Magnetic Field :→ The magnetic field is the space around a current carrying conductor or space around a magnet in which its magnetic effect can be felt. Denoted by $\vec{B}$ and SI unit is Tesla (T).

• Magnetic force on a moving Charge

The magnetic force ($\vec{F_m}$) on a charge q moving with velocity $\vec{v}$ in a magnetic field $\vec{B}$ is given, both in magnitude and direction by

$$\vec{F_m} = q(\vec{v} \times \vec{B})$$ In magnitude $\boxed{F_m = Bqv\sin\theta}$ — ①

where θ is the angle between $\vec{v}$ and $\vec{B}$.

Note: $\vec{F_m} = 0$ → if $\vec{B} = 0$; if $q = 0$; if $\vec{v} = 0$

Force is maximum when $\theta = 90°$

minimum when $\theta = 0°$ or $180°$ i.e $\vec{v} \uparrow\uparrow \vec{B}$ or $\vec{v} \uparrow\downarrow \vec{B}$

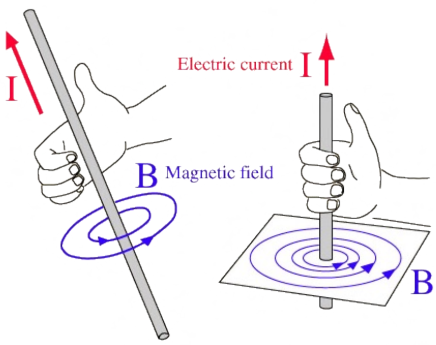
Direction of $\vec{F_m}$:→ $\vec{F_m}$ is perpendicular to both $\vec{v}$ and $\vec{B}$, and given by Right hand rule.

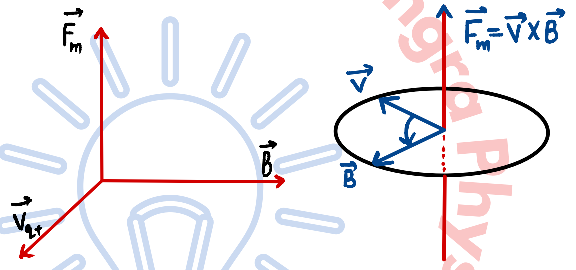
if q is positive then $\vec{F_m} \uparrow\uparrow \vec{v} \times \vec{B}$

if q is negative then $\vec{F_m} \uparrow\downarrow \vec{v} \times \vec{B}$

Rules to Find direction of Magnetic Field and Direction of Force

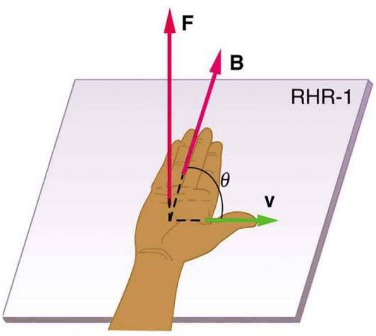
• **Right Hand Thumb Rule** **Right Hand Rule**





Right-hand rule

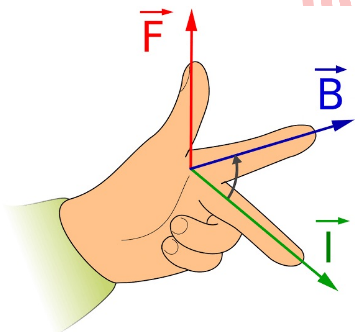
• **Right Hand Palm Rule**



$F = qvB\sin\theta$

F ⊥ plane of v and B

• **Fleming left Hand Rule**



• By Convention the direction of Magnetic Field $\vec{B}$ perpendicular to the paper going inwards is shown by ⊗ and direction perpendicular to the paper coming out is shown by ⊙.

