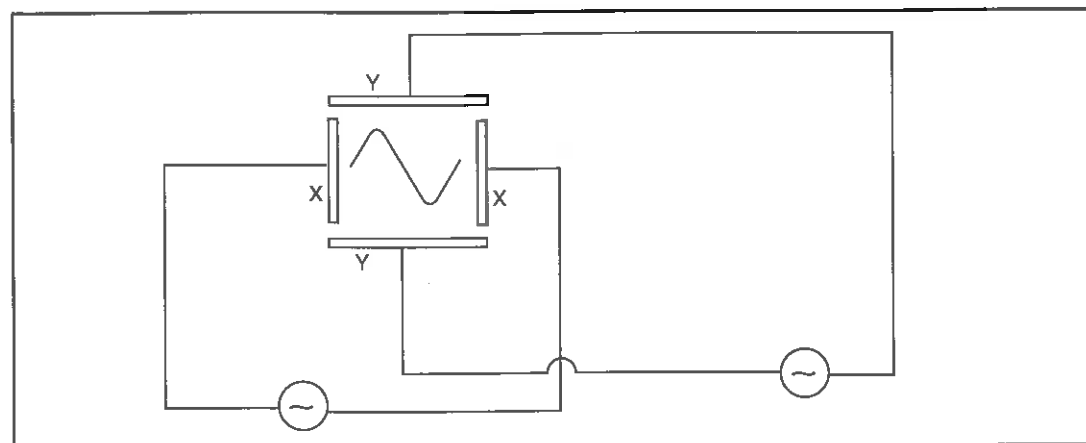


Fig. 7.13: Simultaneous application of a.c. at Y-plates and time base at X-plates

The Screen

The screen is coated with a fluorescent substance (such as zinc sulphide) called a phosphor. This glows on impact with electrons. It has a persistence of about 0.05 s, i.e., it continues to glow even after the beam has passed the point of impact. This, plus the natural persistence of vision of the eye, makes a waveform to be observed on the screen.

The inside of the tube is coated with graphite, which has three functions:

- Conduction of electrons to earth.
- Shielding the beam from external electric fields.
- Accelerating the electrons towards the screen, since it is at the same potential (ground) as the anode.

Uses of the C.R.O.

C.R.O as a Voltmeter

The time base is switched off, the X-plates earthed and the voltage to be measured connected across the Y-plates. The vertical displacement of the spot on the screen is measured and the voltage determined using the formula;

$$\text{voltage} = \text{displacement} \times \text{sensitivity (volts per division)}$$

The level of sensitivity is selected using the Y-gain knob, which automatically connects the input signal through an amplification system. This ensures that even very weak signals are raised to the levels where they cause measurable deflection of the beam.

As a voltmeter, the C.R.O is advantageous over conventional meters because it:

- has infinite resistance and does not therefore take any current. It does not therefore interfere with the circuit to which it is connected.
- can measure both direct and alternating voltages.
- responds instantaneously, unlike ordinary meters whose pointers swing momentarily about the correct reading due to inertia.
- can measure large voltages without getting damaged.

Determining the Frequency of an a.c. Signal

The signal is fed into the Y-plates of a C.R.O. with the time base on. The time base control is then adjusted to give one or more cycles of the input signal on the screen, see figure 7.14.

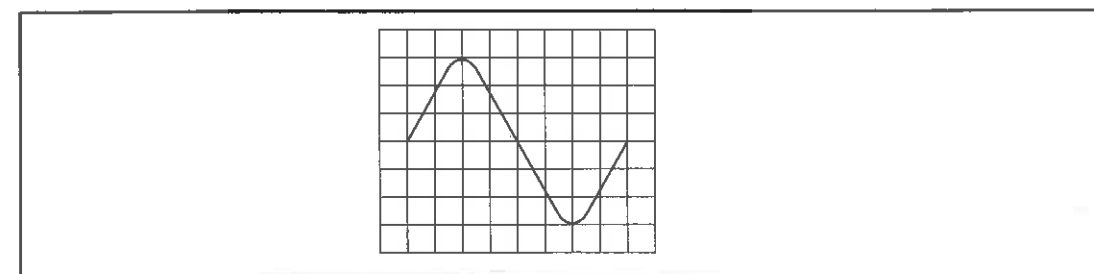


Fig. 7.14: Determining frequency of an a.c. signal

The time T of the signal is then determined by relating the trace of the signal on the screen with time base setting. The frequency f can then be calculated as $f = \frac{1}{T}$

Example 1

Given that in figure 7.14, the time base control is set at 10 ms/div, determine the frequency of the a.c. signal on the screen.

Solution

Time base setting = 10 ms/div

Number of cycles shown = 1

Number of divisions covered by 1 cycle = 8

Period $T = 8 \times 10$

= 80 ms

$$= 80 \times 10^{-3} \text{ s}$$

$$\begin{aligned} \text{Frequency} &= \frac{1}{80 \times 10^{-3}} \\ &= 12.5 \text{ Hz} \end{aligned}$$

Example 2

A d.c. voltage of 50 V when applied to the Y-plates of a C.R.O. causes a deflection of the spot on the screen as shown in figure 7.15.

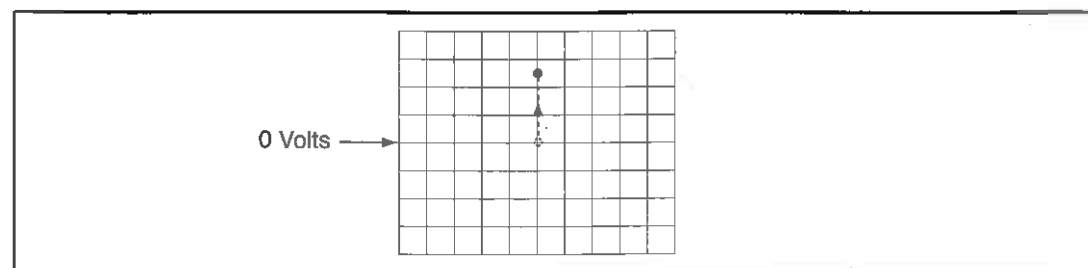


Fig. 7.15

- Determine the sensitivity of the Y-gain.
- Show what will be observed on the screen if an a.c. of peak voltage 40 V is fed onto the Y-plates.

Solution

- Spot deflection on the screen = 2.5 divisions.
Voltage = 50 V

$$\begin{aligned} \text{Sensitivity} &= \frac{\text{voltage}}{\text{number of divisions}} \\ &= \frac{50}{2.5} \\ &= 20 \text{ V/div} \end{aligned}$$

- Peak voltage = 40 V
Y-gain = 20 V/div

$$\begin{aligned} \text{Number of divisions} &= \frac{\text{voltage}}{\text{Y-gain}} = \frac{40}{20} \\ &= 2 \text{ divisions} \end{aligned}$$

Voltage is a.c., hence ± 2 divisions from zero.

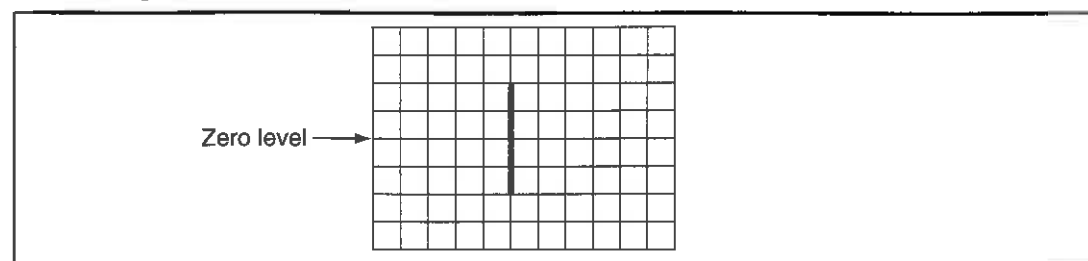


Fig. 7.16: Corresponding trace on the screen

Example 3

Figure 7.17 shows the trace on the screen of an a.c. signal connected to the Y-plates of a CRO with time base on.

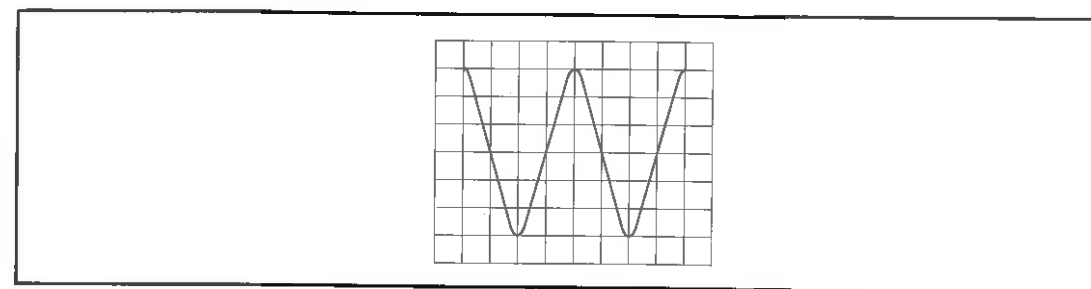


Fig. 7.17

Given that the time base control is 5 ms/div and the Y-gain is at 100 V/div, determine:

- the frequency of the a.c. signal.
- the peak voltage of the input signal.

Solution

- Time base control = 5 ms/div
Number of divisions covered = 8
Total time = 8×5
= 40 ms
Total number of cycles = 2

$$\begin{aligned} \text{Time per cycle (periodic time } T) &= \frac{40}{2} \\ &= 20 \text{ ms} \end{aligned}$$

$$\begin{aligned} \text{Frequency} &= \frac{1}{20 \times 10^{-3}} \\ &= 50 \text{ Hz} \end{aligned}$$

- Y-gain = 100 V/div
Deflection = 3 div from zero level
Peak voltage = Y-gain $\times$ number of divisions
= 100×3
= 300 V

The Television Tube

The television tube is a cathode ray tube with the following modifications:

The deflection of the spot is by magnetic coils

These are positioned in pairs to effect vertical and horizontal deflections of the beam, see figure 7.18.

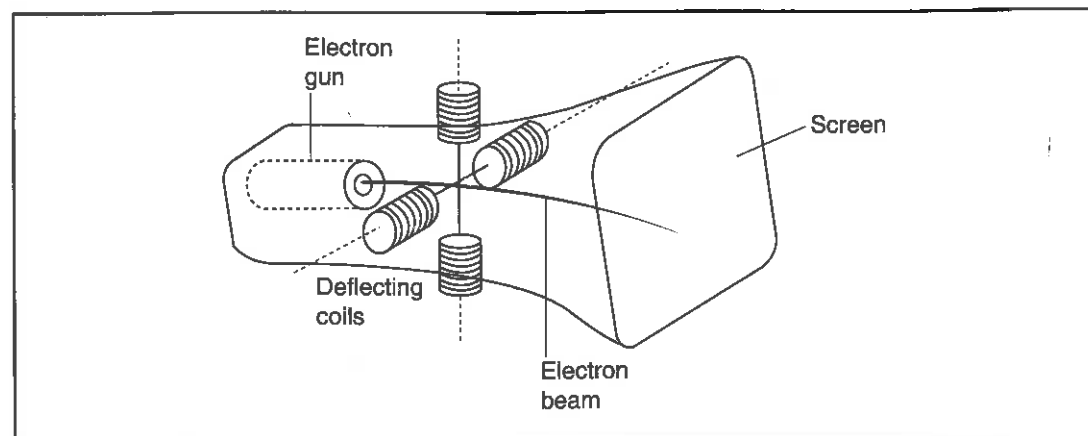


Fig. 7.18: Deflection coils in the TV tube

Magnetic fields are preferred to electric fields as they give a wider deflection of the beam. This makes it possible to work with a wide screen with a relatively short tube.

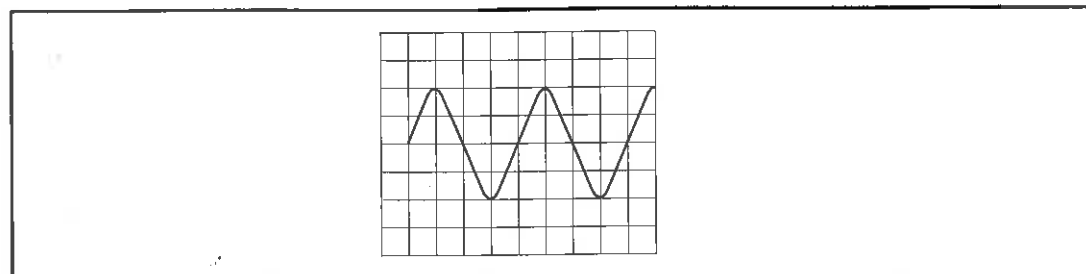
The Incoming signal from the aerial is fed into the grid

This effects variations on the intensity of the beam as it sweeps across the screen. Dots of varying brightness in successive lines build up the image on the screen. Since this occurs at very high frequency, there is persistence of vision which gives an impression of a steady picture.

A colour television has three electron guns, each carrying the color detail of one of the three primary colours (red, green and blue). The screen has a matrix of different colour emitting phosphor dots such that when they are stimulated, they give the coloured pictures.

Revision Exercise 7

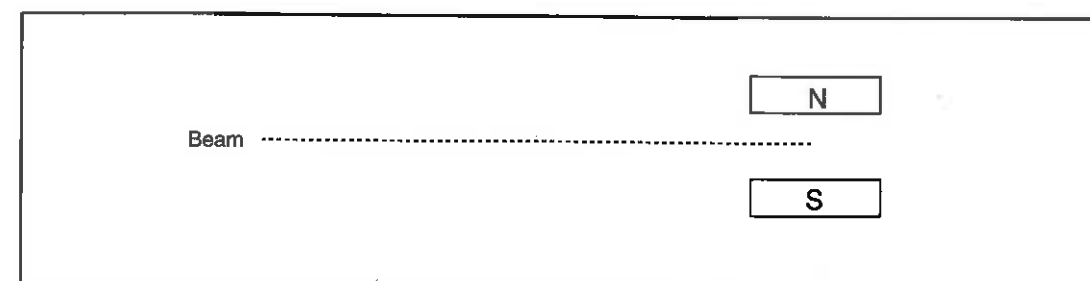
1. With the aid of a diagram, explain how cathode rays are produced in the cathode ray tube.
2. The figure below is a display of an a.c. signal on the CRO screen:



Determine the frequency, given that the time base setting is 200 ms/div.

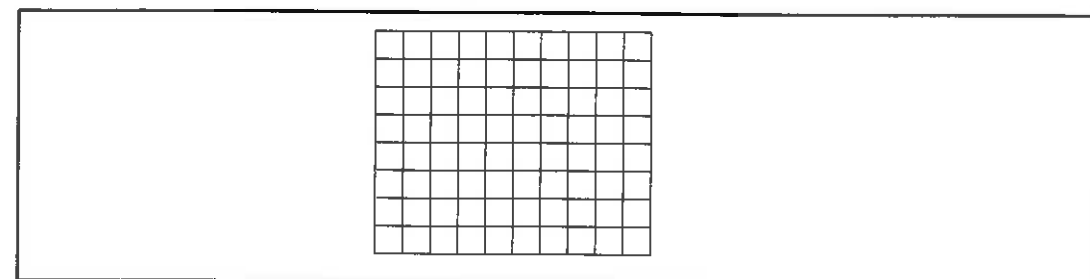
3. Explain why the CRO is a more accurate device as voltmeter than the moving-coil meter.
4. What is meant by thermionic emission?

5. Explain why heated cathodes are coated with oxides of such metals as barium, strontium or thorium.
6. With the aid of a diagram, illustrate how cathode rays are deflected by electric fields.
7. What is the use of the grid in the electron gun of a CRT?
8. Draw a diagram to show the essential features of a CRO and use it to explain how:
 - (a) electrons are produced.
 - (b) electrons are accelerated.
 - (c) the beam of electrons is focused.
 - (d) the brightness of the spot is controlled.
9. Briefly explain the properties of cathode rays.
10. The figure below represents a cathode ray beam passing between pole pieces of a permanent magnet:



Describe the path followed by the electrons and give reasons for your answer.

11. On the grid provided below, show the display on the CRO screen of an a.c. signal, peak voltage 300 V and frequency 50 Hz when the time base is on. (Take: Y-gain at 100 V/div, time base setting at 10 ms/div).



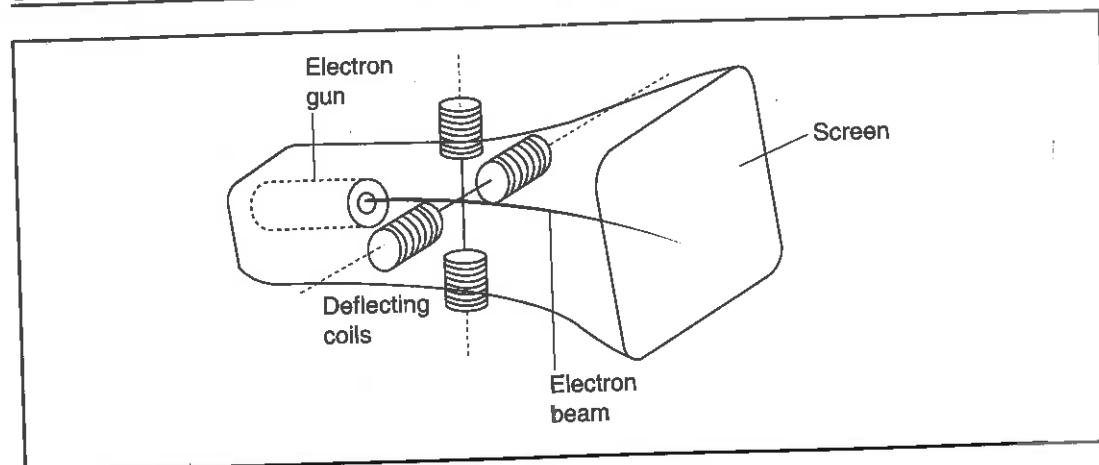


Fig. 7.18: Deflection coils in the TV tube

Magnetic fields are preferred to electric fields as they give a wider deflection of the beam. This makes it possible to work with a wide screen with a relatively short tube.

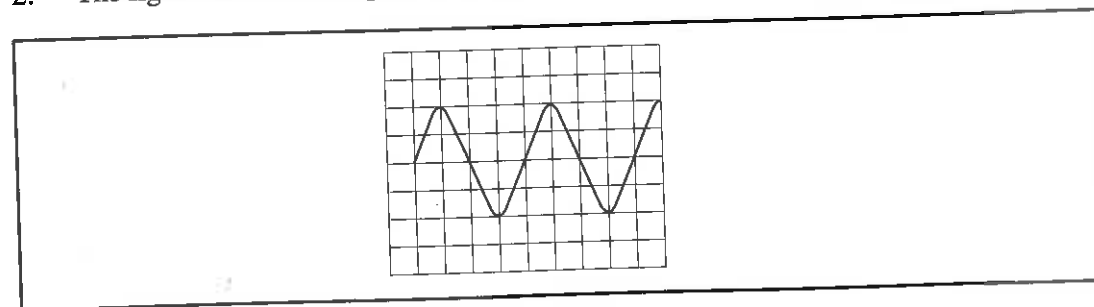
The Incoming signal from the aerial is fed into the grid

This effects variations on the intensity of the beam as it sweeps across the screen. Dots of varying brightness in successive lines build up the image on the screen. Since this occurs at very high frequency, there is persistence of vision which gives an impression of a steady picture.

A colour television has three electron guns, each carrying the color detail of one of the three primary colours (red, green and blue). The screen has a matrix of different colour emitting phosphor dots such that when they are stimulated, they give the coloured pictures.

Revision Exercise 7

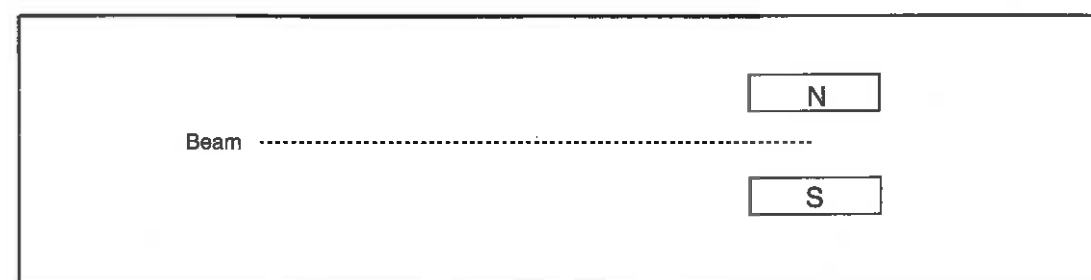
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- The figure below is a display of an a.c. signal on the CRO screen:



Determine the frequency, given that the time base setting is 200 ms/div.

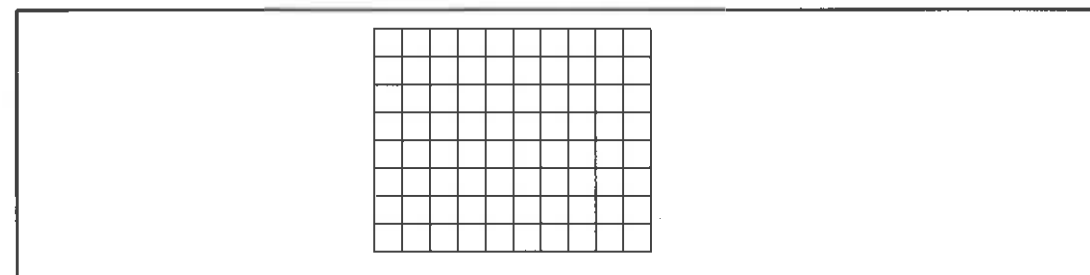
- Explain why the CRO is a more accurate device as voltmeter than the moving-coil meter.
- What is meant by thermionic emission?

- Explain why heated cathodes are coated with oxides of such metals as barium, strontium or thorium.
- With the aid of a diagram, illustrate how cathode rays are deflected by electric fields.
- What is the use of the grid in the electron gun of a CRT?
- Draw a diagram to show the essential features of a CRO and use it to explain how:
 - electrons are produced.
 - electrons are accelerated.
 - the beam of electrons is focused.
 - the brightness of the spot is controlled.
- Briefly explain the properties of cathode rays.
- The figure below represents a cathode ray beam passing between pole pieces of a permanent magnet:



Describe the path followed by the electrons and give reasons for your answer.

- On the grid provided below, show the display on the CRO screen of an a.c. signal, peak voltage 300 V and frequency 50 Hz when the time base is on. (Take: Y-gain at 100 V/div, time base setting at 10 ms/div).



moving electrons as a result of a high accelerating voltage. They have very short wavelength and thus high penetrating power. They can penetrate the flesh, but are absorbed by bones.

Soft X-rays are produced by electrons moving at relatively lower velocities than those that produce hard X-rays. They have less energy, longer wavelengths, hence less penetrating power compared to hard X-rays. They are used to show malignant growth in tissues, since they only penetrate soft flesh but are absorbed by such growths.

Intensity (Quantity) of X-rays

The intensity of X-rays is controlled by the heating current. The greater the heating current, the greater the number of electrons produced, hence the more the X-rays. The strength (quantity) of the X-rays will however remain the same. The strength of the X-rays depends on the speed of the electrons, which in turn depends on the accelerating potential difference between the cathode and the anode.

Uses of X-rays

In Medicine (Radiography and Radiotherapy)

X-rays are used in hospitals and medical research centres for diagnosis and treatment of diseases. The diagnosis involves a process called X-ray imaging, in which X-rays are allowed to cast a shadow onto a photographic film. Examination of the photographic film reveals the injury or the infection of the tissue. This is because of the difference in the absorption of X-rays by different tissues of the body. A broken limb, for example, when X-rayed will reveal the nature of the fracture on the bone.

Diagnosis of softer tissues such as the lungs, liver, spleen, the heart, kidneys and other internal organs with the conventional X-ray equipment are not accurate enough, hence special X-ray equipment is required. Computed tomography (CT) employs a special X-ray equipment and computer processing of image data taken from different angles around the body, to show cross-sections of body tissue and organs. CT imaging can show, with great clarity, several types of tissue, e.g., lung, bone, and blood vessels. This therefore makes it possible for radiologists to diagnose different cancers including those of the lung, liver and pancreas. CT imaging can also quickly reveal injuries to the liver, spleen, kidneys and other internal organs of people who have had accidents.

X-rays are also used for the treatment of tumours. In this regard, CT examinations are used to plan and properly administer radiation treatment for tumours.

Note:

During the X-ray photography, a point source of the X-rays is needed. This is because although X-rays travel in straight lines, unlike light they cannot be focused by lenses. For X-rays to produce shadows with sharp edges, the rays must come from a point source. The CT scan gives this readily.

X-rays are also used to detect foreign objects in the body, eg, safety pin if swallowed accidentally.

In Industry

X-rays are used to detect flaws in metal castings and welding. The radiation is also used to sterilise surgical equipment before packaging.

In Crystallography

X-rays are used to study the crystal structure of substances. The regular arrangement of atoms within a crystal produces diffraction effects when X-rays are passed through it. This is because a crystal has regularly arranged atomic planes which are very close together, making it act like a diffraction grating. The spacings of the planes are of the order of the wavelength of X-rays.

An analysis of the diffraction pattern can therefore reveal detailed information on the structure of the crystal.

Security, e.g., in Airports

X-rays are used to inspect luggage for any weapons that may be hidden in them, see figure 8.3.

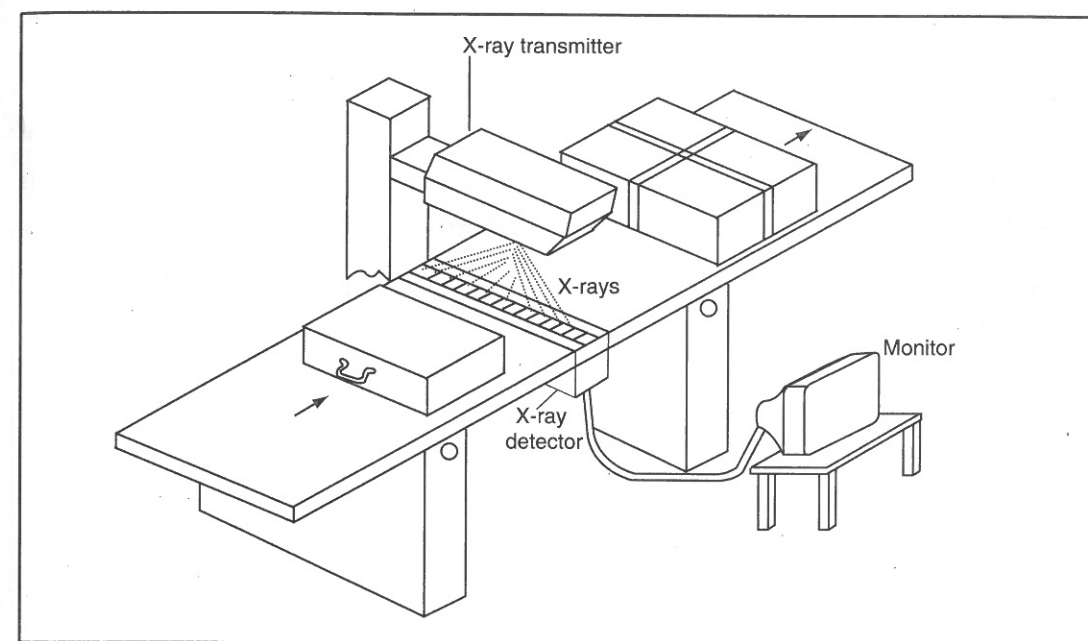


Fig. 8.3: X-rays used in airport security

Dangers of X-rays

Excessive exposure of living tissue to X-rays is dangerous as the radiations can damage or kill cells.

Since the effect of exposure is cumulative it is important that exposure be limited to as short periods, as necessary and as few times as possible in one's lifetime.

X-ray machines have a protective lead shield to protect the operators from stray radiation. The machines are operated in rooms that have concrete walls to absorb any leaking radiation.

Revision Exercise 8

Take electron mass = 9.1×10^{-31} kg, $e = 1.6 \times 10^{-19}$ C, $h = 6.63 \times 10^{-34}$ Js and $c = 3.0 \times 10^8$ ms $^{-1}$

1. (a) How are X-rays produced?
- (b) How can the intensity of an X-ray beam be increased?
- (c) State four uses of X-rays.
- (d) Distinguish between hard and soft X-rays.

2. (a) Why is it difficult to verify the wave nature of X-rays by refraction experiment?
 (b) What is the minimum possible wavelength of X-rays produced in an X-ray tube operating at 10 kV?
 (c) Calculate the energy gained in (b) above when the operating voltage is raised to 100 kV?
3. (a) State the features which facilitate efficient cooling of the anode during the operation of an X-ray tube. Briefly explain how they achieve cooling of the anode.
 (b) Briefly describe an experiment to show that X-rays are not charged particles.
4. (a) State three properties that confirm X-rays as part of the electromagnetic spectrum.
 (b) An X-ray tube operating at 50 kV has a tube current of 20 mA.
 (i) How many electrons are hitting the target per second?
 (ii) If only 0.5 % of the energy of the electrons is converted to X-rays, estimate the quantity of heat produced per second.
 (iii) Find the X-ray power output.
5. An X-ray tube operates at a potential of 80 kV. Only 0.5 % of the electron energy is converted to X-rays, while heat is generated at the anode at the rate of 100 Js^{-1} . Determine:
 (a) the tube current.
 (b) the average velocity of the electrons hitting the target.
 (c) the minimum wavelength of the X-rays.

Chapter Nine

PHOTOELECTRIC EFFECT

We have seen that a metal surface will, if provided with appropriate amount of heat energy, emit electrons. Radiations of appropriate strengths can also produce a similar effect.

When an electromagnetic radiation of sufficient frequency is radiated on a metal surface, electrons are emitted. These electrons are called **photoelectrons** and the phenomenon is known as **photoelectric effect**.

*EXPERIMENT 9.1: To demonstrate photoelectric effect**(a) Using Neutral Plates**Apparatus*

Ultraviolet lamp (mercury vapour lamp), two metal plates, power source, galvanometer, connecting wires, glass plate (barrier).

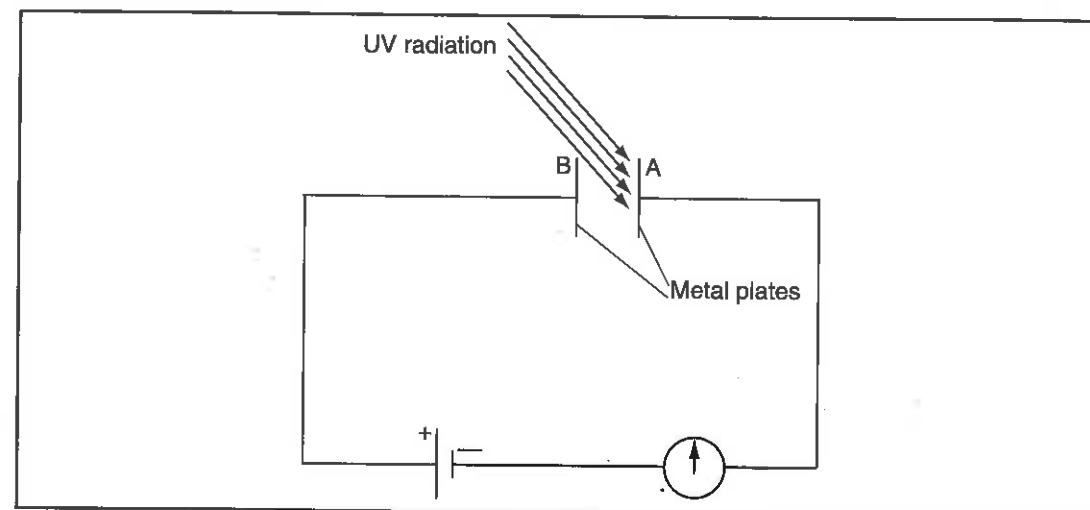


Fig. 9.1: Photoelectric effect

Procedure

- Set up the apparatus as shown in figure 9.1.
- Direct UV-radiation towards plate A. Observe what happens to the galvanometer.
- Place the glass barrier in between the source and plate A and again observe what happens.

Observation

When ultraviolet radiation is allowed to fall on metal plate A, the galvanometer shows deflection. When the barrier is introduced so that the radiation is cut off, the galvanometer shows no deflection.

Explanation

When ultraviolet radiation energy falls on a metal surface, some electrons absorb this energy and are dislodged from the surface. The deflection of the galvanometer indicates that electrons

are emitted at plate A and attracted by the plate B, causing a current to flow.

The glass plate, however, cuts off the ultraviolet radiation.

(b) Using Charged Electroscope

Apparatus

Zinc plate, gold leaf electroscope, ultraviolet lamp.

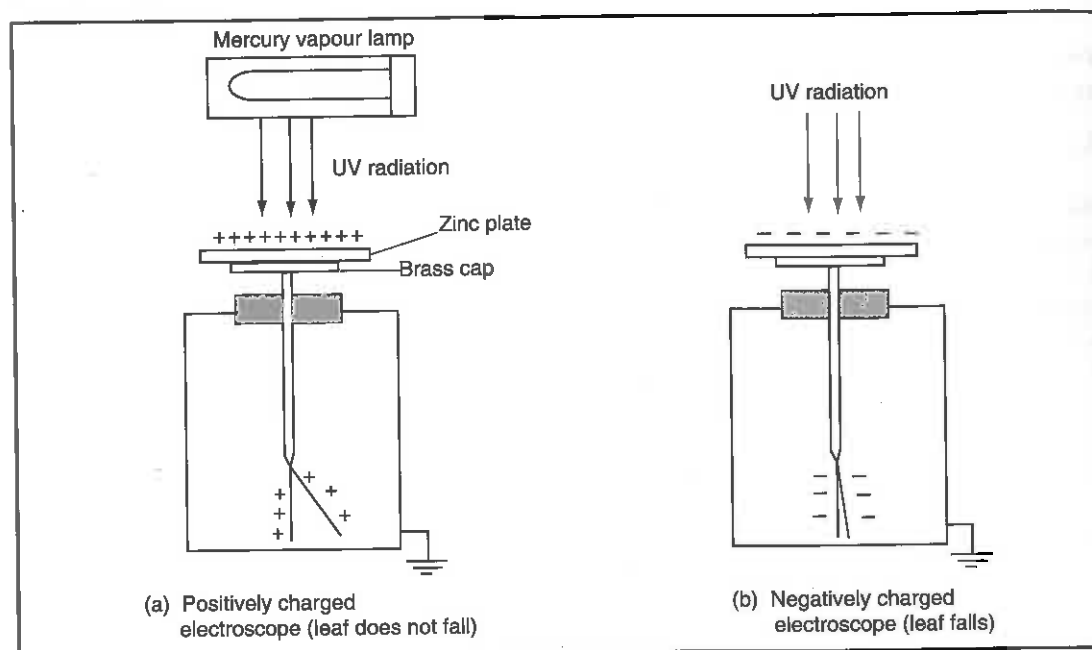


Fig. 9.2: Effect of UV-radiation on charged electroscope

Procedure

- Direct ultraviolet radiation from a mercury vapour lamp onto the zinc plate and observe the divergence of the leaf when the electroscope is positively charged, see figure 9.2 (a).
- Repeat the above procedure using a negatively charged electroscope, see figure 9.2 (b).

