

TOPIC 1: THIN LENSES

1.1: Introduction

A lens is generally a transparent material having at least one curved surface. A lens works by way of refraction of light. There are two common types of lenses:

1. Converging/convex lens- it is thicker at the middle.

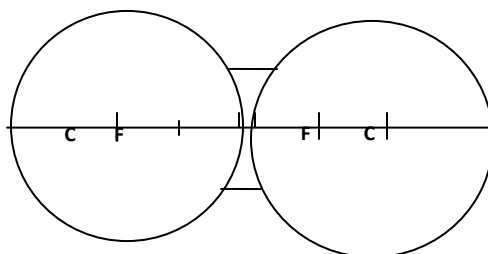
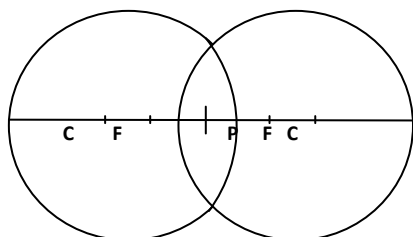


2. Diverging/concave lens- it is thinner at the middle.



1.2: Terms used

a) Centre of curvature, C- it is the centre of the sphere of which the surface of the lens is part. A lens has two centres of curvature.

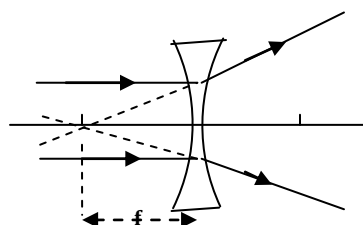
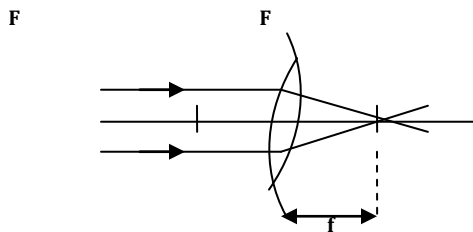


b) Radius of curvature, r - it is the radius of the sphere of which the lens is part.

c) Principal axis- a straight line joining the two centres of curvature.

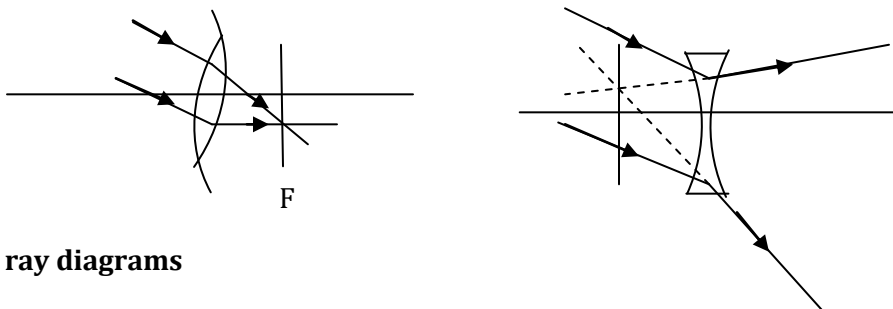
d) Optical centre, P- it is a point on the principal axis midway between the lens surfaces.

e) Principal focus, F- for a converging lens, it is the point along the principal axis at which rays parallel and close to the principal axis converge after refraction by the lens. For a diverging lens, it is the point along the principal axis from which rays parallel and close to the principal axis seem to diverge from after refraction by the lens.



f) Focal length, f - it is the distance between the optical centre and the principal focus. It is real for a converging lens and virtual (negative) for a diverging lens.

g) Focal plane- when parallel rays which are not parallel to the principal axis are incident on a lens, the rays converge at or appear to diverge from a point which is perpendicular to the principal axis and passes through the principal focus, F. this plane is called the focal plane.



1.3: Lens ray diagrams

There are three main rays in ray diagrams as shown below:

- a. A ray parallel to the principal axis



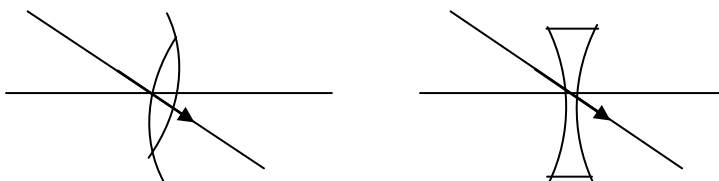
For a converging lens, the rays converge at F after refraction while for a diverging lens, the rays appear to diverge from F after refraction.

- b. A ray passing through or appearing to pass through F.



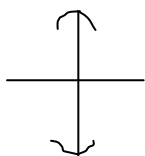
In both cases, the refracted rays are parallel to the principal axis.

- c. A ray directed to the optical centre of the lens.

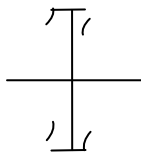


In both cases, the rays pass undeviated.

NB: in ray diagrams, the following symbols are used for the two lenses:



Converging lens



Diverging lens

Note that in ray diagrams:

1. Real rays, real objects and real images are represented using continuous lines.
2. Virtual rays and virtual images are represented using broken lines.
3. To locate an image, there must be at least two rays intersecting, whether real or virtual.

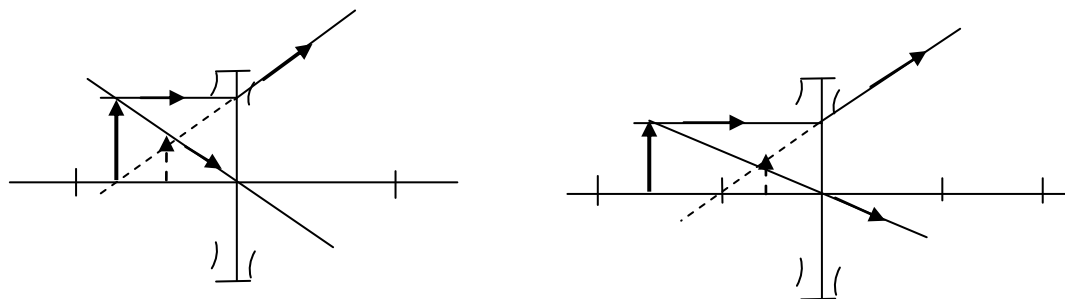
Sometimes, a scale may be used in ray diagrams. If used, then the scale chosen for object and image distances need not be necessarily equal to that of the object and image heights but the two must be given on the diagram.

1.4:Image formation by thin lenses

1.4.1:Image formation by a converging lens.

This is summarized by the table below:

Position of object	Ray diagram	Characteristics of image
Between F and the lens		Image is: - Virtual - Upright/erect - Magnified - On same side as the object
At F		Image is: - Real - Inverted - At infinity
Between F and C		Image is: - Real - Inverted - Magnified - Beyond C
At C		Image is: - Real - Inverted - Same size as object - At C
Beyond C		Image is: - Real - Inverted - Diminished
At infinity		Image is: - Real - Inverted - Diminished - At F

1.2:Image formation by a diverging lens

Generally, a diverging lens forms a virtual, upright and diminished image regardless of the position of the object.

1.5:The lens formula and magnification

The equation $1/f = 1/u + 1/v$ where f is the focal length of the lens, u is the object distance and v the image distance, is called the lens formula. The equation takes into account the signs of u , v and f and holds for both the converging and diverging lens.

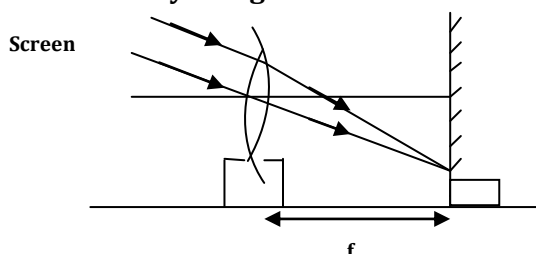
The ratio of the image size to the object size is called magnification of the lens. When the magnification is less than one the image is diminished while when it is more than one, the image is magnified. When the magnification is one, then the object and image are of the same size.

Magnification can also be obtained from the ratio of image distance to object distance i.e.

Magnification, $m = \text{image height/object height} = \text{image distance, } v/\text{object distance, } u$

Example 1.1

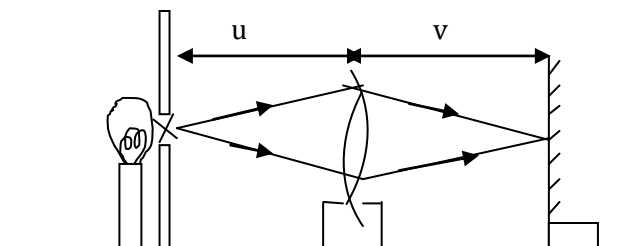
1. An object is placed in front of a converging lens of focal length 12cm. determine the position of the image and the magnification of the image. Hence state the nature of the image formed when the object distance is:
 - a. 16cm (**ans: $v=48\text{cm}$, image real and magnified**)
 - b. 8cm (**ans: $v= -24\text{cm}$, image is virtual and upright**)
2. An object is placed 4cm in front of a diverging lens of focal length 6cm. find the position and magnification of the image formed. Hence state its nature.
3. An object 10cm high is placed 5cm in front of a converging lens of focal length 20cm. determine the position and height of the image by:
 - a. Calculation
 - b. Scale drawing

1.6:Determination of the focal length of a converging lens.**Method 1: By using the lens formula**

- Focus clearly the image of a distant object like tree or window on the screen by adjusting the position of the lens appropriately. Measure the distance between the lens and screen,

$f = \dots\dots\dots\text{cm}.$

- Now set up the apparatus as shown below:



- Set the object distance, $u=65\text{cm}$. adjust the position of the screen until a sharp image of the object is observed. Measure the distance, v .
- Reduce the object distance in steps of 10cm and measure the corresponding values of v .
- Record your results and complete the table the table below:

$u(\text{cm})$	65.0	55.0	45.0	10.0	25.0
$V(\text{cm})$					
$1/u(\text{cm}^{-1})$					
$1/v(\text{cm}^{-1})$					

- Plot a graph of $1/u$ against $1/v$. hence determine the focal length, f of the lens.

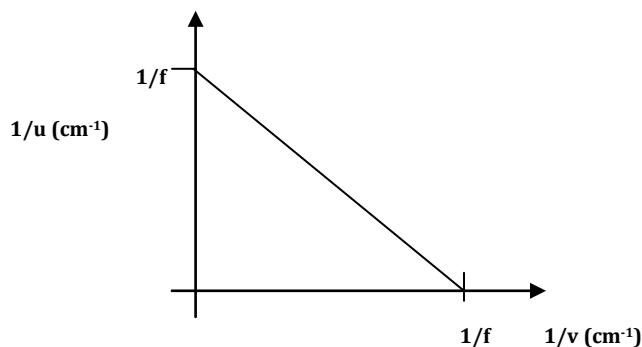
Note that from the lens formula, $1/f = 1/u + 1/v$

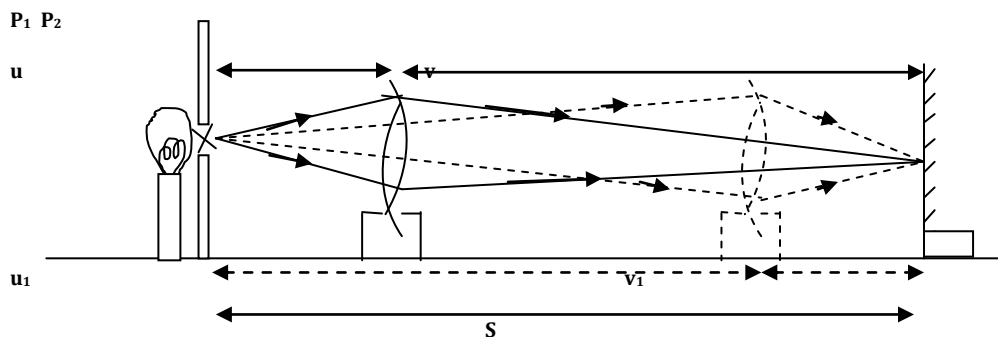
Making $1/u$ the subject of the formula, we have $1/u = -1/v + 1/f$.

When $1/v=0$, $1/u=1/f$ i.e. y-intercept

And when $1/u=0$, $1/v=1/f$ i.e. x-intercept.

Therefore the graph is a straight line whose slope is -1 and the y-intercept and x-intercept give $1/f$. if the values of the two intercepts are different, then their average is obtained.



Method 2: Displacement method

- Estimate the focal length of the lens by focusing a distant object.

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

- Set up the apparatus as shown above. The distance, S should be equal to or more than $4f$. adjust the position of the lens to a position P_1 where a sharp image of the object is obtained on the screen. Measure and record u and v .
- Keeping S constant, move the lens to another position P_2 where another clear but diminished image of the object is formed on the screen. Measure and record u_1 and v_1 .
- Increase the value of S in steps of 5cm and repeat steps 2 and 3 above. Complete the table below:

$S(\text{cm})$					
$U(\text{cm})$					
$V(\text{cm})$					
U_1					
V_2					
$d=v-u$					
$(S^2-d^2)(\text{cm}^2)$					

- Plot a graph of (S^2-d^2) against S .
- Given that the equation $S^2 = 4fS + d^2$ satisfies the graph drawn, determine the value of f .

Note that $S = u + v \dots\dots\dots (i)$

And $d = u_1 - u$ or $d = v - v_1$

But $u_1 = v$ and $v_1 = u$

Therefore, $d = v - u \dots\dots\dots (ii)$

Adding equations (i) and (ii), we obtain;

$$S + d = u + v + v - u = 2v$$

$$V = (S + d)/2 \quad \dots\dots\dots (iii)$$

Also subtracting equation (ii) from (i), we get;

$$S - d = u + v - v + u = 2u$$

$$u = (S - d)/2 \quad \dots\dots\dots (iv)$$

Substituting equations (iii) and (iv) in the lens formula, we get;

$$1/f = 1/\{(S-d)/2\} + 1/\{(S+d)/2\}$$

$$1/f = 2/(S-d) + 2/(S+d)$$

$$1/f = 4S/(S^2 - d^2)$$

$$(S^2 - d^2) = 4Sf$$

Hence a graph of $(S^2 - d^2)$ against S is a straight line through the origin and whose slope equal to $4f$.

The two positions P_1 and P_2 are known as conjugate points.

1.7: Other possible graphs from the lens formula

1. From the lens formula; $1/f = 1/u + 1/v$

$$1/f = (v+u)/uv$$

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

Hence a graph of uv against $(u+v)$ is a straight line through the origin and whose slope equal to the focal length, f of the lens.

2. Also, from the lens formula; $1/f = 1/u + 1/v$

Multiplying through by v , we obtain $v/f = v/u + 1$

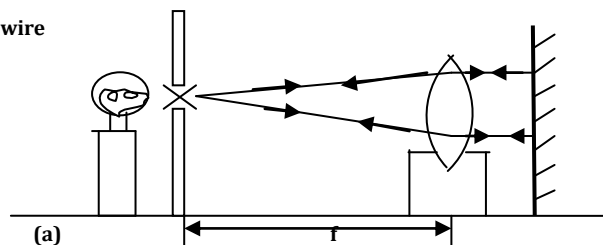
But $v/u = m$

Therefore, $m = v/f - 1$

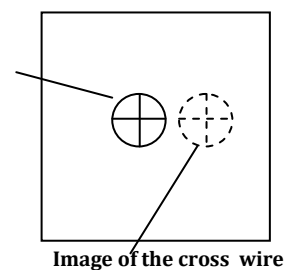
Hence a graph of m against v is a straight line whose slope equal to $1/f$ and the y -intercept = -1 .

Method 3: Plane mirror method

Cross wire

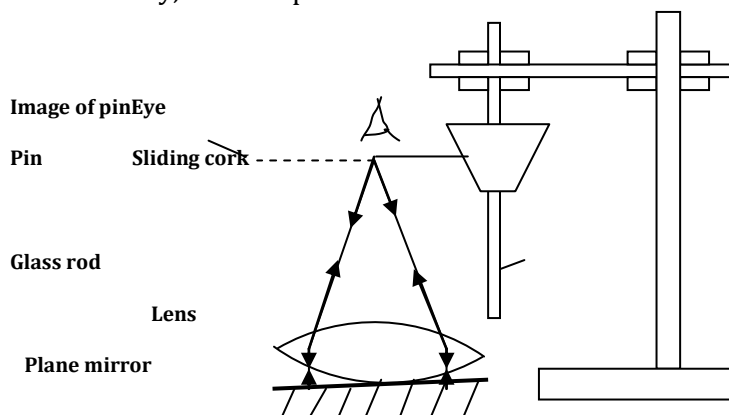


(b)



Adjust the position of the object until a sharp image of the cross wire is formed alongside (close to) the object cross wire as shown in (b) above. The distance between the object and the centre of the lens gives the focal length f of the lens.

Alternatively, the set up below can be used to determine f :



Adjust the position of the cork up and down until the pin and its image just coincide i.e. no parallax between the object pin and its image. The distance between the centre of the lens and the pin gives the focal length of the lens.

1.8: Power of a lens

It is the measure of the refracting ability of the lens. It is expressed as the reciprocal of the focal length

i.e. power of a lens = $1/\text{focal length}$

It is measured in dioptre (D).

The shorter the focal length the higher its refracting ability. The power of a converging lens is positive while that of a diverging lens is negative.

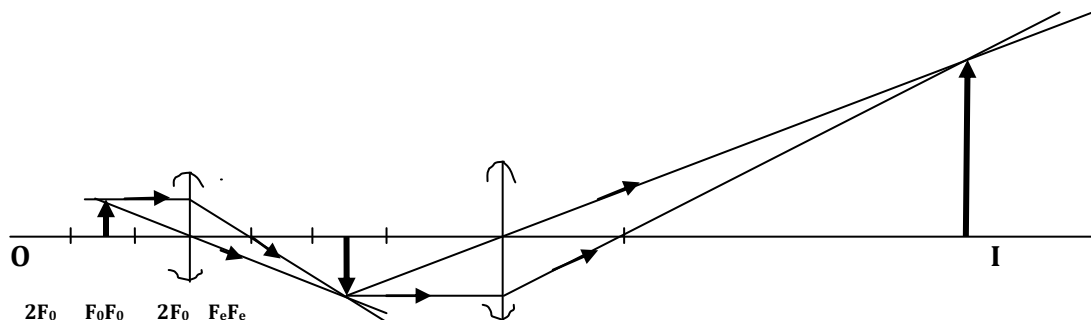
1.9: Applications of lenses

➤ A simple microscope

It is also known as a magnifying glass. When a converging lens is used such that the object is found between its principal focus and the lens, it forms a virtual, upright and magnified image. When used this way it serves as a simple microscope.

➤ A compound microscope

It consists of two converging lenses, objective lens and eyepiece lens both of short focal lengths. The lens closer to the object is called the objective lens while that closer to the eye is called the eyepiece lens. The focal length of the eyepiece lens is longer than that of the objective lens. The object is found between F and C of the objective lens.



The first image formed by the objective lens is real, inverted and magnified. This image then acts as the object for the eyepiece lens. The eyepiece lens forms a final image which is greatly magnified. Assuming the magnification of the objective lens is m_o and that of the eyepiece lens is m_e , then the total magnification of the compound microscope $m = m_o \times m_e$.

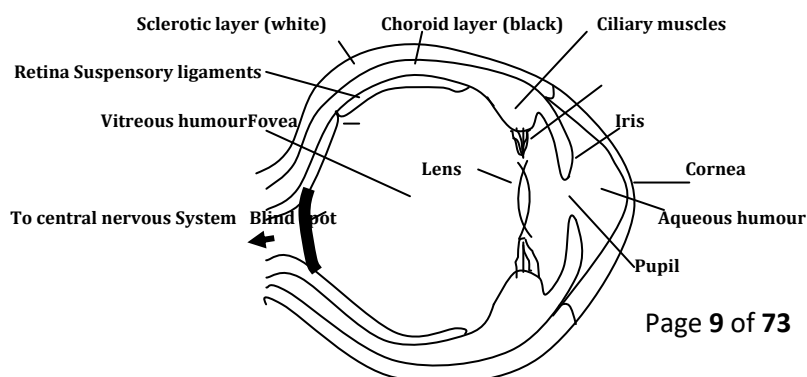
Example 1.2

1. In a compound microscope, the focal length of the objective lens is 2.0cm and that of the eyepiece lens is 2.2cm and they are placed at a distance of 8.0cm. a real object of size 1.00mm is placed 3.0cm from the objective lens.
 - a) Use the lens formula in turn for each lens to find the position of the final image formed.
 - b) Calculate the magnification produced by the arrangement of these lenses and the size of the final image viewed by the eye.

