BASIC ELECTRICAL ENGINEERING

(BEE)

SAVITRIBAI PHULE PUNE UNIVERSITY

First Year Engineering
(Choice Based Credit System)
(2019 Course)

BASIC ELECTRICAL ENGINEERING (103004)

Teaching scheme

Lectures - 3Hrs/Week

Practical -2Hrs/Week

Examination scheme

In-sem – 30 Marks

End-sem-70 Marks

Practical - 25 Marks

BASIC ELECTRICAL ENGINEERING

APPROXIMATE EXAMINATION PATTERN

	IN-SEM EXAM	END-SEM EXAM	TOTAL WEIGHTAGE
UNIT-I	15	-	15
UNIT-II	15	-	15
UNIT-III	-	17	17
UNIT-IV	-	18	18
UNIT-V	-	17	17
UNIT-VI	-	18	18
	30	70	100

Unit I

Electromagnetism (6Hrs)

Review: resistance, emf, current, potential, potential difference and Ohm's law

Electromagnetism: Magnetic effect of an electric current, cross and dot conventions, right hand thumb rule, nature of magnetic field of long straight conductor, solenoid and toroid. Concept of mmf, flux, flux density, reluctance, permeability and field strength, their units and relationships. Simple series magnetic circuit, Introduction to parallel magnetic circuit(Only theoretical treatment), comparison of electric and magnetic circuit, force on current carrying conductor placed in magnetic field, Fleming's left hand rule. Faradays laws of electromagnetic induction, Fleming's right hand rule, statically and dynamically induced e.m.f., self and mutual inductance, coefficient of couplings. Energy stored in magnetic field.

Unit II

Electrostatics and AC Fundamentals (6 Hrs)

A) **Electrostatics:** Electrostatic field, electric flux density, Electric field strength, absolute permittivity, relative permittivity and capacitance. Capacitor, capacitors in series and parallel, energy stored in capacitors, charging and discharging of Capacitors (no derivation) and time constant. (2Hrs)

B) **AC Fundamentals:** Sinusoidal voltages and currents, their mathematical and graphical representation, Concept of cycle, Period, frequency, instantaneous, peak(maximum), average and r.m.s. values, peak factor and form factor. Phase difference, lagging, leading and in phase quantities and phasor representation. Rectangular and polar representation of phasor. (4Hrs)

Unit III

Single Phase AC Circuits (06 Hrs)

Study of AC circuits consisting of pure resistance, pure inductance, pure capacitance, series R-L, R-C and R-L-C circuits, phasor diagrams, voltage, current and power waveforms, resonance in series RLC circuits, concept of impedance, concept of active, reactive, apparent, complex power and power factor, Parallel AC circuits (No numericals), concept of admittance

Unit IV

Polyphase A.C. Circuits and Single phase Transformers (06Hrs)

A) Polyphase A.C. Circuits:

Concept of three-phase supply and phase sequence. Balanced and unbalanced load, Voltages, currents and power relations in three phase balanced star-connected loads and delta-connected loads along with phasor diagrams. (3Hrs)

B) Single phase transformers:

principle of working, construction and types, emf equation, voltage and current ratios. Losses, definition of regulation and efficiency, determination of these by direct loading method. Descriptive treatment of auto-transformers. (3Hrs)

Unit V
DC Circuits (06 Hrs)

Classification of electrical networks, Energy sources – ideal and practical voltage and current sources, Simplifications of networks using series and parallel combinations and star-delta conversions, Kirchhoff's laws and their applications for network solutions using loop analysis, Superposition theorem, Thevenin's theorem.