Observation

For the positively charged electroscope, the leaf divergence remains the same. However, for the negatively charged electroscope, the leaf divergence decreases.

Explanation

When the zinc plate is irradiated with ultraviolet radiation, electrons are emitted from its surface. The photoelectrons emitted from the positively charged zinc plate do not escape due to attraction by the positive charge on the plate and the leaf divergence therefore remains the same. However, the photoelectrons emitted from the negatively charged zinc plate are repelled and the electroscope becomes discharged as a result of which the leaf divergence decreases.

If a sheet of ordinary glass (which absorbs ultraviolet radiation) is introduced between the negatively charged zinc plate and the ultraviolet source, the leaf divergence remains same.

Light Energy and Quantum Theory

Max Planck in 1901 came up with the idea that light energy is propagated as small packets of energy. Each packet is called a **quantum** of energy (*plural: quanta*). In light, these discrete amounts of energy are called **photons**. According to Planck, the energy E possessed by one photon is given by;

$E = hf$, where, h is Planck's constant equal to 6.63×10^{-34} Js and f the frequency of the radiation.

From the general wave equation;

$$c = f\lambda$$

$$\text{Hence, } f = \frac{c}{\lambda}$$

Thus, $E = h \frac{c}{\lambda}$, where c is the velocity of the radiation in vacuum and λ the wavelength.

Since the velocity c of the radiation and the Planck's constant h are constants, a radiation of longer wavelength λ has lower energy.

Example 1

Compare the energy contained in a photon of red light of wavelength 7.0×10^{-7} m and violet light of wavelength 4.0×10^{-7} m (Take Planck's constant as 6.63×10^{-34} Js and c as 3.0×10^8 ms⁻¹)

Solution

For red light;

$$E = h \frac{c}{\lambda}$$

$$\begin{aligned} \text{Hence, } E &= \frac{6.63 \times 10^{-34} \times 3.0 \times 10^8}{7.0 \times 10^{-7}} \\ &= 2.84 \times 10^{-19} \text{ J} \end{aligned}$$

For violet light;

$$\begin{aligned} E &= \frac{6.63 \times 10^{-34} \times 3.0 \times 10^8}{4.0 \times 10^{-7}} \\ &= 4.97 \times 10^{-19} \text{ J} \end{aligned}$$

Hence, a photon of violet radiation contains more energy than that of red radiation.

Einstein's Equation of Photoelectric Effect

When a photon strikes an electron, all its energy is absorbed by the electron. Some of the absorbed energy is used to dislodge the electron from the metal surface while the rest appears as the kinetic energy of the emitted electron. The energy transformation during photoelectric emission is thus summed as follows;

$$\text{Energy of photon} = \left[\begin{array}{l} \text{energy needed to dislodge an} \\ \text{electron from metal surface} \end{array} \right] + \left[\begin{array}{l} \text{maximum K.E. gained} \\ \text{by the electron} \end{array} \right]$$

The minimum amount of energy needed to dislodge an electron from a metal surface is called the **work function** (W_0) of the metal. This energy varies from metal to metal. The work function is expressed in a unit called electron-volt (eV) or Joules (J).

$$1 \text{ eV} = 1.6 \times 10^{-19} \text{ J.}$$

Emission of photoelectrons will not occur from a metal surface if the frequency of the radiation falling on it is below a certain value. This minimum frequency is known as the **threshold frequency (f_0)** for the metal. The corresponding wavelength is called the **threshold wavelength λ_0** , the maximum wavelength beyond which no photoelectric emission will occur. The work function is thus given by;

$$W_0 = hf_0$$

This can be expressed as:

$$W_0 = h \frac{c}{\lambda_0}$$

For any radiation of frequency f less than f_0 , hf will be lower than W_0 and emission will not occur. When the frequency of the radiation is f_0 , $hf_0 = W_0$ (the work function), and emission occurs. When the frequency of the radiation $f > f_0$, $hf > W_0$ and the excess energy in this case appears as the kinetic energy of the emitted electron.

Thus, $hf - W_0 = \frac{1}{2}m_e v^2$, where m_e is the mass of an electron and v the velocity of the electron emitted.

$$hf = W_0 + \frac{1}{2}m_e v^2$$

This is **Einstein's photoelectric equation**.

Since $W_0 = hf_0$, this can also be written as;

$$hf = hf_0 + \frac{1}{2}m_e v^2$$

$$\text{Hence, } hf = h \frac{c}{\lambda_0} + \frac{1}{2}m_e v^2$$

Table 9.1 shows the work functions and threshold frequencies of some common metals.

Table 9.1

Metal	Symbol	Work function W_0		Threshold frequency, f_0 ($\times 10^{14}$ Hz)
		eV	($\times 10^{-19}$ J)	
Potassium	K	2.22	3.56	5.37
Lead	Pb	4.01	6.42	9.68
Tin	Sn	4.28	6.86	10.35
Zinc	Zn	4.33	6.94	10.47
Copper	Cu	4.40	7.05	10.63
Silver	Ag	4.44	7.11	10.72

Example 2

The minimum frequency of light that will cause photoelectric emission from potassium surface is 5.37×10^{14} Hz. When the surface is irradiated using a certain source, photoelectrons are emitted with a speed of $7.9 \times 10^5 \text{ ms}^{-1}$. Calculate:

- the work function of potassium.
 - the maximum kinetic energy of the photoelectron.
 - the frequency of the source of irradiation.
- (Take $h = 6.63 \times 10^{-34} \text{ Js}$, $m_e = 9.11 \times 10^{-31} \text{ kg}$)

Solution

$$\begin{aligned} \text{(a) Work function, } W_0 &= hf_0 \\ &= 6.63 \times 10^{-34} \times 5.37 \times 10^{14} \text{ J} \\ &= 3.56 \times 10^{-19} \text{ J} \end{aligned}$$

$$\begin{aligned} \text{(b) K.E.}_{\text{max}} &= \frac{1}{2}m_e v_{\text{max}}^2 \\ &= \frac{1}{2} \times 9.11 \times 10^{-31} \times (7.9 \times 10^5)^2 \\ &= 2.84 \times 10^{-19} \text{ J} \end{aligned}$$

$$\begin{aligned} \text{(c) } hf &= hf_0 + \frac{1}{2}mv^2 \\ &= 3.56 \times 10^{-19} + 2.84 \times 10^{-19} \\ &= 6.4 \times 10^{-19} \\ \therefore f &= \frac{6.4 \times 10^{-19}}{6.63 \times 10^{-34}} \\ &= 9.65 \times 10^{14} \text{ Hz} \end{aligned}$$

Example 3

The threshold wavelength of a photoemissive surface is $0.45 \mu\text{m}$. Calculate:

- its threshold frequency.
- the work function in eV.
- the maximum speed with which a photoelectron is emitted if the frequency of the radiation is $7.5 \times 10^{14} \text{ Hz}$ (Take Planck's constant $h = 6.63 \times 10^{-34} \text{ Js}$ and $m_e = 9.11 \times 10^{-31} \text{ kg}$)

Solution

$$\begin{aligned} \text{(a) } \lambda_0 &= 0.45 \mu\text{m} \\ &= 4.5 \times 10^{-7} \text{ m} \\ c &= f_0 \lambda_0 \\ \text{So, } f_0 &= \frac{c}{\lambda_0} \\ \therefore f_0 &= \frac{3.0 \times 10^8}{4.5 \times 10^{-7}} \\ &= 6.67 \times 10^{14} \text{ Hz} \end{aligned}$$

$$\begin{aligned} \text{(b) } W_0 &= hf_0 \\ &= 6.63 \times 10^{-34} \times 6.67 \times 10^{14} \\ &= 4.42 \times 10^{-19} \text{ J} \end{aligned}$$

$$1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$$

$$W_0 = \frac{4.42 \times 10^{-19}}{1.6 \times 10^{-19}} \\ = 2.76 \text{ eV}$$

$$\begin{aligned} \text{(c)} \quad \frac{1}{2} m v_{\text{max}}^2 &= hf - W_0 \\ &= 6.63 \times 10^{-34} \times 7.5 \times 10^{14} - 4.42 \times 10^{-19} \\ &= 4.97 \times 10^{-19} - 4.42 \times 10^{-19} \\ &= 5.53 \times 10^{-20} \end{aligned}$$

$$\therefore v_{\text{max}}^2 = \frac{2 \times 5.53 \times 10^{-20}}{9.11 \times 10^{-31}}$$

$$V_{\text{max}} = \sqrt{\frac{2 \times 5.53 \times 10^{-20}}{9.11 \times 10^{-31}}} \\ = 3.48 \times 10^5 \text{ ms}^{-1}$$

Factors Affecting Photoelectric Effect

The ability of a radiation to eject photoelectrons from a metal surface is determined by three main factors, namely:

- intensity of the radiation.
- energy of the radiation.
- type of metal.

Intensity of Radiation

The intensity of a radiation is the rate of energy flow per unit area when the radiation is normal to the area.

$$\text{Intensity} = \frac{\text{work (W)}}{\text{area (A)} \times \text{time (t)}}$$

$$I = \frac{W}{At}$$

$$\text{But } \frac{W}{t} = P, \text{ where } P \text{ is power.}$$

$$\therefore \text{Intensity} = \frac{P}{A}$$

It can be shown experimentally that intensity is inversely proportional to the square of distance r from the source, i.e., $I \propto \frac{1}{r^2}$

The apparatus is set up as shown in figure 9.3. Intensity is varied by changing the distance r of the photocell from the source and noting the corresponding values of current.

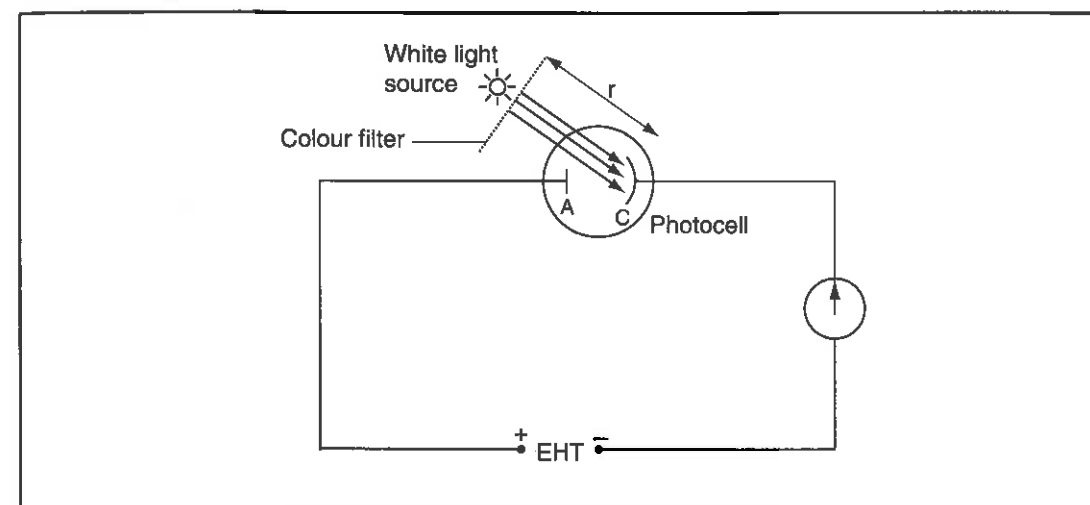


Fig. 9.3: Effect of intensity on number of photoelectrons emitted

Experimental results show that as distance r decreases, the value of current increases. The photocurrent I is directly proportional to the number of photoelectrons emitted per second. Thus, the number of photoelectrons produced is directly proportional to the intensity.

Energy of Radiation

The circuit shown in figure 9.4 can be used to investigate the relationship between the frequency of the radiation and the kinetic energy of the photoelectrons.

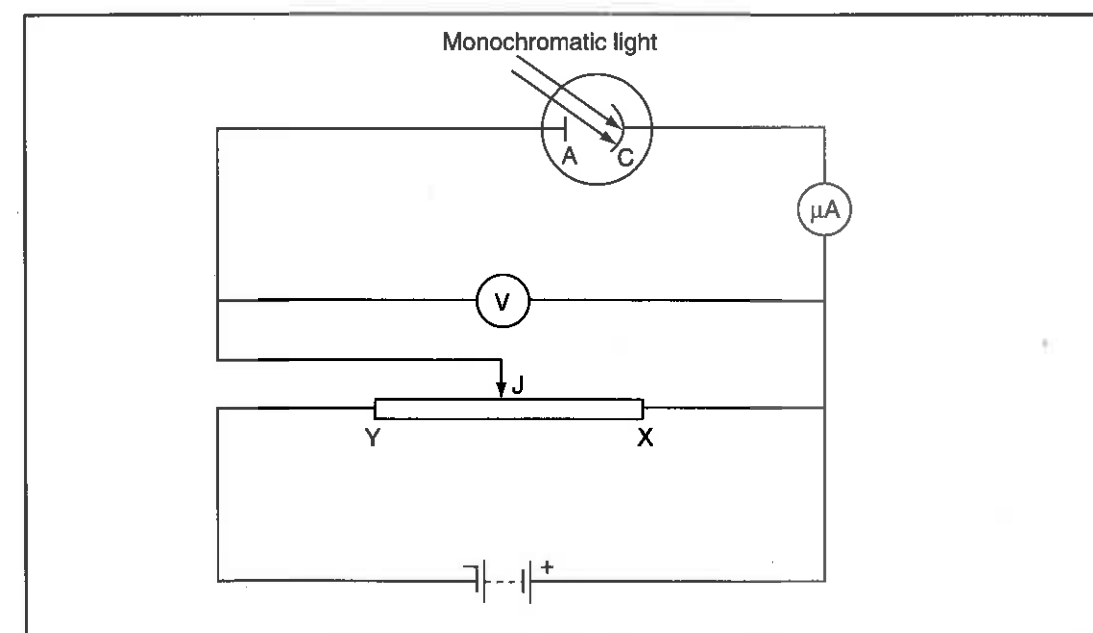


Fig. 9.4: Variation of stopping potential and frequency

The frequency is varied by using different colour filters. For each colour filter, the potential difference is varied by moving the jockey J between X and Y until no current is registered.

Note that the battery is connected in such a way that it opposes the ejection of the electrons by attracting the photoelectrons back to the cathode. The voltmeter reading gives the stopping potential for a given frequency.

Table 9.2 gives typical results obtained using different frequencies and their corresponding stopping potentials.

Table 9.2: Colours and their frequencies

Colour	Frequency f ($\times 10^{14}$ Hz)	Stopping potential V_s
Violet	7.5	1.2
Blue	6.7	0.88
Green	6.0	0.60
Yellow	5.2	0.28
Orange	4.8	0.12

Figure 9.5 shows a plot of the graph of stopping potential V_s against frequency.

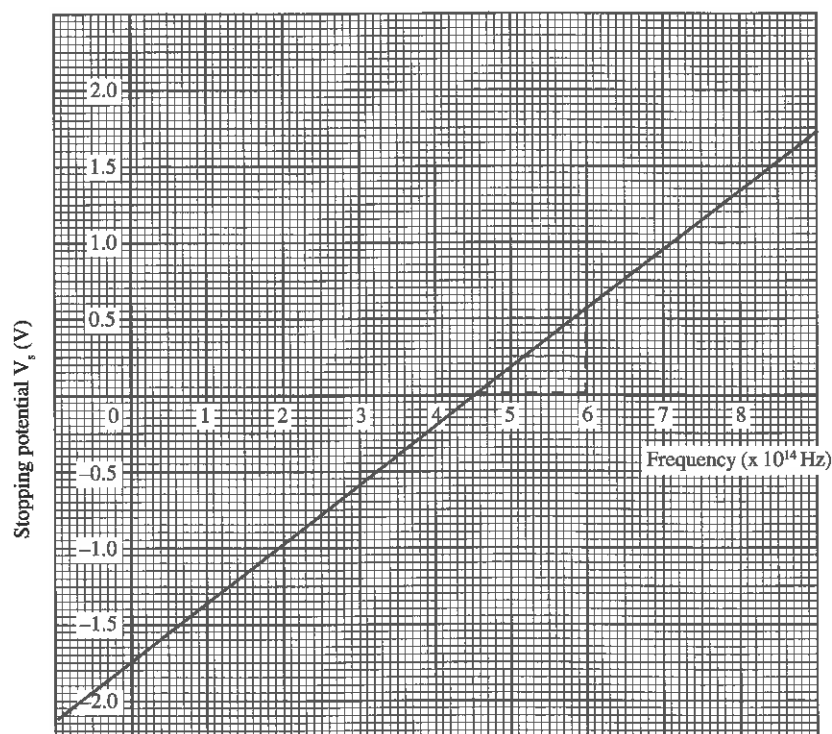


Fig. 9.5: Graph of stopping potential against frequency

The graph is a straight line. From Einstein's photoelectric equation;

$$hf = hf_0 + \frac{1}{2}mv_{\max}^2$$

Work done by stopping potential is given by eV_s .

By work energy theorem, $eV_s = \frac{1}{2}mv^2$

Substituting in Einstein's photoelectric equation;

$$hf = hf_0 + eV_s$$

Therefore, $eV_s = hf - hf_0$

$$\text{Thus, } V_s = \frac{hf}{e} - \frac{hf_0}{e}$$

But hf_0 is equal to work function W_0 . Hence, the graph of V_s against f is straight line cutting

the f -axis at f_0 . The slope of the graph is $\frac{h}{e}$ and the V_s intercept is $-\frac{W_0}{e}$. Both Planck's constant h and the work function W_0 can therefore be calculated from the graph.

Example 4

From the results in table 9.2 and the graph of figure 9.4, determine:

- the threshold frequency of the metal.
- Planck's constant h .
- the work function of the metal in electron, volts.

(Take charge on an electron $e = 1.6 \times 10^{-19}$ C)

Solution

- Using the equation $eV_s = hf - hf_0$;

$$V_s = \frac{hf}{e} - \frac{hf_0}{e} \quad (\text{compare } y = mx + c)$$

$$\text{When } V_s = 0, 0 = \frac{hf}{e} - \frac{hf_0}{e}, \text{ and } f = f_0.$$

$$\therefore f_0 = 4.5 \times 10^{14} \text{ Hz}$$

- Gradient = $\frac{\Delta V_s}{\Delta f}$

$$= \frac{0.6 - 0}{(6.0 - 4.5) \times 10^{14}}$$

$$= 4.0 \times 10^{-15}$$

$$h = 4.0 \times 10^{-15} \times 1.6 \times 10^{-19} \\ = 6.4 \times 10^{-34} \text{ Js}$$

- Work function, $W_0 = hf_0$
 $= 6.4 \times 10^{-34} \times 4.5 \times 10^{14}$
 $= 2.88 \times 10^{-19} \text{ J}$

$$\text{But } 1.6 \times 10^{-19} \text{ J} = 1 \text{ eV}$$

$$\begin{aligned}\text{Work function in eV} &= \frac{2.88 \times 10^{-19}}{1.6 \times 10^{-19}} \\ &= 1.8 \text{ eV}\end{aligned}$$

Note that the value of y-intercept gives the work function in electron volts, since;

$$V_s = \frac{hf}{e} - \frac{W_0}{e}$$

Type of Metal

Every metal surface has its own minimum frequency of radiation called threshold frequency (f_0), below which no photoemission takes place, no matter how intense the radiation is. For example, zinc metal has a threshold frequency equal to 10.47×10^{14} Hz. Any radiation with a frequency lower than 10.47×10^{14} Hz cannot therefore eject an electron from zinc plate.

The results on photoelectric effect can be summed up as follows:

- (i) The rate of emission of photoelectrons is directly proportional to the intensity of the incident radiation.
- (ii) Each metal surface has its own minimum frequency for photoemission.
- (iii) The emitted photoelectrons have kinetic energies ranging from zero to maximum value. Increasing the frequency of incident radiation increases the kinetic energy of the photoelectrons.

Applications of Photoelectric Effect

Photoemissive Cell

Figure 9.6 (a) shows photoemissive cell. It has two electrodes, the anode and the cathode. The cathode is a curved photosensitive plate. The emission surface of the cathode faces the anode.

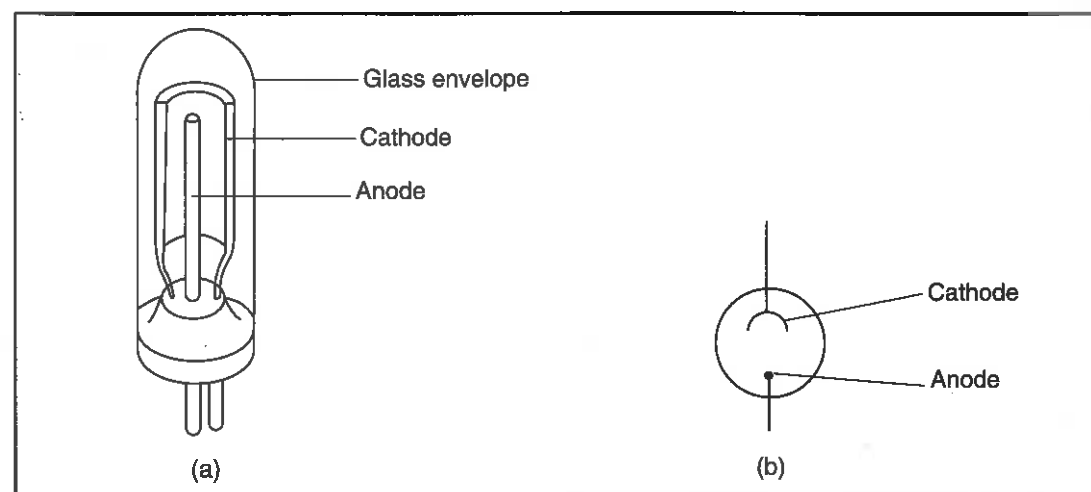


Fig. 9.6: Photoemissive cell

When light falls on the cathode, photoelectrons are emitted. These are attracted by the anode, causing a current to flow in a given circuit. Figure 9.6 (b) shows the symbol for photoemissive cell.

Photomissive cells are used in:

- (i) counting vehicles or items on a conveyor belts in factories.
- (ii) burglar alarms.
- (iii) opening doors.

Figure 9.7 shows how the cell can be used to count items on a conveyor belt.

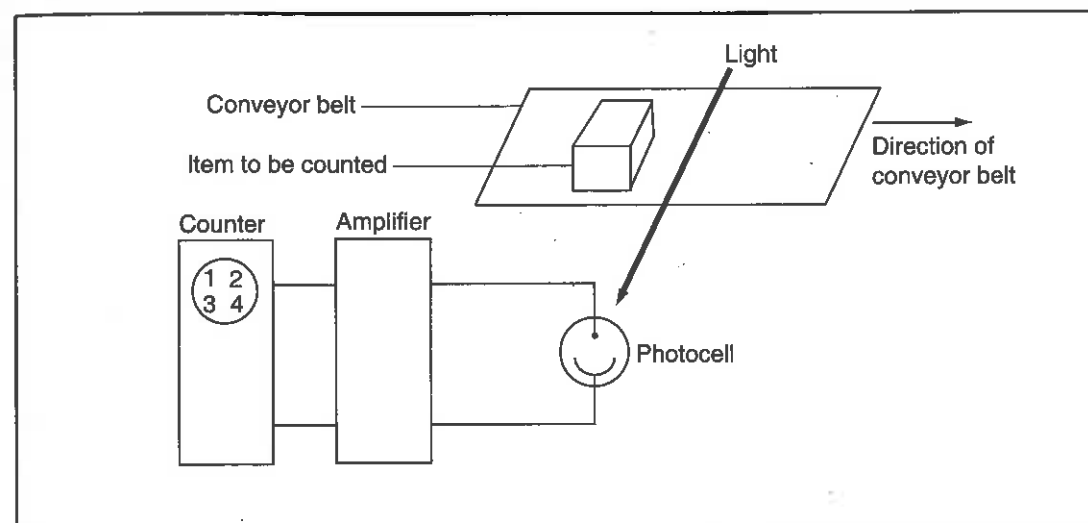


Fig. 9.7: Use of photoemissive cell in counting

As the item moves along the conveyor belt, it blocks light from reaching the photocell, stopping the current flow. After the item has passed, a current flows again and pulse is registered in the counter.

The photoemissive cell can also be used to reproduce sound from a film. An exciter lamp focuses light through the sound track along the side of a moving film, onto a photocell.

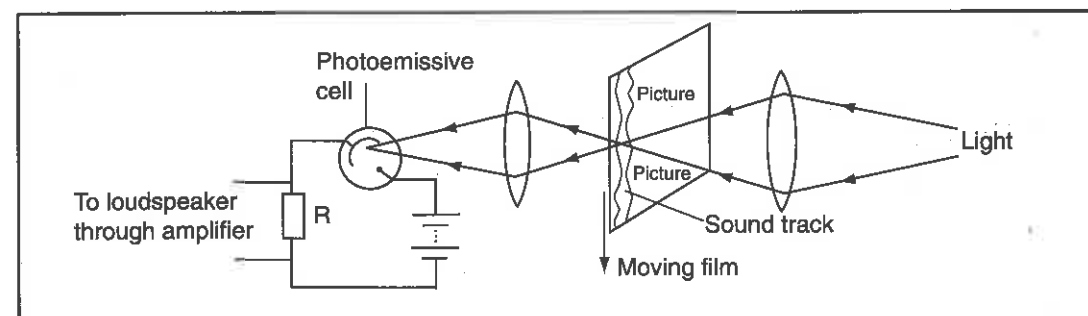


Fig. 9.8: Photoemissive cell used to reproduce sound

The varying width of the track varies the intensity of the light passing to the cell. The cell accordingly creates a varying current in line with current obtained from the microphone when the film was made. The current develops a varying potential difference across the resistor R. This is amplified and the output converted into sound by the loudspeaker.

Photovoltaic Cells

Figure 9.9 (a) shows one form of a photovoltaic cell consisting of a copper disc which is oxidised on one face. On the free copper oxide surface, a film of gold is deposited. This film is thin enough to allow light to pass through it.

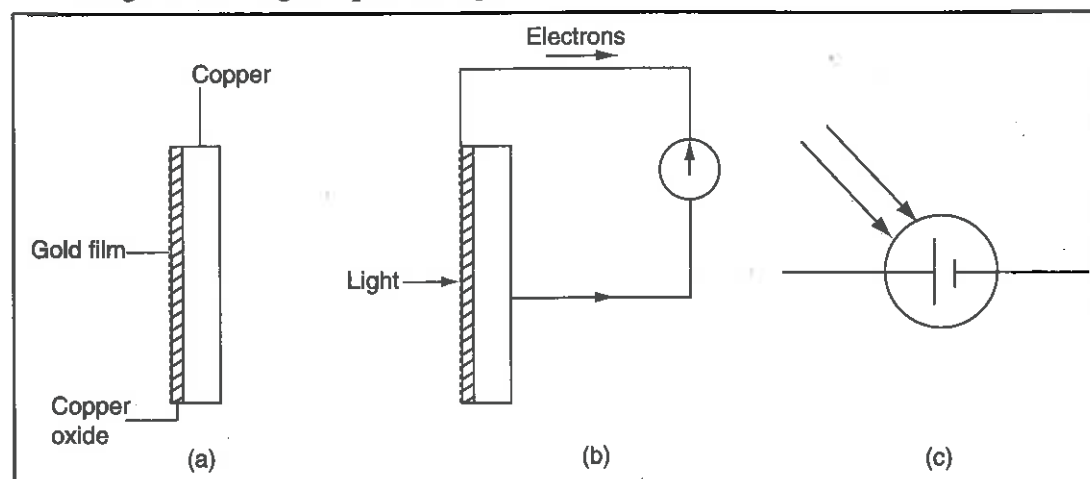


Fig. 9.9: Photovoltaic cell

When light strikes the copper oxide surface, electrons are knocked off. The copper oxide acquires a negative potential and copper a positive potential. A potential difference therefore exists and a current flows through a wire connecting the gold film and copper. This can be shown by a galvanometer included in the circuit as shown in figure 9.9 (b). However, this current is low in the order of milliamperes, depending on the intensity of the light source.

Such cells are used in light meters, e.g., exposure meters in photography. Figure 9.9 (c) shows the symbol for the photovoltaic cell.

Photoconductive Cell or Light-dependent Resistor (LDR)

Figure 9.10 (a) shows one form of photoconductive cell. It consists of a grid like metal structure having a thin layer of a semiconductor material called cadmium sulphide. It is enclosed in a casing covered with a transparent window to allow light to fall on it.

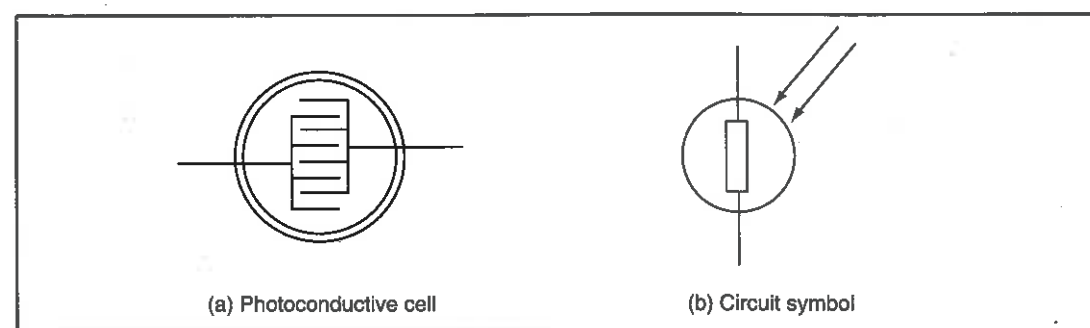


Fig. 9.10: Photoconductive cell (light-dependent resistor)

Light energy reduces the resistance of the cell from $10\text{ M}\Omega$ in the darkness to $1\text{ k}\Omega$ in bright light. Photons of light set the electrons on the semiconductor free, causing an increase in conduction. Figure 9.10 (b) shows a circuit symbol for the photoconductive cell. Photoconductive cells are used in fire alarms and also in exposure meters of cameras.

Other photoelectric devices are the solar cell and the photodiode

Revision Exercise 9

Where necessary, take:

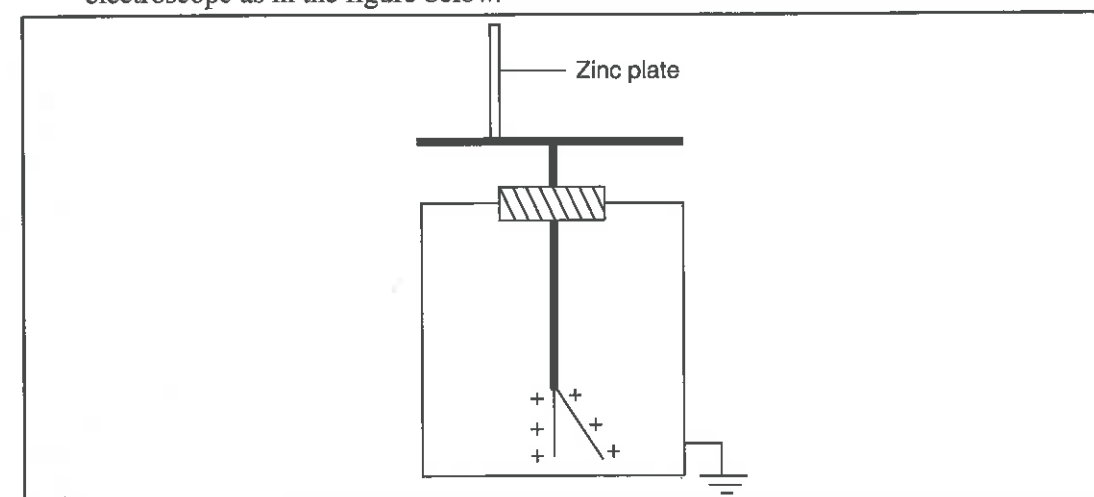
planck's constant, $h = 6.63 \times 10^{-34}\text{ Js}$

mass of electron, $m_e = 9.11 \times 10^{-31}\text{ kg}$

charge on electron, $e = 1.6 \times 10^{-19}\text{ C}$

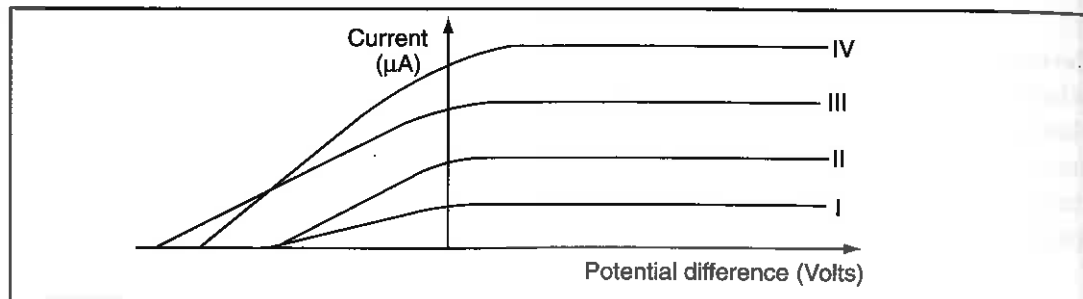
speed of light in a vacuum, $c = 3.0 \times 10^8\text{ ms}^{-1}$

- Define the following:
 - Photoelectric effect.
 - Work function.
 - Threshold frequency.
- A clean zinc plate was charged and then placed on the cap of a positively charged electroscope as in the figure below.