Outside the plane of paper [Direction of $\vec{B}$ perpendicular to paper outwards]

Inside the plane of paper [Direction of $\vec{B}$ perpendicular to paper inwards]

Definition of $\vec{B}$

if $v = 1$, $q = 1$ and $\sin\theta = 1$ or $\theta = 90°$ then from ① eq $F = 1 \times 1 \times 1 \times B = B$

i.e the magnetic field induction or magnetic flux density at a point in the magnetic field is equal to the force experienced by a unit charge moving with a unit velocity perpendicular to the direction of magnetic field at that point.

Unit of $\vec{B}$: SI unit of magnetic field is Tesla (T) or weber/metre² i.e Wb/m^2 or $NsC^{-1}m^{-1}$.

we know that $F = qvB\sin\theta$

and $B = \dfrac{F}{qv\sin\theta} = \dfrac{1\,N}{C\,m/s} = 1$ Tesla.

Dimension of B $= \dfrac{MLT^{-2}}{AT\,LT^{-1}} \Rightarrow [MA^{-1}T^{-2}]$

- Path of a Charged Particle in Uniform Magnetic field.

- When $\vec{V} \perp \vec{B}$ then
  $F = qVB$, This magnetic Force is Perpendicular to the velocity at every instant. Hence Path is Circle.

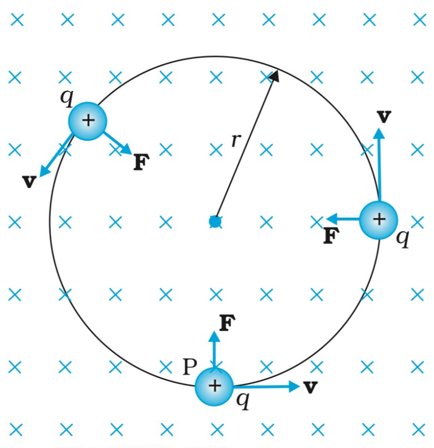


FIGURE 4.5 Circular motion

Here Centripetal force = Magnetic force

$$\frac{mv^2}{r} = qVB$$

$$\boxed{r = \frac{mv}{qB}} \quad P = mv \text{ so } r = \frac{P}{qB}$$

and P = momentum $= \sqrt{2Km}$ K = kinetic energy

so $r = \frac{\sqrt{2Km}}{qB}$ and $K = qV$

Time Period of Circular path $T = \frac{2\pi r}{v}$ or $T = \frac{2\pi m}{Bq}$

angular Speed $\omega = \frac{2\pi}{T} = \frac{Bq}{m}$

and frequency of rotation $f = \frac{1}{T}$ $\boxed{f = \frac{Bq}{2\pi m}}$

- When $\vec{V}$ makes an angle θ with $\vec{B}$. In this Case velocity Can be resolved in two Components (i.e along $\vec{B}$ and perpendicular to $\vec{B}$.)

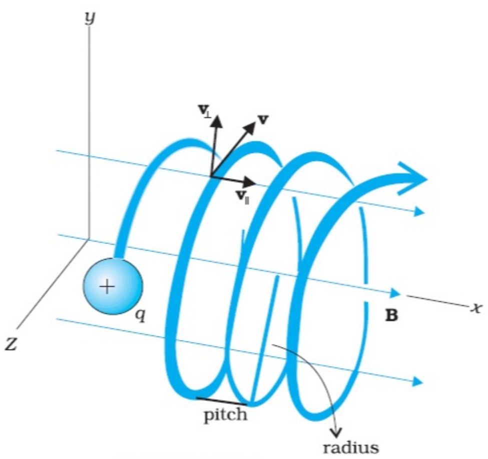
$V_{\parallel} = v\cos\theta$ & $V_{\perp} = v\sin\theta$