➤ The lens camera

A camera is a device that is used to take photographs. It consists of a converging lens, a light- sensitive film enclosed in a light-tight box blackened on the inside and a shutter. Light from the object enters the camera through the shutter which closes automatically after a given length of time. The amount of light reaching the lens is controlled by the diaphragm (stop). The light reaching the lens is refracted to form a real, inverted and diminished image on the film. To clearly focus the image, the distance between the lens and film is adjusted accordingly. The film has some light- sensitive chemicals which change on exposure to light. This can then be developed and printed to get a photograph.

➤ The human eye



The human eye is a natural optical instrument. It comprises of the following parts:

- Sclerotic layer- encloses the eye. The front part (cornea) is transparent to allow in light. It is the white part of the eye.
- Aqueous humour- it is a clear fluid/liquid found between the cornea and the lens. This helps to maintain the shape of the eye.
- Iris- it is responsible for the colour of the eye. It has the pupil in the middle which allows for passage of light. By changing the size of the pupil, the iris controls the amount of light entering the eye.
- Lens- it is a natural converging lens. With the help of the ciliary muscles, its focal length can be adjusted for fine focusing.
- Vitreous humour- it is a jelly-like substance and transparent in nature found between the lens and retina.
- Retina- images are formed here. It has light-sensitive cells.
- Fovea- it is the central part of the retina. This is where the eye has the best details and colour vision.
- Blind spot- has cells which are non-sensitive to light.
- Ciliary muscles- they suspend/support the lens. It is also responsible for controlling the shape of the lens.

When the muscles relax, the focal length of the lens increases. This enables the eye to focus a distant object. Contraction of the muscles on the other hand reduces tension in the lens, thus reducing its focal length. This enables it focus near objects.

This automatic adjustment of the eye lens to bring to focus on the retina images of both distant and near objects is referred to as **accommodation**.

The closest/shortest distance a normal eye can focus clearly is known as its **near point** while the farthest distance a normal eye can focus clearly is known as its **far point**. For a normal eye, the near point is usually 25cm.

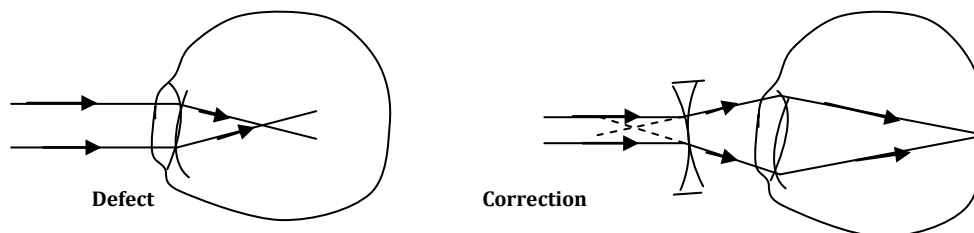
Note that the distance between the retina and the eye lens is always constant.

1.9.1: Eye defects

Despite the adjustments made by the eye, some eyes cannot produce clear images within the normal range of vision. There are two common eye defects namely myopia (shortsightedness) and hypermetropia (long-sightedness).

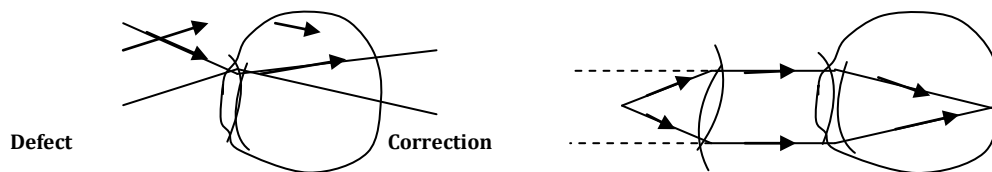
Myopia (shortsightedness)

Having this defect means clear vision for near objects but images of distant objects are formed in front of the retina. The cause of the defect is the eyeball being too long or shorter focal length. The defect is corrected by using a diverging lens of appropriate focal length so that the rays reaching the eye lens appear as if they are coming from a near object.



Hypermetropia (long-sightedness)

A person who is long-sighted has clear vision of distant objects but cannot see clearly closer objects clearly. It is caused by the eyeball being too short or longer focal length so that the image of a closer object is formed behind the retina. The defect is corrected by using a converging lens of appropriate focal length.



1.9.2: Similarities and differences between the eye and lens camera

Similarities

1. Both use converging lenses.
2. In both cases, the amount of light allowed in can be controlled. The eye does it through the iris while the camera does this through the diaphragm.
3. In both, a real, inverted and diminished image is formed. For the eye, the image is formed on the retina while for the camera, it is formed on a light-sensitive film.
4. In both cases the inner part is black; for the eye, there is the choroid layer which is black and for the camera, the inner part is painted black. This is to absorb stray rays.

Differences

1. The focal length of the eye lens changes while that of the lens camera is constant.
2. The distance between the lens and film in a lens camera can be varied by zooming while the distance between the eye lens and retina is constant.
3. A camera can take only one photo at a time when the shutter is open while the eye forms constantly changing pictures.

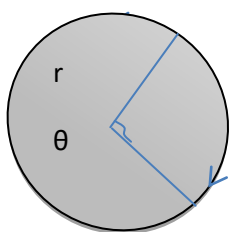
TOPIC 2: UNIFORM CIRCULAR MOTION**2.1: Introduction**

This is motion around a curved path in which the speed of the particle is uniform. Although the speed is the same, velocity of the body keeps varying since there is a constant change in direction. The velocity of such a body at any instant is always directed along the tangent of the curve such that if the body breaks away, it moves along the tangent.

Since the velocity is constantly changing, a body undergoing uniform circular motion is always accelerating.

2.2: Terms used in uniform circular motion

- Angular displacement, θ - is the angle swept at the centre by an arc. It is measured in radian, θ^c .



$\theta = (\text{arc length, } S / \text{radius, } r) \text{ radians}$

When $S = r$, then $\theta = S/r = 1 \text{ radian}$.

A radian is therefore the angle subtended at the centre of a circle by an arc length equal to the radius of the circle.

Note that $2\pi^c = 360^\circ$

- Angular velocity, ω - it is the rate of change of angular displacement.

$$\omega = \Delta\theta / \Delta t$$

The SI unit of angular velocity is radian per second (rads^{-1}).

Remember $\theta = S/r$

Therefore, $\Delta\theta = \Delta S/r$, since r is constant.

$$\text{Thus } \omega = \Delta\theta / \Delta t = \Delta S / r \Delta t$$

But $\Delta S / \Delta t = \text{velocity, } v$

$$\text{Hence } \omega = v/r$$

Thus a body in circular motion has both linear and angular velocities.

- Period, T - it is the time taken by a body to make one complete revolution.

Period, $T = \text{circumference } (2\pi r) / \text{linear velocity, } v$.

Therefore $T = 2\pi r / r\omega$ since $v = r\omega$

$$\text{And } T = 2\pi / \omega$$

Recall frequency, $f = 1/T$

Therefore $f = 1/(2\pi/\omega) = \omega/2\pi$

Or simply $\omega = 2\pi f$

- Angular acceleration, α - it is the rate of change of angular velocity.

$$\alpha = \omega/t$$

- Centripetal acceleration, a - it is the acceleration of a body undergoing uniform circular motion and is always directed towards the centre of the circle.

It is given as $a = v^2/r$.

But $v = r\omega$

Therefore $a = (r\omega)^2/r = r\omega^2$.

- Centripetal force, F_c - it is the force which keeps the body on its circular path. It is expressed as $F_c = m v^2/r = ma$

Where m - is the mass of the particle

v - is its linear velocity

r - is the radius of the path

a - is the centripetal acceleration

Also, $a = r\omega^2$. Thus $F_c = m r \omega^2$

Hence, there are three factors affecting the centripetal force. These are:

- Mass of the body
- Radius of the path
- Angular velocity of the body.

Example 2.1

- A particle moves at an angular velocity of $10\pi \text{ rads}^{-1}$ along a circular path of radius 20cm. calculate its linear speed.

$$v = r\omega = 0.2 \times 10\pi = 6.8 \text{ m/s.}$$

- A car of mass 100kg moves round a circular track of radius 100m with a linear speed of 20m/s. calculate:

a) The angular velocity

$$\omega = v/r = 20/100 = 0.2 \text{ rads}^{-1}$$

b) The centripetal force

$$F_c = m v^2/r = (100 \times 20^2)/100 = 400 \text{ N}$$

c) The centripetal acceleration

$$a = v^2/r = 20^2/100 = 4 \text{ m/s}^2$$

- Calculate the period and frequency of a particle in a circular path moving at an angular velocity of $4\pi \text{ rads}^{-1}$.

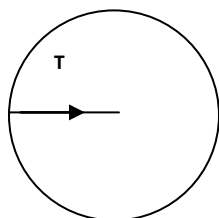
$$T = 2\pi/\omega = 2\pi/4\pi = 0.5 \text{ s}$$

$$f = 1/T = 1/0.5 = 2 \text{ Hz}$$

2.3: Motion in a horizontal circle

In a horizontal circle, the tension in the string provides the centripetal force and is directed towards the centre of the circle.

$$F_c = T = m v^2/r$$



For a fixed radius, the tension is constant all round.

Example 2.2

1. A stone of mass 2kg is whirled in a horizontal circle of radius 0.5m. The tension in the string was found to be 64N. Determine the velocity of the stone in the circle.

$$V = (r F_c / m)^{1/2} = (0.5 * 64 / 2)^{1/2} = 4 \text{ m/s}$$

2. A stone of mass 0.6kg attached to a string of length 0.5m is whirled in a horizontal circle at a constant speed. If the maximum tension in the string is 5N before it breaks, calculate:

- a) The maximum speed of the stone

$$V = (r F_c / m)^{1/2} = (0.5 * 5 / 0.6)^{1/2} = 5 \text{ m/s.}$$

- b) The maximum number of revolutions per second it can make

$$f = \omega / 2\pi = v / 2\pi r$$

$$= 5 / 2\pi * 0.5 = 1.593 \text{ Hz.}$$

Assignment 2.1

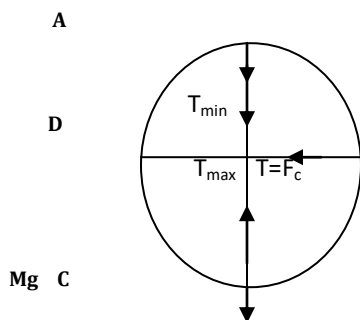
1. A stone of mass 5kg is whirled at the end of a string 5m long in a horizontal circle. If it is whirled at 5 revolutions per second, calculate:

- a) The angular velocity
- b) The linear velocity
- c) The centripetal acceleration
- d) The tension in the string

2. An object of mass 4kg moves round a circle of radius 6m with a constant speed of 12m/s. calculate:

- a) Its angular velocity
- b) The centripetal force

2.4: Motion in a vertical circle



When a body is whirled in a vertical circle, two forces act on it. These are the weight, mg of the body and the tension, T on the string. The tension varies depending on the position of the body. It is always directed towards the centre of the circle.

At the top of the circle, both the weight of the body and the tension are directed to the centre. Hence the centripetal force equal to the sum of the weight of the body and the tension.

$$\text{i.e. } F_c = T_{\min} + mg$$

$$\text{Or } T_{\min} = F_c - mg = mv^2/r - mg$$

At the bottom of the circle, the centripetal force is given by the difference between the weight and the tension;
 $F_c = T_{\max} - mg$

$$\text{Or } T_{\max} = F_c + mg = mv^2/r + mg$$

At B and D, the tension in the string provides the centripetal force;

$$T = F_c = mv^2/r$$

Hence tension is maximum at the bottom and least at the top.

When the tension is minimum, a certain minimum speed must be maintained in order to keep the string taut. Taking minimum tension to be zero, we have;

$$0 = mv^2/r - mg \quad (\text{from the equation of minimum tension})$$

$$mv^2/r = mg$$

$$V^2 = rmg/m = rg$$

$$\text{Therefore, } v = (rg)^{1/2}$$

This is the expression for minimum speed that the body must maintain. It is also called the critical speed.

Example 2.3

1. An object of mass 8kg is whirled round rapidly in a vertical circle of radius 2m with a constant speed of 6m/s. Calculate the maximum and minimum tension in the string. Take $g = 10\text{N/kg}$.

$$T_{\max} = mv^2/r + mg = 8(6^2/2 + 10) = 224\text{N}$$

$$T_{\min} = mv^2/r - mg = 8(6^2/2 - 10) = 64\text{N}$$

2. An object of mass 0.4kg is rotated by a string at a constant speed, v in a vertical circle of radius 1m. If the minimum tension in the string is 3N, calculate :

- a) The speed, v

$$T_{\min} = mv^2/r - mg$$

$$3 = 0.4(v^2/1 - 10)$$

$$V^2 = (3 + 4)/0.4 = 70/4$$

$$V=(70/4)^{1/2}=4.183\text{m/s}$$

- b) Maximum tension in the string

$$T_{\max}=m(v^2/r + g) = 0.4(70/4 + 10)$$

$$= 11\text{N}$$

- c) The tension when the string is just horizontal

$$T=mv^2/r = 0.4*70/4 = 7\text{N}$$

3. A bob of mass 1kg is moving in a uniform circular path in a vertical plane of radius 1m. If it is whirled at a frequency of 2cycles per second, calculate:

- a) The tension in the string when the bob is at the top part of the circle

$$T=mv^2/r - mg = mr\omega^2 - mg = mr(2\pi/f)^2 - mg$$

$$= (1*1*4*\pi^2/2^2) - (1*10)$$

$$= 147.95\text{N}$$

- b) Tension when it is at the bottom

$$T = mr(2\pi/f)^2 + mg$$

$$= (1*1*4*\pi^2/2^2) + (1*10)$$

$$= 167.95\text{N}$$

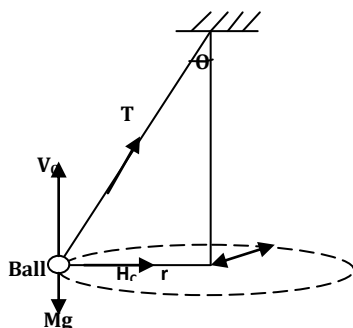
- c) At what position is the string likely to break? Why?

At the bottom of the circle. The string experiences maximum tension at this point.

- d) What is the minimum speed required to maintain the string under tension.

$$V=(rg)^{1/2}=(1*10)^{1/2}= 3.162\text{m/s}$$

2.5: A conical pendulum



When the angular velocity, ω of the ball increases the angle θ also increases and the ball rises. The horizontal component, H_c of the tension provides the centripetal force;

$$\text{i.e. } F_c = H_c = mv^2/r$$

$$\text{But } H_c = T \sin \theta$$

$$\text{Therefore } T \sin \theta = mv^2/r \dots \dots \dots (i)$$

Also $T \cos \theta = mg$(ii)

Dividing equation (i) by (ii), we get;

$$T \sin \theta / T \cos \theta = (mv^2/r)/mg$$

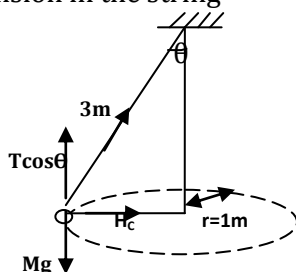
Therefore $\tan \theta = v^2 / rg$

Also $\tan \theta = r\omega^2 / g$ (since $v = r\omega$)

Example 2.4

1. A stone of mass 2kg is attached to a string 3m long made to revolve in a horizontal circle of radius 1m. find:

- a) The tension in the string



$$\theta = \sin^{-1}(1/3) = 19.47^\circ$$

$$\text{Therefore } T = mg / \cos \theta = 20 / \cos 19.47^\circ = 21.21 \text{ N}$$

- b) The linear velocity, v

$$T \sin \theta = mv^2 / r$$

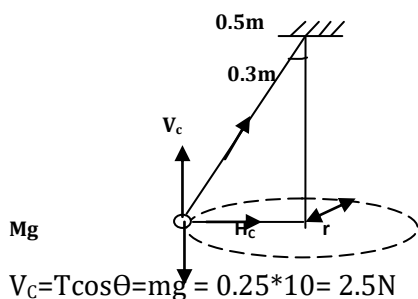
$$\text{Therefore } v = (21.21 \sin 19.47^\circ \cdot 1/2)^{1/2} = 1.88 \text{ m/s}$$

- c) The angular velocity, ω

$$\omega = v/r = 1.88/1 = 1.88 \text{ rad s}^{-1}$$

2. A small pendulum bob of mass 250g is suspended by an inelastic string of length 0.5m. The bob is made to rotate in a horizontal circle of radius 0.4m and whose centre is vertically below the point of suspension. Calculate:

- a) The magnitude of the component forces acting on the bob due to the tension in the string



$$V_c = T \cos \theta = mg = 0.25 \cdot 10 = 2.5 \text{ N}$$

$$\text{But } \cos \theta = 3/5$$

$$\text{So } T = 2.5 \cdot 5/3 = 4.17 \text{ N}$$

$$H_c = T \sin \theta = (12.5/3) \cdot 4/5 = 3.8 \text{ N}$$

- b) The period of rotation of the bob

$$T \sin \theta = m r \omega^2$$

$$\omega = (T \sin \theta / m r)^{1/2} = (3.8 / 0.4 * 0.25)^{1/2}$$

$$= 5.77 \text{ rads}^{-1}$$

$$\text{But period, } T = 2\pi / \omega = 1.0889 \text{ s}$$

Assignment 2.2

1. An object of mass 10kg is whirled round a horizontal circle of radius 4m by a revolving string inclined to the vertical. If the uniform speed of the object is 5m/s, calculate:

- The tension in the string
- The angle of inclination of the string to the vertical

(Ans. $T=118\text{N}$, $\theta=7^\circ$)

2.6: Case examples of circular motion

2.6.1: movement of cars round a flat (level) bend

In this case, the centripetal force is provided by the frictional force between the tyres and the road, i.e.

$$F_R = F_C = m v^2 / r$$

If the road is slippery, then the frictional force may not be sufficient to provide the required centripetal force. Hence skidding may occur.

To avoid skidding, the speed of the car should not exceed a certain speed limit (critical speed). The critical speed depends on the radius of the bend; the larger the radius the higher the critical speed.

Other factors which affect friction also significant here. These include the nature of the road surface and the nature of the tyres.

