# MAGNETIC FIELDS (A2-22 syllabus)

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## 20 Magnetic fields

### 20.1 Concept of a magnetic field

Candidates should be able to:

1 understand that a magnetic field is an example of a field of force produced either by moving charges or by permanent magnets

2 represent a magnetic field by field lines

### 20.2 Force on a current-carrying conductor

Candidates should be able to:

1 understand that a force might act on a current-carrying conductor placed in a magnetic field

2 recall and use the equation $F = BIL \sin \theta$, with directions as interpreted by Fleming's left-hand rule

3 define magnetic flux density as the force acting per unit current per unit length on a wire placed at right-angles to the magnetic field

### 20.3 Force on a moving charge

Candidates should be able to:

1 determine the direction of the force on a charge moving in a magnetic field

2 recall and use $F = BQv \sin \theta$

3 understand the origin of the Hall voltage and derive and use the expression $V_H = BI/(ntq)$, where $t$ = thickness

4 understand the use of a Hall probe to measure magnetic flux density

5 describe the motion of a charged particle moving in a uniform magnetic field perpendicular to the direction of motion of the particle

6 explain how electric and magnetic fields can be used in velocity selection

### 20.4 Magnetic fields due to currents

Candidates should be able to:

1 sketch magnetic field patterns due to the currents in a long straight wire, a flat circular coil and a long solenoid

2 understand that the magnetic field due to the current in a solenoid is increased by a ferrous core

3 explain the origin of the forces between current-carrying conductors and determine the direction of the forces

### 20.5 Electromagnetic induction

Candidates should be able to:

1 define magnetic flux as the product of the magnetic flux density and the cross-sectional area perpendicular to the direction of the magnetic flux density

2 recall and use $\Phi = BA$

3 understand and use the concept of magnetic flux linkage

4 understand and explain experiments that demonstrate:

- that a changing magnetic flux can induce an e.m.f. in a circuit
- that the induced e.m.f. is in such a direction as to oppose the change producing it
- the factors affecting the magnitude of the induced e.m.f.

5 recall and use Faraday's and Lenz's laws of electromagnetic induction

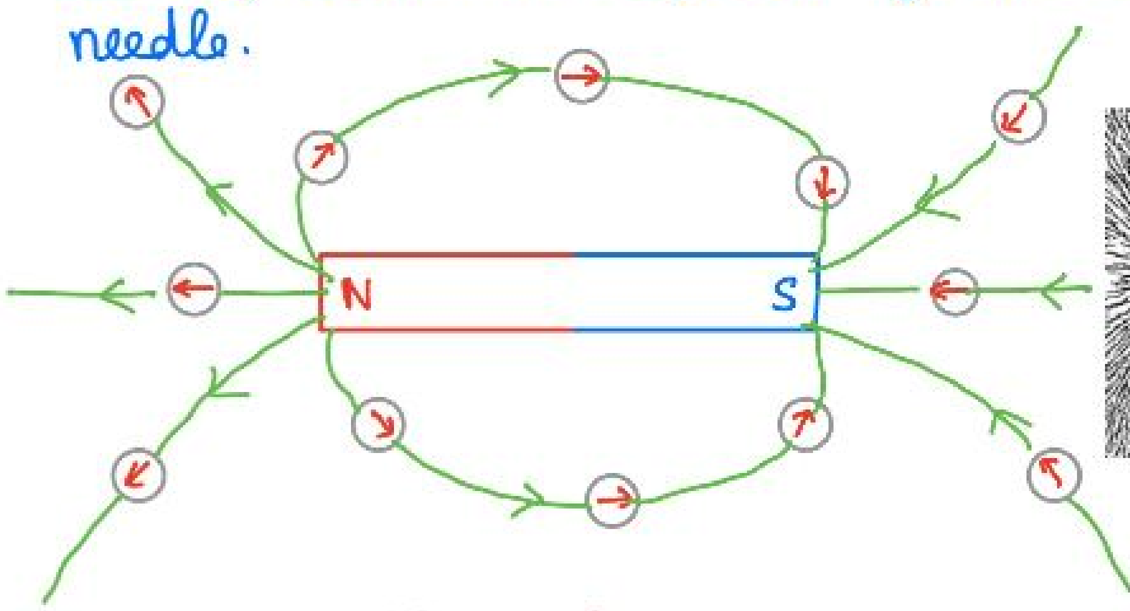
## Magnetic field :-

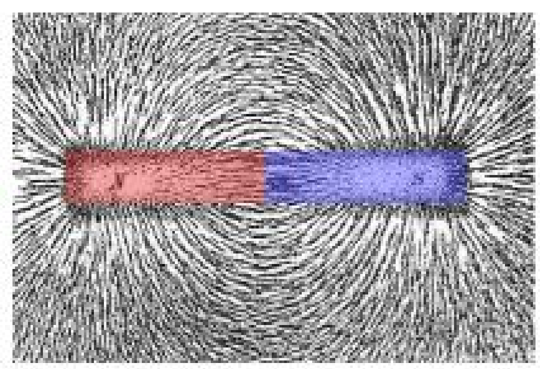
**Meaning:-** field $\longrightarrow$ 3D region or space

Source $\longrightarrow$ (i) Permanent magnet
(ii) Current in the conductor

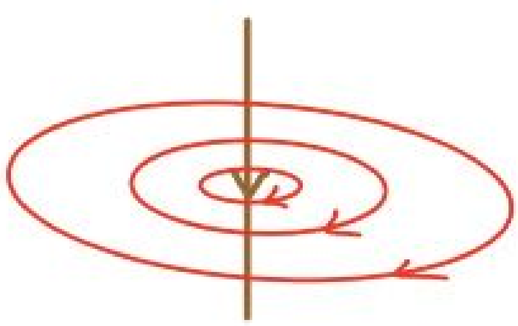
Identify $\longrightarrow$ A moving charged particle experience a deflecting force

**Representation:** By means of field lines i.e each field line represent the deflection of unit North pole of compass needle.

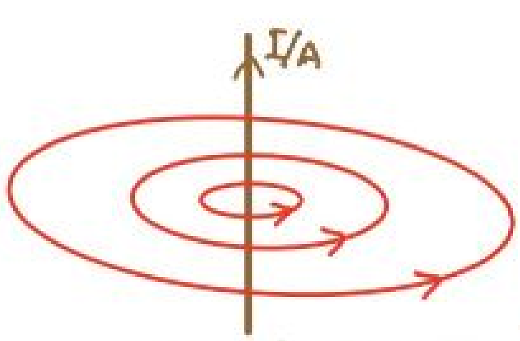


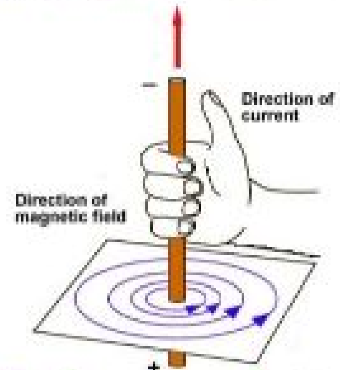



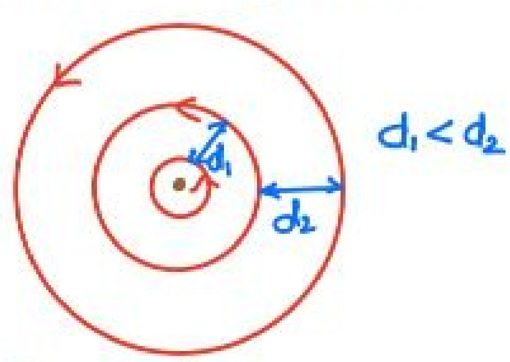
## (a) Magnetic effect of Electric current:-



current is directed into the plane of page



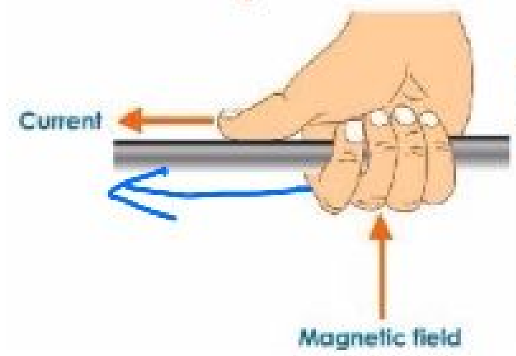




current is directed out of the plane of page

**Field pattern:-** (i) Concentric circular pattern in a plane which is perpendicular to the plane of current in conductor.

(ii) Gap between adjacent field lines increases as one move away from conductor

## Magnitude of magnetic field strength (B):




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

$\mu_0$ : Permeability of free space

$\mu_0 = 4\pi \times 10^{-7}\ H\,m^{-1}$

$I$ : current in conductor

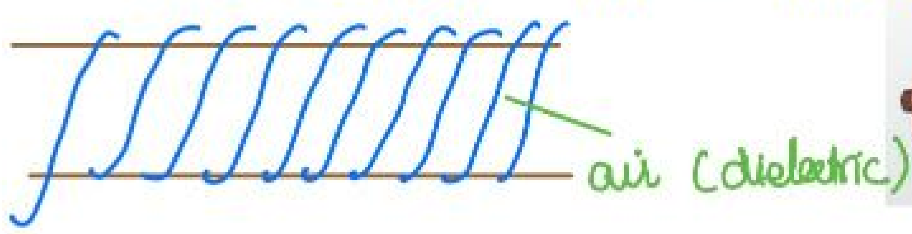
$r$ : Distance of B-field line from current carrying conductor.

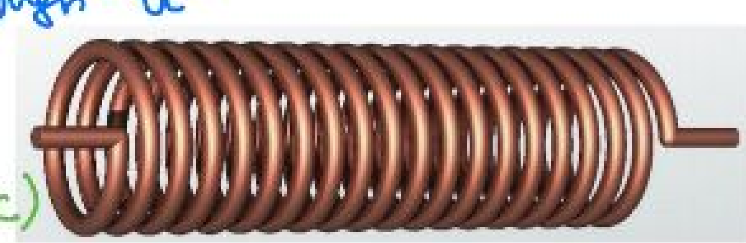
## Direction of B-field lines:-

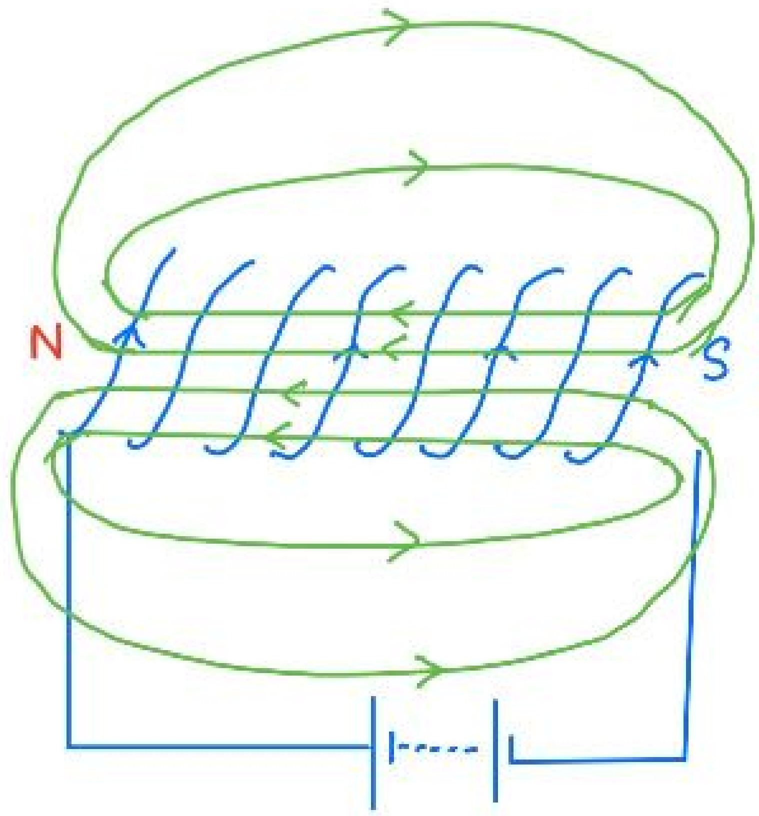
By Right hand Grip rule

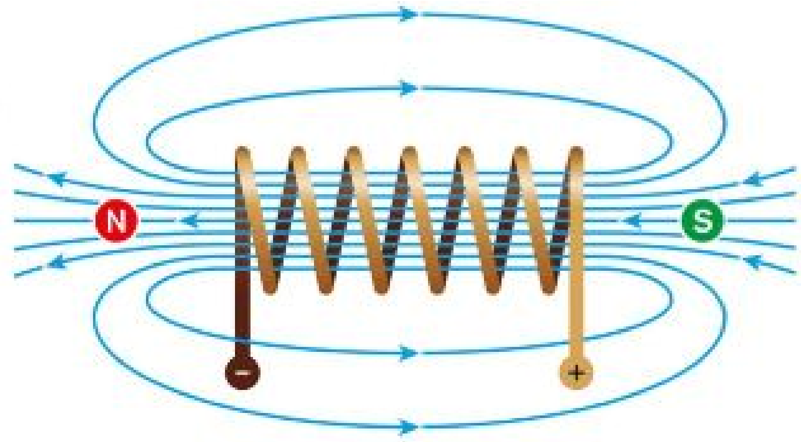
"Point the thumb of Right hand towards current and curl of fingers provide the direction of B-field lines."

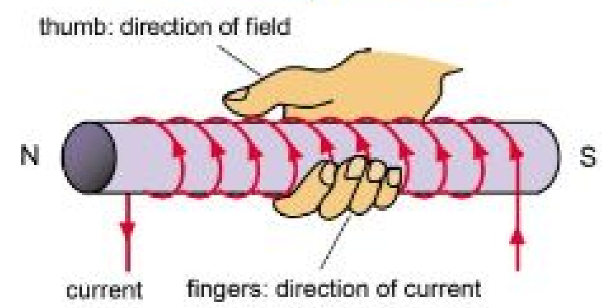
(b) **Coil / Solenoid:** A metallic wire coiled on a dielectric medium form a solenoid. It becomes a magnet when current flows through it.






## Field pattern:

(i) <u>Inside Solenoid</u>:- Uniform field ie equi-distant parallel lines directed from South to North.

(ii) <u>Outside Solenoid</u>:- Non-uniform field i.e gap between adjacent field lines vary and are directed from North to South.

## Magnitude of magnetic field strength (B)

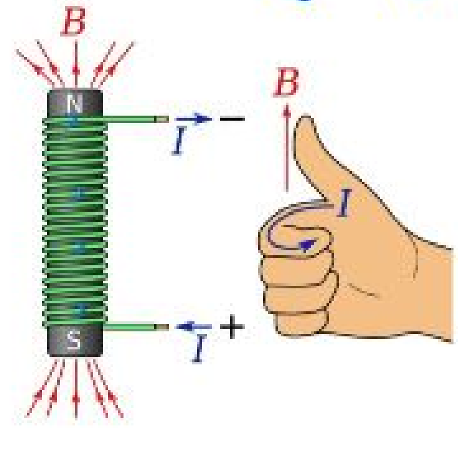
(i) Inside Solenoid: $B = \mu_0 n I$

(ii) Outside Solenoid: $B = \dfrac{\mu_0 n I}{2}$

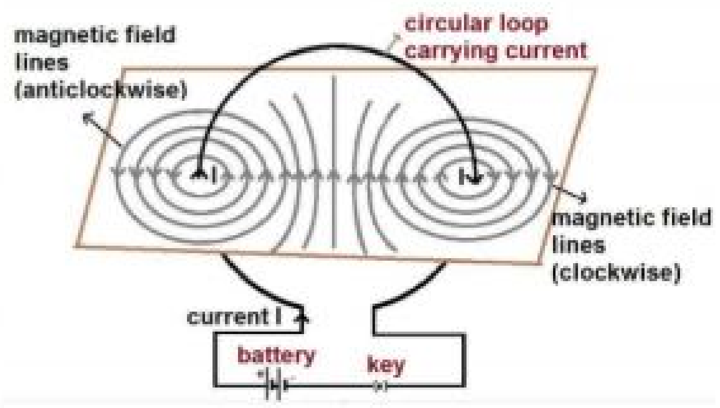
$n = \frac{N}{L}$ ie $n =$ No. of turns per unit length of coil

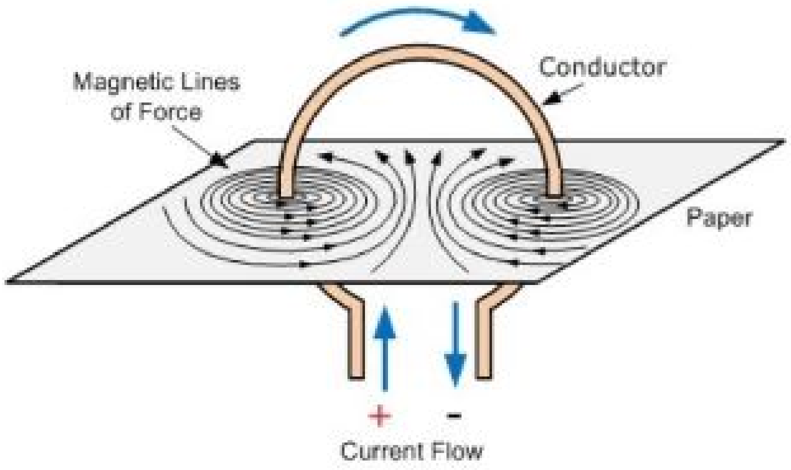
## Direction of B- field lines: Obtained by Right curl hand Rule

"Curl the fingers of Right hand towards current and thumb points towards North pole."



# Flat circular coil:-




## Field pattern:

Around Coil:- Concentric circles in opposite directions and direction is obtained as per Right hand Grip rule.

Space between coil:- Repulsive field as current in parallel conductors are in opposite directions. Magnetic field line at the centre is a straight line.

Magnitude of B-field:- between coils decreases when the distance between wires increases ie diameter of coil increases.

## Helmholtzs' coils :-

Two coils having

(i) same no. of turns

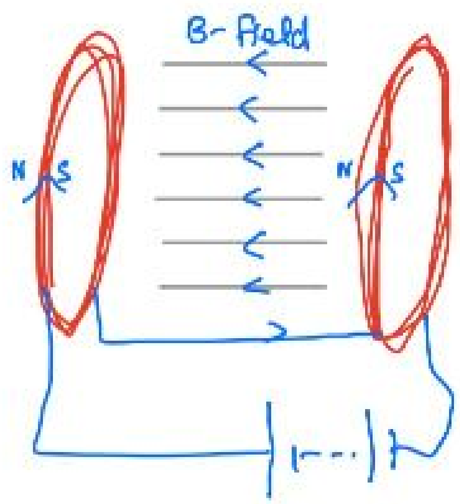
(ii) same current due to series combination

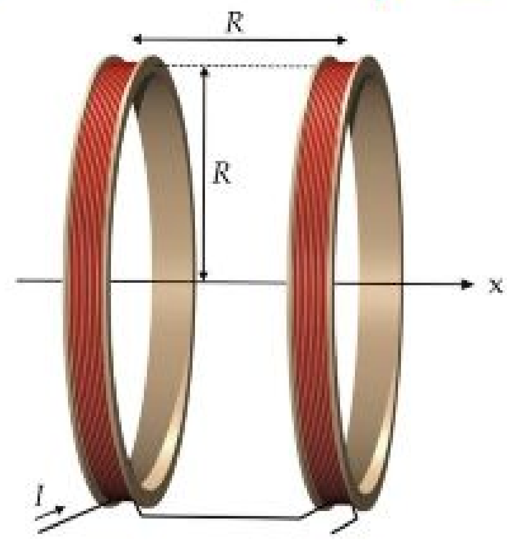
(iii) same central axis

(iv) same radii

(v) their plane parallel to each other

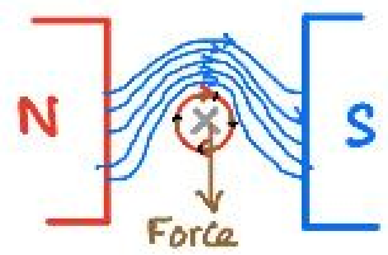
and are used to produce uniform magnetic field in the region between coils iff "separation b/w coils is equal to radius of a coil".

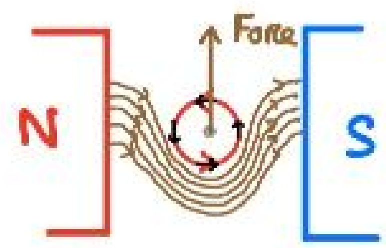



# Force on a current carrying conductor placed in a magnetic field:-

## Concept:






Result: A current carrying conductor placed in a magnetic field experience a force whose magnitude depends upon the following factors.

