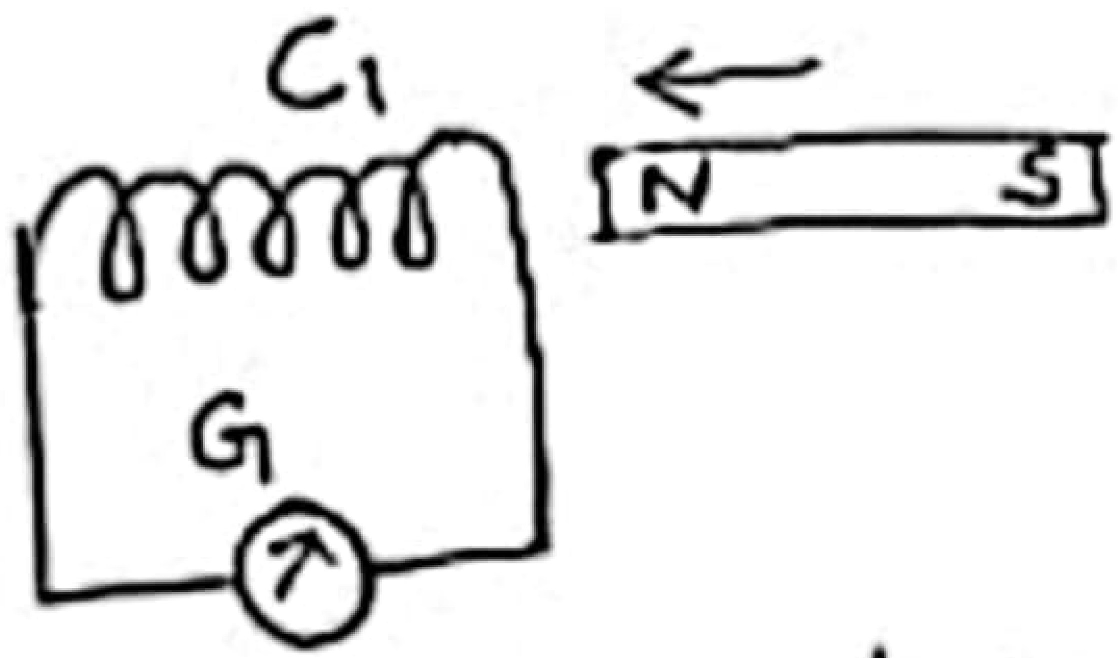
Unit-VI

Electro magnetic Induction

The phenomenon in which electric current is generated by varying magnetic field is called Electromagnetic Induction.

Faraday's Experiments :-

Coil-Magnet Experiment:-



coil-Magnet Experiment.

C_1 is a large coil of several turns of a conductor connected to a sensitive galvanometer (G).

i) When a bar magnet NS is moved towards the coil, the galvanometer shows a deflection.

ii) The galvanometer shows an opposite direction when the magnet is moved away.

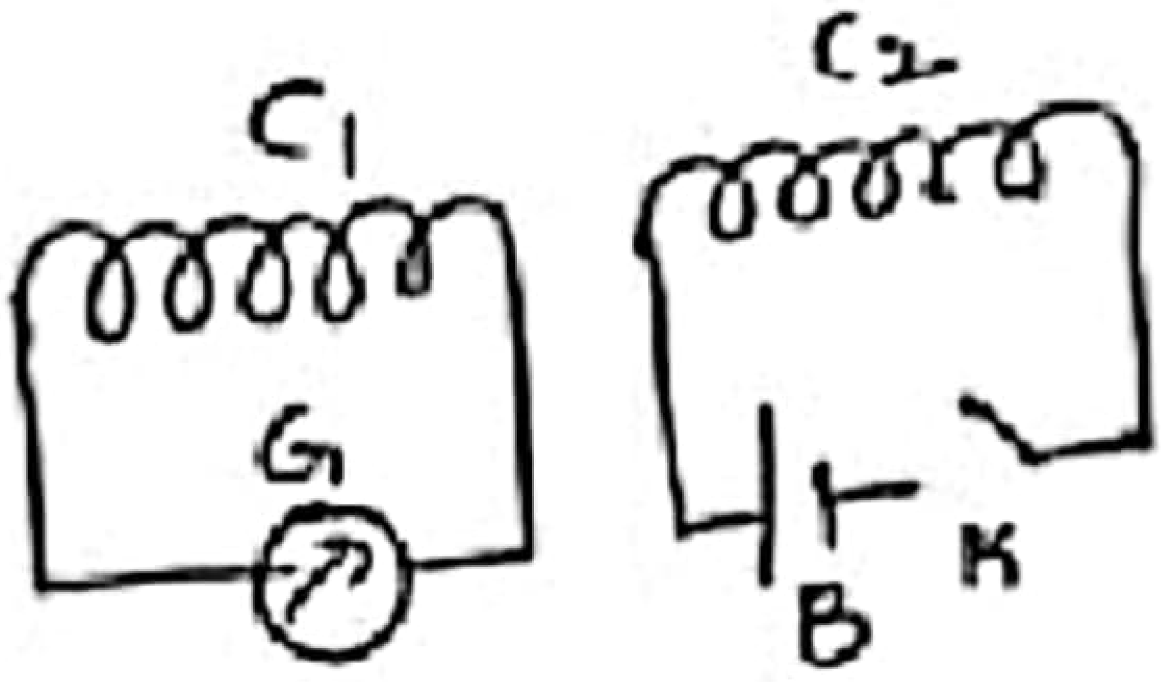
iii) The galvanometer shows a deflection if the coil moves and the magnet is stationary. What matters is the relative motion between the two.

iv) No deflection is observed if neither the coil nor the magnet moves or if there is no relative motion.

v) If the relative motion is brought about faster, the deflection is large.

It shows that the relative motion between the magnet and the coil is responsible for generation (induction) of electric current in the coil.

<u>Coil-coil Experiment</u> :-



In figure the bar magnet is replaced by a second coil C_2 connected to a battery.

1. The steady current in the coil C_2 produces a steady magnetic field.
2. As coil C_2 is moved towards or away from the coil C_1, the galvanometer shows a deflection.
3. This indicates the electric current is induced in coil C_1.
4. When the coil C_2 is held fixed and C_1 is moved, the same effects are observed.

"The relative motion between the coils is responsible for inducing the electric current". From these experiments we note that there is a change in magnetic flux linked with the coil leading to an induced emf and current.

