Date

UNIT – 1
Electromagnetism

Electricity :
The invisible energy that constitutes the flow of electrons in a closed circuit to do work is called "electricity".

1. Resistance(R):
The opposition offered to the flow of electric current or free electrons is called resistance

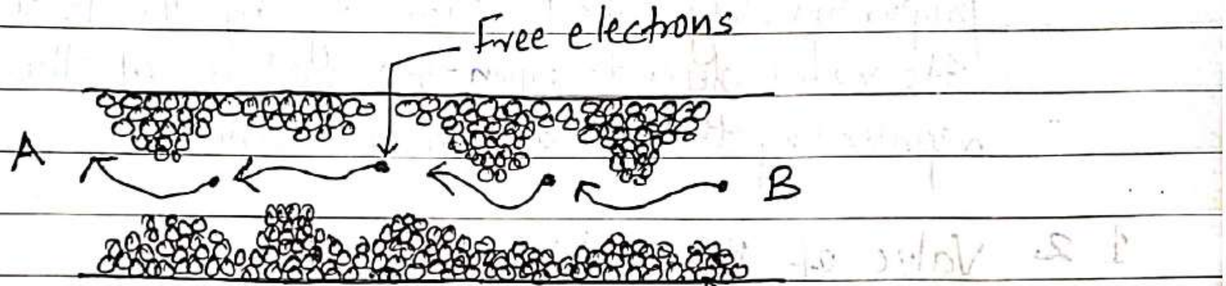


Fig: Opposition offered to electric current

Unit : Resistance is measured in ohm (or kilo ohm) and is denoted by symbol Ω or $K\Omega$.

A wire is said to have a resistance of one ohm if one ampere current passing through it produces a heat of 0.24 caloric (or one joule).

$1\Omega \rightarrow$ 1amp $\rightarrow$ 0.24 caloric or 1 joule

1.1 Laws of Resistance
The resistance (R) of a wire depends upon the following factors;

(i) It is directly proportional to its length, l i.e $R \propto l$
(ii) It is inversely proportional to its area of cross section, a, i.e $R \propto \frac{1}{a}$

(iii) It depends upon the nature (i.e atomic structure) of the material of which the wire is made.

(iv) It also depends upon the temperature of the wire.

Neglecting the last factor for the time being,

$$R \propto \frac{l}{a}$$

$$\text{or } R = \frac{\rho l}{a}$$

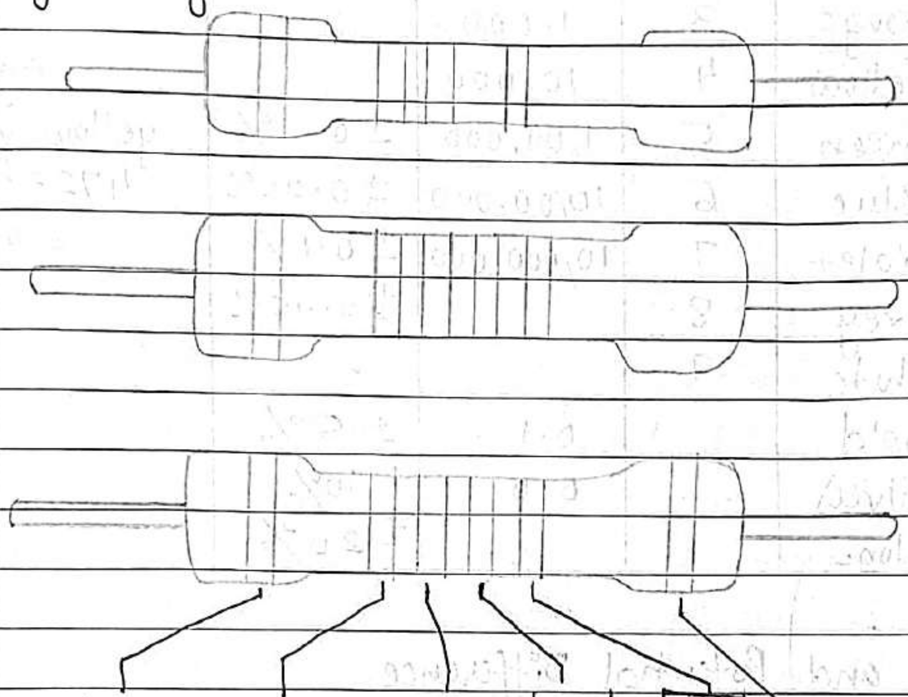
where ρ ('Rho' a greek letter) is a constant of proportionality called resistivity of the wire material. Its value depends upon the nature of the wire materi representing the third factor earlier.

1.2 Value of Resistance.

There are many different types of resistor available which can be used for both electrical and electronic circuits to control the flow of current or to produce a voltage drop in many different ways. But in order to do this the actual resistor needs t have some form of "resistance" value.

The resistance value, tolerance and wattage rating are generally printed onto the body of the resistor as numbers or letters when the resistor body is big enough to read the print, such as large power resistors. But for small resistors, these specifications must be shown in some other manner as the print would be too small to read.

So to overcome this, small resistors use coloured painted bands to indicate both their resistive value and their tolerance with the physical size of the resistor indicating its wattage rating. These coloured painted bands produce a system of identification generally known as a Resistors Colour Code.



	1st Digit	2nd Digit	3rd Digit	Multiplier	Tolerance	Temperature coefficient
				0.01	10%	
				0.1	5%	
Black →	0	0	0	1		
Brown →	1	1	1	10	1%	100ppm
Red →	2	2	2	100	2%	50ppm
Orange →	3	3	3	1K		15ppm
Yellow →	4	4	4	10K		25ppm
Green →	5	5	5	100K	0.5%	
Blue →	6	6	6	1M	0.25%	
Violet →	7	7	7	10M	0.1%	
Grey →	8	8	8		0.05%	
White →	9	9	9			

Digit Digit Multiplier = Colour colour × 10^{colour} in ohm (Ω)

The resistor colour code table

Colour	Digit	Multiplier	Tolerance
Black	0	1	
Brown	1	10	± 1%
Red	2	100	± 2%
Orange	3	1,000	
Yellow	4	10,000	
Green	5	1,00,000	± 0.5%
Blue	6	10,00,000	± 0.25%
Violet	7	10,000,000	± 0.1%
Grey	8		± 0.05%
White	9		
Gold		0.1	± 5%
Silver		0.01	± 10%
None			± 20%

eg: yellow violet Red =
$472 = 47 \times 10^2$
$= 4700\Omega$

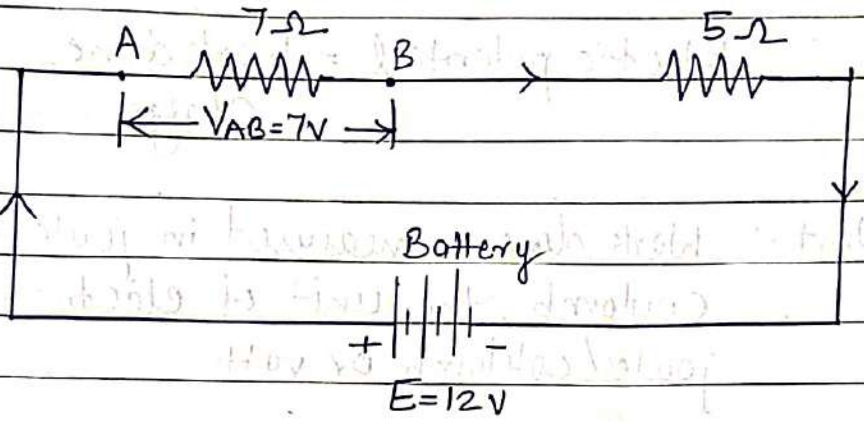
2. EMF and Potential Difference.

The amount of energy supplied by the source to each coulomb of charge is known as emf of the source, whereas the amount of energy used by one coloumb of charge in moving from one point to the other is known as potential difference between the two points.

The difference in the electric potential of the source of the two charged bodies is called potential difference.
Unit : The unit of potential difference is volt.

The electromotive force (emf) of a source, for examp

a battery is a measure of the energy that it gives to each coulomb of charge.
unit is volt.
For instant, consider a circuit as shown in Figure below,



If a battery has an emf of 12V, it means that the battery supplies 12 joule of energy to each Coulomb of charge continuously. When each coulomb of charge travels from positive terminal to negative terminal through external circuit, it gives up whole of the energy originally supplied by the battery.
The potential difference b/w any two points, say A and B, is the energy used by one coulomb of charge in moving from one point (A) to the other (B). Therefore potential difference between point A and B is 7V.

One volt is defined as energy consumption of one joule per electric charge of one coulomb.

$$1V = 1J/C$$

Or One volt is equal to current of 1 ampere times resistance of 1 ohm

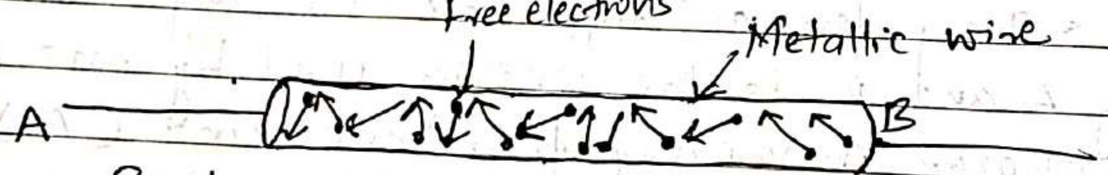
$$1V = 1A \times 1\,\Omega$$

The capacity of a charged body to do work is called electric potential.
The measure of electric potential is the work done to charge a body to one Coulomb, i.e.:

$$\text{Electric potential} = \frac{\text{Work done}}{\text{Charge}} \quad \text{or} \quad V = \frac{W}{Q}$$

Unit : Work done is measured in joule and charge in coulomb, the unit of electric potential is joule/coulomb or volt

3. Electric Current.
When an electric potential difference is applied across the metallic wire, the loosely attached free electrons as shown in the figure, start drifting towards the positive terminal of the cell. This continuous drifting of electrons constitutes the electric current.



Random movement of free electrons in metals.

Therefore a continuous drifting of electrons in an electric circuit is called electric current.

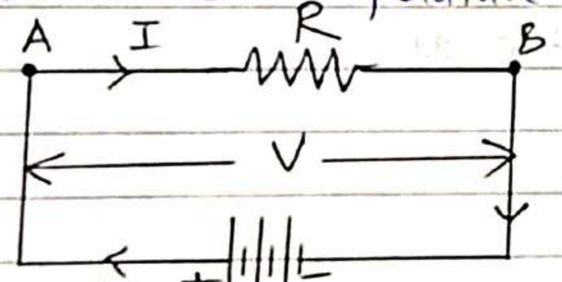
The magnitude of flow of current at any section of the conductor is the rate of flow of electrons i.e. charge flowing per second. It can be expressed mathematically as follows:

current, $I = Q/t$

Unit : Since charge is measured in coulomb and time in second, the unit of electric current is Coulomb/ sec (s) or ampere (A).

1 ampere is defined as 1 coulomb of charge per second.
An ampere is a unit of measure of the rate of electron flow or current in an electrical conductor.

