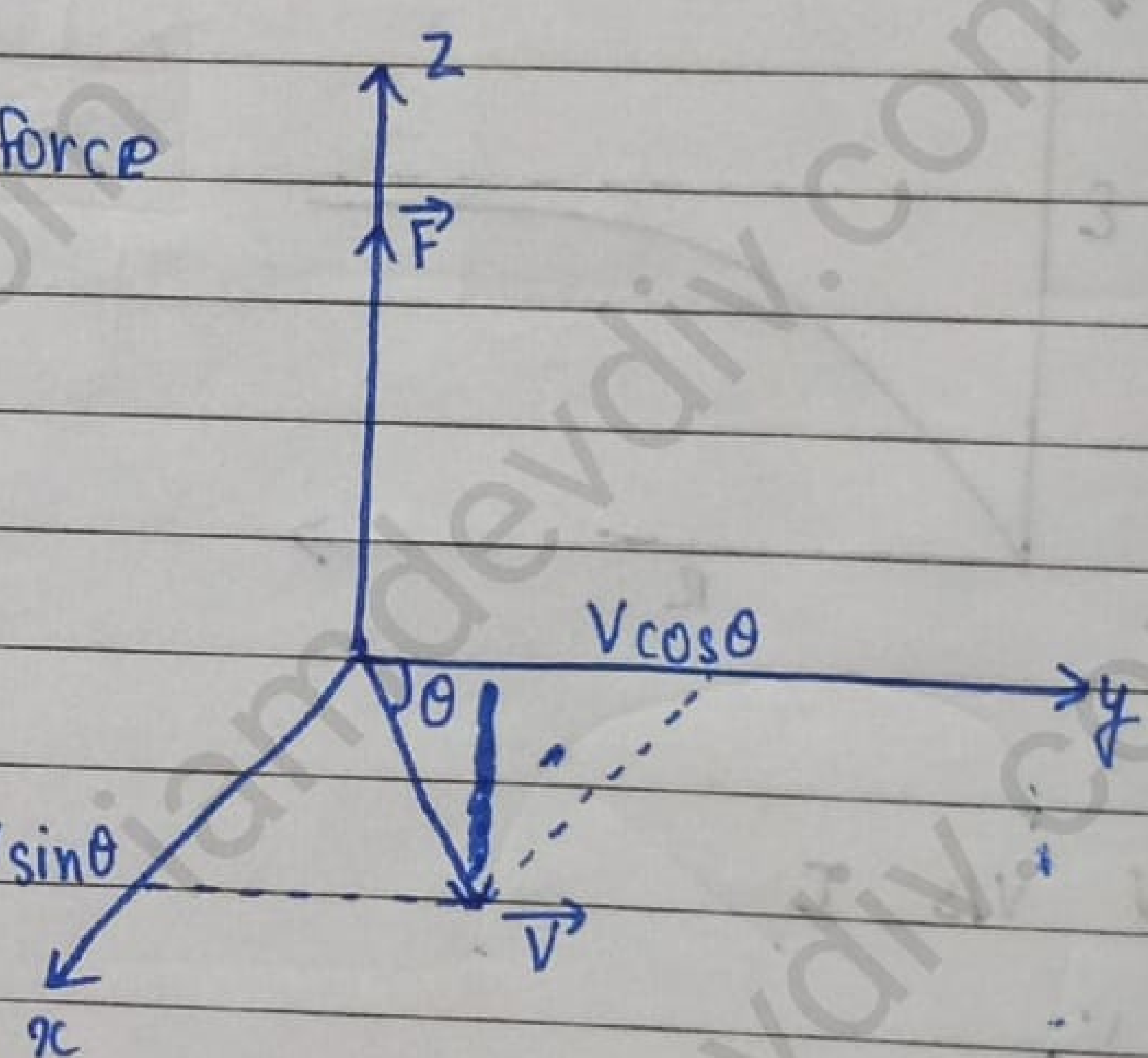
13/7/23

CHAPTER-4
MOVING CHARGES AND MAGNETISM

☆ MAGNETIC FIELD

The space or region around a magnet or a current carrying conductor, in which its magnetic effect can be felt, is known as Magnetic Field.
It is also known as Magnetic Flux Density and Magnetic Induction.

- **FORCE ON A MOVING CHARGE IN UNIFORM MAGNETIC FIELD**



Experimentally, it is found that, force experienced by the charge q is
1. $F \propto q$
2. $F \propto B$
3. $F \propto V\sin\theta$

$F \propto qVB\sin\theta$
$\Rightarrow F = k\,qVB\sin\theta$
$k = 1$
$\Rightarrow F = qVB\sin\theta$
where, F = Magnetic Lorentz Force

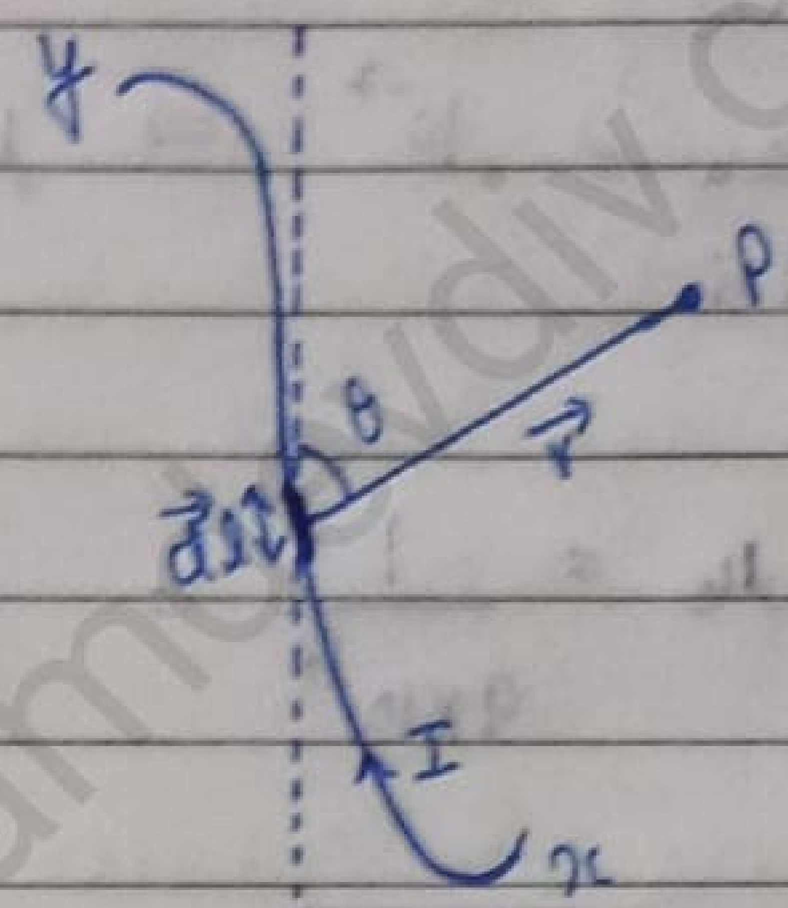
In vector form,
$\vec{F} = q(\vec{V} \times \vec{B})$
Direction $\Rightarrow$ Right hand screw rule