Faraday's laws of Electromagnetic Induction

I law:- An induced emf is set up in a conductor when the magnetic flux linked with the conductor is changing. This induced emf lasts only as long as the flux linked with the conductor keeps changing.

II law:- The magnitude of the induced emf (e) in a circuit is equal to the rate of change of magnetic flux (ϕ) linked with the circuit i.e., $e = -\frac{d\phi}{dt}$

If the coil contains N turns, then

$$e = -N\frac{d\phi}{dt} = \frac{-d}{dt}(N\phi)$$

where '$N\phi$' is total flux linked with the coil of N turns.

$$e = \frac{-d}{dt}(N\phi) = \frac{-d}{dt}(N\,BA\cos\theta)$$

~~The~~ Negative sign is in accordance with Lenz's law. The above law is also called Neumann's law.

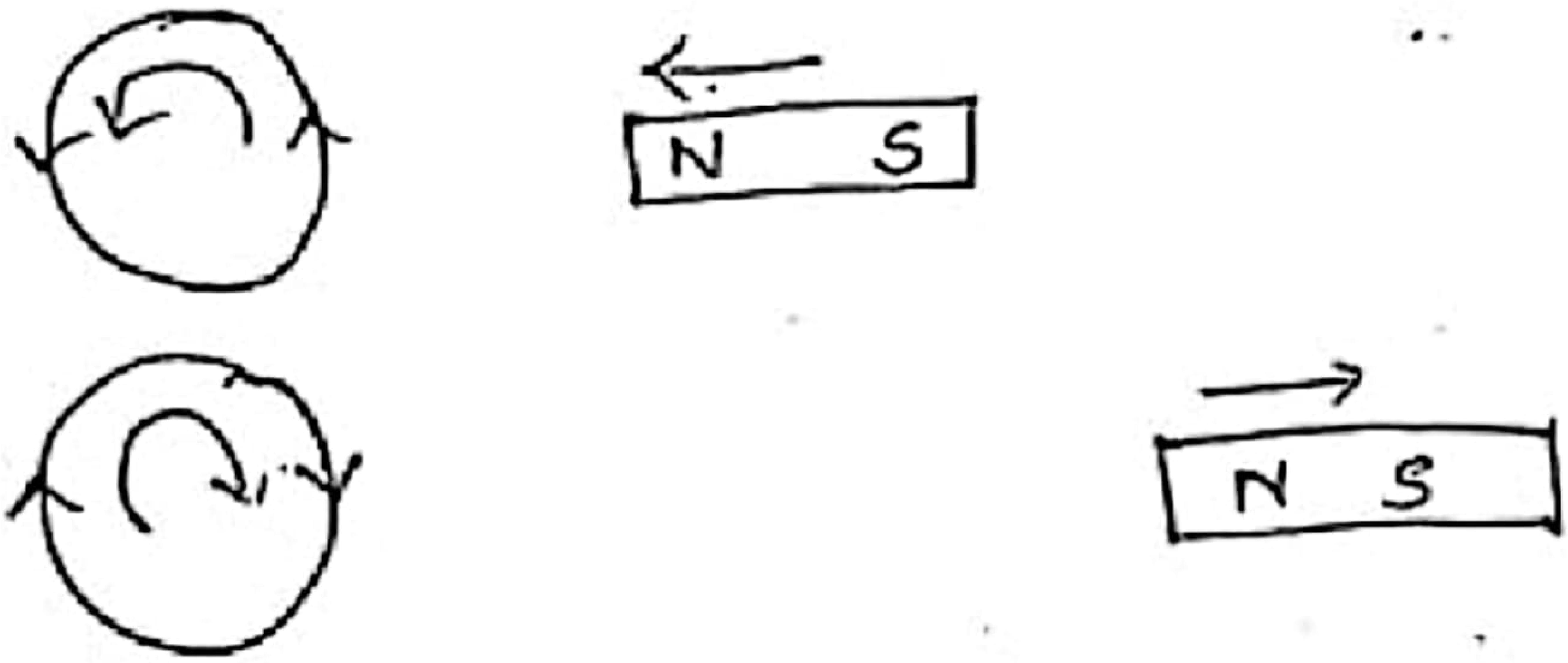
Lenz's law and conservation of energy

The direction of induced emf is always such that it tends to produce a current which opposes the change in magnetic flux that produced it.

An emf is induced by an increasing magnetic flux, the induced current produces a magnetic field which tries to reduce the increasing flux.

Conversely if an emf is induced by a decreasing magnetic flux, the induced current tries to prevent the decreasing flux.

In the figure, current flows in the coil such that the end M facing the magnet behaves like a north pole when the north pole of the magnet approaches the coil and tries to push the magnet back.



Similarly if the magnet is taken away from the coil, the induced current flows in clock wise direction.

Thus, induced emf opposes the change in magnetic flux.

Therefore, the change in the external magnetic field and flux is always opposed. So some external work is needed to overcome the opposition. The energy needed to do the work is converted into the electrical energy to establish current in circuit by obeying law of conservation of energy.

Expression for Induced EMF, Induced Current and Induced charge

Induced EMF:- Let ϕ_1 be magnetic flux linked with a coil at any instant, ϕ_2 be magnetic flux linked with the same coil after a time dt.

Applying Faraday's second law and Lenz's law, the induced emf is given by

$$e = -\frac{d\phi}{dt} \text{ volt}$$

If the coil has N turns then,

$$e = -N\frac{d\phi}{dt} \Rightarrow e = -N\frac{(\phi_2-\phi_1)}{dt} \Rightarrow \boxed{e = -N\frac{d\phi_B}{dt}}$$

$d\phi_B$ is small change in magnetic field

-ve sign indicates that the induced emf is produced in such a way that the current due to it opposes the change in the magnetic flux. This is according to Lenz's law.