4. Ohm's law
Ohm's law states that the current flowing between any two points of a conductor (or circuit) is directly proportional to the potential difference across them, as shown in figure below, provided physical conditions i.e temperature etc do not change.



Mathematically, $I \propto V$

or $\frac{V}{I}$ = constant or $\frac{V_1}{I_1} = \frac{V_2}{I_2} = \dots \frac{V_n}{I_n}$ = const.

In other words:
The ratio of potential difference across any two points of a conductor to the current flowing

between them is always constant, provided the physical conditions, i.e temperature etc do not change. This constant is called the resistance (R) of the conductor.

$$\therefore \frac{V}{I} = R$$

$$V = IR \text{ and } I = \frac{V}{R}$$

In a circuit, when current flows through a resistor the potential difference across the resistor is known as voltage drop across it, i.e $V = IR$

4.1 Limitations of ohm's law

Ohm's law cannot be applied to the non-linear circuits such as circuits containing electronic tubes or transistors and the circuits used to produce electric arc.

5. Electromagnetism

Electromagnetism is the branch of engineering dealing with the magnetic effects of an electric current.

5.1 Important Properties of magnet.

(i) It attracts small pieces of iron

(ii) When freely suspended by a piece of silk fibre, it sets itself in a definite direction so that its north pole points towards the north direction and the south pole points towards the south direction.

(iii) Like magnetic poles repel and unlike poles attract each other.

5.2 Laws of magnetism

The two fundamental laws of magnetism are as follows :

(i) As already mentioned above, the first law states that like magnetic poles repel and unlike poles attract each other.

(ii) The second law states that the force (F) exerted by one pole on another pole is directly proportional to the product of the pole strength and inversely proportional to the square of the distance (d) between them. It also depends on the nature of the medium surrounding the poles

i.e.

$$F \propto \frac{m_1 m_2}{d^2}$$

$$\therefore F = K \frac{m_1 m_2}{d^2}$$

Where m_1 and m_2 are the poles' strengths.
The value of the constant K depends on the nature of the surrounding medium.

5.3 Magnetic Field

The region in the neighbourhood of a magnet within which the influence of the magnet is felt is termed as magnetic field.

5.4 Magnetic Lines of Force.

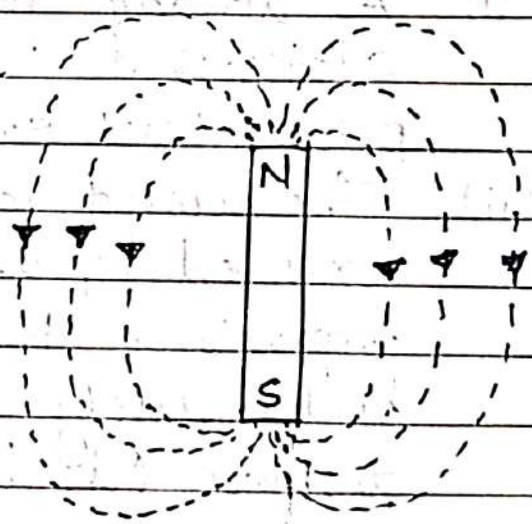
These are the imaginary lines (having no physical existence) introduced by Faraday for the pictorial representation of the distribution of a magnetic field

Properties of lines of force :

(i) Lines of force are always in the form of closed curves originating on a N-pole and terminating on a S-pole

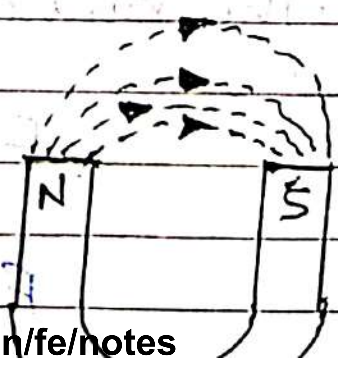
(ii) Lines of force never cross one another

(iii) Parallel lines of force acting in the same direction repel one another

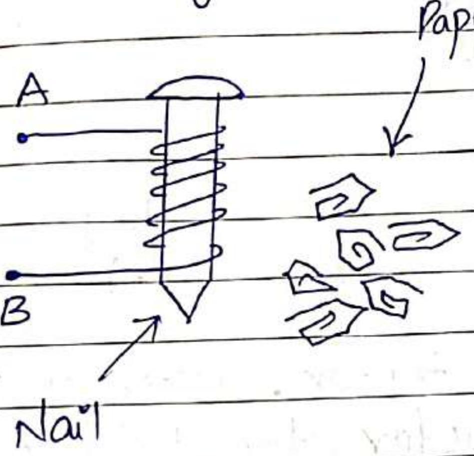


(iv) Lines of force always try to contract in length and thus behave like stretched elastic threads

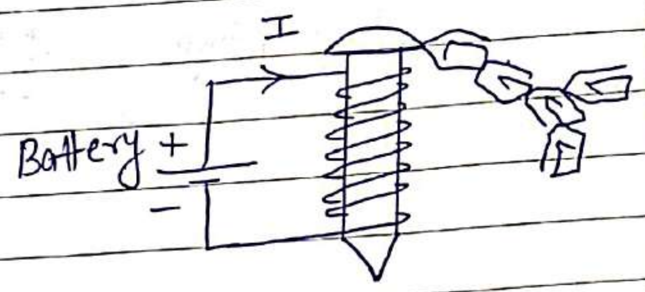
(v) Magnetic lines of force always take the path of least reluctance (opposition).



6. Magnetic Effect of an electric current.
Hans christial oersted had show that the electric current generates a magnetic field and this is called electromagnetism.



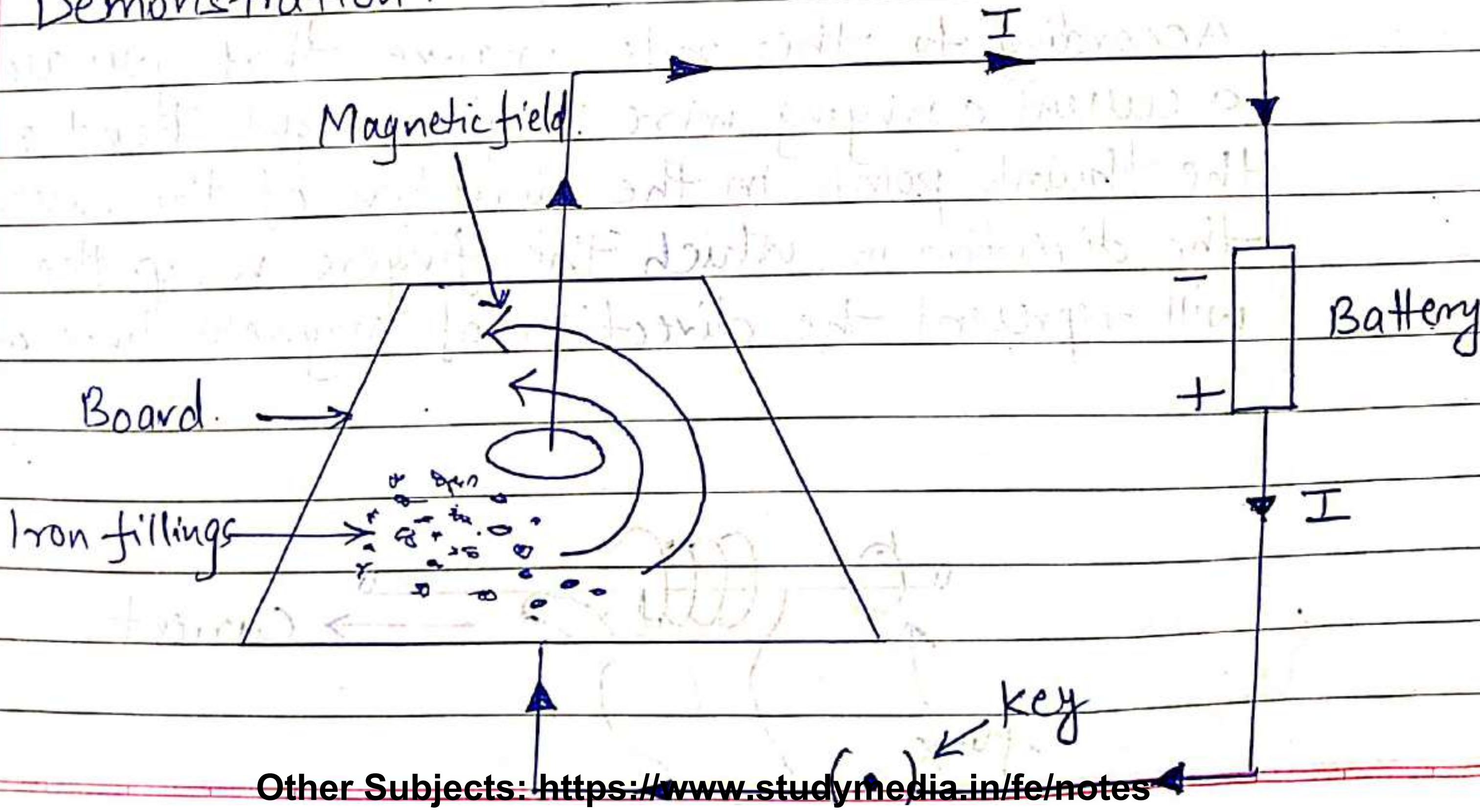
Nail is not energised, hence paper clips are not attracted by iron nail

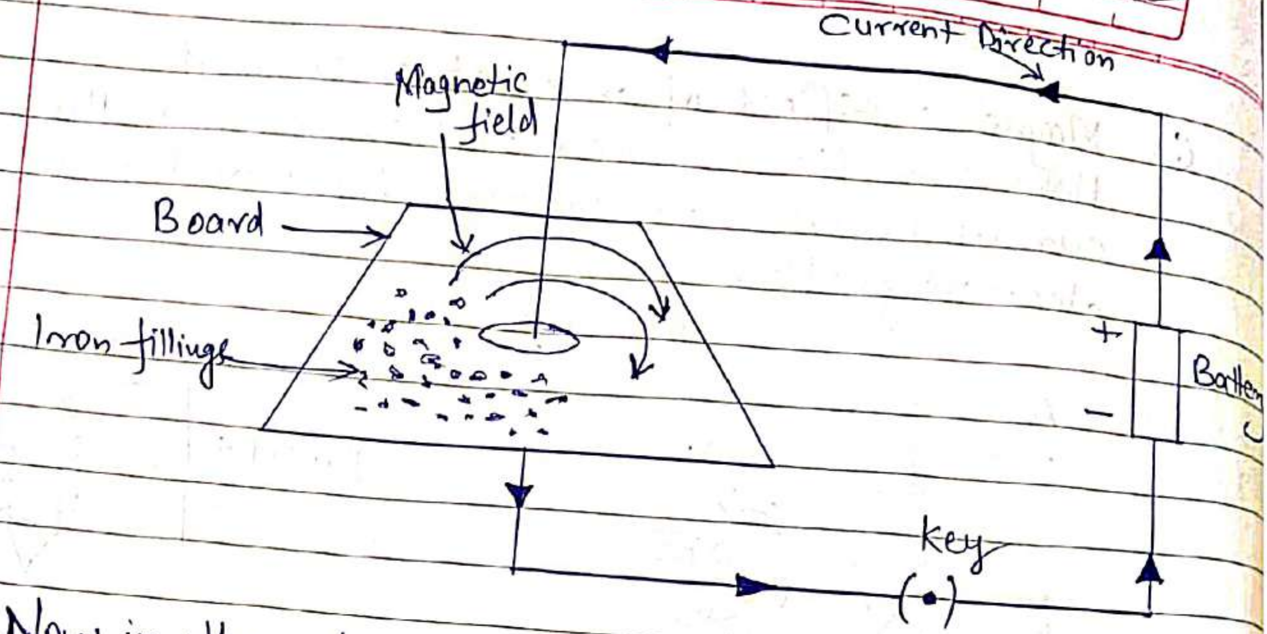


When the iron nail is connected to a battery, then iron nail is attracting paper clips because of the current flowing through it.