Unit of $\vec{B}$ $\Rightarrow$ SI Unit = Tesla (T)
CGS Unit = Gauss (G) $\rightarrow$ emu unit
1 Tesla = 10^4 Gauss

Dimensional formula of $\vec{B}$ = $[ML^0T^{-2}A^{-1}]$
Nature of $\vec{B}$ = vector

☆ BIOT - SAVART'S LAW

According to Biot-Savart Law, the magnitude of magnetic field $d\vec{B}$ at point P is,



1. $dB \propto I$
2. $dB \propto dl$
3. $dB \propto \frac{1}{r^2}$
4. $dB \propto \sin\theta$

$$dB \propto \frac{I\,dl\,\sin\theta}{r^2}$$

$$\Rightarrow dB = \frac{\mu_0}{4\pi} \times \frac{I\,dl\,\sin\theta}{r^2}$$

Where, μ_0 = Permeability of free space

$\frac{\mu_0}{4\pi} = 10^{-7}$ T m/A

$I\vec{dl}$ = Current element

~~Vector form of~~

- VECTOR FORM OF BIOT- SAVART LAW

$$\boxed{d\vec{B} = \frac{\mu_0}{4\pi}\left(\frac{I\,\vec{dl} \times \vec{r}}{r^3}\right)}$$

~~EA~~

- SPECIAL CASES

* CASE - 1

When $\theta = 0$,

$dB = 0$

* CASE - 2

When $\theta = 90^\circ$

$dB = \frac{\mu_0}{4\pi} \times \frac{I\,dl}{r^2} \longrightarrow$ MAX

RELATION BETWEEN μ_0 AND ε_0

$$\frac{1}{4\pi\varepsilon_0} = 9\times10^9 \Rightarrow \varepsilon_0 = \frac{1}{4\pi\times9\times10^9}$$

$$\frac{\mu_0}{4\pi} = 10^{-7} \Rightarrow \mu_0 = 4\pi\times10^{-7}$$

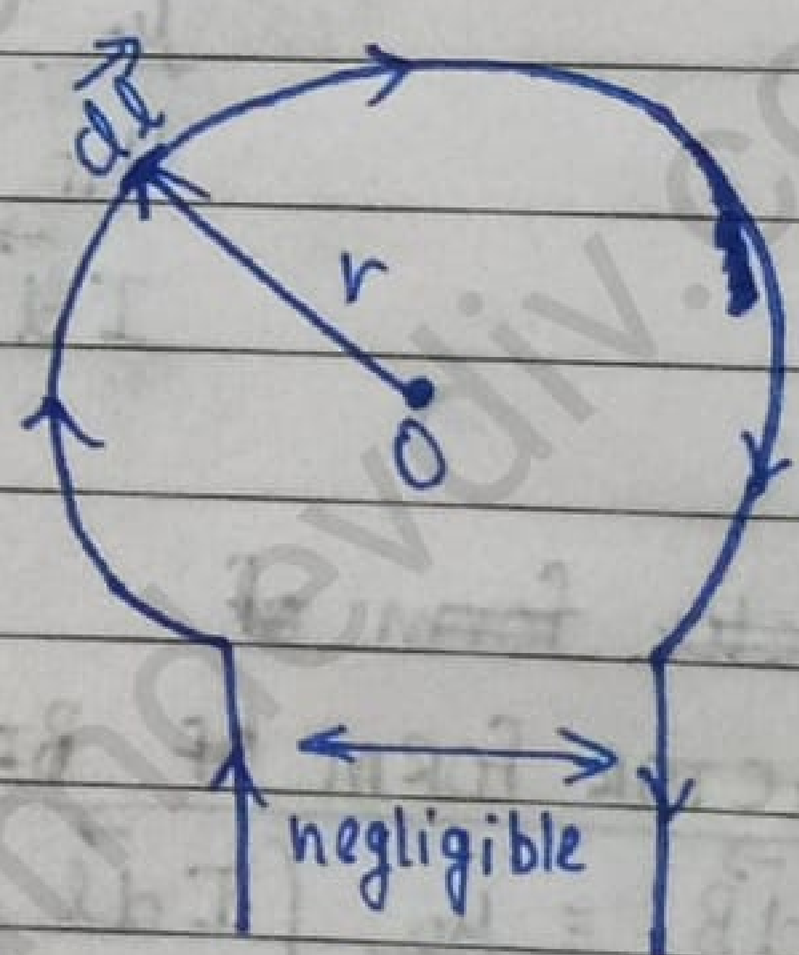
$$\varepsilon_0\mu_0 = \frac{1}{9\times10^{16}} = \frac{1}{(3\times10^8)^2}$$

$$\boxed{\varepsilon_0\mu_0 = \frac{1}{c^2}} \quad \text{OR} \quad \boxed{c = \frac{1}{\sqrt{\mu_0\varepsilon_0}}}$$

☆ MAGNETIC FIELD DUE TO CIRCULAR COIL CARRYING CURRENT

According to Biot-savart's law,

$$dB = \frac{\mu_0}{4\pi}\times\frac{I\,dl\sin\theta}{r^2}$$



Here, $I\vec{dl} \perp \vec{r}$

$\theta = 90^\circ$

$$dB = \frac{\mu_0}{4\pi}\times\frac{I\,dl}{r^2} \quad \text{—— (1)}$$

Total magnetic field due to circular coil is,

$$B = \oint dB \quad \text{—— (2)}$$

From (1) and (2),

$$B = \oint\frac{\mu_0}{4\pi}\times\frac{I\,dl}{r^2}$$

$$\Rightarrow B = \frac{\mu_0 I}{4\pi r^2}\oint dl$$

$$\Rightarrow B = \frac{\mu_0 I}{2\cancel{4\pi r^2}}\times\cancel{2\pi r}$$

$$\Rightarrow B = \frac{\mu_0 I}{2r}$$

- SPECIAL CASE

If the circular coil consists of n- turns,

$$B = \frac{\mu_0 I}{4\pi r^2} \oint dl$$

$$\because \oint dl = 2\pi r n$$

$$\Rightarrow B = \frac{\mu_0 I}{4\pi \cancel{r^2}} \times 2\pi \cancel{r} n$$

$$\Rightarrow B = \frac{\mu_0 I}{4\pi r} \times \theta$$

here, $2\pi n$ is the angle subtended at the centre due to circular coil.

Q Define one Tesla.

Ans. One tesla is defined as the field intensity generating one newton of force per ampere of current per meter of conductor.

Q Compare Biot-Savart's law and Coulomb's law.

Ans. Similarities

(i) Both the laws for fields are long range, since in both the laws, the field at a point varies inversely as the square of the distance from the source to point of observation.

(ii) Both the fields obey superposition principle.

(iii) The magnetic field is linearly related to its source, namely the current element $I d\vec{l}$ and the electric field is linearly related to its source, namely the electric charge q.