Induced current:- If the magnetic flux in a coil of resistance R changes from ϕ_1 to ϕ_2 in a time 'dt', then a current 'i' is induced in the coil as

$$I = \frac{\text{Induced emf}}{\text{Resistance in the circuit}} = \frac{e}{R}$$

$$I = \frac{1}{R}\left(\frac{-d\phi_B}{dt}\right)$$

For N turns, $I = \frac{N}{R}\left(\frac{-d\phi_B}{dt}\right)$

Induced charge :- The amount of charge induced in a conductor is given as follows

$$I = \frac{e}{R} \quad \text{or} \quad I = \frac{1}{R}\left(\frac{-d\phi}{dt}\right)$$

$$\frac{dq}{dt} = \frac{-1}{R}\frac{d\phi}{dt} \qquad \left[\because I = \frac{dq}{dt}\right]$$

$$dq = -\frac{1}{R}\,d\phi$$

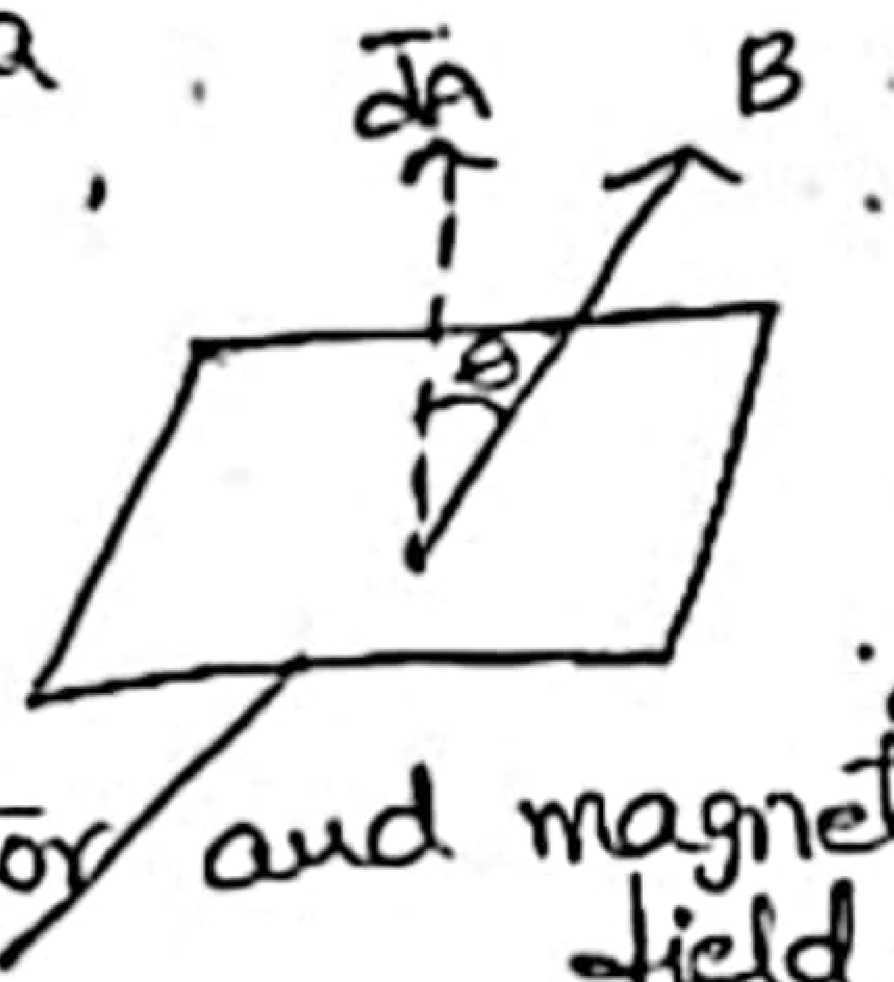
$\therefore$ Induced charge, $q = -\frac{1}{R}\int_{\phi_i}^{\phi_f} d\phi$

$$q = -\frac{1}{R}\left[\phi_f - \phi_i\right] \quad \text{or} \quad Q = \frac{\phi_i - \phi_f}{R}$$

$\therefore$ In general, Induced charge is given by

$$Q = \frac{\text{change of magnetic flux}}{\text{Resistance}}$$

Magnetic flux :- The total number of magnetic lines of force passing normally through an area placed in a magnetic field is equal to the magnetic flux linked with that area.



Net flux through the surface

$$\phi = \oint \vec{B} \cdot \vec{dA} = BA\cos\theta$$

θ is the angle between area vector and magnetic field.

If $\theta = 0°$, then $\boxed{\phi = BA}$, If $\theta = 90°$, then $\boxed{\phi = 0}$

Motional E.M.F :-

changing the value of magnetic field B.

Induced emf is two types :

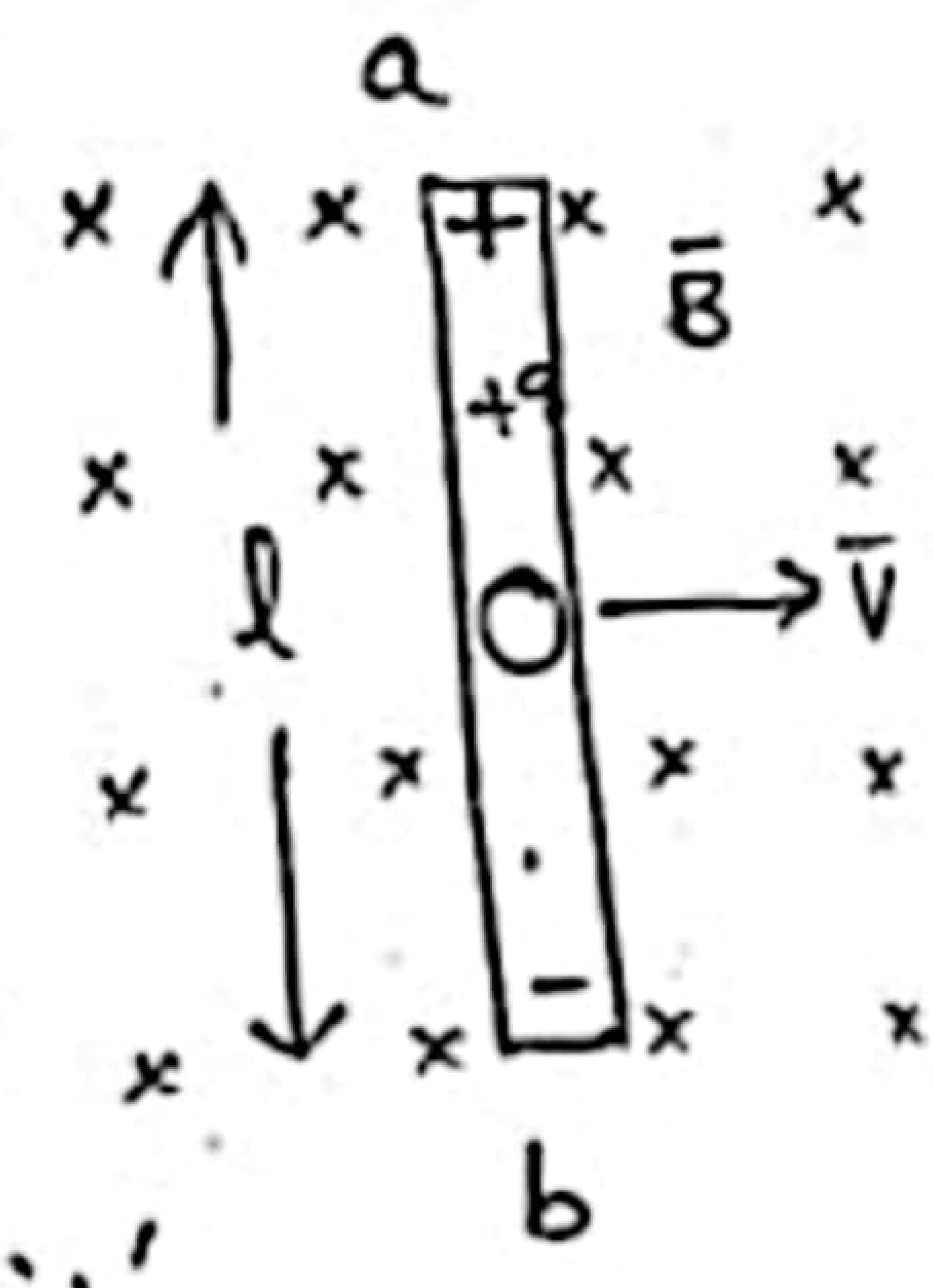
1. Motional emf   2. changing field emf.