It shows that electric current generates a magnetic field around a material.

Demonstration:



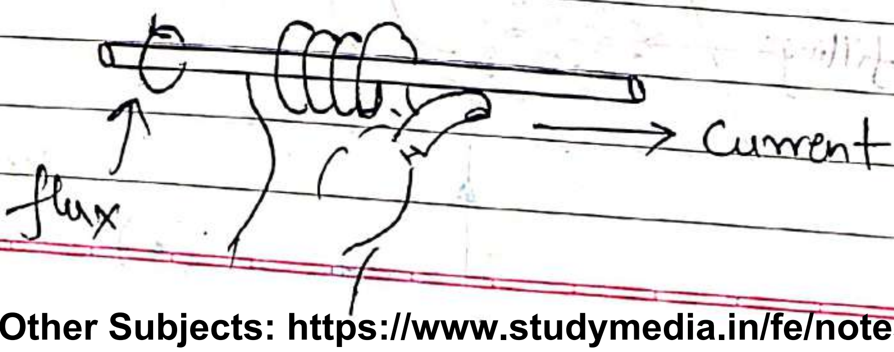


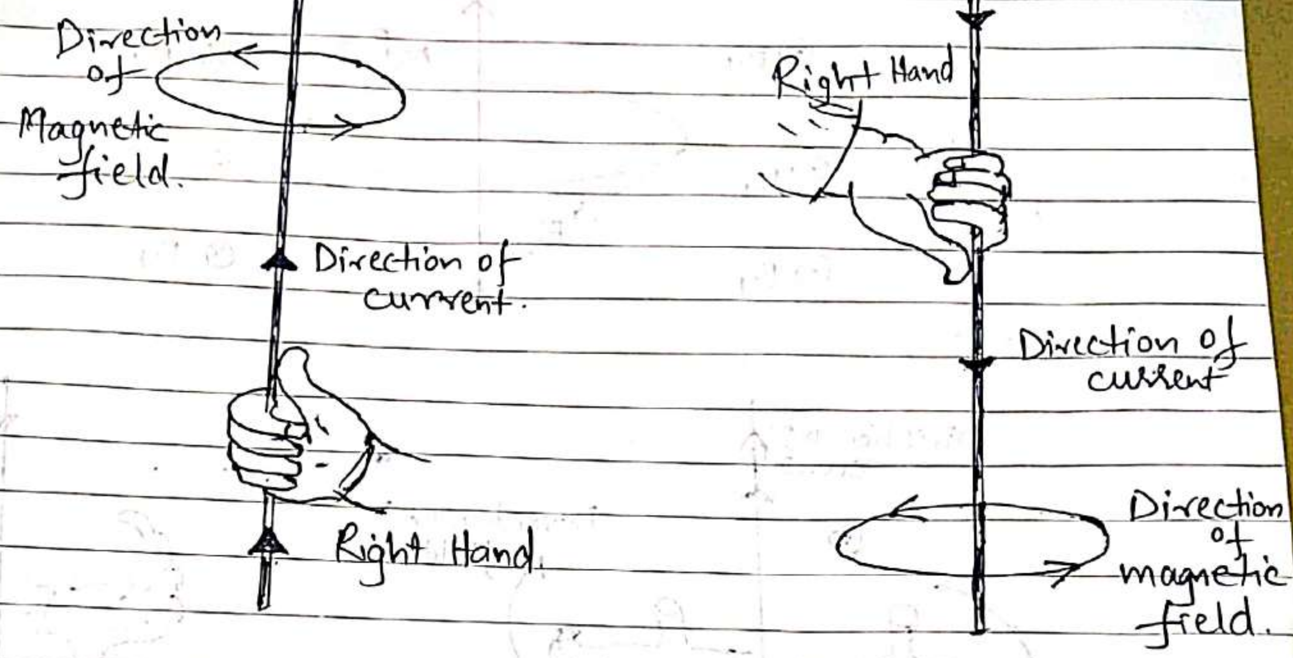
Now in the above demonstration, when a current is flowing through the conductor, the field is generated across the conductor. Because of this, iron fillings gets attracted and exerts a force. The direction of magnetic field is given by Right Hand thumb Rule.

7. Right Hand Thumb Rule.

Right Hand Thumb Rule was given by Maxwell. So this rule is also known as Maxwell's right hand thumb rule.

According to this rule, imagine that you are holding a current carrying wire in your right hand so that the thumb points in the direction of the current, then the direction in which the fingers wrap the wire will represent the direction of magnetic lines of force.





Right Hand Thumb Rule

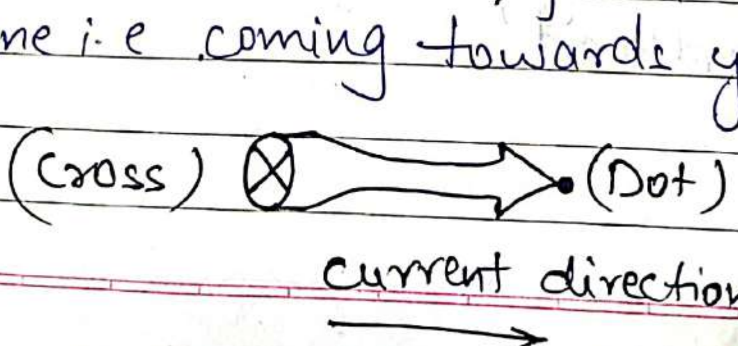
Application:
It is used to find the direction of the magnetic field lines around a current carrying conductor.

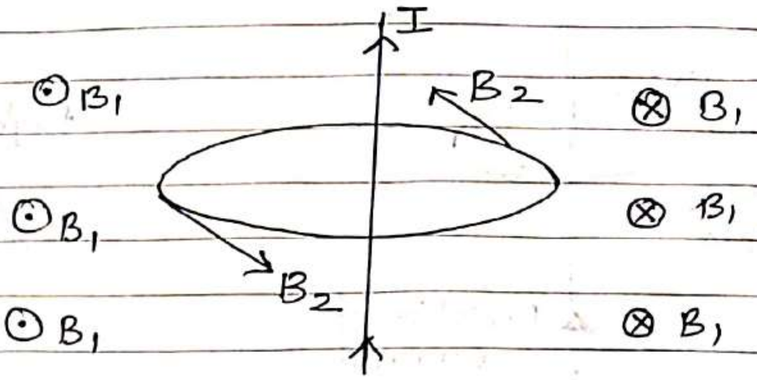
8 Cross and Dot Conventions

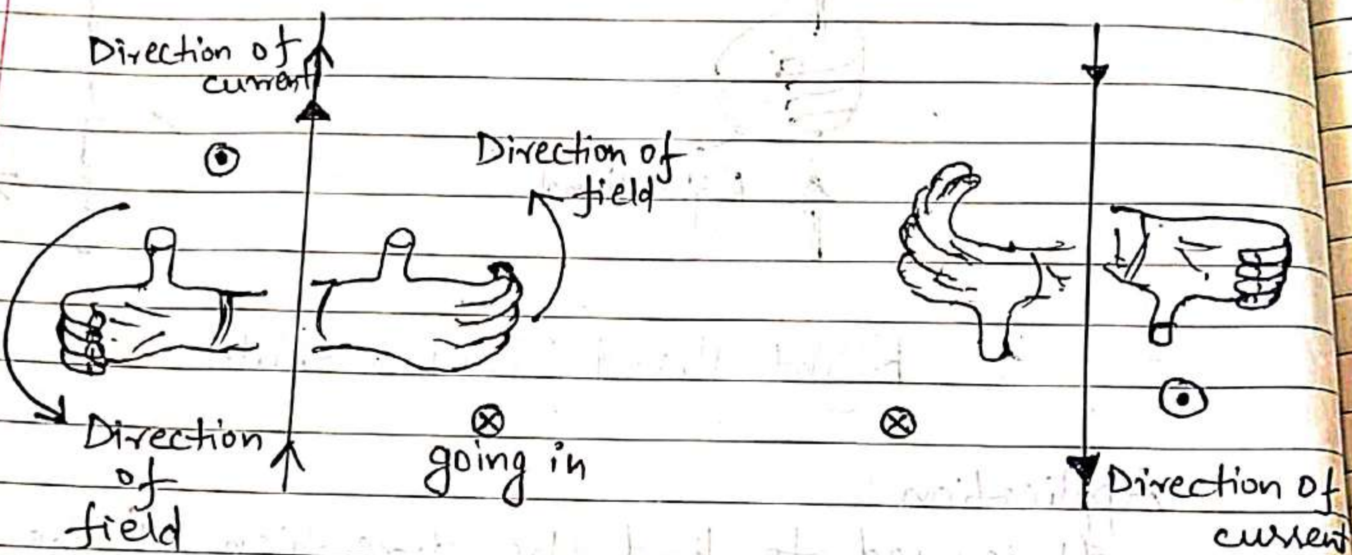
Cross and Dot convention applies on electric current. It is generally used to denote the direction of an electric current passed through a conductor.

Cross (x) means current is going into the plane i.e away from you.

Dot (·) means current/field is going out from the plane i.e coming towards you.