NOTE: $V_{\perp}$ gives a Circular path and $V_{\parallel}$ gives straight line path. The resultant path is a helix as shown in figure. The radius of this helical path is

$$r = \frac{mV_{\perp}}{Bq} = \frac{mv\sin\theta}{Bq}$$

and

Time Period $T = \frac{2\pi m}{qB}$ and $f = \frac{Bq}{2\pi m}$



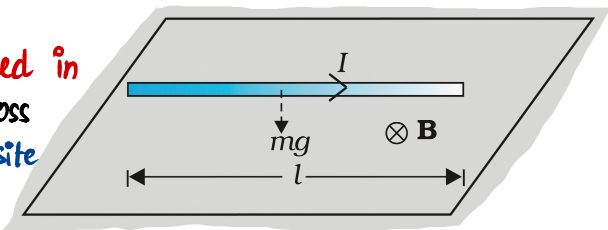
Helical motion

Pitch :→ Pitch is defined as the distance travelled along magnetic field in one complete cycle.

i.e $P = V_{\parallel}T \Rightarrow P = (v\cos\theta)\frac{2\pi m}{Bq}$

- Magnetic Force on a Current Carrying Conductor

Suppose a conducting wire carrying a current i, is placed in a magnetic field $\vec{B}$. The length of wire is l and area of Cross section is A. The free electrons drift with a speed V_d opposite to the direction of Current. The magnetic force exerted on the electron is $d\vec{F}_m = -e(\vec{V} \times \vec{B})$

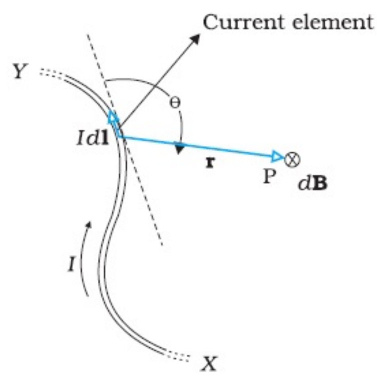


total force on wire is $\vec{F}_m = -e(nAl)(\vec{V}_d \times \vec{B})$ where n = number of free electron per unit volume of the wire.

and $\vec{F}_m = i(\vec{l} \times \vec{B})$ where $neAV_d = i$

Biot Savart Law :→ This Law gives the magnetic field due to an infinitesimally small Current Carrying wire at a some point.

the magnetic field $d\vec{B}$ at a point P associated with a length element $d\vec{l}$ of a wire carrying a steady current i.



$$d\vec{B} = \frac{\mu_0}{4\pi}\frac{i(d\vec{l} \times \hat{r})}{r^2} \quad \text{where } \hat{r} = \frac{\vec{r}}{r} \text{ and } \frac{\mu_0}{4\pi} = 10^{-7}\,\frac{Tm}{A}$$

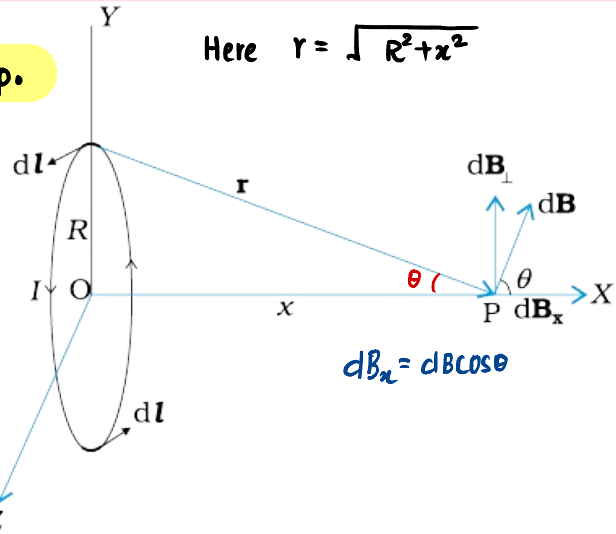
Magnitude of $d\vec{B}$ is $|d\vec{B}| = \frac{\mu_0}{4\pi}\frac{idl\sin\theta}{r^2}$

{NOTE $d\vec{l}$ = which points in the direction of Current}.