$F \propto B$ (Magnetic field strength / magnetic flux density)

$F \propto I$ (current in conductor)

$F \propto L$ (Length of current carrying conductor inside B-field)

$F \propto \sin\theta$ ($\theta$ - Angle b/w current and B-field)

Combining above factors

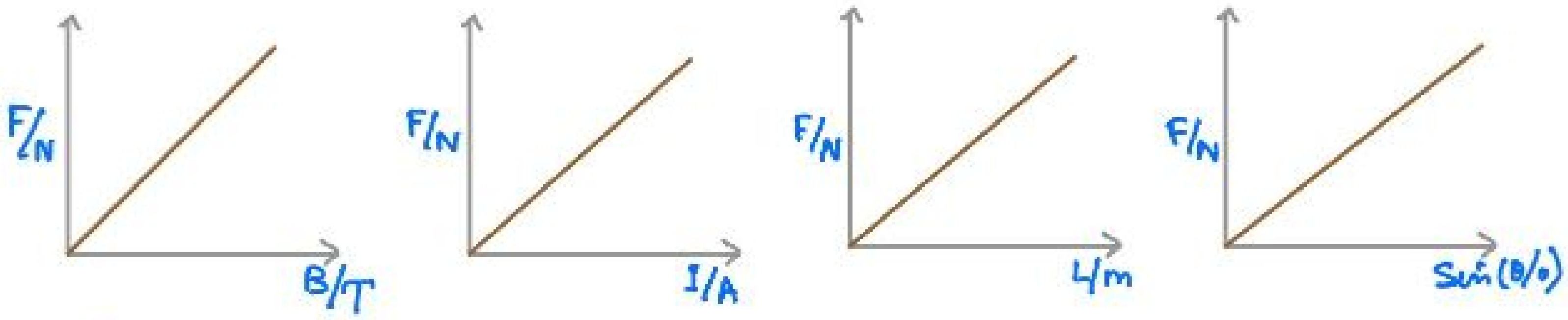
$$F \propto BIL\sin\theta$$

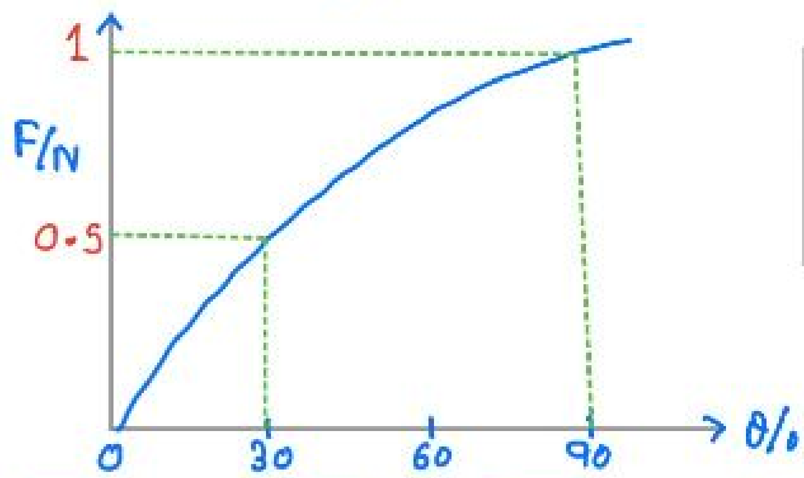
$$F = KBIL\sin\theta$$

Here $K = 1$ in S.I.

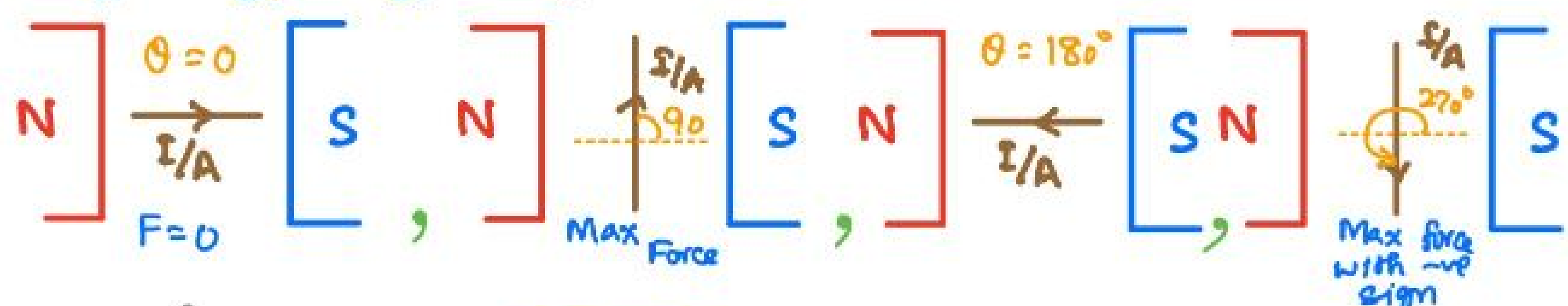
$$\boxed{F = BIL\sin\theta}$$

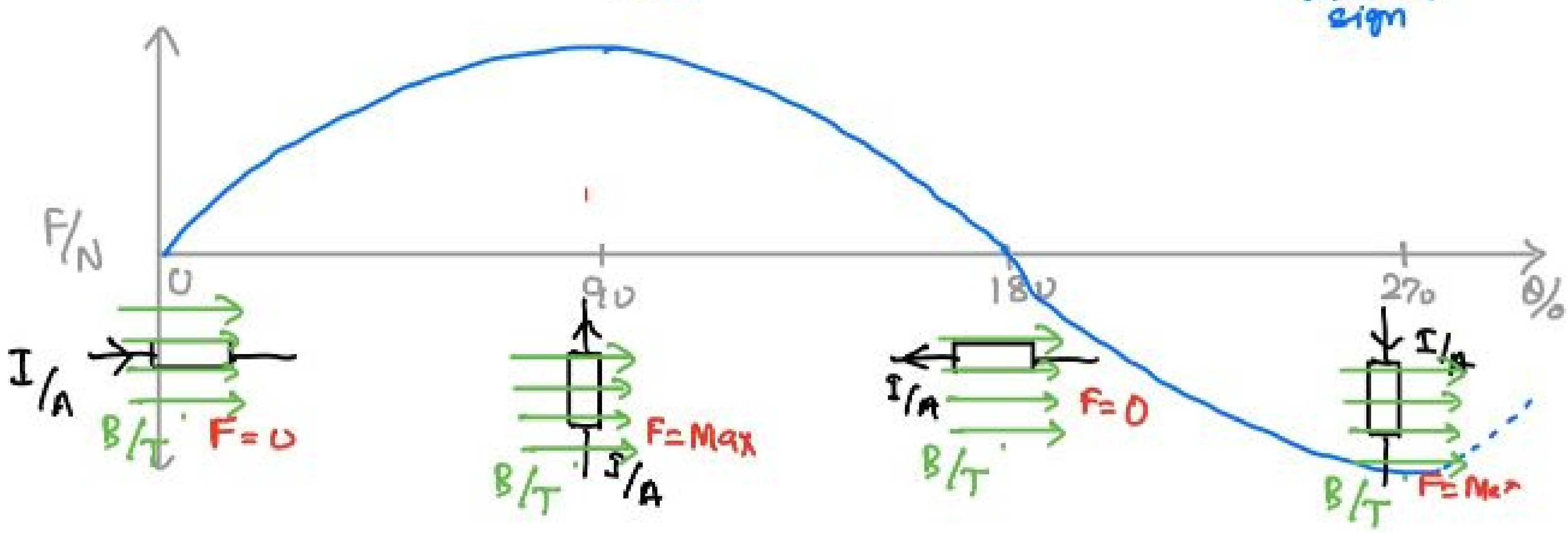
## Dependance:-




| θ/° | 0 | 30 | 60 | 90 |
|---|---|---|---|---|
| Sin(θ/°) | 0 | 0.5 | 0.866 | 1 |



## Direction of magnetic force:

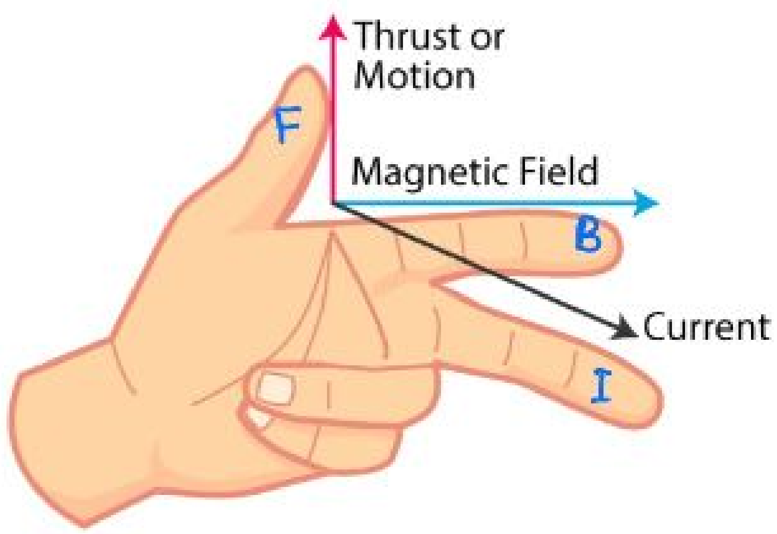
Obtained from Flemming's Left hand rule

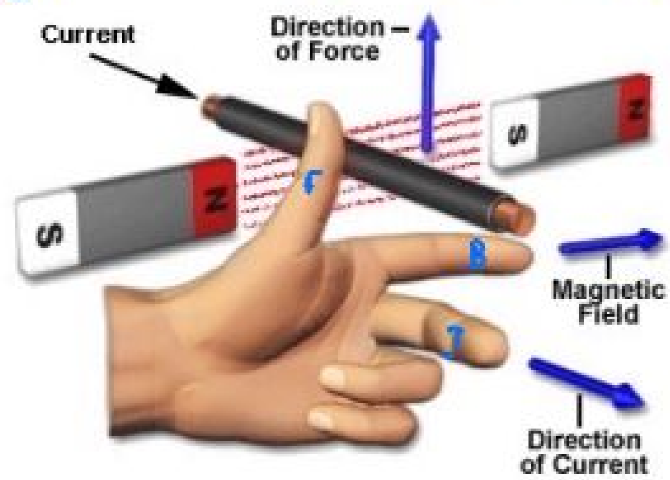
F — Force ⟶ Thumb

B — Magnetic flux density ⟶ 1st finger

I — Current ⟶ 2nd finger

All are mutually perpendicular to each other




## Magnetic flux density:

$$F = BIL\sin\theta$$

$$F = BIL\sin 90^\circ$$

$$B = \frac{F}{IL\sin 90^\circ}$$

**Definition:**

Magnetic flux density is equal to the force experienced per unit length of a conductor per unit current when placed perpendicular to magnetic field lines.

**P.S.** Vector

**Direction:** Towards the deflection of North pole of magnetic needle.

**Units:** Tesla (T)

**Def. of Tesla:-**

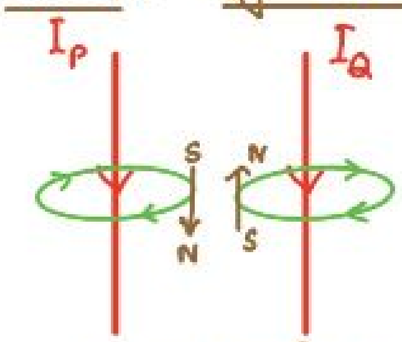
$$B = \frac{F}{IL \sin 90^\circ}$$

$$1T = \frac{1N}{(1A)(1m)\sin 90^\circ}$$

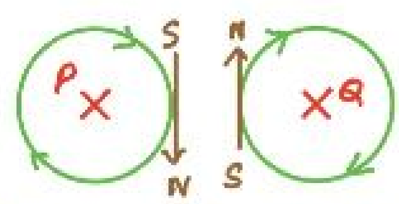
Magnetic flux density is 1 Tesla if a force of 1 Newton is experienced by 1 meter length of a conductor carrying 1 Ampere current when placed perpendicular to magnetic field lines.

## Force b/w two parallel current carrying straight conductors:

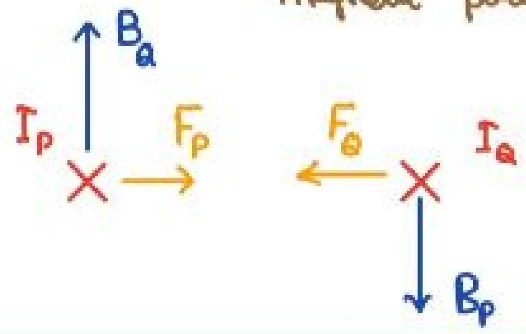
**Case 1: If direction of current is same:-**




Attractive force

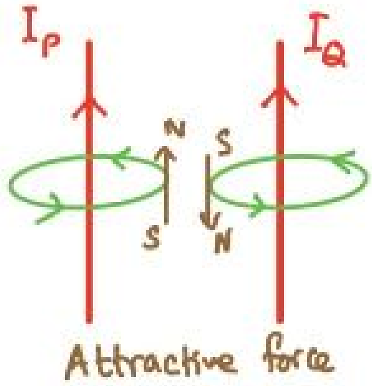



Attractive force exists as opposite magnetic poles are near each other

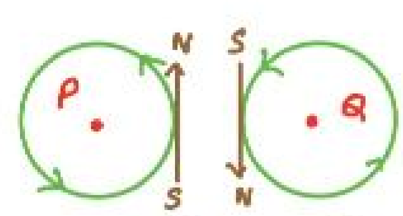



By Newton's Third law

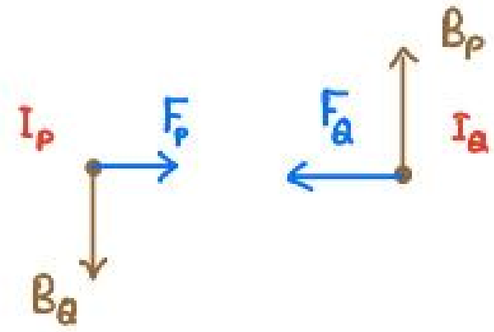
$F_P = -F_Q$




Attractive force

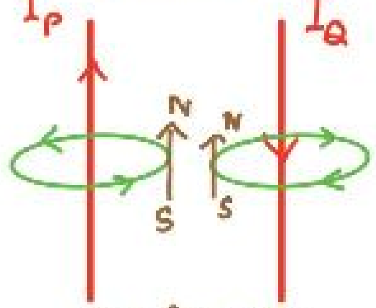



Attractive force exists as opposite magnetic poles are near each other

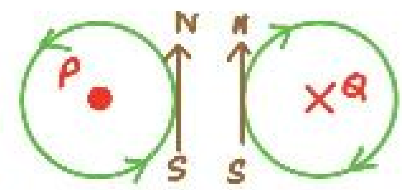



$F_P = -F_Q$ by Newton's third law.

## Case 2: If direction of current is in opposite directions




Repulsive force




Repulsive force exists as like magnetic poles are near each other


$F_P = -F_Q$

## Magnitude of magnetic force:-

Force on conductor P placed in the perp. magnetic field of Q.

$$F_P = B_Q I_P L_P \sin 90^\circ$$

$$F_P = B_Q I_P L_P$$

But $B = \dfrac{\mu_0 I}{2\pi x} \Rightarrow B_Q = \dfrac{\mu_0 I_Q}{2\pi x}$

$$F_P = \left(\frac{\mu_0 I_Q}{2\pi x}\right) I_P L_P \Rightarrow \frac{F_P}{L_P} = \left(\frac{\mu_0}{2\pi x}\right) I_P I_Q$$

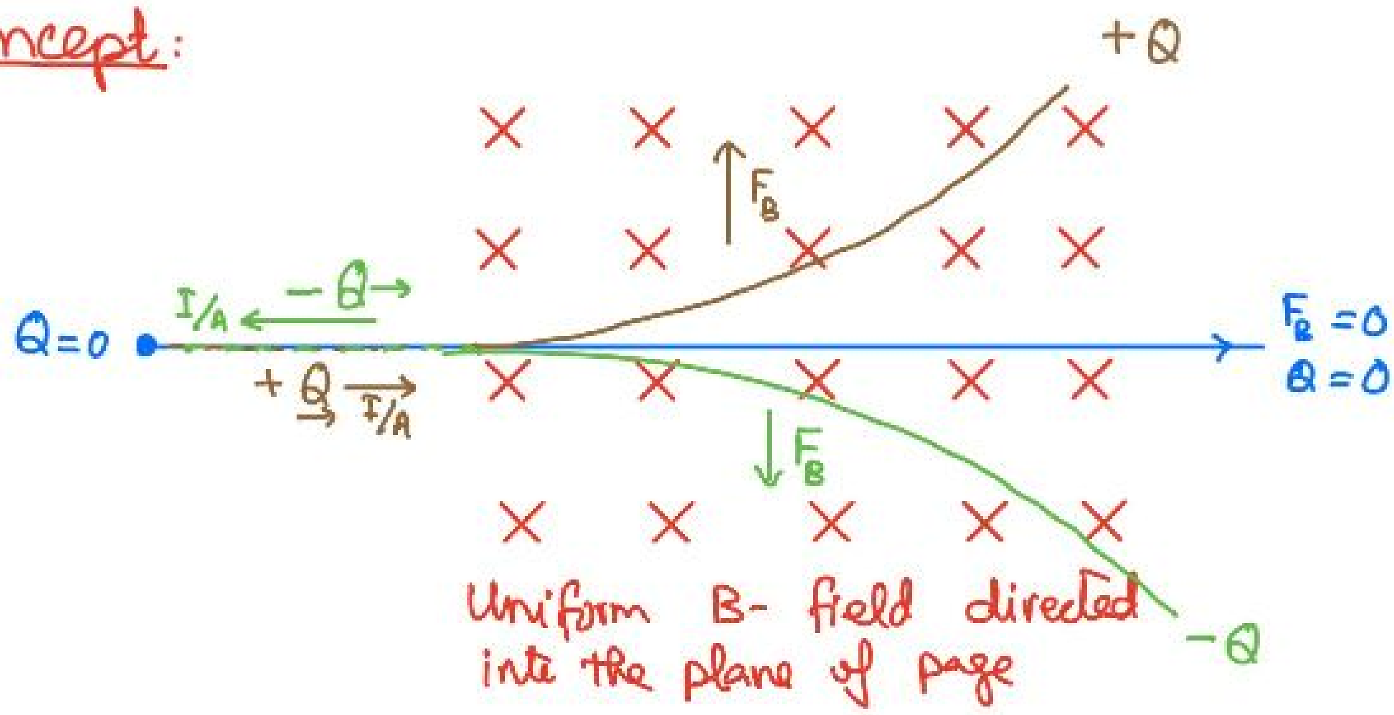
$$\frac{F_P}{L_P} = (\text{constant}) I_P I_Q \Rightarrow \frac{F_P}{L_P} \propto I_P I_Q$$

Force per unit length $\propto$ Product of current in parallel conductors.

Here '$x$' is the separation b/w parallel conductors.

# Force on a charged particle in a magnetic field:-

## Concept:




A moving charged particle in a magnetic field experience a force whose magnitude depends upon the following factors.