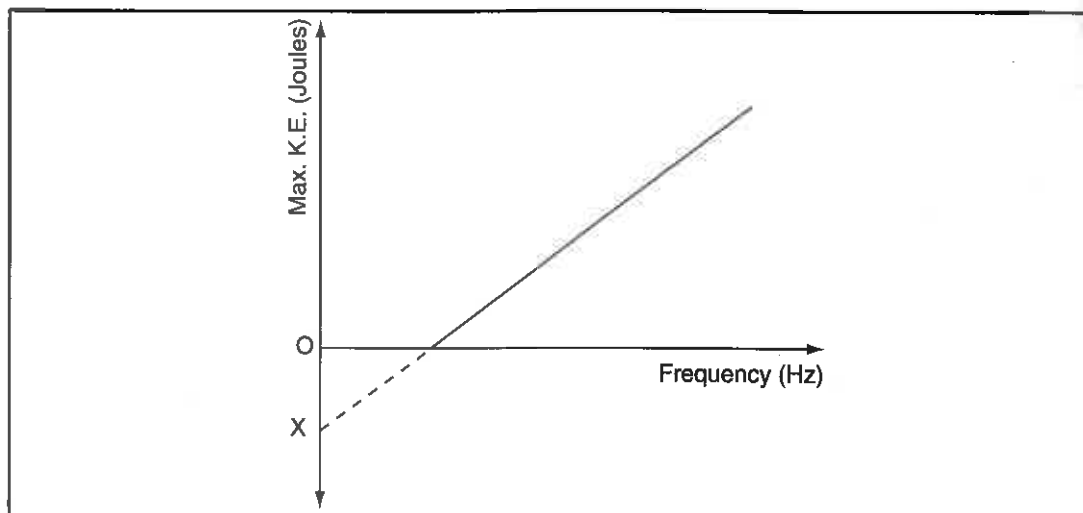


- State the charge on the plate before it was placed on the cap of the electroscope.
 - What would happen to the leaf of the electroscope if ultraviolet light was made to fall on the zinc plate?
 - Why is the zinc plate cleaned?
- Two metals X and Y are found to emit electrons when irradiated in turn with a light beam A, while only metal X emits electrons when irradiated with a second light beam B.
 - What are the possible distinctions between:
 - light A and light B?
 - metal X and metal Y?
 - What would be the effect of using on metal X:
 - a light beam of the same colour but greater intensity.
 - light of shorter wavelength.

4. (a) How does the kinetic energy of a photoelectron depend on the frequency of the incident radiation?
 (b) The figure shows the plots of current versus corresponding potential difference between the plates of a photocell when various beams of light are directed to its cathode, one at a time. Which of the beams has the lowest wavelength?



5. (a) A graph of kinetic energy of photoelectrons emitted by metal surface against the frequency of radiation used is shown in the figure below.



The graph is extrapolated to intersect the K.E. axis:

- From the graph, state the relationship between KE and frequency.
 - What is the significance of the gradient of the graph?
 - What is the significance of OX from the graph?
- (b) The experiment is repeated with a photocell of a metal surface B which has a lower work function than metal A. Sketch on the same axes the expected graph if metal surface B photocell were used.
6. The minimum frequency of light which will cause photoelectric emission from a metal surface is 5.0×10^{14} Hz. If the surface is illuminated by light of frequency 6.5×10^{14} Hz, calculate:
- the work function of the metal surface.
 - the maximum K.E. (in eV) of the electrons emitted.
 - the maximum speed of the electrons.

7. The work function of a clean metal surface is 4.5 eV. Calculate:
- the minimum frequency of radiation that will cause the emission of electrons from the surface.
 - the maximum energy of the electrons emitted when the surface is illuminated with a radiation of frequency 1.2×10^{15} Hz.
8. A sodium surface is illuminated by light of wavelength 3.0×10^{-7} m. The work function for sodium metal is 2.46 eV. Find:
- the kinetic energy of the ejected photoelectrons.
 - the cut-off frequency for sodium.
9. The table below shows the stopping potential and the corresponding frequencies for a certain photocell:

Stopping potential V_s (V)	0.2	0.6	1.10	1.42	1.83
Frequency f ($\times 10^{14}$ Hz)	4.0	5.0	6.0	7.0	8.0

Plot a graph of stopping potential V_s (y-axis) against frequency and from the graph, determine:

- the threshold wavelength.
 - Planck's constant.
 - the work function of the metal.
10. Sodium has work function of 2.3 eV. Calculate:
- its threshold frequency.
 - the maximum velocity of the photoelectron produced when its surface is illuminated by light of wavelength 5.0×10^{-7} m.
 - the stopping potential of this energy.
11. A metal surface has work function of 4.92 eV.
- Find the maximum wavelength of radiation that will cause the emission of photoelectrons from the metal.
 - Calculate the maximum kinetic energy in joules of the electrons emitted when the metal is irradiated with ultraviolet light of frequency 1.8×10^{15} Hz.
 - What is the stopping potential of this metal?
12. (a) What is meant by threshold wavelength?
 (b) The maximum kinetic energy of the photoelectrons emitted from a metal is 1.8×10^{-19} J when the frequency of the incident radiation is 8.5×10^{14} Hz. Calculate the maximum wavelength of the radiation that can just emit an electron from the metal.
13. When light of wavelength $1.0 \mu\text{m}$ is radiated onto a metal, it ejects an electron with a velocity of $3.0 \times 10^5 \text{ ms}^{-1}$. Calculate the:
- work function of the metal.
 - threshold frequency of the metal.
14. (a) Describe a simple experiment which can be used to explain Quantum Theory.
 (b) One would suffer from skin burn when a photon of energy of about 3.0 eV is radiated to our bodies. Find the wavelength of this radiation.

RADIOACTIVITY

In 1896, a French scientist, Henri Becquerel, observed that when a metallic object was placed between a photographic plate wrapped in black paper and a crystal of uranium compound, an image of the object was formed. Since the black paper was opaque, he concluded that the radiations which penetrated the paper must have emanated from the uranium compound. Other scientists Marie Curie and Pierre Curie carried out related investigations, from which they concluded that the radiations originated from the nucleus. They called this phenomenon **radioactivity**.

Atomic Structure

Figure 10.1 shows the structures of some atoms.

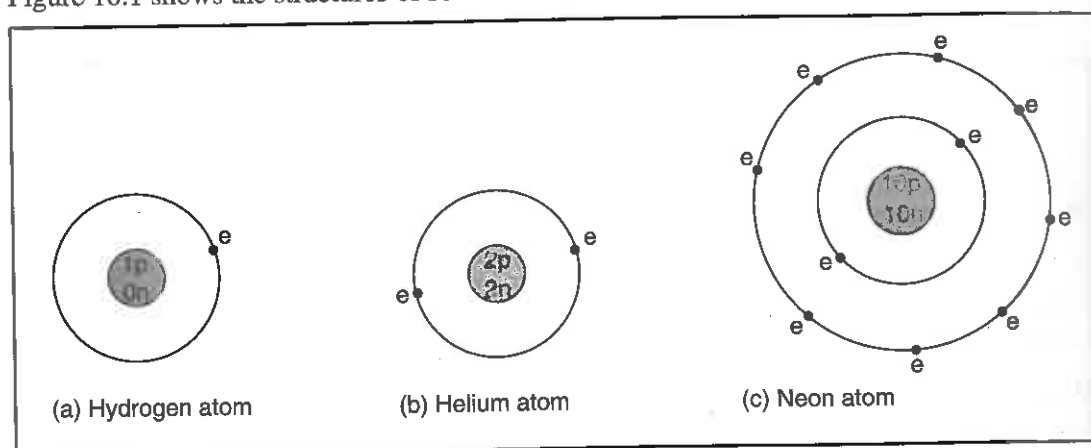


Fig. 10.1: Structure of atoms

The nucleus of an atom has a specific number of protons and neutrons. The number of protons in the nucleus is called the **atomic or proton number**, while the sum of the number of protons and neutrons is called the **mass or nucleon number**. Figure 10.1 (a) shows a hydrogen atom having 1 proton in the nucleus and 1 electron around it, 10.1 (b) shows the helium atom having 2 protons, 2 neutrons and 2 electrons, 10.1 (c) shows the neon atom having 10 protons, 10 neutrons and 10 electrons around it.

If an atom X has atomic number Z with N neutrons and mass number A, it can be represented as ${}^A_Z\text{X}$, where $A = Z + N$.

Thus, hydrogen can be represented by ${}^1_1\text{H}$, helium by ${}^4_2\text{He}$ and neon by ${}^{20}_{10}\text{Ne}$.

Some atoms have same atomic number but different mass numbers. Such atoms are said to be **isotopes**. For example, carbon-12 and carbon-14 are isotopes of carbon and are represented as ${}^{12}_6\text{C}$ and ${}^{14}_6\text{C}$.

Nuclear Stability

Stable nuclides have a proton to neutron ratio of about 1:1. However, as atoms get heavier, there is a marked deviation from this ratio, with the number of neutrons far superseding that of protons. In such circumstances, the nucleus is likely to be unstable. When this happens, the nucleus is likely to disintegrate in an attempt to achieve stability. Figure 10.2 shows a graph of number of neutrons N against number of protons Z for known stable and unstable nuclides.

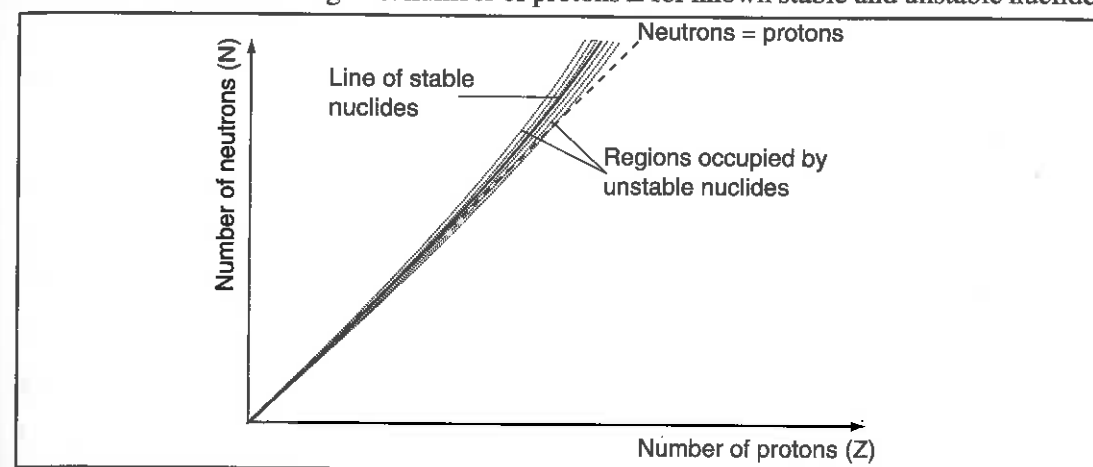


Fig. 10.2: Stability curve

From the graph, it is observed that the unstable nuclides are outside the stability line. Those nuclides above the stability line have too many neutrons, hence decay in such a way that the proton number increases. Those below the stability line have too many protons and therefore decay in such a way that their proton number decreases.

Types of Radiations

Radiations emitted by radioactive elements are identified according to the properties they exhibit.

The radiations behave differently when subjected to strong magnetic field. Figure 10.3 shows how the radiations from a radium source are deflected by a magnetic field.

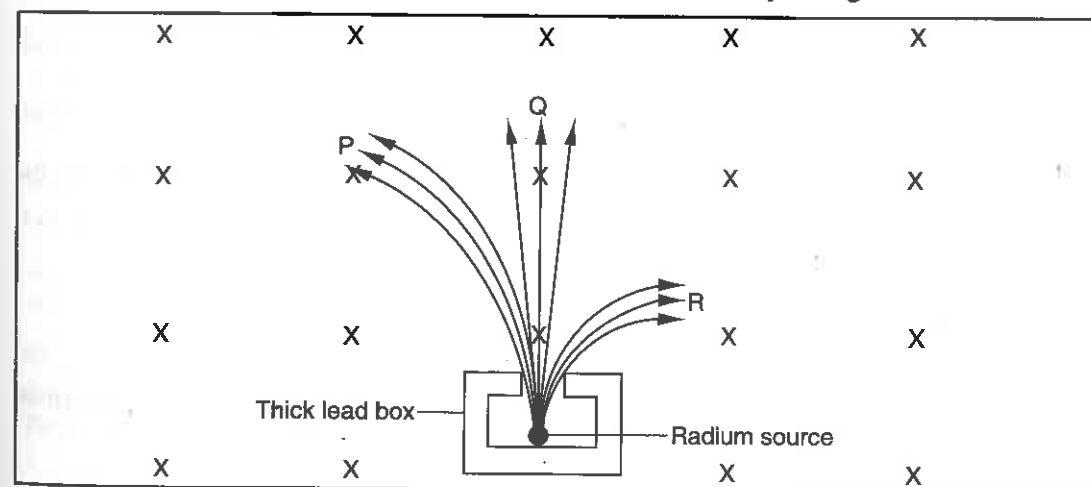


Fig. 10.3: Radiations from radium source

The radium source is placed in a thick lead box with a small opening. When a strong magnetic field is introduced perpendicular to the path of radiations, some are deflected. Using Fleming's left-hand rule, it can be shown that radiation P is positively charged, R negatively charged and Q carries no charge.

The positively charged radiation is called alpha (α) particles, the negatively charged beta (β) and the uncharged gamma (γ) radiation. It is further observed that alpha particles are deflected less compared to beta particles. This suggests that alpha particles are heavier than beta particles. Further research reveals that an α -particle is basically a helium nucleus, denoted by ${}^4_2\text{He}$. The β -particles are found to be electrons, denoted by ${}^0_{-1}\text{e}$.

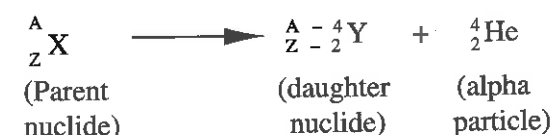
Radioactivity

Radioactivity is the spontaneous random emission of particles from the nucleus of an unstable nuclide. The process of radioactivity is not affected by such external factors as temperature, pressure or chemical composition.

When a nuclide emits the radiation, it is said to undergo radioactive decay. During radioactive decay, the nuclide will emit alpha or beta particles and this may be accompanied by a release of energy in form of gamma radiation.

Alpha Decay

If the nuclide decays by release of an alpha particle, the mass number decreases by 4 and the atomic number by 2. This is expressed as;



Uranium, for example, decays by emitting an alpha to become thorium. The decay is expressed as;

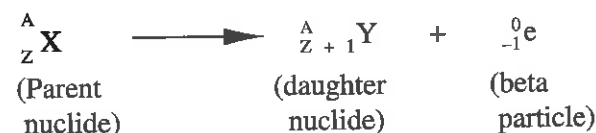


Similarly, polonium undergoes alpha decay to become lead.



Beta Decay

If the nuclide decays by release of a β -particle, the mass number remains the same but the atomic number increases by 1. This is expressed as;



Radioactive sodium, for example undergoes beta decay to become magnesium. This is written as;



Gamma Radiation

Some nuclides might be in an excited state and to achieve stability, they may emit energy in form of gamma radiation, without producing new isotopes. For example:

(i) Cobalt-60;



(ii) Thorium-230;

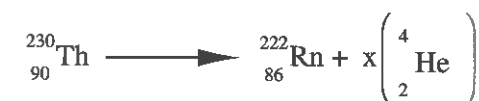


Example 1

Thorium-230 $\left({}^{230}_{90}\text{Th}\right)$ undergoes decay to become Radon-222 $\left({}^{222}_{86}\text{Rn}\right)$. Find the number of alpha particles emitted.

Solution

Let the number of alpha particles emitted be x . The expression for the decay is;



Thus;

$$4x + 222 = 230 \quad \quad 2x + 86 = 90$$

$$4x = 8 \quad \quad \text{or} \quad \quad 2x = 4$$

$$x = 2 \quad \quad \quad x = 2$$

Two alpha particles are emitted.

Example 2

Lead-214 $\left({}^{214}_{82}\text{Pb}\right)$ decays to polonium-214 $\left({}^{214}_{84}\text{Po}\right)$ by emitting β -particles. Calculate the number of β -particles emitted.

Solution

Let x be the number of β -particles emitted.



$$82 = 84 - x$$

$$x = 2$$

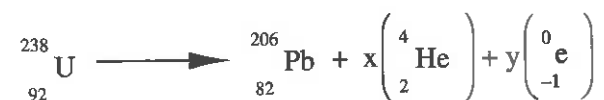
Two β -particles are emitted.

Example 3

Uranium - $^{238}_{92}\text{U}$ undergoes decay to become lead-206 $^{206}_{82}\text{Pb}$. Find the number of α and β -particles emitted in the process.

Solution

Let the number of α and β -particles emitted be x and y respectively.



$$238 = 206 + 4x$$

$$4x = 32$$

$$x = 8$$

Also;

$$92 = 82 + 2x - y$$

$$92 = 82 + 16 - y$$

$$92 = 98 - y$$

$$y = 6$$

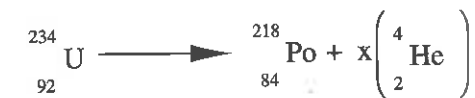
Eight α -particles and six β -particles are emitted.

Example 4

Uranium $^{234}_{92}\text{U}$ decays to polonium $^{218}_{84}\text{Po}$ by emitting alpha particles. Write down the nuclear equation representing the decay.

Solution

Let the number of alpha particles (helium) be x .



$$234 = 218 + 4x$$

$$16 = 4x$$

$$x = 4$$

The decay equation is, therefore;

**Penetrating Power**

The penetrating power of radioactive radiations can be determined by first placing a radioactive source a few centimetres away from a radioactive detector, e.g., a Geiger-Muller tube. If the

detector is connected to an amplifier, clicks can be heard. This means that the source is emitting radiations.

Different absorbers (paper, aluminium foil, aluminium plates and lead of varying thickness are then placed between the source and the detector for the different radiations, see figure 10.4. The kind and thickness of absorber which completely absorbs each radiation is noted.

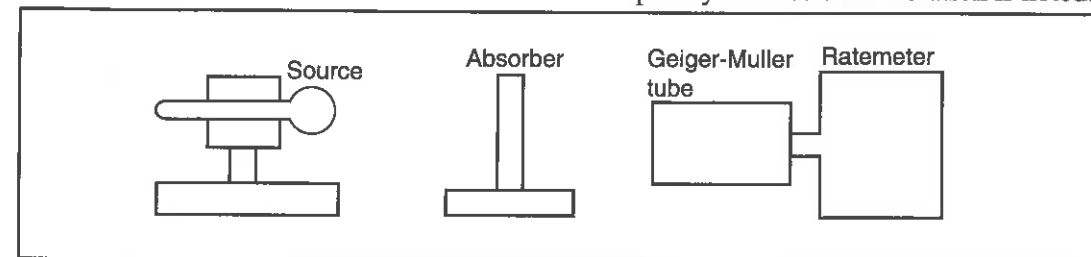


Fig. 10.4: Determining penetration of radioactive radiations

Figure 10.5 shows the penetration power of radioactive radiation in various materials.

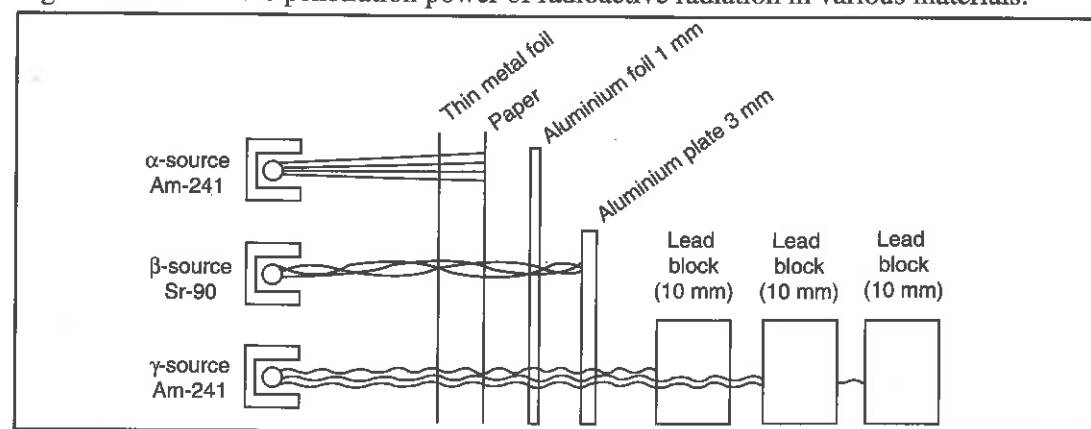


Fig. 10.5: Penetrative power of radioactive particles

Alpha particles are able to penetrate a thin metal foil, but are stopped by a paper few millimetres thick. Their range in air is about 5 centimetres.

Beta particles are able to penetrate thin metal foil and paper but are stopped by aluminium about 3 mm thick.

Gamma is capable of penetrating materials and is only substantially minimised by thick lead block. Lead of about 1 cm thick will lower the intensity of gamma radiation by half. So, if the radiation penetrates a second block of lead 1 cm thick, the intensity falls to one quarter of the original value, and so on. Thus, 1 cm thickness of lead is referred to as **half-thickness** for lead, since it lowers the intensity of the radiation to half the original volume.

Gamma rays can penetrate most materials and are only stopped by a block of lead about 5 cm thick or very thick concrete wall.

Note:

Gamma rays have neither mass nor charge. They are similar to X-rays, but have a generally shorter wavelength. The main difference between X-rays and gamma rays is that gamma rays originate from energy changes in the nucleus of atoms while X-rays originate from energy changes associated with electron structure of atoms.

Ionising Effect of the Radiations

When alpha, beta or gamma radiations pass through air, they knock off electrons from air molecules, resulting in the formation of positive ions. This effect is called **ionisation**.

Since an alpha particle is heavy and slow, it takes quite sometime to pass through air. It is therefore able to knock off more electrons than beta particles and gamma rays which are light and very fast.

Table 10.1 shows the properties of the radiations.

Table 10.1: Properties of radioactive radiations

Type of radiation	Nature	Electrical charge	Relative mass	Velocity	Absorbed by	Ionising power	Effect of magnetic or electric field
Alpha particles	A stream of helium nuclei	+2e	4 units	$\frac{1}{20}$ of velocity of light	Thin paper	Strong	Slightly deflected
Beta particles	A stream of electrons	-e	$\frac{1}{1840}$ of a unit (negligible)	3 - 99% velocity of light	Aluminium plate	Weak	Greatly deflected
Gamma rays	Electromagnetic radiation	No charge	Negligible	Velocity of light	Thick block of lead	Weak	Not deflected

RADIATION DETECTORS

Photographic Emulsions

All the three radiations affect photographic emulsion or plate. Photographic films are very useful to workers who handle radioactive materials. These workers are given special badges which contain a small piece of unexposed photographic film. If, during the time it had been worn, the worker was exposed to radiations, it should darken on development, implying that further safety precautions should be taken.

Cloud Chamber

When air is cooled until the vapour it contains reaches saturation, it is possible to cool it further without condensation occurring. Under these conditions, the vapour is said to be super-saturated. This can only occur if the air is free of any dust, which normally acts as a nuclei on which the vapour can condense to form droplets. Gaseous ions can also act as a nuclei for condensation. The ionisation of air molecules by radiations is investigated by a cloud chamber. The common types of cloud chambers are expansion cloud chamber and diffusion cloud chamber. In both types, saturated vapour (water or alcohol) is made to condense on air ions caused by radiations. Whitish lines of tiny liquid drops show up as tracks when illuminated.

Expansion Cloud Chamber

Figure 10.6 shows an expansion cloud chamber. When a radioactive element emits radiations into the chamber, the air inside is ionised.

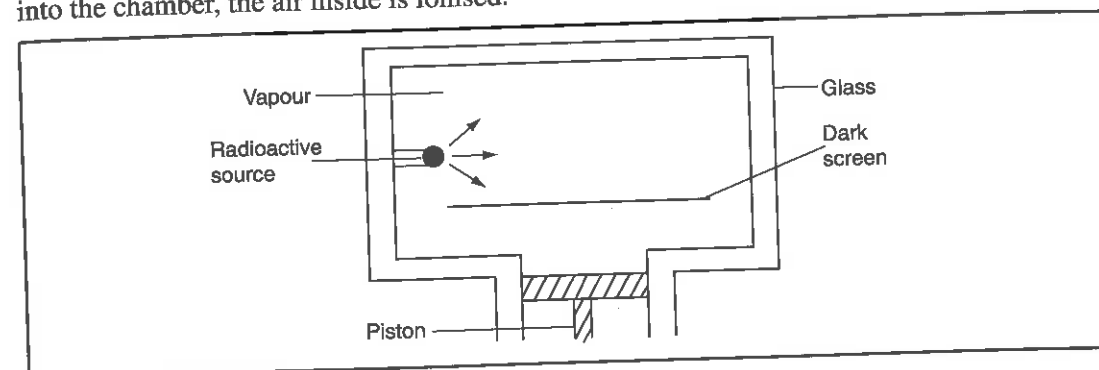


Fig. 10.6: Expansion cloud chamber

If the piston is now moved down suddenly, air in the chamber will expand and cooling occurs. When this happens, the ions formed act as nuclei on which the saturated alcohol or water vapour condenses, forming tracks.

Diffusion Cloud Chamber

The common diffusion cloud chamber is made up of a cylindrical transparent container. It is partitioned into two compartments by a blackened metal plate. The upper compartment is fitted with a transparent perspex lid and its top is lined with a thin strip of felt ring soaked in alcohol. The bottom compartment is fitted with a sponge and closed with removable cover. The upper compartment contains air, which is at the room temperature at the top. The air at the bottom is at a temperature of about -78°C due to a layer of dry ice placed in the lower compartment. The felt ring at the top is soaked in alcohol. This alcohol vaporises in the upper warm region, diffuses down and is then cooled, see figure 10.7.

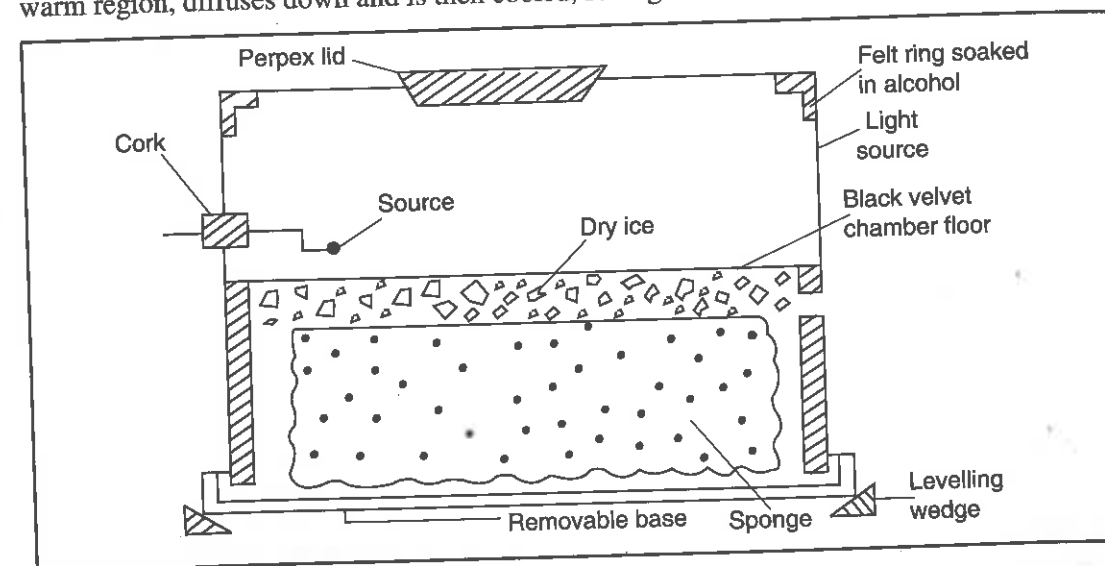


Fig. 10.7: Diffusion cloud chamber

At a certain height above the base of the chamber, the air contains a layer of saturated alcohol vapour. Here, alcohol droplets form on the air ions produced by the radiation. These are seen as tracks along the path of radiation. The tracks are well defined if an electric field is created by frequently rubbing the perspex lid of the chamber with a piece of cloth.

The tracks obtained in the above cloud chambers vary according to the type of radiation. The tracks due to alpha particles are short, straight and thick. This is because:

- (i) alpha particles cause heavy ionisation, rapidly losing energy, hence their short range.
- (ii) they are massive and their path cannot therefore be changed by air molecules.
- (iii) alpha particles cause more ions on their paths as they knock off more electrons, see figure 10.8.

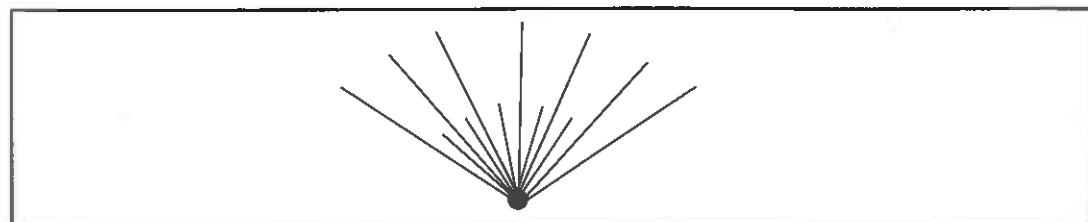


Fig. 10.8: Tracks due to alpha particles

The tracks formed by beta particles are generally thin and irregular in direction. This is because beta particles, being lighter and faster, cause less ionisation of air molecules. In addition, the particles are repelled by electrons of atoms within their path. Figure 10.9 shows the tracks, formed by beta particles.

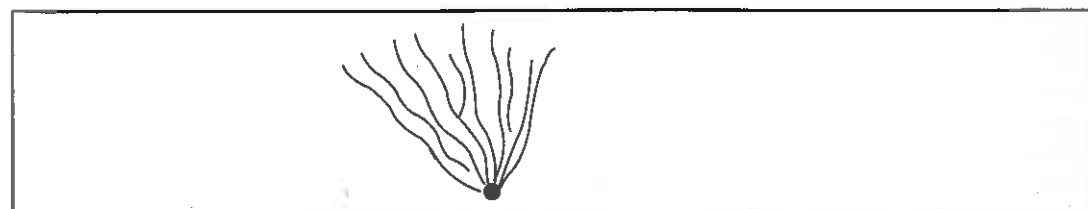


Fig. 10.9: Tracks due to beta particles

Gamma rays produce scanty disjointed tracks, as shown in figure 10.10.

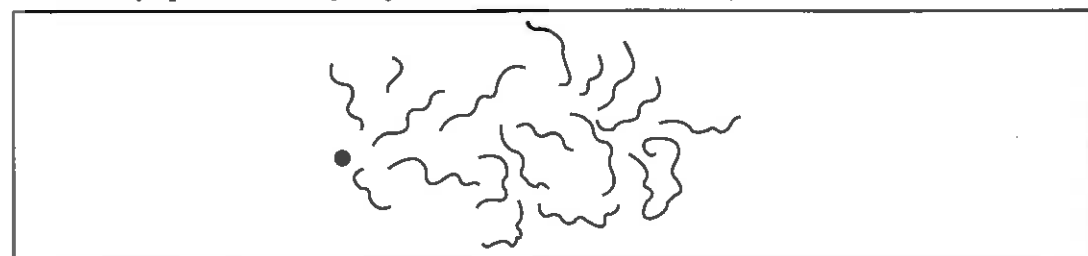


Fig. 10.10: Tracks due to Gamma rays

The rays eject electrons from their molecules. These electrons behave like weak beta particles, which are responsible for the tracks seen.

Geiger-Muller Tube

The Geiger-Muller (G-M) tube is a type of ionisation chamber. Figure 10.11 shows a G-M tube commonly used in elementary work.

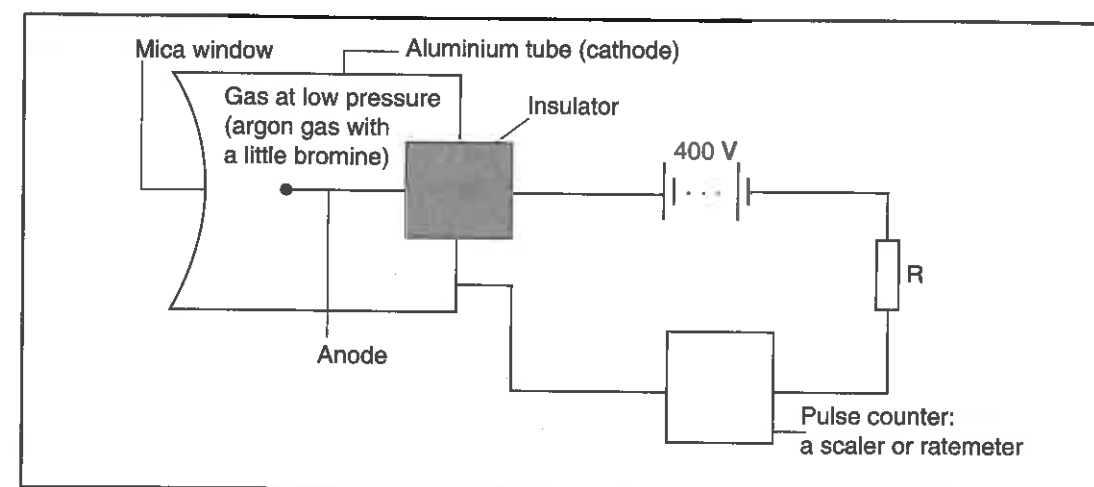


Fig. 10.11: Geiger-Muller tube

The tube consists of a thin mica (or aluminium) window at one end of a closed glass tube which contains argon gas and a little bromine gas at low pressure. A thin wire runs through the centre of the tube and is connected to the positive terminal of a high voltage supply. The walls of the tube are coated with a conductor and connected to the negative terminal of the power supply.