Direction of $d\vec{B}$: $d\vec{B} \uparrow\uparrow (d\vec{l} \times \hat{r})$, so $d\vec{B}$ is along $d\vec{l} \times \vec{r}$ and $d\vec{B} = 0$, if $d\vec{l}$ is in the plane of paper.

• Magnetic field on the axis of a Circular Current Loop.

Here $r = \sqrt{R^2 + x^2}$



$dB_x = dB\cos\theta$

Acc. to Biot Savart's law

$dB = \frac{\mu_0}{4\pi} \frac{i\,dl \sin 90^\circ}{r^2}$ Because R is very small, therefore angle between $d\vec{l}$ & $\vec{r}$ is 90°.

So $dB = \frac{\mu_0\, i\,dl}{4\pi (R^2+x^2)}$ — ①

This dB is perpendicular to plane formed by $d\vec{l}$ and $\vec{r}$ i.e $(d\vec{l} \times \vec{r})$

dB is resolved in two component dB_x and $dB_\perp$.

Here summation of $dB_\perp$ over the complete cycle is zero.

So magnetic field is due to only dB_x component.

i.e $B = \int dB\cos\theta = \int \frac{\mu_0}{4\pi} \frac{i\,dl}{(R^2+x^2)} \cos\theta$ Here $\cos\theta = \frac{R}{(R^2+x^2)^{1/2}}$

$B = \frac{\mu_0}{4\pi} i \int \frac{dl}{(R^2+x^2)} \frac{R}{(R^2+x^2)^{1/2}} \Rightarrow B = \frac{\mu_0 i R}{4\pi (R^2+x^2)^{3/2}} \int dl \Rightarrow B = \frac{\mu_0 i R \times 2\pi R}{4\pi (R^2+x^2)^{3/2}} \Rightarrow \boxed{B = \frac{\mu_0 i R^2}{2(R^2+x^2)^{3/2}}}$

For N Turn

$B = \frac{\mu_0 N i R^2}{2(R^2+x^2)^{3/2}}$

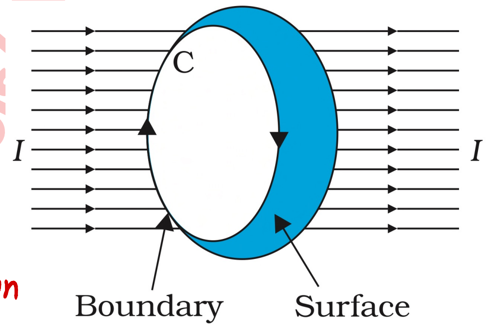
• Magnetic Field at the centre of a Current loop.

so $x = 0$ $B = \frac{\mu_0 N i R^2}{2R^3} \Rightarrow \boxed{B = \frac{\mu_0 N i}{2R}}$

Ampere's Circuital Law : The line integral of magnetic field induction $\vec{B}$ around any closed path in vacuum is equal to μ_0 times the total current threading the closed path i.e

$$\oint \vec{B} \cdot d\vec{l} = \mu_0 I$$

At every point of the closed path $\vec{B} \parallel d\vec{l}$.

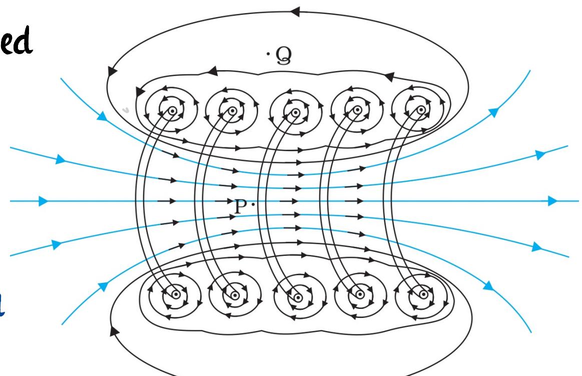


• Ampere's Circuital Law holds good for a closed path of any size and shape around a current carrying conductor because the relation is independent of distance from conductor.