$F \propto B$ (Magnetic field strength/magnetic flux density)

$F \propto Q$ (Charge on particle)

$F \propto v$ (velocity of charged particle inside B-field)

$F \propto \sin\theta$ ($\theta$ - Angle b/w moving charged particle and B-field)

Combining above factors

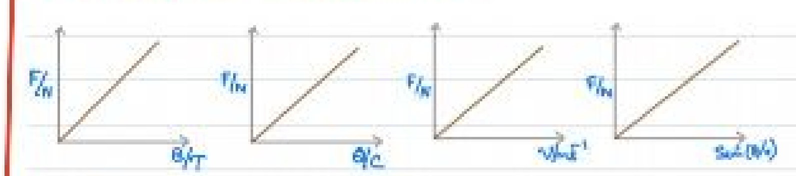
$$F \propto BQv\sin\theta$$

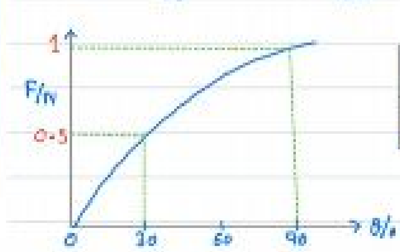
$$F = KBQv\sin\theta$$

Here $K = 1$ in S.I.

$$\boxed{F = BQv\sin\theta}$$

## Graphical dependance:



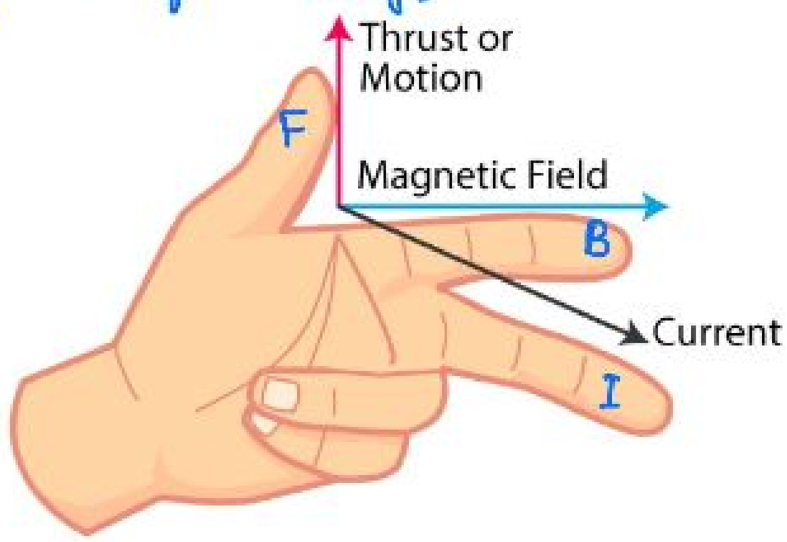

| θ/° | 0 | 30 | 60 | 90 |
|---|---|---|---|---|
| Sin(θ/°) | 0 | 0.5 | 0.866 | 1 |

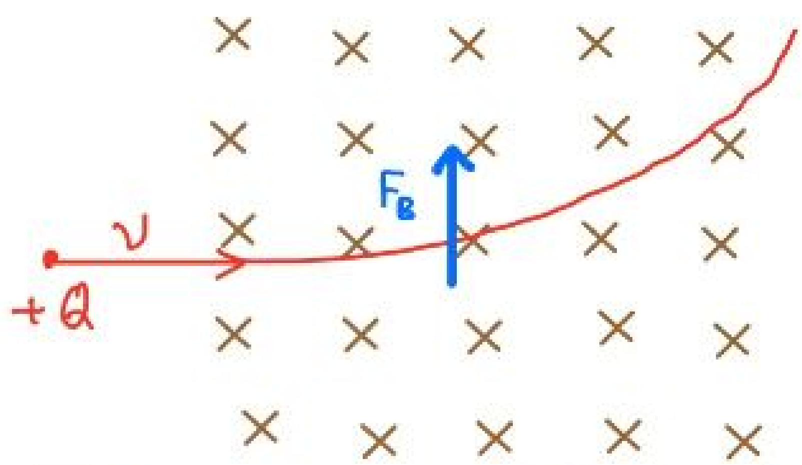
# Direction of magnetic force:

Obtained from Flemming's Left hand rule

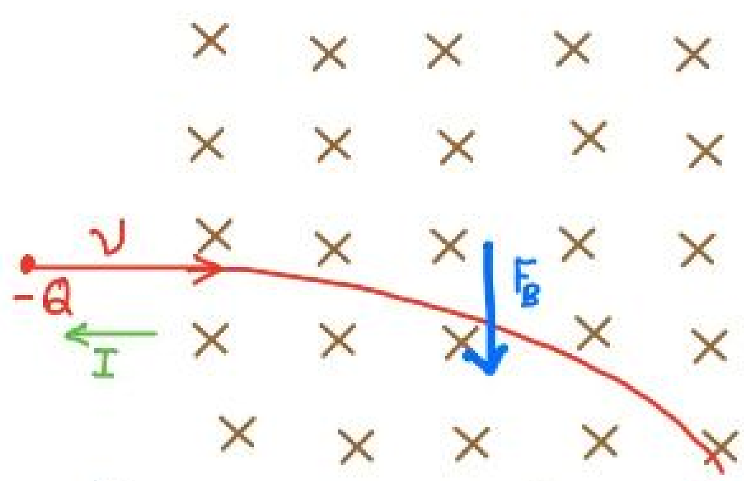
F — Force ⟶ Thumb
B — Magnetic flux density ⟶ $1^{st}$ finger
I — Current ie in the direction of motion of +ve charges ⟶ $2^{nd}$ finger

} All are mutually perpendicular to each other




Uniform Magnetic field directed into the plane of page




Uniform Magnetic field directed into the plane of page

## Radius of path traced by a charged particle in a perpendicular B-field:

Since a moving charged particle trace a curved path in a perpendicular magnetic field. So centripetal force acts on it. The origin of centripetal force is the magnetic force.

$$F_B = F_c$$

$$BQ\cancel{v}\sin 90^\circ = \frac{mv^{\cancel{2}}}{r} \Rightarrow BQ = \frac{mv}{r}$$

$$\boxed{r = \frac{mv}{BQ}}$$

But momentum ie $p = mv$

$$\boxed{r = \frac{P}{BQ}}$$

Q) Calculate the ratio of the radii of the paths traced by Alpha ($^4_2He$) and –ve Beta ($^0_{-1}\beta$) particles if both enter with same velocity in a perpendicular uniform magnetic field.

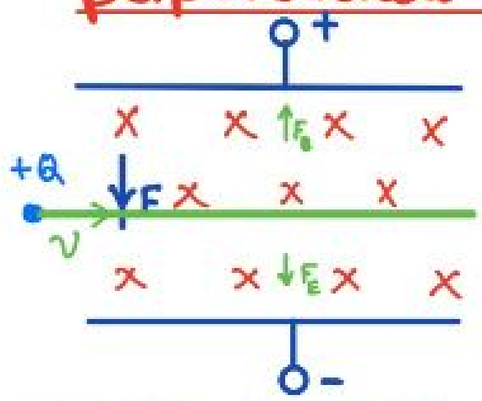
| | |
|---|---|
| elementary charge | $e = 1.60 \times 10^{-19}$ C |
| unified atomic mass unit | $1u = 1.66 \times 10^{-27}$ kg |
| rest mass of electron | $m_e = 9.11 \times 10^{-31}$ kg |

$$\frac{r_\alpha}{r_\beta} = \frac{\dfrac{m_\alpha \cancel{v}}{\cancel{B} Q_\alpha}}{\dfrac{m_\beta \cancel{v}}{\cancel{B} Q_\beta}} \Rightarrow \frac{r_\alpha}{r_\beta} = \left(\frac{m_\alpha}{Q_\alpha}\right)\left(\frac{Q_\beta}{m_\beta}\right)$$

$$\frac{r_\alpha}{r_\beta} = \left[\frac{4(1.66\times10^{-27})}{2(1.60\times10^{-19})}\right]\left[\frac{1.60\times10^{-19}}{9.11\times10^{-31}}\right]$$

$$\frac{r_\alpha}{r_\beta} = 3.64\times10^{3}$$

# Path of a charged particle in a mutually perpendicular E-field and B-field:-

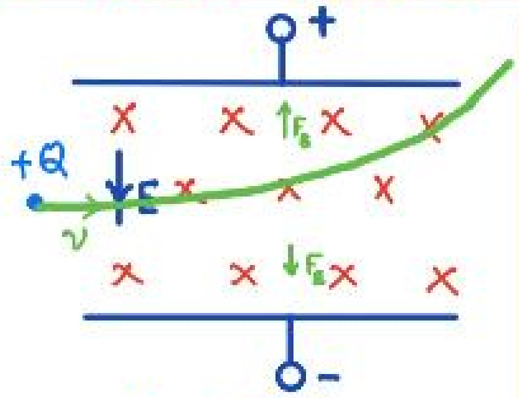



upward $F_B$ = Downward $F_E$

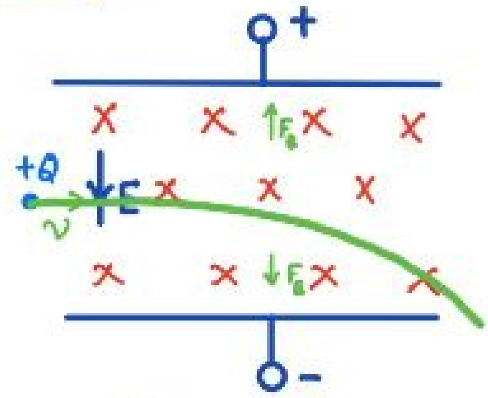
$$B\cancel{Q}v\sin 90 = E\cancel{Q}$$

$$Bv = E$$

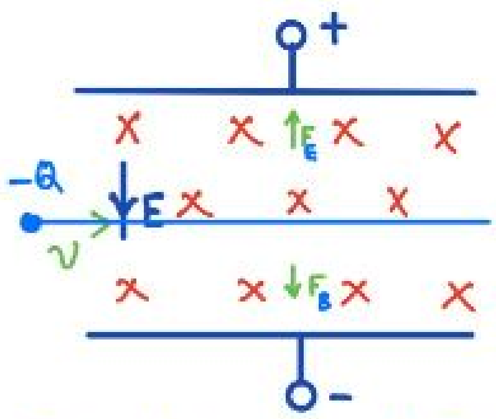
$$v = \frac{E}{B}$$




$F_B > F_E$




$F_E > F_B$

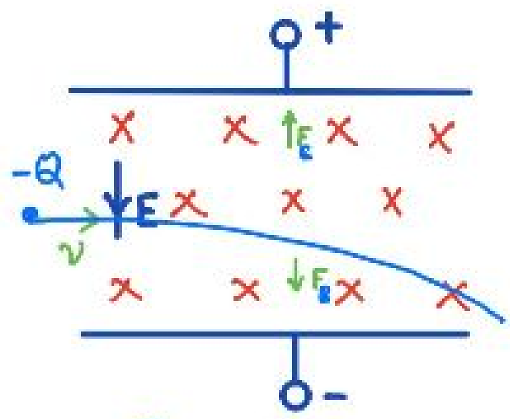



Downward $F_B$ = upward $F_E$

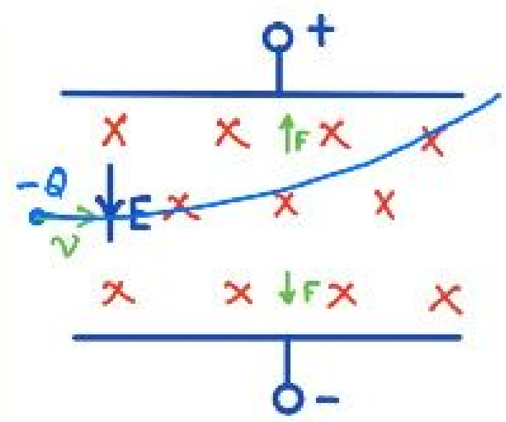
$$B\cancel{Q}v\sin 90 = E\cancel{Q}$$

$$Bv = E$$

$$v = \frac{E}{B}$$




$F_B > F_E$




$F_E > F_B$

## Specific charge:-

Def. Charge to mass ratio of a particle is specific charge.

Symbol: $\frac{Q}{m}$

Expression:

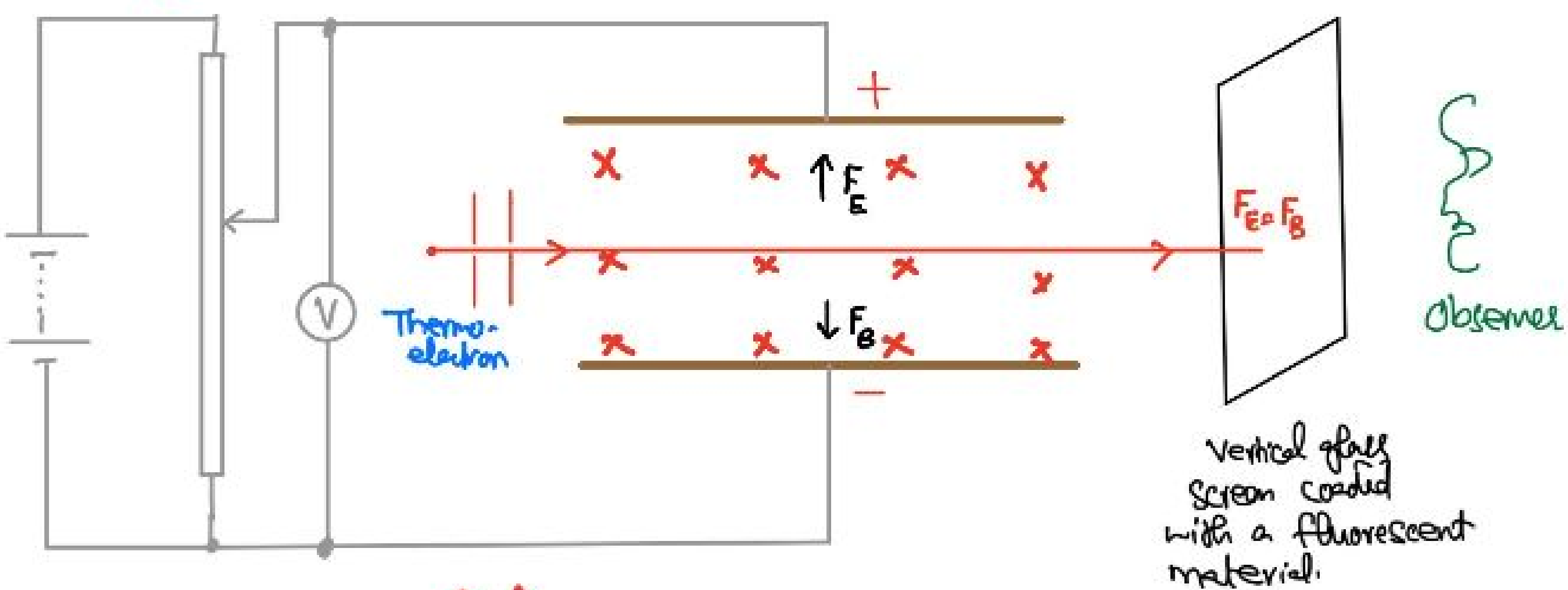
$$F_B = F_c$$

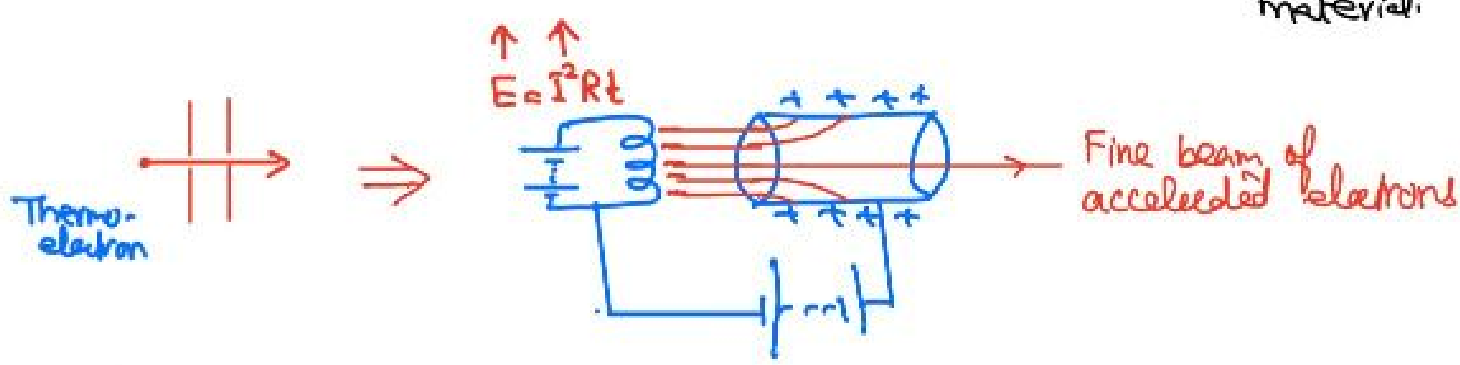
$$BQ\cancel{v}\sin 90 = \frac{mv^{\cancel{2}}}{r}$$

$$BQ = \frac{mv}{r} \Rightarrow \boxed{\frac{Q}{m} = \frac{v}{Br}}$$

**Note:** $\left(\frac{Q}{m}\right)$ is used to identify the nucleus/particle ie if $\left(\frac{Q}{m}\right) = \frac{1}{2}$, so particle is a Helium nucleus or an Alpha particle.

## Determination of velocity of a charged particle by selection method:-




**Procedure:** Adjust the sliding contact of potential divider to vary p.d across parallel plates so that upward electric force can be varied and locate a position where fast moving electron continue its motion in a straight line path in a mutually perpendicular E/Vm⁻¹ and B/T field.

**Analysis:** In equilibrium state

Upward $F_E$ = Downward $F_B$

$$\frac{V\cancel{q}}{d} = B\cancel{q}v\sin 90^\circ$$

$$v = \left(\frac{V}{d}\right)\left(\frac{1}{B}\right)$$

But Uniform E-field, $E = \frac{V}{d}$

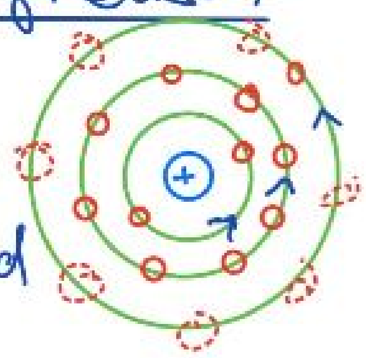
$$\boxed{v = \frac{E}{B}}$$

**Result:** Ratio of Electric to magnetic field strength defines velocity.

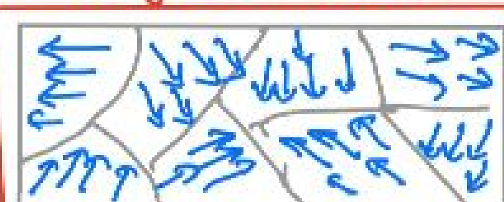
## Types of materials in magnetism.

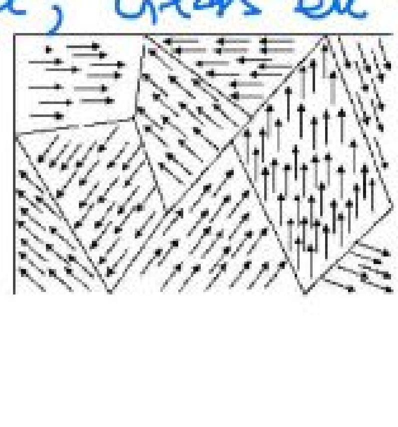
**Tiny magnet / Atomic magnet:**

Magnetic effect of an atom due to motion of electrons around the nucleus



N ⟵ S

| Non-magnetic material | magnetic material | magnet |
| --- | --- | --- |
|  |  |  |
| Alignment of tiny magnets in a domain/sector is random ie Copper, Aluminium, Gold, Silver, Wood, Plastic, Glass etc. | Alignment of tiny magnets in a domain/sector is same but is random in adjacent sectors. e.g Iron, Nickel, Cobalt, Steel and their alloys. | Alignment of tiny magnets in every domain is same. |

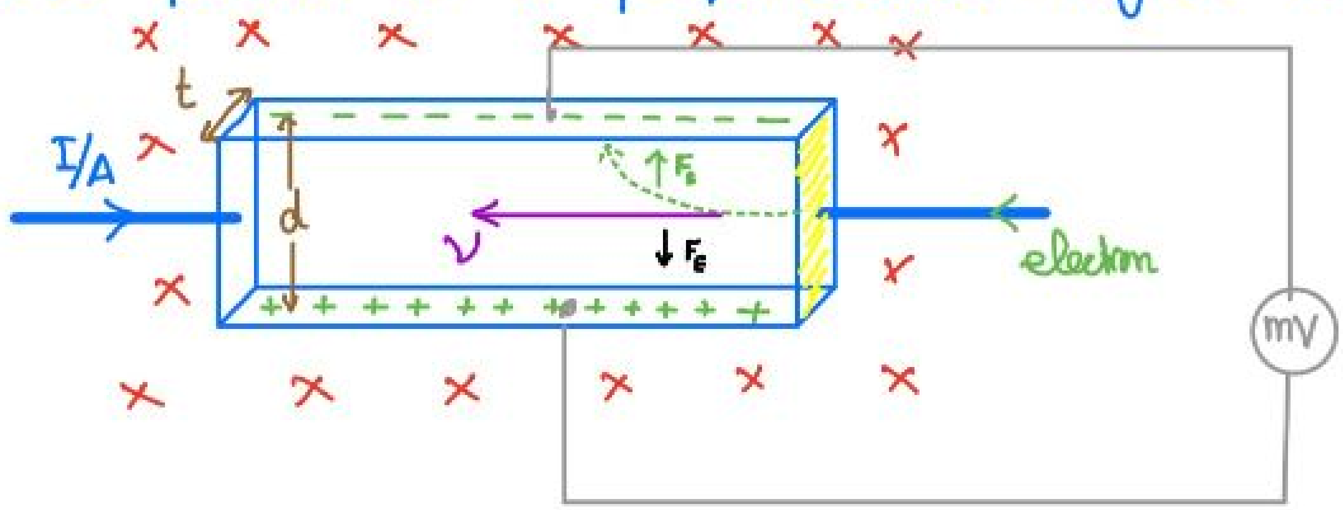


## Force on a particle in G, E and B-field:-

| S.No. | Property | G-field | E-field | B-field |
|---|---|---|---|---|
| 1. | Source | Masses of particles / objects | Charges on particle | Permanent magnet or current carrying conductor. |
| 2. | Formula | $F_G = G\frac{m_1 m_2}{r^2}$ | $F_E = \frac{1}{4\pi\varepsilon_0}\left(\frac{Q_1 Q_2}{r^2}\right)$ | $F_B = BQv\sin\theta$ |
| 3. | Dependance of Force | $F_G \neq 0$ if masses are at rest | $F_E \neq 0$ if charges are at rest | $F_B = 0$ if a charge particle is at rest ($v=0$) |
| 4. | Direction of Force | Towards centre of massive object ie towards field lines | Parallel to field lines | Perpendicular to field lines |
| 5. | Dependancy on medium | independent of medium between two masses. | Dependent on medium between two charges i.e $\varepsilon_0$ - permittivity of free space $\varepsilon_0 = 8.85\times10^{-12}\ Fm^{-1}$ | Dependent on medium b/w two magnets ie permeability of free space $\mu_0 = 4\pi\times10^{-7}\ Hm^{-1}$ |
| 6. | Nature of force | Attractive force | Either attractive or repulsive | Either attractive or repulsive |

## Hall effect:

**Statement:** The phenomena in which a transverse p.d/voltage is developed across a current carrying conductor placed in a perpendicular magnetic field.