Dis-similarities

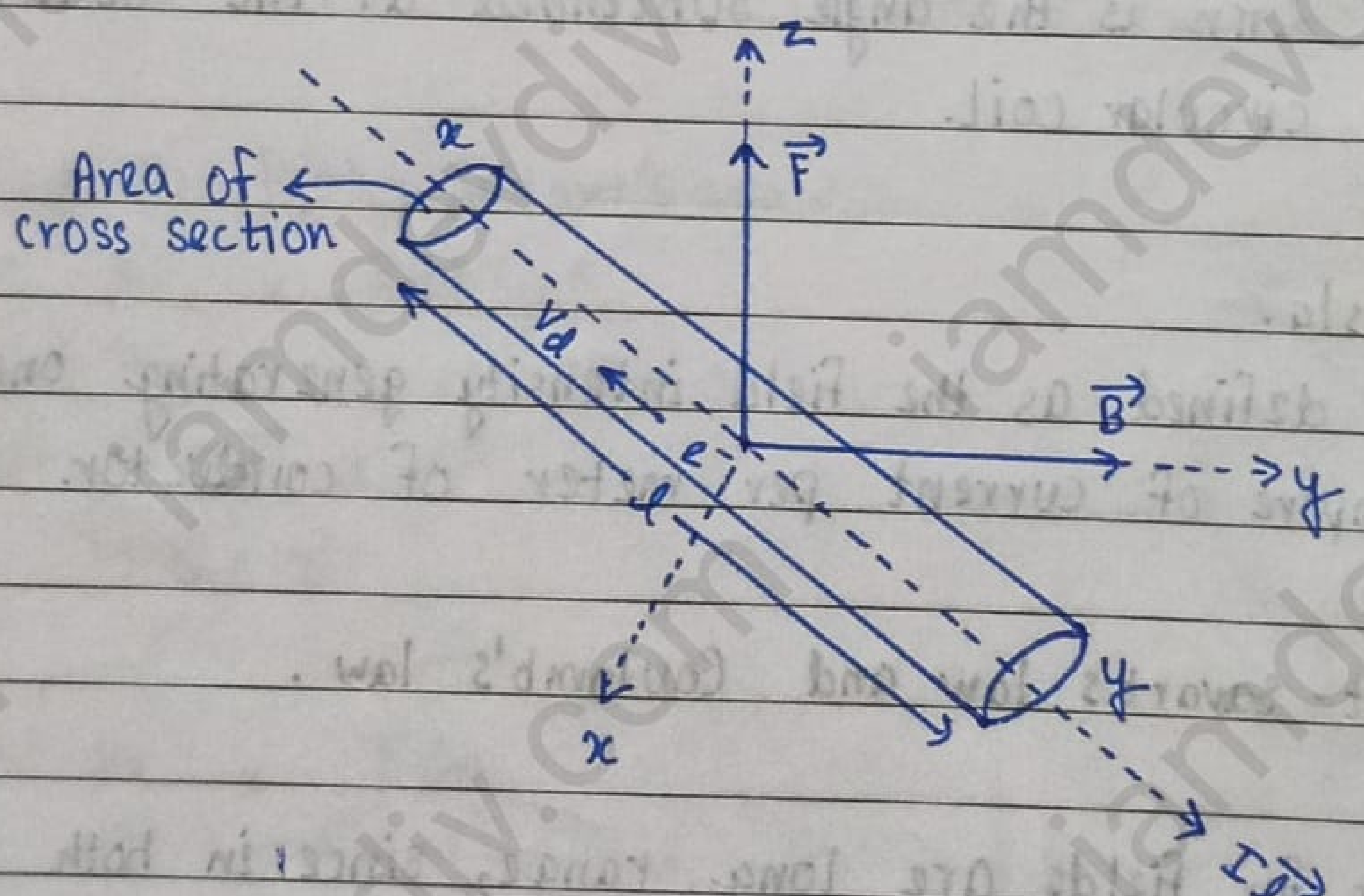
(i) The electrostatic field is produced by a scalar source namely, the electric charge q and the magnetic field is produced by a vector source, a current element $I\vec{dl}$.

(ii) The electrostatic field is acting along the displacement vector, i.e., line joining the source and the field point. The magnetic field is acting perpendicular to the plane containing the current element $I\vec{dl}$ and displacement vector $\vec{r}$, i.e., along the direction of $(I\vec{dl} \times \vec{r})$.

(iii) Coulomb law is independent of angle whereas the Biot-Savart's law is angle dependent.

★ FORCE ON CURRENT CARRYING CONDUCTOR IN UNIFORM MAGNETIC FIELD

Experimentally, it is found that when a current carrying conductor is placed in uniform magnetic field, it ~~experiments~~ experiences a force.



Let's consider a current carrying conductor of length l is placed in uniform magnetic field $\vec{B}$

Let,

V_d = drift velocity of free e^-

$I\vec{l}$ = Current element

Thus, force experienced by an electron in magnetic field $\vec{B}$,

$$\vec{F}' = q(\vec{V_d} \times \vec{B})$$

$\because q = ne$ and $n = 1 \Rightarrow q = e$

$\Rightarrow \vec{F}' = -e\,(\vec{V_d} \times \vec{B})$

↳ -ve sign is used here as the direction of current element $I\vec{l}$ is opposite to that of $\vec{V_d}$

If n = electron density (no. of e^- / volume)
N = Total no. of e^-
$\Rightarrow N = nAl$

Total force experienced by the conductor
$\vec{F} = N\vec{F}'$
$\Rightarrow \vec{F} = -nAle\,(\vec{V_d} \times \vec{B})$
$\Rightarrow \vec{F} = -enA\,(l\,\vec{V_d} \times \vec{B})$

$\because$ the direction of current element $I\vec{l}$ is opposite to that of the direction of $\vec{V_d}$

Thus, $-l\vec{V_d} = \vec{l}\,V_d$
There fore,
$\vec{F} = enA\,(V_d\vec{l} \times \vec{B})$
$\vec{F} = neAV_d\,(\vec{l} \times \vec{B})$
$\because I = neAV_d$