Application of Ampere's Circuital law

Solenoid : A Solenoid is a closely wound helix of insulated copper wire.

• All the magnetic field lies within the core of solenoid i.e (uniform). • Outside the solenoid there is no magnetic field.



Magnetic Field due to Solenoid

Figure A shows a longitudinal cross-section of part of such a solenoid carrying current i. Since solenoid is ideal $\vec{B}$ in the interior is uniform and parallel to axis and $\vec{B}$ in the exterior is 0.

Consider the rectangular path of length l and width w.

Now apply Ampere's Circuital law to this path

$\int_{cd} (\vec{B} \cdot d\vec{l}) = 0 \because B = 0$ $\int_{bc \text{ or } da} (\vec{B} \cdot d\vec{l}) = 0 \because \vec{B} \perp d\vec{l}$

and $\int_{ab} (\vec{B} \cdot d\vec{l}) = Bl = \mu_0 N i$

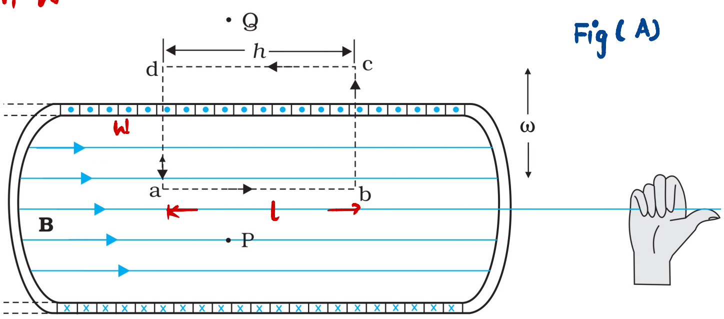
N = Total no. of Turns

n = no. of turns per unit length.

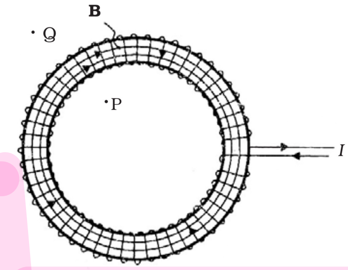
$B = \mu_0 \frac{N}{l} i$ $n = \frac{N}{l}$

$B = \mu_0 n i$

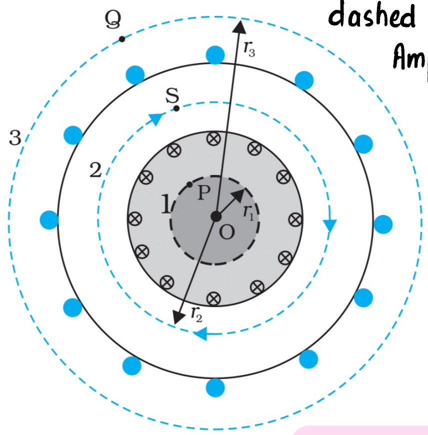
Fig (A)



Toroid: A toroidal Solenoid is an anchor ring around which is large number of turns of a copper wire are wrapped.
A toroid is an endless Solenoid in the form of a ring.



• Magnetic Field due to Toroid



dashed lines are Amperian loop.

Figure Shows a cross-sectional view of toroidal Solenoid.