## Analysis:-

1- Electrons always move from low to high potential against the direction of current. So electrons entering from right side in a horizontal conductor placed in a perpendicular magnetic field directed into the plane of page experience an upwards magnetic force and accumulate at the upper side of conductor as shown.

$$F_B = B q v \sin 90^\circ$$
$$F_B = B q v \quad \text{-----} \ (1)$$

(2) The -ve charge at upper side induces equal and opposite charge at lower side of conductor. So new incoming electrons also

experience a downward electric force.

$$F_E = \frac{Vq}{d} \quad \text{--------} \ (2)$$

(3) A stage will come when upward magnetic force becomes equal to downward electric force and new incoming electrons/charge carriers continue their motion in a straight line path with uniform velocity.

In equilibrium state,

$$\text{Upward } F_B = \text{Downward } F_E$$

$$B\cancel{q}v = \frac{V\cancel{q}}{d}$$

$$V = Bvd$$

$$\text{or} \quad \boxed{V_H = Bvd}$$

But drift velocity, $v = \dfrac{I}{nqA}$

$$V_H = B\left(\frac{I}{nqA}\right)d$$

$$V_H = \frac{BI\cancel{d}}{nq(t\cancel{d})}$$

$$\boxed{V_H = \frac{BI}{nqt}}$$

## Hall probe:-

Def. Instrument which is used to measure magnetic flux density of a magnet by relative comparison method.

Principle:- Hall effect

Construction:

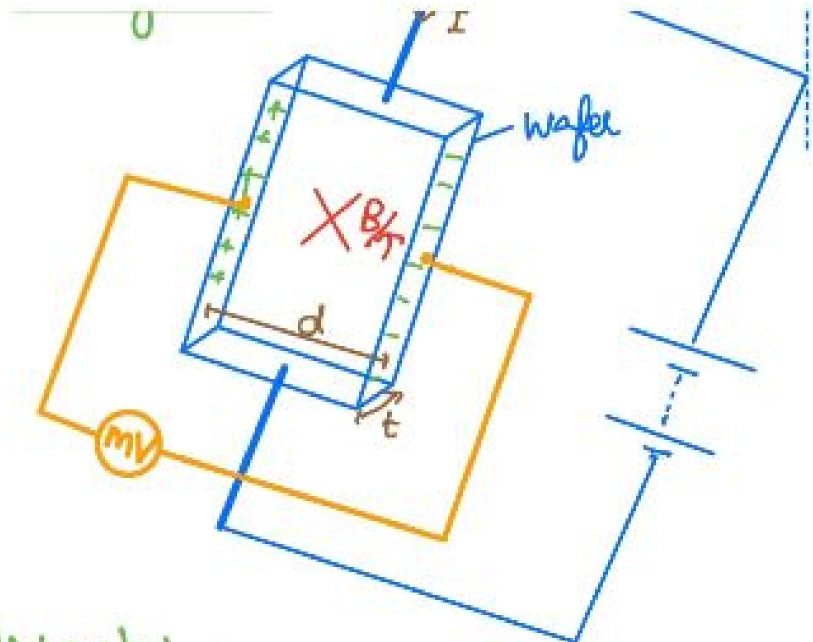
(i) Semi-conductor wafer

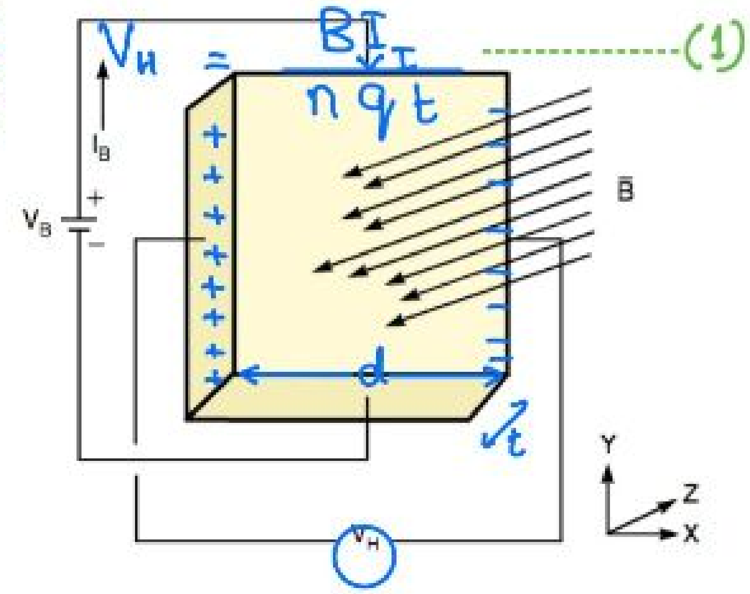
(ii) Connecting wires

(iii) DC source

(iv) Milli-voltmeter to measure Hall p.d.

Diagram:-




## Working:-

**Step 1:** Place the Hall probe wafer at a distance $x$ in front of a magnet perpendicularly whose magnetic flux density is to be determined and measure the Hall voltage / p.d. developed.

$$V_H = Bvd \quad \text{-------------- (1)}$$

$$V_H = \frac{BI}{nqt} \quad \text{--------- (1)}$$

**Step 2:** Now again place the Hall probe wafer perpendicularly at the same defined distance $x$ infront of another magnet whose magnetic flux density is already known to us and measure its new Hall voltage ($V_H'$).

$$V_H' = B'vd \quad \text{-------------- (2)}$$

$$V_H' = \frac{B'I}{nqt} \quad \text{--------- (2)}$$

**Step 3:** Divide (1) by (2)

$$\frac{V_H}{V_H'} = \frac{B\cancel{vd}}{B'\cancel{vd}}$$

$$\frac{V_H}{V_H'} = \frac{\frac{B\cancel{I}}{\cancel{nqt}}}{\frac{B'\cancel{I}}{\cancel{nqt}}}$$

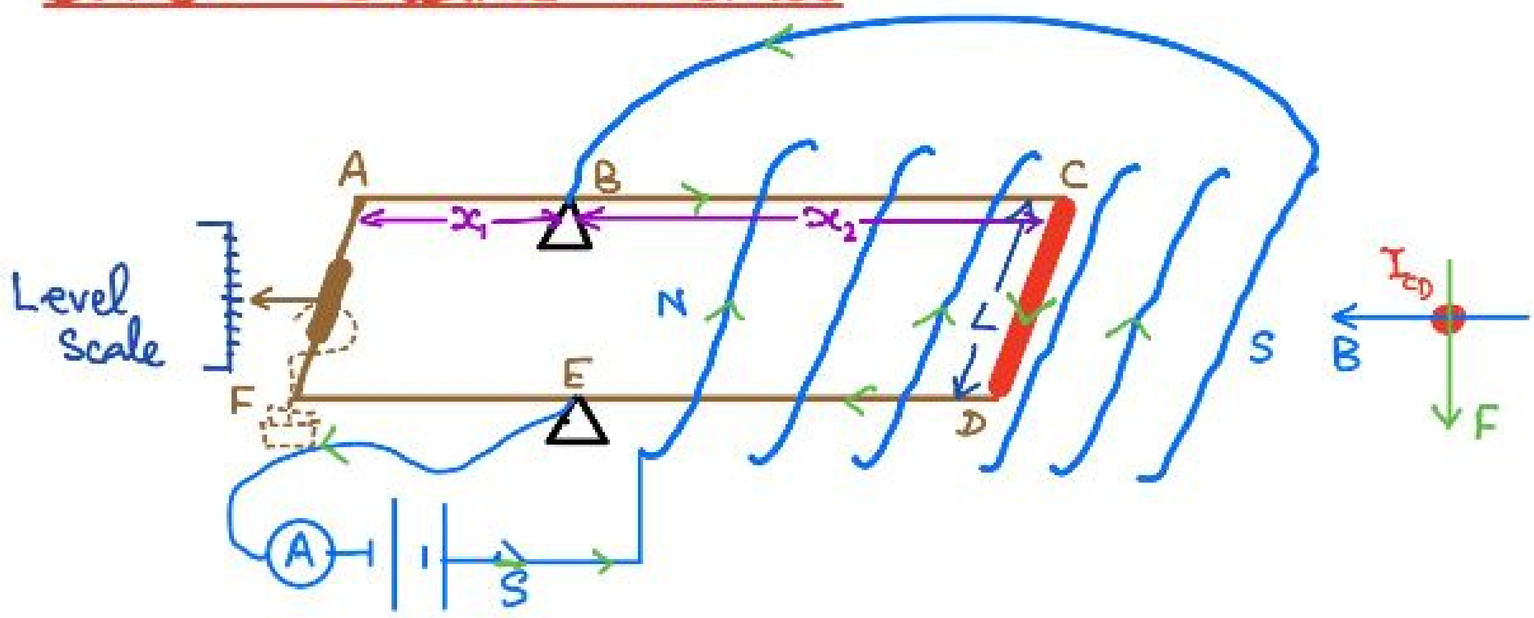
$$\frac{V_H}{V_H'} = \frac{B}{B'}$$

$$\boxed{B = \left(\frac{V_H}{V_H'}\right) B'}$$

Here $V_H$ - Hall p.d. for unknown magnetic field ($B$)

$V_H'$ - Hall voltage for known magnetic field ($B'$)

## Determination of magnetic flux density by current balance method:-




* ABCDEF assembly is in horizontal plane pivoted on wedges B and E.
* BAFE is insulating and BCDE is conducting path
* CD is the length of conductor perpendicular to magnetic field and direction of current is from C to D ie out of the plane of page.

## Analysis:-

1- Current carrying conductor CD experience force in downward direction which causes moment about pivots B and E.

$$C.W.M = (F_B)(x_2)$$
$$= (BIL \sin 90°)(x_2)$$
$$C.W.M = BILx_2 \quad \text{------------------------------} \quad (1)$$

2- To bring assembly in horizontal equilibrium, standard masses are hung near the pointer AF which causes anti-clockwise moment due to weight of suspended masses.

$$A.C.W.M = (W)(x_1)$$
$$= mgx_1 \quad \text{------------------------------} \quad (2)$$

3- In horizontal equilibrium state,

$$C.W.M = A.C.W.M$$
$$BIL\,x_2 = mg\,x_1$$
$$\boxed{B = \frac{mg\,x_1}{IL\,x_2}}$$

Here m - Mass of suspended slotted masses

$x_1, x_2$ - Distance from pivots measured by tail of vernier Caliper or metre rule

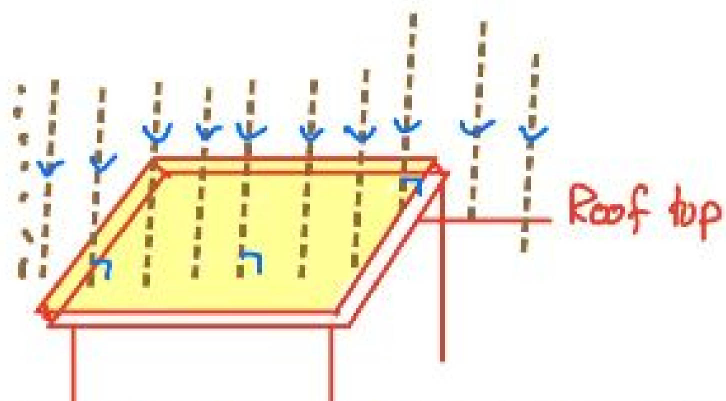
I - current in conductor measured by Ammeter

L - Length of conductor CD inside magnetic field.

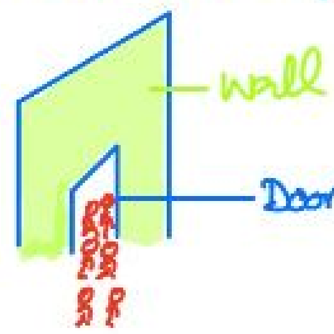
# ELECTROMAGNETIC INDUCTION:-

## Flux:

**Concept:**



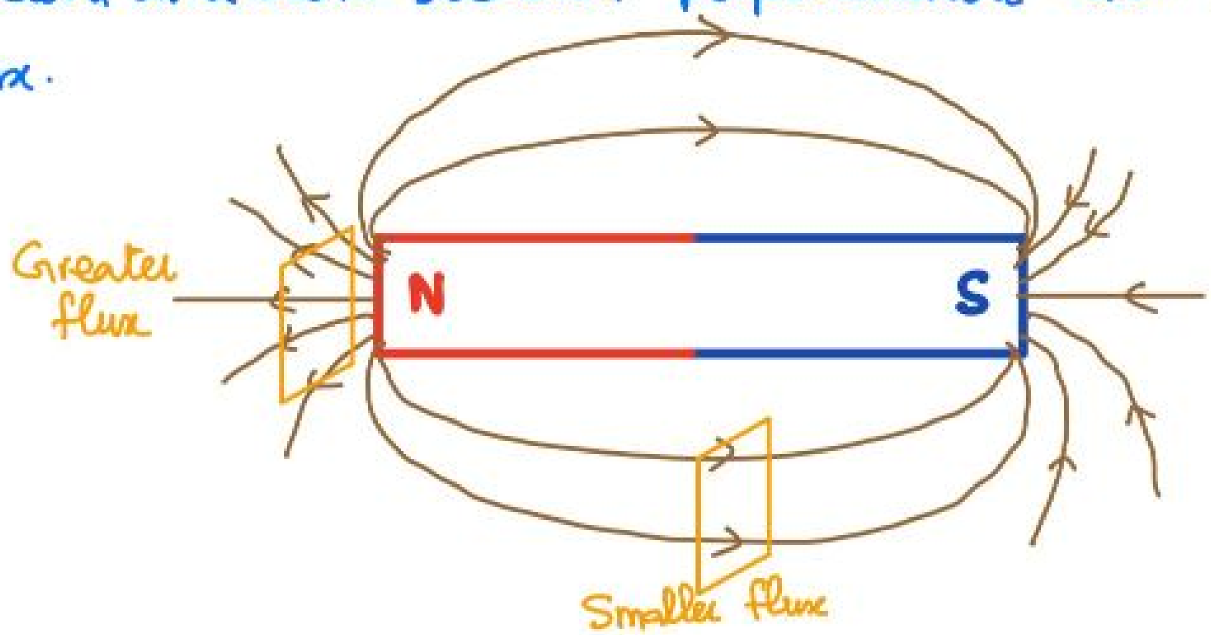

No. of rain droplet incident at perpendicular area of roof-top is rain flux




No. of students passing through perpendicular area of door in a wall is students' flux.

## Magnetic flux:-

**Concept:** No. of magnetic lines of force passing through/incident at a cross-sectional perpendicular area is magnetic flux.

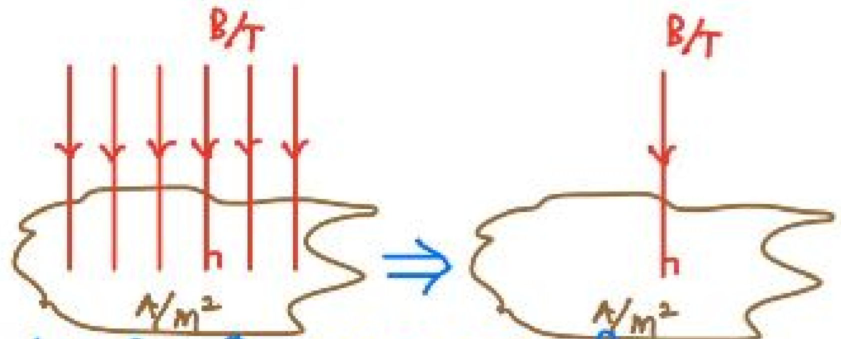



**Def.** Product of magnetic flux density and cross-sectional area perpendicular to magnetic field lines is magnetic flux.

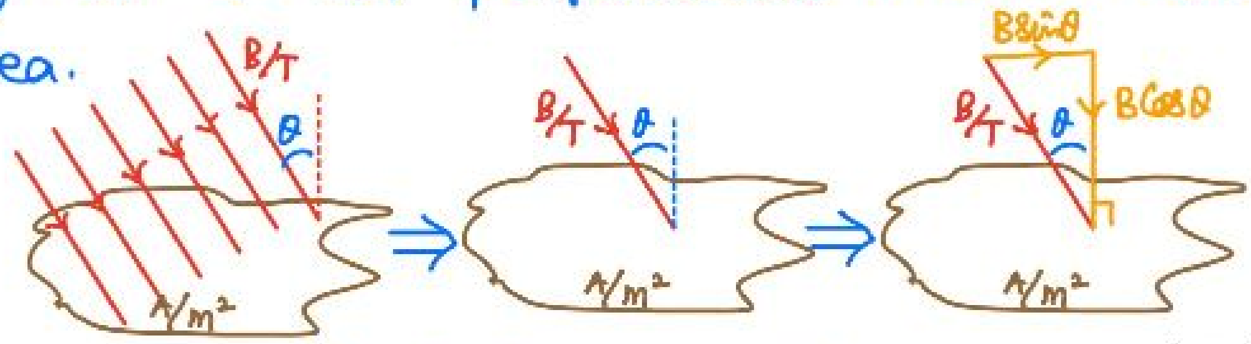
Symbol: $\phi$

Formula.

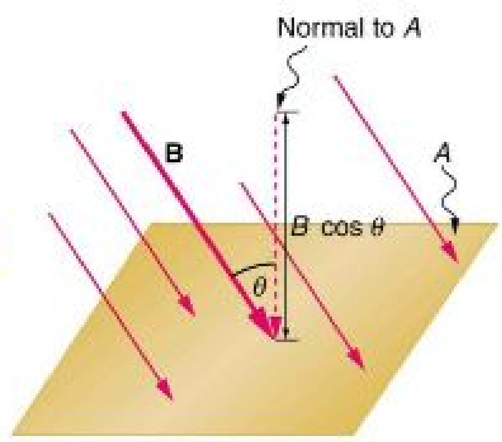
(i) $\boxed{\phi = (B)(A)}$




(ii) If B/T is not perpendicular to cross-sectional area.




$\phi = \begin{pmatrix}\text{Component of B/T} \\ \text{perpendicular to} \\ \text{area}\end{pmatrix}\begin{pmatrix}\text{Perpendicular} \\ \text{cross-sectional} \\ \text{Area}\end{pmatrix}$




$\phi = (B\cos\theta)(A) \Rightarrow \boxed{\phi = BA\cos\theta}$

P.S. Scalar

Units Weber (Wb)

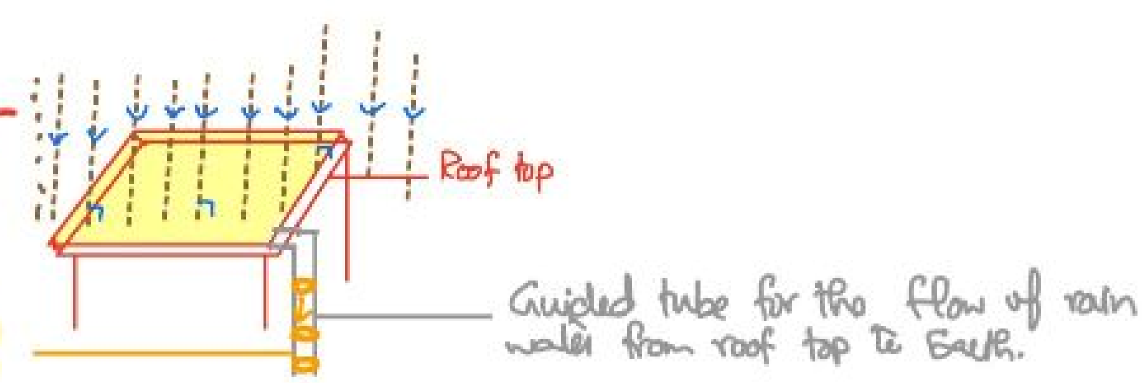
Definition of Weber (Wb): $\phi = (B)(A)$

$1 \text{ Weber} = (1 \text{ Tesla})(1 \text{ metre}^2)$

If a magnetic flux density of 1 Tesla is incident at 1 metre$^2$ perpendicular cross-sectional Area, then magnetic flux is 1 Weber.