9. Nature of magnetic field on long straight conduct

A straight conductor carrying an electric current is always surrounded all along its length by a magnetic field

The lines of force are in the form of concentric circles in planes at right angles to the conductor and their direction is dependent on the direction of the current producing them. This can be very well demonstrated by passing the straight conductor through a cardboard

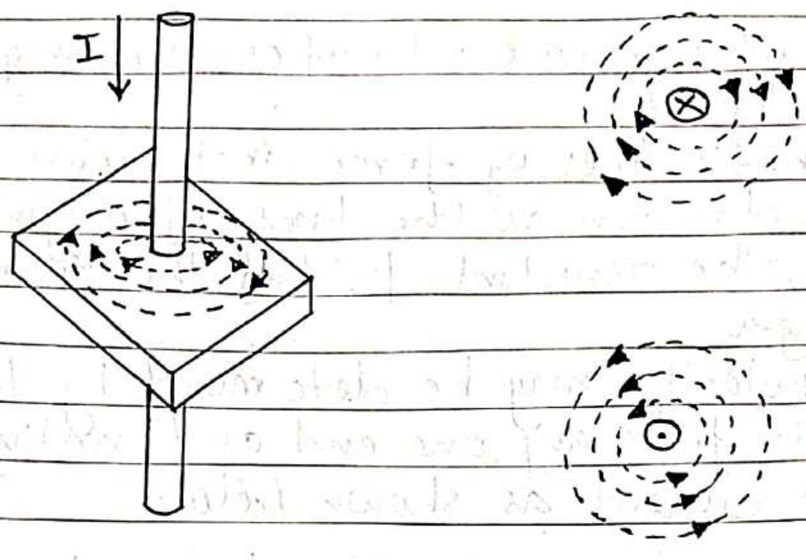


Fig: Magnetic field set up around a current carrying conductor

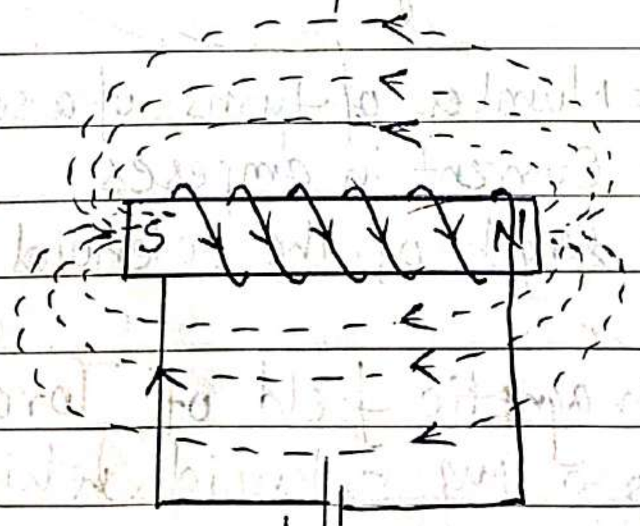
10. Nature of magnetic field of solenoid.

Solenoid: A Solenoid is a coil of wire in a corkscrew shape wrapped around a piston often made of Iron.

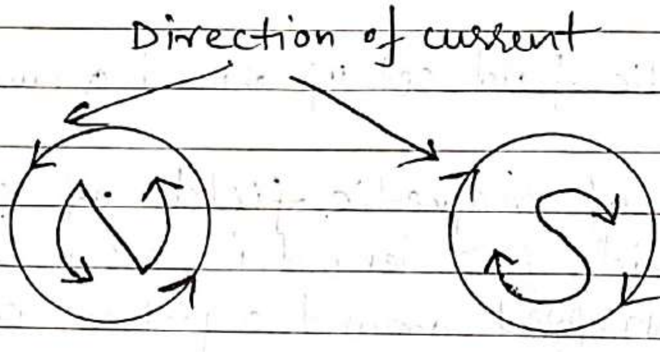
Or

when a long conductor is wound with number of turns close together to form a coil whose axial length is several times greater than the diameter of its turns, it is known as solenoid.

When current is passed through the solenoid, the magnetic field produced by it acts through the coil along its axis in the space around the solenoid.



use of iron core intensifies the magnetic field of the solenoid.
Magnetic lines of force in the core being in the same direction as the lines of original magnetic field, the resultant field of the solenoid becomes stronger
The polarity may be determined by looking at the solenoid from any one end and noting the direction of the current as shown below.



Magnetic field strength inside a long solenoid :
The magnetic field strength along the axis of a solenoid is a function of the numbers of turns of the coil and the magnitude of the current flowing through it and is given by the following expression :

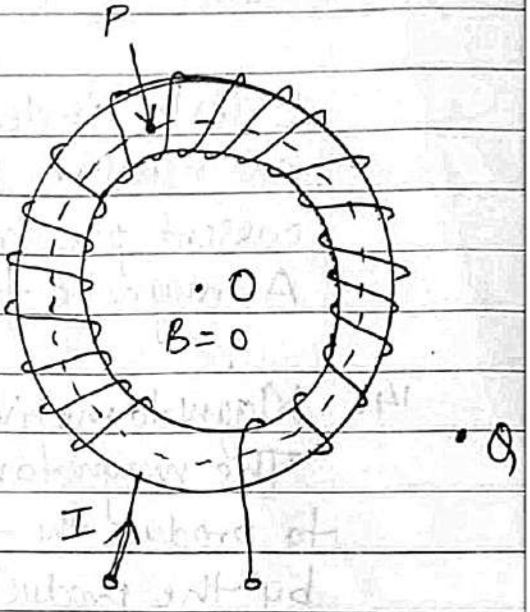
$$H = \frac{NI}{l} \text{ newtons / weber or amp / metre}$$

Where, N = Number of turns of a solenoid
I = Current in amperes
l = length of the solenoid in metres.

1. Nature of magnetic field of Toroid.
A toroid is a long solenoid which is bend into

circular form. So, toroid is equivalent to the solenoid having infinite length but it has finite no. of circular turns. Consider a toroid having radius r, carrying a current I through it. If N is the number of turns in toroid and n be the no. of turns per unit length, then

$$n = \frac{N}{2\pi R}$$



Then the magnetic field due to infinite solenoid is

$$B = \mu_0 n I$$

then the magnetic field due to toroid is

$$B = \mu_0 \frac{N I}{2\pi R} \text{ Tesla.}$$

The magnetic field exists only in the tabular area bound by the coil and does not exist in the area inside and outside the toroid.

i.e. B is zero at O and Q and non zero at P.

12. Magnetic Flux (ϕ)

The total number of lines of force in any particular magnetic field is called the magnetic flux.

Its unit is Weber

1 Weber means 10^8 lines

The weber is the magnetic flux that linking a circuit of one turn, would produce in it an electromotive force of 1 volt if it were reduced to zero at a uniform rate in 1 second.

13. Magnetic Flux density (B)
The flux per unit area (a) in a plane at right angles to the flux is known as flux density.

$$\boxed{B = \frac{\phi}{a}}$$

unit : Tesla (T) or wb/m^2.

1 Tesla is defined as the field intensity generating one newton (N) of force per ampere (A) of current per meter of conductor.
A magnetic field of one Tesla is quite strong

14. Magnetomotive force (MMF)
The magnetomotive force which produces or tends to produce the flux in the magnetic circuit is given by the product of turns on the magnetising coil (N and the current flowing in the coil (I) i.e

$$\boxed{MMF = NI \text{ amperes}}$$

Or,
The magnetomotive force is usually defined as the work done in joules on a unit magnetic pole in taking it once round a closed magnetic circui

15. Magnetic Field Strength (H)
The force experienced by unit North pole (i.e N pole with one weber pole strength) placed at any point in a magnetic field is known as magnetic field strength at that point.

unit : Newtons per weber (N/Wb)
Amperes per metre (A/m)

16. Permeability

It may be defined as the ease with which a magnetic flux permeates a medium or in other words, it is the receptiveness of the medium in having flux set up in it.

16.1 Permeability of free space or Magnetic space constant (μ_0)

For a magnetic field in vacuum (or free space) the ratio of flux density (in tesla) to magnetic field strength (in amperes / metre) producing that flux density is called the permeability of free space or magnetic space.

$$\boxed{\therefore \mu_0 = \frac{B_0}{H} = 4\pi \times 10^{-7} \ H/m}$$

16.2 Absolute Permeability

The ratio of magnetic flux density in a particula medium (other than vacuum) to the magnetic field strength at the same location producing that flux density is called the absolute permeability of that medium.

$$\boxed{\mu = \frac{B}{H} \ H/m}$$

16.3 Relative Permeability

The ratio of the flux density produced in a material to the flux density produced in a vacuum (or free space) by the same magnetic field strength under identical conditions is called the relative permeability of that material

$$\boxed{\mu_r = \frac{B}{B_0}}$$

We have =

$$\mu_0 = \frac{B_0}{H} \implies B_0 = \mu_0 \cdot H$$

$$\mu = \frac{B}{H} \implies B = \mu \cdot H$$

$$\therefore \mu_r = \frac{B}{B_0} = \frac{\mu \cdot H}{\mu_0 \cdot H} = \frac{\mu}{\mu_0}$$

$$\therefore \boxed{\mu = \mu_0 \cdot \mu_r}$$

Relative permeability is a ratio of absolute permeability to permeability of free space, has no unit.

For air and non-magnetic materials,

$$\mu_r = 1$$

$$\therefore \boxed{\mu = \mu_0}$$

17. Reluctance (S)

Reluctance is the resistance offered by a meterial to the passage of magnetic flux through it.

$$S = \frac{l}{\mu_0 \mu_r \cdot a} \text{ amperes / weber}$$

From the above equation,

$S \propto$ length of the magnetic circuit

$\propto \frac{1}{\text{cross sectional area}}$

$\propto \frac{1}{\text{relative permeability}}$

18. Permeance

The permeance is defined as that property of the magnetic circuit due to which it permits the passage of magnetic flux through it.

$$\text{Permeance} = \frac{1}{\text{Reluctance}} \text{ (Wb / amp)}$$

we know,

$$H = \frac{NI}{l}$$

$$B = \mu \cdot H \Rightarrow \mu_0 \mu_r \cdot H$$

$$B = \mu_0 \mu_r \cdot \frac{NI}{l}$$

$$\phi = B \cdot a$$

$$\phi = \mu_0 \mu_r \cdot \frac{NI}{l} \cdot a$$

$$\phi = \frac{NI}{\left[\frac{l}{\mu_0 \mu_r \cdot a}\right]} \text{ (wb)}$$

$$\boxed{\phi = \frac{NI}{S} = \frac{MMF}{S}}$$

19. Magnetic circuits

We know that electric circuit is the path provided for electric current.

On similar lines, the magnetic circuit can be defined as the closed path traversed by the magnetic flux.

In the electrical circuit, various electrical quantities like current, emf and resistance can be easily calculated with the help of the simple ohm's law.

In the magnetic circuit also, it is possible to determine the values of different magnetic quantities associated with the circuit with the help of simple quantitative relations existing between them.

19.1 Series Magnetic circuits

A magnetic circuit may consist of several parts of different magnetic materials with different lengths, cross sectional areas and permeabilities. such a circuit is known as composite magnetic circuit.

In a composite magnetic circuit, when the various parts are connected one after the other in such a way that they form a chain, it is called a series magnetic circuit.