Example 2.5

- A car of mass 1200kg is moving with a velocity 25m/s round a flat bend of radius 150m. Determine the minimum frictional force between the tyres and the road that will prevent the car from sliding off.

$$F_R = m v^2 / r = 1200 * 25^2 / 150 = 5000 \text{ N}$$

- A glass block of mass 100g is placed in turn at various distances from the centre of a table which is rotating at a constant angular velocity. It is found that at a distance 8cm from the centre, the block just starts to slide off the table. If the frictional force between the block and the table is 0.4N, determine:

- The angular velocity of the table

$$F_R = m r \omega^2$$

$$\omega = (0.4 / 0.1 * 0.08)^{1/2} = 7.07 \text{ rads}^{-1}$$

- The force required to hold the block at a distance of 12cm from the centre of the table.

$$F = mr\omega^2 = 0.1 \times 0.12 \times 50 = 0.6 \text{ N}$$

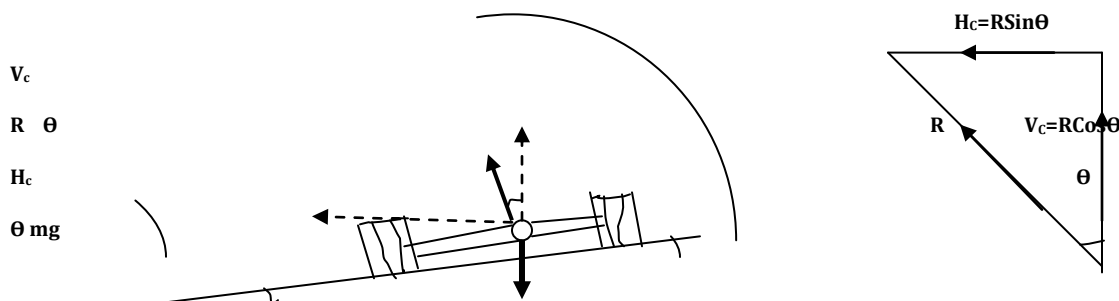
- c) A block of mass 200g is now placed 8cm from the centre of the table and the table rotated at the same angular velocity. State with a reason whether or not the block will slide off.

$$F_c = mr\omega^2 = 0.2 \times 0.08 \times 50 = 0.8 \text{ N}$$

Since the required centripetal force is greater than the frictional force, the block will slide off.

2.6.2: Banked road

Banking refers to raising the outer edge of the road away from the centre of the curve. The angle through which the road is raised is called the angle of banking. Banking minimizes chances of skidding/overturning.



In this case, the centripetal force is provided by the horizontal component of the normal reaction.

Therefore $F_c = R \sin \theta = mv^2/r$ (i)

Also $R \cos \theta = mg$ (ii)

Dividing equation (i) by (ii), we get;

$$\tan \theta = v^2/rg$$

Note that for no skidding to occur, $\tan \theta$ must be greater than v^2/rg ($\tan \theta > v^2/rg$) and the critical speed, v is given by;

$$v = (rg \tan \theta)^{1/2}$$

Hence the critical speed, v depends on the radius, r of the curve and the angle of banking, θ .

Example 2.6

1. The maximum speed at which a motorist can negotiate a corner on a level ground is 20m/s. if the radius of the curve is 100m, calculate:
 - a) The coefficient of friction, μ

$$F_R = F_c = mv^2/r = \mu R = \mu mg$$

Therefore $v^2/r = \mu g$

$$\mu = 20^2/100 \times 10 = 0.4$$

- b) The angle at which the road should be banked to enable the motorist negotiate the corner at a critical speed of 20m/s.

$$\tan \theta = v^2/rg = 0.4$$

$$\theta = \tan^{-1} 0.4 = 21.8^\circ$$

2. A vehicle moves round a banked balanced road at a speed of 20m/s. if the radius of the road is 50m, calculate the angle of banking.

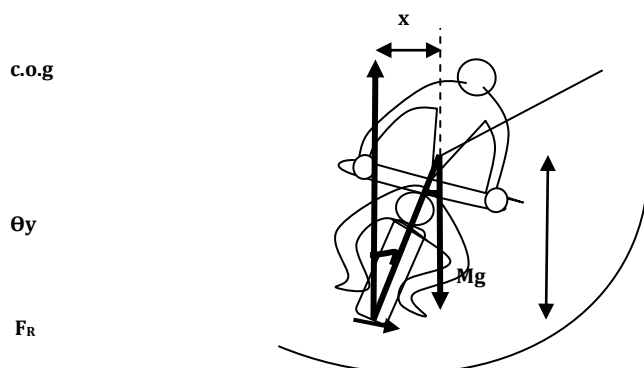
$$\tan \theta = v^2/rg = 20^2/50 \times 10 = 0.8$$

$$\theta = \tan^{-1} 0.8 = 38.7^\circ$$

2.6.3: Aircraft banking

An aircraft turning in air achieves banking by lowering one of its wings and raising the other. This enables it turn at extremely high speed without overturning.

2.6.4: A cyclist moving round a circular track.



For a flat road surface, frictional force between the tyres and the road provides the centripetal force;

$$F_R = F_C = mv^2/r$$

In cases when the frictional force is not sufficient, the cyclist is likely to skid. To avoid this, the cyclist is advised to lean inwards. Thus the frictional force, F_R and the normal reaction, R produce a turning effect about the centre of gravity.

Thus taking moments about the c.o.g., we get;

$$\text{Clockwise moment} = Rx$$

$$\text{And anticlockwise moment} = F_R y$$

For no skidding to occur, clockwise and anticlockwise moments should be equal;

$$Rx = F_R y$$

$$F_R/R = x/y$$

But $\tan\theta = x/y$ and $R = mg$

Therefore $\tan\theta = F_R/mg = \mu$

Where μ is the coefficient of friction.

Hence skidding only occurs when $\tan\theta$ is greater than μ ($\tan\theta > \mu$).

Example 2.7

1. A cyclist who is travelling at 20m/s negotiates a bend of radius 45m. he inclines at an angle θ to the vertical. Calculate:

- a) The centripetal acceleration

$$a = v^2/r = 20^2/45 = 8.889\text{m/s}^2$$

- b) The angle of inclination θ

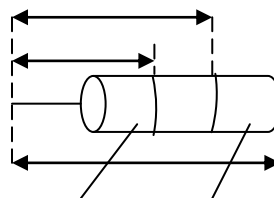
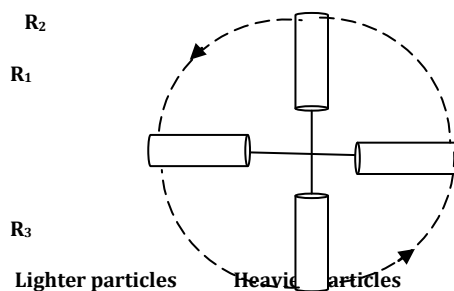
$$\tan\theta = v^2/rg$$

$$\theta = \tan^{-1}(20^2/45 \times 10) = 41.65$$

2.7: Applications of circular motion

2.7.1: Centrifuges

A centrifuge is a device that is used to separate substances of different densities e.g. immiscible liquids or solids suspended in liquids. The mixture is put in tubes which are then set into rotation. At a particular speed, the more dense particles or substance move further away from the centre of rotation while the less dense particles move inwards towards the centre of rotation.



Since centripetal force varies directly as the mass and inversely as the radius, for a larger radius the mass must be higher for the same amount of centripetal force. Hence denser particles are far away from the centre of rotation.

When the rotation stops, the tubes return to the vertical position with the denser particles at the bottom.

2.7.2: Satellites

When two bodies of mass m_1 and m_2 are separated by a distance r , there exists an attractive force between them given by; $F = Gm_1m_2/r^2$

Where G is the universal gravitational constant. The above equation is referred to as Newton's law of universal gravitation. Consider a satellite of mass m orbiting the earth at a distance of r metres away. Suppose the mass of

the earth is M , then the centripetal force that keeps the satellite on the circular path is provided by the gravitational force of attraction.

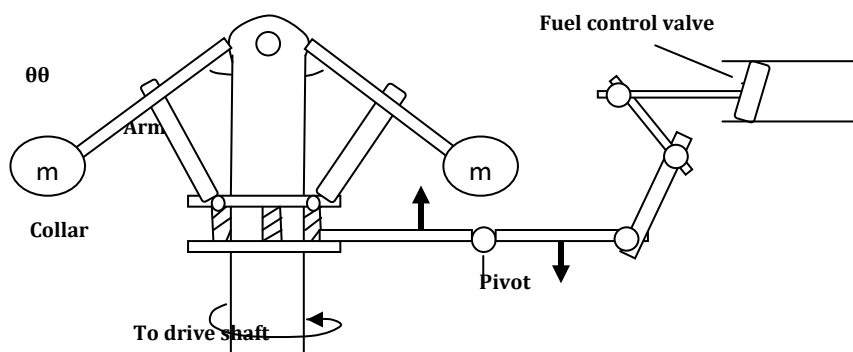
Hence $F_c = mv^2/r = GMm/r^2$

And $v = (GM/r)^{1/2}$

Where v is the velocity of the satellite.

When a satellite has the same periodic time as that of the earth, it will appear stationary when viewed from the earth's surface. Such satellites are said to be in a **parking orbit**. They are widely used in weather forecasting and in telecommunication.

2.7.3: Speed governor



As the shaft rotates, the masses also rotate with increasing angular velocity. Thus the angle θ enlarges. The collar is then pulled upwards by the arms which in turn pulls the lever up. The lever is connected to the fuel/steam valve which regulates the flow of fuel or steam which in turn controls the speed of the engine.

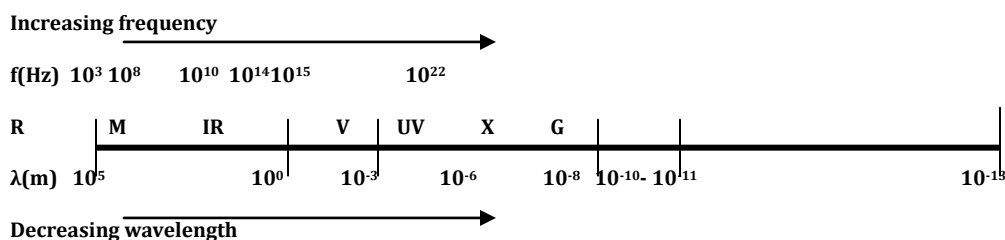
TOPIC 3: ELECTROMAGNETIC SPECTRUM

3.1: Introduction

We have seen that waves can be categorized either electromagnetic or mechanical in nature. Electromagnetic waves are waves resulting from the interaction of oscillating electric and magnetic fields. They include visible light, radio waves, x-rays, infra red, ultraviolet, microwaves and gamma radiations.

When these waves are arranged in a certain pattern e.g in the order of increasing frequency or wavelength then we get an **electromagnetic spectrum**.

3.2: The electromagnetic spectrum



Where **R**- Radio waves

M- Microwaves

IR- Infra red

V- Visible light

UV- Ultraviolet

X- X-rays

G- Gamma radiation

[**Hint:** Roast(R) maize (M) is (IR) a very (V) unusual (UV) x-mass(X) gift (G)].

3.3: Properties of electromagnetic waves

The following properties are common to all electromagnetic waves:

- ✓ Travel in a vacuum with a speed of $3.0 \times 10^8 \text{ m/s}$.
- ✓ Do not require material medium for their propagation.
- ✓ Transverse in nature.
- ✓ Posses and transfer energy. The amount of energy possessed by an electromagnetic wave of frequency f is expressed as $E = hf$, where h is Plank's constant and is equal to $6.63 \times 10^{-34} \text{ Js}$. The wave equation $c = f\lambda$ also apply for electromagnetic waves.
- ✓ Carry no charge (not charged) and are not deflected by a magnetic or electric field.
- ✓ Undergo reflection, refraction, diffraction, interference and polarization effects.

- ✓ Can be emitted, transmitted and absorbed by matter.

3.4: Production, detection and applications of electromagnetic radiations

The table below summarizes the production, detection and applications of the various electromagnetic radiations:

Radiation	Production	Detection	Application
Radio waves	From oscillating electrical circuits.	Antennae (aerials), diodes, earphones.	In telecommunication- radio broadcast, TV and satellite communication, cellular telephone, radar and navigation equipments etc.
Microwaves	From special vacuum tubes called magnetrons within microwave ovens.	Crystal detectors, solid state diodes, antennae.	Cooking in microwave cookers. In communication- mobile phones. In speed cameras.
Infra red	From thermal vibration of atoms in very hot bodies e.g the sun.	Thermopile, bolometer, thermometer, photographic film. Heating effect on the skin.	Burglar alarms, in military night vision missiles, cooking, heating and drying of grains, in green housing, in remote controls for TVs and VCD/DVDs, in photography.
Visible light	Sun, hot objects, lamps, laser beams.	The eye, photographic film, photocell.	Vision (sight), photography, photosynthesis and optical fibre. Laser beams used in laser printers, weapon aiming systems, CD players.
Ultraviolet	The sun, sparks, mercury vapour lamps.	Photographic film, photocells, fluorescent materials e.g quinine sulphate.	Detection of forgeries, skin treatment and killing of bacteria, spectroscopy and mineral analysis, making of clothes and a source of vitamin D.
X-rays	In X-ray tubes	Fluorescent screen and photographic film.	Radiography (identification of internal body structures e.g bones), cancer therapy, crystallography (study of crystal structure), pest and germ control and airport security checks.
Gamma radiation	Emitted by radioactive substances.	Radiation detectors e.g GM tube.	Sterilizing medical equipment and food. Killing of cancer cells and other malignant growths. Pest control. Detection of flaws in metals.

3.5: Dangers of electromagnetic waves

1. Some of the electromagnetic waves like X-rays, ultraviolet and gamma radiation possess a lot of energy. Therefore when exposed to the body in large doses, they can damage the body cells, cause skin burns or affect the eyes. Similarly, radio waves can cause cancer, leukemia among other disorders.
2. Nuclear reactor explosions may lead to losses of lives.

Example 3.1

- 1) A radio transmitter produces waves of frequency $1.0 \times 10^8 \text{ Hz}$. Calculate the wavelength of the signal.

$$c = f\lambda$$

$$3.0 \times 10^8 \text{ m/s} = 1.0 \times 10^8 \times \lambda$$

$$\lambda = 3.0 \text{ m}$$

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

- a) The frequency of the radiation.

$$c = f\lambda$$

$$3.0 \times 10^8 \text{ m/s} = f \times 1.0 \times 10^{-11} \text{ m}$$

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

- b) The energy content of the radiation. Take $h = 6.63 \times 10^{-34} \text{ Js}$.

$$E = hf = 6.63 \times 10^{-34} \text{ Js} \times 3.0 \times 10^{19} \text{ Hz}$$

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

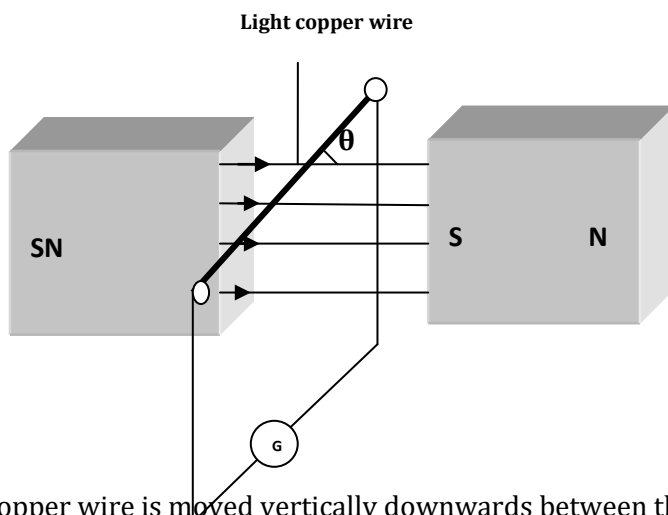
- 3) Arrange the following radiations in order of increasing wavelength: infra red, blue light, UV light, radio waves and X-rays.

X-rays, UV light, blue light, infra red and radio waves.

TOPIC 4: ELECTROMAGNETIC INDUCTION**4.1: Introduction**

When a conductor moves within a magnetic field at an angle greater than zero, current is produced in the conductor which can be shown by connecting a galvanometer in series with the conductor. This method of generating electricity is called **electromagnetic induction**. It was first discovered by Michael Faraday about the year 186.

Electromagnetic induction has been widely used to produce in large scale electrical energy in power stations.

4.2: Factors affecting the size of the induced electromotive force and Faraday's law

When the copper wire is moved vertically downwards between the poles of the magnet, the galvanometer is observed to deflect. However, the direction of deflection changes when the wire is now moved vertically upwards. When the conductor is kept stationary between the poles of the magnet, no deflection occurs. Similarly when the wire is placed parallel to the magnetic field, no deflection is observed.

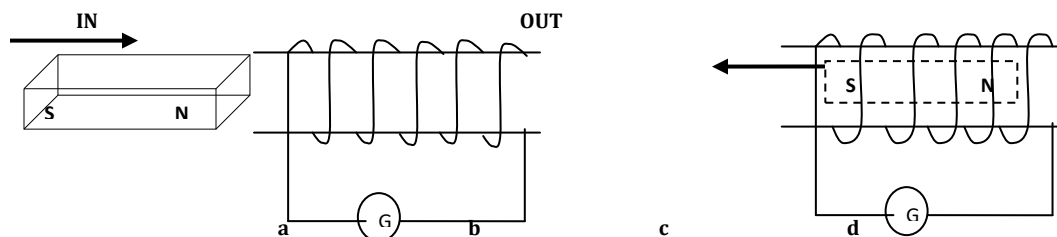
A deflection of the galvanometer indicates presence of induced electromotive force while absence of deflection indicates no induced electromotive force.

The deflection is maximum when the **angle between the wire and the field is 90°** , a stronger magnet is used and when the wire is moved very swiftly (at a high speed).

These factors can be summed up in Faraday's law which state: **the magnitude of the induced emf is directly proportional to the rate of change of the magnetic flux linkage**. Magnetic flux linkage refers to the number of magnetic field lines cut by the conductor per unit area.

4.3: Lenz's law

Electromotive induction also occurs when a magnet is moved to and back within a solenoid as shown below:

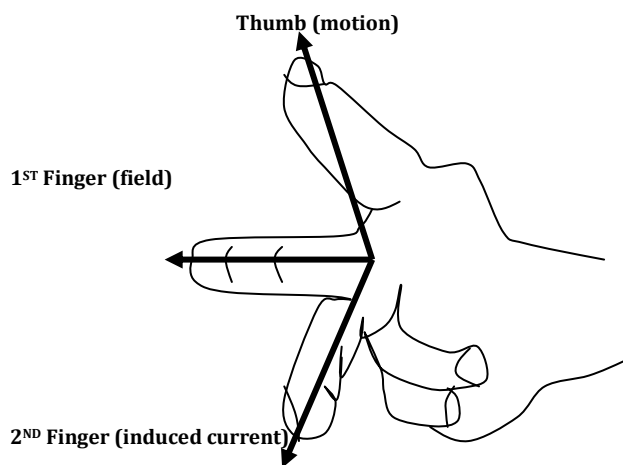


When the magnet is pushed into the solenoid, the galvanometer is observed to deflect same to when it is brought out but in opposite directions. However, when the magnet is kept stationary in the solenoid no deflection occurs.

Specifically, when the north pole of the magnet is brought into the solenoid the galvanometer deflects towards the left showing that current flows from **b to a** but deflects towards the right when the magnet is moved away from the solenoid showing that current flows from **c to d**.

These observations are summarized in Lenz's law which state: **the induced current flows in such away to oppose the change causing it**. It is based on the principle of conservation of energy i.e the mechanical energy of the moving magnet is converted to electrical energy in the form of the induced current.

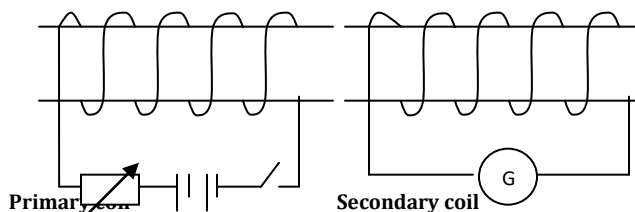
The direction of the induced current can be predicted by Fleming's right hand rule: if the thumb, first and second fingers of the right hand are held mutually at right angles to each other with the **F**irst finger pointing the direction of the **F**ield, thumb pointing the direction of the **M**otion then the se**C**ond finger points in the direction of the **C**urrent. It is also called the Dynamo rule.



4.4: Mutual induction

Mutual induction occurs when a varying current in one coil induces current in another close coil. The first coil in which current flows is called the **primary** coil while the second coil in which current is induced is called the **secondary** coil.

The varying current in the primary coil produces a magnetic field which links with the secondary coil inducing current in it.



When the switch is closed, current in the primary coil increases from zero to maximum. As a result, the magnetic flux linking up with turns of the secondary coil also increases from zero to maximum. This changing magnetic

flux induces current in the secondary coil which makes the galvanometer to deflect. Once the current has reached maximum value, there will be no further increase in the magnetic flux and the pointer goes back to zero.