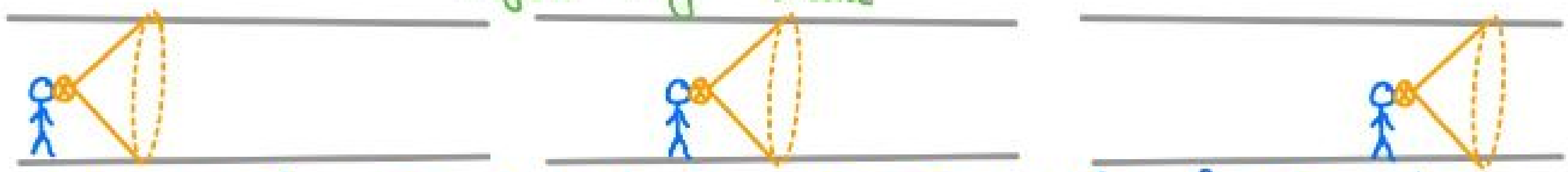
Flux linkage:-

Concept:

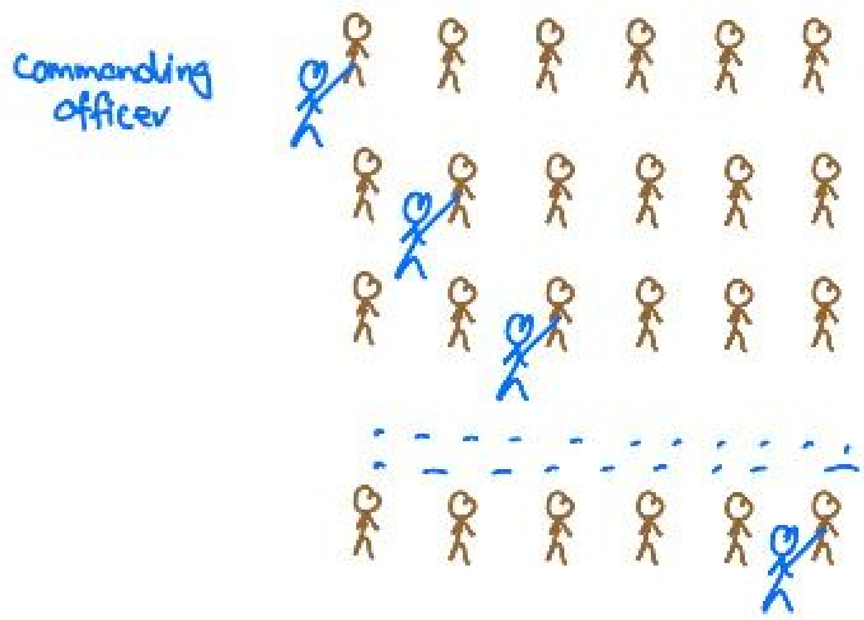



Rain water flux linkage with wall of guided tube.

## Light ray flux



Light ray flux is linked up with the walls of mine due to motion of a person inside it.




Commanding officer shake hand with soldiers one at a time with the soldiers.
So commanding officer linked up with soldiers.

## Magnetic flux linkage:-

**Def.** Product of magnetic flux density, perpendicular area and no. of turns of coil.

**Symbol:** $\phi$

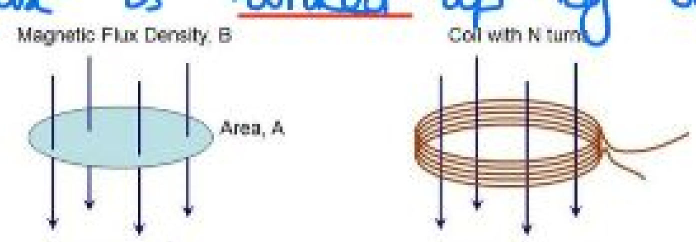
**Formula:** $\phi = NBA$ ,
N - No. of turns of coil
B - Magnetic flux density
A - cross-sectional area of coil

**Units:** turn weber (turn Wb) or weber (Wb)

**Note:**

(1) Magnetic flux is cut by a rod / sheet

(2) Magnetic flux is linked up by a coil.



## Faraday's Law of electromagnetic induction:-

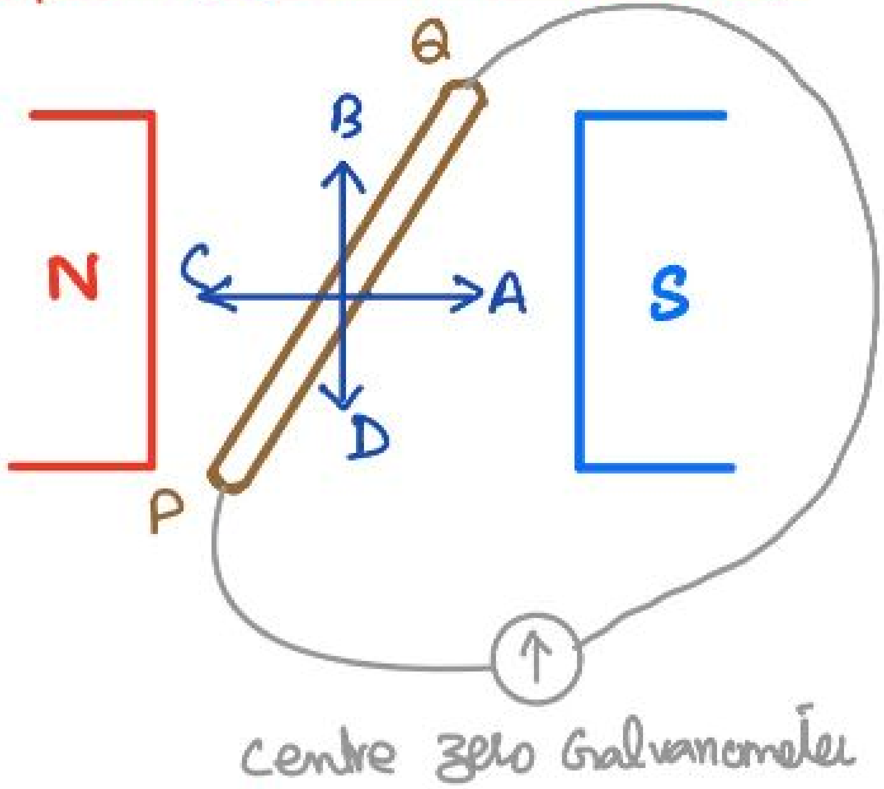
**Statement:** Rate of change of magnetic flux cutting or linkage is directly proportional to the e.m.f. induced.

**Mathematical form:** $e.m.f \propto -\dfrac{\Delta \phi}{\Delta t}$

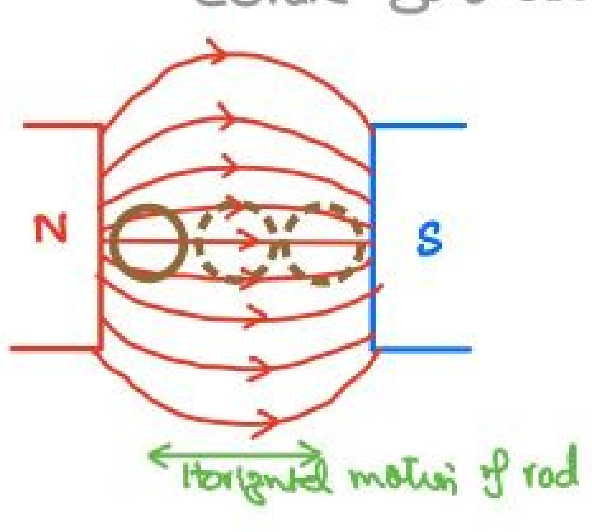
$-ve$ sign is due to Lenz's law

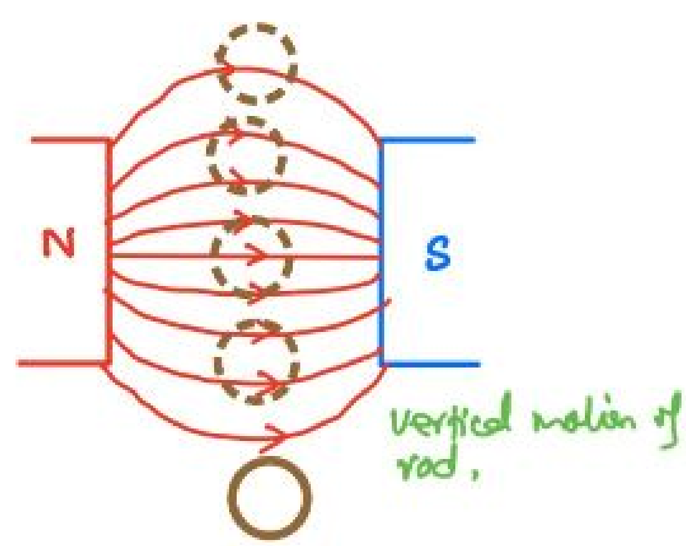
| For a rod | For a coil |
|---|---|
| $\phi = BA$ | $\phi = NBA$ |
| $e.m.f \propto -\dfrac{\Delta(BA)}{\Delta t}$ | $e.m.f \propto -\dfrac{\Delta(NBA)}{\Delta t}$ |

### Experiment 1: For a rod:-

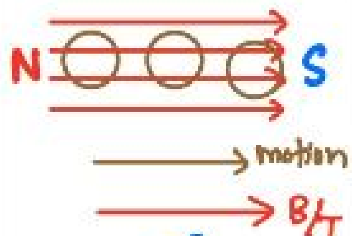
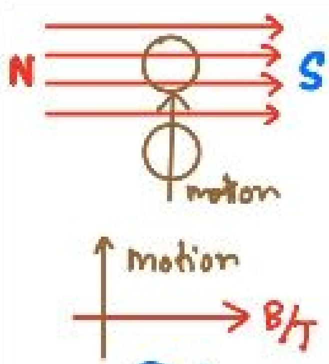
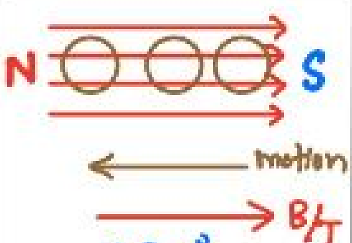
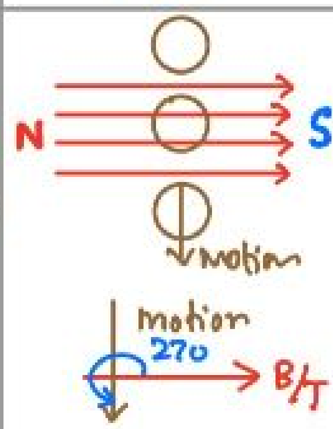



Rod PQ is in horizontal plane and its length/axis is perpendicular to magnetic field lines.



## Observational Analysis:

| S.No | Motion of rod | Angle b/w motion and B-field lines | e.m.f induced | Reason | Direction of induced current by F.R.H.Rule |
|---|---|---|---|---|---|
| | Towards A |   0° | No | Flux is cut by the rod but does not change per unit time to induce e.m.f. | — |
| 2. | Towards B |   90° | Yes | Change of magnetic flux cutting per unit time induces e.m.f. | P to Q |
| 3 | Towards C |   180° | No | Flux is cut by the rod but does not change per unit time to induce e.m.f. | — |
| 4. | Towards D |   270° or -90° | Yes | Change of magnetic flux cutting per unit time induces e.m.f | From Q to P |

**Result:** e.m.f is only induced in rod if there is a rate of change of magnetic flux cutting.

**Dependance:** Magnitude of induced e.m.f. and hence induced current increases if

(i) B ↑ ie stronger magnet is used or decrease separation between opposite poles of magnets

(ii) A ↑ ie diameter or cross-sectional Area of rod increases.

(iii) (time) ↓ i.e speed of motion of rod perpendicular to magnetic field lines increases. (Same distance is now travelled in less time to increase speed)

$$E \propto -\frac{\Delta(\overset{\uparrow}{B}A)}{\Delta t}$$

or

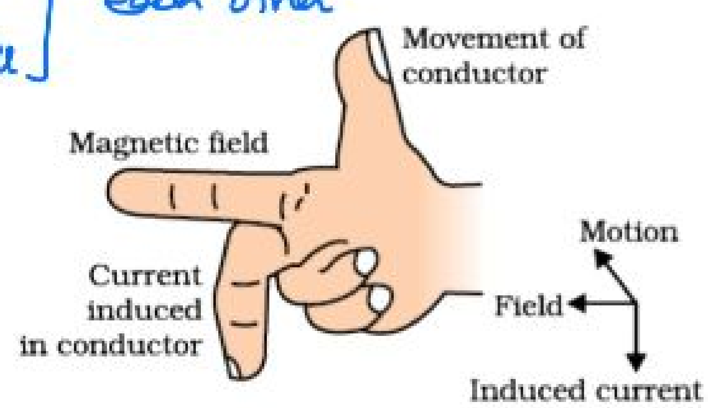
$$E \propto \frac{\Delta(BA)}{\underset{\downarrow}{\Delta t}}$$

$$\overset{\uparrow}{\text{Speed}} = \frac{\text{Distance}}{\text{time}\downarrow}$$

**Direction of Induced current:-** obtained from Flemming's <u>Right</u> Hand Rule.

F : Force (motion) ⟶ Thumb
B : Magnetic flux density ⟶ $1^{st}$ finger
I : Current induced ⟶ $2^{nd}$ finger

All are mutually perpendicular to each other

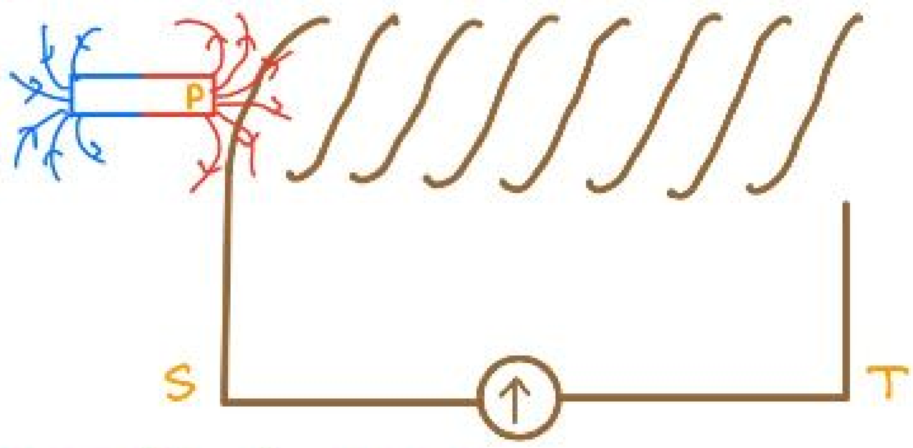


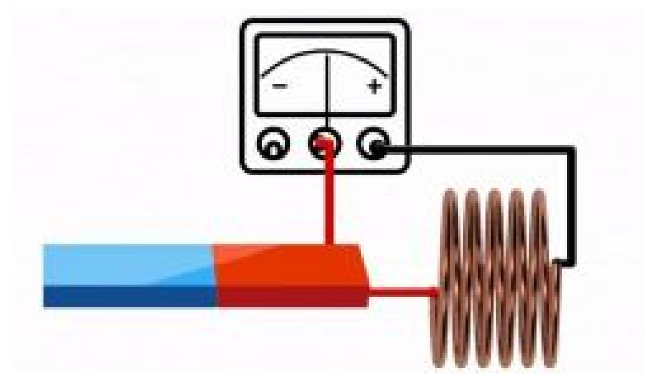

**Note:** We use Flemming's

(1) Left hand rule if current produces motion (Motor rule)

(1) Right hand rule if motion induces current (Generator rule)

## Experiment 2: For a coil:




## Observational Analysis:

| S.No | Pole of magnet at P | Motion of magnet | Current detected by Galvanometer | Reason | Direction of current in ST | Reason |
|---|---|---|---|---|---|---|
| 1. | North | into the coil | Yes | Change of magnetic flux linkage per unit time induces e.m.f by Faraday's Law | T to S | Lenz's Law and Right Hand curl rule |
| 2. | // | Stationary inside the coil | No | Flux is linked up with coil but does not change per unit time to induce e.m.f. | — | // |
| 3. | // | Out of the coil | Yes | Same as in S.No. 1 | S to T | // |
| 4. | South | Into the coil | // | // | S to T | // |
| 5. | // | Stationary inside the coil | No | Same as in S.No.2 | — | // |
| 6. | // | Out of the coil | Yes | Same as in S.No.1 | T to S | // |

**Result:** e.m.f is only induced in coil if there is a rate of change of magnetic flux linkage due to motion of magnet relative to coil.

## Magnitude of induced e.m.f and hence current:

(e.m.f) ↑ if

(i) a stronger magnet is used (B ↑)

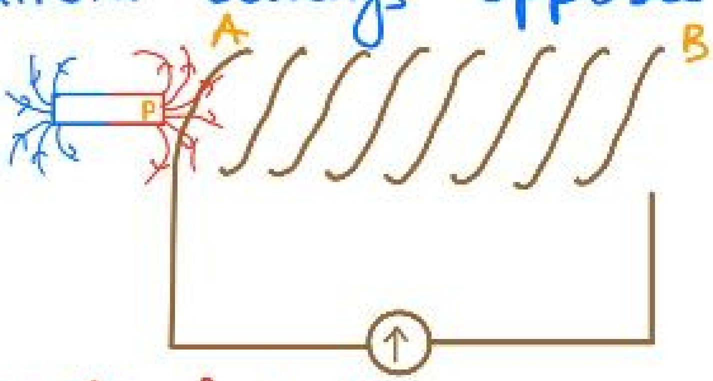
(ii) no. of turns of coil increases (N ↑)

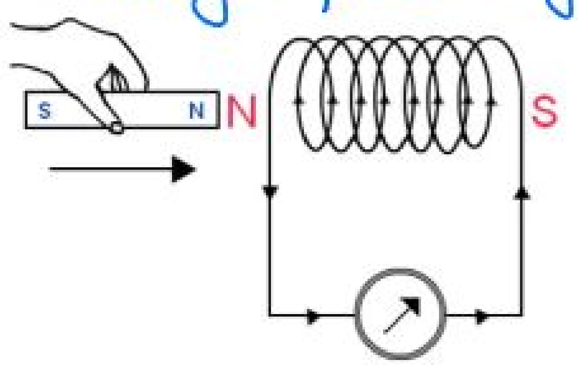
(iii) Speed of motion of magnet relative to coil increases.