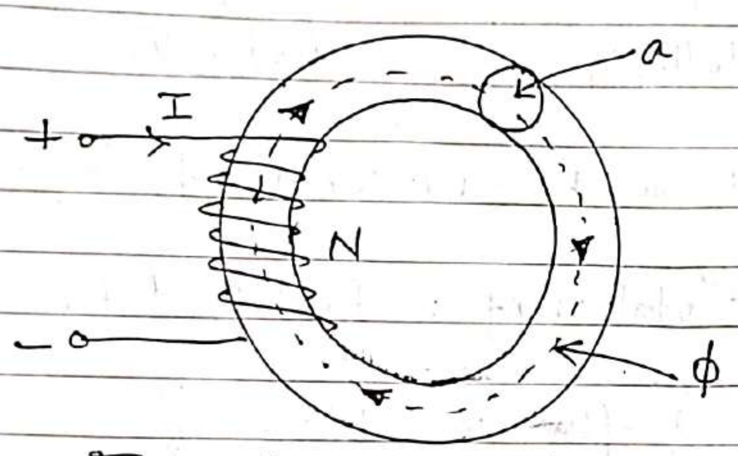
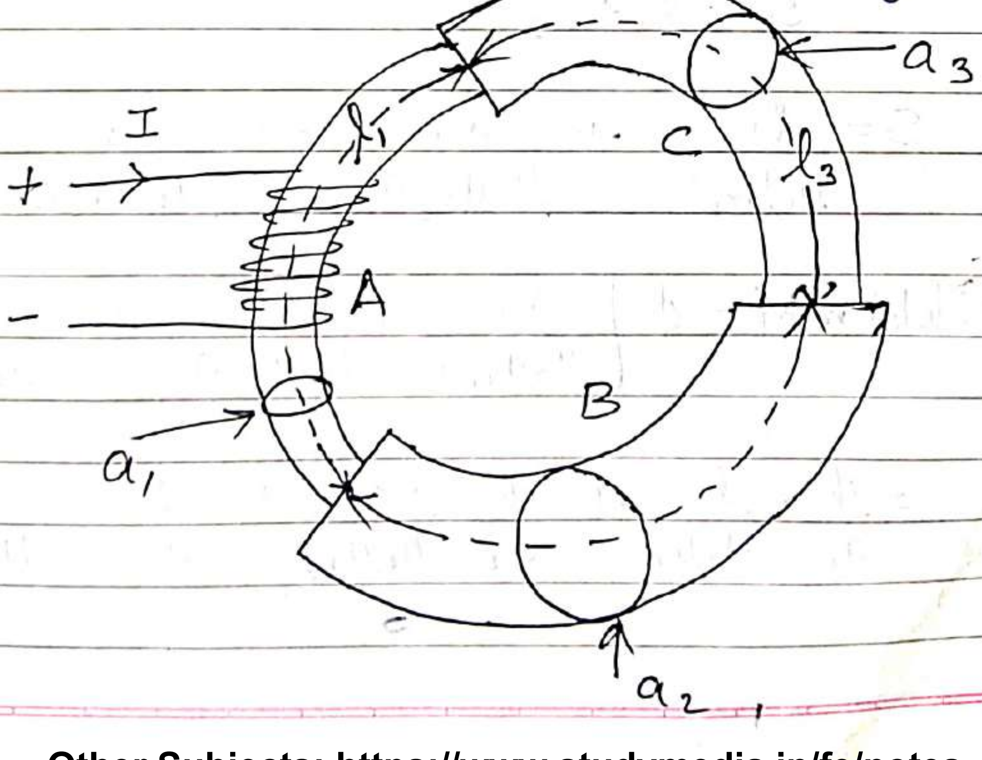


Fig: Simple Magnetic circuit.

Consider a series magnetic circuit consisting of three parts A, B, C of different magnetic materials.



Let l_1, l_2 and l_3 be the lengths ; a_1, a_2 and a_3 be the cross sectional areas and μ_{r_1}, μ_{r_2} and μ_{r_3} be the relative permeabilities of the parts A, B and C.

If S_1, S_2 and S_3 are the reluctances of these three parts then by equation,

$$S_1 = \frac{l_1}{\mu_0 \mu_{r_1} a_1} \; ; \; S_2 = \frac{l_2}{\mu_0 \mu_{r_2} a_2} \; ; \; S_3 = \frac{l_3}{\mu_0 \mu_{r_3} a_3}$$

If F_1, F_2 and F_3 are the mmfs of three parts then

$$\text{Total mmf} = F_1 + F_2 + F_3$$

$$\left\{ \text{flux} = \frac{\text{MMF}}{\text{Reluctance}} \right\}$$

$$\text{Total mmf} = \phi S_1 + \phi S_2 + \phi S_3$$

$$F = \phi \cdot S$$

$$\phi S = \phi S_1 + \phi S_2 + \phi S_3$$

$$S = S_1 + S_2 + S_3$$

$$S = \frac{l_1}{\mu_0 \mu_{r_1} a_1} + \frac{l_2}{\mu_0 \mu_{r_2} a_2} + \frac{l_3}{\mu_0 \mu_{r_3} a_3}$$

$$\therefore \text{Total mmf} = \phi \left[\frac{l_1}{\mu_0 \mu_{r_1} a_1} + \frac{l_2}{\mu_0 \mu_{r_2} a_2} + \frac{l_3}{\mu_0 \mu_{r_3} a_3} \right]$$

$$= \frac{\phi}{a_1} \cdot \frac{l_1}{\mu_0 \mu_{r_1}} + \frac{\phi}{a_2} \cdot \frac{l_2}{\mu_0 \mu_{r_2}} + \frac{\phi}{a_3} \cdot \frac{l_3}{\mu_0 \mu_{r_3}}$$

$$= \frac{B_1}{\mu_0 \mu_{r_1}} \cdot l_1 + \frac{B_2}{\mu_0 \mu_{r_2}} \cdot l_2 + \frac{B_3}{\mu_0 \mu_{r_3}} \cdot l_3$$

$$= H_1 l_1 + H_2 l_2 + H_3 l_3$$

19.2 Parallel magnetic circuits

When a magnetic circuit has two or more flux paths in parallel, it is called a parallel magnetic circuit.

Total flux, $\phi = \phi_1 + \phi_2 + \phi_3, \ldots \phi_n$

$$\therefore \frac{1}{S} = \frac{1}{S_1} + \frac{1}{S_2} + \frac{1}{S_3} + \ldots \frac{1}{S_n}$$

In shell type transformers and most of the electrical machines, magnetic circuits are in the form of parallel symmetrical pairs and involve series and parallel combinations of branch reluctances.

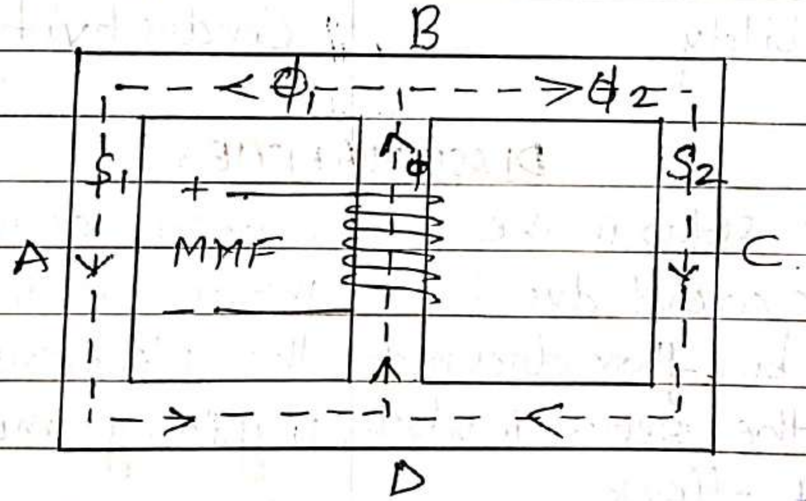


Fig: A series parallel magnetic circuit.

Difference between electric and magnetic circuit

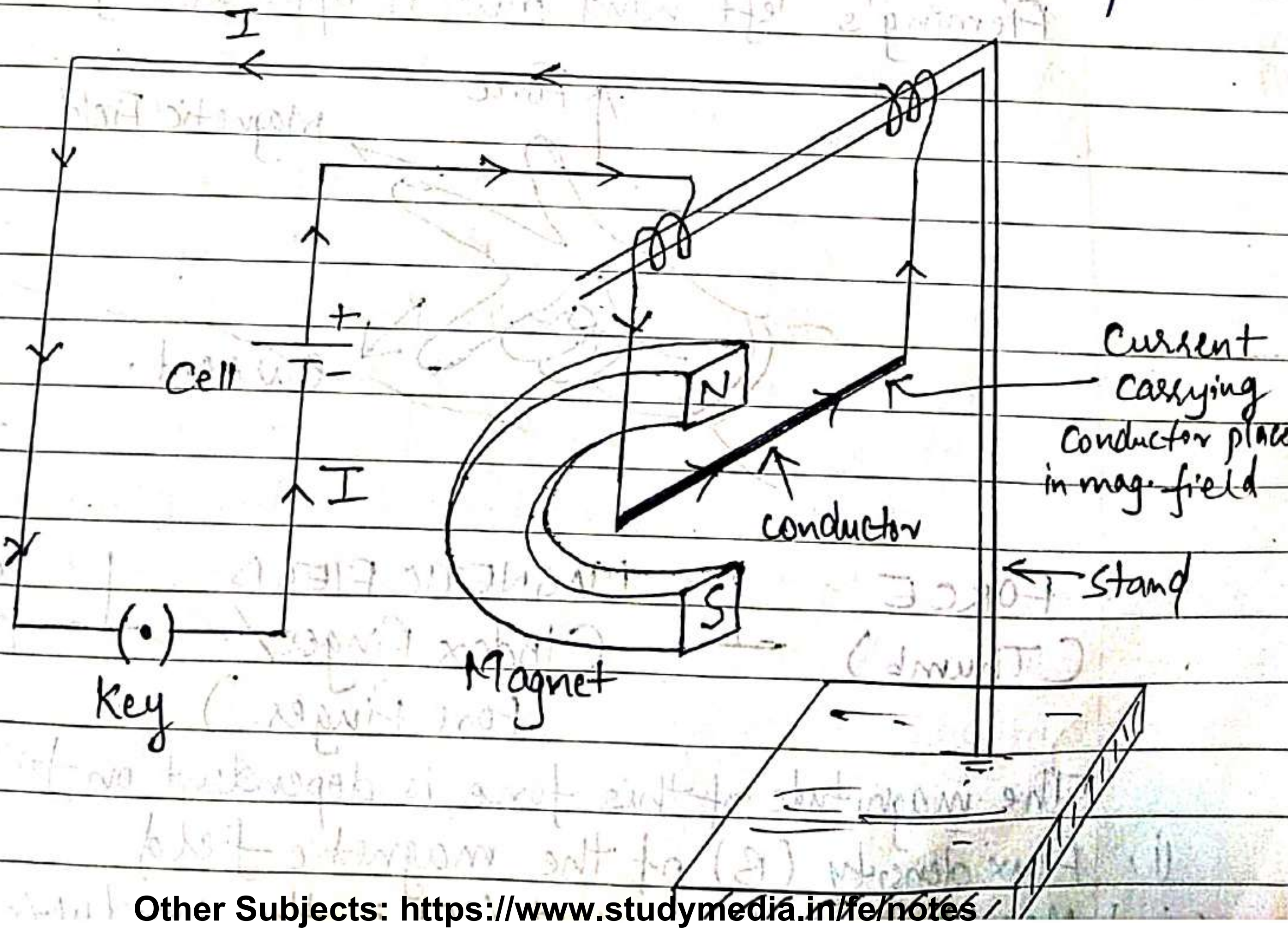
	MAGNETIC CIRCUIT	ELECTRIC CIRCUIT
	SIMILARITIES	
1.	Magnetic circuit is the path for magnetic flux	Electric circuit is the path for electric current
2.	MMF (ampere)	EMF (volt)
3.	Magnetic flux, ϕ (Wb)	Electric current, I (ampere)
4.	Reluctance, S (A/Wb) $S = \frac{1}{\mu_0 \mu_r} \times \frac{l}{a}$	Resistance, R (ohm) $R = \rho \frac{l}{a}$
5.	$\phi = \frac{MMF}{S}$	$I = \frac{EMF}{R}$
6.	Flux Density, B (Tesla) $B = \frac{\phi}{a}$	Current Density, J (A/m^2) $J = \frac{I}{a}$
7.	Permeance $= \frac{1}{S}$	Conductance $= \frac{1}{R}$
8.	Permeability	Conductivity
	DISSIMILARITIES	
1.	Flux is setup in the magnetic circuit due to MMF, but flux does not flow in the sense in which current flows.	Current actually flows in the electric circuit as the electrons drift or physically move.
2.	Initially energy is needed only for creating the flux in the magnetic circuit	Energy is continuously required to maintain the flow of current in the electric circuit

3.	Impossible to confine all the flux to one path	Possible to confine the current to a definite path using insulation
4.	Permeability changes depending on the flux density. Hence reluctance changes. S = function of permeability	Resistance almost constant under steady temperature conditions. ∴ conductivity almost constant.