The motional emf is the emf which results from relative motion between a conductor and the source of magnetic field.

The figure shows a uniform magnetic field $\bar{B}$ directed into the plane of the paper. A rod is moved towards the right with a constant velocity $\vec{v}$. A charged particle +q in the rod then experiences a magnetic force

$$F = qvB \rightarrow (1)$$ in the upward direction

i.e from 'b' to 'a'



The magnetic force causes the charges in the rod to move, creating an excess of positive charge at the upper end 'a' and negative charge at the lower end 'b'.

This creates an electric field within the rod, in the direction from 'a' to 'b'.

charge continues to accumulate at the ends of the rod until $\bar{E}$ becomes large enough for the downward electric force to cancel exactly the upward magnetic force.

The electric force $F = qE \rightarrow ②$

If charges are in equilibrium ① = ②

$$qE = qVB$$

$$E = VB$$

we know the potential difference between two ends of rod $V_{ab} = El$.

$$\therefore V_{ab} = VBl$$

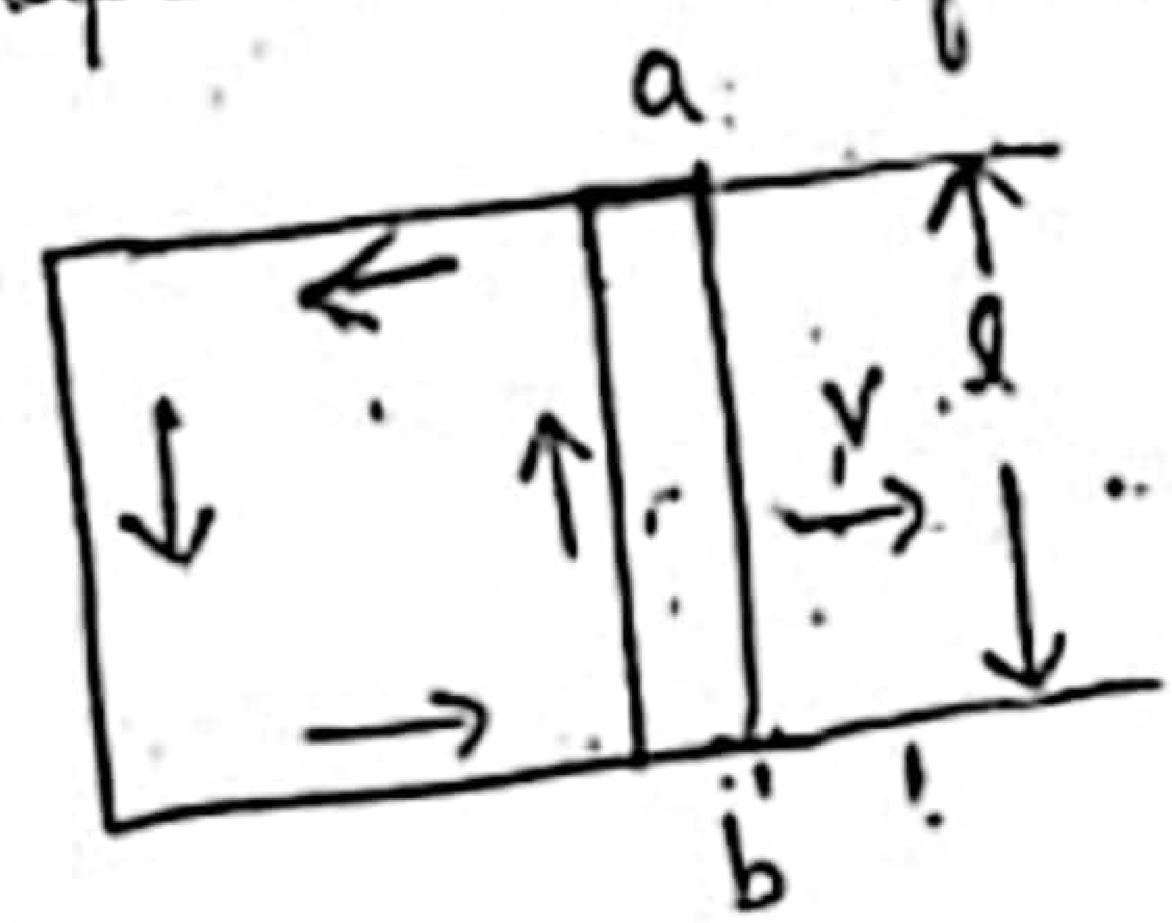
This is the emf induced in the rod due to its motion in the magnetic field (B)

This is called motional emf, given by

$$\boxed{e = VBl} \quad \text{or} \quad \boxed{e = Blv\sin\theta}$$

'θ' be the angle between velocity of direction of B.

Now suppose the moving rod slides along a stationary U- shaped conductor forming a complete circuit.



Due to charges redistribution in the rod, it creates an electric field.

This field establishes a current in the direction shown.

when the device is connected to an external circuit, the direction of current is from 'b' to 'a' in the device and from 'a' to 'b' in the external circuit.