When a radioactive substance is placed in front of the window, the emitted radiations enter the tube through the window and ionise the argon gas. The negative ions move towards the central wire (anode), while the positive ions move towards the wall (cathode). As the ions accelerate, they collide with more particles on their paths, resulting in further ionisation. This secondary ionisation ultimately results in an **avalanche of electrons**. A pulse current therefore flows. A single ionising particle is able to produce as many as 10^8 electrons due to the pressure of the argon gas. The process is referred to as gas amplification.

A corresponding pulse voltage is registered across the high resistance R . These currents can be amplified and if passed through a loudspeaker, clicks are heard. The loudspeaker can be replaced by a scaler or ratemeter to give the exact count rate of the radiation. The amplification increases the sensitivity of the tube, making it possible to register very small currents from beta and gamma radiations. During this process, the positive ions are supposed to move to the cathode. However, because of their mass, the movement is slow. They produce a shielding effect on the anode, reducing the electric field between anode and cathode. Any ionisation caused by an incoming radioactive emission will therefore not be detected. The time taken by the positive ions to move away from the anode (reducing the shielding effect) so that the field comes to normal is called '**dead time**'.

The bromine molecules inside the tube absorb the kinetic energy of the positive ions as they move towards the cathode. If the positive ions were to collide with the cathode, electrons would be produced which would cause a second electron avalanche, resulting in a false pulse. Bromine gas acts as a quenching agent.

Background Radiation

When carrying out experiments using radioactive materials, it is observed that the counter registers some readings even in the absence of a radioactive source. This implies presence of radiation. This radiation is called **background radiation**. The count registered in the absence of the radioactive source is called **background count**. Some sources of these background radiation include:

- (i) cosmic rays from outer space.
- (ii) radiations from the sun.
- (iii) some rocks which contain traces of radioactive material, e.g., granite.
- (iv) natural and artificial radioisotopes.

Artificial Radioactivity

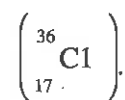
Some naturally occurring nuclides can be made artificially radioactive by bombarding them with neutrons, protons or alpha particles.

For example, when nitrogen-14 $\left({}^{14}_7\text{N} \right)$ nuclide, which is stable, is bombarded with

fast moving alpha particles, radioactive oxygen is formed. This is represented by;



Other artificially radioactive nuclides are silicon-27 $\left({}^{27}_{14}\text{Si} \right)$, sulphur-35 $\left({}^{35}_{16}\text{S} \right)$ and chlorine-36



Decay Law

Radioactive decay is a spontaneous, random process in which one cannot point out the nuclide that will disintegrate next. The choice of the nuclide that decays is governed by chance. This is because extremely large number of atoms is usually involved.

The decay law states that the rate of disintegration at a given time is directly proportional to the number of nuclides present at that time. This can be expressed as;

$$\frac{dN}{dt} \propto -N, \text{ where } N \text{ is the number of nuclides present at a given time. It follows that;}$$

$$\frac{dN}{dt} = -\lambda N, \text{ where } \lambda \text{ is a constant known as the decay constant.}$$

The negative sign shows that the number N decreases as time increases.

$$\frac{dN}{dt} \text{ is referred to as the activity of the sample.}$$

Half-life

The rate of decay of any radioactive material depends on the number of nuclides present. The time taken for half the number of nuclides initially present in a radioactive sample to decay is called its **half-life**.

Consider 2 g of radium, whose half-life is 1 600 years. In 1 600 years 1 g will have decayed. In the next 1 600 years, $\frac{1}{2}$ g of the sample will be the remaining. This is illustrated in table 10.2.

Table 10.2

No. of years	No. of half-lives	Mass decayed (g)	Mass remaining (g)
0	0	0	2
1 600	1	1	1
3 200	2	$1\frac{1}{2}$	$\frac{1}{2}$
4 800	3	$1\frac{3}{4}$	$\frac{1}{4}$
6 400	4	$1\frac{7}{8}$	$\frac{1}{8}$

It can be shown that the number of nuclides remaining undecayed, N , after time T is given by;

$$N = N_0 \left(\frac{1}{2} \right)^{\frac{T}{t}}, \text{ where } N_0 \text{ is the original number of nuclides and } t \text{ the half-life.}$$

Figure 10.12 illustrates the graph of number of radioactive nuclides remaining against the time T .

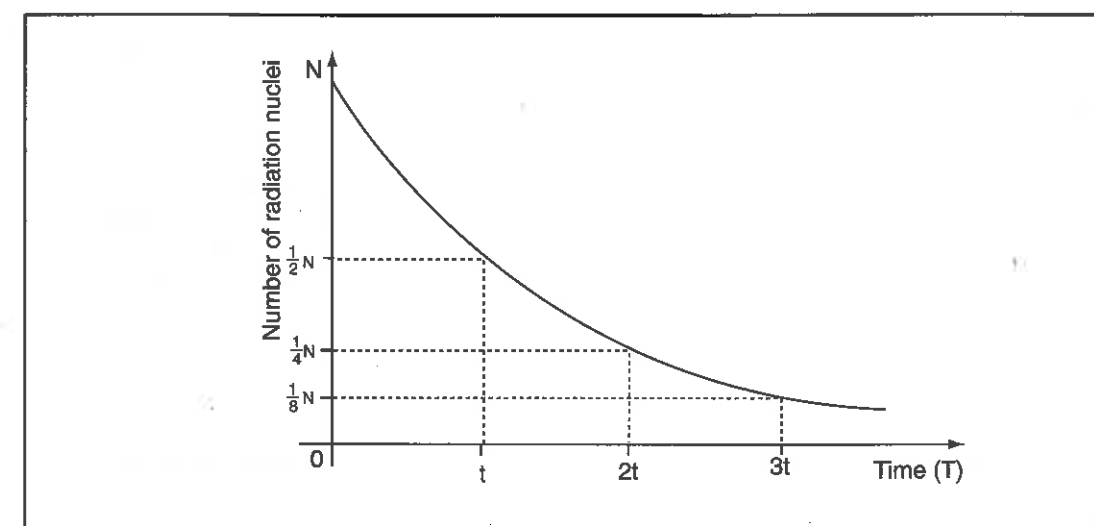


Fig. 10.12: Radioactive decay graph

Example 5

The half-life of a certain radioactive element is 16 years.

- (a) What fraction of the element will be remaining after 48 years?
 (b) What fraction of the element will have decayed after 64 years?

Solution

(a) From the formula $N = N_0 \left(\frac{1}{2}\right)^{\frac{t}{T}}$

$$\text{Fraction remaining} = \frac{N}{N_0}$$

$$= \left(\frac{1}{2}\right)^{\frac{t}{T}}$$

$$= \left(\frac{1}{2}\right)^{\frac{48}{16}}$$

$$= \left(\frac{1}{2}\right)^3$$

$$= \frac{1}{8}$$

(b) Number of half-lives after 64 years $= \frac{64}{16}$
 $= 4$

$$\text{Fraction remaining after 4 half-lives} = \left(\frac{1}{2}\right)^4$$

$$= \frac{1}{16}$$

$$\text{Fraction decayed} = 1 - \frac{1}{16} = \frac{15}{16}$$

Example 6

A certain volume of a solution containing a radioactive isotope was found to have an activity of 24 000 disintegrations per hour. The half-life of the isotope is 15 hours. This solution was mixed with blood in such a way that the ratio of solution to blood was 3 : 1. After 30 hours, the activity of 1.0 cm³ of the mixture was found to be 5 disintegrations per hour. Find the volume of the blood that was mixed with the solution.

Solution

After 30 hours, there are two half-lives. Expected count-rate of solution is 6 000 counts per hour. Since the ratio of the solution to blood in the mixture 3 : 1, the solution containing the radioactive material is $\frac{3}{4}$ cm³ in 1.0 cm³ of the mixture.

$$\therefore 5 \text{ counts correspond to } \frac{3}{4} \text{ cm}^3$$

6 000 counts would result from;

$$\frac{6\,000}{5} \times \frac{3}{4} = 900 \text{ cm}^3$$

$$\therefore \text{Volume of blood } \frac{1}{4} \times 900 = 225 \text{ cm}^3$$

Example 7

For a certain radioactive material, the average count-rate is found to be 82 counts per second. After a time of 210 seconds, the count rate had dropped 19 counts per second. The average background count-rate remained constant at 10 counts per second. What is the half-life of the material?

Solution

Let the half-life be x seconds.

$$\text{Number of half-lives} = \frac{210}{x}$$

Since the background count is 10, the initial and final count rates due to the material are; 82 – 10 = 72 and 19 – 10 = 9 respectively.

$$\text{Remaining fraction} = \frac{9}{72}$$

$$= \left(\frac{1}{2}\right)^{\frac{210}{x}}$$

$$\text{But } \frac{9}{72} = \frac{1}{8}$$

$$= \left(\frac{1}{2}\right)^3$$

$$\text{So, } \frac{210}{x} = 3$$

$$\therefore x = \frac{210}{3}$$

$$= 70 \text{ seconds}$$

The half-life of the material is 70 seconds.

Alternatively;

Number of half-lives for count rate to drop 72 to 9 is 3, i.e.,

$$72 \longrightarrow 36 \longrightarrow 18 \longrightarrow 9$$

$$\text{Therefore, half-life} = \frac{210}{3}$$

$$= 70 \text{ seconds}$$

Example 8

The following were obtained from the reading of a counter connected to a Geiger-Muller tube placed in front of a radioactive source. Plot a graph of the count-rate against time and deduce the half-life of the source.

Table 10.3

Time(s)	0	20	40	60	80	100	120
Corrected counts	120	74	48	30	20	12	8

Solution

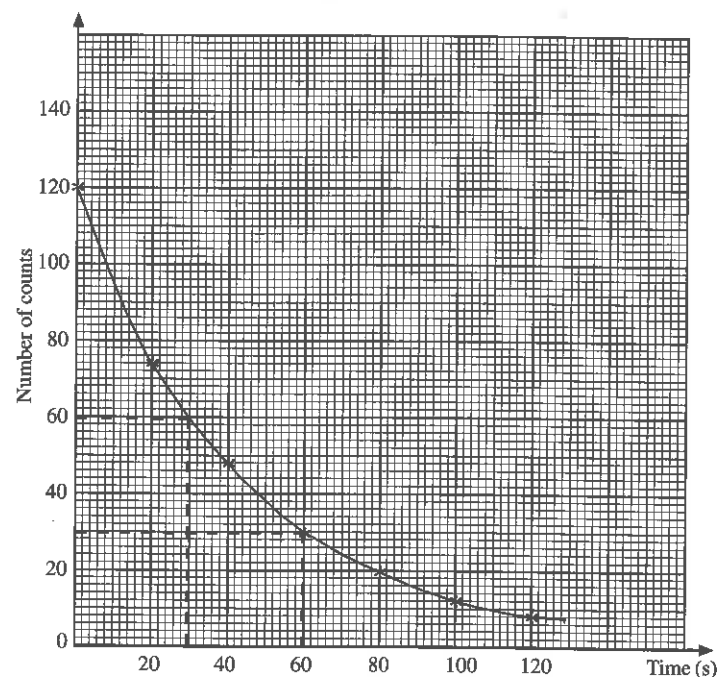


Fig. 10.13

From the graph, the count rate drops to half the original value in 30 seconds and this therefore is the half-life of the material.

Example 9

The table below shows the variation of count-rate recorded by the ratemeter when a source of radioactive material is held near a Geiger-Muller tube. If the count-rate for background radiation is 150 counts per minute, determine the half-life of the source by plotting a graph.

Table 10.4

Time (minutes)	0	4	8	12	16
Count rate per minute	950	670	495	375	295

Solution

The table below shows the variation of count-rate with the corrected background radiation.

Table 10.5

Time (minute)	0	4	8	12	16
Count rate per minute	800	520	345	225	145

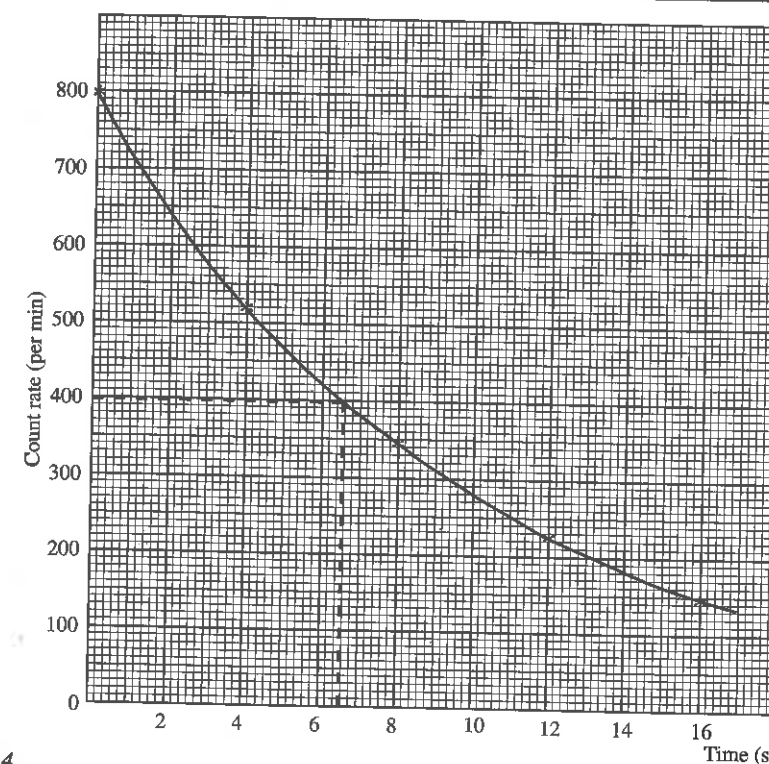


Fig. 10.14

Figure 10.14 shows graph of count-rate (per minute) against time (min). Half-life of the source is 6.6 minutes.

Applications of Radioactivity

Carbon Dating

Living organisms take in small quantities of radioactive carbon-14, in addition to the ordinary carbon-12. The ratio of carbon-12 to carbon-14 in the organisms remains fairly constant. The count-rate can give this value.

When the organisms die, there is no more intake of carbon and therefore the ratio changes due to the decay of carbon-14. The count-rate of carbon-14 therefore declines with time. The new ratio of carbon-12 to carbon-14 is then used to determine the age for the fossil.

Medicine

Gamma rays, like X-rays, are used in the control of cancerous body growths. The radiation kills cancer cells when the tumour is subjected to it. Gamma rays are also used in the sterilisation of medical equipment, and for killing pests or making them sterile.

Detecting Pipe Bursts

Underground pipes carrying water or oil may suffer bursts or leakages. If the water or oil is mixed with radioactive substances from the source, the mixture will seep out where there is an opening. If a detector is passed on the ground near the area, the radiations will be detected.

Determining Thickness of Metal Foil

In industries which manufacture thin metal foils, paper and plastics, radioactive radiations can be used to determine and maintain the required thickness. If a beta source, for example, is placed on one side of the foil and G-M tube on the other, the count rate will be a measure of the thickness of the metal foil, see figure 10.15.

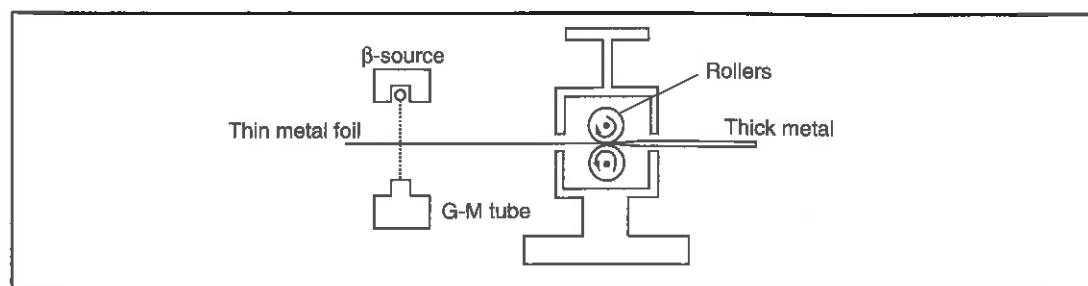


Fig. 10.15: Determining thickness of metal foil

A thickness gauge can be adapted for automatic control of the manufacturing process.

Trace Elements

The movement of traces of a weak radioisotope introduced into an organism can be monitored using a radiation detector. In agriculture, this method is applied to study the plant uptake of fertilisers and other chemicals.

Detection of Flaws

Cracks and airspaces in welded joints can be detected using gamma radiation from cobalt-60. The cobalt-60 is placed on one side of the joint and a photographic film on the other. The film, when developed, will show any weakness in the joint.

Hazards of Radiation

When the human body is exposed to radiation, the effect of the radiation depends on its nature, the dose received and the part irradiated.

Gamma rays present the main radiation hazard. This is because they penetrate deeply into the body, causing damage to body cells and tissues. This may lead to skin burns and blisters, sores and delayed effects such as cancer, leukaemia and hereditary defects. Extremely heavy doses of radiation may lead to death.

Precautions

Radioactive elements should never be held with bare hands. Forceps or well protected tongs should be used when handling them. For the safety of the users, radioactive materials should be kept in thick lead boxes. In hospitals and research laboratories, radiation absorbers are used.

Nuclear Fission

It was discovered that if a nucleus of uranium is bombarded with a neutron, the uranium nucleus splits into two almost equal nuclei. When a nucleus is bombarded and it splits, it is said to have undergone nuclear fission. When uranium-235 is bombarded with a neutron, it becomes uranium-236, which is more active than uranium-235. Uranium-236 splits into barium-144 and krypton-90, as shown below.



Protons and neutrons (nucleons) are kept together in the small volume of the nucleus by what is called binding energy. To split the nucleus, this binding energy has to be released. The energy released during the splitting is called **nuclear energy**.

The emitted neutrons may encounter other uranium nuclides, resulting in more splitting with further release of energy. The produced neutrons are called **fission neutrons**. Figure 10.16 shows how one neutron bombarding a uranium nucleus can produce fission of many atoms. When this occurs, it is called a **chain reaction**.

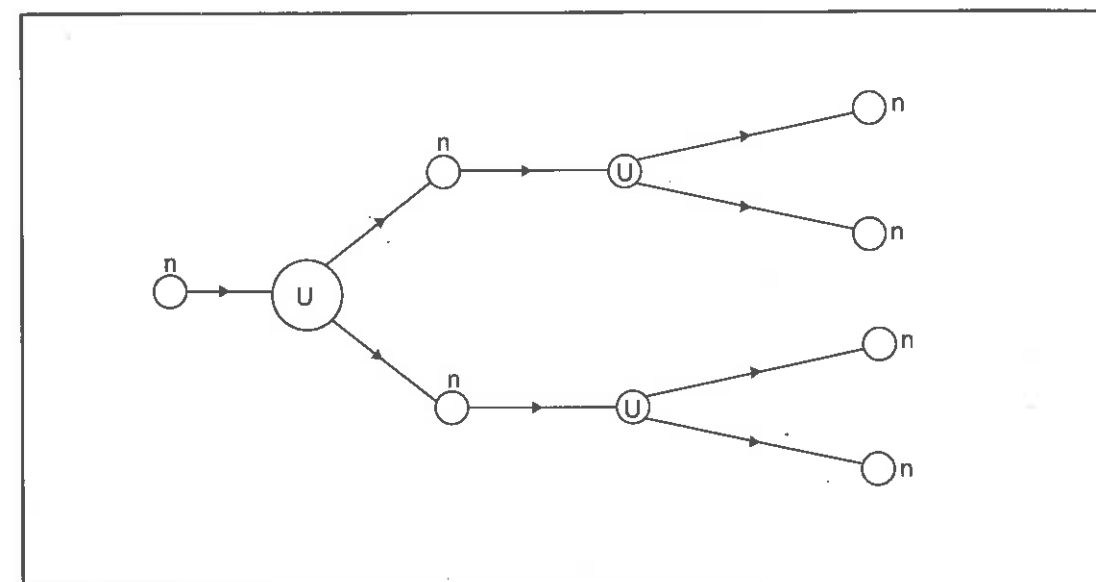


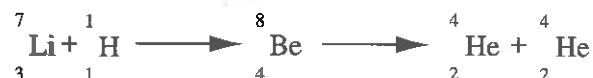
Fig. 10.16: Chain reaction

Note that when the reaction is triggered, the number of nuclides involved builds up rapidly as the released neutrons collide with more nuclides in their paths. The number of neutrons released in successive stages is geometric progression ($2^0, 2^1, 2^2, 2^3 \dots 2^n$). The production of neutrons at every stage is used to sustain the reaction.

In a chain reaction, a lot of energy is produced. Unless this reaction is controlled, an explosion may occur. In practical nuclear reactors, boron rods are used to absorb neutrons and therefore check the reaction. The neutron is commonly used in bombarding the nuclei because it has no charge and so can approach the nucleus without repulsion.

Nuclear Fusion

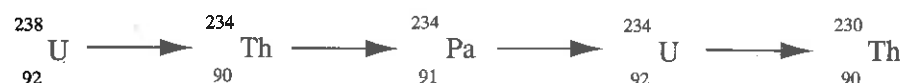
Experiments show that a lot of energy is released when the nuclei of light elements fuse together to form a heavier nucleus. The fusing together of nuclei to form a heavier nucleus is called **nuclear fusion**. An example of nuclear fusion is the formation of alpha particles when lithium fuses with hydrogen;



The fusion is possible since the nuclei of the two atoms are small, hence less repulsion force. The beryllium formed is radioactive. Consequently, it disintegrates into two alpha particles. This fusion is accompanied by the release of a lot of energy.

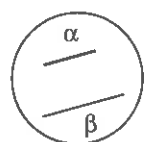
Revision Exercise 10

1. The following is part of a decay series of uranium-238:

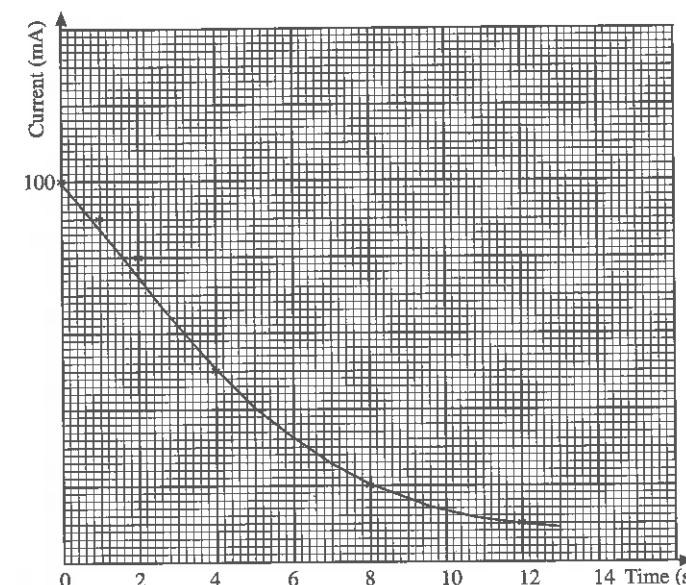


State the particles emitted during each decay.

2. (a) Define the terms radioactivity and half-life.
(b) Describe briefly how you would distinguish between alpha, beta and gamma radiations.
3. A radioactive source emits α , β and γ -radiations of the same intensity. Describe how you would show that these radiations have different penetrating powers.
4. (a) The figure below shows the tracks left in a cloud chamber by α and β -particles of the same energy. Explain why the α -particle has a shorter track than the β -particle.



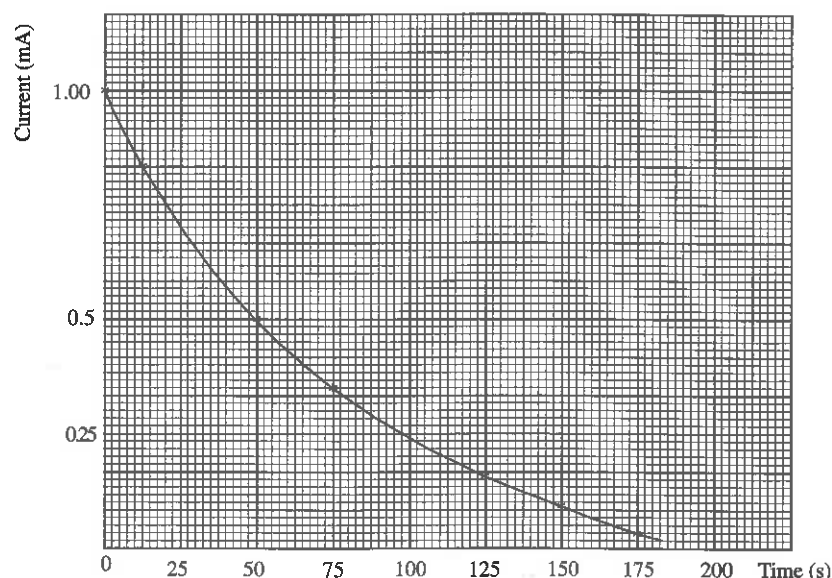
- (b) An alpha particle of energy $5 \times 10^{-13} \text{ J}$ travels a distance of 5 cm in air before coming to rest. Each air molecule needs $2 \times 10^{-18} \text{ J}$ to be ionised. How many ions does the alpha particle create in each centimetre of its travel?
5. What is meant by chain reaction in radioactivity?
6. Beta particles can be used to determine the thickness of cloth. With the help of a diagram, explain how this is done.
7. The figure below shows a decay of a certain element. The diagram is drawn to scale.



From the graph find:

- (a) the half-life of the element.
- (b) the number of half-lives it will have undergone when the count is 0.25 mA.
8. Briefly describe three uses of radioisotopes.
9. (a) What is meant by background radiation?
(b) Thorium-234 is a radioactive element with half-life of 24 days. Calculate the time taken by 1 g of it to decay to $\frac{1}{8}$ g.
10. Give the numerical values of a, b, c, d, e and f in the nuclear equation:

$${}_b^a\text{Po} \longrightarrow {}_{82}^{206}\text{Pb} + {}_d^c\alpha + {}_f^e\gamma$$
11. Radon-219 has half-life of 4 seconds. What fraction of it will remain after 20 seconds?
12. Describe the structure of a:
 - (a) Geiger-Muller tube.
 - (b) cloud chamber.
13. When carrying out experiments using a cloud chamber, thin white lines are always observed. How are these lines formed and what do they consist of?
14. (a) State two precautions that have to be observed when using radioactive substances.
(b) A radioactive material has half-life of 20 minutes. Calculate :
 - (i) the number of half-lives in one hour.
 - (ii) the fraction of the original mass remaining after one hour.
 - (iii) the fraction that would decay in two hours.
15. In an experiment to determine the half-life of thoron-220, the results were plotted as shown in the figure below.



From the graph, determine:

(a) the half-life of thoron.

(b) the activity (current) due to thoron after three half-lives.

16. The table below shows the results of an experiment to determine half-life of a radioactive source. By plotting a graph of counts per second against time in minutes, determine the half-life of the source.

Time (min)	0	20	40	60	80	100	200
Counts per second	10 000	7 420	5 340	3 960	3 060	2 190	650

Chapter Eleven

ELECTRONICS

Advancements in industrial technology, communication, medical services and leisure are largely attributed to the ever developing electronic applications. Domestic devices such as the radio, telephone, television and the cellphone make use of electronic circuits.

The functioning of electronic components such as the diode and integrated circuits (IC), is based on the behaviour of certain materials called **semiconductors**. Common examples of semiconductors are silicon and germanium. The electrical conductivity of conductors, semiconductors and insulators can be explained using the **energy band theory**.

Energy Band Theory

The atomic structure reveals that electrons revolve around the nucleus in energy levels, see figure 11.1 (a). According to the energy-band theory, when two or more atoms are brought closer to each other, the energy levels split into smaller energy levels called **bands**, see figure 11.1 (b). This follows from the interaction of both electric and magnetic fields of electrons as they revolve in their energy levels.

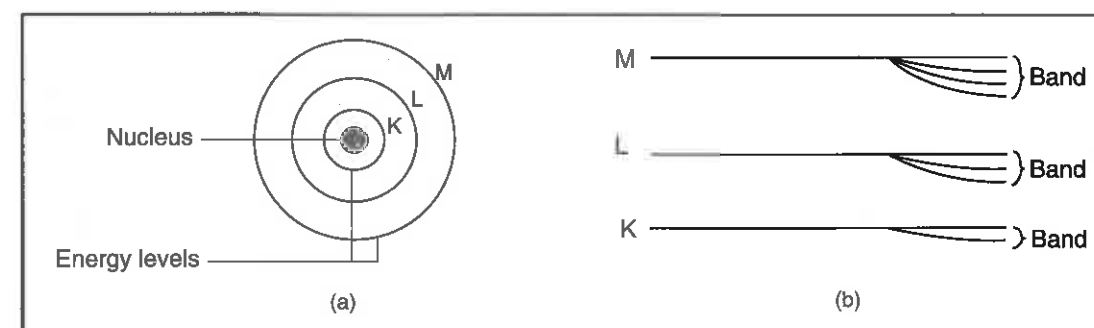


Fig. 11.1: Energy levels

The outermost energy level containing valence electrons splits more easily into many bands than the inner levels. The most important bands in electronics are the valence and conduction bands, which contain valence and conduction electrons respectively. The splitting of the energy levels into bands and the inter-band distances dictate the electrical, optical and magnetic properties of a given material. The energy gap between the conduction and valence bands is called the forbidden energy gap and can be used to distinguish between insulators, conductors and semiconductors.

Insulators

Under normal conditions, there exists a large energy gap of approximately 3 eV between an empty (no electrons) conduction band and completely filled valence band, see figure 11.2. Insulators thus have infinitely high resistance (resistivity) to the flow of electric current.

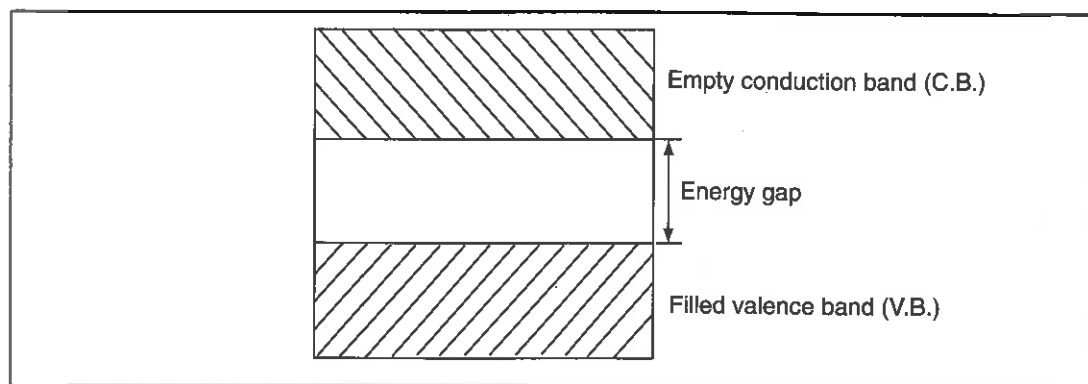


Fig. 11.2: Energy-band for an insulator

A tightly bound electron in the valence band requires large amount of energy to dislodge it from the parent atom and make it cross the forbidden energy gap to find a place in the conduction band. On the other hand, this amount of energy if supplied to an electron in a crystal will break down the crystal. The absence of electrons in the conduction band renders a material a poor electrical conductor. Temperature increase or addition of impurities to insulators has no effect on their conductivity.

Conductors

In conductors, the valence and conduction bands overlap, see figure 11.3. Electrons move freely from the partly filled valence band to the conduction band. Many electrons in the conduction band are thus available (free) for electric conduction. The flow of current in conductors is by movements of electrons.

A rise in temperature increases the vibrations of the atoms and this interferes with the electron flow. Hence, the resistance of a conductor increase with temperature.

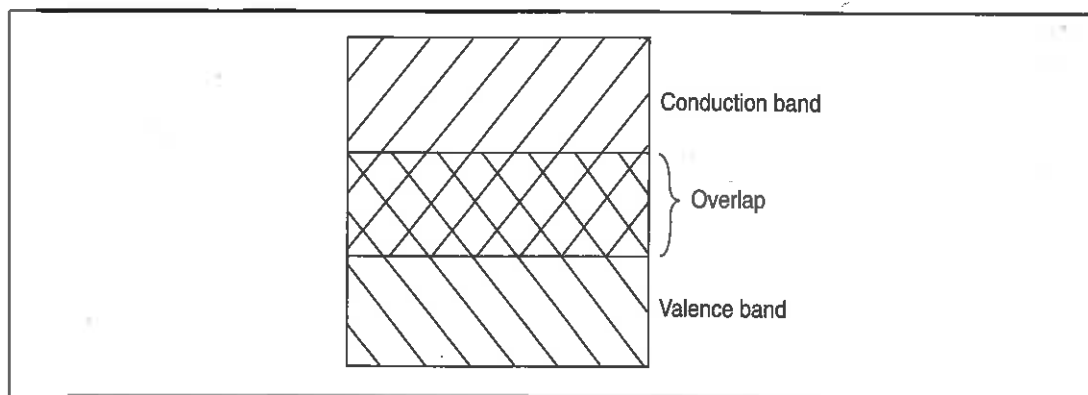


Fig. 11.3: Energy-band of conductor

Semiconductors

The energy-band diagram for a semiconductor is as shown in figure 11.4 (a). The forbidden energy gap is small compared to that of insulators. The conduction band has almost no electrons while the valence band is almost completely filled.