Unit VI

Work, Power, Energy and Batteries (06 Hrs)

A) Work, Power, Energy:

Effect of temperature on resistance, resistance temperature coefficient, insulation resistance, conversion of energy from one form to another in electrical, mechanical and thermal systems. (4Hrs)

B) Batteries :

Different types of batteries (Lead Acid and Lithium Ion), construction, working principle, applications, ratings, charging and discharging, concept of depth of charging, maintenance of batteries, series -parallel connection of batteries (2Hrs)

Text Books:

1. V.D. Toro, Principles of Electrical Engineering, Prentice Hall India, 1989
2. D. P. Kothari, I.J. Nagrath, Theory and Problems of Basic Electrical Engineering, PHI Publication
3. V.K. Mehta, RohitMehata Basic Electrical Engineering, S Chand Publications
4. B.L. Theraja, A text book on electrical technology Vol-I

Reference Books:

1. H Cotton, Electrical technology, CBS Publications
2. L. S. Bobrow, —Fundamentals of Electrical Engineering, Oxford University Press, 2011.
3. E. Hughes, —Electrical and Electronics Technology, Pearson, 2010.
4. D. C. Kulshreshtha, —Basic Electrical Engineering, McGraw Hill, 2009.

IMPORTANCE OF ELECTRICITY

- Electricity is one of the most important blessings that science has given to mankind.
- It has also become a part and parcel of modern life and one cannot think of a world without Electricity.
- Used for lighting rooms, working of fans, domestic appliances (AC, TV, Refrigerator, washing machine etc) which provide comfort to people .
- In factories, large machines are working with the help of electricity.
- Electric trains , Electric cars, computers and robots
- Electricity plays a pivotal role in the fields of medicines and surgery too — such as X-ray, ECG. The use of electricity is increasing day by day.

Electricity is the ***purest*** form of energy.

It is ***efficiently*** transmitted and ***easily*** controlled and converted in to other forms.

Electrical Engineering

Summerised in to four catogories

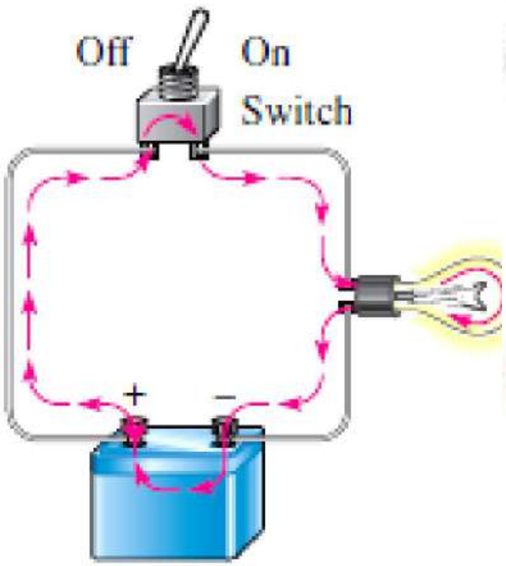
1. The production of electrical energy.
2. The transmission of electrical energy.
3. The application of electrical energy.
4. The control of electrical energy.