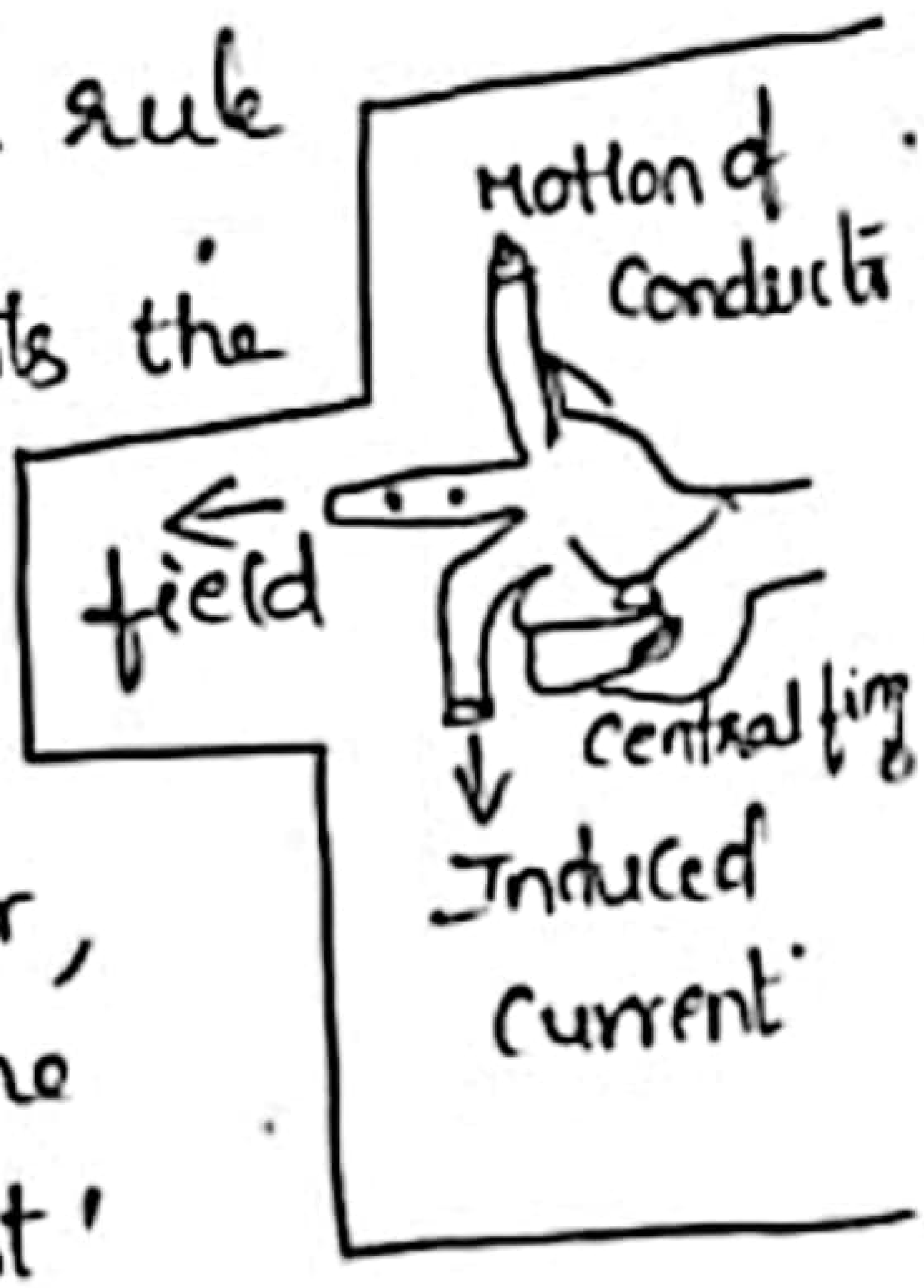
The direction of induced emf can be deduced by using Lenz's law.

For any conducting loop, the total emf is

$$e = \oint (\bar{v} \times \bar{B}) \, d\bar{l}.$$

Fleming's Right hand Rule:-

The direction of induced current in relation to the direction of magnetic field and the direction of motion of the conductor is given by fleming's right hand rule



If the fore finger represents the direction of magnetic field and thumb represents the direction of motion of conductor, then central finger indicates the direction of induced current.