- Amperian loop 1 encloses no Current i.e $i_{net} = 0$ so $B = 0$
- For Amperian loop 3, the Current Coming out of the plane of the paper is exactly by the current going into it.
- Now consider the Amperian loop 2, then

$\oint \vec{B} \cdot d\vec{l} = \mu_0 i_{net} \Rightarrow B(2\pi r) = \mu_0 N i$ or $B = \dfrac{\mu_0 N i}{2\pi r}$

$\dfrac{N}{2\pi r} = n$ (number of turns per unit length of torus). $B = \mu_0 n i$

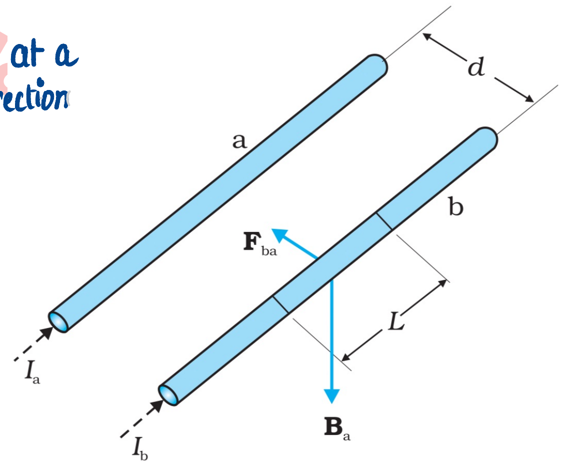
Force Between Parallel Current Carrying wires

Consider two long wire a and b kept parallel to each other at a distance d and carrying currents i_a and i_b resp. in the same direction

Magnetic field on wire b due to Current i_a is

$B_a = \dfrac{\mu_0 i_a}{2\pi d}$ (In ⊗ direction)

Magnetic force on a small element L of wire b due to this magnetic field is $F_{ba} = i_b L B_a \Rightarrow F = i_b L \dfrac{\mu_0 i_a}{2\pi d}$



F_{ba} = Force on b due to a

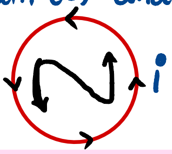
Force per unit length of wire b due to wire a is $\dfrac{F_{ba}}{l} = \dfrac{\mu_0 i_a i_b}{2\pi r}$

Similarly $\dfrac{F_{ab}}{l} = \dfrac{\mu_0 i_a i_b}{2\pi r}$

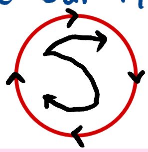
NOTE:→ The wires attracts each other if currents in the wires are flowing in same direction and they repel each other if the currents are in opposite directions.

Magnetic Dipole:→

Every current carrying loop in a magnetic dipole. it has two poles South (S) and North (N). This is similar to a bar Magnet. It is denoted by M.



$\vec{M} = i\vec{A}$



Magnetic dipole moment is a vector quantity. it's direction from South to North Pole.

• Torque on a Current loop placed in Uniform Magnetic Field.

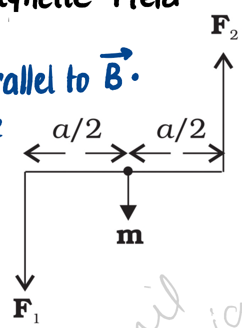
Case-I when $\vec{M} \perp \vec{B}$

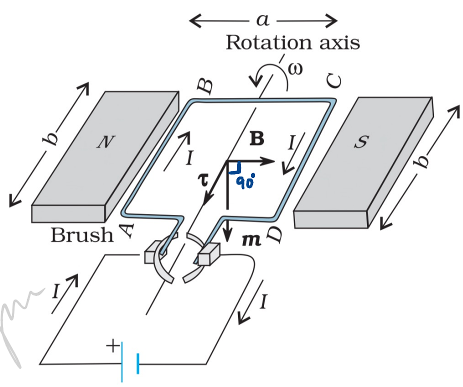
There are no force on arm AD and CB ∵ length of arm Parallel to $\vec{B}$.
And force on arm AB and DC are equal and opposite. Hence net force on the loop is zero. So Torque is there.

Torque = |either Force| × ⊥ distance between Forces.

i.e $\tau = IbB \times a \Rightarrow \tau = IAB$

A = Area of rectangular loop i.e $A = ba$





• Case-2: When $\vec{M}$ makes an angle θ with B

The Forces on arm AB and CD are equal and opposite. i.e Net Force is zero.