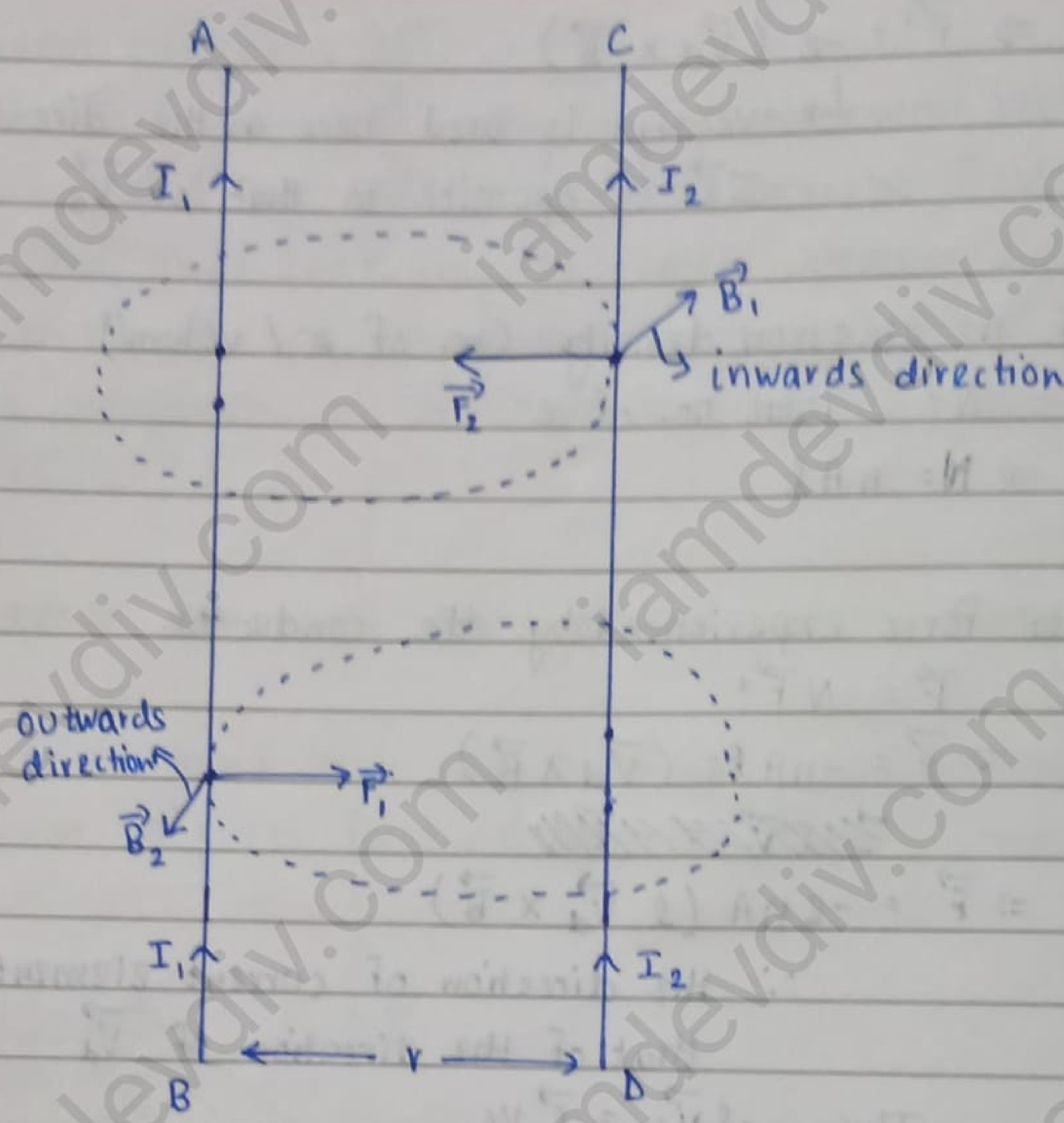
Thus,
$\boxed{\vec{F} = I\,(\vec{l} \times \vec{B})}$

In magnitude,
$\boxed{F = IlB\sin\theta}$

★ FORCE BETWEEN TWO PARALLEL WIRES CARRYING CURRENT

Let's consider two straight wires AB and CD held parallel with each other, carrying current I_1 and I_2.

P.T.O.



Magnetic field due to wire AB,

$$B_1 = \frac{\mu_0 I}{2\pi r} \quad \text{--- (1)}$$

Force experienced by wire CD due to the magnetic field of B,

$$F_2 = I_2 B_1 l \sin\theta$$

$$\because \vec{l} \perp \vec{B} \Rightarrow \theta = 90^\circ$$

$$\Rightarrow F_2 = I_2 B_1 l \quad \text{--- (2)}$$

From (1) and (2),

$$F_2 = I_2 \times \frac{\mu_0 I}{2\pi r} \times l$$

$$\Rightarrow \boxed{F_2 = \frac{\mu_0 I_1 I_2 l}{2\pi r}}$$

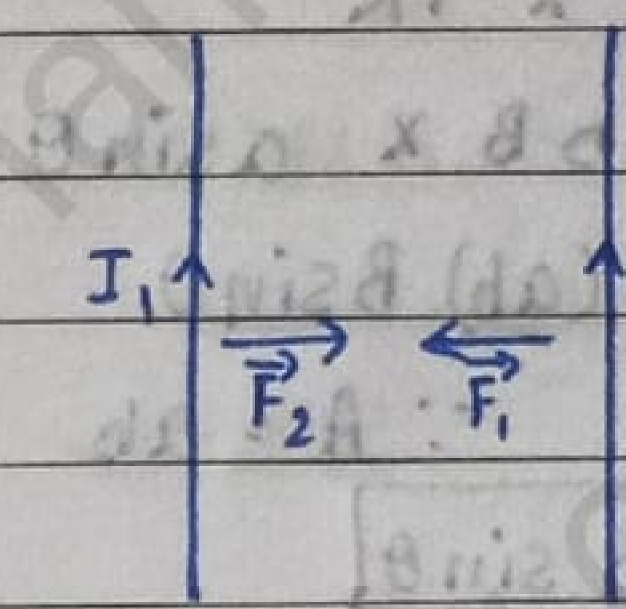
Similarly,

$$\boxed{F_1 = \frac{\mu_0 I_1 I_2 l}{2\pi r}}$$

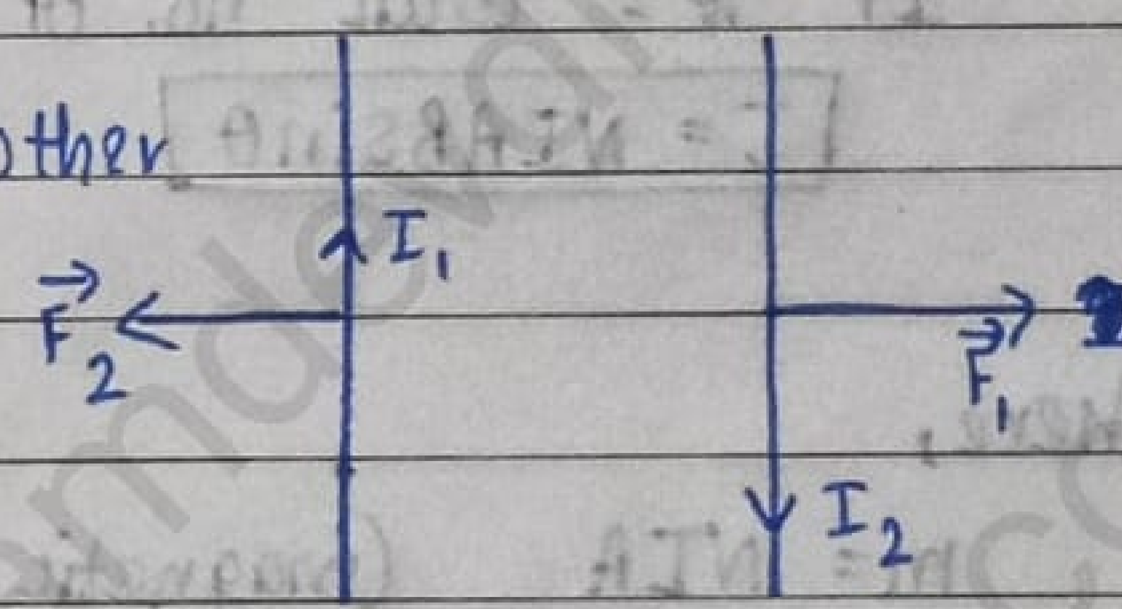
NOTE → Force per unit length on the wire