**Direction of induced current:** obtained by using Lenz's law and Right hand Coil/Solenoid rule.

## Lenz's Law:-

**Statement:** The magnetic effect of induced current always opposes the change producing it.



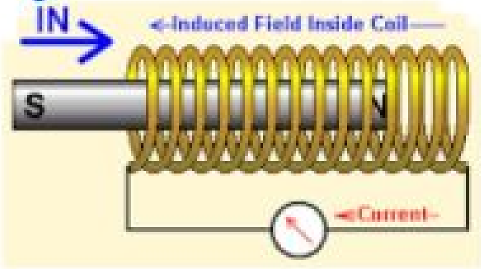



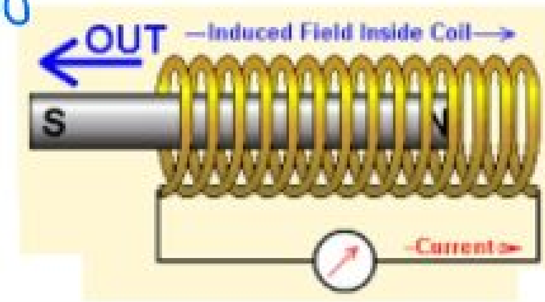

**Observational Analysis:**

| S.No | Pole of magnet at P | Motion of magnet | Current detected by Galvanometer | Pole induced at end A | Pole induced at end B | Reason |
|---|---|---|---|---|---|---|
| 1. | North | into the coil | Yes | North | South | Repulsive force opposes the motion of magnet into the coil |
| 2. | North | Out of the coil | Yes | South | North | Attractive force opposes the motion of magnet out of the coil |
| 3. | South | into the coil | Yes | South | North | Same as in S.No. 1 |
| 4. | South | out of the coil | Yes | North | South | Same as in S.No. 2 |

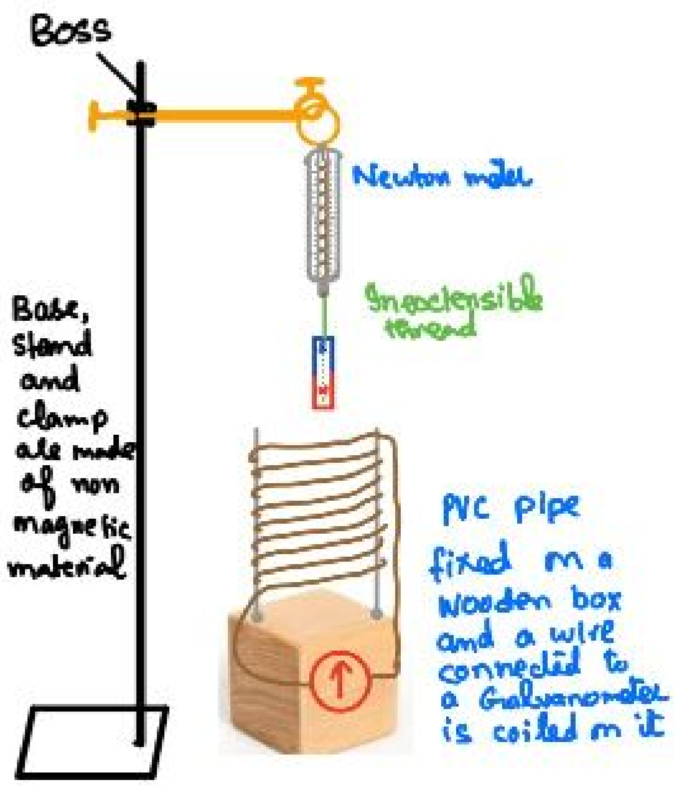
**Note:**

Lenz's Law is based upon the principle of conservation of energy.



# Experimental verification of Lenz's Law:-




## Observational Analysis:

| S.No. | Motion of the coil | Reading on Galvanometer | Reading of Newton-meter | Result |
|---|---|---|---|---|
| 1. | Rest | Zero | 10N | upward restoring force on spring balances downward weight of magnet ie. $F_s = W = 10N$ |
| 2. | Move coil upward so that magnet can enter into it from its top side | Deflects to one side | Decreases | Apart from force on spring, an upward magnetic force also act on magnet |
| 3. | Rest and magnet is inside the coil | Zero | 10N | $F_{spring}$ = Weight = 10N |
| 4. | Move coil downward so that magnet comes out from its top side | Deflects to opposite side of S.No. 2 | Increases | Downward magnetic force now develops as per Lenz's law apart from weight |

**Conclusion:** The variation in the Newton meter readings signifies that an opposing force is developed due to magnetic effect of induced current.

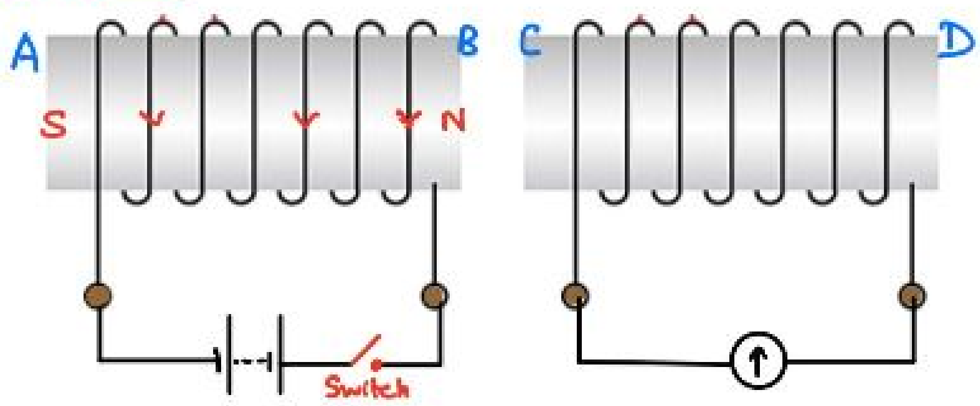
## Mutual Induction:-

**Meaning:** The e.m.f. induced in the secondary coil due to varying current in the primary coil is mutual induction.

**Primary coil:** Coil connected to an e.m.f. source is the primary coil.

**Secondary coil:** Coil in which e.m.f and hence current is induced is secondary coil.

## Experiment - 1:




## Observational Analysis:-

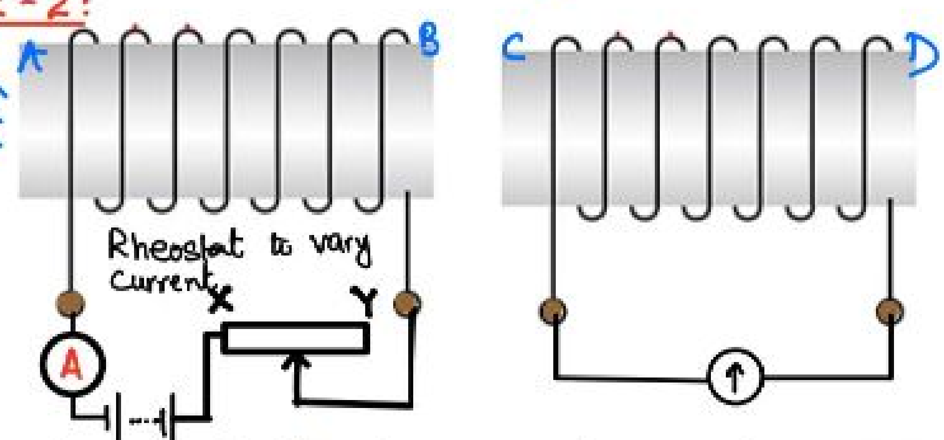
| S.No. | Switch | Poles produced at A | Poles produced at B | Deflection of Galvanometer | Reason | Poles induced at C | Poles induced at D | Reason | Direction of Galvanometer |
|---|---|---|---|---|---|---|---|---|---|
| 1. | open | — | — | No | $\frac{\Delta\phi}{\Delta t}=0$ | — | — | — | — |
| 2. | Instantly closed | South | North | Yes | $\frac{\Delta\phi}{\Delta t}\neq 0$ | North | South | Lenz's Law | Towards left |
| 3. | Remain closed | South | North | No | $\frac{\Delta\phi}{\Delta t}=0$ | — | — | — | — |
| 4. | Instantly opened | South but about to cease | North | Yes | $\frac{\Delta\phi}{\Delta t}\neq 0$ | South | North | Lenz's Law | Towards right |

**Result**: An emf is only induced in the secondary coil if the current to the primary coil is switched ON and OFF.

## Experiment - 2:

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

So $\phi\uparrow$



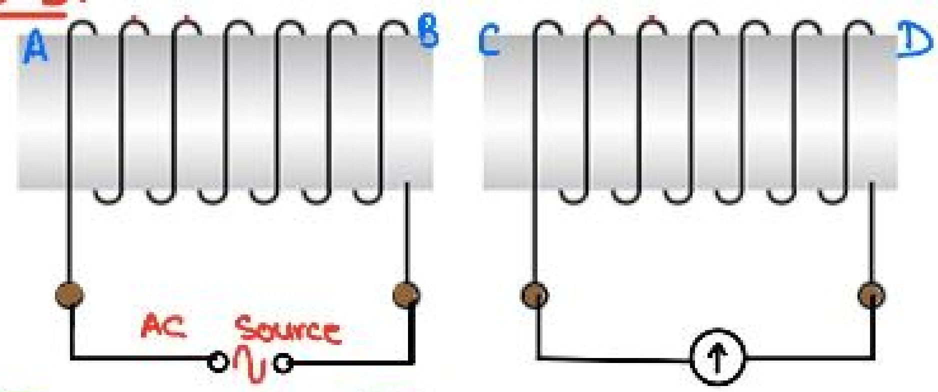

| S.No. | Position of Slider | Current in Primary coil | Poles at A | Poles at B | Deflection of Galvanometer | Reason | Poles induced at C | Poles induced at D | Reason | Direction of Galvanometer |
|---|---|---|---|---|---|---|---|---|---|---|
| 1. | Rest at centre | Constant | S | N | No | $\frac{\Delta\phi}{\Delta t}=0$ | - | - | - | - |
| 2. | Move towards left side (X) | Increases | S strength increases | N | Yes | $\frac{\Delta\phi}{\Delta t}\neq 0$ | North | South | Lenz's Law | Towards Left |
| 3. | Now move towards right side (Y) | Decreases | S strength decreases | N | Yes | $\frac{\Delta\phi}{\Delta t}\neq 0$ | South | North | Lenz's Law | Towards Right |

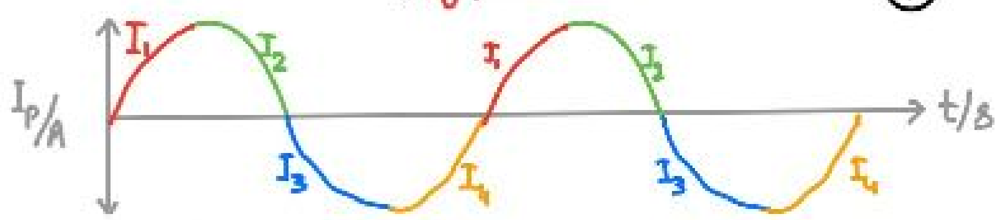
**Result**: An emf is only induced in the secondary coil if the current to the primary is varied.

## Experiment 3:

$B \propto I$

$\phi \propto B$




### Observational Analysis:-

| S.No. | Part of AC in primary coil | Poles produced at A | Poles produced at B | Deflection of Galvanometer | Reason | Poles induced at C | Poles induced at D | Reason | Direction of Galvanometer |
|---|---|---|---|---|---|---|---|---|---|
| 1. | $I_1$ ie magnitude of current in one direction increases | South and their strength increases | North | Yes | $\frac{\Delta\phi}{\Delta t}=0$ | North | South | Lenz's Law | Left side |
| 2. | $I_2$ i.e magnitude of current in same direction decreases | South and their strength decreases | North | Yes | $\frac{\Delta\phi}{\Delta t}=0$ | South | North | Lenz's Law | Right side |
| 3. | $I_3$ ie magnitude of current in opposite direction increases | North and their strength increases | South | Yes | $\frac{\Delta\phi}{\Delta t}=0$ | South | North | Lenz's Law | Right side |
| 4. | $I_4$ ie magnitude of current in opposite direction decreases | North and their strength decreases | South | Yes | $\frac{\Delta\phi}{\Delta t}\neq 0$ | North | South | Lenz's Law | Left side |

**Result**:

Continuous Alternating current is induced in the output secondary coil due to change in magnitude and direction of AC in the primary coil.

**Application**:- Transformer

[Further detail of transformer is excluded from June 22 syllabus]

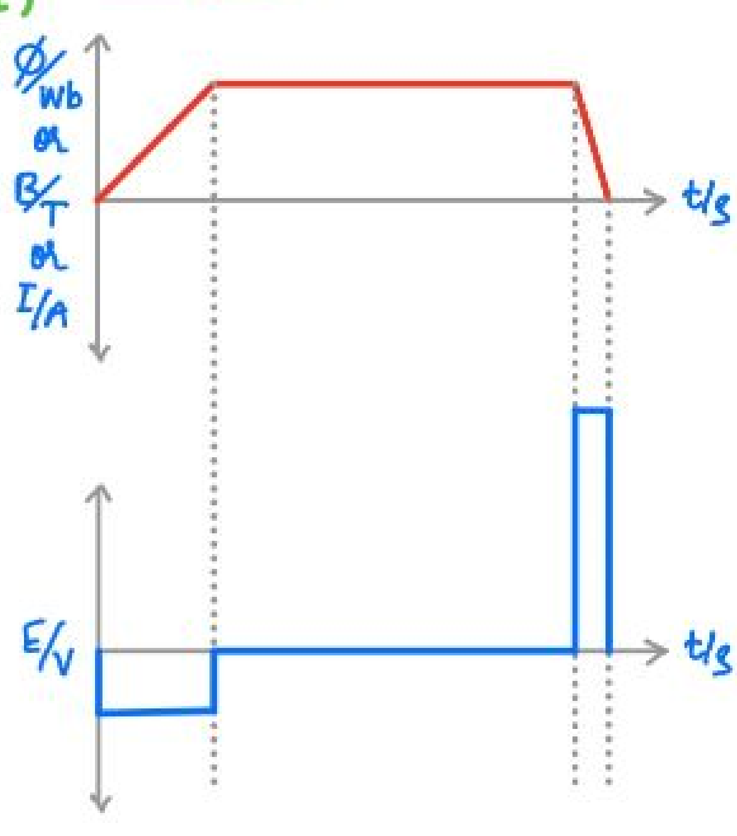
## e.m.f. – time graph from

| Flux-time graph | Magnetic flux density-time graph | Current against time graph |
|---|---|---|
| $e.m.f \propto -\frac{\Delta\phi}{\Delta t}$<br>e.m.f = –ve gradient of magnetic flux against time graph. | $e.m.f \propto -\frac{\Delta\phi}{\Delta t}$<br>But for a coil, $\phi = NBA$<br>$e.m.f \propto -\frac{\Delta(NBA)}{\Delta t}$<br>or<br>$e.m.f \propto -\frac{\Delta B}{\Delta t}$<br>i.e<br>e.m.f. = –ve gradient of magnetic flux density against time graph | $e.m.f \propto -\frac{\Delta\phi}{\Delta t}$<br>But for a coil, $\phi = NBA$ and $B = \mu_0 n I$<br>So<br>$e.m.f \propto -\frac{\Delta[N(\mu_0 n I)A]}{\Delta t}$<br>$e.m.f \propto -\frac{\Delta I}{\Delta t}$<br>i.e.<br>e.m.f. = –ve gradient of current against time graph |

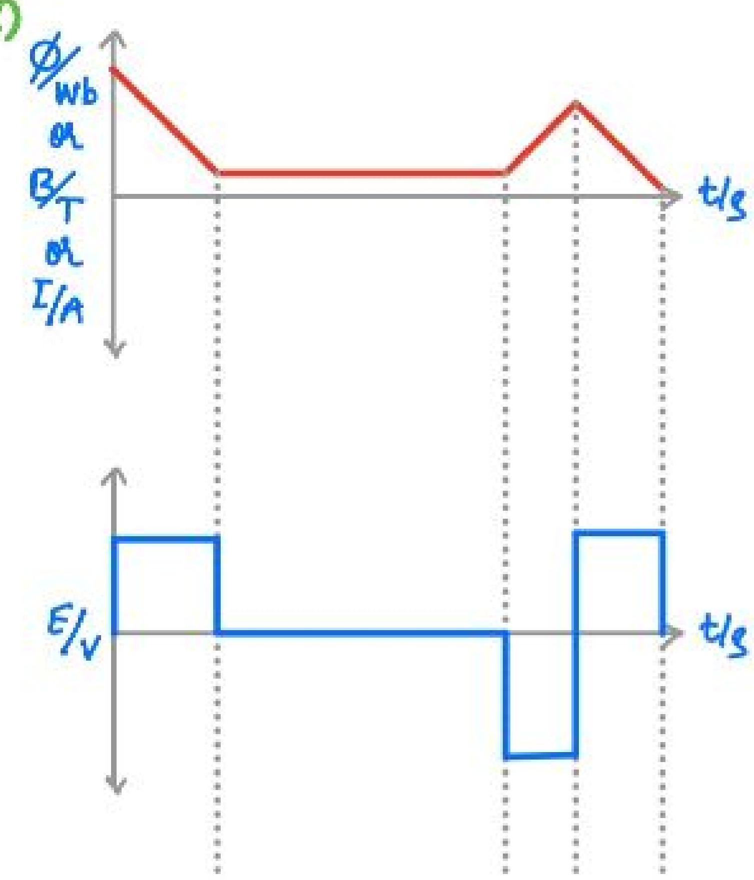
**Result**: e.m.f – time graph = –ve [Gradient of flux – time or magnetic flux density – time or current against time graph]

**Examples:-**

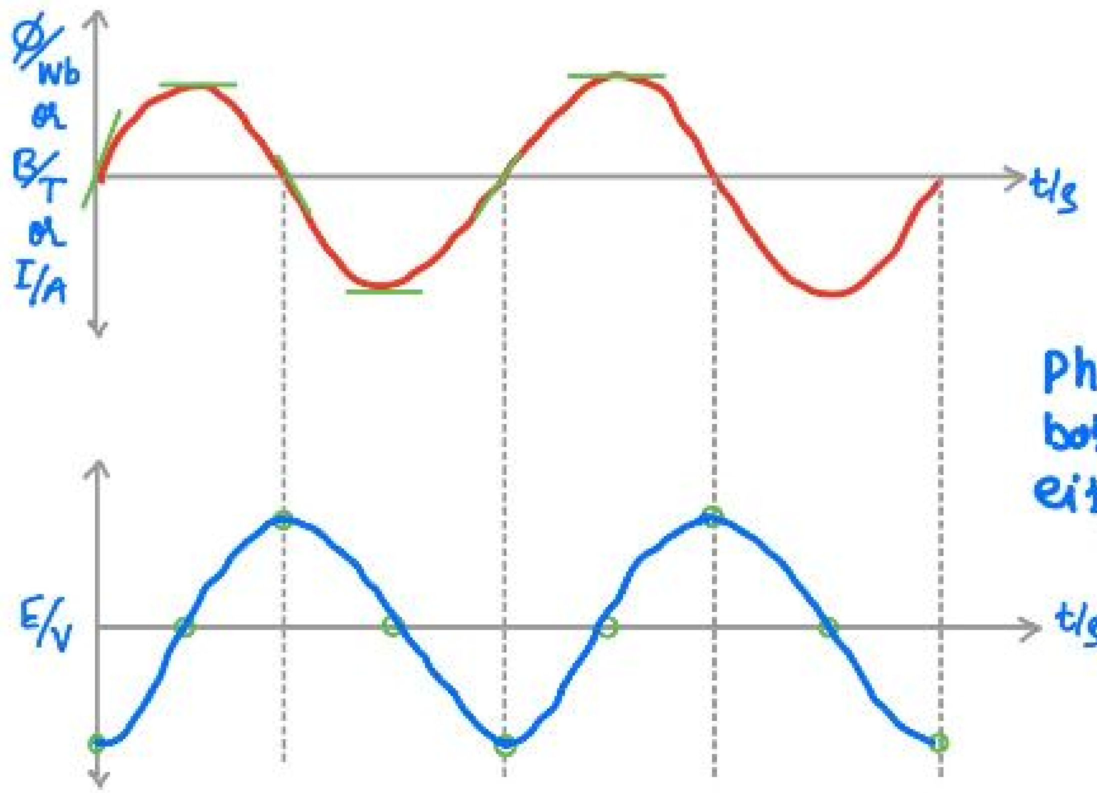
(1)




(2)