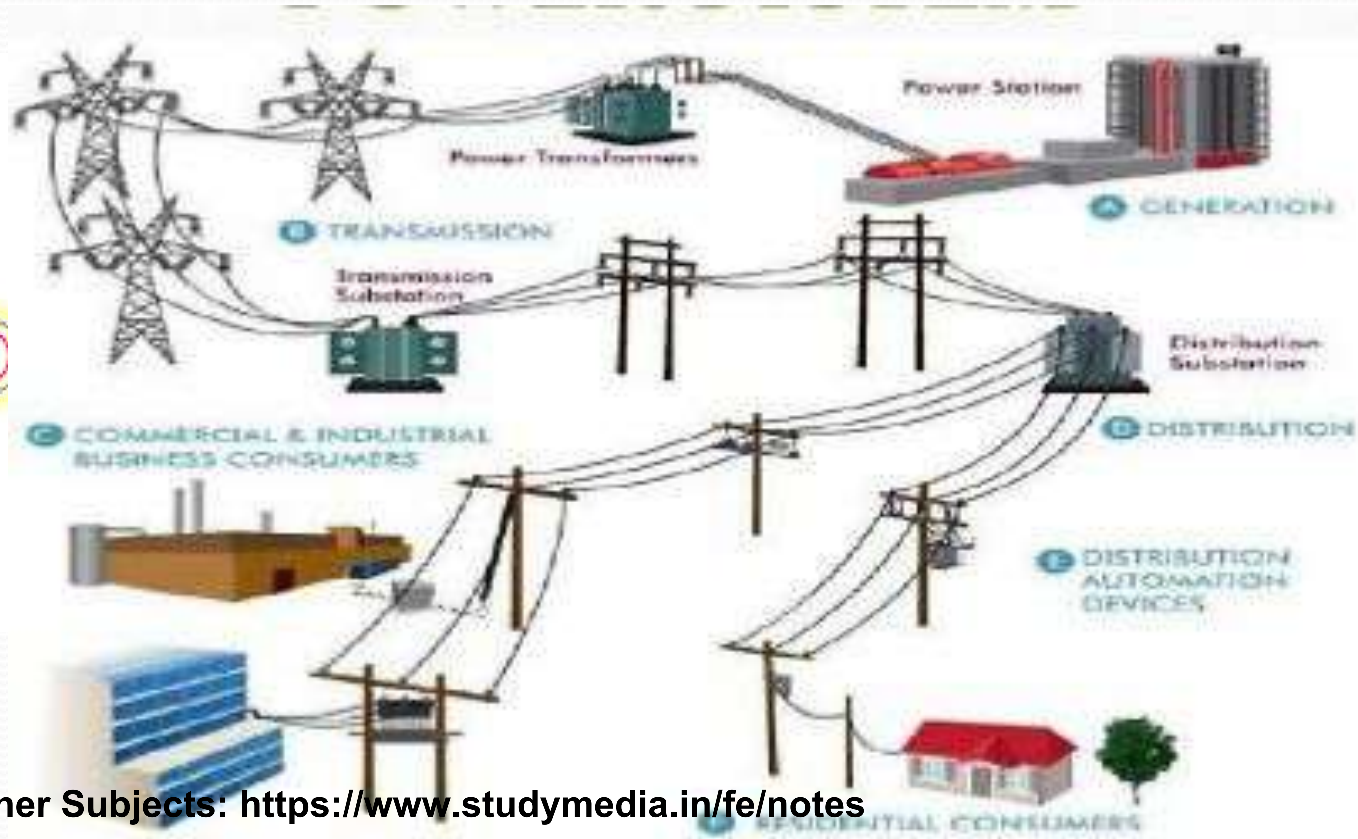
1. *The source. The function of the source is to provide the energy for the* electrical system. A source may usually be thought of as a battery or a generator, although for simplicity we might even think of a socket outlet as a source.

2. *The load. The function of the load is to absorb the electrical energy* supplied by the source. Most domestic electrical equipment constitutes loads. Common examples include lamps and heaters, all of which accept energy from the system.

3.*The transmission system*. *This conducts the energy from the source to the* load. Typically the transmission system consists of insulated wires and transmission lines.

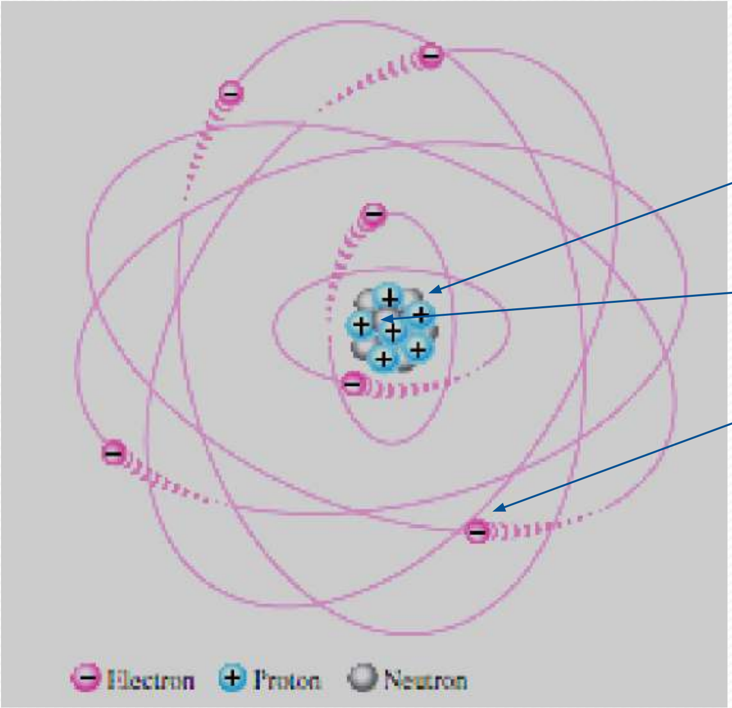
4. *The control apparatus*. *As the name suggests, its function is to control. The* most simple control is a switch which permits the energy to flow or else interrupts the flow.