When the switch is open, the current falls from maximum to zero within a very short time. This implies that the magnetic flux of the primary coil takes a very short time to change. The shorter the time the higher the induced current and thus a larger deflection. Hence more current is induced during switching off than during switching on.

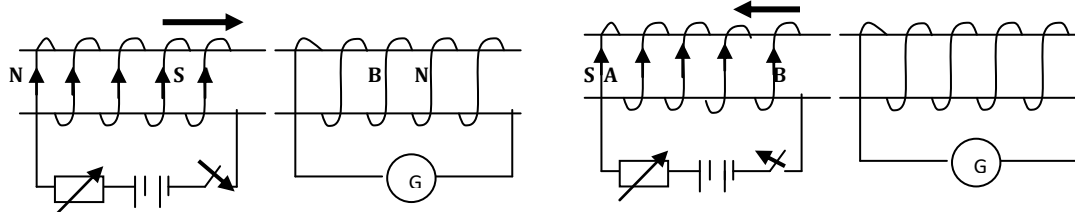
The magnetic flux of the primary coil linking up with the secondary coil can be varied by:

- Switching the current on and off.
- Varying the current in the primary coil using a rheostat.
- Applying an alternating current.

The direction of the induced current can be predicted applying the **Right-hand grip rule** and **Lenz's law** simultaneously. When doing so, the primary coil is treated as if it were a bar magnet moving into the secondary coil during switching on and as a bar magnet moving away from the secondary coil during switching off.

South pole approaching

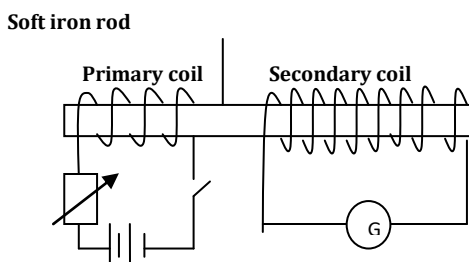
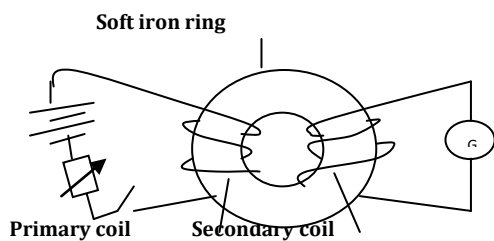
South pole receding



Thus by Lenz' law, during switching on the end A attains a South pole and B a North pole while during switching off the end A attains a North pole and B a South pole such that in each case the effect of the primary field is being opposed by that of the secondary coil.

The induced emf and current in the secondary coil can be increased by:

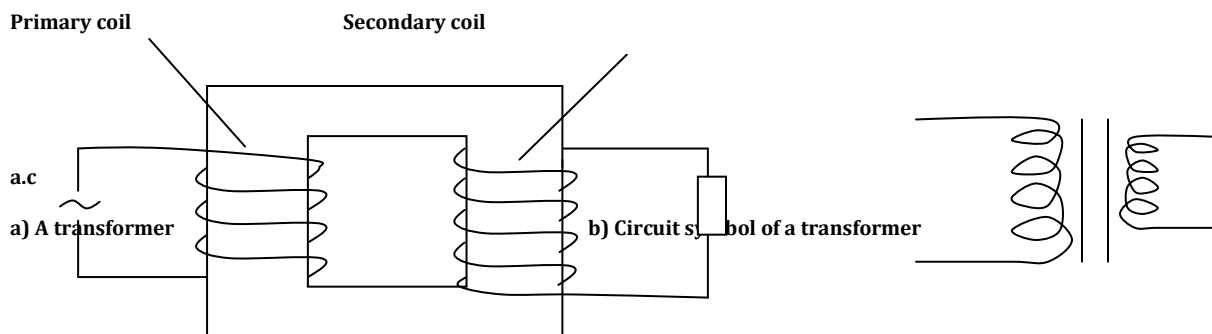
- Increasing the number of turns in the secondary coil so that many turns can link up with the magnetic field of the primary coil.
- Winding both the primary and secondary coils on a soft iron ring or soft iron rod. This will help to concentrate the magnetic field lines within the secondary coil. Soft iron is also easier to magnetize and demagnetize.



4.5: Applications of electromagnetic induction

4.5.1: Transformer

A transformer is a device that transfers electrical energy from one circuit to another by mutual induction. It comprises of two coils; the primary and secondary coils. An alternating current is fed into the primary coil whose magnetic flux links up with the secondary coil inducing current in it. Both the primary and the secondary coils are wound on a common soft iron core to enhance its effectiveness.



For any transformer, the ratio of the number of turns of the secondary coil n_s to the number of turns of the primary coil n_p is called the turn's ratio;

i.e turn's ratio = n_s/n_p .

For an ideal transformer (100% efficient);

Power fed into the primary coil (power input) = power generated at the secondary coil (power output).

i.e $V_p I_p = V_s I_s$.

Rearranging the above equation, we obtain:

$V_s/V_p = I_p/I_s$.

Hence when the voltage is stepped up the current is stepped down.

Therefore, for an ideal transformer:

$n_s/n_p = V_s/V_p = I_p/I_s$.

The efficiency of a transformer = {power output/power input} $\times 100$.

The equation $n_s/n_p = V_s/V_p$ is referred to as the transformer equation.

There are two types of transformers namely step-down and step up transformer.

a) Step down transformer

In a step-down transformer, there are more turns on the primary coil than the secondary coil ($n_p > n_s$, thus the turn's ratio is less than one (1).

A step down transformer steps down voltage but steps up current. Hence the input voltage is less than the output voltage.

b) Step up transformer

A step up transformer steps up voltage but steps down current. In a step up transformer, there are more turns on the secondary coil than the primary coil. Thus the turn's ratio is more than one. The output voltage is greater than the input voltage.

Example 4.1

1. Calculate the number of turns of the secondary coil of a step down transformer which would enable a 12V bulb to be used with a 240V ac supply if there are 480 turns in the primary coil.

$$n_s/n_p = V_s/V_p$$

$$n_s/480 = 12V/240V$$

$$n_s = (480 \times 12)/240 = 24 \text{ turns}$$

2. What current will flow in the secondary coil when the primary current is 0.5A if the voltage in the primary coil is 240V and that in the secondary coil is 48V? Assume the energy loss is negligible.

$$V_s/V_p = I_p/I_s$$

$$48V/240V = 0.5A/I_s$$

$$I_s = (0.5 \times 240)/48 = 2.5A$$

3. A student designed a transformer to supply a current of 10A at a potential difference of 60V to an electric motor from an ac supply of 240V. if the efficiency of the transformer is 80%, calculate:

a) The power supplied to the transformer.

$$\text{Efficiency} = (\text{power output} / \text{power input}) \times 100$$

$$80 = [(60 \times 10) / \text{power input}] \times 100$$

$$\text{Power input} = (60 \times 10 \times 100) / 80$$

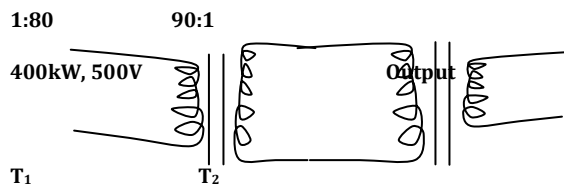
$$= 750W$$

b) The current in the primary coil

$$\text{Power input} = V_p I_p$$

$$I_p = 750W / 240V = 3.125A$$

4. A model of a transformer system consists of a power generator, a step up transformer, transmission cables and a step down transformer.



Given that the total resistance of the cables is 200Ω , transformer T_1 is 100% efficient and T_2 is 95% efficient, calculate:

a) The current through the primary coil of T_1 .

$$\text{Power input} = V_p I_p$$

$$100,000W = 500V \times I_p$$

$$I_p = 100,000 / 500 = 800A$$

b) The voltage across the secondary coil of T_1 .

$$n_s / n_p = V_s / V_p$$

$$80 / 1 = V_s / 500V$$

$$V_s = 500 \times 80 = 40000V$$

c) The voltage across the primary coil of T_2 .

$$V_p I_p = V_s I_s$$

$$400,000 = 40000V \times I_s$$

$$I_s = 400,000 / 40,000 = 10A$$

This is the current flowing through the secondary coil of T_1 .

Hence the voltage dropped across the cables (lost through resistance) = IR

$$V = 10 \times 200 = 2000V$$

Therefore the voltage across the primary coil of $T_2 = 40,000 - 2000$

$$= 38,000V.$$

d) The maximum power output of the transformer T_2 .

$$\text{efficiency} = (\text{power output} / \text{power input}) \times 100$$

$$95 = (\text{power output} / 38000 \times 10) \times 100$$

$$\text{Power output} = [95 \times 38000 \times 10] / 100$$

$$= 361,000V$$

➤ Energy losses in transformers

There are four main causes of energy losses in transformers:

i. Flux leakage

When part of the magnetic flux of the primary coil fails to reach the secondary coil, it is referred to as magnetic flux leakage.

In order to minimize energy loss through flux leakage can be reduced by winding the primary and secondary coils next to each on a common core. Alternatively, the secondary coil can be wound on top of the primary coil.

ii. Resistance

As current flows through the coils, heat is generated due to the resistance of the coils. The electrical power loss as a result of resistance is given by I^2R .

Energy loss through resistance can be minimized by using thicker copper wires.

iii. Eddy currents

As the current alternates the magnetic flux also keeps alternating in the soft iron core producing eddy currents. These currents are sufficient enough to generate heat within the core.

The energy loss can be minimized by laminating the core i.e. using thin sheets of soft iron plates insulated from each other.

iv. Hysteresis loss

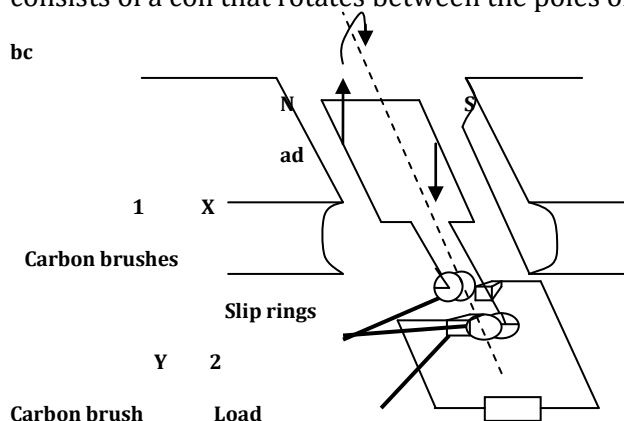
The process of magnetization and demagnetization any time current reverses do generate heat within the core. Energy loss in this way is referred to as hysteresis loss.

Hysteresis loss can be minimized by using soft iron core which is easier to magnetize and demagnetize.

Note that despite the above measures, some of significant heat is still generated within the transformers. This is further cooled using oil.

4.5.2: Alternating current (ac) generator

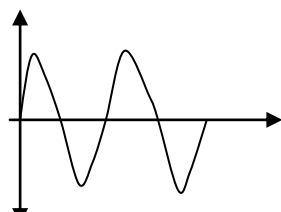
It is also called the alternator. A generator is a device that converts mechanical energy into electrical energy. It consists of a coil that rotates between the poles of a strong magnet.



Suppose the coil is rotated in the clockwise direction as shown above, then the sections **ab** and **cd** cut through the magnetic field between the poles of the magnet inducing current in the coil. Applying Fleming's right hand rule on the section **ab**, the induced current flows in the direction **abcd** and through the load via the slip ring 2 and carbon brush Y.

The induced current is maximum when the coil is horizontal and reduces to zero when the coil is at the vertical position. At the vertical position, the coil is parallel to the magnetic field and thus no current is induced in the coil. Beyond the vertical position, the induced current increases from zero to maximum when the coil is once again at the horizontal position.

Applying Fleming's right hand rule again, the induced current flows in the direction **dcba** and through the load via the slip ring 1 and carbon brush X. Hence in second half cycle, current direction is reversed. The induced emf or current by the ac generator appears as shown by the graph below:

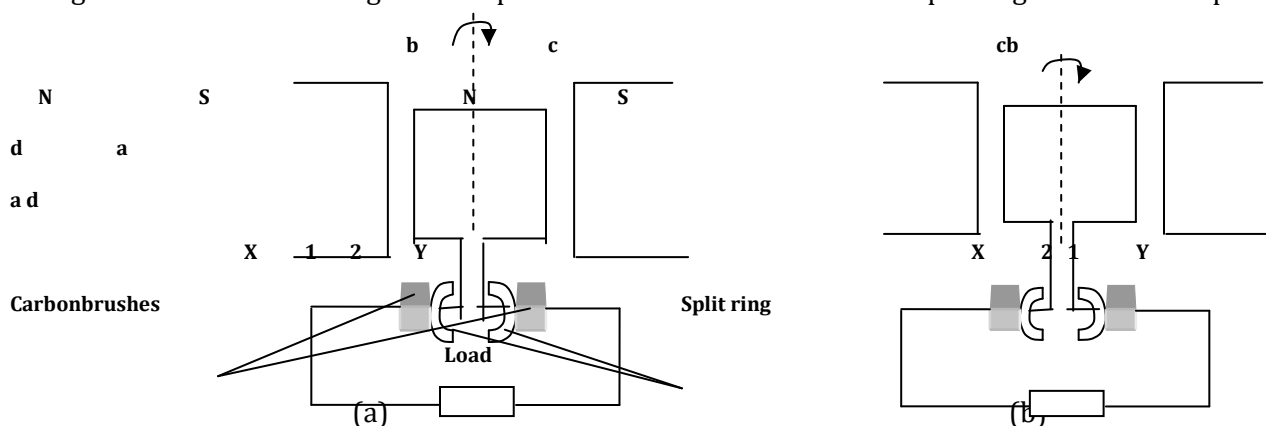


Induced emf/
current

0 180 360 540 720 angle made with the field.

4.5.3: Direct current (dc) generator

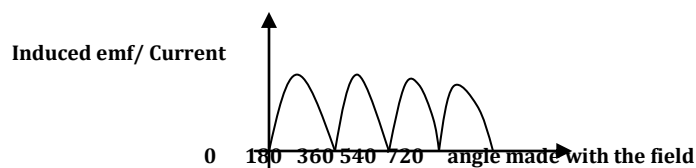
This generator unlike the ac generator produces direct current. It uses a split ring instead of a slip ring.



As the coil rotates from the horizontal position to the vertical position, the induced current reduces from maximum to zero. When the coil is rotated in the clockwise direction as shown in figure (a), the induced current flows in the direction **abcd** and through the load via the half split ring 2 and carbon brush Y.

At the vertical position the carbon brushes touch the gaps between the commutators (half split rings). When the coil goes past the vertical position, the half split rings automatically exchange the carbon brushes as shown in figure (b) above. Applying Fleming's right hand rule again, the induced current flows in the direction **dcba** and through the load via the half split ring 1 and carbon brush Y. thus the direction of current through the load is in one direction only hence direct current generator.

The graph of induced current/emf by a dc generator appears as shown below:



Note that the magnitude of the induced current and electromotive force produced by both the ac and dc generators can be increased in the following ways:

- ✓ Using a stronger magnet.
- ✓ Increasing the number of turns of the secondary coil.

- ✓ Increasing the speed of rotation of the coil.
- ✓ Winding the coil on a soft iron core.

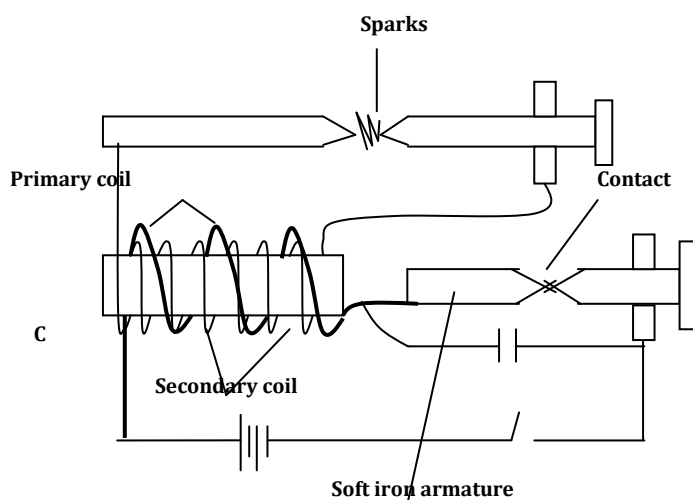
In some generators like the bicycle dynamo, the coil is kept stationary while the magnet rotates.

4.5.4: Induction coil

An induction coil consists of a primary coil of fewer turns and a secondary coil of many turns, both wound on a soft iron core. When the switch is closed, the soft iron core becomes magnetized and attracts the soft iron armature. This breaks the contact and current stops flowing. The core is thus demagnetized. The armature is released and the contact is remade. The process is repeated as long as the switch is closed.

The changing magnetic flux during magnetization and demagnetization produces an induced emf and current in the secondary coil. The induced current in the secondary coil produces sparks as current flows through the air across the gaps at the ends of the secondary coil as the shown in the figure below:

..

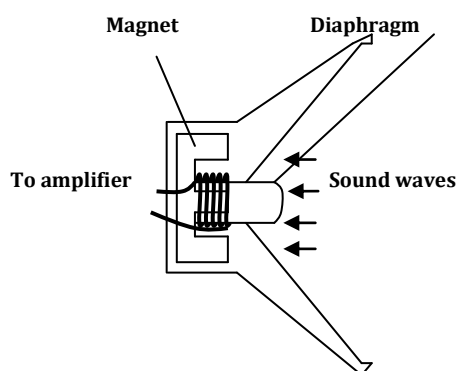


The capacitor is used to store charge and thus reduce sparking.

The sparks produced can be used to ignite an air-petrol mixture such as in the car ignition system.

4.5.5: The moving coil microphone

A moving coil loudspeaker converts sound energy into electrical energy.



When a person speaks into the microphone, the sound waves set the diaphragm into vibration. This makes the coil to move forward and back cutting through the magnetic field inducing current in the coil. The induced current flows to the amplifier for amplification before it is relayed to the loudspeaker where it is converted back to sound energy.

TOPIC 5: MAINS ELECTRICITY**5.1: Introduction**

Mains electricity refers to the electrical power supplied to households. The power is generated at the power station and then transmitted to the consumers either through overhead transmission lines or underground cables.

Some of the sources of mains electricity include water in high dams, geothermal, wind, solar energy, coal and diesel engine generators, nuclear energy and tidal waves.

Note that the choice of the source of mains electricity to use is dependent on its availability and abundance as well as the implications it has on the environment.

In Kenya, the most utilized source of mains electricity is hydroelectricity. Today, there is also increased usage of solar energy, geothermal energy, wind energy and coal.

5.2: Electrical power transmission

This is process by which electrical power is relayed from the generation plant to the consumers at their homes, institutions, schools, industries, factories etc. In Kenya, electrical power is distributed using the national grid system. The national grid system is a network of cables connecting at a common point all the power generation plants and then distributed to the consumers. This way it ensures availability of power even when one of the stations is shut down.

Before power is fed into the national grid system, it is stepped up i.e. voltage is stepped up but current is stepped down. Most power stations generate between 11kV and 25kV which is stepped up to between 17kV and 400kV. At the consumer end, a step down transformer is used to step down the voltage to about 11kV at a substation. However, this value is still large to be used the way it is. The power is then distributed by cables to another step down transformer which is situated just near the consumer. This transformer further steps down the voltage to a consumable value of 240V for domestic use or 415V for factories.

High voltage transmission has the following three benefits:

- ✓ Power loss due to resistance of the cables is minimal.
- ✓ Thin cables could be used.
- ✓ Reduced cost in acquiring cables and poles.

However, high voltage transmission has some limitations. These include:

- High risks of electric shock in case the poles collapse or the cables hang very low.
- High risks of fire outbreak on nearby buildings and vegetation when the cables hang too low or when the cables touch each other.
- Harmful effects of strong magnetic fields due to the current flowing in the cables.