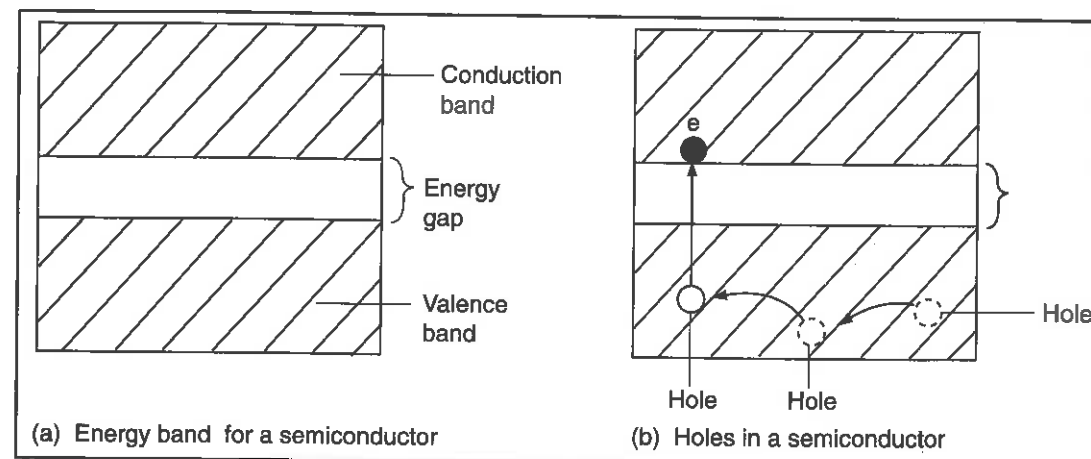


Fig. 11.4

An increase in temperature increases the chance of an electron moving from the valence band to conduction band, see figure 11.4 (b). Conductivity is thus enhanced. The electrical conductivities of semiconductor materials lie between those of good conductors and insulators. When an electron in the valence band is liberated to cross over to the conduction band, a hole (absence of an electron and regarded positive) is created in the valence band. Another electron within the valence band jumps into the hole, thereby creating another hole which is subsequently filled by yet another electron, and the process continues. A hole is therefore seen to be moving in the valence band, generating hole current (conventional current). The flow of electrons in the conduction band constitutes electron current. Total current flow in semiconductors is therefore due to the flow of electrons and holes. The electrical resistance of semiconductors thus reduces with increase in temperature.

Intrinsic and Extrinsic Semiconductors

An **intrinsic semiconductor** is an extremely pure semiconductor, e.g., silicon (Si) and germanium (Ge). Their atoms have four electrons in the outermost shell, which combine covalently with electrons from the neighbouring atoms to form a crystal. Each atom is thus surrounded by four other atoms, see figure 11.5.

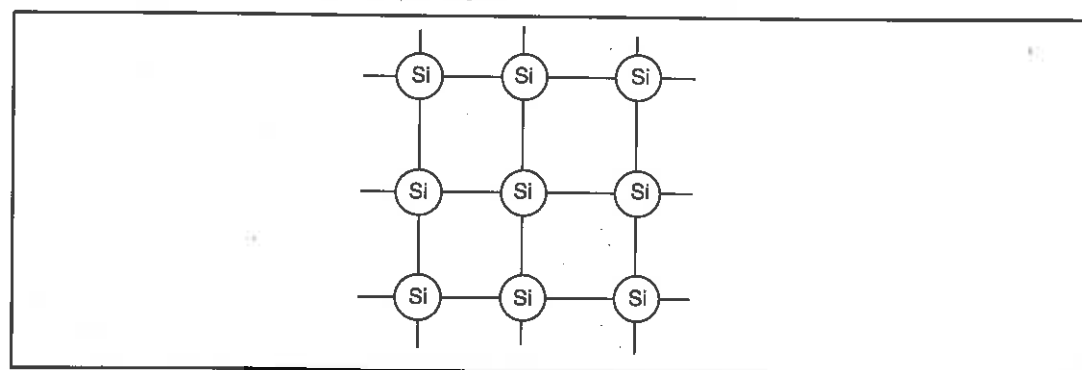


Fig. 11.5: Crystal lattice for silicon

At absolute zero temperature, the crystal is an insulator. At room temperature, some electrons in the valence band gain energy and jump into the conduction band, leaving behind an equal number of holes in the valence band. The material therefore becomes a conductor. At higher temperatures, more electron-hole pairs are created, increasing the conductivity of the material. In an intrinsic semiconductor, the number of electrons equals the number of holes.

The electrons and holes are known as charge carriers. Small quantities of impurities may be added to an intrinsic semiconductor to enhance its conductivity. This is called **doping**. An intrinsic semiconductor to which some impurities have been added to enhance conductivity is called an **extrinsic semiconductor**. There are two types of extrinsic semiconductors, namely, the **n-type** and **p-type**.

The n-type Semiconductor

The n-type semiconductor is formed by doping an intrinsic semiconductor with pentavalent atoms like antimony, phosphorus or arsenic, see figure 11.6.

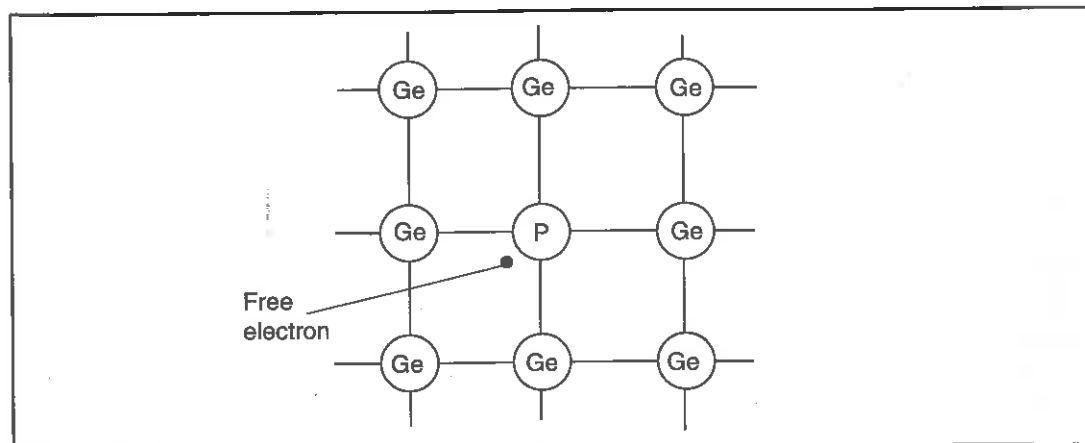


Fig. 11.6: n-type semiconductor

A phosphorus atom has five electrons, four of which participate in forming covalent bonds with four neighbouring atoms of the pure semiconductor. The remaining electron is thus donated for electrical conductivity. The phosphorus atom is thus referred to as **donor atom** or **n-type impurity**. The electrons become the majority charge carriers while holes are the minority charge carriers. Note that the n-type semiconductor is electrically neutral since the total number of electrons is equal to the total number of protons in the material.

The p-type Semiconductor

The p-type semiconductor is obtained by doping intrinsic semiconductors with trivalent atoms, e.g., boron, gallium or indium.

Boron has three electrons available for bond formation whereas silicon has four. When boron fits in the silicon crystal lattice, it will have one electron less to complete the bonding. The vacant place due to a missing electron is called a **hole**. The silicon crystal becomes an **extrinsic semiconductor**, with the holes as majority charge carriers. It is called a p-type semiconductor because the majority charge carriers are holes, which have an effective positive

charge. Since a trivalent atom accepts to complete the bonding with one electron less, it is referred to as **acceptor atom**, see figure 11.7.

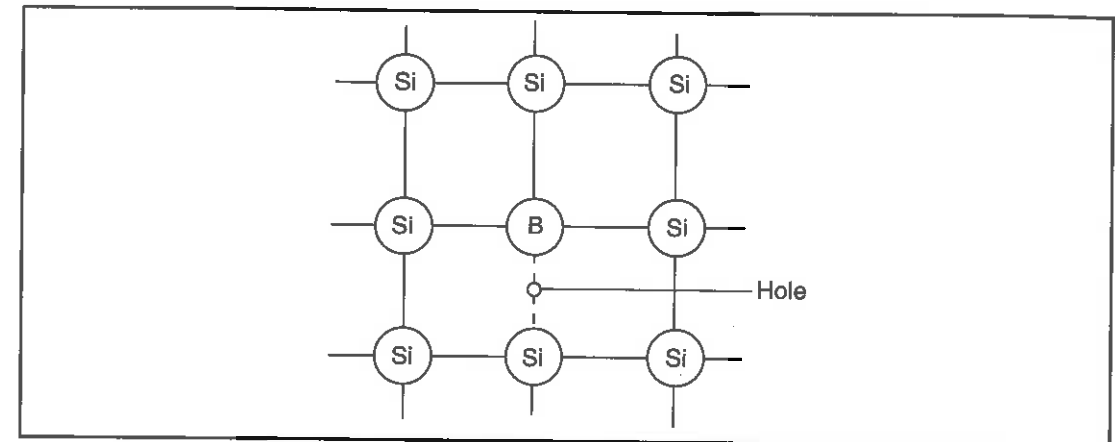


Fig. 11.7: p-type semiconductor

Electrons are the minority charge carriers. The p-type semiconductor is not positively charged but electrically neutral since the impurity introduces equal number of electrons and protons found in the nucleus.

Fixed Ions, Majority and Minority Charge Carriers

In the p-type semiconductor, holes are majority charge carriers, but as a hole moves away from the parent atom, the parent atom becomes a negative ion, which is fixed in the crystal. The ion does not take part in conduction. Electrons (which are thermally generated) exist as minority charge carriers, see figure 11.8 (a).

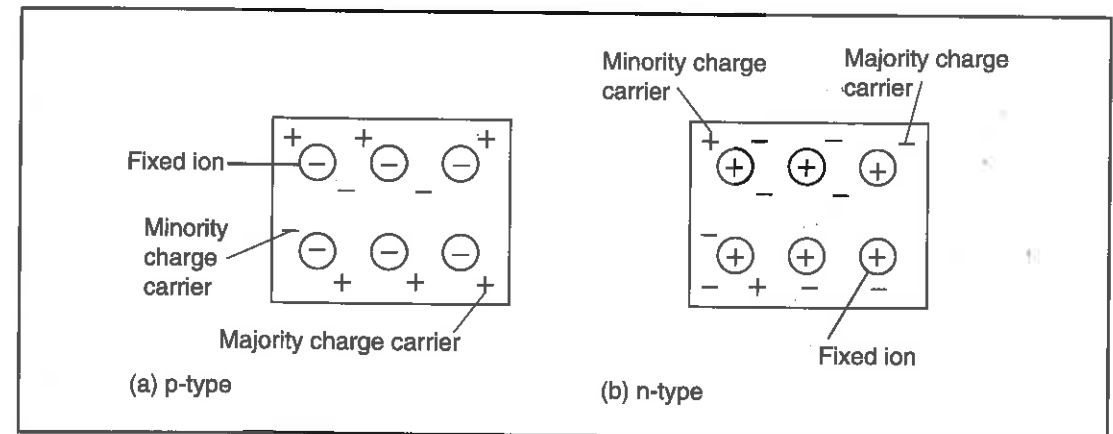


Fig. 11.8: Fixed ions

In the n-type semiconductor, see figure 11.8 (b), an electron moving away from a parent atom generates a fixed positive ion. The holes are thermally generated while the electrons are a result of doping.

The p-n Junction

An intrinsic semiconductor can be doped simultaneously by trivalent and pentavalent atoms such that one half of it becomes a p-type and the other half an n-type semi-conductor. A junction known as the p-n junction is then formed between the two regions, see figure 11.9.

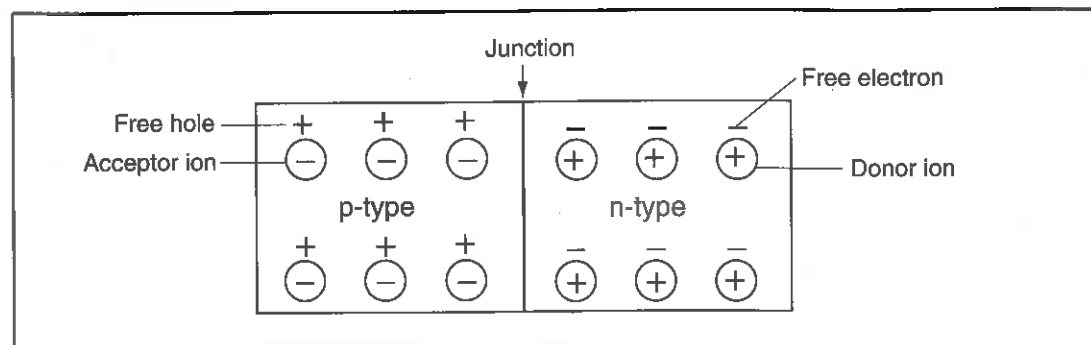


Fig. 11.9: p-n junction

Eventually, the free electrons and holes near the junction diffuse across the junction, such that the electrons enter the p-zone as holes move into the n-zone, see figure 11.10 (a). Re-combination of the mobile charge carriers takes place on either side of the junction, thus depleting mobile charge carriers within a region of about 10^{-4} to 10^{-6} m, see figure 11.10 (b).

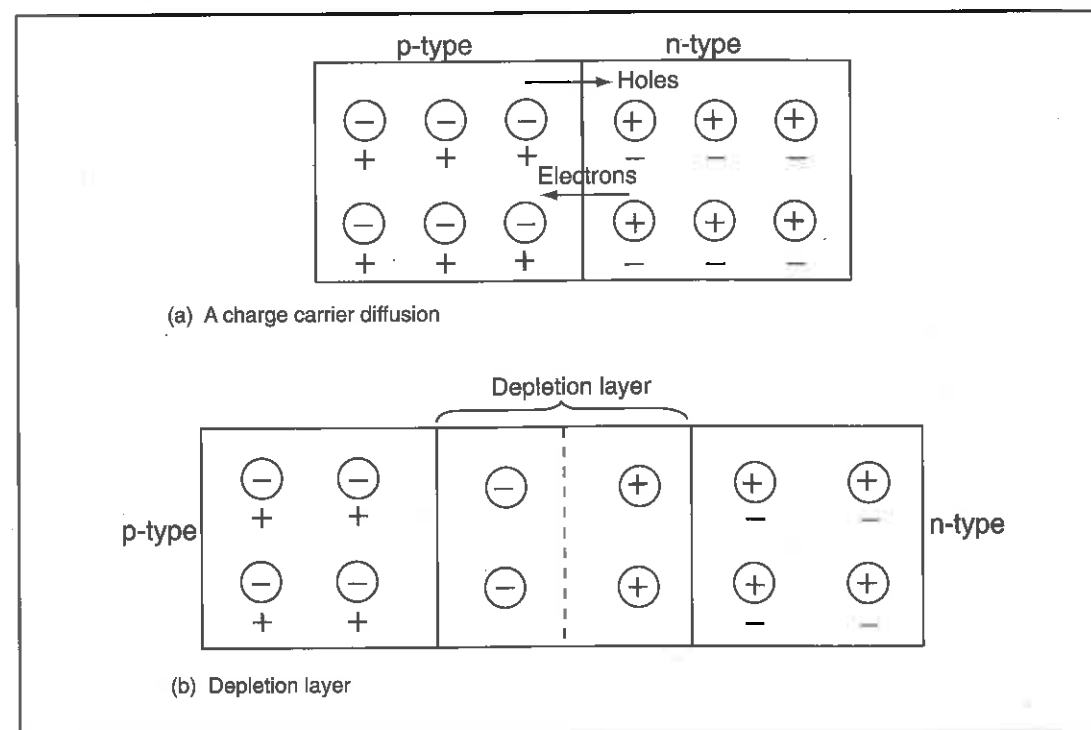


Fig. 11.10

This forms a region of uncovered fixed ions on either side of the junction. The uncovered ions set up a potential difference (potential barrier) which in turn sets up a field that stops further diffusion of mobile charges. This region occupied by the uncovered fixed ions is called the **depletion layer**. A potential barrier (V_B) of about 0.3 V is set up for germanium and 0.7 V for silicon. The potential barrier can be discerned as a 'hill' which the holes in the p-region have to surmount for them to move from p-type to n-type zone. The same electrical 'hill' stops electrons intending to cross from the n-type zone to the p-type zone, see figure 11.11.

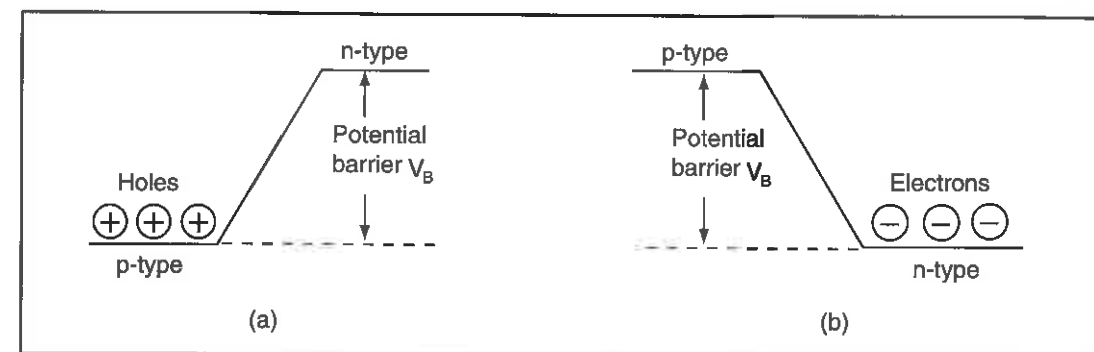


Fig. 11.11: Potential 'hill'

Biasing the p-n Junction

A p-n junction is said to be biased when a potential difference is applied across it.

Forward Biasing

A p-n junction is forward biased when the **p-type** region is connected to the **positive** and the **n-type** region to the **negative** terminal of an external cell or battery, see figure 11.12 (a). Before the p-n junction is biased, a potential barrier V_B exists, as in figure 11.11 (a) and (b).

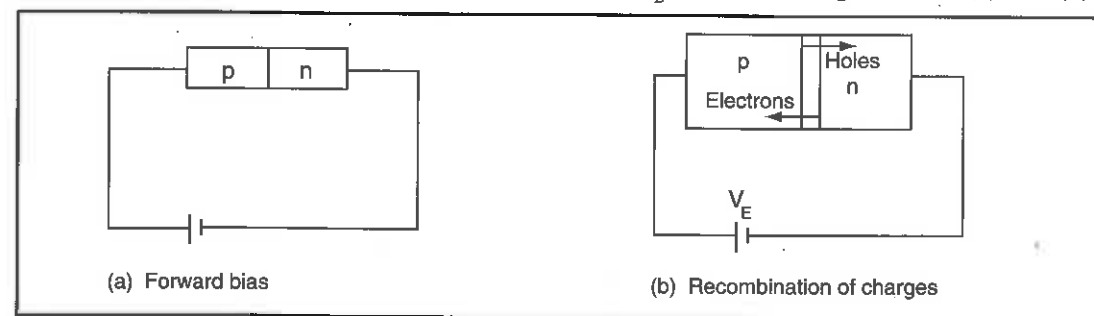


Fig. 11.12

The applied voltage, V_E , which is greater than the internal potential barrier V_B , opposes the latter by repelling holes from the p-type and electrons from the n-type, enabling the fixed ions in the depletion layer to regain their holes and electrons, see figure 11.12 (b). This reduces the potential barrier V_B and the thickness of the depletion layer considerably, thereby reducing the electrical 'hill' as shown in figure 11.13. The forward resistance is thus reduced as more charges flow across the junction with ease. Thus, a large forward current flows in the circuit.

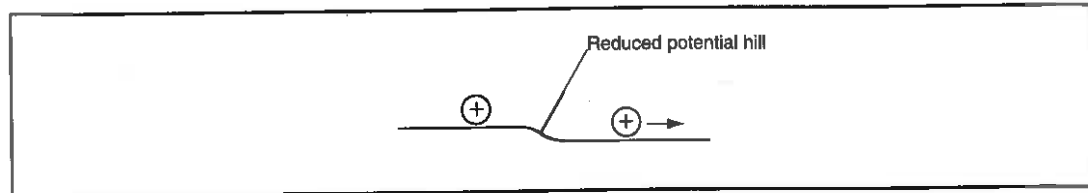


Fig. 11.13: Potential barrier overcome

Reverse Biasing

A p-n junction is reverse biased when the p-region is connected to the negative terminal while the n-region is connected to the positive terminal of a cell or battery, see figure 11.14 (a). The external voltage V_E is in the same direction as the potential barrier.

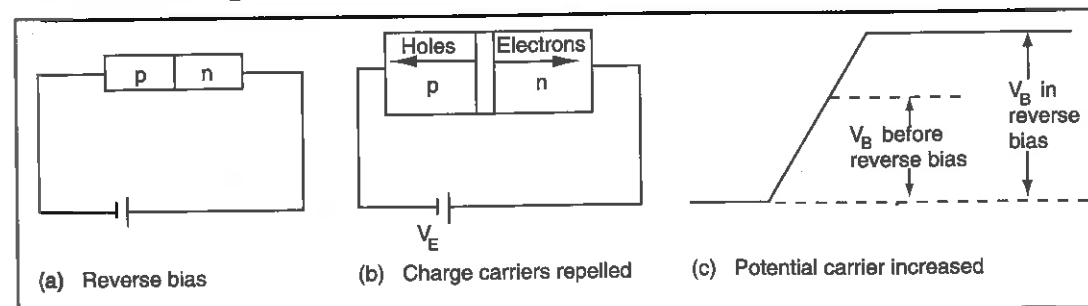


Fig. 11.14

The holes and electrons in their respective regions are attracted away from the junction by the external voltage, as shown in figure 11.14 (b). This increases the concentration of the fixed positive and negative ions and increases the thickness of the depletion layer. The potential barrier increases, hence increasing the resistance of the p-n junction, see figure 11.14 (c). However, a small current due to the flow minority charge carriers (**leakage current**) flows.

Semiconductor Diode (p-n Junction Diode)

This is a one-way conduction device consisting of a p-n junction and having two terminals, the anode and the cathode. Its circuit symbol is shown in figure 11.15.

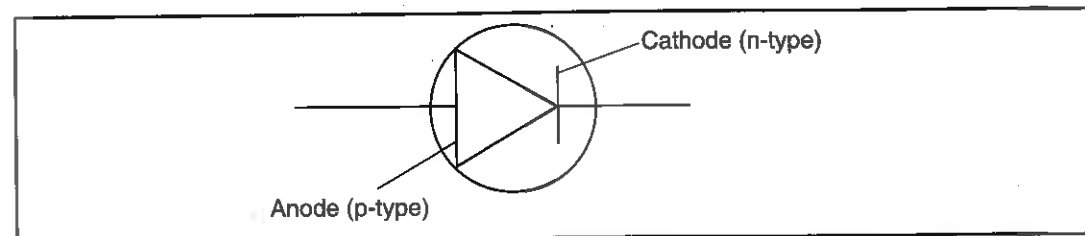


Fig. 11.15: Diode

The anode (p-type) and cathode (n-type) are represented by an arrowhead and a bar respectively. The arrowhead indicates the direction of conventional current when the diode is forward biased. Figure 11.16 (a) and (b) show the circuit diagrams of a diode in forward and reverse bias.

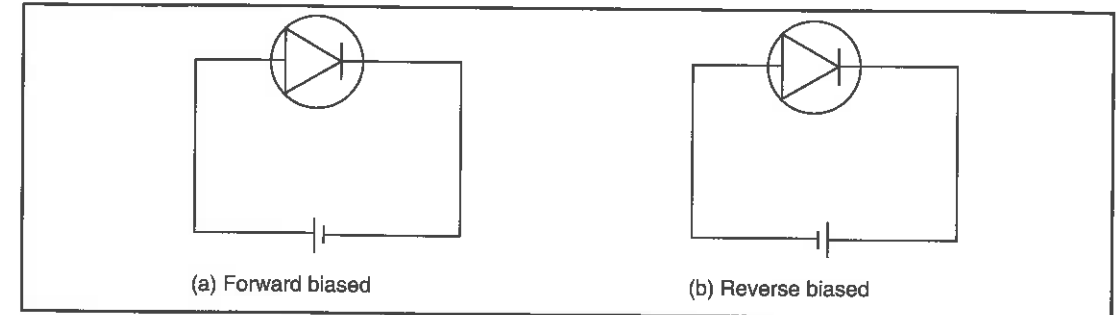


Fig. 11.16: Diode biasing

Diode Characteristics

EXPERIMENT 1.1: To study the forward and reverse characteristics of a p-n junction diode

Apparatus

Diode, potential divider, ammeter, voltmeter, cell.

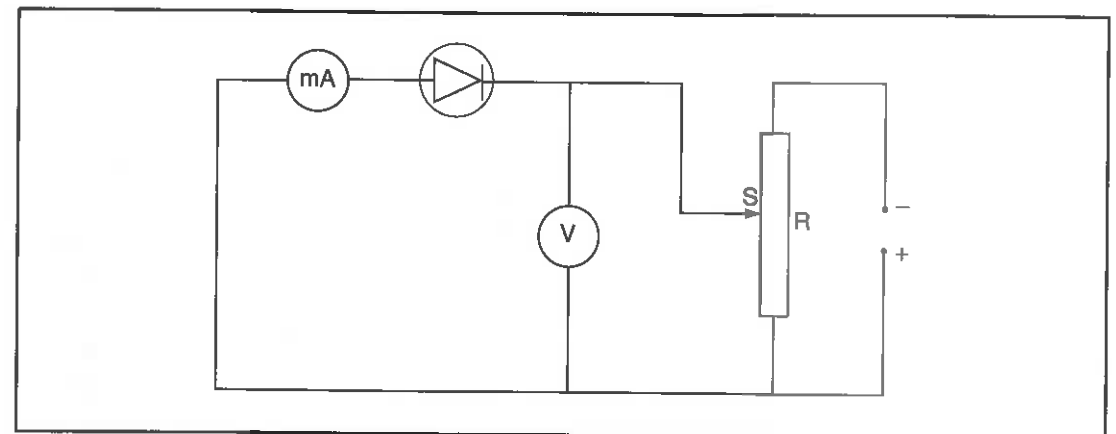


Fig. 11.17: Diode characteristics

Procedure

- Set up the circuit as shown in figure 11.16 for forward biasing.
- Increase the forward bias voltage in steps from zero and record the corresponding values of current in table 11.1.

Table 11.1

$I \text{ (mA)}$					
V_{FB}					

- Use the results in the table to plot a graph of $I \text{ (mA)}$ against $V_{FB} \text{ (V)}$.
- Repeat the experiment with the diode reverse biased and fill table 11.2.

Table 11.2

$I \text{ (mA)}$					
V_{RB}					

- Plot a graph of reverse bias current I against reverse bias voltage (V_{RB}).

Observation

When the graph is plotted for the forward bias the curve in figure 11.17 (a) is obtained.

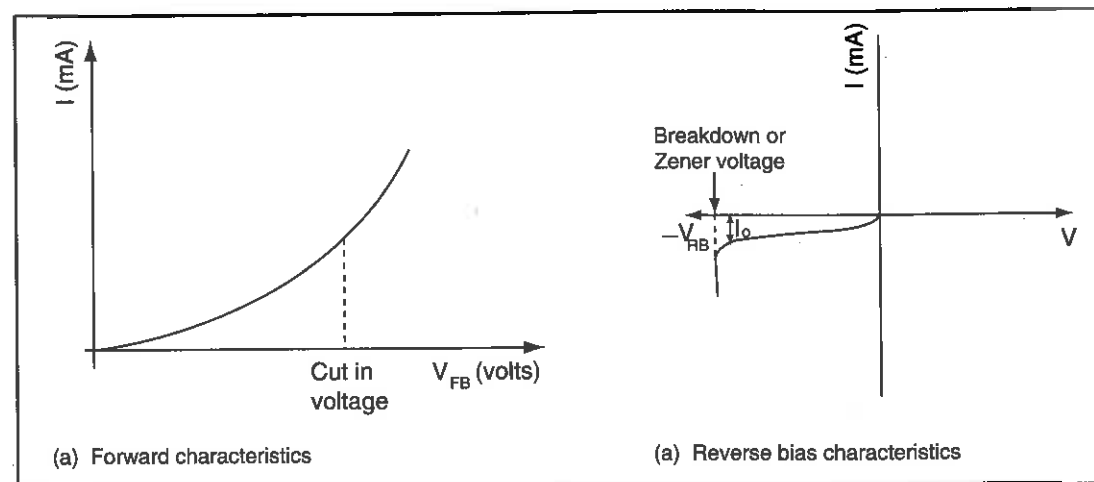


Fig. 11.18

The curve is non-linear, showing that a diode is non-ohmic. The current increases rapidly when the forward bias voltage is increased. For the reverse bias, see figure 11.17 (b), when the reverse bias voltage is zero, a small current (leakage current) flows. As reverse bias voltage is increased, there is no significant change in the current until a particular voltage (Zener or breakdown voltage) when a current surge is noted.

Explanation

As the voltage is increased from zero, a very small current flows through the diode because forward bias voltage is insufficient in opposing the potential barrier. Leakage current due to flow of minority charge carriers flows. When the potential barrier is completely overcome by the bias at the cut-in voltage (threshold or breakpoint voltage), charges easily flow across the junction, giving rise to the sharp increase in forward current.

When the diode is reverse biased, its resistance is high. The flow of leakage current results from flow of minority charge carriers. At breakdown or Zener voltage, some covalent bonds rupture, liberating electrons. This is called Zener breakdown. As the electrons move because of the applied voltage, they collide with some atoms, causing ionisation. This is called **avalanche breakdown**. The two processes produce excess electrons which are responsible

for the heavy conduction. When a diode is reverse biased to its breakdown voltage, it gets damaged. A damaged diode conducts irrespective of biasing. However some diodes (Zener diodes) are designed to operate within the breakdown region. Figure 11.18 shows the circuit symbol of a Zener diode.

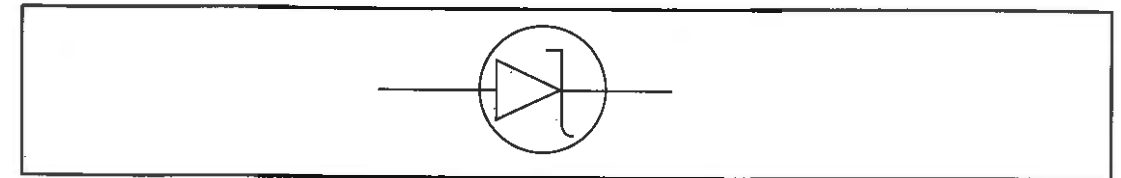


Fig. 11.19 Zener diode

In general, the combined characteristic of a diode is shown in figure 11.19.

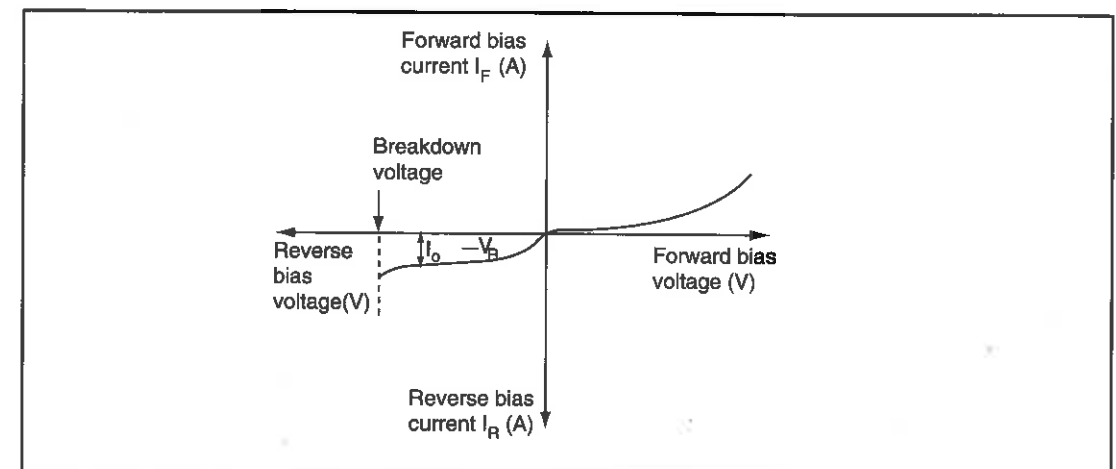


Fig. 11.20: Combined characteristics of a diode

Example 1

Find the current flowing through the resistors and voltage drops in figure 11.20. (Assume the diodes are ideal).

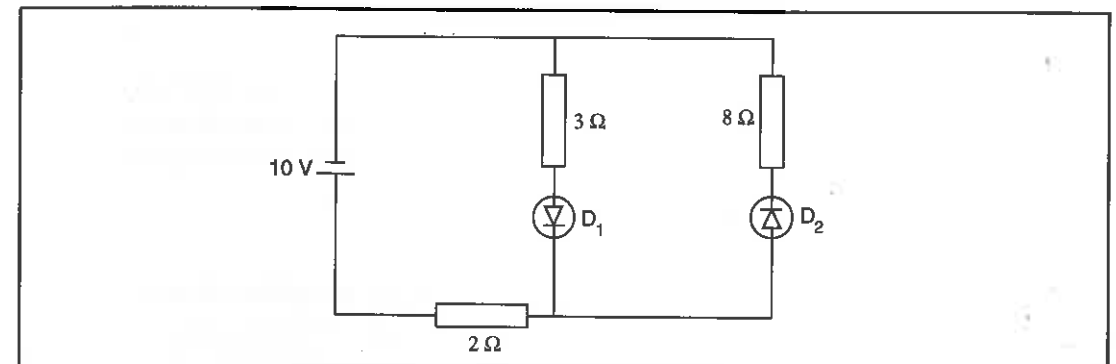


Fig. 11.21

Solution

Since diode D_1 is reverse biased, current does not flow through the $3\ \Omega$ resistor. Hence, there is no voltage drop across it. D_2 is forward biased, hence current flowing through the $2\ \Omega$ and $8\ \Omega$ resistors, taken to be in series, is given by;

$$I = \frac{V}{R}$$

$$= \frac{10}{10}$$

$$= 1\text{ A}$$

$$\therefore \text{Voltage across the } 2\ \Omega = 1 \times R$$

$$= 1 \times 2$$

$$= 2\text{ V}$$

Voltage across $8\ \Omega$ resistor is given by $1 \times 8 = 8\text{ V}$

Example 2

In the circuit diagram shown in figure 11.21, explain what happens when:

- S_1 is open and S_2 closed.
- S_1 is closed and S_2 open. The bulbs L_1 and L_2 are identical.