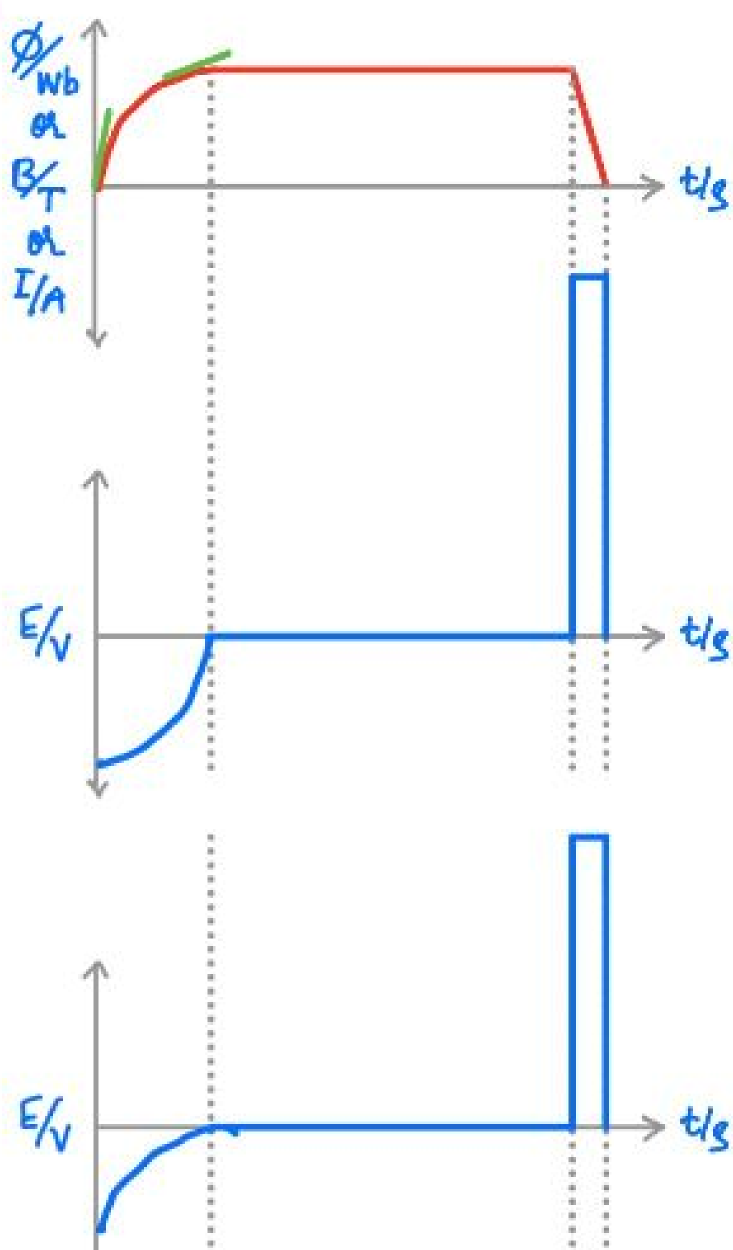


(3)



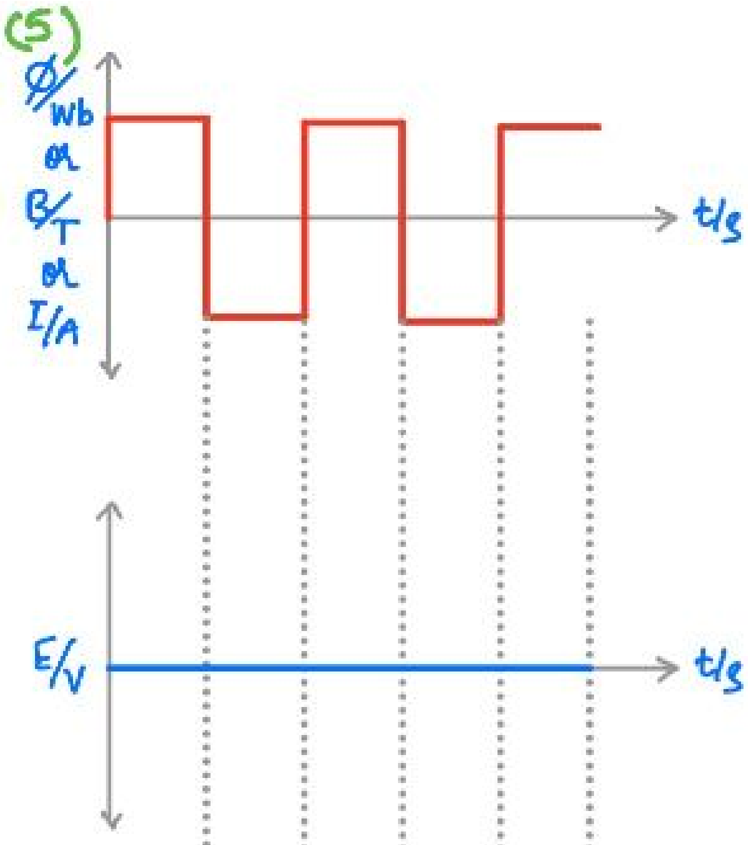

Phase angle in both graphs is either 90° or 270°

(4)




Both graphs are correct as per marking keys.

(5)



# MAGNETIC FIELD

1 **(a)** Define the *tesla*.

$$B = \frac{F}{IL\sin\theta}$$

$$1T = \frac{1N}{(1A)(1m)\sin 90}$$

[3]

**(b)** A large horseshoe magnet produces a uniform magnetic field of flux density *B* between its poles. Outside the region of the poles, the flux density is zero.
The magnet is placed on a top-pan balance and a stiff wire XY is situated between its poles, as shown in Fig. 6.1.

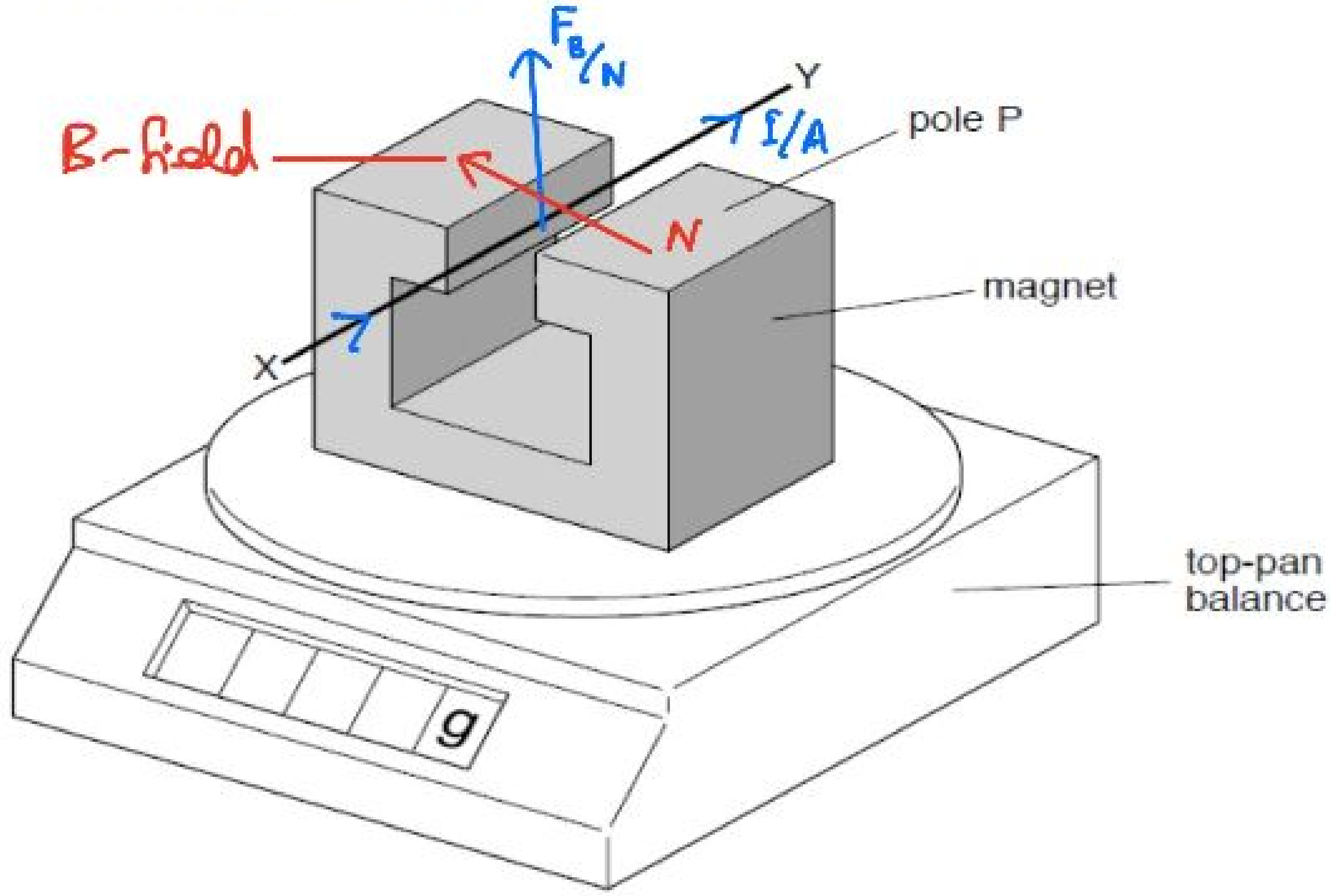



**Fig. 6.1**

The wire XY is horizontal and normal to the magnetic field. The length of wire between the poles is 4.4 cm.
A direct current of magnitude 2.6 A is passed through the wire in the direction from X to Y.
The reading on the top-pan balance increases by 2.3 g.

**(i)** State and explain the polarity of the pole P of the magnet.

Downward force on magnet measured by top pan balance indicates an upward force on wire XY by Newton's third law of motion. So pole at P is North by Flemming's left hand rule. [3]

(ii) Calculate the flux density between the poles.

$$F_B = W$$

$$BIL \sin 90^\circ = mg$$

$$B = \frac{mg}{IL} = \frac{(2.3\times10^{-3})(9.81)}{(2.6)(4.4\times10^{-2})}$$

flux density = 0.197 T [3]

(c) The direct current in **(b)** is now replaced by a very low frequency sinusoidal current of r.m.s. value 2.6 A.
Calculate the variation in the reading of the top-pan balance.

$$I_{rms} = \frac{I_0}{\sqrt{2}} \Rightarrow 2.6 = \frac{I_0}{\sqrt{2}} \Rightarrow I_0 = 3.67\,A$$

2.6 A current increases reading by: 2.3g

3.67 A ——— $= \left(\frac{2.3}{2.6}\right)(3.67)$

$= 3.25g$

variation in reading = ........................ g [2]

Increase in reading

$I_0 = 3.67A$ So

Decrease in reading

total variation for both half cycles of AC $= 2(3.25)$

$= 6.50g$

2 The current in a long, straight vertical wire is in the direction XY, as shown in Fig. 6.1.

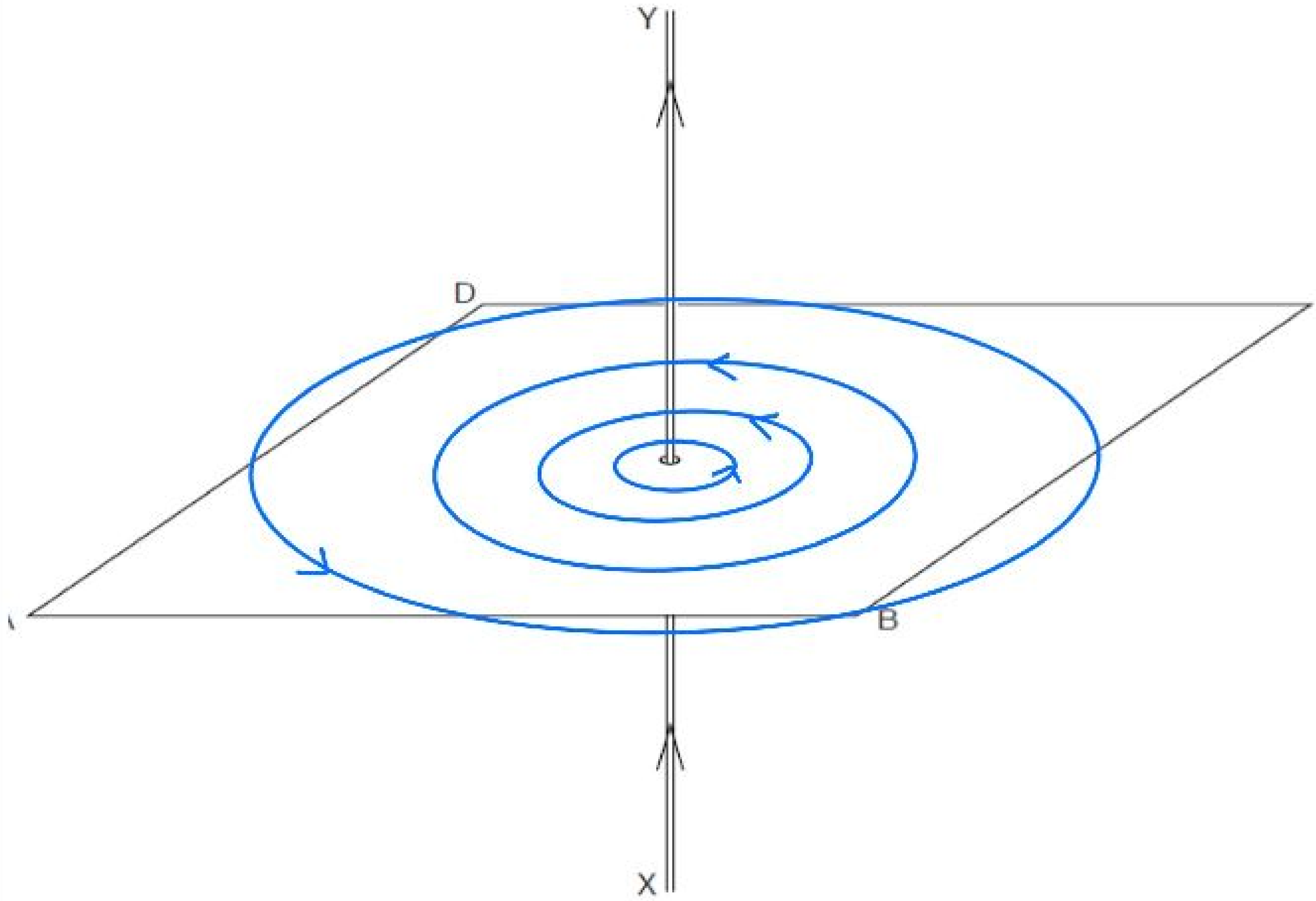



**Fig. 6.1**

**(a)** On Fig. 6.1, sketch the pattern of the magnetic flux in the horizontal plane ABCD due to the current-carrying wire. Draw at least four flux lines. [3]

**(b)** The current-carrying wire is within the Earth's magnetic field. As a result, the pattern drawn in Fig. 6.1 is superposed with the horizontal component of the Earth's magnetic field.

Fig. 6.2 shows a plan view of the plane ABCD with the current in the wire coming out of the plane.

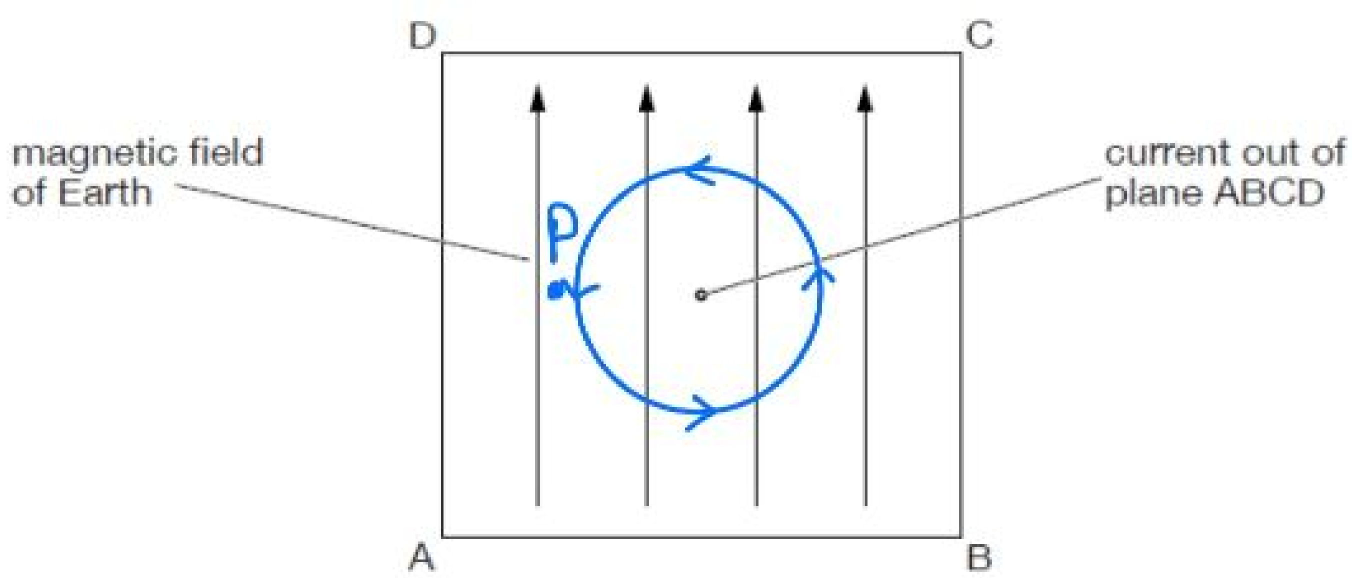



**Fig. 6.2**

2 The horizontal component of the Earth's magnetic field is also shown.

(i) On Fig. 6.2, mark with the letter P a point where the magnetic field due to the current-carrying wire could be equal and opposite to that of the Earth. [1]

(ii) For a long, straight wire carrying current $I$, the magnetic flux density $B$ at distance $r$ from the centre of the wire is given by the expression

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

where $\mu_0$ is the permeability of free space.

The point P in **(i)** is found to be 1.9 cm from the centre of the wire for a current of 1.7 A.

Calculate a value for the horizontal component of the Earth's magnetic flux density.

$$B_{Earth} = B_{current} = \frac{\mu_0 I}{2\pi r}$$

$$= \frac{(4\pi \times 10^{-7})(1.7)}{(2\pi)(1.9 \times 10^{-2})}$$

flux density = $1.79 \times 10^{-5}$ T [2]

(c) The current in the wire in **(b)(ii)** is increased. The point P is now found to be 2.8 cm from the wire.

Determine the new current in the wire.

$$B_{Earth} = B_{current} = \frac{\mu_0 I}{2\pi r}$$

$$1.79 \times 10^{-5} = \frac{(4\pi \times 10^{-7})\, I}{(2\pi)(2.8 \times 10^{-2})}$$

$I =$ ______ A

current = .............................................. A [2]

3 Two long straight vertical wires X and Y pass through a horizontal card, as shown in Fig. 5.1.

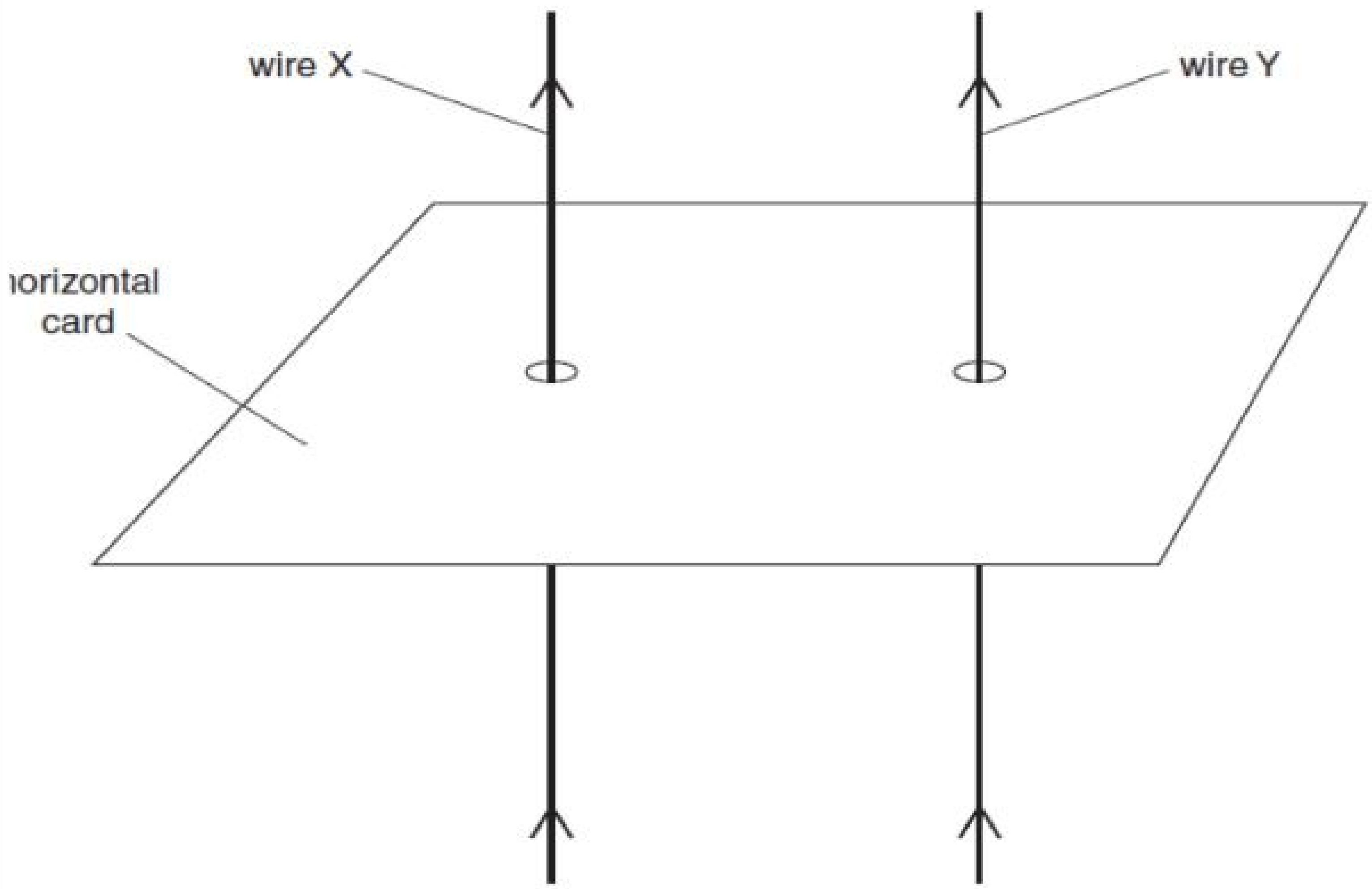



**Fig. 5.1**

The current in each wire is in the upward direction.