Torque = | either force | x ⊥ distance between them.

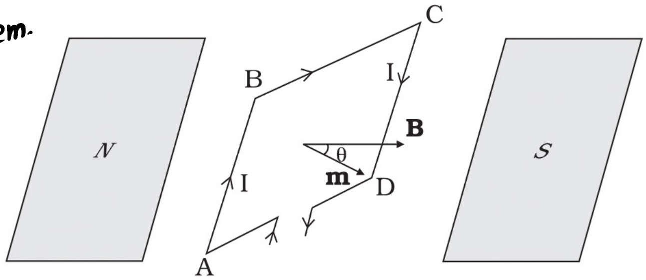
$\tau = IbB \times a\sin\theta$

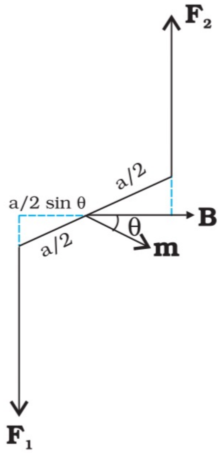
$\tau = IAB\sin\theta$ $\quad$ $A = ab$ (area)

$\tau = MB\sin\theta$ $\quad$ $\because M = IA$

$\vec{\tau} = \vec{M} \times \vec{B}$

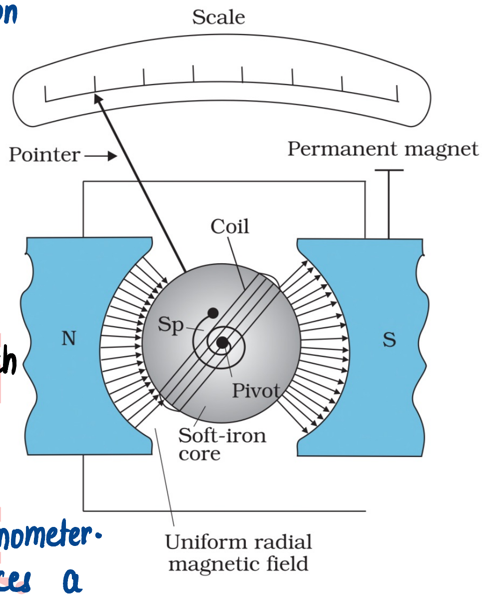
it is a vector quantity, is in th direction of $\vec{M} \times \vec{B}$.





Galvanometer :→ The moving coil galvanometer is a device used to measure an electric current.

Principle :→ Action of a moving coil galvanometer is based upon the principle that when a current carrying coil is placed in a magnetic field it experiences a torque whose magnitude depends on the magnitude of current.



Construction : The main parts of a moving coil galvanometer are shown in figure. The galvanometer consists of a coil, with many turns free to rotate about a fixed vertical axis in a uniform radial magnetic field. There is a cylindrical soft Iron core, which not only makes the field radial but also increases the strength of magnetic field.

Theory :→ The current to be measured is passed through the galvanometer. As the coil is in the magnetic field (of constant magnitude) it experiences a torque given by $\tau = MB\sin\theta$ $\quad$ $M = NiA$ $\quad$ N = Total no. of Turns in the coil.

$\tau = NiAB\sin\theta$

The poles pieces are made cylindrical, the magnetic field always remains parallel to the plane of the coil. (or angle between $\vec{B}$ and $\vec{M}$ always remains 90°.

Therefore $\quad \tau = NiAB$

This torque rotates the coil. The spring S shown in figure provides a counter torque $k\phi$ that balance above torque NiAB. In equilibrium

$$k\phi = NiAB \qquad i = \left(\frac{k}{NAB}\right)\phi \qquad i = G\phi \qquad G = \frac{k}{NAB}$$

i.e $\quad i \propto \phi$

where N = total number of turns of the coil.

i = Current passing through the coil.

A = Area of cross-section of the coil.