Electrical power is generated and distributed as alternating current. This is because of the following reasons:

- i. Transformers work on alternating current/voltage only.
- ii. It is easier to step up or down.

- iii. Alternating current is easier to rectify.

Example 5.1

1. Some length of a power line has a resistance of 10Ω and is transmitting 11kV and a current of 1A . If the voltage is stepped up to 160kV by a transformer, calculate:

- a) The initial power loss

$$\text{Power loss} = I^2 R = 1^2 \times 10$$

$$= 10\text{W}$$

- b) The power loss after step up

$$V_P I_P = V_S I_S$$

$$10\text{kV} \times 1\text{A} = 160\text{kV} \times I_S$$

$$I_S = (10/160) = 0.06875\text{A}$$

$$\text{Hence, power loss} = 0.06875^2 \times 10$$

$$= 0.048\text{W}$$

2. A power station produces 50kW at 240V . The power is transmitted through cables with a resistance of 0.4Ω . Calculate the percentage power loss during transmission.

$$\text{Power} = VI$$

$$50,000\text{W} = 240\text{V} \times I$$

$$I = 50,000/240 = 208.8\text{A}$$

$$\text{Hence, power loss} = 208.37 \times 0.4$$

$$= 17,360.556\text{W}$$

$$\% \text{power loss} = (17360.556/50000) \times 100 = 9.72\%$$

5.3: Domestic wiring

From the step down transformer near the consumer, power is transmitted by two cables; the live and neutral wire to the consumer's meter which measures and registers the amount of power consumed. The live wire is at full potential of 240V while the neutral wire is at zero potential since it has been earthed at the sub-station. From the meter, electricity enters the fuse box which comprises of the following:

- ✓ Main switch- controls all the live and neutral wires simultaneously. It is normally useful during repairs.
- ✓ Live busbar- it is a brass bar on which all the live wires of all the circuits have been connected. Each live wire is connected to the live busbar through a fuse.
- ✓ Neutral busbar- it is a brass bar to which all neutral wires of all the circuits have been connected.

- ✓ Earth terminal- it is used to earth the circuit. This can be done by burying a thick copper wire deep underground or through a metallic water piping.

A fuse is a thin wire with very low melting point such that if it is overheated it melts and the circuit gets disconnected. This way it is used to safeguard electrical appliances. Fuses are rated in amperes. Normally, the fuse rating is slightly above the maximum current requirement of the appliance. All fuses must be connected along the live wire.

In domestic wiring, there are three important types of wires commonly used namely live wire, neutral wire and earth wire.

- ✓ Live wire- it transmits alternating current from the source to the appliance or plug. It is normally red or brown in colour.
- ✓ Neutral wire- it is the return wire i.e. it returns the current back to the source completing the circuit. It is usually at zero potential. It is normally blue or black in colour.
- ✓ Earth wire- it earths the circuit. It is normally green or yellow in colour

However, at times the fuse may melt off and thus fail to serve its rightful purpose. Some causes that can lead to melting off of the fuse include:

- Short circuiting when bare conductors touch each other.
- Overloading the circuit with more appliances than the fuse can accommodate.
- Using a fuse of lower rating than the current requirement of the appliance.
- Using a faulty fuse whose wire could have been oxidized.

Example 5.2

1. An electric cooker has an oven rated 3kW, a grill rated 2kW and two rings each rated 500W. The cooker operates from 240V mains. Would a 5A fuse be suitable for the cooker assuming that all the parts are switched on?

$$I_{\text{oven}} = 5000/240 = 12.5\text{A}$$

$$I_{\text{grill}} = 2000/240 = 8.8\text{A}$$

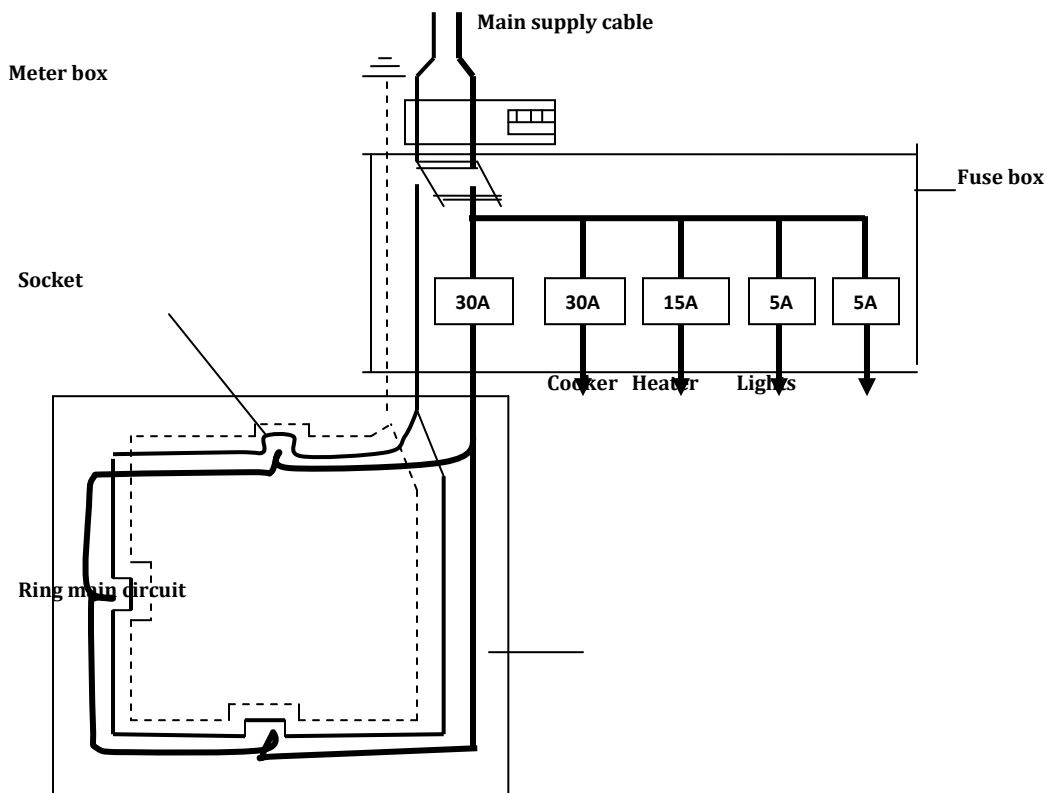
$$2I_{\text{rings}} = (2 \times 500)/240 = 4.17\text{A}$$

$$\begin{aligned}\text{Total cooker current} &= 12.5 + 8.8 + 4.17 \\ &= 25.0\text{A}\end{aligned}$$

With a fuse rated 5A, it is suitable.

Note that a circuit breaker can also be used to serve the same purpose as the fuse. It should be noted that a circuit breaker is better than a fuse since for a fuse once it has blown off it must be replaced while for a circuit breaker, it does not need to be replaced. Instead, the strip just needs time to cool off and then the circuit will be complete once again.

The diagram below shows a typical house wiring system:



5.3.1: The lighting circuit

This is the circuit that controls all the lamps within the house. Lamps are always connected in parallel so that they are operated from the same mains voltage. This also ensures that the other lamps continue to work when one is faulty. The lighting circuit uses very low current and therefore thin wires are usable. This is also the reason why the lighting circuit needs not to have the earth wire. It also has a low rated fuse, mostly 5A fuse.

A two-way switch circuit

In this circuit, a lamp is operated by two switches i.e. one can put the lamp on and the off and vice versa. Such a circuit is very convenient for lighting a staircase or corridors.

Note that all switches are connected along the live wire.

5.3.2: The cooker circuit

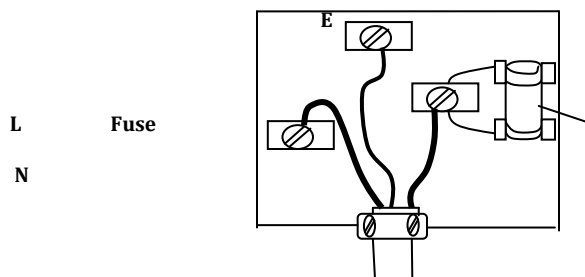
The electric cooker and water heater both use a lot more current and therefore require a high rated fuse. In most cases, they are normally supplied with their own circuits. Such circuits are usually earthed and use thicker wires.

5.3.3: The ring main circuit

This circuit supplies power to the sockets around the house. It also uses more current compared to the lighting circuit.

Sockets are used with plugs. There are two types of plugs namely a two-pin plug and a three-pin plug. A two-pin plug has only the live pin and the neutral pin while a three-pin plug has in addition to the above two an earth pin which is normally longer than the other two pins. This pin has two roles:

- i. It is used to open the blinds (socket) for the other two pins.
- ii. It is used to leak out the charges which could have developed in the socket.



Some plugs have a fuse inserted in them along the live wire to safeguard appliances in case of excessive current.

5.4: The cost of electrical energy

The cost of electrical energy consumed depends on the power rating of the appliances used and the duration of use. The electrical energy used is measured by the meter in kilowatt-hours (kWh). It is given by the product of the power in kilowatts and the time in hours;

Electrical energy consumed = power (kW) x time (h).

One kilowatt-hour is also referred to as one unit;

1kWh = 1unit

The total cost of electrical energy consumed by a household is given by the product of the number of units consumed and the charges per unit;

Total cost = number of units used x cost per unit.

Example 5.3

1. A six bulb arrangement in a house runs for 8hours every night for 5days. If each bulb is rated 100W and the cost of electrical energy is sh. 2.60 per unit, how much will the owner of the house pay at the end of the five days?

Electrical energy consumed = $(6 \times 0.1 \times 8) \times 5 = 24\text{kWh}$

Total cost = $24\text{kWh} \times \text{sh } 2.60 = \text{ksh. } 62.40$

2. An electric cooker has an oven rated 3kW, a grill rated 2kW and two rings each rated 500W. The cooker operates from a 240V mains. What is the cost of operating all the parts for 5minutes if electricity costs Sh 1.50 per unit?

Total units consumed = $[3 + 2 + (2 \times 0.5)] \times 5 / 60$

$$=3\text{kWh}$$

$$\text{Total cost} = 3\text{kWh} \times \text{sh } 1.50$$

$$= \text{Ksh } 4.50$$

TOPIC 6: CATHODE RAYS AND CATHODE RAY TUBE**6.1: Introduction**

When a metal surface is heated, the electrons gain energy and become excited. At very high temperatures, the electrons may break off from the force of attraction of the nuclei. When heat is used to extract electrons from the surface of a metal, it is referred to as **thermionic emission**.

Cathode rays are streams of fast moving electrons emitted from the surface of a heated cathode inside a vacuum.

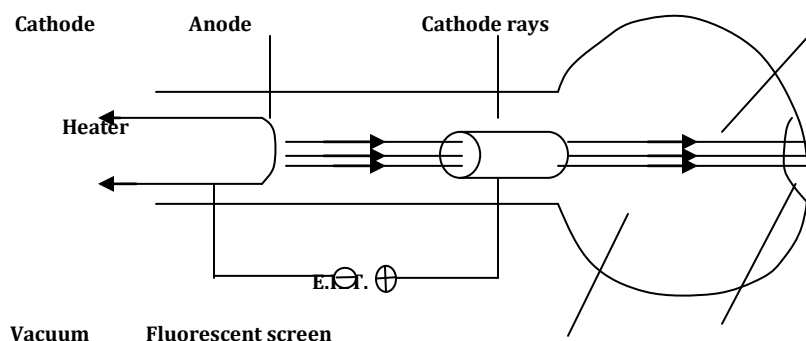
6.2: Production of Cathode Rays.

Fig.1 Cathode Ray Tube

Cathode rays are produced in a cathode ray tube. The cathode is heated by the heater emitting electrons through thermionic emission. Note that the cathode rays are streams of negatively charged particles (electrons). Thus once emitted at the cathode, the electrons will be attracted by the anode which is at a positive potential. Hence the role of the anode is to accelerate the electrons towards the screen. The anode is connected to an extra high tension (EHT) source.

The tube is evacuated. This is to prevent the electrons from interacting with any particles before reaching the screen. The screen is coated using a fluorescent material that glows when struck by the electrons.

6.3: Properties of Cathode Rays

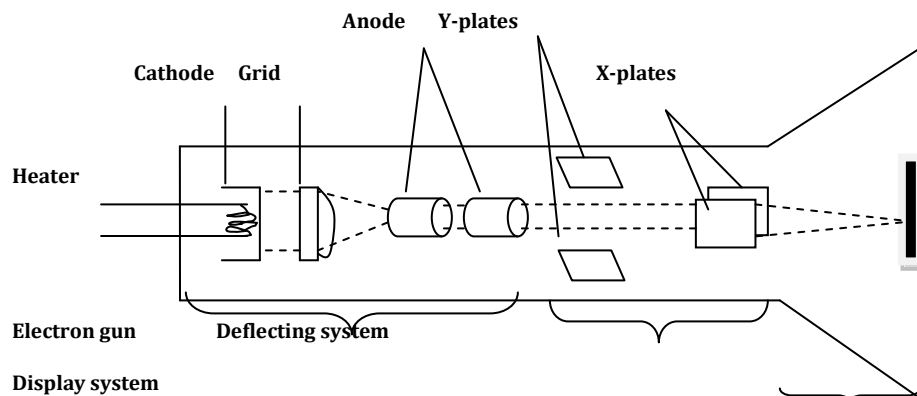
1. They travel in straight lines. When an opaque object is placed along the path of the rays, a sharp shadow of the object is formed on the screen.
2. They are charged. Hence they are deflected by both magnetic and electric fields.
3. They possess kinetic energy.
4. They can cause certain substances e.g zinc sulphide screen to glow or fluoresce.
5. They can produce X-rays when they are suddenly stopped by a metal target.

6.4: The Cathode Ray Oscilloscope (CRO)

This is an electrical instrument developed from the cathode ray tube and which can be used to display and analyze waveforms. It can display both alternating current and direct current waveforms. Furthermore, it can be used to measure voltages that vary over time.

A cathode ray oscilloscope has three main components:

- ✓ The electron gun.
- ✓ The deflecting system.
- ✓ The display system.



a) The electron gun

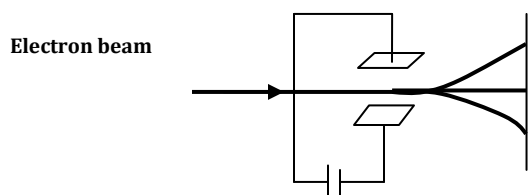
It consists of three parts namely the cathode, grid and anode. The cathode emits electrons through thermionic emission. The grid concentrates the electrons into a tight beam. It is connected to the negative terminal of the EHT and thus it is at a negative potential. When the negative voltage of the grid is raised, fewer electrons will move towards the screen and thus the spot will be less bright. However, when the grid voltage is lowered, more electrons will move towards the screen and thus the spot will be brighter. In general, the grid controls the rate of flow of electrons to the screen i.e. intensity.

The anode on the other side is at a positive potential and is used to accelerate the emitted electrons towards the screen. It also focuses the electrons to a point on the screen.

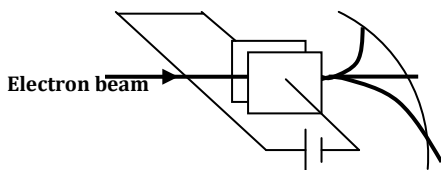
b) The deflecting system

This system places the electron beam on the screen. It comprises of two pairs of parallel plates namely the Y-plates and X-plates.

The Y-plates are responsible for the vertical deflection. When the upper plate is at a positive potential for instance, the beam is deflected upwards while if the lower plate is now at a positive potential, the beam is deflected downwards. However, when both plates are at a zero potential the beam will pass undeflected.



The X-plates are responsible for the horizontal deflection of the electron beam.



There is no deflection when the potential difference across the plates is zero but deflects towards the plate at a positive potential when connected to a source of voltage as shown on the figure above.

If an alternating voltage is applied simultaneously to both the Y and X-plates, then the spot on the screen would oscillate up and down and at the same time move across the screen from left to right tracing a wave on the screen. When the spot reaches the extreme end it flies back to the starting point and process is repeated.

The speed with which the spot moves on the screen can be adjusted by the time base knob.

6.5: Uses of the CRO

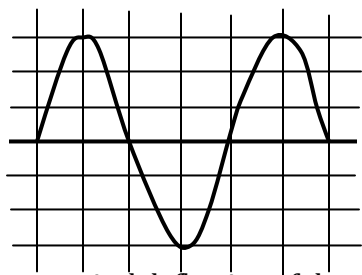
i. Used as a voltmeter.

The time base is switched off while the voltage to be measured is fed through the Y-gain of the CRO. The applied voltage displaces the spot vertically on the screen. The Y-gain control knob can be used to amplify the display on the screen by setting it to a certain value. This is referred to as the sensitivity of the CRO.

Hence the corresponding voltage to the signal on the screen is expressed as;

Voltage (V) = vertical deflection (cm) x Y-gain setting or sensitivity (volts/cm)

Consider the waveform shown in the figure below:



The maximum vertical deflection of the signal is 3cm or 3divisions on either side. Suppose the Y-gain setting is 50V/cm;

Then the peak voltage represented by the signal = vertical displacement (cm) x Y-gain setting (V/cm).

$$= 3\text{cm} \times 50\text{V/cm} = 150\text{V}$$

When used as a voltmeter, a CRO has the following advantages over the ordinary voltmeters:

- ✓ Can measure both direct and alternating voltages.
- ✓ Can measure very large voltages without being damaged.
- ✓ Does not take any current in the circuit since it has infinite resistance.
- ✓ It responds instantly. The pointer of ordinary voltmeters always swings about the correct value.

ii. Used to measure frequency

The signal whose frequency is to be measured is fed into the Y-gain and the time base is switched on and adjusted so that the waveform appears stationary on the screen. Suppose the time base setting is 10ms/cm, it

implies that the wave takes 10ms to cover 1cm horizontally. This can be used to determine the time of one wave i.e period T.

Recall: frequency = $1/\text{period T}$.

In the example above, suppose the time base is set at 40ms/cm;

Then, period T = number of divisions fitting one wave x time base setting

$$= 4\text{cm} \times (40/1000) \text{ s/cm}$$

$$= 0.16\text{s}$$

Hence frequency of the signal = $1/0.16 = 6.25\text{Hz}$

Other uses of the CRO include:

- ✓ Measurement of small time intervals.
- ✓ Measurement of amplitudes of direct and alternating voltages.
- ✓ Display of electrical signals whose variations can be put in the form of voltage.

6.6: The television tube

A television tube comprises of three electron guns, two sets of coils for deflection and a fluorescent screen. There are two types TV tubes namely the black and white tube and a coloured tube. The signal is fed into the television through the control grid. This varying incoming signal regulates the number of electrons being emitted by the electron gun at any instant. This in turn regulates the brightness of the spot on the screen.

The screen is coated using green, blue and red phosphors. When a red colour is required for instance, the red electron gun emits a red electron beam which strikes the red phosphor on the screen. The same happens for green and blue colours.

For white colour, all the three electron guns simultaneously fire electrons to the screen. However, for black colour, no beam is fired to the screen. The rest of the colours are just obtained from a combination of any two of the three colours.