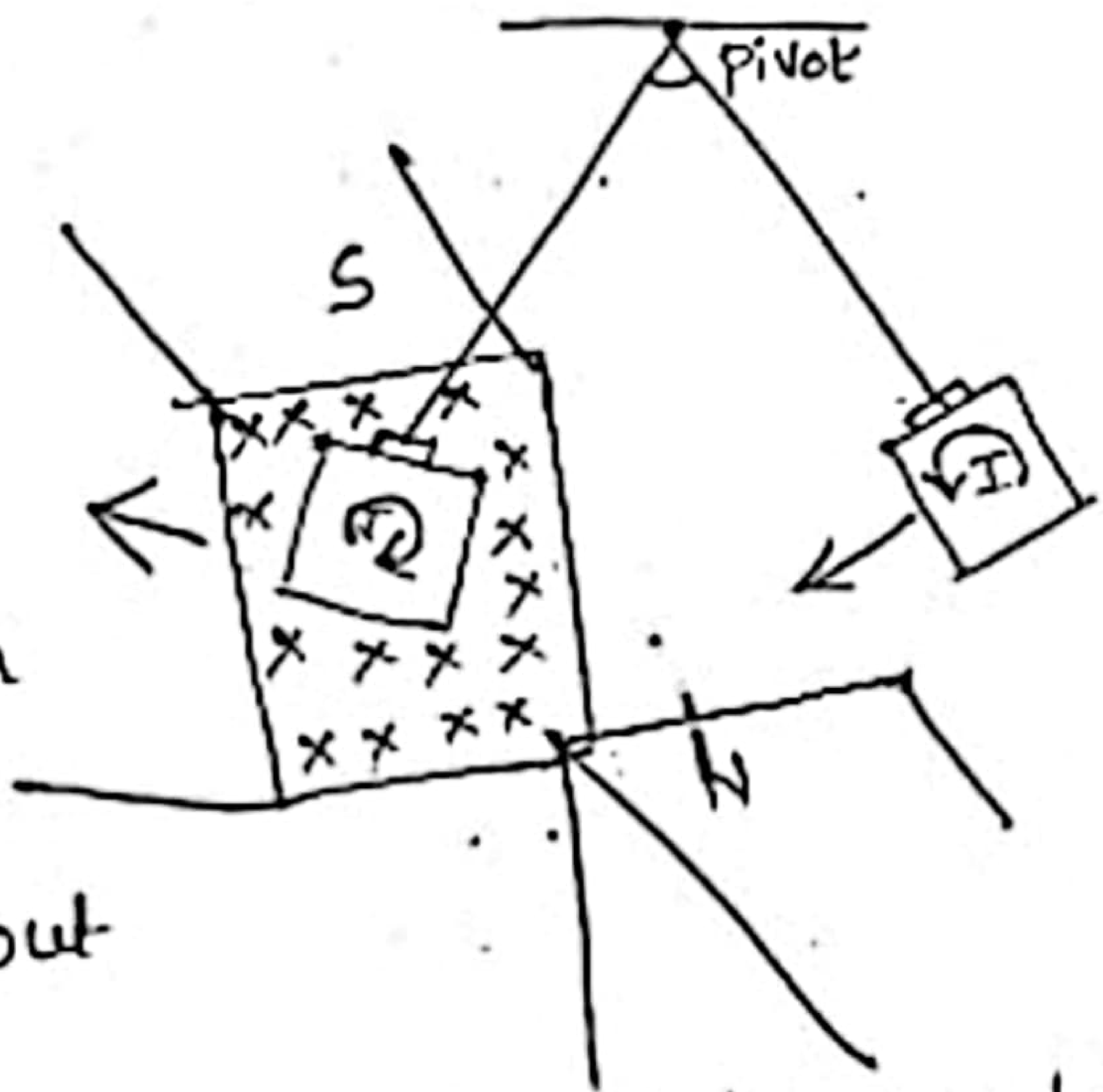
Eddy currents :-

when a metallic plate is placed in a time varying magnetic field, the magnetic flux linked with the plate changes, the induced currents are set up in the plate. these currents are called eddy currents.

The flow patterns of induced currents resemble the swirling eddies in water. This effect was discovered by Foucault and these currents are called eddy currents (or) Foucault currents.

These currents are sometimes so strong, that the metallic plate becomes red hot.

The directions of eddy currents are opposite when the plate swings into the region between the poles and when it swings out of the region.



The pendulum plate with holes or slots reduces electromagnetic damping.

Eddy currents heat up the metallic cores and dissipate electric energy in the form of heat in the devices like transformers, electric motors and other such devices.

<u>Inductance</u> :- An electric current can be induced in a coil by change of flux produced by same coil or by another coil in its vicinity.

The flux through a coil is directly proportional to the current (I) i.e

$$\phi_B \propto I$$

If coil has N turns, the flux linkage for a closely wound coil is equal to $N\phi_B$ and is proportional to current I.

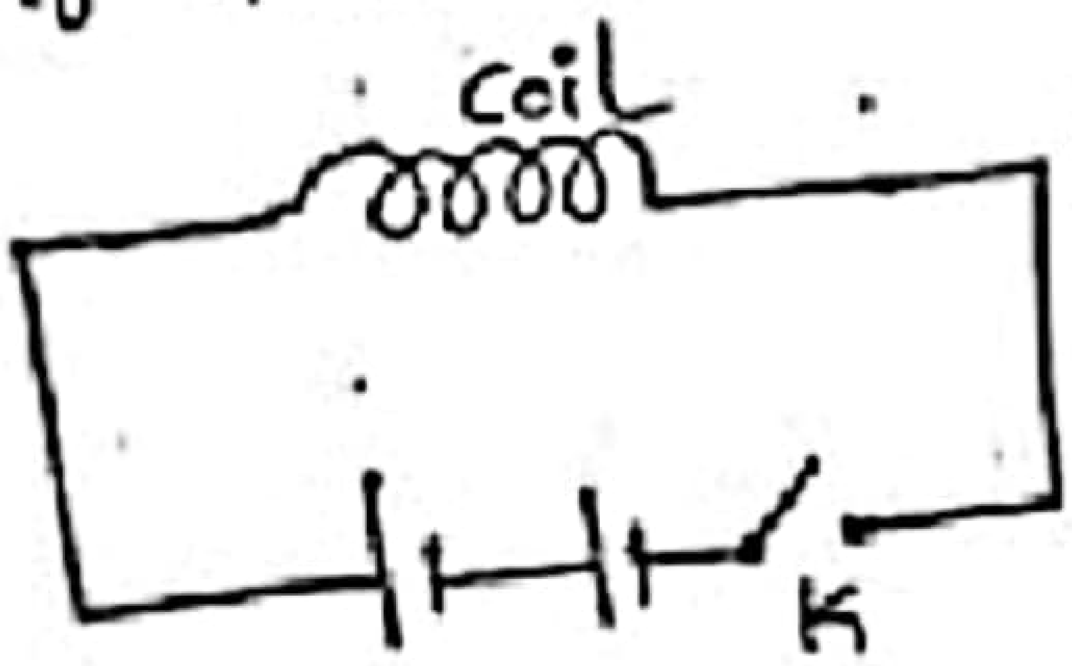
So, $N\phi_B \propto I$.

The constant of proportionality in this relation is called inductance. The S.I unit of inductance is henry and is denoted by H.

Self Induction :- self induction is the property of a coil by virtue of which it opposes the growth or decay of the current flowing through it.

(or)

The phenomenon of an emf being induced in a coil due to a varying current in the same coil is called Self Induction.



The current in the coil increases gradually from zero to a maximum during the growth of current.

Due to self induction, this growth of current is opposed and an emf is induced. this emf opposes the applied emf and is called back emf.

This induced emf opposes the decay of current and is opposite to the applied emf. This induced emf during decay time is called the direct emf.

Self inductance :- The flux linked with the coil is proportional to the current I, flowing through it

i.e $\phi \propto I$

$\phi = LI$

where "L" is known as coefficient of self induction (or) self inductance.

for 'N' turns $N\phi = LI$.

If $I = 1A$, $N\phi = L$

coefficient of self induction of a coil is defined as the magnetic flux linked with the coil when unit current flows in it.

$$e = -N\frac{d\phi}{dt} = -N\frac{d}{dt}\left(\frac{LI}{N}\right)$$

$$e = -L\frac{dI}{dt}$$

If $\frac{dI}{dt} = 1$, $\boxed{e = -L}$

$\boxed{L = -e}$

coefficient of self induction of a coil is defined as the negative induced emf in the coil when the rate of change of current in the coil is unity.

S.I unit of coefficient self induction is henry (H).