$$\boxed{F = \frac{\mu_0 I_1 I_2}{2\pi r}}$$

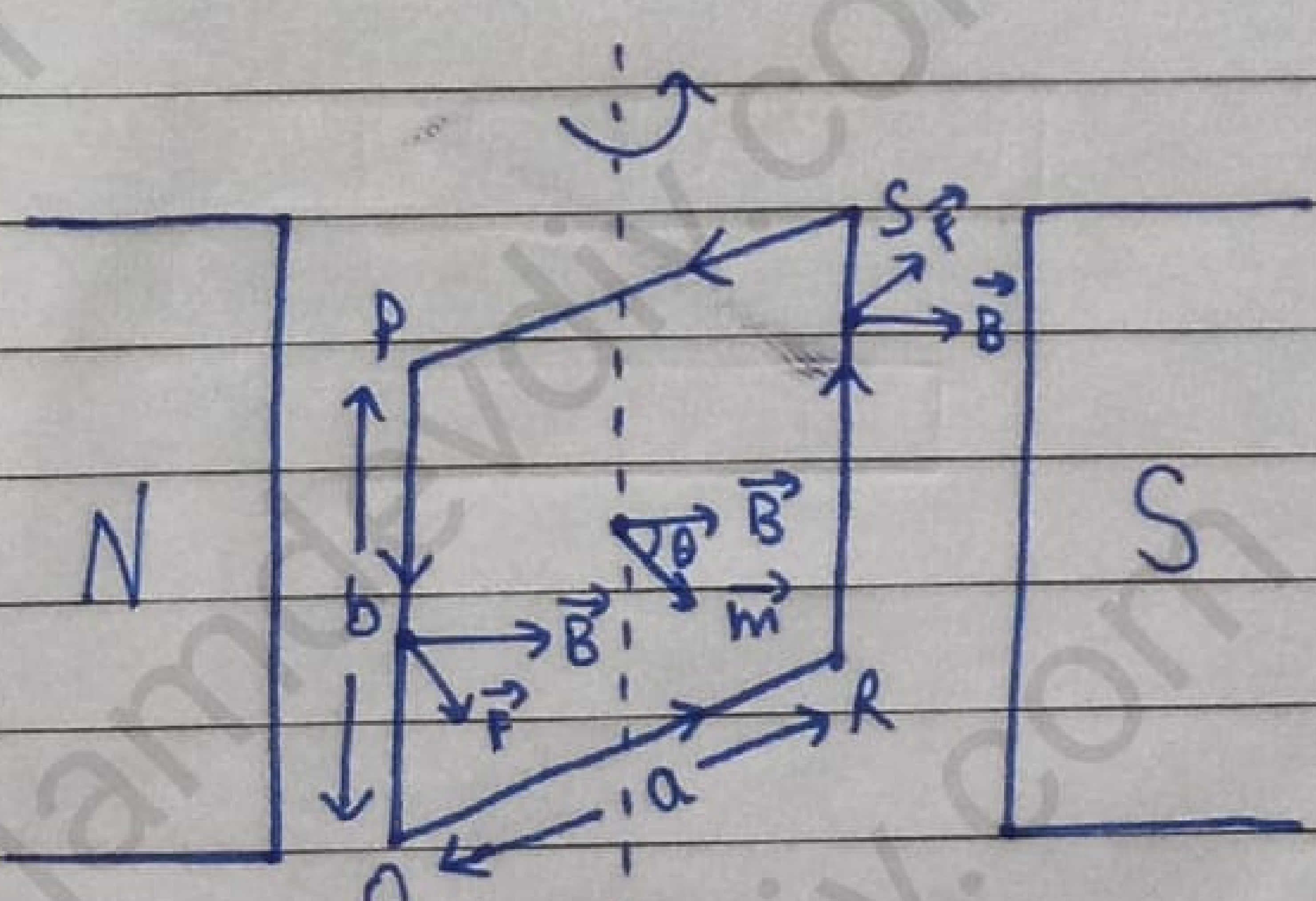
Parallel current ⇒ Attract each other



Anti-parallel current ⇒ Repel each other



☆ TORQUE ON A CURRENT CARRYING LOOP IN UNIFORM MAGNETIC FIELD



Let's consider a rectangular loop PQRS carrying current I is placed in uniform magnetic field $\vec{B}$

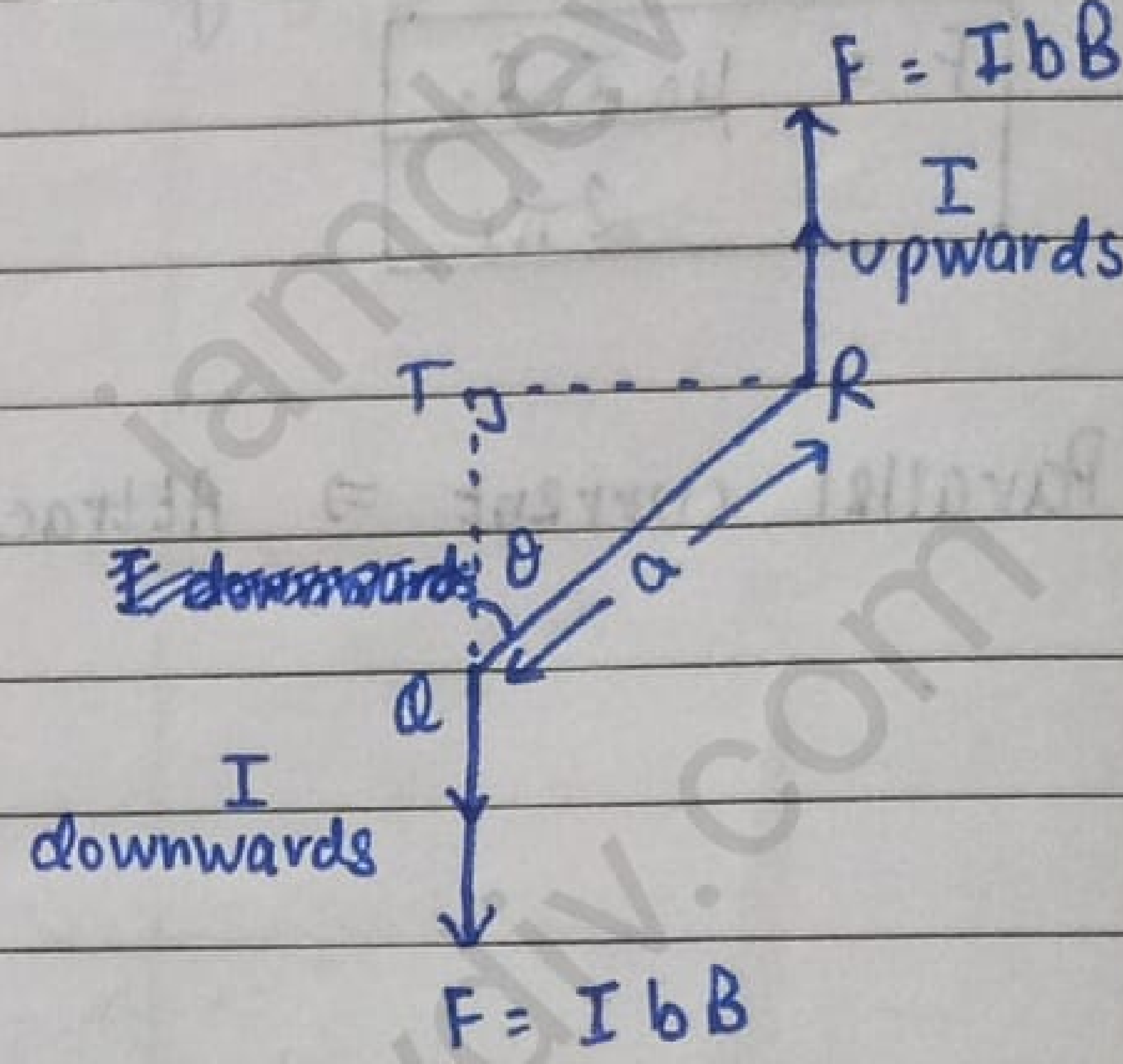
Let,

a and b = sides of rectangular loop (PQRS)