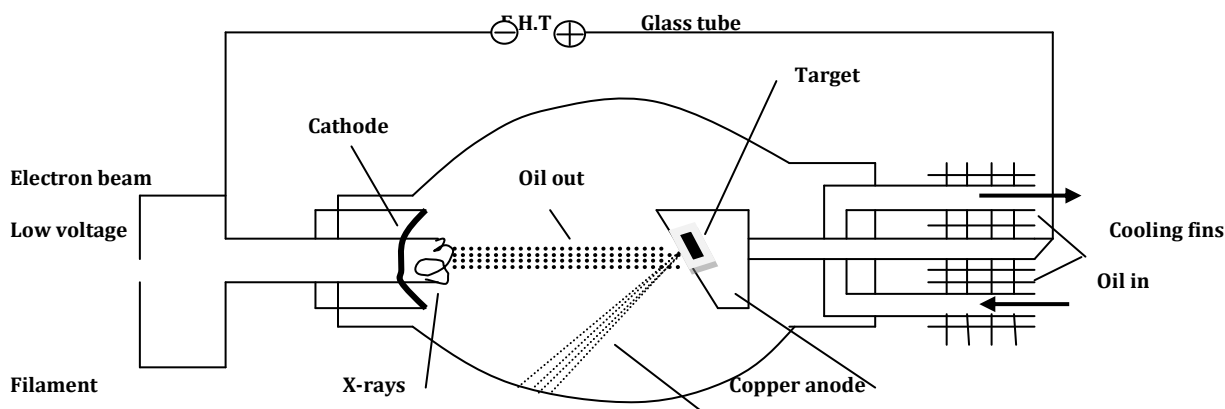
The deflection of the beams is done by the two coils; one responsible for the vertical deflection and the other for the horizontal deflection. A current is fed into these coils producing a magnetic field. As the electrons pass between the coils, the resultant force on them causes them to deviate.

A magnetic field is preferred to an electric field in a TV tube because it gives a wider deflection on the screen and thus a shorter tube can be used.

TOPIC 7: X-RAYS**7.1: Production of x-rays**

X-rays are produced when fast moving electrons are suddenly stopped by a metal target. At the time of their discovery by a German Physicist Röntgen, their nature was unknown and hence their name x-rays. Generally, x-rays are uncharged electromagnetic radiations of short wavelength and high penetrating ability (power).

X-rays are produced in an x-ray tube:



Current in the filament emits electrons at the cathode by thermionic emission. These electrons are then attracted towards the anode by the high potential difference that exists between the cathode and anode. On striking the target, the electrons transfer their kinetic energy to the metal target. About 99.5% of this energy is converted to heat at the target and only 0.5% of the energy is responsible for the production of x-ray radiations.

As such, the material of the target must be one that has a high melting point like molybdenum or tungsten. The anode should also be a good thermal conductor like copper so as to ensure efficient dissipation of heat.

Further cooling at the anode is enhanced by a circulation of oil around the anode and the presence of cooling fins. In some tubes, the target is made in such a way to rotate so as to change the point of impact and thus reduce wear and tear.

The target is inclined at an angle to direct the x-rays out of the tube. The glass tube is also evacuated to **prevent interference with the electron beam before reaching the target**. The cathode is concave in shape **to focus the emitted electrons to the target**. The high potential difference is used to accelerate the emitted electrons towards the anode.

The x-ray tube is well shielded using lead which absorbs any stray rays thereby protecting the user.

7.2: Properties of X-rays

- Travel in straight lines with the speed of light in air; $3.0 \times 10^8 \text{ m/s}$. When an opaque object like a bone is placed on the path of x-rays a sharp shadow of the object is formed on the screen.
- They carry no charge. Hence x-rays are not deflected by either magnetic fields or electric fields.
- Ionize air molecules on their paths by knocking off electrons in them.
- They cause certain substances and salts to fluoresce.
- They cause photographing emulsion, a property used in x-ray photography.

- They cause photoelectric effect when incident on the surface of some metals.
- They can readily penetrate matter. The degree of penetration depends on the density of the material and the quality of the x-rays.
- They obey the wave equation $v=f\lambda$.
- They undergo interference, reflection, refraction and diffraction effects.

7.3: Energy and Quality of x-rays

When an electron of charge **e** is accelerated by a voltage **V** applied across the tube, the electron gains an amount of energy equivalent to **eV** (electron volts). This energy is converted into kinetic energy of the electron;

i.e **eV=K.E**

eV = $\frac{1}{2}mv^2$, where m- mass of the electron ($m=9.11 \times 10^{-31} \text{kg}$) and v- the velocity of the electron.

Also, according to Plank's theory, the energy of any electromagnetic radiation x-rays included is given by;

Energy, **E** = hf , where h- is Plank's constant and f- is the frequency of the radiation.

Hence for x-rays; **eV** = $\frac{1}{2}mv^2 = hf = h\nu/\lambda$.

Generally, most energetic x-rays are those with higher frequency or shorter wavelength while the least energetic x-rays are those with lower frequency or longer wavelength.

The energy of x-rays depends on the accelerating potential between the cathode and the anode. The higher the accelerating potential, the higher the energy of the electrons. Since it is the energy of the electrons that is converted into x-rays, the higher the energy of the electrons the higher the energy of the x-rays.

X-rays produced by high energetic electrons or high accelerating voltage are referred to as **hard x-rays**. They are high quality x-rays, have very high frequency and high penetrating power.

X-rays produced from low energy electrons or low accelerating voltage are called **soft x-rays**. They are low quality x-rays, have low energy content, low frequency and low penetrating power.

7.4: Intensity of X-rays

Intensity of x-rays refers to the number of x-rays produced per second. It depends on the number of electrons striking the target per second. This is controlled by the filament current. The higher the filament current the higher number of electrons emitted and hence the greater the intensity of the x-rays.

7.5: Detection of X-rays

X-rays can be detected by:

- Using a fluorescent screen. The screen glows when struck by the x-rays.
- Using a photographic plate. The plate is blackened when exposed to x-rays.

7.6: Uses of X-rays

In medicine

- Detection of fractures, displaced bones or other strange objects within the body.
- Destruction of cancerous growths and other malignant growths.
- Testing densities of bones.
- Detection of lungs with tuberculosis.

In industries

- Detection of flaws in metals and welded joints.
- Checking percentages of certain elements in an ore.
- For security checks in airports.
- To check the purity or genuineness of certain precious stones like gold, silver etc.
- To sterilize surgical equipment before packaging.
- Detection of leakages in water pipes.

In crystallography

- To study the crystal structure of substances.

7.7: Dangers of X-rays

Excessive exposure of living body tissues to x-rays may lead to damage or killing of the cells. X-rays can cause deep rooted burns, mutation and serious diseases.

These can be minimized by:

1. Limiting the exposure time of living tissues to x-rays.
2. X-ray sources should be well screened or shielded.

Example 7.1 (take $h=6.63 \times 10^{-34} \text{Js}$, $e=1.6 \times 10^{-19} \text{C}$, $m_e=9.11 \times 10^{-31} \text{kg}$ and $v=3.0 \times 10^8 \text{m/s}$)

1. Calculate the energy of x-rays whose frequency is $3 \times 10^{16} \text{Hz}$.

$$E = hf = 6.63 \times 10^{-34} \text{Js} \times 3 \times 10^{16} \text{Hz}$$

$$= 1.989 \times 10^{-17} \text{J}$$

2. In an x-ray tube, an electron is accelerated by a potential difference of 1kV.

a) Determine the velocity of the electron as it is reaching the target.

$$eV = \frac{1}{2}mv^2$$

$$1.6 \times 10^{-19} \text{C} \times 1000 \text{V} = \frac{1}{2} \times 9.11 \times 10^{-31} \text{kg} \times v^2$$

$$v^2 = 3.5126 \times 10^{14}$$

$$v =$$

b) How much kinetic energy will the electron have acquired when it hits the target?

$$eV = K.E = 1.6 \times 10^{-19} C \times 10000 V$$

$$= 1.6 \times 10^{-16} J$$

3. Explain how you can increase:

a) Quality of x-rays.

By increasing the accelerating potential between the cathode and the anode.

b) Intensity of the x-rays.

By increasing the filament current so that more electrons are emitted per unit time.

4. An x-ray tube operates at 10kV and a current of 15mA. Calculate the number of electrons hitting the target per second.

$$I = ne$$

$$15 \times 10^{-3} A = n \times 1.6 \times 10^{-19} C$$

$$n = 9.375 \times 10^{16} \text{ electrons.}$$

5. An x-ray tube operates at 20kV. What is the shortest wavelength in its x-ray beam?

$$eV = h\nu/\lambda$$

$$1.6 \times 10^{-19} \times 20000 V = (6.63 \times 10^{-34} J \cdot s \times 3.0 \times 10^8) / \lambda$$

$$\lambda = 6.2156 \times 10^{-11} m$$

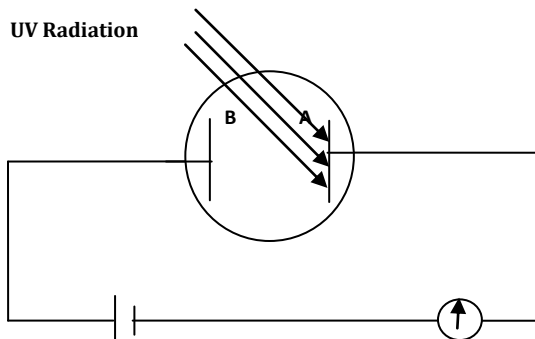
6. State any differences between x-rays and cathode rays.

- X-rays are uncharged while cathode rays are charged.
- X-rays are produced in an x-ray tube while cathode rays are produced in a cathode ray tube.

TOPIC 8: PHOTOELECTRIC EFFECT**8.1: Photoelectric emission**

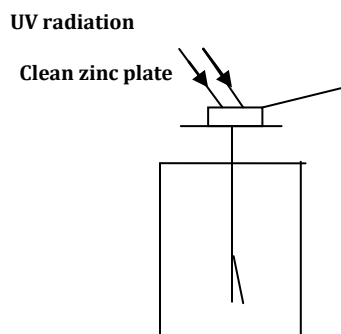
We have already seen that when a metal surface is heated to a certain extent, electrons are dislodged. This is called thermionic emission. Similarly when a metal surface is irradiated using an electromagnetic radiation of a certain amount of energy, electrons are emitted. This process is called photoelectric emission or effect. The energy of the radiation is transferred to the electrons in the atoms of the metal. The electrons gain enough energy and get dislodged from the metal surface. These electrons are called photoelectrons.

Photoelectric emission can be shown by the following set-ups:

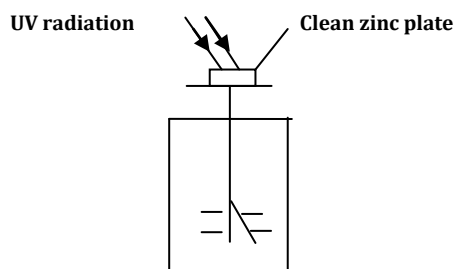
8.1.1: Using a galvanometer

When the UV radiation is incident on the metal plate A, electrons are emitted which are then attracted towards plate B due to its positive potential. This completes the circuit and the galvanometer deflects.

However, when a glass barrier is placed along the path of the UV radiation no deflection will be observed as the glass cuts off the radiation from reaching the metal plate hence no photoelectrons are emitted.

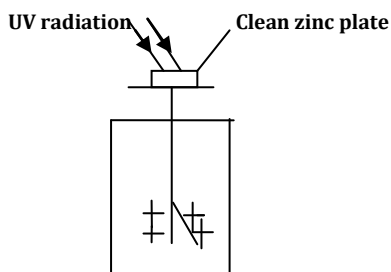
8.1.2: Using a clean zinc plate and uncharged electroscope.

When UV radiation is incident on the clean zinc plate, electrons are dislodged from the zinc plate. The zinc plate thus loses electrons. Some electrons are then attracted from the plate and leaf of the electroscope towards the zinc plate leaving the electroscope positively charged. Hence the leaf of the electroscope diverges.

8.1.3: Using a clean zinc plate and a charged electroscope

The UV radiation dislodges electrons from the surface of the zinc plate leaving it with a deficit of electrons. It then attracts some electrons from the leaf of the electroscope. This in effect discharges the electroscope and the leaf divergence reduces with time.

However, when a positively charged electroscope is used, the UV radiation dislodges electrons which are immediately attracted back by the positive charges on the electroscope. Thus the leaf divergence remains unchanged.



8.2: The quantum theory and Einstein's equation

This theory was advanced by Max Plank. He says that electromagnetic radiations like light are propagated in small packets of energy called **quanta [singular- quantum]**. The amount of energy of a quantum is referred to as a **photon**.

According to Plank, the energy of a photon is directly proportional to the frequency of the radiation;

$$E \propto f$$

Thus, $E=hf$: where h is Plank's constant [i.e $h=6.63 \times 10^{-34}$ Js].

Since all electromagnetic radiations obey the equation $c=f\lambda$;

$$E=hc/\lambda, \text{ where } c \text{ is the velocity of the radiation in a vacuum and } \lambda \text{ is the wavelength.}$$

Hence the larger the frequency [the shorter the wavelength] the greater the energy of a radiation.

Note that all the energy of one photon is absorbed by one electron. This implies that the energy of the radiation must be sufficient to dislodge an electron from the surface of the metal otherwise no electron would be emitted. Electrons of various metals require different amounts of energy to be emitted.

The minimum energy requirement of any metal to emit an electron is referred to as the **workfunction, w_0** of that metal. This implies that the radiation being used must meet a certain minimum frequency below which no photoemission occurs. This minimum frequency is called the **threshold frequency, f_0** .

$$\text{Hence workfunction, } w_0=hf_0.$$

For any radiation of frequency f which is less than the threshold frequency f_0 of the metal surface, the energy, hf of the radiation will be less than the workfunction, w_0 of the metal. Hence no photoemission takes place. However, when the frequency, f of the radiation is greater than the threshold frequency f_0 of the metal, then the amount of energy equivalent to the workfunction of the metal will be used to emit an electron and the rest of the energy will be converted into kinetic energy of the electron.

i.e energy of the radiation= workfunction + kinetic energy of the electron.

$$E=w_0 + k.e$$

$hf = hf_0 + \frac{1}{2}mv^2$, where m - mass of an electron ($9.11 \times 10^{-31} \text{kg}$) and v - the velocity of the electron.

This equation is known as Einstein's equation of photoelectric emission.

Alternatively, the radiation being used must not exceed a certain maximum wavelength for photoemission to occur [**recall** $w_0 = hf_0 = hc/\lambda_0$]. this is called threshold wavelength.

The kinetic energy of an electron is sometimes expressed in terms of electron-volt (eV). It is the kinetic energy gained by an electron when it passes through a potential difference of one volt;

i.e $1 \text{eV} = [1 \text{V} \times (1.602 \times 10^{-19} \text{C})] = 1.602 \times 10^{-19} \text{J}$.

Example 8.1

1. Calculate the energy of a photon of light of frequency $5.0 \times 10^{14} \text{Hz}$ in (a) joules (b) electron-volt.
 - a) $E = hf = 6.63 \times 10^{-34} \times 5.0 \times 10^{14} = 3.315 \times 10^{-19} \text{J}$
 - b) $\{(3.315 \times 10^{-19} \text{J} \times 1 \text{eV}) / (1.602 \times 10^{-19} \text{J})\} = 2.0693 \text{eV}$
2. Light of frequency $4.3 \times 10^{14} \text{Hz}$ is irradiated on a surface of metal whose workfunction is 2.6eV . Explain whether photoelectric emission will occur or not.

$$\text{Energy of the radiation} = hf = [6.63 \times 10^{-34} \times 4.3 \times 10^{14}] / [1.602 \times 10^{-19}] = 1.7796 \text{eV}$$

Since the energy of the radiation is less than the workfunction, no photoelectric emission will occur.

Alternatively;

$$\text{Workfunction} = hf_0 = 2.6 \times 1.602 \times 10^{-19}$$

$$f_0 = [2.6 \times 1.602 \times 10^{-19}] / [6.63 \times 10^{-34}] = 6.34 \times 10^{14} \text{Hz}$$

Since the frequency of the radiation is less than the threshold frequency of the metal, there is no photoelectric emission.

8.3: Factors affecting photoelectric emission

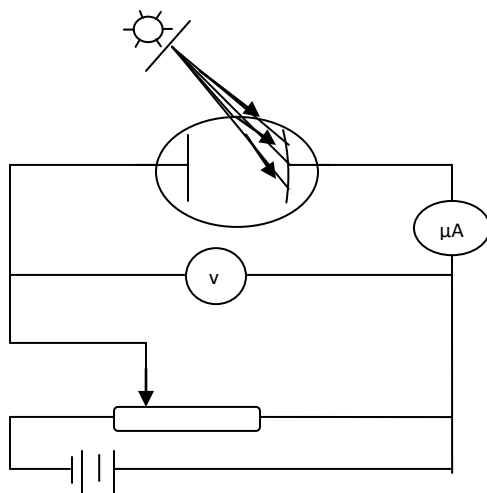
There are three main factors affecting photoelectric emission namely:

- Energy of the radiation
- Intensity of the radiation
- Type or nature of the metal

8.3.1: Energy of the radiation

The amount of energy of the emitted electrons is directly proportional to the frequency of the radiation. This can be shown by using radiations of different frequencies and investigating the stopping potential for each radiation. Stopping potential is the potential difference at which none of the emitted electrons reach the anode.

Colour filter



Various filters are used in turn to give light of different frequencies. For each filter, the variable resistor is used to vary the resistance until no current is registered by the micro-ammeter. Note that the source of d.c voltage is connected in such away that it opposes the flow of the ejected electrons i.e it works against the kinetic energy of the ejected electrons.

The absence of a reading on the micro-ammeter indicates no flow of electrons.

Hence, when no electron flows; $eV_s = k.e$

$$eV_s = \frac{1}{2}mv^2.$$

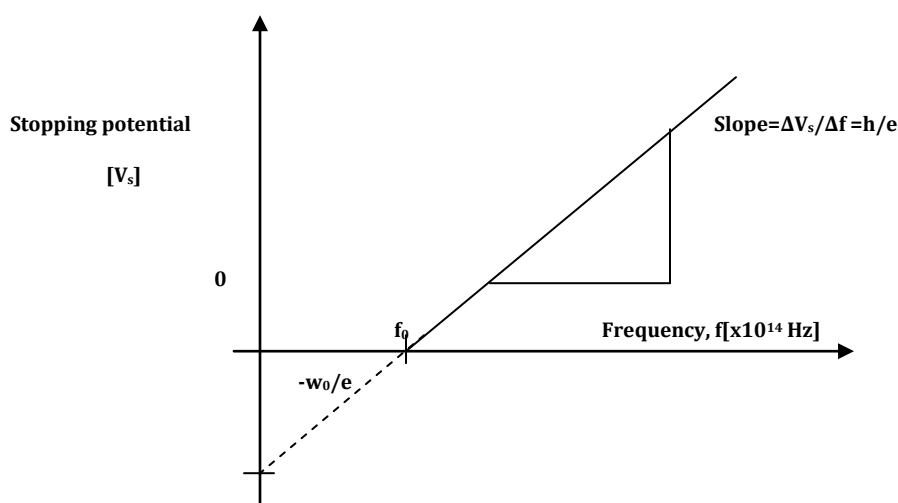
Substituted in the Einstein's equation, we obtain:

$$hf = hf_0 + eV_s.$$

Below is a typical result obtained by using different colour filters of different frequencies and their corresponding stopping potentials:

Frequency, $f(\times 10^{14})\text{Hz}$	1.65	1.9	1.17	1.00
Stopping potential, $V_s(\text{V})$	0.20	0.40	0.60	0.98

When a graph of the stopping potential V_s against frequency is plotted, the graph would appear as shown below:



8.3.2: Intensity of the radiation

It is defined as the rate of energy flow per unit area when the radiation is normal to the surface (area);

$$\text{Intensity} = E/At$$

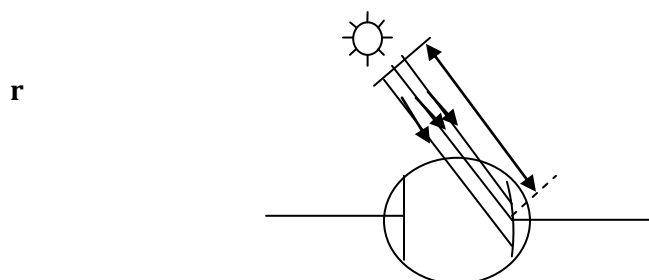
But $E/t = \text{power, } P$.

$$\text{Hence, Intensity} = P/t.$$

Suppose the source of the radiation is a distance r from the metal plate, then the intensity of the radiation is inversely proportional to the square of the distance r ;

$$I \propto 1/r^2.$$

Thus as the distance r decreases the intensity of the radiation increases and hence the value of the current is increased.