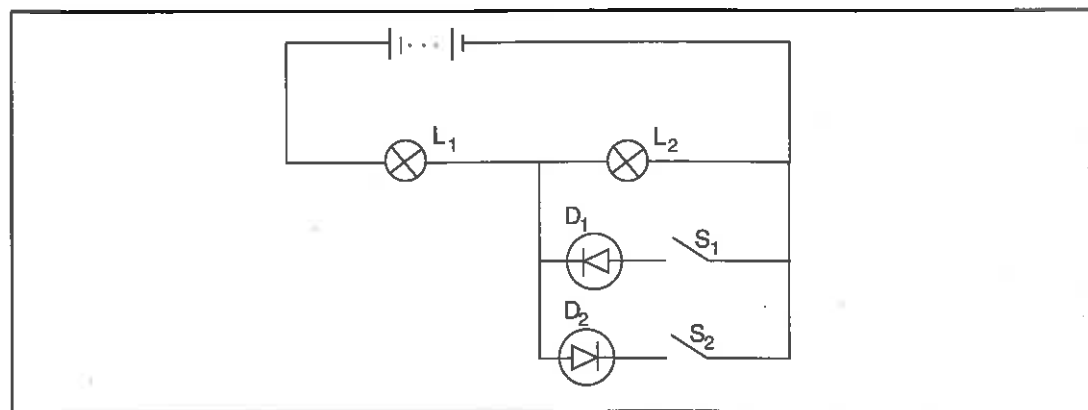


Fig. 11.22

Solution

- When S_1 is open and S_2 closed, the diode D_2 conducts heavily, hence short circuits bulb L_2 . Consequently, only L_1 lights brightly, because most of the voltage drop is across it.
- When S_1 is closed and S_2 open, D_1 is reverse biased, hence it does not take up any current. The two bulbs light dimly because they share the voltage supply.

Applications of Junction Diodes in Rectification

A rectifier is a device used in transforming an alternating voltage into a direct or unidirectional voltage. The process is called **rectification**. There are two types of rectification, namely:

- half-wave rectification.
- full-wave rectification.

A diode is used in rectification because it offers high resistance when reverse biased and low resistance when forward biased.

Half-wave Rectification

Half-wave reflection can be achieved by connecting a single diode in series with the load cross which a unidirectional voltage is required. This is shown in figure 11.22.

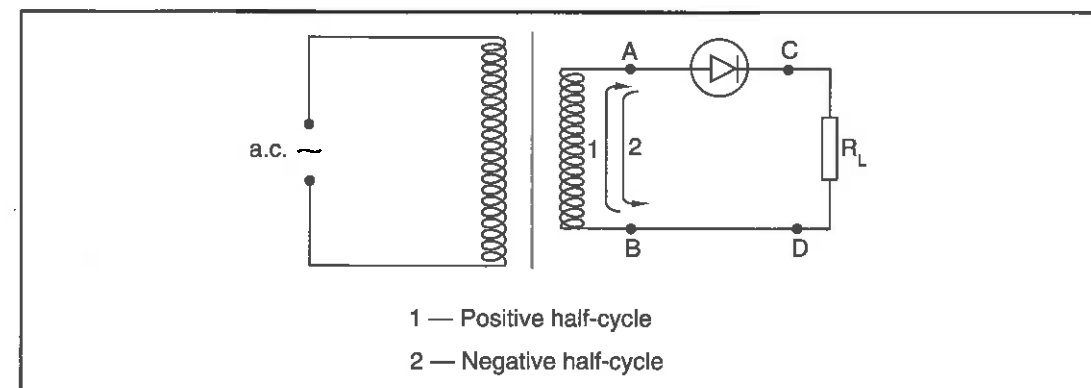


Fig. 11.23: Half-wave rectification

During the first half (positive) cycle, the diode is forward biased, so it conducts. Current flows through R_L , building a voltage across it which decreases as the first half-cycle comes to an end. On the onset of the second half-cycle (negative), the diode is reverse biased and so it does not conduct. The action repeats itself so long as the input voltage is being supplied.

When a CRO is connected across the points A and B, a trace obtained on the screen is as shown in figure 11.23 (a). When connected across points C and D, the trace is as shown in figure 11.23 (b).

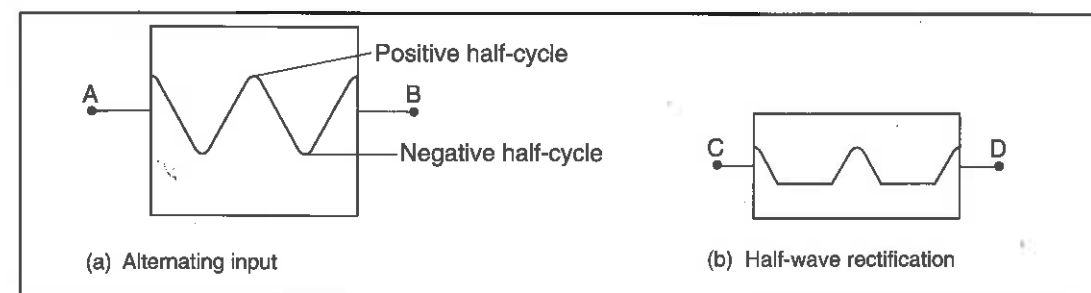


Fig. 11.24

The process is referred to as half-wave rectification because half of the input cycle is phased out in the output. The disadvantage of this rectification is that the output is not smooth and there is much power loss as one of the half-cycles is eliminated.

Full-wave Rectification

Full-wave rectification can be achieved using:

- (i) two diodes and center-tapped transformer.
- (ii) four diodes (the bridge rectifier).

Using Two Diodes

A centre-tapped transformer must be used to split the transformer output. Two diodes are connected in such a way that each conducts a current through the load resistor during a particular half cycle. Two possible circuits for this type of rectification are shown in figure 11.24 (a) and (b).

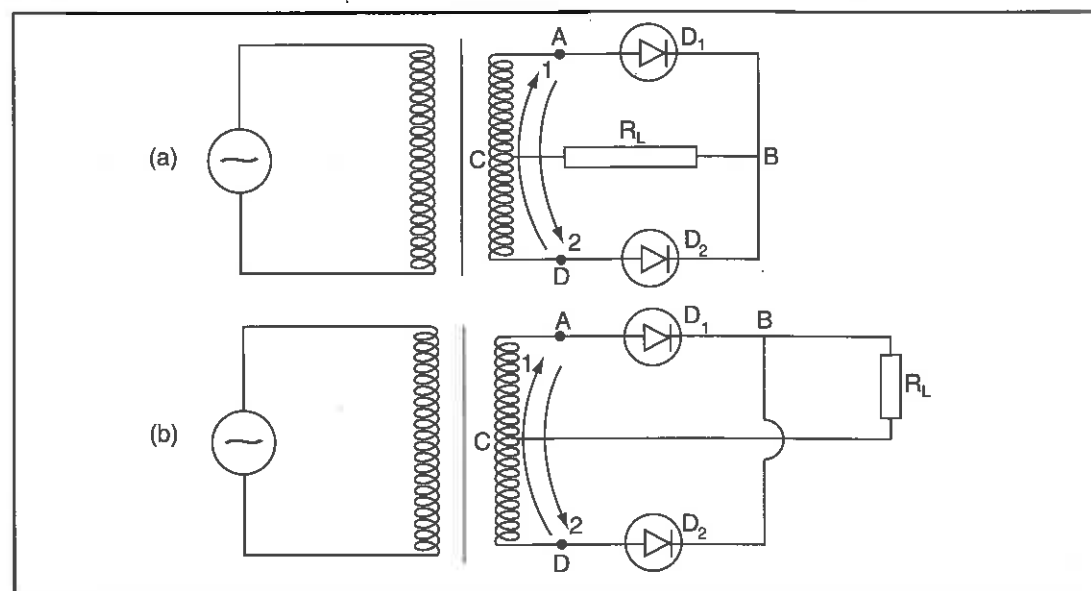


Fig. 11.25: Full-wave rectification

During the first half-cycle D_1 is forward biased while D_2 is reverse biased. Hence, the path taken by the current is AD_1BCA . During the next half-cycle, D_2 is forward biased while D_1 is reverse biased and the path of the current is DD_2BCD .

Notice that during both half-cycles, current flows through the resistor in the same direction. Figure 11.25 shows the contribution of each diode to make up the effective output.

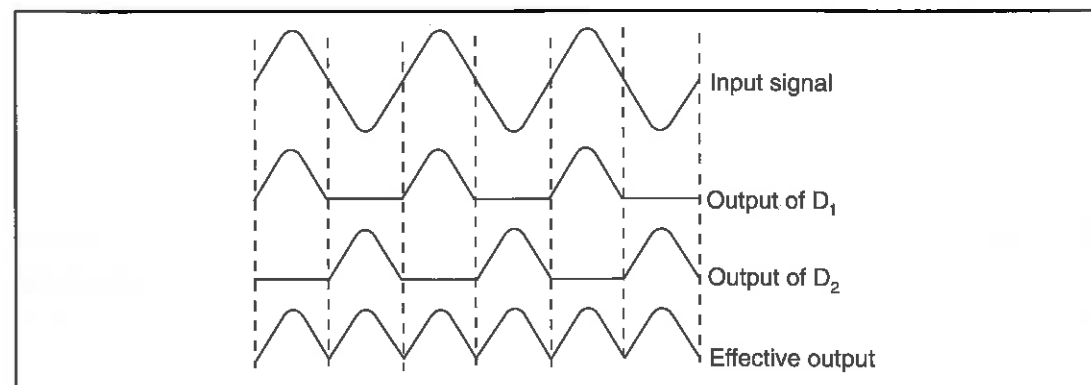


Fig. 11.26: CRO display of full-wave rectification

Bridge Rectifier

The bridge circuit consists of four diodes connected as shown in figure 11.26.

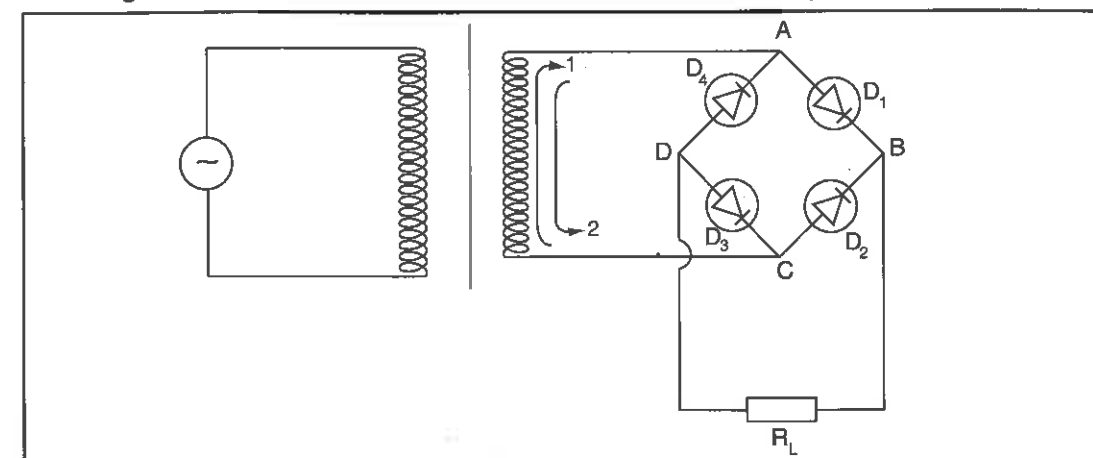


Fig. 11.27: Bridge rectifier

During the first half-cycle, point A is positive with respect to C, hence D_1 and D_3 are forward biased while D_2 and D_4 are reverse biased. The path of the current is thus $ABDCA$. During the second half-cycle, point A becomes negative with respect to C and diodes D_2 and D_4 become forward biased while D_1 and D_3 are reverse biased. The path of the conventional current is then $CBDAC$.

Notice that during both half-cycles, current flows through the load resistor R_L in the same directions. Some advantages of the bridge rectifier are:

- (i) a smaller transformer can be used, because there is no need for centre-tapping.
- (ii) it is suitable for high voltage regulation.

In general, the full-wave rectifier gives a stronger and smoother output than the half-wave rectifier. If a capacitor is connected across the resistor as shown in figure 11.27 (a), the rectified output is smoothened. Figure 11.27 (b) shows smoothened half-wave rectified output and 11.27 (c) smoothened full-wave rectified output.

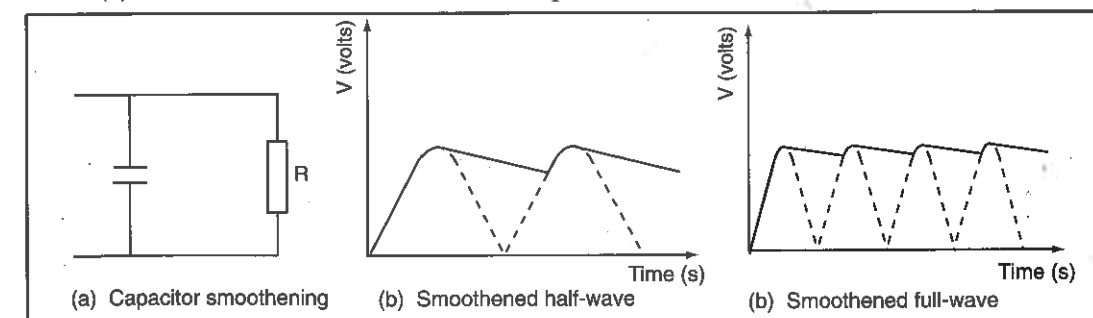


Fig. 11.28

Revision Exercise 11

1. Distinguish between conductors, semiconductors and insulators.
2. Explain why the conductivity of a metallic conductor decreases with increase in temperature while that of a semiconductor increases.

3. Define the following terms:

- Doping.
- A hole.
- Donor and acceptor impurities.
- n-type and p-type semiconductors.
- Acceptor and donor ions.

4. (a) Sketch the crystal structure of silicon containing a donor impurity atom.

(b) Describe how an n-type semiconductor is made. Is it negatively charged? Explain.

5. (a) What constitutes major parts of current in an intrinsic semiconductor?

(b) Explain why doping materials are called impurities.

6. (a) Draw circuit diagrams to distinguish between forward and reverse bias of a p-n junction diode.

(b) In an experiment to investigate the variation of current with voltage for a certain semiconductor diode, the following results were obtained:

Voltage (V)	0	0.8	1.0	1.2	1.4	1.6	1.8	2.0
Current (mA)	0	1	3	5	15	25	45	90

(i) Draw a possible circuit used to obtain these semiconductor results.

(ii) Plot the characteristics of the semiconductor from the results.

(iii) Find the resistance when the voltage is 1.8 V.

7. (a) What is a reverse characteristic?

(b) Plot the following reverse characteristic for a diode:

Voltage (V)	0	5.4	5.5	5.6	5.7	5.8
Current (A)	0	0.5	2.0	15	37.5	70

(c) What is the breakdown voltage for the diode?

8. (a) Explain what happens to the depletion layer when a diode is:

(i) forward biased.

(ii) reverse biased.

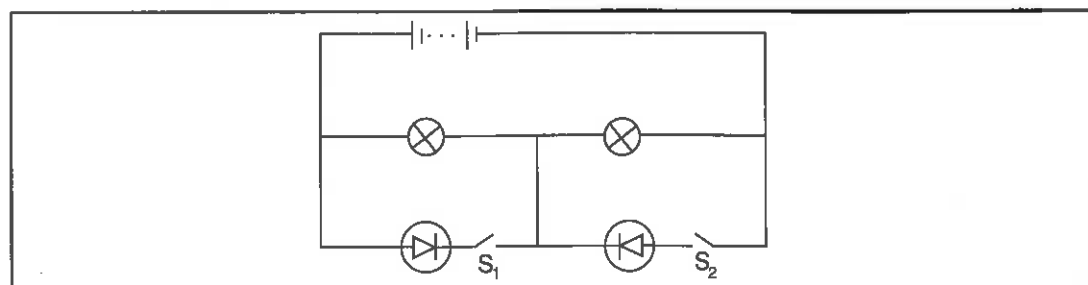
(b) How does the reverse saturation current of a p-n vary with temperature?

9. (a) Describe half-wave and full-wave rectification of an a.c. voltage by junction diodes.

(b) By drawing sketches, show the difference between a smoothed output of a full-wave rectifier and half-wave rectifier.

(c) Why is the bridge rectifier circuit better than the single diode rectifier?

10. (a) The figure below shows a diode circuit:



(i) Explain what happens when S_1 and S_2 are closed.

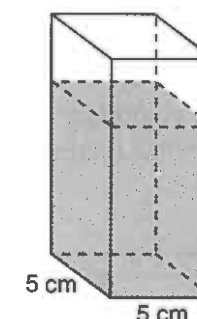
(ii) Explain what happens when only S_2 is closed.

(iii) What is a Zener diode?

Sample Papers

SAMPLE PAPER ONE

1. The figure below shows a perspex container with a square base of side 5 cm carrying water to a height of 7 cm.



When a pebble is immersed into the water, the level rises to 10 cm. What is the volume of the pebble? (2 marks)

2. Explain why a needle dropped on water sinks and yet if it is placed gently, it floats. (1 mark)

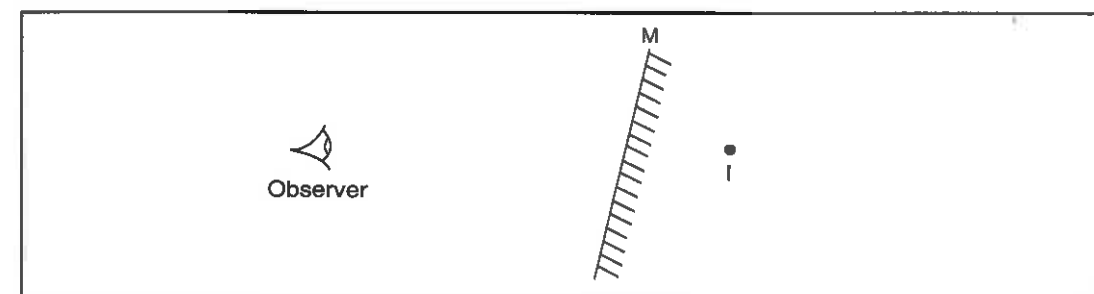
3. The lift pump is effective for pumping water as long as the well is less than 10 m deep. Explain. (2 marks)

4. What happens to the motion of smoke particles in the smoke cell experiment when the apparatus is moved from a warm to a cooler environment? (1 mark)

5. State the law of electrostatic charges. (1 mark)

6. Give a reason why a concrete beam reinforced with steel does not crack when subjected to changes in temperature. (1 mark)

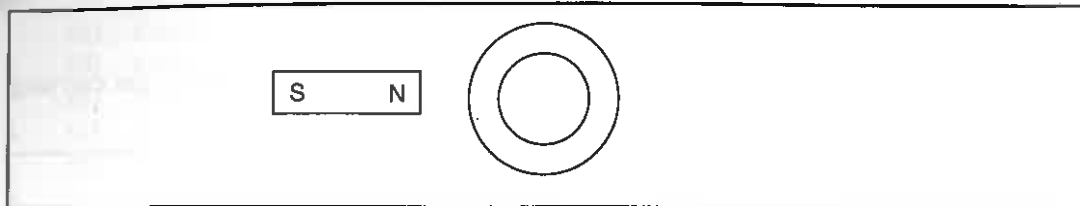
7. The figure shows the image I of an object placed in front of the mirror M.



By ray diagram construction, locate the position of the object. (3 marks)

State one advantage of lead-acid accumulator over nickel-alkaline cell. (1 mark)

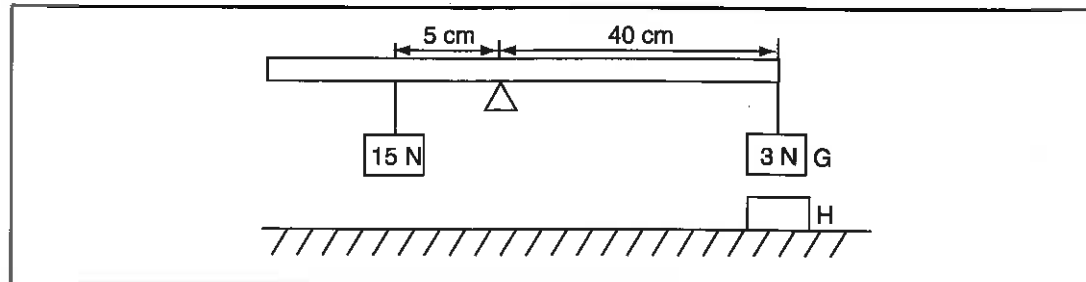
9. The figure below shows a copper ring lying next to the north pole of a magnet.



Complete the diagram to show the correct magnetic field pattern for the arrangement. (2 marks)

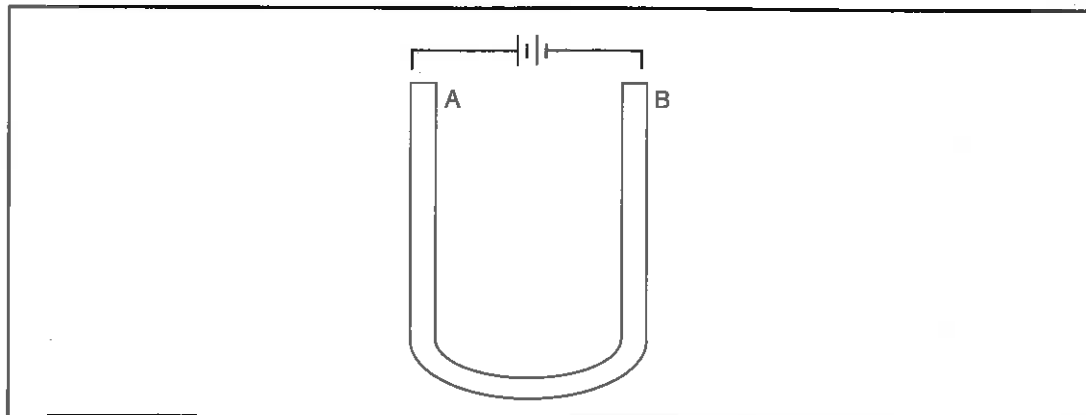
10. In an oil-drop experiment, a student estimated the diameter of an oil molecule as 1.62×10^{-9} m. Given that the volume of the oil drop was 0.22 mm^3 , determine the area of the patch. (3 marks)

11.



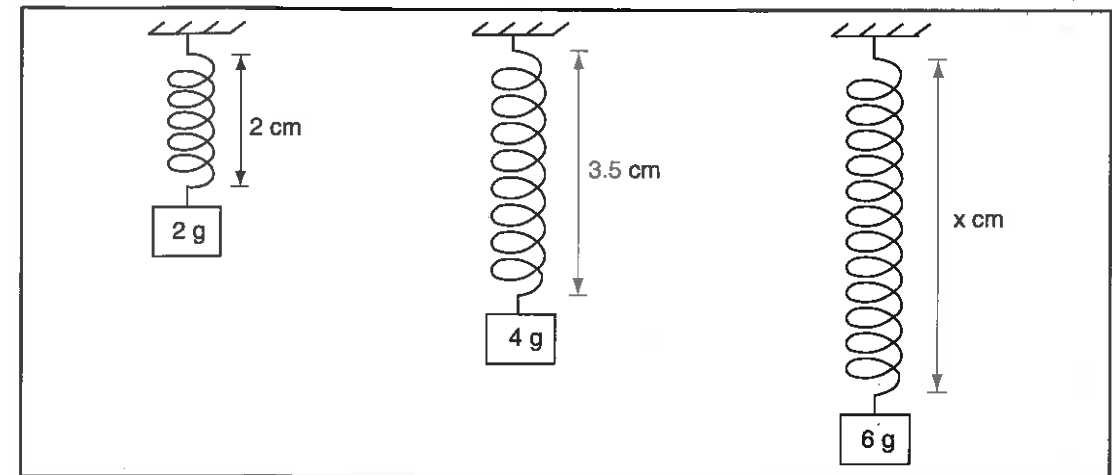
The figure above shows a light rod balanced due to the action of the forces shown. G is a magnet of weight 3 N and H is a permanent magnet which is fixed. Determine the force between G and H, stating whether it is attractive or repulsive. (3 marks)

12. Name and explain the features that make a retort stand stable. (2 marks)
13. A girl observes her face in a concave mirror of focal length 90 cm. If the mirror is 70 cm away, state two characteristics of the image observed. (2 marks).
14. The figure below shows a U-shaped magnetic material with an incomplete electric circuit:



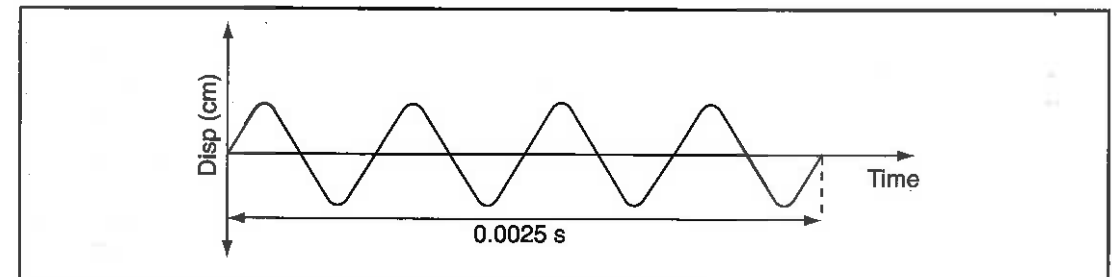
Complete the winding to give a north pole at A and south pole at B.

15. The figure below shows three identical springs which obey Hooke's law:



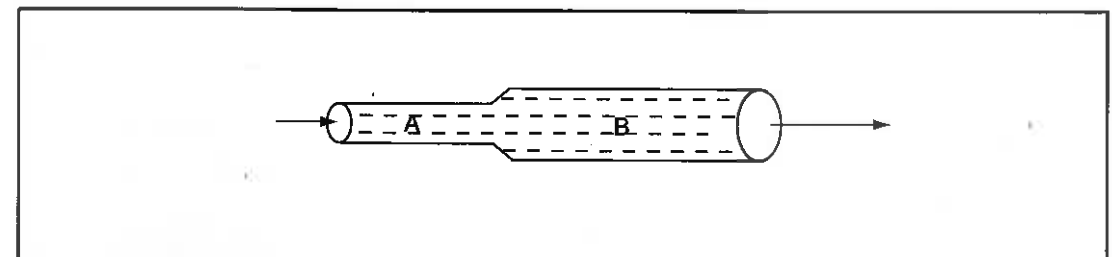
Determine the value of x. (2 marks)

16. The figure below shows a displacement-time graph:



What is the frequency of the waveform shown? (2 marks)

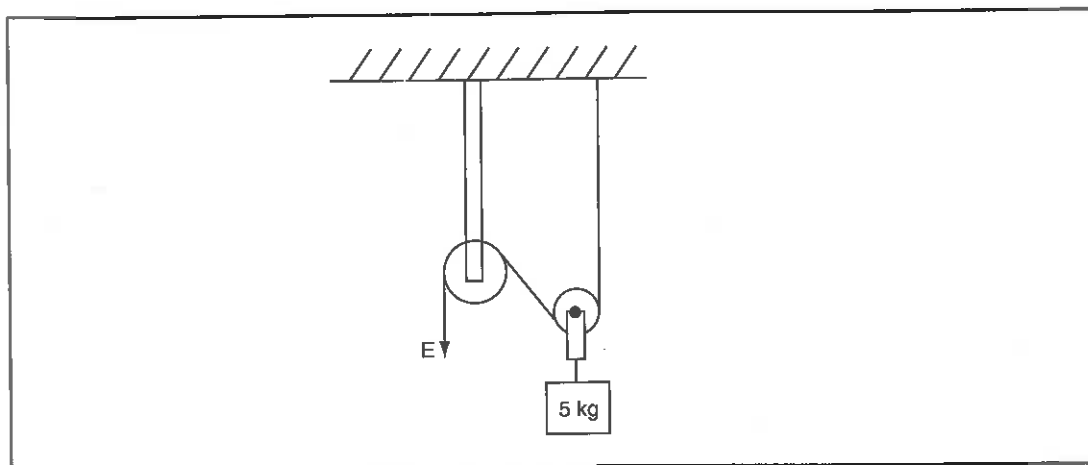
17. State two factors affecting the speed of sound in air. (2 marks)
- 18.



Water flows in a horizontal pipe of varying diameter as shown above. If the cross-sectional area of A is 4.5 cm^2 and that of B is 50 cm^2 , and the rate at which water flows at A is 100 ms^{-1} , calculate the speed of water through B. (3 marks)

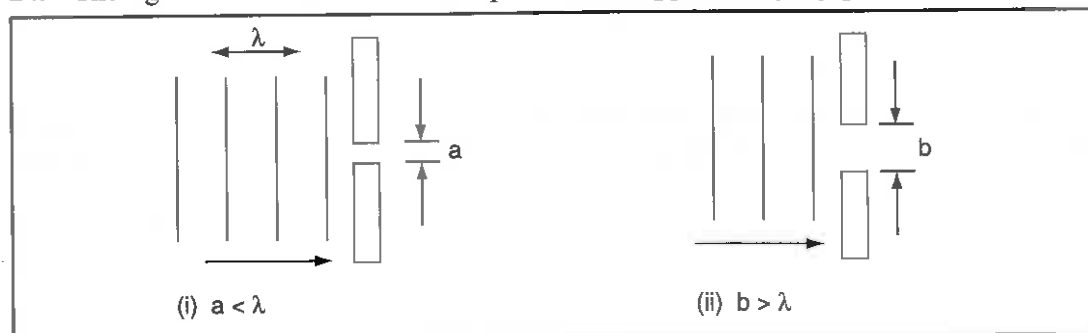
19. A body accelerates uniformly from initial velocity u to final velocity v in time t . If acceleration during this motion is a and the distance covered is S , show that $v^2 - u^2 = 2aS$. (3 marks)

20. State the two necessary conditions for total internal reflection to occur. (2 marks)
21. A rain drop falling from 500 m high is not likely to attain a velocity of 100 ms^{-1} . Explain. (2 marks)
22. The figure represents a pulley system supporting a load of 5 kg:



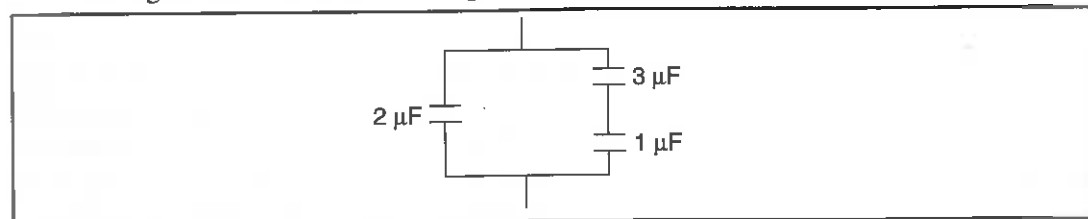
Given that efficiency of the system is 80 %, determine the effort E. (3 marks)

23. A cell drives a current of 2.5 A through a 0.8Ω resistor. When the same cell is connected to a 1.40Ω resistor, the current that flows is 1.6 A. Find the internal resistance and e.m.f. of the cell. (3 marks)
24. The figure below shows a series of plane waves approaching a gap:



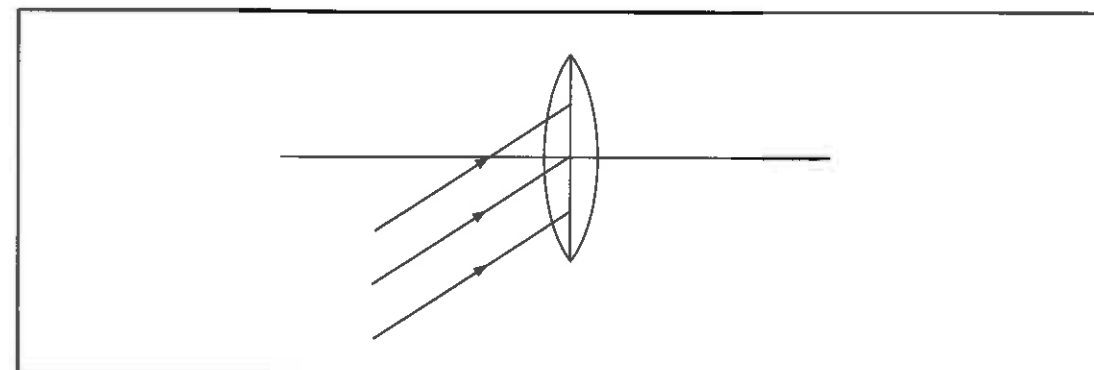
Complete the diagrams to show the wave after passing through the gap. (2 marks)

25. The figure shows a network of capacitors:



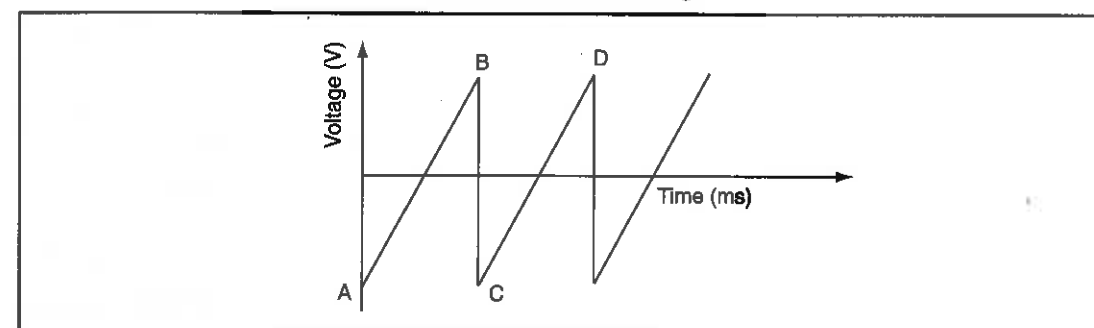
Determine the combined capacitance for the network. (2 marks)

26. The element of an electric hot plate has a resistance of 60Ω . What is the energy dissipated when the element is kept on for 20 minutes on a 240 V supply? (3 marks)
27. Distinguish between heat capacity and specific heat capacity of a body. (1 mark)
28. A given mass of gas has a volume 0.3 m^3 at a temperature of 47°C . If it is now heated to 127°C without change in pressure, what will be its new volume? (3 marks)
29. The figure below shows three parallel rays incident on a convex lens.