A = area of rectangular loop ($A = ab$)

I = Current flowing through the loop

m = magnetic moment



Torque = Force x ⊥ distance

$\Rightarrow \tau = F \times TR$

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

$\Rightarrow \tau = I(ab)B\sin\theta$

$\because A = ab$

$\Rightarrow \boxed{\tau = IAB\sin\theta}$

If N = total no. of turns

$\boxed{\tau = NIAB\sin\theta}$

here,

$m = NIA$ (magnetic moment)

- Unit = Amp-m^2 ($A\text{-}m^2$)
- Dimension = $[L^2A]$
- Nature = Vector

There fore,

$\tau = mB\sin\theta$

In vector form,

$\boxed{\vec{\tau} = \vec{m} \times \vec{B}}$

- Special Cases

* Case-1

When the coil is parallel with the magnetic field

$\theta = 90^\circ$ $[\vec{m} \perp \vec{B}]$

$\tau = mB\sin\theta$

$\boxed{\tau_{max} = mB}$

* CASE - 2

When the coil is perpendicular with the magnetic field

$\theta = 0°$ $[\vec{m} \parallel \vec{B}]$

$\boxed{\tau = 0}$

☆ METHODS OF PRODUCING ~~MA~~ MAGNETIC FIELD

1. When current is flowing through a wire.
2. When charge is in motion.
3. By changing the electric field

☆ MOVING COIL GALVANOMETER (MCG)

OR

DEAD BEAT GALVANOMETER

A moving coil galvanometer is an instrument which is used to detect the presence of electric current and its direction.

A galvanometer which produces large deflection even for a negligible electric current, is called dead beat galvanometer.

- PRINCIPLE OF WORKING

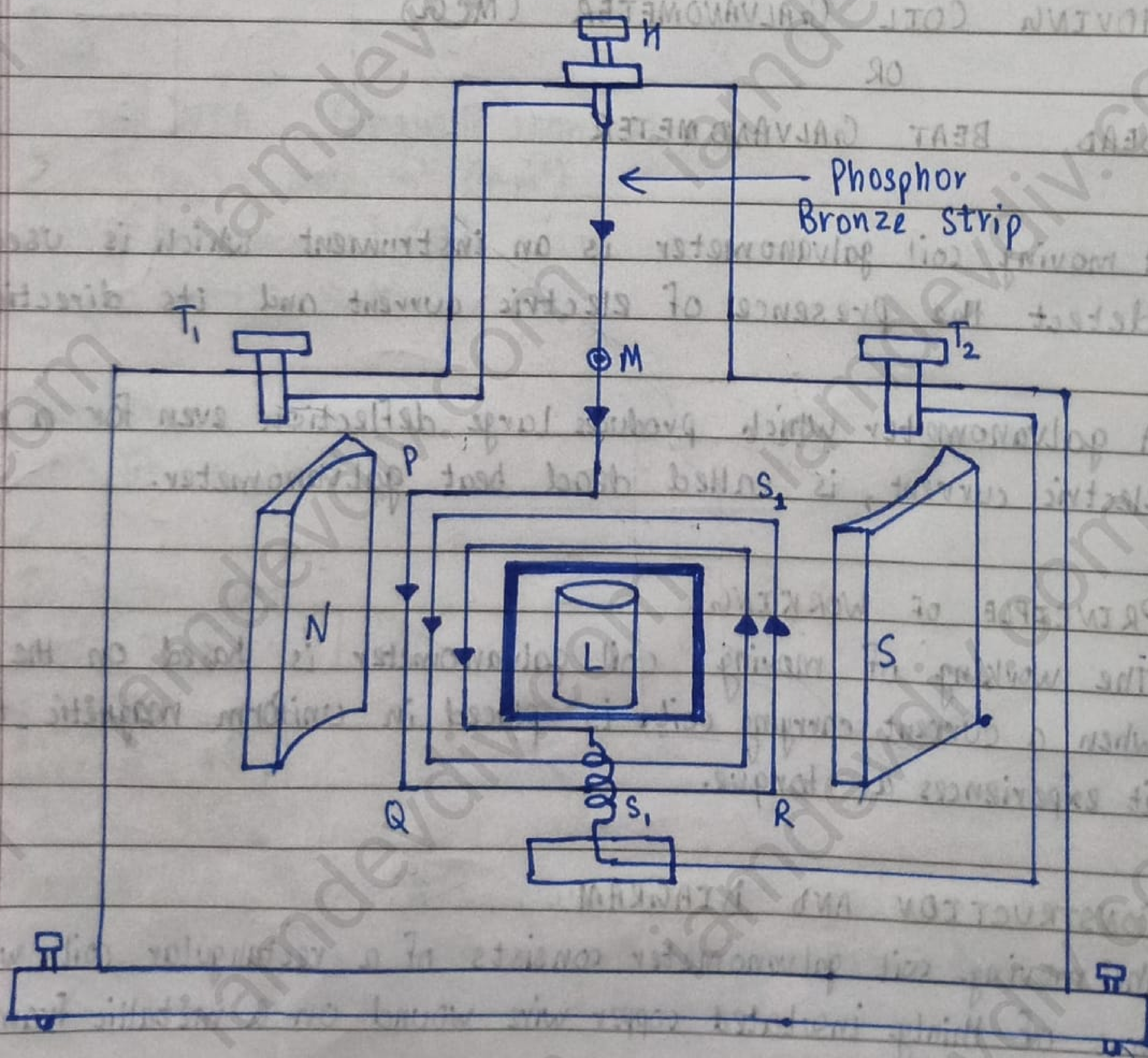
The working of moving coil galvanometer is based on the principle, when a current carrying coil is placed in uniform magnetic field, it experiences a torque.

- CONSTRUCTION AND DIAGRAM

The moving coil galvanometer consists of a rectangular coil with many turns of thinly insulated copper wire wound on a metallic frame. It can rotate freely around a fixed axis and is suspended in a uniform radial magnetic field using a phosphor-bronze strip connected to a movable torsion head.

The suspension material requires high conductivity and a low torsional constant. Inside the coil, a cylindrical soft iron core enhances the magnetic field's strength and radial direction. The lower part of the coil is linked to a phosphor-bronze spring with a few turns, which provides a counter torque balancing the magnetic torque, ensuring steady angular deflection.

To measure the coil's deflection, a plane mirror attached to the suspension wire, along with a lamp and scale arrangement, is used. The scale's zero-point is at the center.