Review Elementary Concepts

All matters (solid , liquid, and gasses) is made of atoms; and all atoms consist of electrons, protons, and neutrons. An **atom** is the smallest particle of an **element** that retains the characteristics of that element.



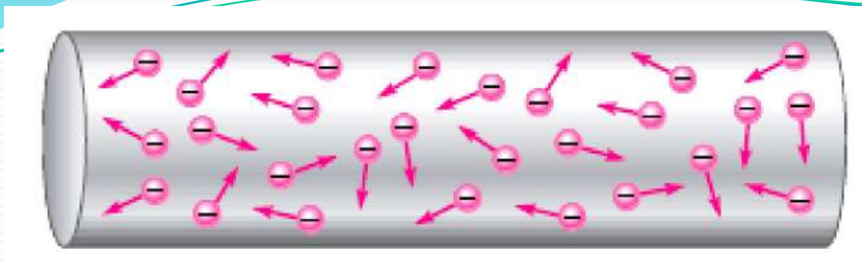
Nucleus

Proton + ve Charged

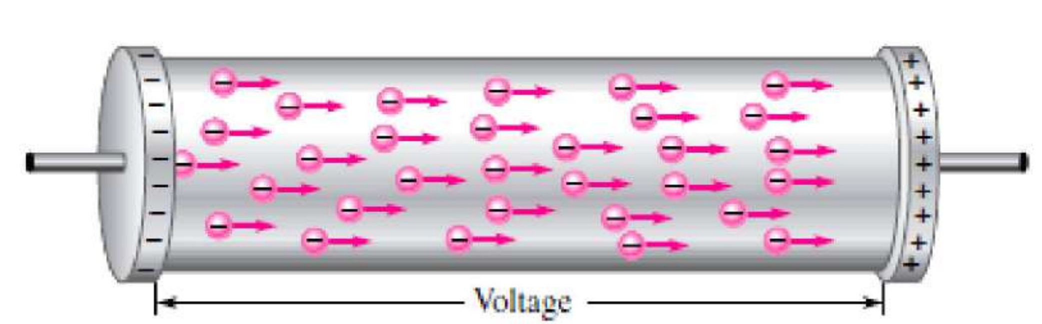
Electrons – ve Charged

Neutrons are Neutral

Valence / free electrons



Random motion of free electrons in a material.



Electrons flow from negative to positive when a voltage is applied across a conductive or semiconductive material.

The charge of an electron and that of a proton are equal in magnitude. Electrical **charge** is an electrical property of matter that exists because of an excess or deficiency of electrons. Charge is symbolized by the letter *Q*.

Coulomb: The Unit of Charge

Electrical charge (*Q*) is measured in coulombs, symbolized by C.

One coulomb is the total charge possessed by 6.24×10^{18} **electrons.**

A single electron has a charge of 1.6×10^{-19} C.

Categories of Materials

Depending upon the free electrons the materials are electrically classified as conductors, semiconductors, and insulators.

Conductors

Conductors are materials that readily allow current. They have a Large number of free electrons and are characterized by one to three valence electrons in their structure. Most metals are good conductors.

Silver,Copper, Gold and Alluminium

Copper is the most widely used conductive material because it is less expensive than silver. Copper wire is commonly used as a conductor in electric circuits.

Semiconductors

Semiconductors are classed below the conductors in their ability to carry current because they have fewer free electrons than do conductors. Semiconductors have four valence electrons in their atomic structures. However, because of their unique characteristics, certain semiconductor materials are the basis for **electronic** devices such as the diode, transistor, and integrated circuit.

Silicon and germanium are common semiconductive materials.