Complete the diagram to show the effect of the lens on the rays. (2 marks)

30. A bucket full of water is whirled in a vertical circular path of radius 1.6 m. Determine the minimum speed required to keep the water intact. (3 marks)
31. A body weighs 3.8 N in air and 2.8 N when fully immersed in water. Find the density of the body. (Density of water is 1 gcm^{-3}) (3 marks)
32. The following form part of the electromagnetic spectrum; gamma rays, visible, light, X-rays, microwaves, radio waves. Arrange them in order of increasing frequency. (1 mark)
33. State the role of the aluminium former in the moving-coil milliammeter. (1 mark)
34. Define the kilowatt-hour. (1 mark)
35. The figure below is a sketch of the time-base voltage:



State what happens to the spot along sections:

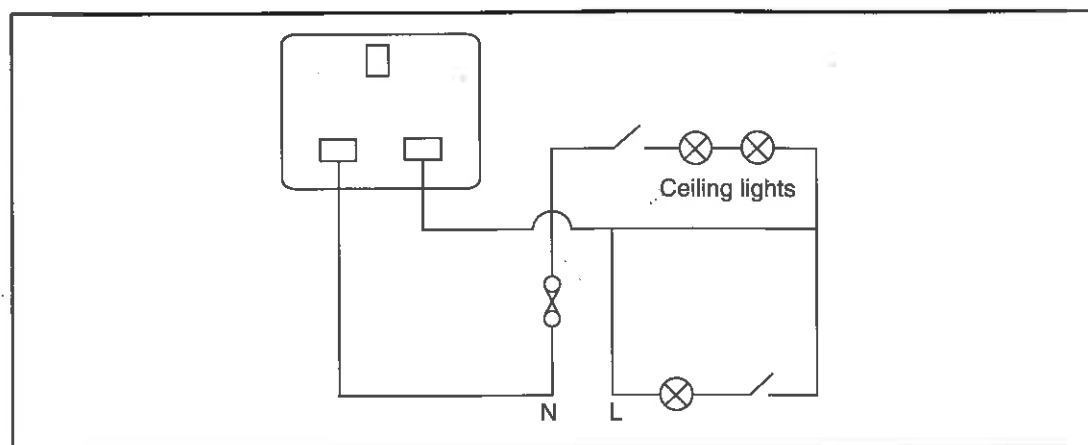
- (a) AB.
(b) BC.

36. What are the main charge carriers in an n-type semiconductor? (2 marks)

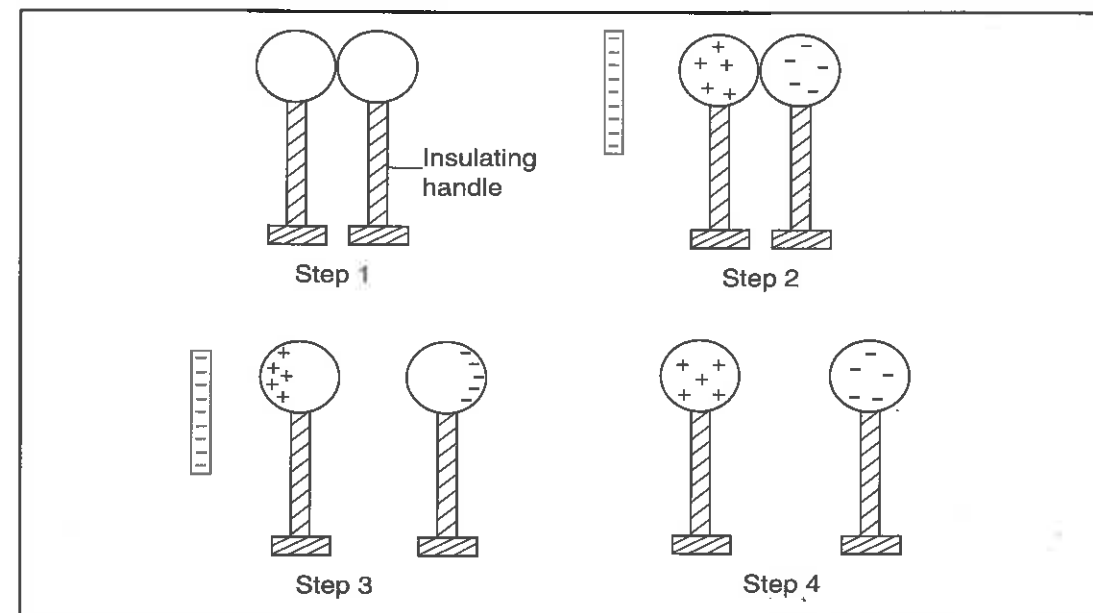
(1 mark)

SAMPLE PAPER TWO

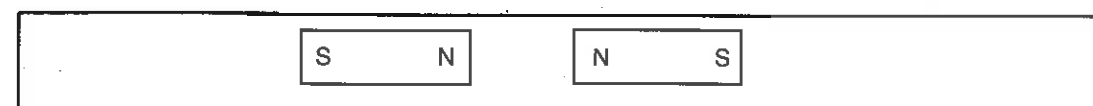
1. (a) The figure below shows a domestic wiring system.



- (i) Study the diagram and point out two faults in the circuit. (2 marks)
 - (ii) What is the fuse made of and why is it necessary in the circuit? (2 marks)
 - (iii) The power cables are usually thicker than the cables in the lighting system. Why? (1 mark)
- (b) (i) Draw a circuit that you could use to measure the internal resistance and the e.m.f. of a cell. (2 marks)
- (ii) Using your labelled diagram, describe carefully an experiment to determine the internal resistance and the e.m.f. of a cell, stating the assumption made. (6 marks)
2. (a) A block of metal A having a mass of 40 kg requires a horizontal force of 100 N to drag it with uniform velocity along a horizontal surface.
- (i) Calculate the coefficient of friction. (3 marks)
 - (ii) Determine the force required to drag a similar block of metal B having a mass of 30 kg along the same horizontal surface. (2 marks)
 - (iii) If the two metal blocks A and B are connected with a tow-bar and a force of 200 N is applied to pull the two along the same surface, calculate:
 - (a) the tension in the tow-bar. (1 mark)
 - (b) the acceleration. (3 marks)
 - (iv) If the tow-bar is removed and the 40 kg block of metal moves around a smooth path of radius 10 m at a constant speed of 24 ms^{-1} , calculate the centripetal force. (3 marks)
 - (v) At the end of the circular path, the 40 kg mass drops vertically in a trench 10 m high and falls freely. Determine the time it takes to land at the bottom of the trench. (3 marks)
3. (a) The following represents the steps followed in charging a body:

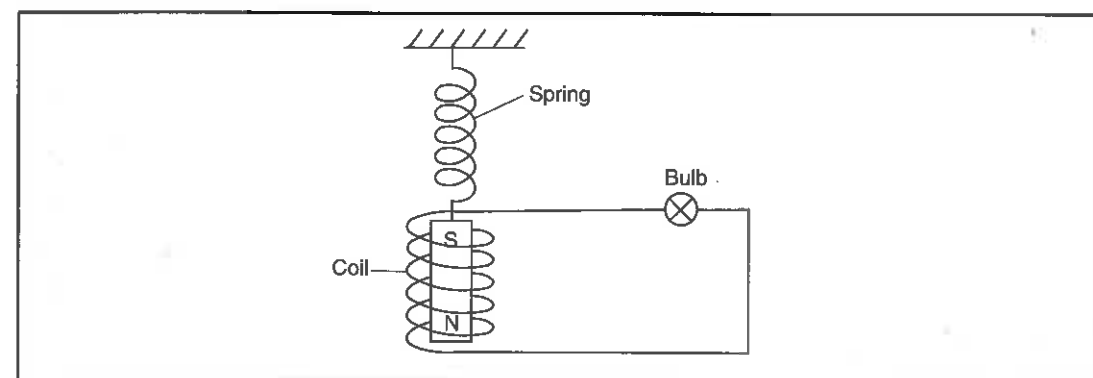


- (i) What name is the method given? (1 mark)
 - (ii) Briefly explain each of the steps:
 - Step 1.
 - Step 2.
 - Step 3.
 - Step 4.
- (b) The diagram below shows two bar magnets placed on a flat surface: (4 marks)

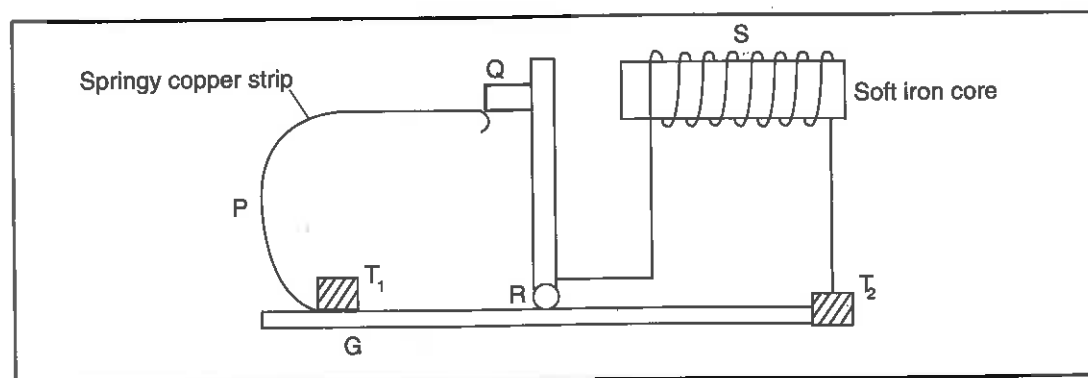


Complete the diagram to show magnetic field patterns around the magnets.

- (c) For the arrangement shown, the magnet is made to oscillate inside a coil connected to a bulb:

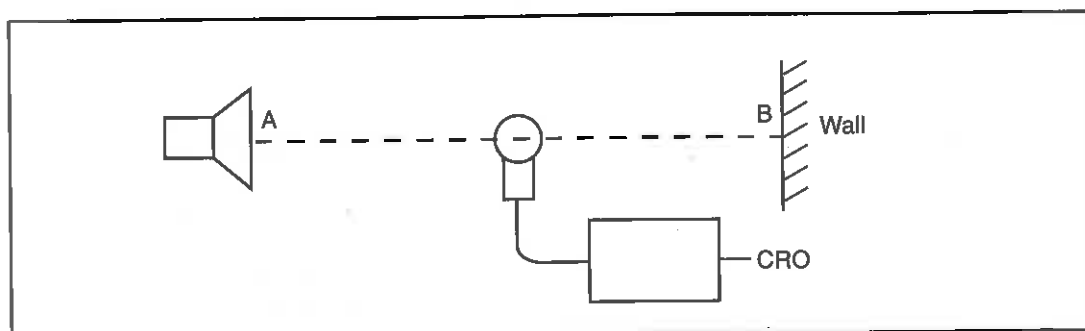


- (i) Explain what is observed. (2 marks)
 (ii) How can the arrangement be developed to make the bulb light longer? (1 mark)
 (d) A circuit-breaker is designed to disconnect a circuit if current is excessive. Below is model of circuit breaker:



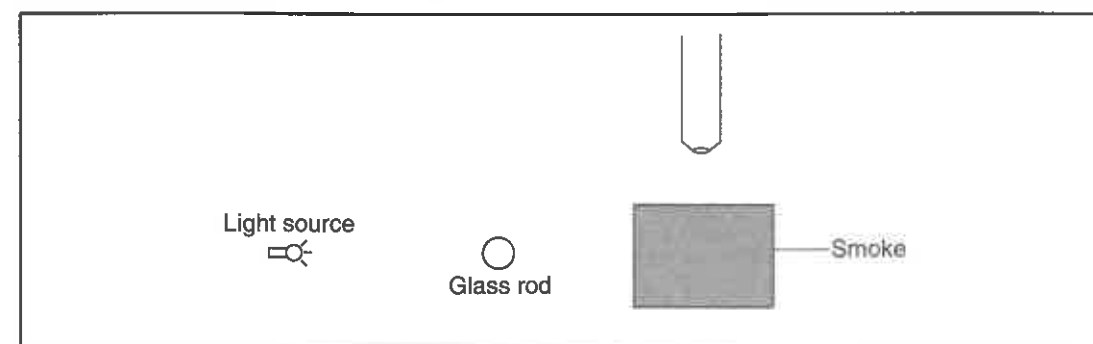
Current enters at terminal T_1 to terminal T_2 through P, Q, R and S. QR is pivoted at R. Study the diagram and explain how it works. (3 marks)

4. (a) The diagram below shows an arrangement that can be used to determine the speed of sound in air.

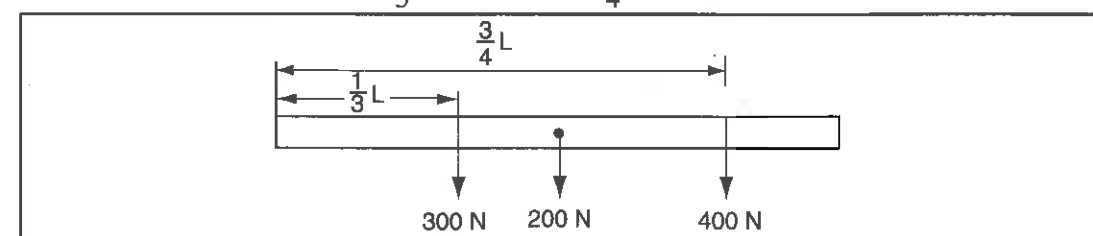


A microphone connected to a CRO with its time-base off is moved along an imaginary line AB between the wall and the loudspeaker.

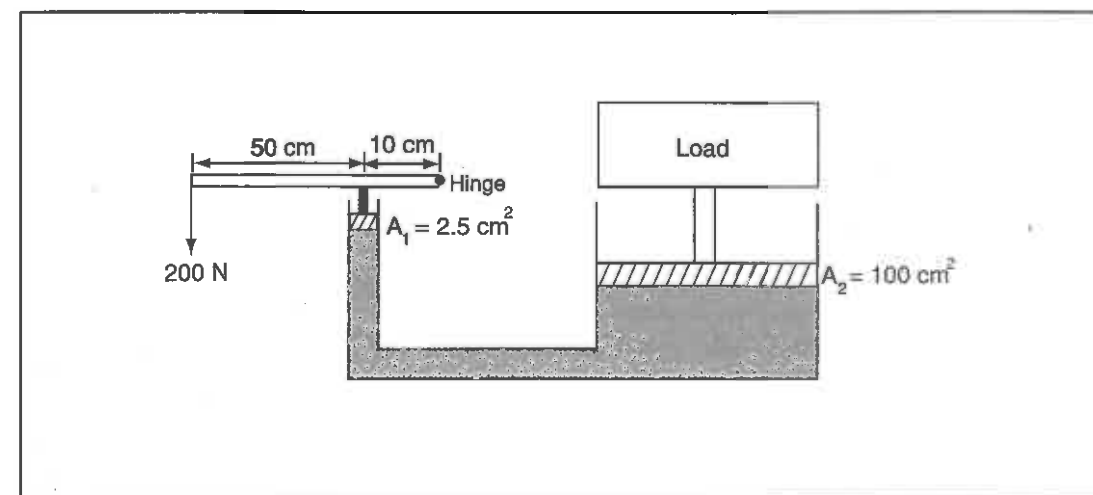
- (i) Use a diagram to explain what is observed as the CRO is moved from A to B.
 (ii) If the frequency of the sound emitted by the loudspeaker is 1 650 Hz and the distance between a minimum and the next maximum is 0.05 m, calculate the velocity of sound in air. (3 marks)
 (iii) If the frequency of the vibrating loudspeaker is decreased, what happens to the distance between two adjacent maximum? (1 mark)
 (b) You are provided with a glass block, two drawing pins, plain paper, softboard and four optical pins. Describe an experiment to verify Snell's law. (7 marks)
 5 (a) The diagram below shows apparatus used to study Brownian motion using smoke trapped in a glass cell.



- (i) Explain what is seen when looking at the trapped smoke using the microscope. (2 marks)
 (ii) What is the purpose of the glass rod? (2 marks)
 (iii) State two advantages of using smoke particles in the experiment. (2 marks)
 (b) The figure below shows a uniform plank of length weighing 200 N, carrying weights of 300 N at $\frac{1}{3}L$ and 400 N at $\frac{3}{4}L$ from one end:

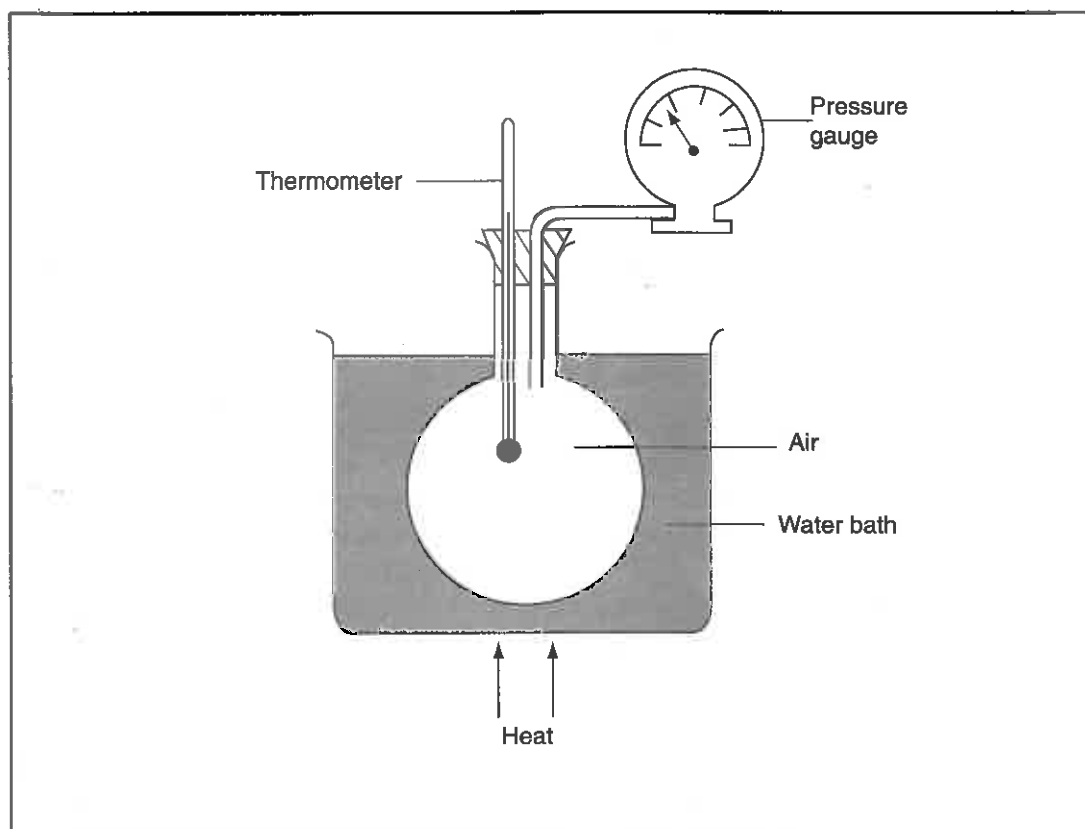


- (i) Find single force required to produce equilibrium. (1 mark)
 (ii) Through which point does the force act? (3 marks)
 (c) The figure below shows a hydraulic lift used to lift a load:



An effort of 200 N is applied to the lever. Determine the load that can be supported. (3 marks)

6. (a) The figure below shows a set-up of apparatus that may be used to verify the pressure law:



(i) State the necessary measurements used to verify the law. (2 marks)

(ii) State the assumptions made. (1 mark)

- (b) The table below shows values of pressure P in fresh water at different depths, h .

Pressure P (kPa)	110	140	180	200	220
Depth h (m)	1.0	4.0	8.0	10	12.2

(i) Plot a graph of pressure (y-axis) against depth. (5 marks)

- (c) Given the equation $P = P_0 + \rho gh$, determine from the graph:

(i) the value of P_0 .
(ii) the density ρ of fresh water. (3 marks)

- (d) In an experiment to determine the relative density of a liquid, the following measurements were obtained:

Weight of block in air = 0.237 N

Weight of block in water = 0.207 N

Weight of block in a liquid = 0.213 N

Use the measurements to determine the relative density of the liquid. (3 marks)

7. (a) What is radioactivity? (1 mark)

- (b) A radioactive source placed at 12 cm from the detector produced a constant count rate of 5 counts per minute. When the source is moved close to 3 cm, the count rate varied as follows:

Time (min)	0	20	40	60	80
Count-rate	101	65	43	29	21

(i) What type of radiation is being emitted? (1 mark)

(ii) Explain the constant count rate when the source is at a distance 12 cm away. (2 marks)

(iii) Plot a graph of count rate versus time. (5 marks)

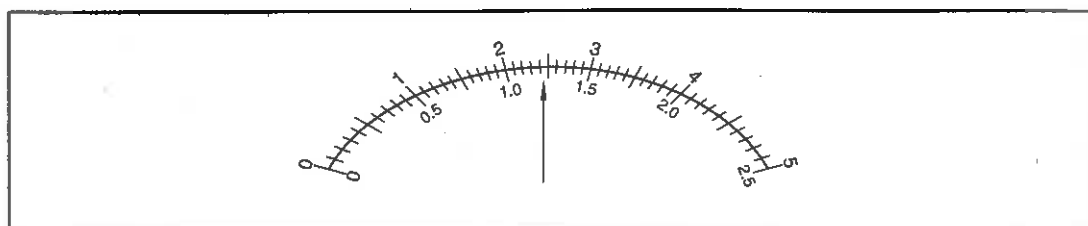
(iv) From the graph, estimate the half-life for the source. (2 marks)

- (c) State **one** similarity and **one** difference between X-rays and gamma rays. (2 marks)

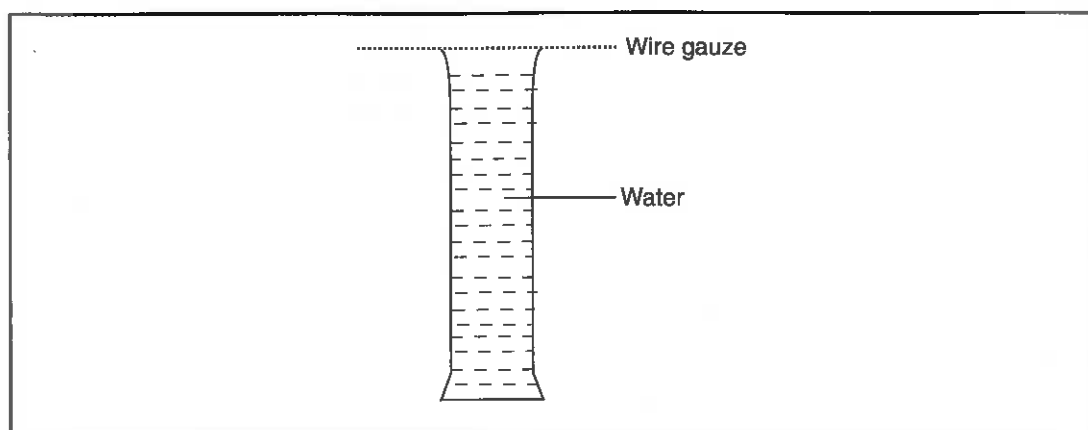
- (d) A sample of a certain nuclide which has a half-life of 1 500 years has an activity of 32 000 counts per hour presently. Plot a graph of activity of this sample over the period in which it will reduce to $\frac{1}{16}$ of its present value. (2 marks)

SAMPLE PAPER THREE

1. What is the reading on the lower scale of the meter shown below? (1 mark)

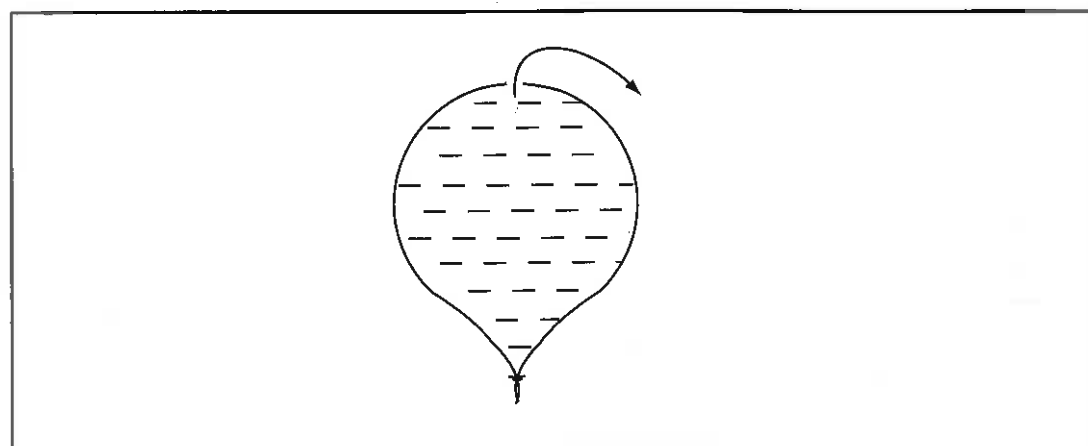


2. The figure 2 below is of a gas jar completely filled with water and then covered with a wire gauze.



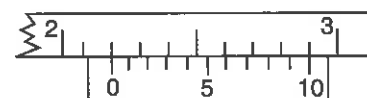
Explain why the water does not flow through the gauze when the set-up is suddenly inverted. (2 marks)

3. The figure below is of a polythene bag full of water and pierced at the upper part:



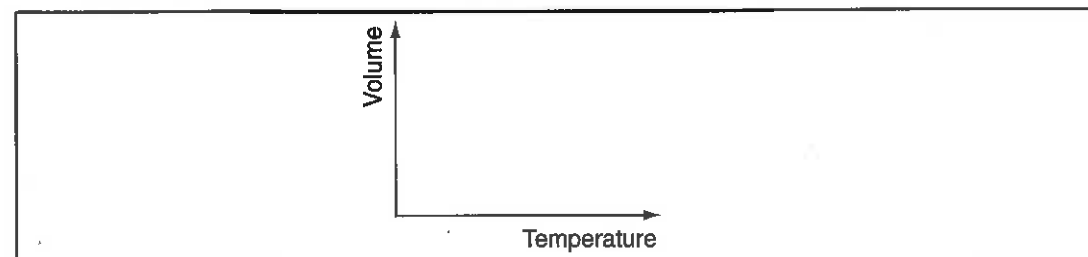
Explain why a jet of water flows outwards as shown. (2 marks)

4. The figure below shows vernier callipers scale.

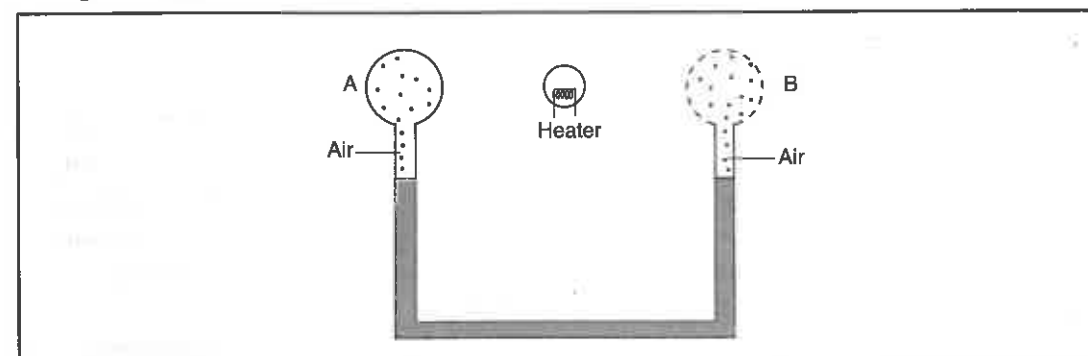


State the correct reading of scale if the instrument has a zero-error of -0.02 cm. (2 marks)

5. Give a reason why attraction in magnetism is not regarded as a reliable method of testing polarity of a magnet. (1 mark)
6. Equal volumes of water and paraffin at 0°C are subjected to heat up to 10°C . On the same axes below, sketch graphs of their volumes against temperature. (2 marks)

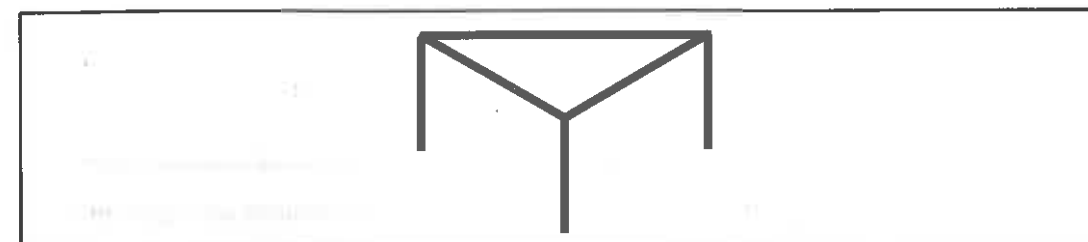


7. The figure below shows two bulbs A and B interconnected by U-shaped glass tube containing light oil. Bulb A is painted white while B is colourless. An electric heater is placed equidistant from the bulbs:

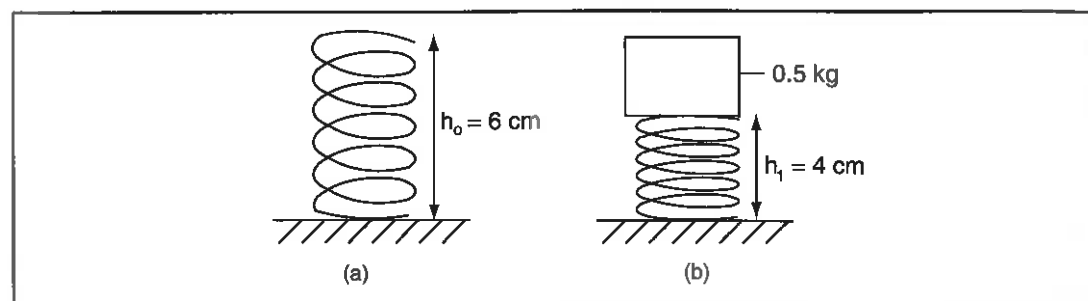


State and explain the observations made when the heater is switched on for some time. (3 marks)

8. The figure below shows a metal tripod stand. Complete the diagram to show how you would estimate its centre of gravity. (2 marks)

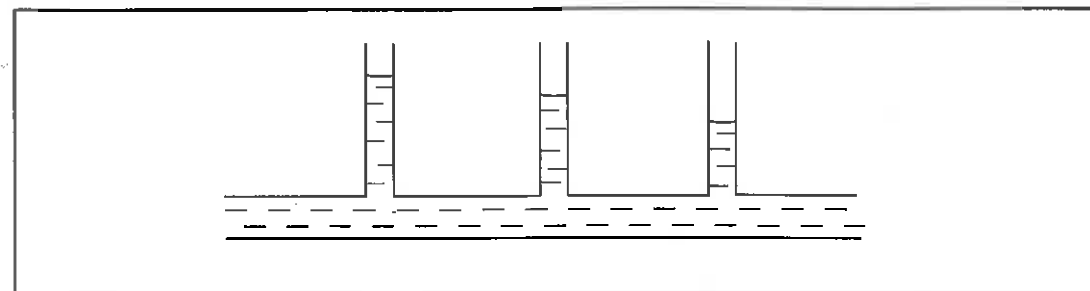


9. Explain why it is difficult to close a door by pulling it next to the hinges. (2 marks)
10. The figure below shows a spiral spring fixed on a bench vertically. A mass of 0.5 kg is placed on top as shown in (b).

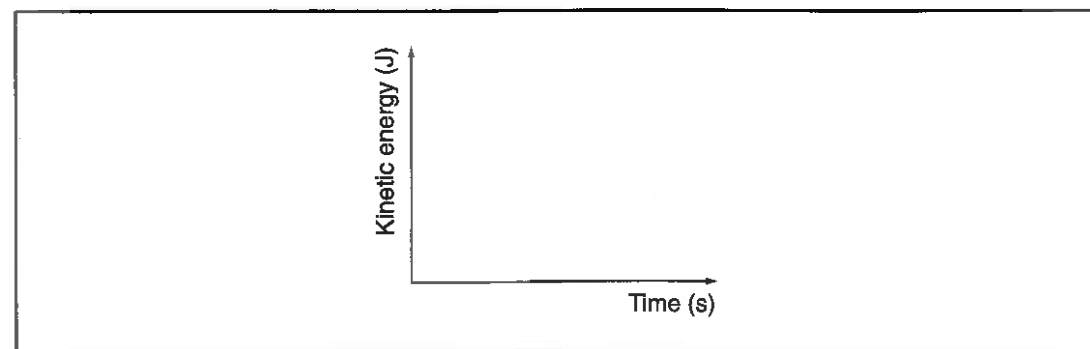


In (a) the height h_0 of spring is 6 cm while in (b), the height h is 4 cm. Find energy stored in the spring in (b). (3 marks)

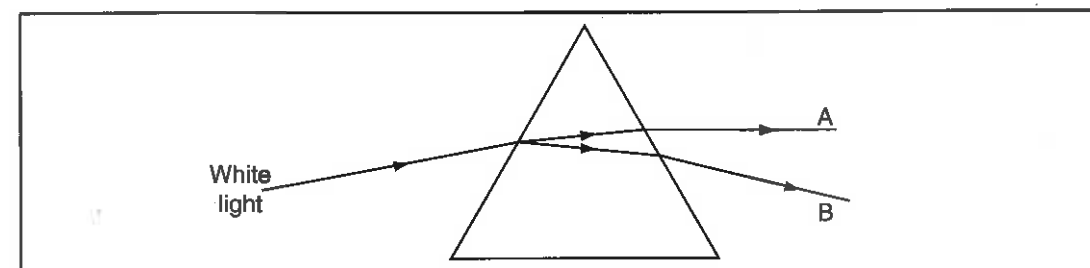
11. With the aid of a diagram, explain what is meant by two transverse waves being in phase.
12. An echo sounder sends sound signals to the bottom of a lake and receives them back after 0.08 seconds. Find the depth of the lake.
13. The figure below shows water flowing through a pipe with three similar vertical columns:



- (a) Indicate the direction of the flow in the main pipe. (1 mark)
- (b) Explain why the water levels in the columns are not the same. (2 marks)
14. A fruit drops from a tree from a height of 5.0 m. On the axes shown, sketch the kinetic energy-time curve for the motion.