The top view of the card, seen by looking vertically downwards at the card, is shown in Fig. 5.2.

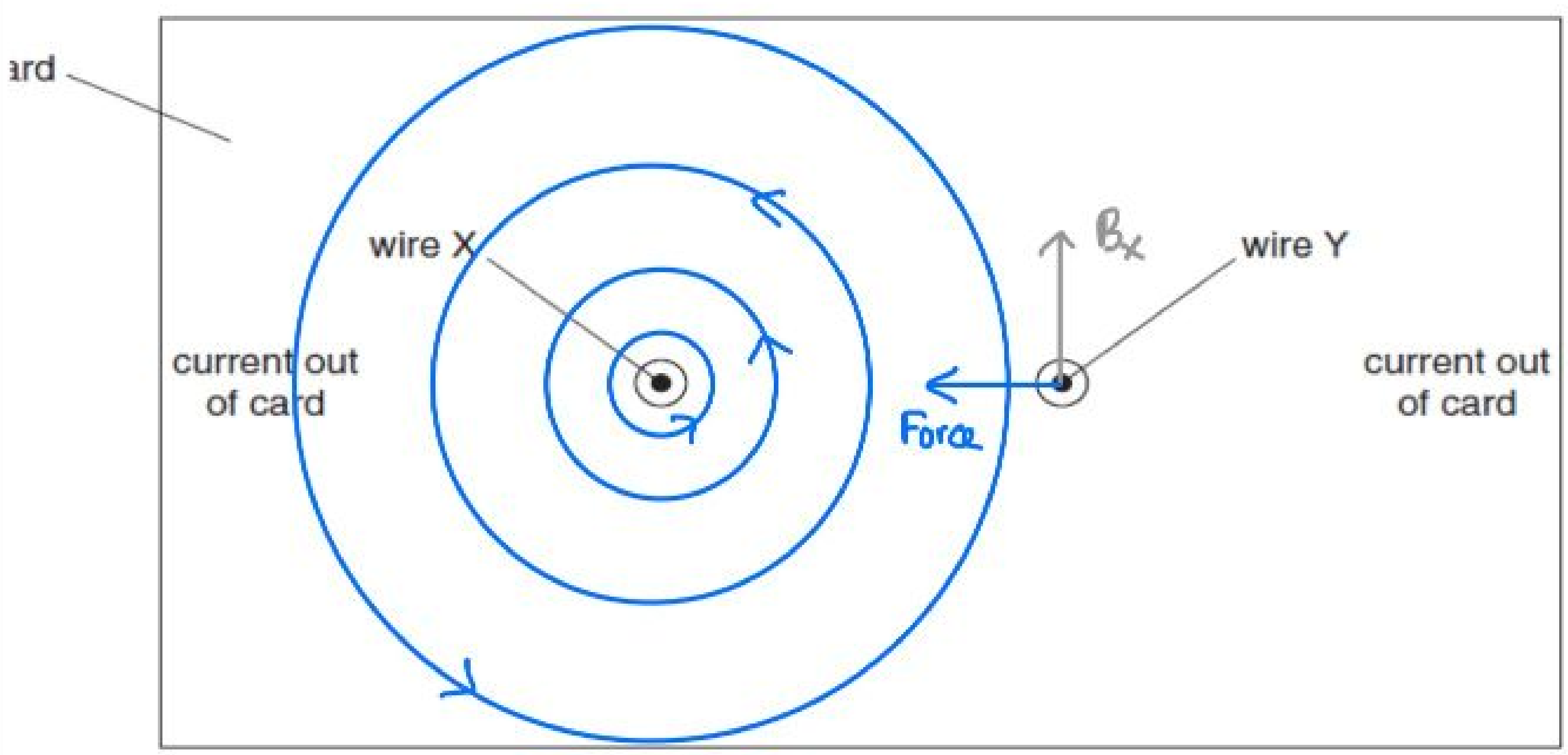



**Fig. 5.2** (not to scale)

4 **(a)** A uniform magnetic field has constant flux density $B$. A straight wire of fixed length carries a current $I$ at an angle $\theta$ to the magnetic field, as shown in Fig. 6.1.

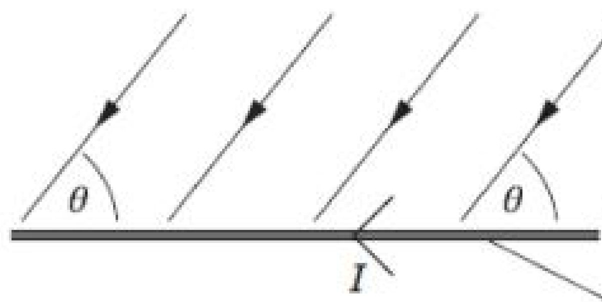



**Fig. 6.1**

**(i)** The current $I$ in the wire is changed, keeping the angle $\theta$ constant.
On Fig. 6.2, sketch a graph to show the variation with current $I$ of the force $F$ on the wire.

$F = BIL \sin\theta$

$F \propto I$

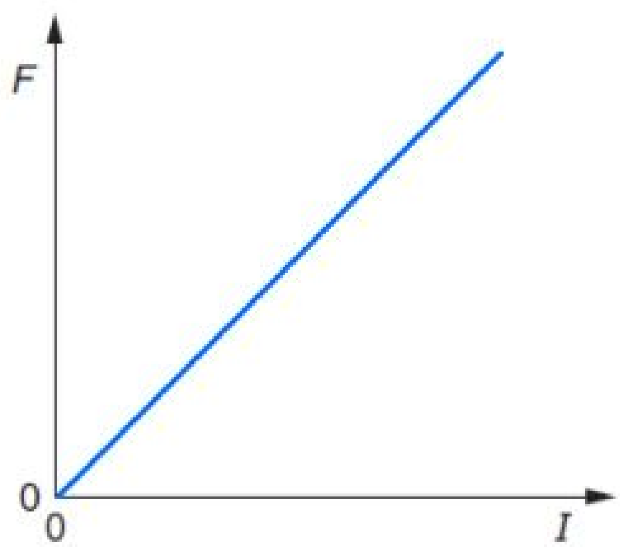



**Fig. 6.2**

[2]

**(ii)** The angle $\theta$ between the wire and the magnetic field is now varied. The current $I$ is kept constant.
On Fig. 6.3, sketch a graph to show the variation with angle $\theta$ of the force $F$ on the wire.

$F \propto \sin\theta$

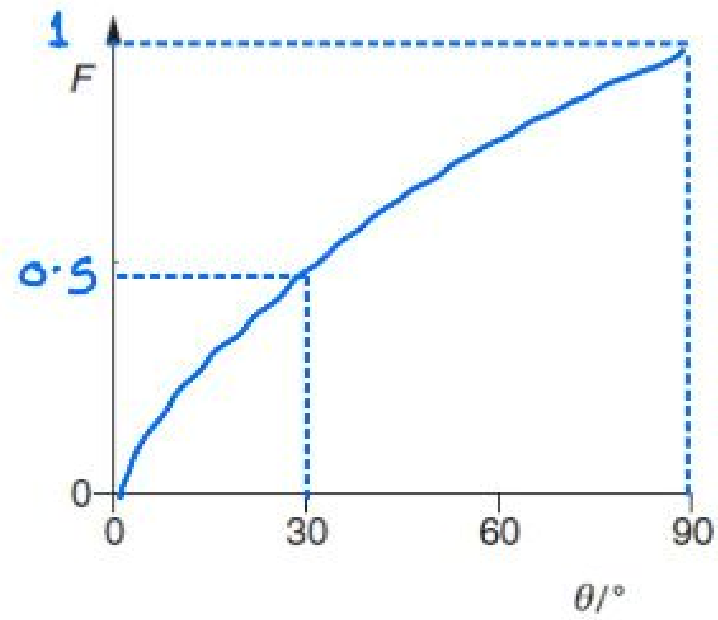
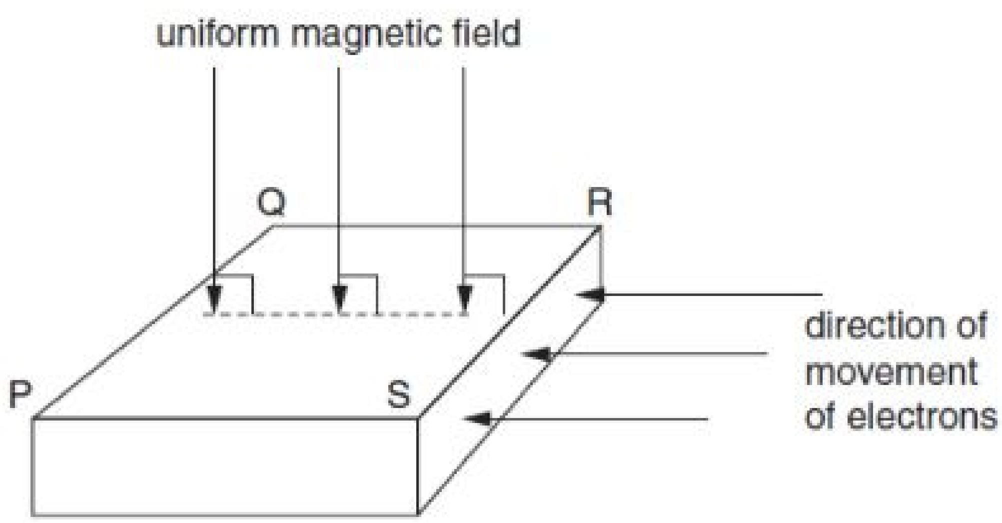



**Fig. 6.3** [3]

**(b)** A uniform magnetic field is directed at right-angles to the rectangular surface PQRS of a slice of a conducting material, as shown in Fig. 6.4.



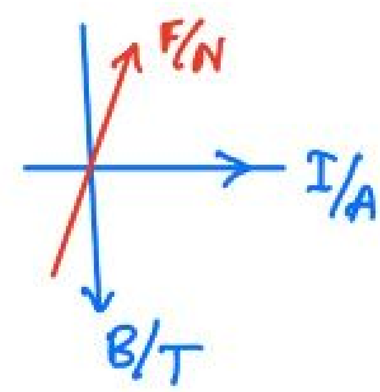




**Fig. 6.4**

Electrons, moving towards the side SR, enter the slice of conducting material. The electrons enter the slice at right-angles to side SR.

**(i)** Explain why, initially, the electrons do not travel in straight lines across the slice from side SR to side PQ.

Because a moving charged particle in a peependicular magnetic field experience a perpendicular magnetic force. [2]

**(ii)** Explain to which side, PS or QR, the electrons tend to move.

Towards QR by Flemming's Left Hand rule.

[2]

5 Positive ions are travelling through a vacuum in a narrow beam. The ions enter a region of uniform magnetic field of flux density $B$ and are deflected in a semi-circular arc, as shown in Fig. 5.1.

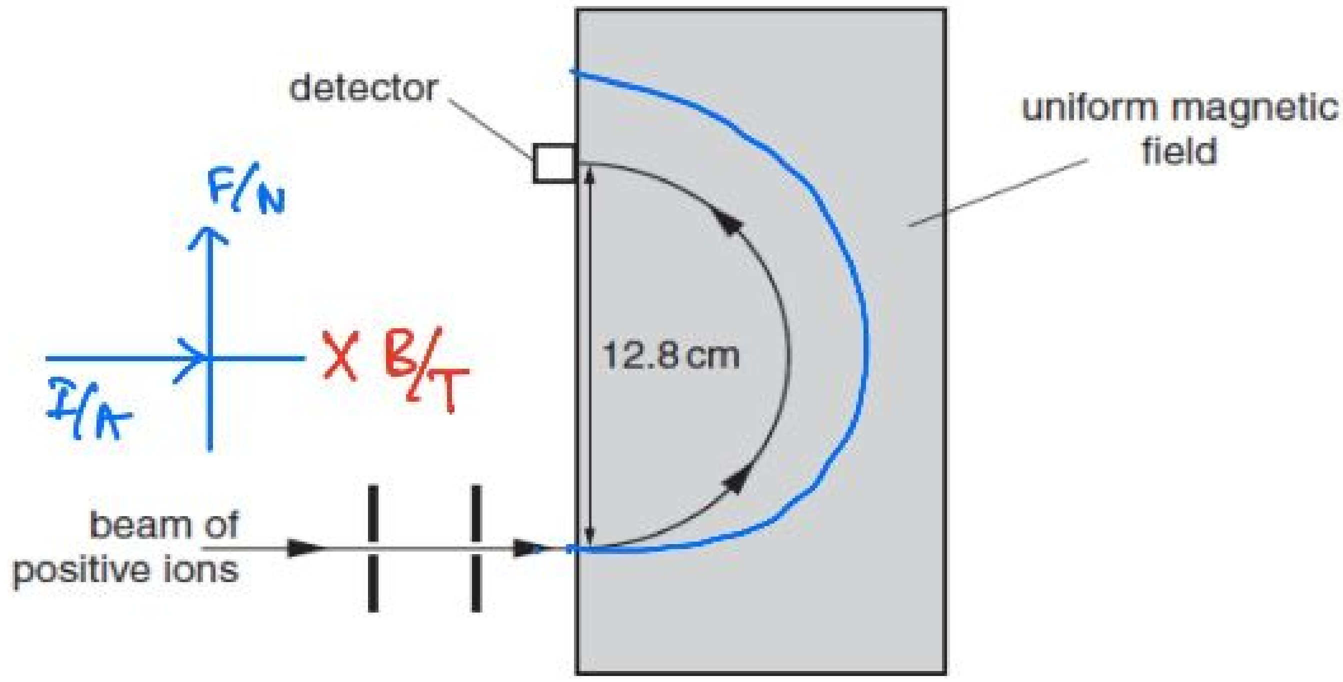



**Fig. 5.1**

The ions, travelling with speed $1.40 \times 10^5\,\mathrm{m\,s^{-1}}$, are detected at a fixed detector when the diameter of the arc in the magnetic field is 12.8 cm.

**(a)** By reference to Fig. 5.1, state the direction of the magnetic field.

into the plane of page. ..................... [1]

**(b)** The ions have mass 20 u and charge $+1.6 \times 10^{-19}$ C. Show that the magnetic flux density is 0.454 T. Explain your working.

$$F_B = F_c$$

$$BQv\sin 90^\circ = \frac{mv^2}{r}$$

$$B = \frac{mv}{Qr} = \frac{(20 \times 1.66 \times 10^{-27})(1.40 \times 10^{5})}{(1.6 \times 10^{-19})(6.4 \times 10^{-2})}$$

[3]

$$B = 0.454\,\mathrm{T}$$

(c) Ions of mass 22 u with the same charge and speed as those in **(b)** are also present in the beam.

$B = \frac{mv}{Qr} \Rightarrow r = \frac{mv}{BQ}$

(i) On Fig. 5.1, sketch the path of these ions in the magnetic field of magnetic flux density 0.454 T. [1]

(ii) In order to detect these ions at the fixed detector, the magnetic flux density is changed.
Calculate this new magnetic flux density.

$$\frac{m_2 \cancel{v}}{B_2 \cancel{Q}} = \frac{m_1 \cancel{v}}{B_1 \cancel{Q}}$$

$$B_2 = \frac{(B_1)(m_2)}{m_1} = \frac{(0.454)(22\cancel{u})}{20\cancel{u}}$$

magnetic flux density = 0.499 T [2]

# ELECTROMAGNETIC INDUCTION

1 A small rectangular coil ABCD contains 140 turns of wire. The sides AB and BC of the coil are of lengths 4.5 cm and 2.8 cm respectively, as shown in Fig. 6.1.

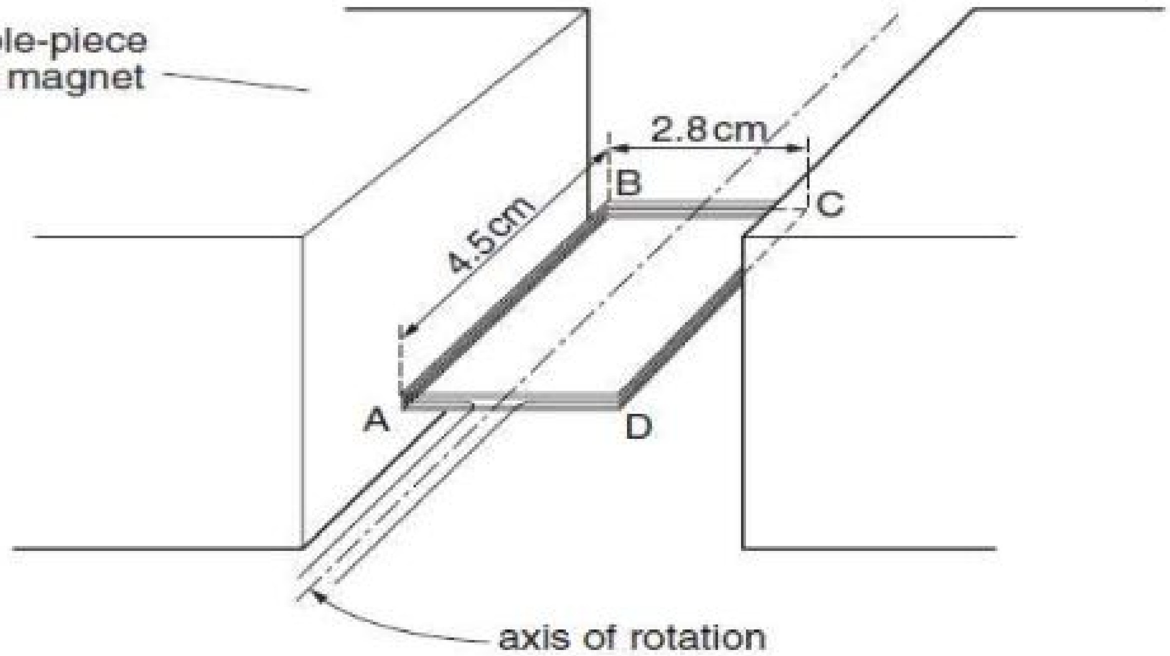



**Fig. 6.1**

The coil is held between the poles of a large magnet so that the coil can rotate about an axis through its centre.
The magnet produces a uniform magnetic field of flux density $B$ between its poles.
When the current in the coil is 170 mA, the maximum torque produced in the coil is $2.1 \times 10^{-3}$ N m.

**(a)** For the coil in the position for maximum torque, state whether the plane of the coil is parallel to, or normal to, the direction of the magnetic field.

Parallel to the field lines ....[1]

**(b)** For the coil in the position shown in Fig. 6.1, calculate the magnitude of the force on

(i) side AB of the coil,

$$T = (F_{AB})(d)$$

$$2.1 \times 10^{-3} = (F_{AB})(2.8 \times 10^{-2})$$

$$F_{AB} = \underline{0.075} \text{ N}$$

force = .................................... N [2]

(ii) side BC of the coil.

Zero because current is parallel to the field lines

force = ............0............ N [1]

(c) Use your answer to **(b)(i)** to show that the magnetic flux density $B$ between the poles of the magnet is 70 mT.

$F = BINL \sin 90^{0}$

$0.075 = (B)(170\times10^{-3})(140)(4.5\times10^{-2})(1)$

$B = \underline{70\times10^{-3}}\,T$

[2]

(d) (i) State Faraday's law of electromagnetic induction.

Rate of change of magnetic flux linkage/cutting is directly proportional to the e.m.f induced.
...................................................................................................................................... [2]

(ii) The current in the coil in **(a)** is switched off and the coil is positioned as shown in Fig. 6.1.
The coil is then turned through an angle of 90° in a time of 0.14 s.
Calculate the average e.m.f. induced in the coil.

$$e.m.f = -\frac{\Delta\phi}{\Delta t} = -\frac{NBA}{\Delta t}$$

$$E = \frac{(140)(70\times10^{-3})(4.5\times2.8\times10^{-4})}{0.14}$$

e.m.f. = ............................................. V [3]