20. Force on current carrying conductor placed in a magnetic field.

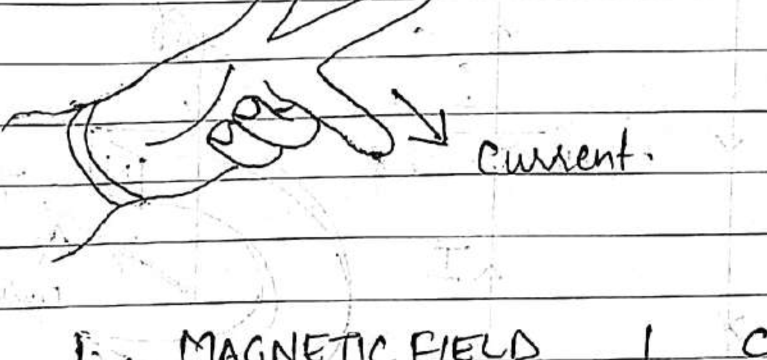
It is very interesting to know that what will happen when a current carrying conductor will be placed in a magnetic field.

To understand this, we will demonstrate an experiment



As a result of this experiment, it is observed that a force will be acting on the conductor which will make the wire to deflect.
Now, if the force is acting on the conductor then what will be the direction of the force?
So, the direction of the force can be easily find out by using Fleming's Left Hand Rule.

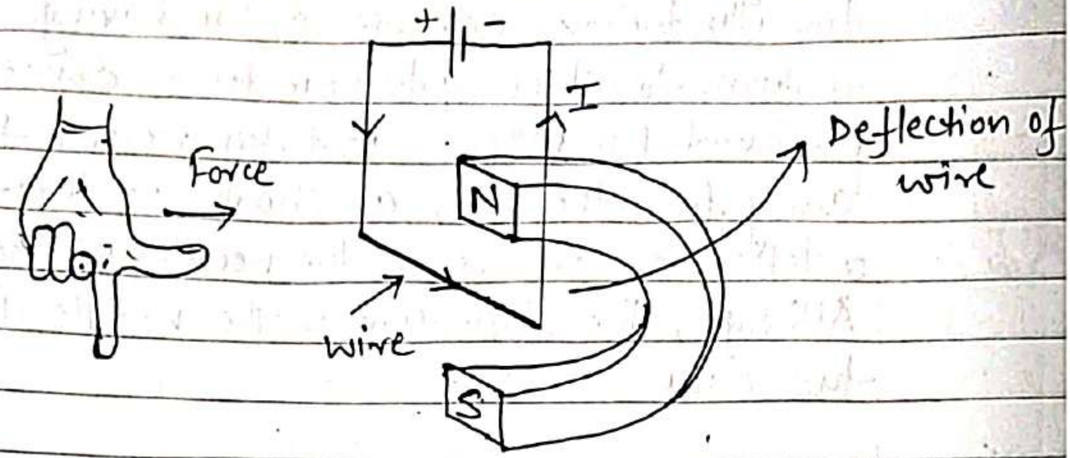
2) Fleming's Left Hand Rule
According to Fleming's Left Hand Rule, if the thumb, fore-finger and middle finger of the left hand are stretched to be perpendicular to each other as shown in the figure below and if the fore finger represents the direction of magnetic field, the middle finger represents the direction of current, then the thumb represents the direction of force.
Fleming's left hand rule is applicable for motors.



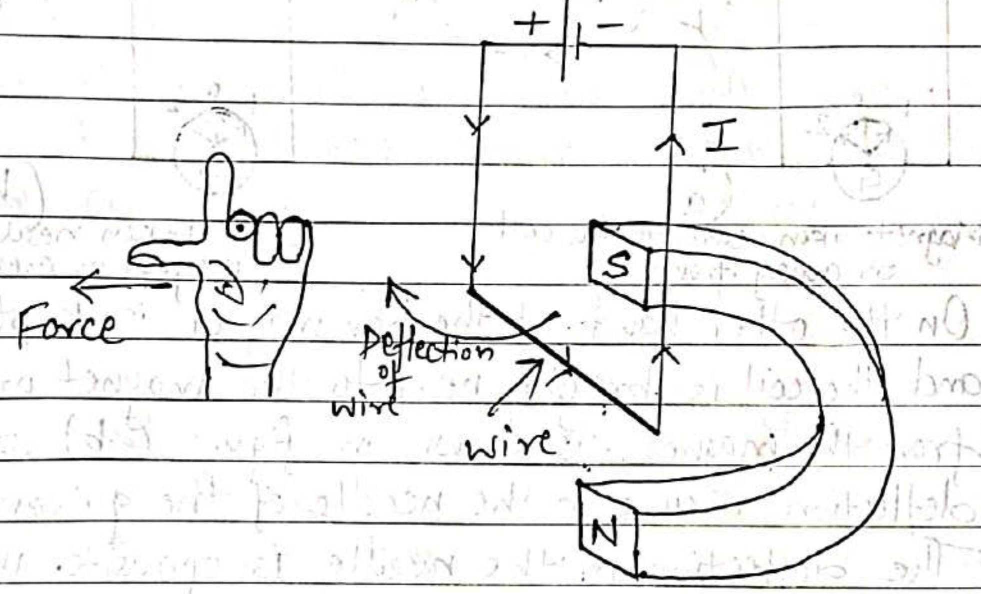
FORCE (Thumb) $\perp$ MAGNETIC FIELD (Index Finger/ Fore Finger) $\perp$ CURRENT (Middle Finger)

The magnitude of this force is dependent on followings factors
i) Flux density (B) of the magnetic field
ii) Magnitude of the current (I) in the conductor in amperes
iii) length (active length) of the conductor.
Active length is the part of the total length of conductor which actually lies in the mag. field.

$F = BIl$ newtons



Movement towards left

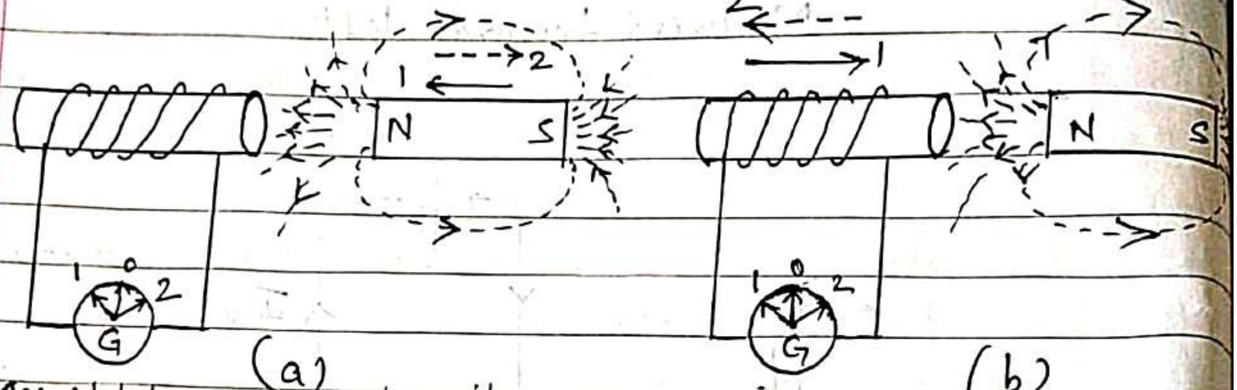


Movement towards Right.

22. Electromagnetic Induction.

The phenomenon by which an emf is induced in a circuit (and hence current flows when the circuit is closed) when magnetic flux linking with it changes is called electromagnetic Induction.

For illustration, consider a coil having a large number of turns to which galvanometer is connected. When a permanent bar magnet is taken nearer to the coil or away from the coil, as shown in the figure below(a) a deflection occurs in the needle of the galvanometer. Although, the deflection in the needle is opposite in the two cases.



(a) Magnet taken nearer to the coil or away from it.

(b) Coil taken nearer to the magnet or away from it.

On the other hand, if the bar magnet is kept stationary and the coil is brought near to the magnet or away from the magnet as shown in figure (b), again a deflection occurs in the needle of the galvanometer. The deflection in the needle is opposite in the two cases. However if both the magnet and the coil are kept stationary, no matter how much flux is linking with the coil, there is no deflection in the galvanometer needle.

The following points are worth noting.

1. The deflection in the galvanometer needle shows that emf is induced in the coil. This condition occurs only when flux linking with the circuit changes i.e either magnet or coil is in motion.

2. The direction of induced emf in the coil depends upon the direction of magnetic field and the direction of motion of coil.

Summing the results of the above experiments, we get the famous law known as Faraday's law of electromagnetic Induction.

Ist - The Faraday's law of electromagnetic induction states that whenever the number of lines of force linking with a circuit changes, an emf is always induced in it.

2nd - The magnetude of this induced emf is proportional to the rate of change of flux linkages (flux x turns) such an emf lasts as long as the change is taking place

Alternatively,
When a conductor cuts or is cut by the magnetic flux, an emf is generated in the conductor and the magnitude of the generated emf is proportional to the rate at which the conductor cuts or is cut by the magnetic flux.

Magnitude of the Induced emf :
If the flux linking with a particular coil having N turns changes from ϕ_1 to ϕ_2 webers in small time of 't' seconds then

Rate of change of flux linkages = $\dfrac{(\text{Final flux linkage}) - (\text{Initial flux linkage})}{\text{time}}$

$$= \frac{N\phi_2 - N\phi_1}{t}$$

According to Faraday's law of electromagnetic inducti[on] the induced emf (e) is given by

$$e \propto \text{Rate of change of flux linkage}$$
$$\propto \frac{N\phi_2 - N\phi_1}{t}$$

$$\therefore \; e = KN\frac{(\phi_2 - \phi_1)}{t} \text{ volts}$$

where K is the constant of proportionality. The uni[t] of emf 'volt' is so defined that
K = 1 in the above expression. (*)

$$\therefore \; e = \frac{N(\phi_2 - \phi_1)}{t} \text{ volts.}$$

* The emf induced in the coil is said to be one volt when a flux of one weber linking a coil of one turn is reduced to zero to a uniform rate in one second. Now

$$e = \frac{KN(\phi_2 - \phi_1)}{t} \text{ volts.}$$

Here $e = 1V$, $N = 1$, $\phi_2 - \phi_1 = 1 Wb$ and $t = 1s$.