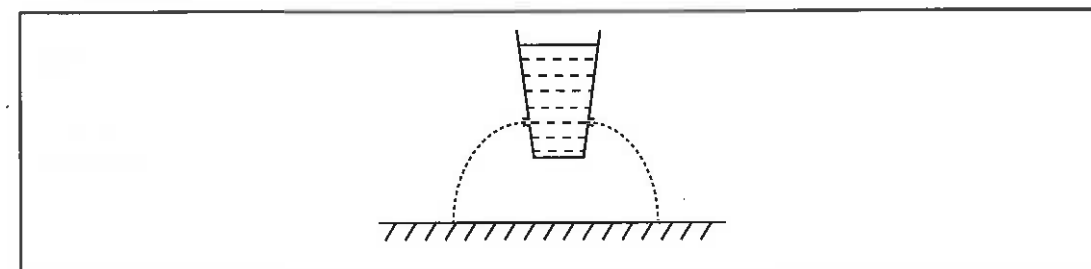


15. The figure below shows how white light behaves when it is incident on a glass prism:



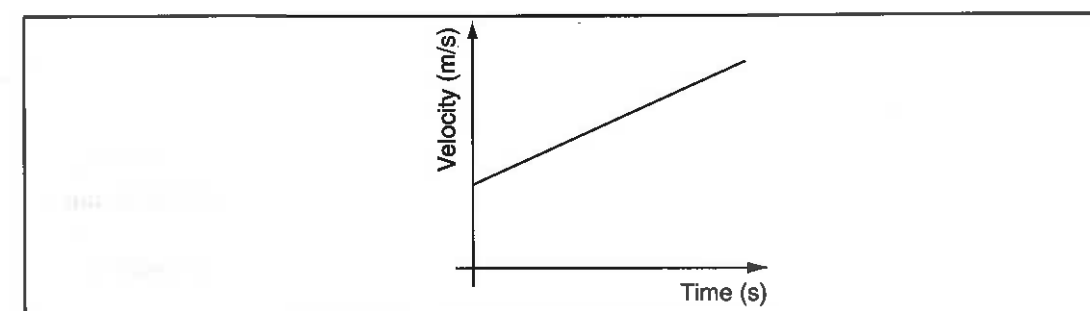
Explain why it splits to different colours between A and B.

16. The figure below shows a metallic container full of water and with jets flowing from it as indicated:



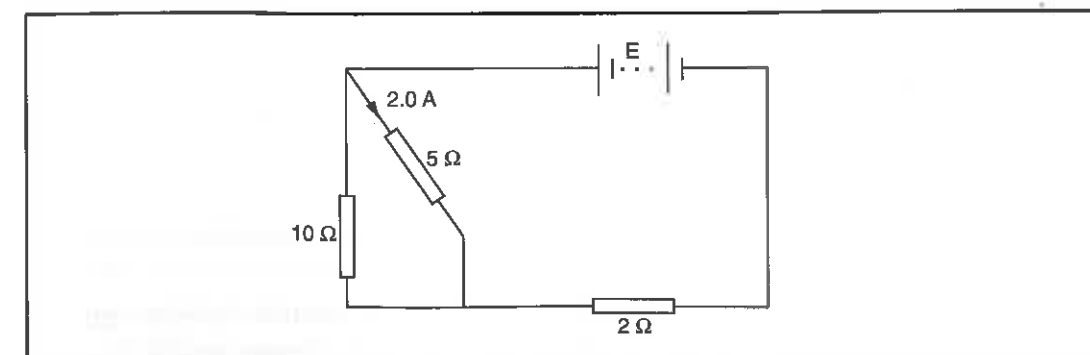
When the container is released from 3.0 m above the ground to fall freely, the jets cease during the fall. Explain.

17. The figure below shows a velocity-time graph for a motion of a particle:

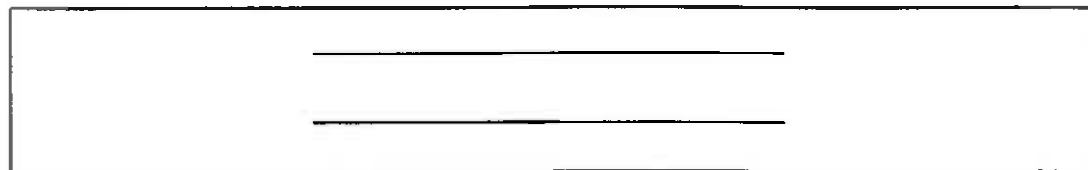


In the space below, sketch the corresponding displacement-time graph.

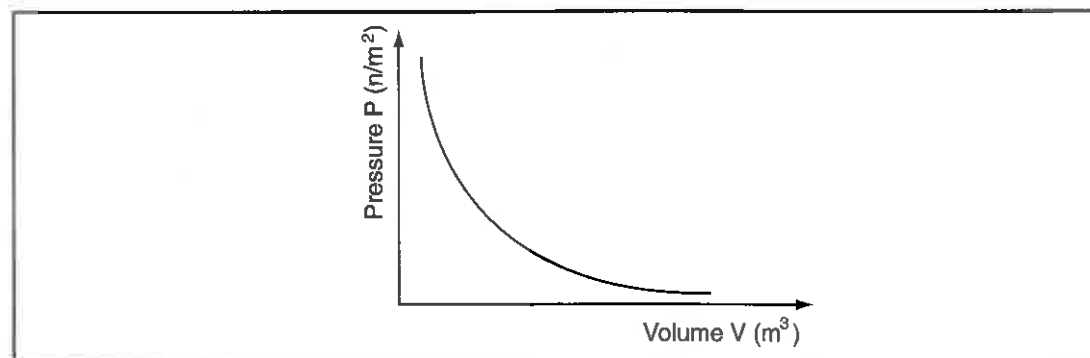
18. Determine the e.m.f. of the battery shown in the figure below:



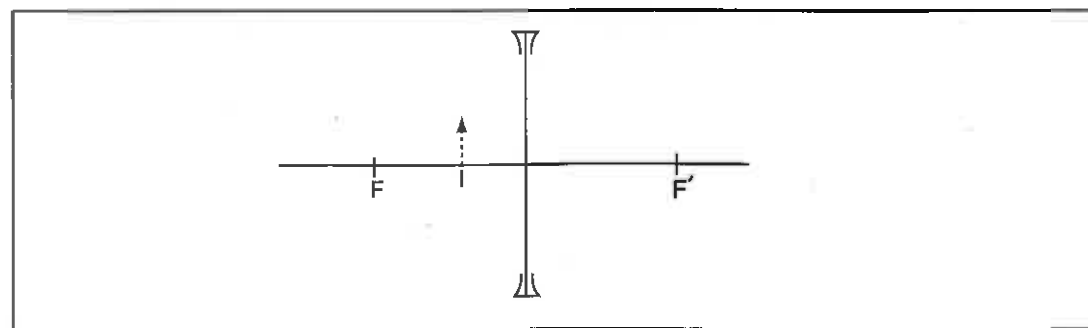
19. In the space below, complete the diagram to show how the air in open organ pipe vibrates with a frequency of first overtone.



20. Sketch the electric field pattern for a negative point charge placed near a positively charged plate.
21. An electric kettle is rated at 1.8 kW, 240 V. Explain the choice of the safest fuse to use for the kettle.
22. When a potential difference of 5.0 V is applied across a heater in a calorimeter, a current of 2.0 A flows. If this raises the temperature of 0.10 kg of methylated spirit from 17 °C to 27 °C in 230 seconds, what is the specific heat capacity of the methylated spirit?
23. The figure below shows the variation of pressure against volume for a given temperature:

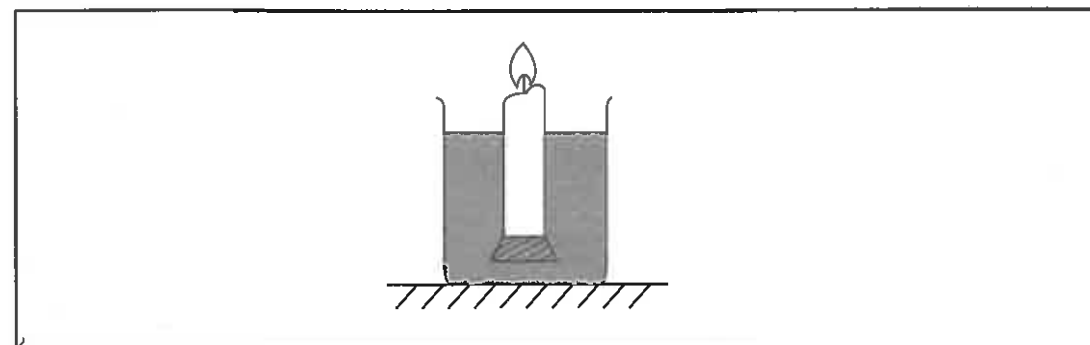


- (a) On the same axes, sketch the curve of pressure versus volume at a lower temperature.
- (b) What law do the curves verify?
24. The figure below shows an image I formed by a concave lens. The principal foci F and F' are as shown.



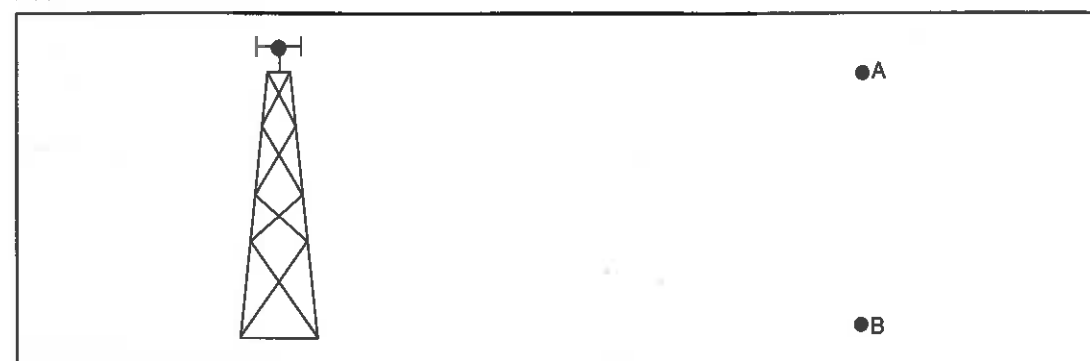
Complete the ray diagram to locate the position of the object.

25. On what principle does a mechanical speed governor limit the speed of a vehicle? Explain.
26. The figure below shows a burning, weighted, dripless candle floating upright in water:



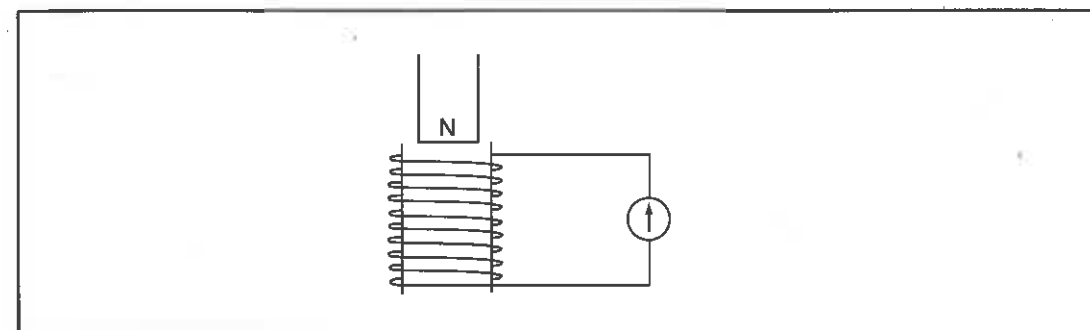
Explain what happens to the candle as it continues to burn.

27.



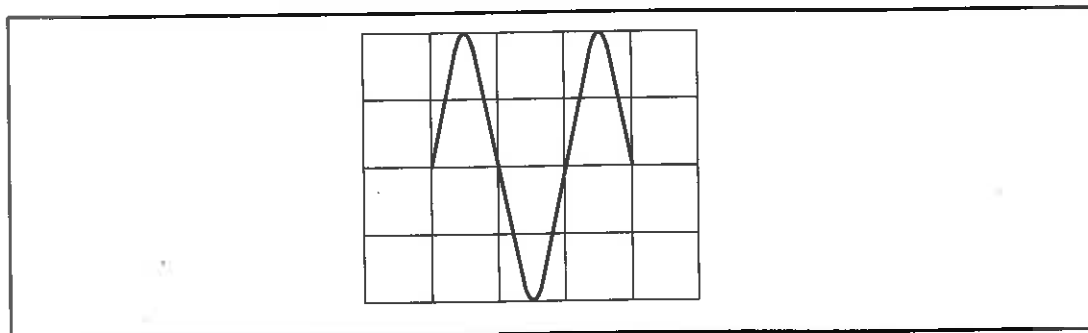
The figure above shows the antenna of a cellphone emitter for a certain service provider. Give a possible reason why an observer at A is better able to receive the signal than that at B at the same horizontal distance from the antenna. (2 marks)

28. The magnet below dropped right through the coil, north pole first. What will happen to the needle of the galvanometer? Explain your answer.



29. Four 40 W bulbs and seven 100 W bulbs are switched on for 3 hours a day for domestic use in a certain country. Find the monthly bill for the consumer given that the cost of electricity in the country is at sh. 3.50 per unit. (Take 1 month = 30 days, basic charge sh. 270)

30. The figure shows the trace of a signal on the C.R.O.



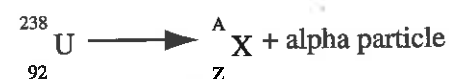
Given that the time base is set at 100 ms/div, determine the frequency of the signal.

(3 marks)

31. What determines the hardness of X-rays? (1 mark)

32. Distinguish between the terms 'photoelectric' and 'thermionic effects'. (2 marks)

33. Uranium ${}_{92}^{238}\text{U}$ emits an alpha particle to become another element X, as shown in the equation below:



Give the value of A and Z.

(2 marks)

34. Draw a circuit diagram of two diodes depicting full-wave rectification. (2 marks)

35. State one difference between an image formed by a plane mirror and that observed through a simple microscope. (1 mark)

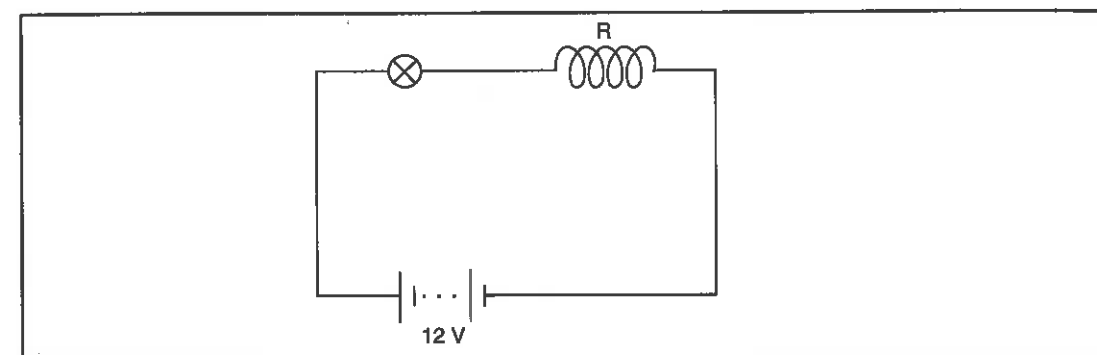
36. State the kinetic theory of matter. (1 mark)

37. In a lightning flash, a total charge of 20 C is transferred in 0.02 seconds. Determine the average current. (3 marks)

38. In what way does polarisation affect the working of a simple cell? (1 mark)

SAMPLE PAPER FOUR

1. The circuit below is used to light a 3 V, 0.2 A bulb from a 12.0 V d.c. supply:

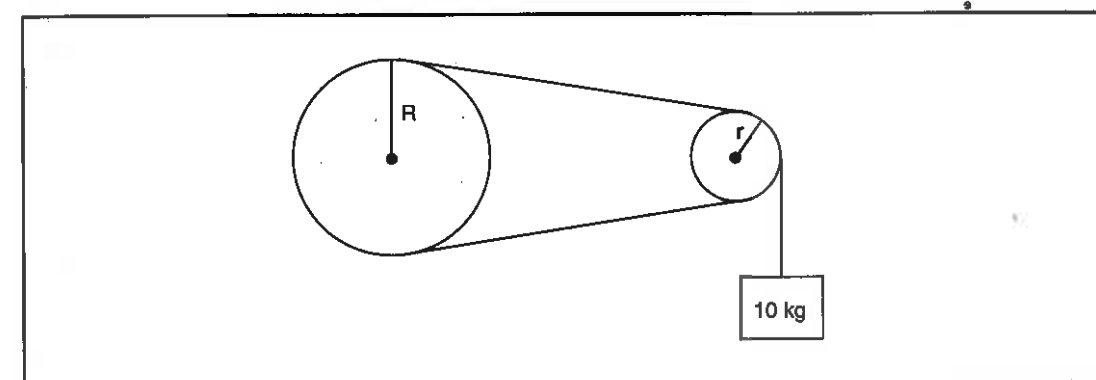


(a) (i) Determine the potential difference across the appliance R at the normal operation of the bulb. (1 mark)

(ii) Determine the rate at which electrical energy is converted into heat energy in the appliance R. (3 marks)

(iii) If the appliance R is an electrical heater and is used to convert 50 g of ice at 10 °C into steam at 100 °C, calculate the time required for the conversion. (Take specific latent heat of fusion for ice as $3.34 \times 10^5 \text{ J kg}^{-1}$, specific heat capacity of water as $4200 \text{ J kg}^{-1} \text{ K}^{-1}$ and specific latent heat of vaporisation of water as $22.6 \times 10^5 \text{ J kg}^{-1}$.)

(b) A steam turbine is used to drive a wheel of radius R equal to 0.3 m attached to a wheel of radius r equal to 0.2 m and the arrangement is used to lift a load of 10 kg as shown below:

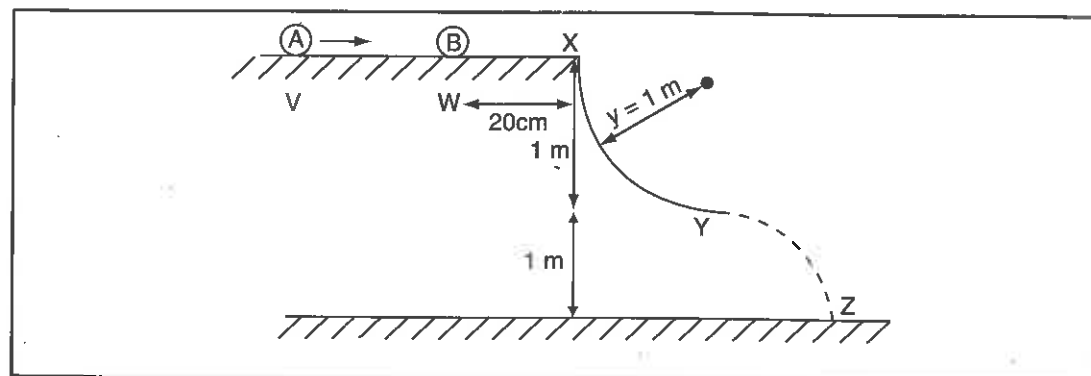


(i) Calculate the velocity ratio of the arrangement of wheels. (1 mark)

(ii) If the efficiency is 80 %, determine the effort used. (3 marks)

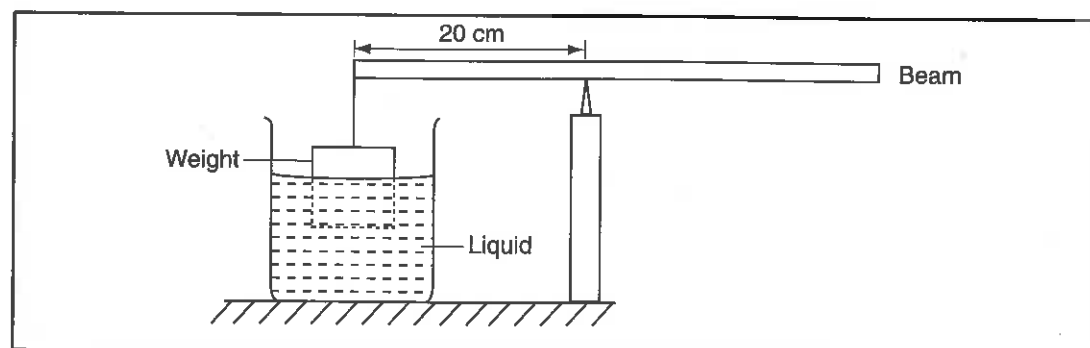
2. (a) State the work-energy principle. (1 mark)

(b) The diagram below shows two balls A and B, each of mass 0.1 kg, used in a pool game.



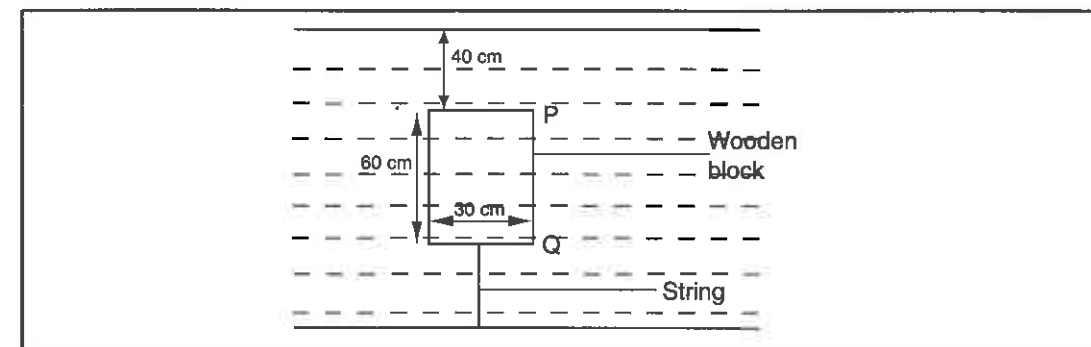
Ball A is hit by a cue stick and its velocity changes from 0.4 ms^{-1} to 0.1 ms^{-1} on impact with ball B. Determine:

- (i) The impulsive force on A, if the collision with B takes $1 \times 10^{-3} \text{ s}$. (2 marks)
 - (ii) The velocity of ball B after it takes off from the impact. (2 marks)
 - (iii) The coefficient of friction between the table and the ball B, if the velocity of B reduces to zero at point X. (2 marks)
- (c) (i) If the ball rolls freely from X to Y, determine the horizontal velocity at Y. (2 marks)
- (ii) If the ball follows a trajectory path from Y, determine its range. (2 marks)
- (d) (i) If the ball continued upwards in a uniform circle along a frictionless track, how far up would it have gone? (1 mark)
- (ii) Determine the reaction force between the ball and the track at Y.
3. (a) A piece of sealing wax weighs 3 N in air and 0.22 N when immersed in water. Calculate:
- (i) its relative density. (2 marks)
 - (ii) its apparent weight in a liquid of density 800 kgm^{-3} . (3 marks)
- (b) The figure below shows a uniform beam one metre long and weighing 2 N kept in horizontal position by a body of weight 5 N immersed in a liquid:

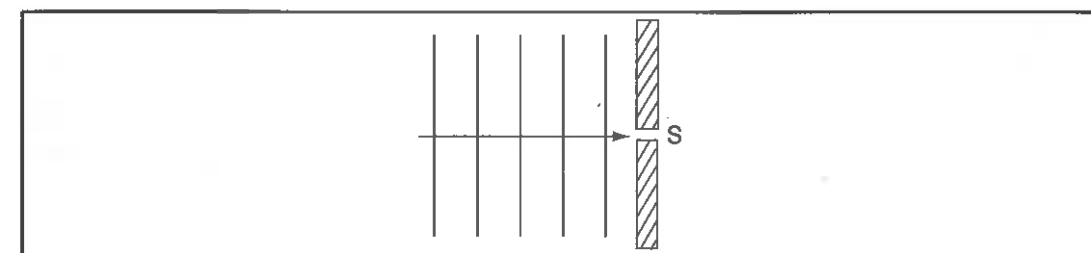


Determine the upthrust on the load. (3 marks)

- (c) The figure below shows a wooden block of dimensions 60 cm by 40 cm by 30 cm held in position by a string attached to the bottom of a swimming pool. The density of the water is 1000 kgm^{-3} :

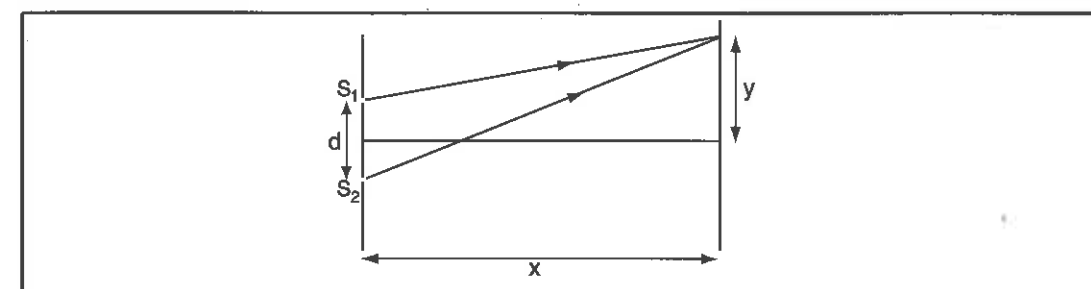


- (i) Calculate the pressure at the bottom surface of the block. (3 marks)
 - (ii) Draw a graph to show how the pressure on the block changes between P and Q. (2 marks)
4. (a) (i) Distinguish between diffraction and refraction of waves. (1 mark)
- (ii) The figure below shows plane waves approaching a very narrow slit, S.



Complete the diagram to show the pattern across the slit. (1 mark)

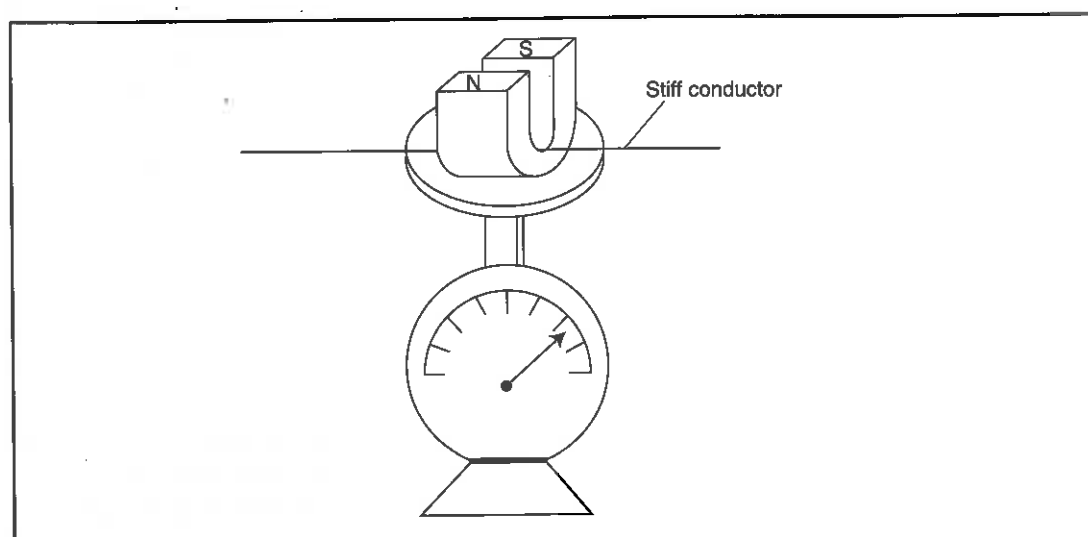
- (iii) The figure below shows two rays of monochromatic light incident on two adjacent slits S_1 and S_2 .



Give an expression for the wavelength of the light in terms of d , x and y .

- (iv) In the space below, sketch the interference pattern observed if white light was used instead of monochromatic light. (2 marks)
- (v) Explain the variation of frequency across the pattern displaced in (iv) above. (1 mark)
- (vi) Given that the wavelength of the monochromatic light used in (iii) above is $1.0 \times 10^{-7} \text{ m}$, calculate its frequency. (Speed of light is $3.0 \times 10^8 \text{ ms}^{-1}$) (3 marks)

- (b) Two observers P and Q are stationed 2.5 km apart, each equipped with a starter gun. Q fires the gun and observes P record the sound 7.75 seconds after seeing the smoke from the gun. Later, P fires the gun and observes Q record the sound 7.25 seconds after seeing the smoke from the gun. Determine :
- the speed of sound in air. (3 marks)
 - The component of the speed of the wind along the straight line joining P and Q. (1 mark)
5. (a) (i) Name all the components of an atom. (1 mark)
- Sketch a labelled diagram of a helium atom. (1 mark)
 - What process would make an electron move from one energy level to another in an atom? (1 mark)
- (b) (i) Name the main features of a cathode ray oscilloscope and state their functions. (4 marks)
- How is the brightness of the spot of light formed on the screen controlled? (1 mark)
- (c) In the television set, magnetic fields are used for deflection systems. Why? (2 marks)
6. (a) (i) Define the term magnetic field. (1 mark)
- Using the domain theory of magnetism, explain the effect of an external magnetic field on a ferromagnetic material. (2 marks)
- (b) A U-shaped magnet is placed on a sensitive compression balance as shown in the figure below. A stiff conductor is fixed on the base of the magnet so that it lies midway between the poles:



A varying current is then passed through the conductor and the following values obtained.

Current (A)	0.9	2.0	3.1	3.8	-1.6
Mass (g)	61.0	61.2	61.4	61.5	60.6

- Complete the diagram by adding a suitable circuit with the necessary components required for the experiment. (3 marks)
 - Plot a graph of current against force. (5 marks)
 - From the graph, determine the mass of the magnet. (2 marks)
 - State any assumptions made. (1 mark)
 - What is the significance of the negative value? (1 mark)
7. (a) Sketch a diagram to illustrate how a convex lens is used as a magnifying glass. (3 marks)
- (b) The table shows values of image distance v and magnification m for a convex lens.
- | | | | | | |
|-------------------------|------|------|------|-------|-------|
| Magnification (m) | 0.09 | 0.4 | 0.78 | 1.49 | 1.74 |
| Image distance v (cm) | 4.41 | 5.62 | 7.10 | 10.05 | 11.10 |
- Plot a graph of m (y-axis) against v . (5 marks)
 - Given the equation $m = \frac{v}{f} - 1$, determine focal length f from the graph. (4 marks)
- (c) Draw a diagram to illustrate the defect corrected by a concave lens. Explain using a diagram how the defect is corrected. (3 marks)

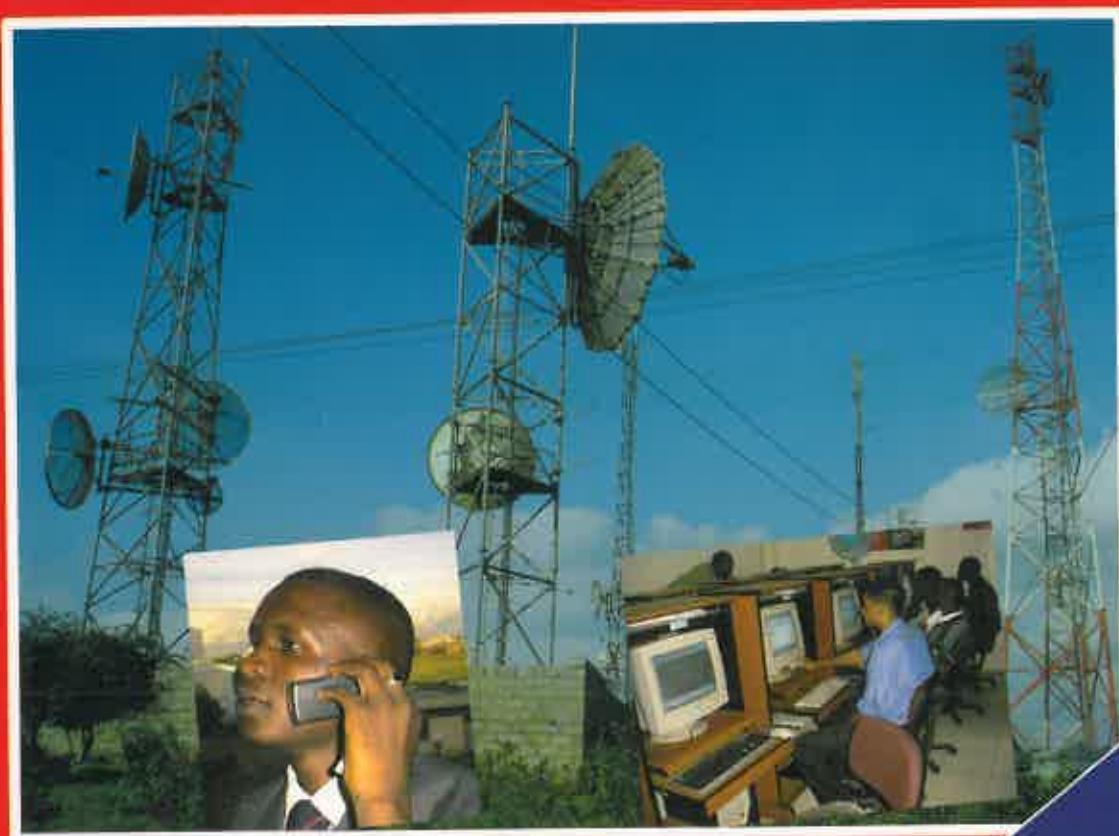
Secondary

Physics

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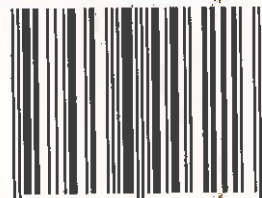
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Cover photograph: *An array of communication antennas and satellite dishes strategically positioned atop a hill. This application of electromagnetic waves has seen spectacular development in two crucial fields, mobile telephony and information technology, inset.*



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