8.3.3: The type (nature) of the metal

Each metal has its own workfunction and hence threshold frequency. If the energy of the radiation striking the metal is below its workfunction then no electron will be ejected despite its intensity.

Example 8.2

1. The threshold wavelength of a photoemissive surface is $0.45\mu\text{m}$. calculate:

- a. The threshold frequency of the surface.

$$f_0 = c/\lambda_0 = [3.0 \times 10^8 \text{ m/s}] / [0.45 \times 10^{-6} \text{ m}]$$

$$= 6.67 \times 10^{14} \text{ Hz.}$$

- b. The workfunction of the surface in eV.

$$W_0 = hf_0 = [6.63 \times 10^{-9} \text{ J} \cdot \text{s}] \times [6.67 \times 10^{14} \text{ s}^{-1}] = 4.42 \times 10^{-19} \text{ J}$$

$$= 2.76 \text{ eV}$$

- c. The minimum speed with which a photoelectron is emitted if the frequency of the radiation is $7.5 \times 10^{14} \text{ Hz}$.

$$6.63 \times 10^{-9} \times 7.5 \times 10^{14} = [6.63 \times 10^{-9} \times 6.67 \times 10^{14}] + [\frac{1}{2} \times 9.11 \times 10^{-31} \text{ v}^2]$$

$$V = [12.081 \times 10^{10}]^{\frac{1}{2}} = 3.4754 \times 10^5 \text{ m/s.}$$

9.4: Applications of photoelectric effect**8.4.1: Photoemissive cell**

It consists of a cathode and an anode. When light falls on a photosensitive cathode, electrons are dislodged which are then attracted by the anode. This completes an external circuit and current flows. When a body passes between the cathode and the source of light, the light is cut off and no photoemission takes place.

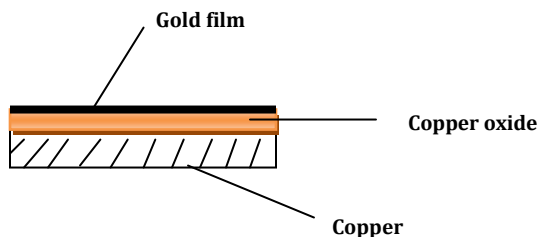
Such cells can be used in:

- ✓ Automatic opening of doors
- ✓ Burglar alarms for security
- ✓ Automated counting machine
- ✓ Reproduction of sound from a film.

Below is the symbol of a photoemissive cell.

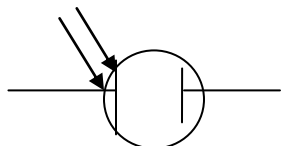


8.4.2: Photovoltaic cells



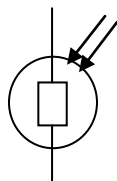
Light strikes the cell on the gold film side which emits electrons from the copper oxide surface. The copper oxide thus acquires a negative potential and copper a positive potential. A potential difference is therefore created and a current flows through a wire connecting the gold film and the copper externally.

Below is the symbol of a photovoltaic cell:



8.4.3: Photo-conductive cell

It is also called the **light dependent resistor**. The resistance of the cell varies with intensity of the light falling on it. In darkness, the resistance of the cell is greatest and least on a bright light. Below is the symbol of the photo-conductive cell:



Light dependent resistor can be used in operating street lights, fire alarms, detection and measurement of infra red radiation.

TOPIC 9: RADIOACTIVITY**9.1: Introduction**

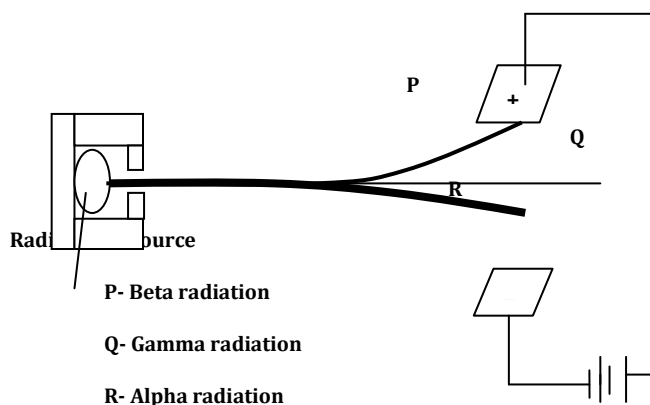
An atom X of mass number A and atomic number Z can be represented as A_ZX . If the number of neutrons in the nucleus is N, then:

$$A = Z + N.$$

Some atoms have the same number of protons in the nucleus yet different mass numbers. Such atoms are referred to as isotopes. Examples of isotopes include carbon- 12 and carbon- 14. The energy holding the protons and neutrons together in the nucleus is called the **binding or nuclear energy**.

When the ratio of the number of protons to the number of neutrons in a nucleus is about 1:1, the nuclide is said to be stable, otherwise it is an unstable. For unstable nucleus, it has to undergo disintegration a process called radioactivity. Radioactivity is the spontaneous disintegration of the nucleus of unstable atom to release radiations.

In the process of radioactivity, there are three radiations which may be emitted namely alpha (α), beta (β) and gamma (γ) radiations. Their behavior can be observed when they are passed through a magnetic or electric field.

**Alpha radiations:**

- ✓ Are positively charged.
- ✓ Are massive or heavy and thus have shorter range in air. They are slightly deflected by strong magnetic or electric field due to their higher mass.
- ✓ Cause the highest ionization effect on the particles on their paths compared to beta and gamma radiations, thereby losing most of their energy.
- ✓ Have the least penetrating ability or power compared to the other two radiations. They can be stopped by a thick sheet of paper.

Beta radiations:

- Are negatively charged.
- Are lighter compared to alpha radiations. Hence they are greatly deflected by strong magnetic or electric field.

- Have longer range in air.
- Cause less ionization compared to alpha radiations. Hence they have a higher penetrating ability or power. They can penetrate a thick sheet of paper but can be stopped by a thin aluminium foil.

Gamma radiations:

- Are massless and do not have charge. Hence they are not deflected by both magnetic and electric fields.
- Are electromagnetic waves.
- Cause very little ionization. Hence most of their energy is intact. They have the highest penetrating ability or power of all the three radiations. They can penetrate thick paper and aluminium but is stopped by thick lead.

9.2: Radioactive decay and the decay equations

The original atom before the decay process is referred to as the **parent/mother** nuclide and the product is referred to as the daughter nuclide. A radioactive decay process consists of a parent nuclide, a daughter nuclide and the emitted radiation(s).

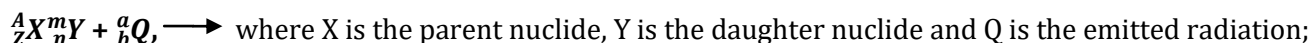


Where X- the parent nuclide

Y- the daughter nuclide

Note that a particular radioactive decay process must not necessarily emit all the three radiations.

Suppose a radioactive decay process takes the form shown by the equation below:



Then, $A=m + a$ and $Z=n + b$.

Radioactive decay is not dependent on physical factors like pressure, temperature or chemical composition of the nuclide.

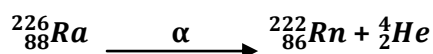
There are three types of radioactive decay:

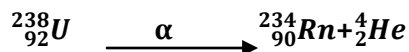
9.2.1: Alpha decay

This decay process emits alpha radiation(s). Alpha radiation is the nucleus of a helium atom represented by ${}^4_2\text{He}$. If a nuclide decays by releasing an alpha particle, the mass number of the parent nuclide is reduced by 4 while atomic number is reduced by 2;



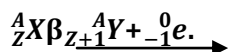
Example 9.1



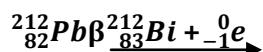
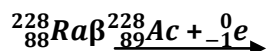


9.2.2: Beta decay

When an atom undergoes beta decay, it emits a beta particle. A beta particle is a fast moving electron represented by ${}_{-1}^0\text{e}$. The mass number of such a nuclide remains the same while its atomic number increases by one (1).



Example 9.2



9.2.3: Gamma decay

Gamma decay does not have any effect on the mass number or atomic number of the nuclide. Instead the nuclide attains stability by simply releasing energy in the form of gamma radiation.

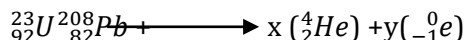


Example 9.3



Example 9.4

1. Uranium ${}_{92}^{238}\text{U}$, undergoes a decay emitting alpha and beta particles to become lead ${}_{82}^{208}\text{Pb}$. Calculate the number of alpha and beta particles emitted.



$$238 = 208 + 4x + 0$$

$$x = 20/4 = 5 \text{ alpha particles}$$

$$\text{Also } 92 = 82 + 2x - y$$

$$y = 82 + 10 - 92 = 0 \text{ Type equation here.}$$

There was no beta particle emitted.

2. Uranium, ${}_{92}^{238}\text{U}$ decays to polonium, ${}_{84}^{218}\text{Po}$ by emitting alpha particles. Write down the nuclide equation to represent the decay process. Hence determine the number of alpha particles emitted.



$$238 = 218 + 4x$$

$$x = 20/4 = 5 \text{ alpha particles.}$$

$$\text{Alternatively, } 92 = 84 + 2x$$

$x=8/2=4$ alpha particles.

9.3: Radiation detectors

Below are some of the radiation detectors:

9.3.1: A photographic film

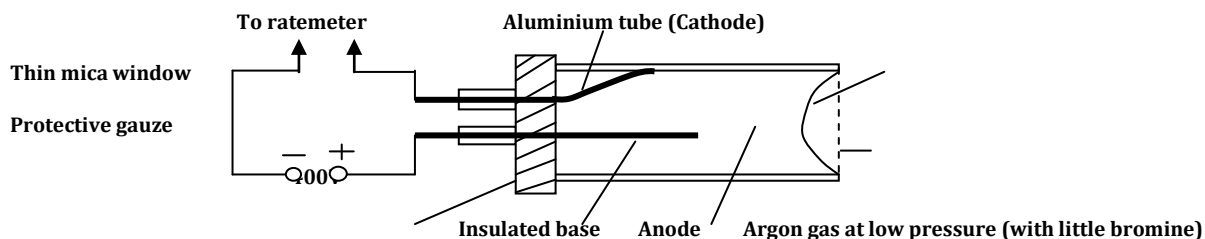
When radioactive radiations strike a photographic film, they cause photographic emulsion i.e the film is blackened.

9.3.2: The leaf electroscope

We have already seen that alpha and beta particles can ionize particles on their paths. This produces ions. If a source of these radiations is brought near the cap of a charged electroscope, the electroscope repels ions of similar charge but attracts those of the opposite charge. This neutralizes the electroscope and the leaf falls.

This method is most suitable for alpha particles since they cause the highest ionization but is not suitable for gamma radiations because they cause the least ionization.

9.3.3: The Geiger Muller (GM) tube



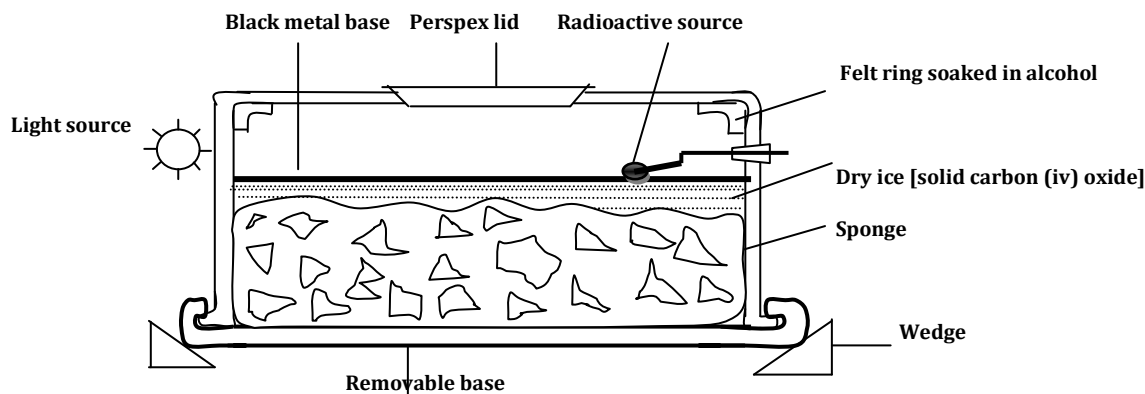
The radiation enters the tube through the thin mica window. The radiation ionizes argon gas. Opposite ions are attracted to either the cathode or the anode making a pulse of current to flow. As these ions move towards either electrode, they continue ionizing the argon gas producing more ions. The current is passed through an amplifier and then to a ratemeter where it is registered.

Note that only one pulse should be registered for each ionizing particle entering the tube. However, due to the high energy content of the positive ions, more electrons may be liberated from the surface of the cathode when struck by the positive ions. Such electrons are called **secondary electrons**. These can cause further ionization rendering the pulse registered incorrect.

To counter this, bromine is used which acts as a quenching agent, absorbing the energy of the positive ions before they reach the cathode.

This method is not suitable for detection of gamma radiations due to its low ionization effect.

9.3.4: The diffusion cloud chamber



This detector uses the concept that when an ionizing radiation passes through air with saturated vapour, then the vapour is observed to condense on the ions formed. This explains why aeroplanes sometime leave trails of cloud behind them as they move through super saturated air.

In the diffusion cloud chamber, alcohol vaporizes and diffuses towards black metal base. When a charged particle from the radioactive source; either alpha or beta particle, knocks the air particles ions are produced. The vaporized alcohol condenses on the formed ions. Since positive ions are heavy, they remain behind forming tracks which can be clearly seen through the Perspex lid. To enhance visibility, a source of light is used to illuminate the chamber.

The dry ice is used to keep the black metal base cool while the sponge is used to keep the dry ice in contact with the black metal base.

Each radiation will produce a specific track as shown below:

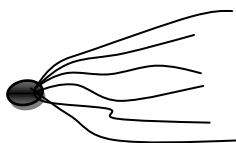
Tracks due to alpha radiation



They are:

- Short, indicating their shorter range in air.
- Straight; due to their mass it is not easy to displace them from their path by air particles.
- Thick, to show they are heavy particles.

Tracks due to beta radiation



They are:

- Long, indicating their longer range in air.
- Thin, indication of their lower mass.

- Irregular in direction (not straight), meaning that they can be displaced by air particles.

Tracks due to gamma radiation



Tracks due to gamma radiation are generally scanty and disjointed. These tracks do not come directly from the source but from electrons released by the gas atoms when they are struck by gamma radiation. The electrons then produce their own tracks.

9.4: Background radiation

Sometimes even in the absence of a radioactive source nearby, a GM tube may still register some radiations. This is called background radiation and it is present within the atmosphere. Some of the causes of background radiation include radioactive substances in air, ground and bricks of buildings, cosmic rays, sun's radiations, some rocks, natural and artificial radioisotopes etc.

9.5: The decay law

A radioactive decay occurs by chance i.e it is non-predictable. The decay states: **the rate of disintegration at any given time is directly proportional to the number of nuclides remaining undecayed;**

$$\delta N / \delta t \propto N$$

$\delta N / \delta t = -\lambda N$, where N is the number of nuclides undecayed (remaining) and λ is the decay constant.

Note that the negative sign indicates that the number N is decreasing with time.

$\delta N / \delta t$ is referred to as the **activity** of the material.

The above equation can be rearranged as;

$$\delta N / N = -\lambda \delta t$$

Suppose N_0 nuclides reduce to N nuclides between a time $t=0$ and $t=T$ in a decay process, then by integration we have;

$$\int_{N_0}^N \delta N / N = \int_0^T -\lambda \delta t$$

$$[\ln N]_{N_0}^N = -\lambda [t]_0^T$$

$$\ln N - \ln N_0 = -\lambda [0 - T]$$

$$\ln (N / N_0) = -\lambda [0 - T] = \lambda T$$

$$N / N_0 = e^{\lambda T}$$

$$N = N_0 e^{\lambda t}$$

9.6: Half life, $t_{1/2}$

This is the time taken for half the number of nuclides initially present in a given radioactive sample to decay.

From the equation, $N = N_0 e^{\lambda t}$;

When $t = t_{1/2}$, $N = \frac{1}{2} N_0$.

Then, $\frac{1}{2} N_0 = N_0 e^{\lambda t_{1/2}}$

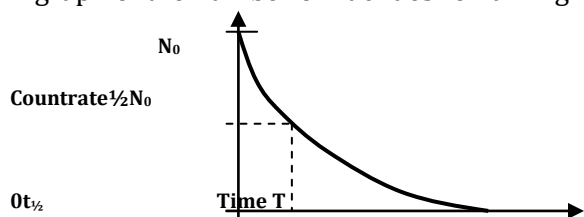
Thus $\ln \frac{1}{2} = \lambda t_{1/2}$

$$0.693 = \lambda t_{1/2}$$

And $t_{1/2} = 0.693/\lambda$, where λ is the decay constant.

It can also be shown that, $N = N_0 \left(\frac{1}{2}\right)^{T/t_{1/2}}$

A graph of the number of nuclides remaining N against time T appears as shown below:



In order to plot the correct graph, it is advisable to first subtract the background radiation if it does exist from each count rate before plotting the values. This will ensure that only count rate due to the radioactive material is used to plot the graph. This is because the value of the background radiation usually fluctuates.

Example 9.5

1. A radioactive substance is found to have an activity of 360 counts per second. 5 minutes later, it was 45 counts per second. Determine its half life.

$$360 \xrightarrow{t_{1/2}} 180 \xrightarrow{t_{1/2}} 90 \xrightarrow{t_{1/2}} 45$$

Hence $3t_{1/2} = 5 \text{ minutes}$

$$t_{1/2} = 5/3 = 10 \text{ minutes.}$$

Alternatively

$$N = N_0 \left(\frac{1}{2}\right)^{T/t_{1/2}}$$

$$45 = 360 \left(\frac{1}{2}\right)^{5/t_{1/2}}$$

$$2^{-3} = 2^{-5/t_{1/2}}$$

$$-3 = -5/t_{1/2}$$

$$t_{1/2} = 5/3 = 10 \text{ minutes}$$

2. A radioactive substance has a half life of 10 hours. Calculate the percentage of the sample that remains after 25 hours.

$$N = N_0 \left(\frac{1}{2}\right)^{25/10}$$

But percentage of the sample remaining after 25 hrs is given by; $[N/N_0] \times 100$

Hence $\left[\frac{N_0(1/2)^{25/10}}{N_0}\right] \times 100 = 17.68\%$

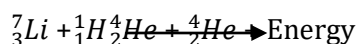
3. A GM tube is used to measure the decay of a certain radioactive substance and the results are as shown in the table below. The background radiation is 25 counts per hour.

Time (hrs)	0	1	2	3	4	5
Countrate (counts/h)	425	255	175	105	73	51

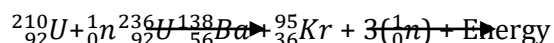
Plot a graph of countrate against time and use it to determine the half life of the material.

9.7: Nuclear fusion and fission

Nuclear fusion is where light nuclei combine to form a heavier nucleus. The process is accompanied by the release of large amounts of energy. Example is the fusion of lithium and hydrogen to give helium.



Nuclear fission occurs when a nucleus splits into smaller more stable nuclei. This happens by the nucleus absorbing a neutron. During nuclear fission, the binding energy is released. Example is the fission of uranium-235;



Nuclear fission is the principle on which hydrogen bombs work. This process if not controlled may lead to explosions.

9.8: Applications of radioactivity

In medicine:

- ✓ Gamma rays can be used to control cancerous growths in the human body.
- ✓ Gamma rays can be used to sterilize surgical equipment.
- ✓ Can be used to monitor blood circulation disorders and the functioning of thyroid gland.

In carbon dating- it uses the ratio of carbon-12 to carbon-14 to estimate the ages of fossils.

Pipe leakages- the content being transported through the pipe is mixed with some radioactive substance which can be detected by a radiation detector on the ground around the area of leakage.

In Agriculture- a radiation detector can be used to monitor the uptake of minerals introduced to plants by mixing it with some weak radioactive substance. Gamma rays can also be used to kill pests or make them sterile.