$\therefore$ By substituting,
we get $K = 1$

Expressing the above equation in differential form, we get

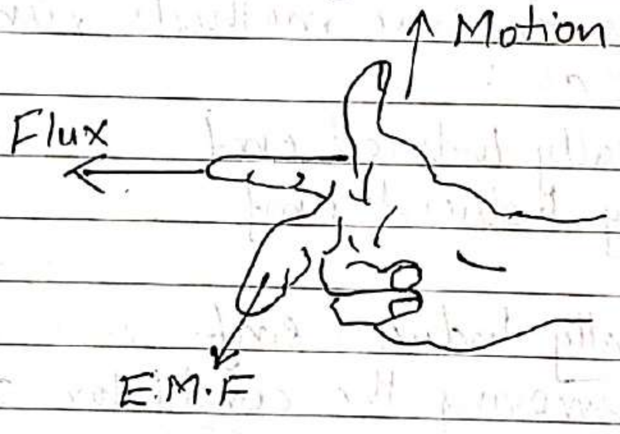
$$e = N\frac{d\phi}{dt} \text{ volts}$$

22.1 Direction of Induced emf

There are two methods for finding the direction of the induced emf.

Fleming's Right Hand Rule.

This rule is very convienient for finding the direction of the induced emf (or current) in the condition where the conductor is moving at right angles to itself and the field.



The rule states:

Arrange the thumb and the first two fingers of your right hand mutually at right angles to one another. Let the first finger point in the directio of the lines of force (N to s) and the thumb in the direction of motion of the conductor. Then, the second finger will point in the direction of the induced emf (or current)

Lenz's law
It states that the direction of an induced emf produced during the process of electromagnetic induction is always such that it tends to set up a current opposing the basic cause responsible for inducing that emf.

22.2 Nature of Induced emf
We know that according to Faraday's law of electromagnetic induction, whenever the total number of lines of force linking with the coil or the circuit as a whole changes, an emf is always induced in it. This change can be brought about by different methods.
Depending on these methods, an induced emf is classified as :

(i) Dynamically Induced emf
(ii) Statically Induced emf

23 Dynamically Induced emf
By either moving the conductor and keeping the magnetic field system stationary, or moving the field system and keeping the conductor stationary so that flux is cut by the conductor, the emf is induced in the conductor is called dynamically induced emf.

Mathematical Expression
Considering a conductor of length 'l' m placed in the magnetic field of flux density B Wb/m^2 is moving

at right angle to the field at a velocity 'v' m/s as shown in fig (a). Let the conductor be moved through a small distance 'dx' "m" in time 'dt' sec. as shown as in fig (b).

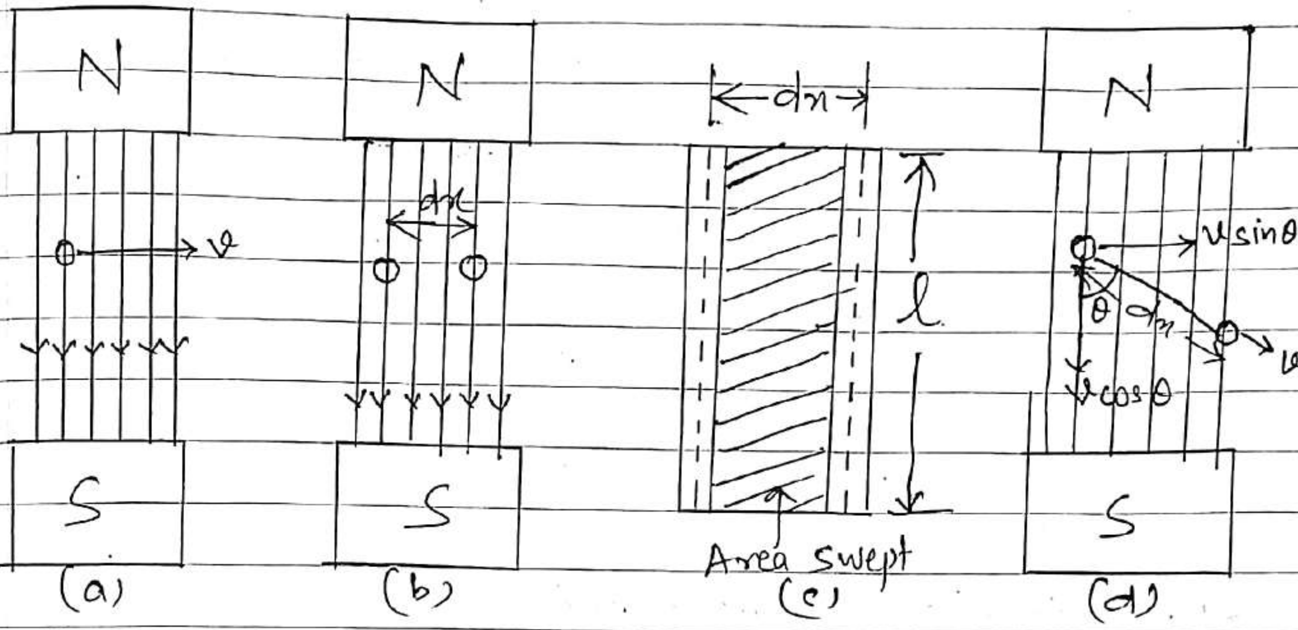


Fig: Dynamically induced emf
(a) Conductor moves perpendicular to the magnetic field.
(b) Distance covered (dx)
(c) Area swept
(d) Conductor moves at an angle θ with the direction of magnetic field

Area swept by the conductor $A = l \times dx$
Flux cut by the conductor, $\phi = B \times A = B l dx$

According to faraday's Law of Electromagnetic Induction
Induced emf, $e = \frac{\text{flux cut}}{\cancel{\text{emf}}\ \text{time}} = \frac{\phi}{dt} = \frac{B l dx}{dt}$

$= B l v \quad \left(\frac{dx}{dt} = v\right)$

Now if the conductor is moved at an angle θ with the direction of magnetic field at a velocity v m/s as shown in fig (d). A small distance covered by the conductor in that direction is dx in time dt sec. Then, the component of distance perpendicular to the magnetic field, which produced emf, is $dx \cdot \sin\theta$

$\therefore$ area swept by the conductor, $A = l \times dx \cdot \sin\theta$

$\therefore$ Flux cut by the conductor, $\phi = B \times A = B l \, dx \cdot \sin\theta$

$\therefore$ Induced emf, $e = \dfrac{B l \, dx \cdot \sin\theta}{dt} = B l v \sin\theta$.

$$\boxed{\therefore e = B l v \sin\theta}$$

24. Statically Induced emf

When both the coil and magnetic field system are stationary but the magnetic field linking with the coil changes (by changing the current producing the field), the emf thus induced in the coil is called statically induced emf. The statically induced emf are of two types:

(i) Self induced emf
(ii) Mutually induced emf

24.1 Self Induced emf

The emf induced in a coil due to the change of flux produced by it linking with its own turns is called self-induced emf.

- The direction of this induced emf is such that it opposes the cause that produces it (lenz's law), i.e change of current in the coil.

Since the rate of change of flux linking with the coil depends upon the rate of change of current in the coil. Therefore, the magnitude of self-induced emf is directly proportional to the rate of change of current in the coil. Therefore, the magnitude of self-induced emf is directly proportional to the rate of change of current in the coil, i.e

$$e \propto \frac{dI}{dt} \quad \text{or} \quad e = L\frac{dI}{dt}$$

where L = a constant of proportionality and is called self inductance or co-efficient of self inductance or inductance of the coil.

24.2 Mutually Induced emf:

The emf induced in a coil due to the change of flux produced by another (neighbouring) coil linking with it is called mutually induced emf.

Since the rate of change of flux linking with coil 'B' depends upon the rate of change of current in coil 'A'. Therefore the magnitude of mutually induced emf is directly proportional to the rate of change of current in coil 'A', i.e.

$$e_m \propto \frac{dI_1}{dt} \quad \text{or} \quad e_m = M.\frac{dI_1}{dt}$$

Where M = a constant of proportionality and is called mutual inductance or co-efficient of mutual inductance

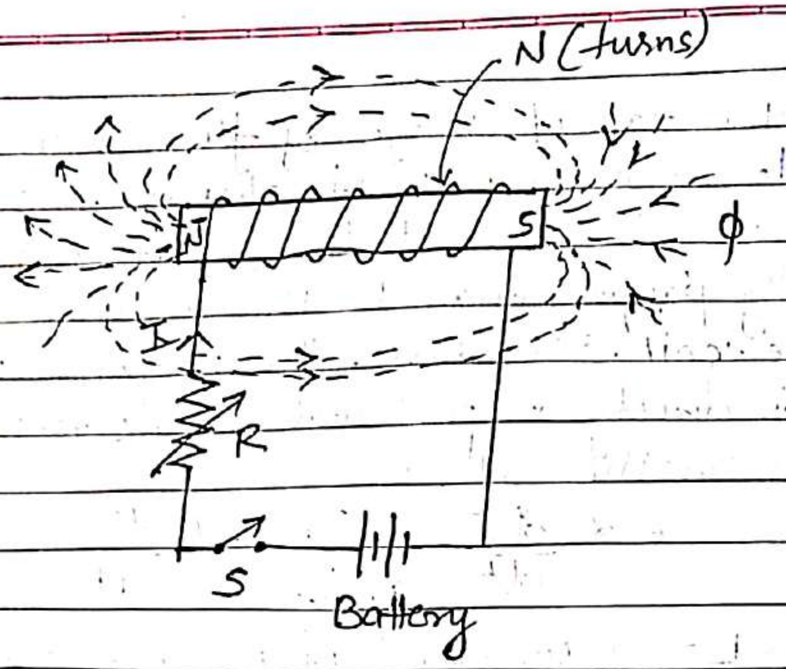


Fig: circuit for self induced emf.