Self inductance of a circular coil :-

$$B = \frac{\mu_0 N i}{2r}$$

Total flux $= NBA = N\left(\frac{\mu_0 N i}{2r}\right)\pi r^2$

$$\therefore \quad N.\phi = \frac{\mu_0 \pi N^2 r i}{2} \rightarrow (1)$$

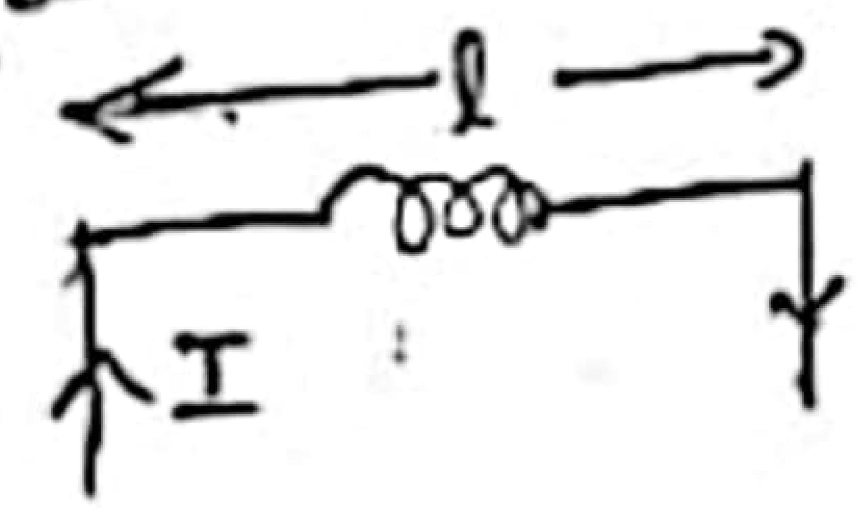
we have $N\phi = LI \quad -(2)$

comparing eq^ns (1) & (2). we get

$$\boxed{L = \frac{\mu_0 \pi N^2 r}{2}}$$

Self inductance of a Solenoid :-

For Solenoid $B = \mu_0 n I$



the magnetic flux linked with each turn of coil is

$$= B \times A = \mu_0 n I A$$

Total magnetic flux linked with the whole solenoid

$$\phi = (BA) n l$$

$$= (\mu_0 n I A) n l$$

$$= \mu_0 n^2 I l A$$

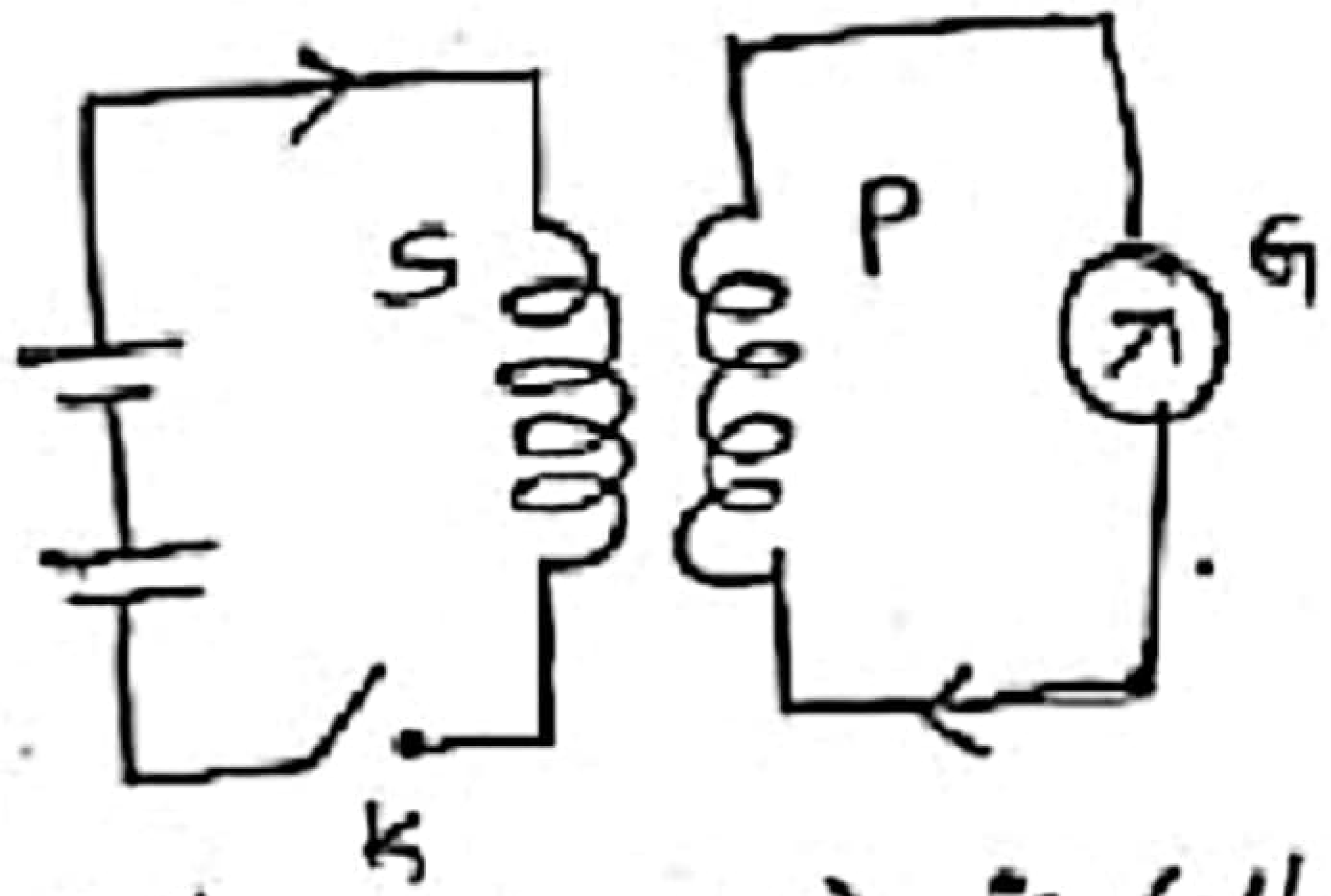
but $\phi = LI$

by comparing $\boxed{L = \mu_0 n^2 A l}$

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

$$\boxed{L = \mu_0 \frac{N^2}{l} A}$$

Mutual Induction:-



The phenomenon of an emf being induced in a coil (secondary) because of a varying current in another coil (primary) is called mutual induction.

$$\phi_s \propto I_p$$

$$\phi_s = M I_p$$

here M is called the mutual inductance between the two coils

If $I_p = 1$, then $\boxed{M = \phi_s}$

Mutual inductance between a pair of coils is numerically equal to the flux linked with one coil due to unit current in the other coil.