Determination of thicknesses of thin metal sheets, paper or plastics- a GM tube is used to measure the thickness of the metal plates, paper or plastic. The source of radiation is placed on one side while the GM tube is placed on the opposite side. The metal plate is passed between the source and the detector. The countrate registered is a measure of the thickness of the metal plate. To be more efficient, a thickness gauge can be adapted which automatically controls the thickness of the metal foils, paper or plastics.

9.9: Hazards of radioactivity and their remedy

The effects of radiation on a human body depends on:

- The nature of the radiation,
- Dosage and
- Part of the body irradiated.

Excessive exposure of body cells to radiations can lead to burn effects or genetic damage. Extreme heavy doses can be fatal. There could also be delayed effects such as cancer, leukemia and hereditary defects.

Gamma rays and beta radiation are more dangerous compared to alpha radiation due to their high degree of penetration.

Precautions should therefore be taken when handling radioactive materials. These include:

- Always use forceps to handle radioactive materials. Never use bare hands to hold such materials.
- Keep radioactive materials in thick lead boxes.
- Use radiation absorbers in hospitals and research laboratories.
- Reduce time spent near radiation sources.

TOPIC 10: ELECTRONICS

10.1: Introduction

This topic is about electronic circuits and their applications. Precisely it looks at the electrical conductivity of materials. Under this title, materials can be classified into three groups:

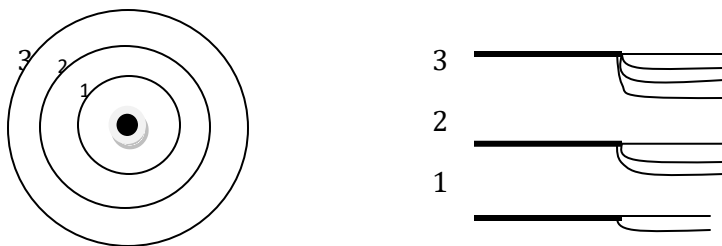
- Conductors
- Semiconductors
- Insulators

Conductors are those materials which allow current to flow through them easily. They are mainly metals like copper.

Materials which do not allow current to flow through them completely are referred to as **insulators**. They include plastic, paper, dry wood, rubber etc.

Semiconductors are those materials whose electrical conductivity lies between that of good conductors and insulators. They include silicon, germanium etc.

According to the **energy band theory**, when two atoms are brought closer to one another, the energy levels around the nucleus split into smaller sub-levels called **bands**. The outer energy level splits more easily giving many bands compared to the inner levels.



There are two important bands in any material which determine its electrical, optical and magnetic properties. These are the valence and conduction bands which are separated by a forbidden gap.

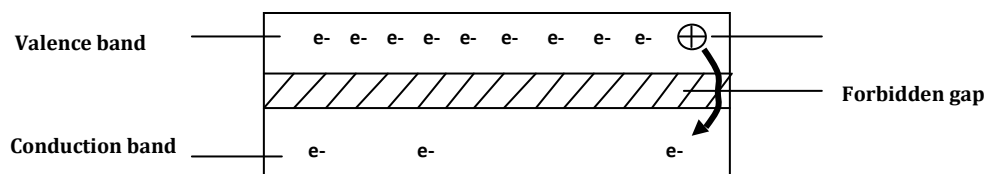
10.2: Semiconductors

Semiconductors are those materials whose electrical conductivity lies between that of good conductors and insulators. They have a smaller forbidden gap. The valence band is almost completely filled with electrons while the conduction band has almost no electrons.

When the temperature of the semiconductor is raised the electrons gain more energy and are able to move from the valence band across the forbidden gap to the conduction band. This increases the electrical conductivity of the semiconductor. Hence conductivity of semiconductors increases with temperature.

When an electron jumps from the valence band into the conduction band, a hole is left in its place. This is treated as a **positive charge**. Another electron in the valence band may jump into the hole formed creating another hole which may be filled by yet another electron and the process continues.

The movement of the electrons generates **electron current** while that of holes constitute **hole current**. Thus the net flow of current in semiconductors is due to the flow of electrons and holes.



There are two types of semiconductors as discussed below:

10.2.1: Intrinsic semiconductors

These are pure semiconductors whose electrical conductivity can be enhanced by increasing the temperature of the semiconductor. They include silicon, germanium etc. They have four electrons in their outermost energy level. Their electrical conductivity is dependent on the electron-hole pair movement. The electrons and the holes are referred to as **charge carriers**. At room temperature, intrinsic semiconductors are insulators.

10.2.2: Extrinsic semiconductors

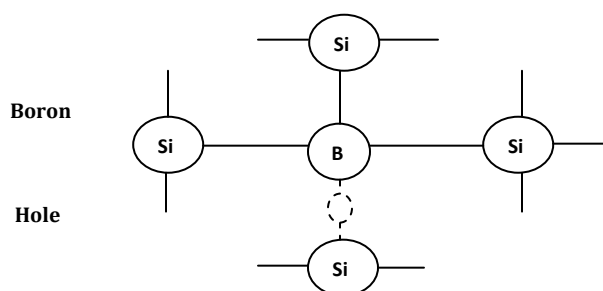
These are semiconductors obtained when a small amount of impurity is added to an intrinsic semiconductor. The process of adding an impurity to a pure semiconductor to improve its electrical conductivity is referred to as **doping**. Generally an extrinsic semiconductor is an impure semiconductor.

The impurity can either be a group three element e.g boron, gallium and indium or a group five element e.g phosphorous, antimony etc.

➤ Doping using a group three element

When silicon is doped using a group three element like boron, all the three electrons on the outermost energy level of boron atom participate in bonding with the neighboring atoms while silicon will have an extra electron. A vacancy will therefore exist due to the missing electron. This is treated as a **hole**. This hole is responsible for the electrical conductivity of the doped semiconductor. Hence holes are the majority charge carriers while electrons are the minority charge carriers. Such an impurity is called an acceptor impurity because they create a hole which can accept an electron.

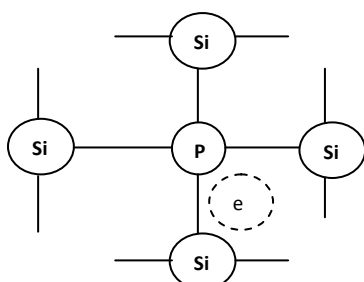
An extrinsic semiconductor in which the majority charge carriers are holes is called a **p-type** semiconductor.



➤ Doping using a group five element

When a pure semiconductor is doped using a group five element like phosphorous having five electrons in their outermost energy levels, four of the electrons participate in bonding with the neighboring atoms while the remaining electron is used for electrical conductivity in the semiconductor. Hence electrons will be the majority

charge carriers while holes will be the minority charge carriers. The impurity is referred to as a **donor impurity** since it donates an electron for electrical conductivity.

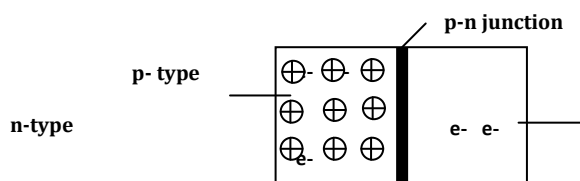


The resultant semiconductor is known as an **n-type** semiconductor.

Note that both p-type and n-type semiconductors are electrically neutral since the impurities added have the same number of electrons as there are protons.

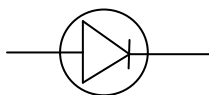
10.3: A P-N Junction diode

A p-n junction diode can be obtained when an intrinsic semiconductor is doped simultaneously using a trivalent and pentavalent impurities such that one half forms a p-type semiconductor while the remaining half forms an n-type semiconductor respectively. The boundary between the p-side and the n-side is referred to as a **p-n junction**.

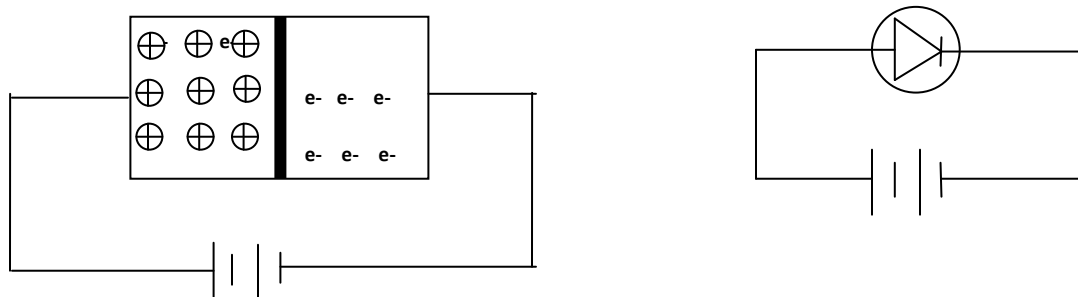


Immediately the junction is formed, a region called **depletion layer** is formed which prevents the free movement of electrons and holes across the junction. Thus the depletion layer develops a **potential barrier** at the junction. It acts as an insulator. For holes to cross to the n-side and electrons to the p-side, the potential barrier **must** be overcome.

The symbol of a p-n junction diode appears as shown below:

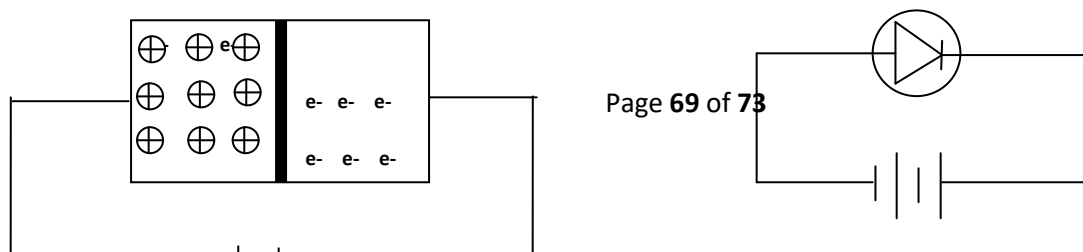


When a p-n junction diode is connected to a power supply it is said to have been **biased**. A p-n junction diode allows current to flow only in one direction when the p-side is connected to the positive terminal of the power source and n-side to the negative terminal of the power source. When connected this way, the diode is said to be **forward biased**.



The cell provides the energy for the electrons to overcome the potential barrier and the holes are also able to cross over to the n-side thereby completing the circuit. The electrons and holes are attracted to the opposite ends. The thickness of the depletion layer is reduced and the charges flow with a lot of ease.

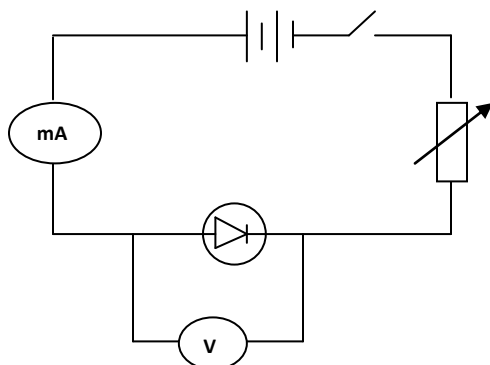
However, when the terminals of the cell are reversed such that the n-side is connected to the positive terminal and the p-side to the negative terminal of the cell, then the diode is said to be **reverse biased**.



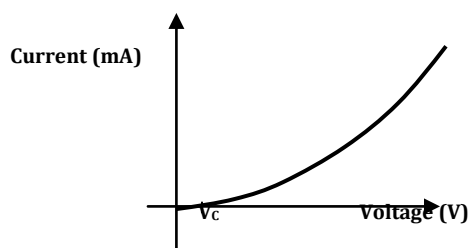
When the diode is connected in this manner, the holes in the p-type are attracted away from the junction by the external negative potential. Also, electrons are attracted away from the junction by the external positive potential. This increases the thickness of the depletion layer. Thus the potential barrier and hence the resistance of the junction is increased. A very small current (leakage current) may flow in the circuit due to the flow of minority charge carriers.

10.4: Diode Characteristics

This is the relationship between current and voltage across a diode when connected to a power source. The set up below shows a circuit in which a diode has been forward biased:



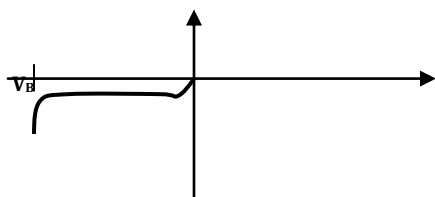
When the switch is closed, current flows through the diode since it is forward biased and it is recorded by the milliammeter. The voltage across the diode is measured by the voltmeter. The variable resistor is used to vary the current through the circuit. When a graph of current against voltage is plotted, the graph will be a curve as shown below:



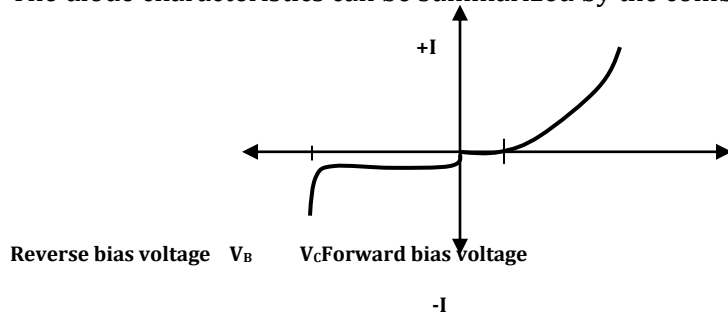
Initially as the forward voltage is increased from zero, no current is registered because the voltage is insufficient to overcome the potential barrier. When the potential barrier is completely overcome current starts to increase. The voltage at which the potential barrier is overcome is referred to as the **cut-in voltage (V_c)**. Charges thereafter flow easily across the junction.

Since the graph is non-linear, it implies that a diode is non-ohmic, i.e. it does not obey Ohm's law.

However, when the diode is reverse biased a small current called leakage current flows. As the reverse voltage is increased the size of the current remains the same until a certain value when an appreciable amount of current starts to flow. This voltage is called the **zener/breakdown voltage (V_B)**. At this voltage the diode is damaged and therefore conducts electric current irrespective of the type of biasing.

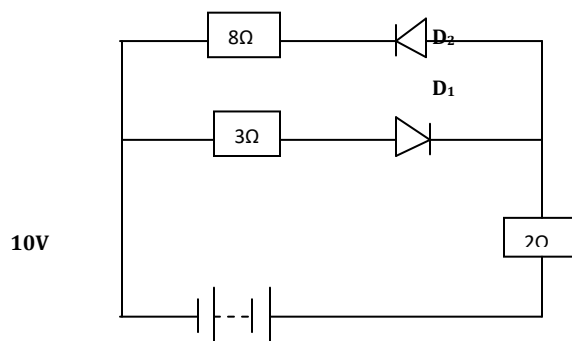


The diode characteristics can be summarized by the combined graph shown below:



Example 10.1

1. Calculate the current flowing through the 2Ω , 8Ω and 3Ω resistors in the figure below. Assume the diodes are ideal. Hence find the voltage drop across each resistor.



D_1 is reverse biased while D_2 forward biased.

Hence; $I_{3\Omega} = 0A$

$$I_{2\Omega} = I_{8\Omega} = 10 / (2 + 8) = 1A$$

Also, $V_{3\Omega} = 0V$

$$V_{2\Omega} = 1 \times 2 = 2V$$

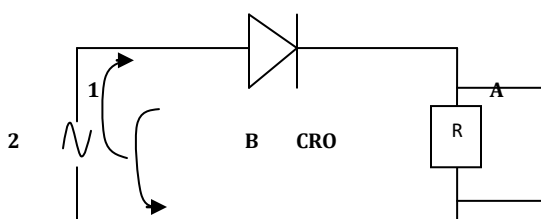
$$V_{8\Omega} = 1 \times 8 = 8V$$

10.5: Applications of diodes

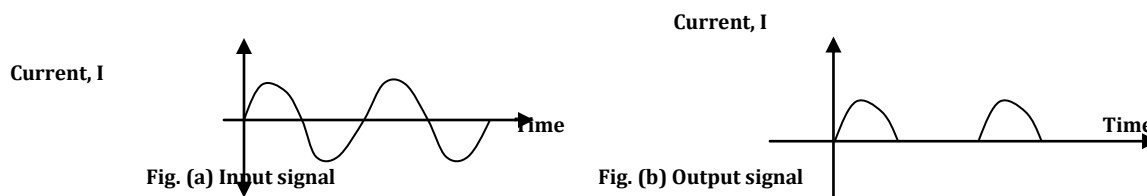
Diodes are used in rectification. Rectification refers to the process of conversion of alternating current to direct current. There are two types of rectification namely half-wave and full-wave rectification.

10.5.1: Half-wave rectification

Here a single diode is used.



During the first half cycle, the diode is forward biased. Current thus flows through the resistor R from the end A to B. During the second half cycle, the diode is reverse biased. No current flows through the diode and hence no current in the circuit. Hence in one complete cycle, one half is wasted. The output will appear as shown below:

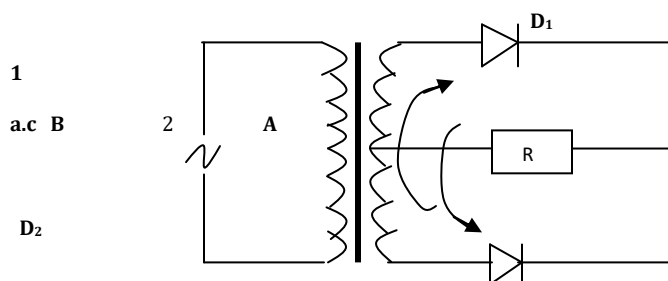


The output signal can be displayed on a CRO screen. In half-wave rectification, half of the input energy in every cycle is wasted. This limitation is eliminated in full-wave rectification.

10.5.2: Full-wave rectification

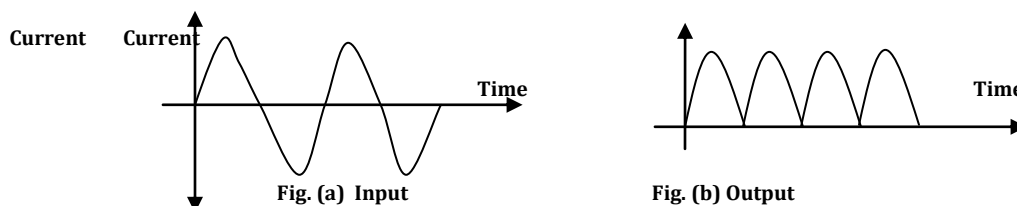
There are two ways of achieving full-wave rectification:

➤ Using two diodes



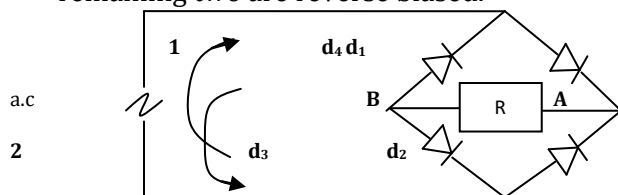
During the first half cycle, diode D_1 is forward biased while D_2 is reverse biased. Current thus flows through the resistor R from the end A towards B. During the second half cycle, diode D_2 will now be forward biased while D_1 is reverse biased. Thus current flows through the resistor from the end A towards B.

Note that in both half cycles, the direction of flow of current through the resistor is the same. The resultant output will therefore take the form shown below:



➤ Using four diodes (bridge rectifier)

A bridge rectifier uses four diodes such that in each half cycle two diodes are forward biased and the remaining two are reverse biased.



During the first half cycle, the diodes d_1 and d_3 are forward biased while d_2 and d_4 are reverse biased. Current thus flows through diode d_1 and d_3 via the resistor R . During the second half cycle, diodes d_1 and d_3 are now reverse biased while d_2 and d_4 are forward biased. Current thus flows through d_2 and d_4 via the resistor R .

Note that in both half cycles current flows through the resistor R in one direction only i.e from end A to B. This kind of rectifier can be used with very high voltages.

If a smooth rectified wave is needed, then a capacitor is connected across the resistor;