B = magnitude of radial magnetic field.

G = Galvanometer Constant.

ϕ = equilibrium deflection.

k = Torsional constant of the spring.

SENSITIVITY OF GALVANOMETER

Current Sensitivity

Deflection per unit current is called sensitivity of galvanometer denoted by i_s.

$$i_s = \frac{\phi}{i} \Rightarrow i_s = \frac{\phi}{k\phi}NAB \Rightarrow \boxed{i_s = \frac{NAB}{k}}$$

Voltage Sensitivity

- Deflection per unit voltage is called Voltage Sensitivity of Galvanometer. It is denoted by V_s.

$$V_s = \frac{\phi}{V} \Rightarrow V_s = \frac{\phi}{iR} \Rightarrow \boxed{V_s = \frac{NAB}{kR}}$$

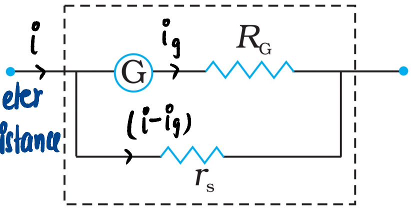
R = Resistance of the wire of coil.

NOTE: Increasing the current sensitivity may not necessarily increase the voltage sensitivity. Because if we increase current sensitivity by making N ⟶ 2N then current sensitivity becomes double but voltage sensitivity remain same because by making N→ 2N R also Ies i.e R→ 2R

Conversion of Galvanometer

Into Ammeter

A galvanometer can be converted into an ammeter by connecting a low resistance into its parallel.



Ammeter

What is Ammeter ?

An ammeter is a low resistance galvanometer used for measuring current in a circuit. It is always connected in series.

From fig. in parallel voltage remain same.

i.e $\quad i_g R_G = r_s (i - i_g)$

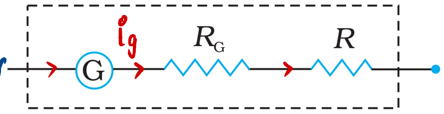
$$r_s = \frac{i_g R_G}{(i - i_g)}$$

R_G = Galvanometer Resistance
r_s = Shunt resistance
i_g = Galvanometer Current
i = Total Current

NOTE:→ The resistance of an ideal ammeter is ZERO.

Into Voltmeter

A Galvanometer can be converted into a voltmeter by connecting a high resistance into its series.



Voltmeter

What is Voltmeter ?

A voltmeter is a high resistance galvanometer used for measuring potential difference between two points.

From figure

Acc. to OHM'S Law $\quad V = i_g(R_G + R)$

$$R = \frac{V}{i_g} - R_G$$

R = Resistance in series.

NOTE: The resistance of an ideal voltmeter is infinity.

Q= Explain why a galvanometer cannot be used to measure the value of current in a given circuit.

Answer:→ Because a). all the currents to be measured passes through coil and it gets damaged easily.
b). its coil has considerable resistance because of length and it may affect original current.

Q= What is the importance of radial magnetic field and how is it produced ?

Answer:→ The uniform radial magnetic field keeps the plane of the coil always parallel to the direction of the magnetic field, i.e the angle between the plane of the coil and the magnetic field is zero for all the orientation of the coil.

Q= Why it is necessary to introduce a cylinderical soft iron core inside the coil of a galvanometer.

Answer: Because it increases it magnetic field. Thus its sensitivity increases and magnetic field become radial.

- **Magnetic Dipole Moment of a Revolving Electron.**

An electron being a charged particle, constitutes a current while moving in its circular orbit around the nucleus. The magnetic dipole moment.

$$M = \frac{e}{4\pi m_e} nh$$

where m_e = mass of electron $\quad h$ = planck's constant
$n = 1, 2, 3 \ldots\ldots$

For $n=1$, M will be minimum

$\therefore \quad M_{min} = \frac{eh}{4\pi m_e}$ known as Bohr's Magneton.