- WORKING

Deflecting torque acting on the coil,

$\tau_{deflection} = NIBA \sin\theta$ $\quad \because \vec{m} \perp \vec{B} \Rightarrow \theta = 90°$

$\Rightarrow \boxed{\tau_{deflection} = NIBA}$ — ①

Resting torque acting on the coil is,

$\boxed{\tau_{resting} = k\alpha}$

$k \rightarrow$ spring constant
$\alpha \rightarrow$ deflection produced

Under balanced condition,

$\boxed{\tau_{deflection} = \tau_{restoring}}$

$\Rightarrow NIBA = K\alpha$

$\Rightarrow I = \left[\frac{K}{NIA}\right]\alpha$

Here, $\frac{K}{NIA} = G$ (Galvanometer constant)

Thus,

$\boxed{I = G\alpha}$

Electric current α Deflection produced

☆ SENSITIVITY OF GALVANOMETER

A galvanometer is said to be most sensitive, if it shows large deflection for a negligible current flowing through it.

- CURRENT SENSITIVITY (I_s)

The deflection produced by a galvanometer per unit electric current flowing through it, is called current sensitivity of the galvanometer.

$I_s = \frac{\alpha}{I}$

- Unit - Division per ampere (div/A)
  - Radian per ampere (rad/A)
- Dimensional formula - $[M^0 L^0 T^0 A^{-1}]$

As we have,

$$I = \left[\frac{K}{NBA}\right]\alpha$$

We get,

$$I_s = \frac{\alpha}{\left(\frac{K}{NBA}\right)\alpha}$$

$$\Rightarrow \boxed{I_s = \frac{NBA}{K}}$$

- **VOLTAGE SENSITIVITY (V_s)**

The deflection produced by a galvanometer per unit voltage applied across its ends, is called voltage sensitivity of the galvanometer.

$$V_s = \frac{\alpha}{V}$$

- Unit – Division / volts (Div / V)
  - Radian / Volts (rad/V)
- Dimensional formula – $[M^{-1}L^{-2}T^{3}I]$

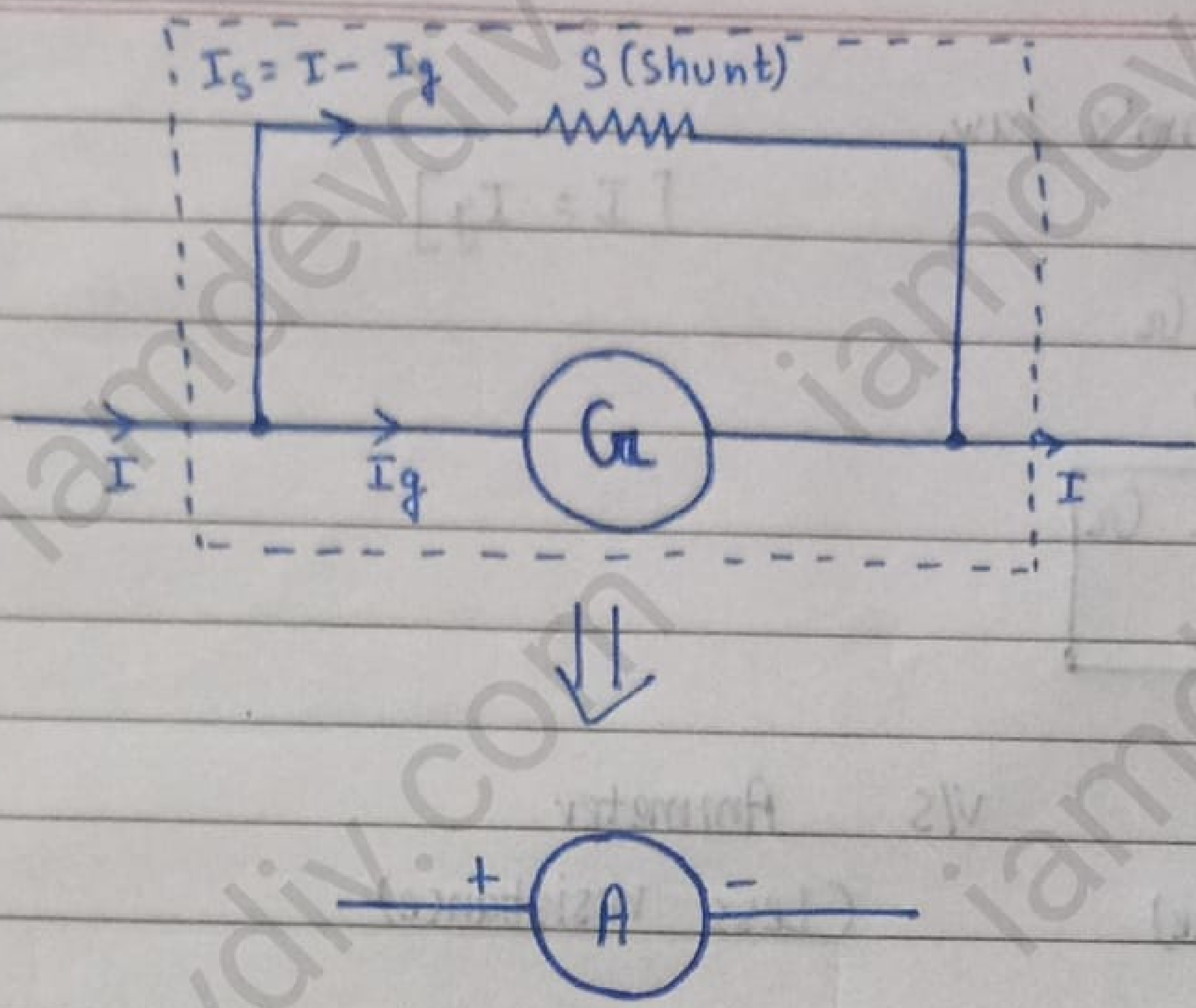
$$\Rightarrow V_s = \frac{\alpha}{IR}$$

$$\Rightarrow V_s = \frac{\alpha}{\left(\frac{K}{NBA}\right)\alpha R}$$

$$\Rightarrow \boxed{V_s = \frac{NBA}{KR}}$$

★ **CONVERSION OF GALVANOMETER INTO AMMETER**

A galvanometer can be converted into an ammeter by connecting a shunt (low valued resistance) in parallel with it.