induced emf is, $e_s = -\frac{d\phi_s}{dt}$

$$e_s = -M \frac{dI_p}{dt}$$

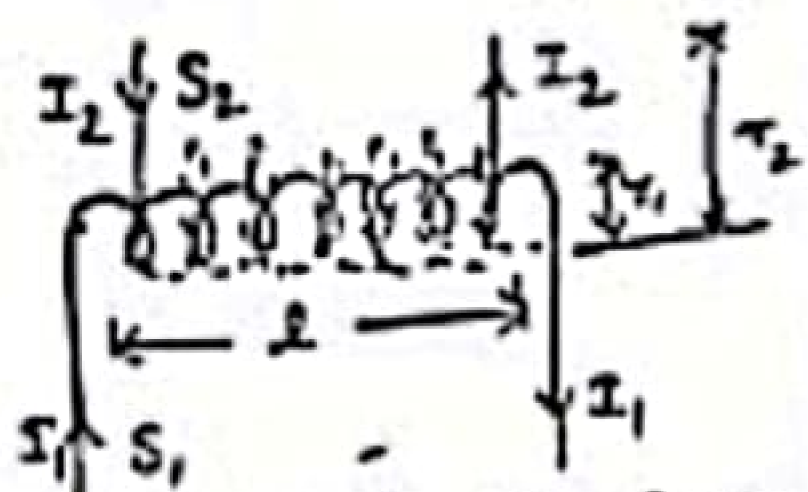
If $\frac{dI_p}{dt} = 1$, $e_s = -M$

$$|e| = M.$$

The mutual inductance between two coils is numerically equal to the emf induced in one of the coils when the rate of change of current in the other coil is unity.

Mutual Inductance of Two long Coaxial Solenoids :-

Consider two long solenoids S_1 and S_2 of same length l, such that solenoid S_2 surrounds solenoid S_1 completely.



Let n_1 be the number of turns per unit length of S_1, n_2 be the number of turns per unit length of S_2, I_1 be current passed through solenoid S_1 and ϕ_{21} be flux linked with S_2 due to current flowing through S_1.

$$\phi_{21} \propto I_1 \quad \text{or} \quad \phi_{21} = M_{21} I_1$$

where, M_{21} is the coefficient of mutual induction of the two solenoids.

When current is passed through solenoid S_1, an emf is induced in solenoid S_2. Magnetic field produced inside solenoid S_1 on passing current through it.

$$B_1 = \mu_0 n_1 I_1$$

Magnetic flux linked with each turn of solenoid S_2 will be equal to B_1 times the area of cross-section of S_1

Magnetic flux linked with each turn of solenoid, $S_2 = B_1 A$.

Therefore, total magnetic flux linked with the solenoid S_2 will be

$$\phi_{21} = B_1 A \times n_2 l$$

$$\phi_{21} = \mu_0 n_1 I_1 \times A \times n_2 l$$

$$\phi_{21} = \mu_0 n_1 n_2 A I_1 l$$

$$M_{21} = \mu_0 n_1 n_2 A l \longrightarrow (1)$$

Similarly, $M_{12} = \mu_0 n_1 n_2 A l$

$$M_{12} = M_{21} = M$$

Hence coefficient of mutual induction between two long solenoids, $M = \mu_0 n_1 n_2 A l$

Eqn (1) $\Rightarrow$ $M = \mu_0 \left(\frac{N_1}{l}\right)\left(\frac{N_2}{l}\right) \pi r_1^2 \times l$

$$M = \frac{\mu_0 N_1 N_2 A}{l}$$

If core of any other magnetic material μ is placed,

then $\boxed{M = \frac{\mu_0 \mu_r N_1 N_2}{l}}$

5.5 COMPARATIVE STUDY OF FERRO, PARA AND DIA MAGNETIC MATERIALS

Ferromagnetism	Paramagnetism	Diamagnetism
1) Substances are strongly attracted by the magnet.	1) They are feebly attracted by the magnet.	1) They are repelled by the magnet
2) These are strongly magnetised in the direction of applied magnetic field.	2) These are weakly magnetised in the direction of applied magnetic field.	2) They are weakly magnetised in a direction opposite to that of magnetic field.
3) When a ferromagnetic bar is suspended in an external magnetic field, it aligns itself parallel to the direction of the field.	3) When a paramagnetic bar is suspended in a uniform magnetic-field, it comes to rest in the direction of the field.	3) When a diamagnetic bar is suspended in a uniform magnetic-field, it comes to rest at right angles to the field.
4) Intensity of magnetisation (I) is very large, positive and varies non-linearly with the field.	4) 'I' is small, positive and varies linearly with field.	4) 'I' is small, negative and varies linearly with the field.
5) Magnetic Susceptibility is high, positive and temperature dependent $\chi = \frac{C}{T - T_c}$ (Curie–Weiss Law) These materials gets converted into Para-magnetic materials above Curie temperature.	5) χ is small, positive and varies inversly with temperature $\chi = \frac{C}{T}$	5) χ is small, negative and independent of temperature. It means materials disobey Curie's Law.
6) Relative permeability (μ_r) is much greater than unity. ($\mu_r >> 1$)	6) μ_r is slightly greater than unity. ($\mu_r > 1$)	6) μ_r is slightly lesser than unity. ($\mu_r < 1$)
7) The magnetic lines of force are pulled in strongly by the substance in a magnetic field. $B >> B_0$. B_0 = Magnetic Induction in vaccum.	7) The lines of force show a little more preference to pass through the sub-stance than through vacuum. $B > B_0$	7) The lines of force passing through these substances are less than those in vacuum $B < B_0$
8) These materials tend to move from weaker to stronger parts of a non-uniform magnetic field.	8) When it is kept in a non-uniform magnetic field, it moves from weaker to stronger field region.	8) When it is kept in a non-uniform magnetic field, it moves from stronger to weaker field region.
9) The atoms possess a permanent magnetic moment and due to the exchange interaction, the adjacent dipoles aligns in the same direction and this region behaves as a domain.	9) The atoms possess permanent magnetic moment and they are called atomic dipoles.	9) The atoms of the diamagnetic substances do not have the resultant magnetic moment.
Ex:- Fe, Co, Steel, Nickel and gadolinium etc.	Ex:- Al, Mn, Pt, Oxygen etc.	Ex:- Cu, Ag, H_2O, Au, Sb, Bi, Hg and diamond etc.