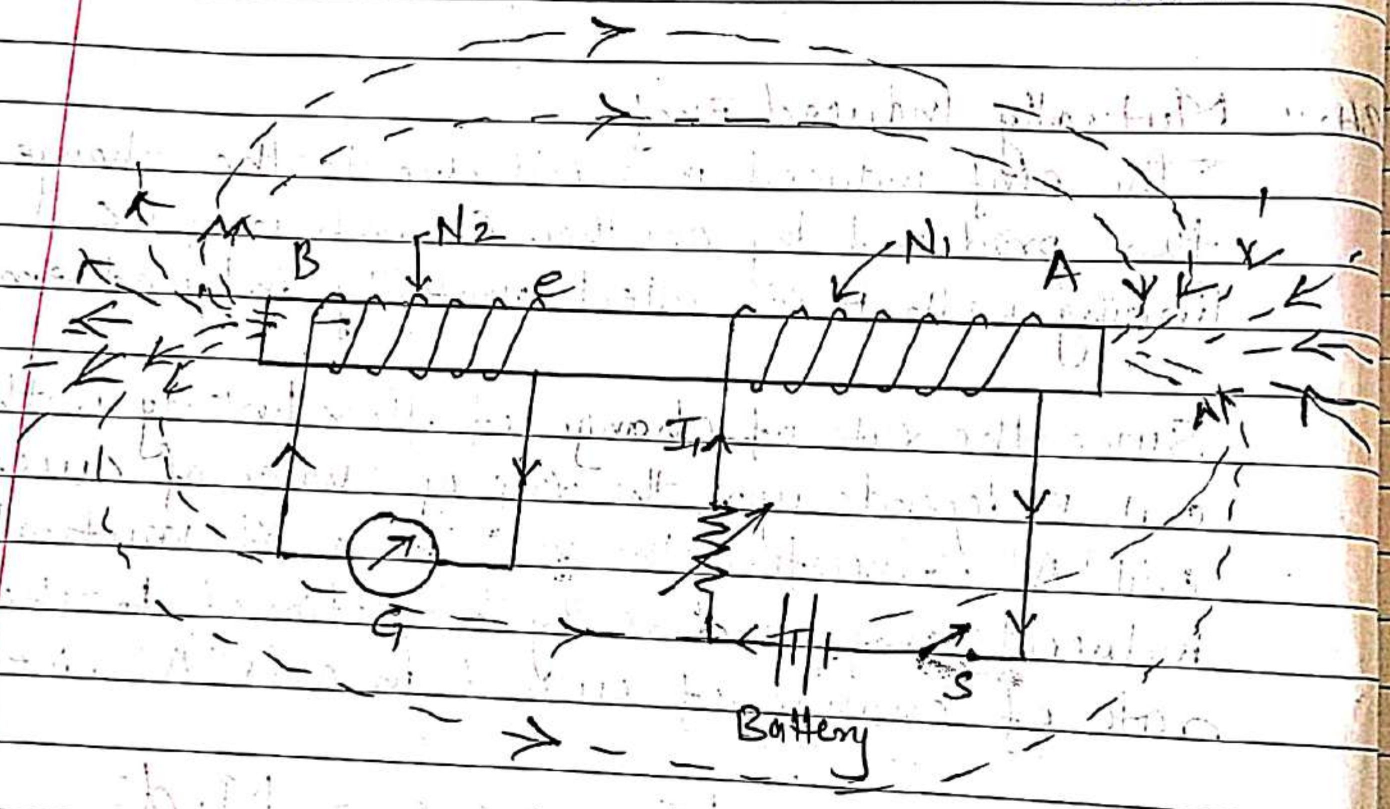


Fig: Circuit for mutually induced emf.

25. Self Inductance

The property of a coil due to which it opposes the change of current flowing through itself is called self-inductance or inductance of the coil.

This property (i.e inductance) is attained by a coil due to self-induced emf produced in the coil itself by the changing current flowing through it.

This property of the coil only opposes the changing current (i.e AC). However it does not affect the steady (i.e DC) current when flows through it. In other words, the self inductance of the coil (by virtue of its geometrical and magnetic properties) will exhibit its presence to the AC, but it will not exhibit its presence to the DC.

We have $e = L\frac{dI}{dt}$

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

$$L = \frac{N\phi}{I} \quad \left\{ e = N\frac{d\phi}{dt} = L\frac{dI}{dt} \right\}$$

$$L = \frac{N^2}{l/a\mu_0\mu_r} \quad \left\{ \phi = \frac{NI}{l/a\mu_0\mu_r} \right\}$$

26 Mutual Inductance

The property of one coil due to which it opposes the change of current in the other (neighbouring) coil is called mutual inductance between the two coils. This property (i.e mutual inductance) is attained by a coil due to mutually induced emf in the coil, while current in the neighbouring coil is changing.

$$e_m = M \cdot \frac{dI_1}{dt}$$

$$\therefore M = \frac{e_m}{dI_1/dt}$$

$$= \frac{N_2 \phi_{12}}{I_1} \quad \left\{ \text{since } e_m = N \frac{d\phi_{12}}{dt} = M \frac{dI_1}{dt} \right\}$$

$$= \frac{N_1 N_2}{l/a\mu_0\mu_r} \quad \left\{ \text{since } \phi_{12} = \frac{N_1 I_1}{l/a\mu_0\mu_r} \right\}$$

We have two formulas

$$e, v \propto \frac{di}{dt} = -L\frac{di}{dt} \quad \{L\text{-self inductance}\} \quad \text{—(1)}$$

From faraday's law

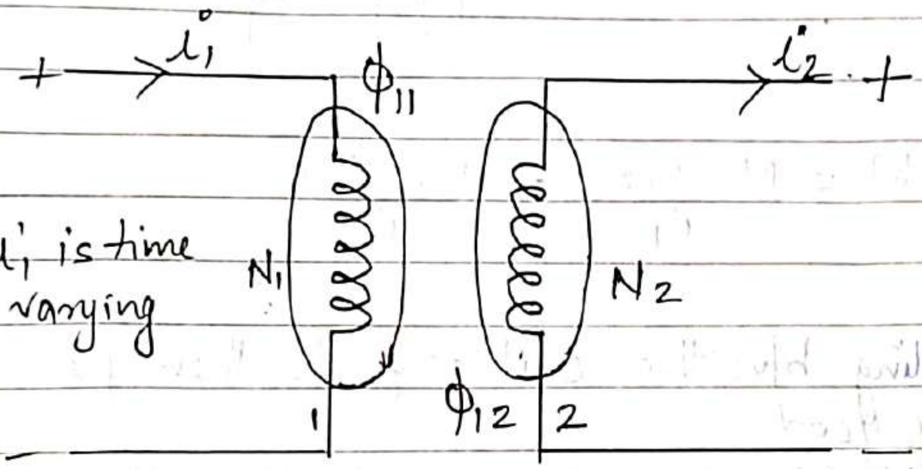
$$e, v \propto \frac{d\phi}{dt} = -N\frac{d\phi}{dt} \quad \text{—(2)}$$

equate (1) and (2)

$$\cancel{-}L\frac{di}{dt} = \cancel{-}N\frac{d\phi}{dt}$$

$$L\,di = N\,d\phi$$
$$Li = N\phi$$
$$L = \frac{N\phi}{i}$$

$N\phi$ - { flux linkage }



ϕ_{12} is also time varying

$$V_2 = -N_2\frac{d\phi_{12}}{dt} \quad \text{— (3)}$$ { N_2 - turns of coil 2

$$V_2 \propto \frac{di_1}{dt} = -M\frac{di_1}{dt} \quad \text{— (4)}$$

equate (3) and (4)

$$V_2 = -M\frac{di_1}{dt} = -N_2\frac{d\phi_{12}}{dt}$$

$$M \cdot di_1 = N_2\, d\phi_{12}$$

$$Mi_1 = N_2\phi_{12}$$

$$\therefore M = \frac{N_2 \phi_{12}}{i_1}$$ {Expression for mutual inductance when the current is flowing in the coil 1}

$||^{ly}$ $$M = \frac{N_1 \phi_{21}}{i_2}$$ {Expression for mutual inductance when the current is flowing in the coil 2}

$$\therefore M = \frac{N_2 \phi_{12}}{i_1} = \frac{N_1 \phi_{21}}{i_2}$$

If coupling b/w the coil is good, then flux linkage will be good.
If coupling b/w the coil is bad, then flux linkage will be poor.

27 Co-efficient of coupling
When current flows through the one coil, it produces flux (ϕ_1). The whole of this flux may not be linking with the other coil coupled to it, as shown in figure. It may be reduced because of leakage flux ϕ_1 by a fraction K known as co-efficient of coupling

Consider the magnetic circuit shown in figure below. When current I_1 flows through coil 1,

$$L_1 = \frac{N_1 \phi_1}{I_1} \quad \text{and} \quad M = \frac{N_2 \phi_{12}}{I_1} = \frac{N_2 K \phi_1}{I_1} \quad -(1)$$

Now, considering coil 2 carrying current I_2;

$$L_2 = \frac{N_2 \phi_2}{I_2} \quad \text{and} \quad M = \frac{N_1 \phi_{21}}{I_2} = \frac{N_1 k \phi_2}{I_2} \quad \text{--- (2)}$$

Multiplying equation (1) and (2) we get,

$$M \times M = \frac{N_2 k \phi_1}{I_1} \times \frac{N_1 k \phi_2}{I_2}$$

$$M^2 = k^2 \frac{N_1 \phi_1}{I_1} \times \frac{N_2 \phi_2}{I_2} = k^2 L_1 L_2$$

$$\therefore M^2 = k^2 L_1 L_2$$

$$M = k\sqrt{L_1 L_2}$$

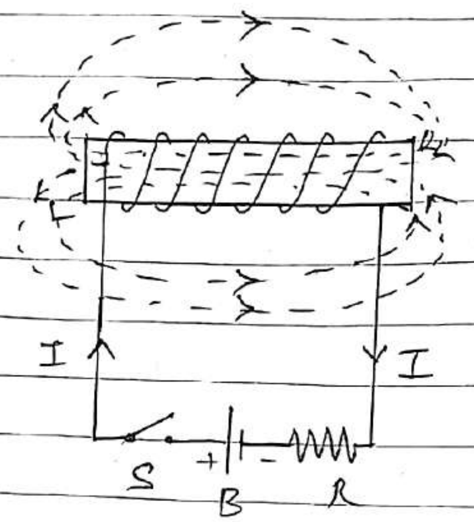
This relation ~~btw~~ is b/w mutual inductance between the two coils and their respective self inductances.

$$\therefore \boxed{k = \frac{M}{\sqrt{L_1 L_2}}}$$

Energy stored in the magnetic field

In magnetic field, Energy is always required for establishing a magnetic field but no energy is required to maintain it.

Consider the below figure,



At an instant 't' seconds after the closure of the switch let the current be 'i' amperes. If this current increases by di amperes in dt seconds then emf induced in the coil,

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

Energy absorbed by the magnetic field during time dt second.

$$= \text{Power} \times \text{time}$$

$$= (-e)\cdot i\cdot dt = L\frac{di}{dt} \times i \times dt$$

$$= Li\,di \text{ joules}$$

Total energy, E absorbed by the magnetic field when the current increases from zero to its final value of I amperes is given by

$$E = L\int_0^I i\cdot di = L \times \frac{1}{2}\left[i^2\right]_0^I$$

$$= \frac{1}{2} L I^2 \text{ joules}.$$

Energy stored per unit volume,

$$E = \frac{1}{2} L I^2 = \frac{1}{2} \frac{N\phi}{I} \cdot I^2$$

$$= \frac{1}{2} N I \phi \text{ joules}$$

But for a solenoid of N turns with length l metres and cross sectional area of square metre

$$NI = Hl \text{ and } \phi = B \cdot a$$

where B and H are the flux density and magnetic field strength

$$E = \frac{1}{2} B \cdot H \cdot a \cdot l \text{ joules}$$

$$a \cdot l = \text{Volume of the field (in } m^3)$$

Energy stored per unit volume of the magnetic field,

$$= \frac{1}{2} BH \text{ joules}$$

$$= \frac{1}{2} \mu H^2 \text{ joules}$$

$$= \frac{1}{2} \frac{B^2}{\mu} \text{ joules}$$

If the medium is air or other non magnetic materials, $\mu_r = 1$

Energy stored per unit volume of the magnetic field $= \frac{1}{2} \mu_0 H^2$ joules

$$= \frac{1}{2} \frac{B^2}{\mu_0} \text{ joules}$$

$$\boxed{E = \frac{1}{2} BH = \frac{1}{2} \mu H^2 = \frac{1}{2} \frac{B^2}{\mu}}$$