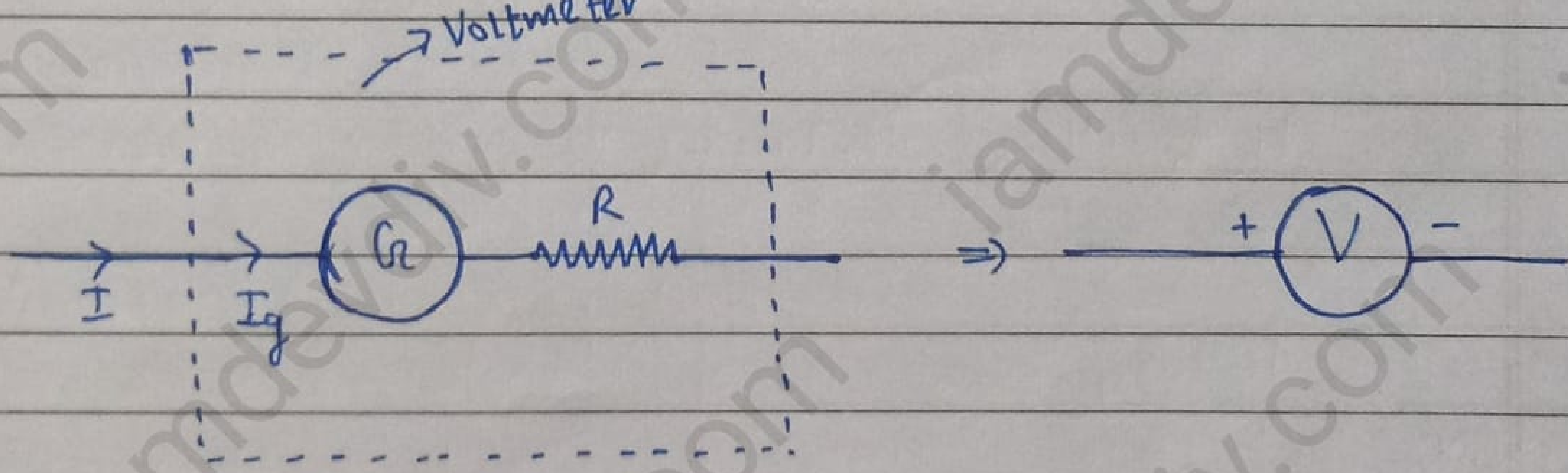
$$S . I_s = G . I_g$$

$$\Rightarrow S(I - I_g) = G . I_g \qquad \because I_s = I - I_g$$

$$\Rightarrow \boxed{S = \left(\frac{I_g}{I - I_g}\right) \times G}$$

★ CONVERSION OF GALVANOMETER INTO A VOLTMETER

A galvanometer can be converted into a voltmeter by connecting a high-valued resistance in series with it.



Here,

G = Galvanometer

R = high-valued resistance

V = Voltage to be measured by voltmeter

I_g = current through the galvanometer

According to ohm's law,

$$I_g = \frac{V}{R+G}$$

$$[I = I_g]$$

$$\Rightarrow I_g(R+G) = V$$

$$\Rightarrow \boxed{R = \frac{V}{I_g} - G}$$

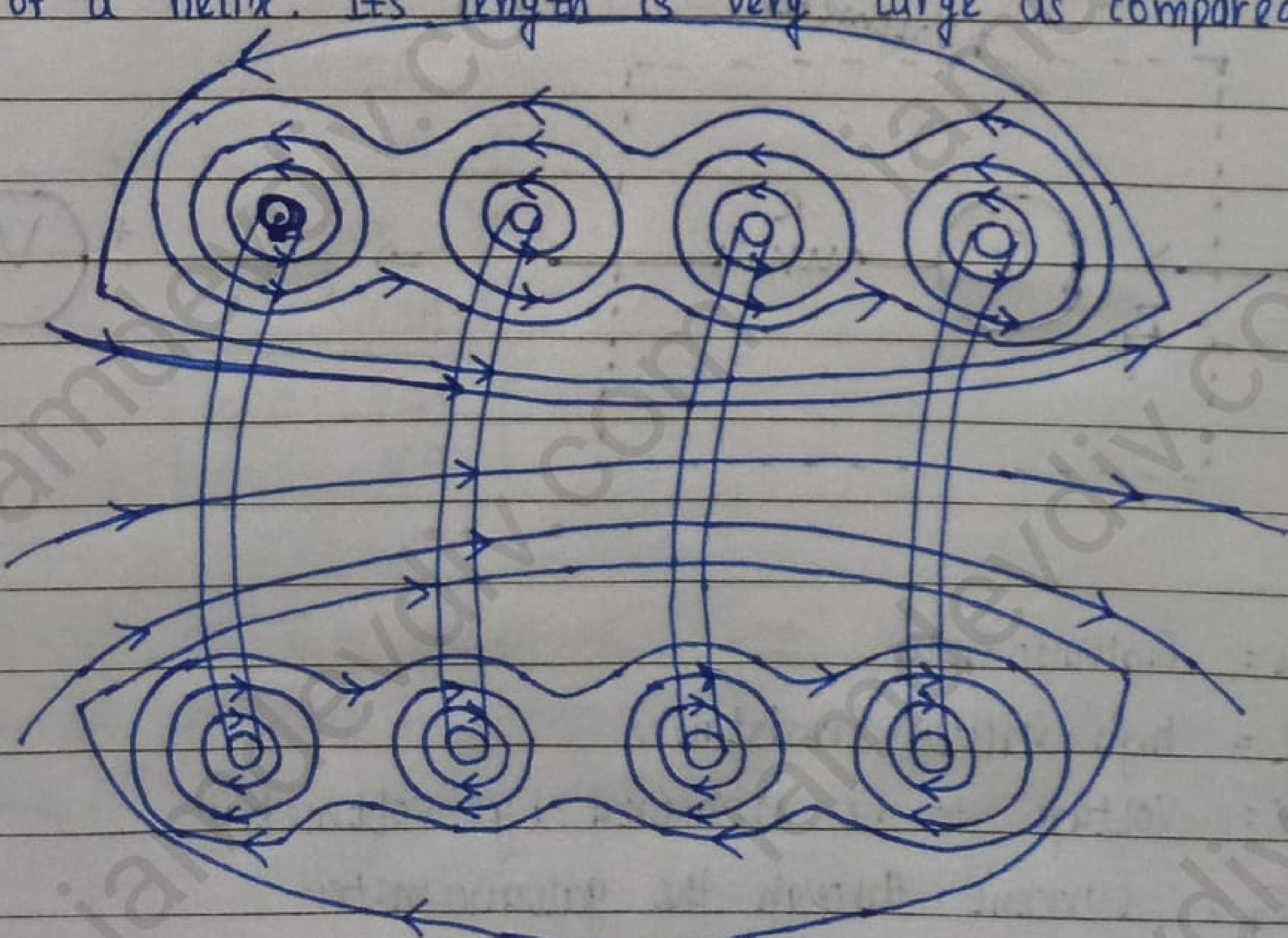
NOTE → ① Milliammeter v/s Ammeter
(More resistance) (Less resistance)

② Millivoltmeter v/s Voltmeter
(Less resistance) (More resistance)

③ G, S, R
$S < G < R$

★ THE SOLENOID

A solenoid is a piece of equipment which is used for generating magnetic field. It consists of an insulating long wire closely wound in the form of a helix. Its length is very large as compared to its diameter.



$$\boxed{B = \mu_0 n I}$$

where, $n =$ no. of turns / unit length

$N =$ total no. of turns

$$n = \frac{N}{l}$$

$$\boxed{B = \frac{\mu_0 N I}{l}}$$

$$\boxed{B_{outside} = 0}$$

* Magnetic field inside the solenoid carrying current is uniform, whereas the magnetic field outside the solenoid is non-uniform

* The magnetic field produced by a current carrying solenoid is similar to the magnetic field produced by a bar magnet.

* The magnetic field lines inside the solenoid are in the form of parallel straight lines.

* The strength of magnetic field is the same at all points inside the solenoid.