Insulators

Insulators are nonmetallic materials that are poor conductors of electric current; they are used to prevent current where it is not wanted. Insulators have no free electrons in their structure. The valence electrons are bound to the nucleus and not considered "free." Most practical insulators used in electrical and electronic applications are compounds such as **Glass, Porcelain, Teflon, Mica, Bakelite PVC, Wood** etc. to name a few.

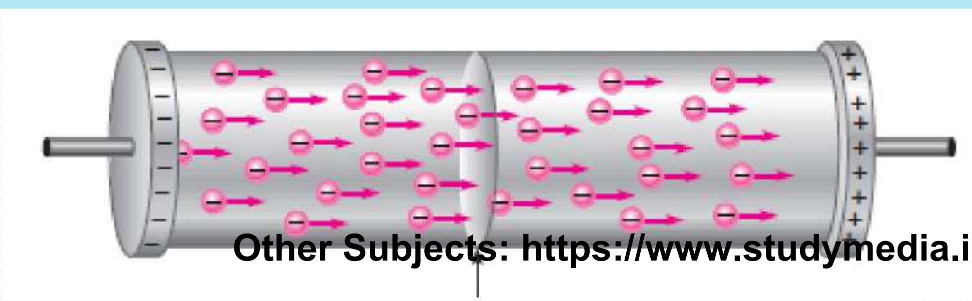
Electrical **current** is the rate of flow of charge. It is measured in Ampere.

$$I = \frac{Q}{t} = \frac{dQ}{dt} = \frac{coulombs}{sec} = Ampere$$

where I is current in amperes (A),
Q is charge in coulombs (C), and
t is time in seconds (s).

One ampere (1 A) is the amount of current that exists when a number of electrons having a total charge of one coulomb (1 C) move through a given cross-sectional area in one second (1 s).

1 Ampere current= Flow of 6.24×10^{18} electrons per sec

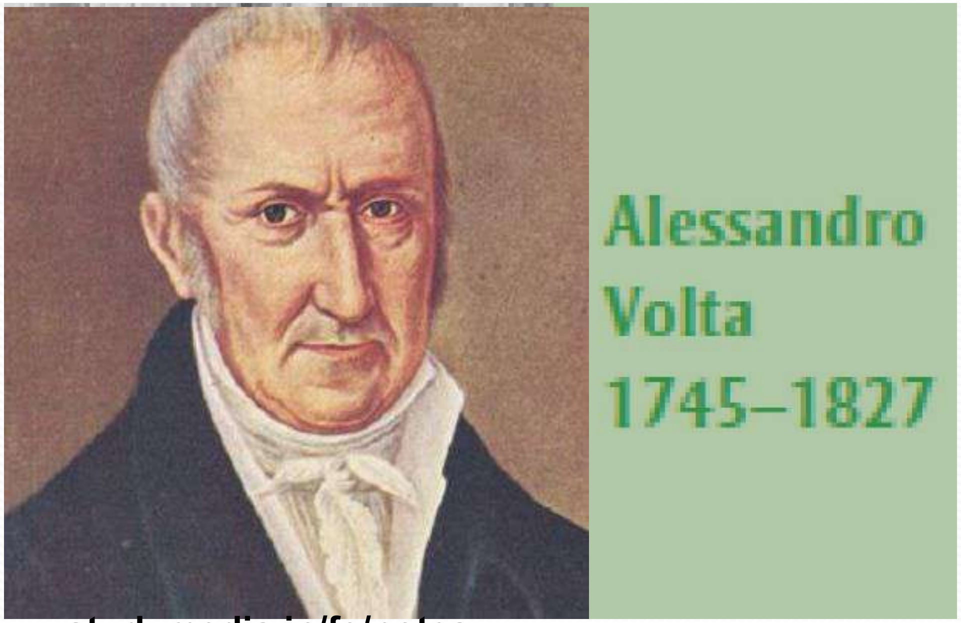


Other Subjects: https://www.studymedia.in/fe/notes

Potential Difference

When two charged particles are brought near to one another their exit a force of attraction or repulsion. A certain amount of energy must be exerted, in the form of work, to overcome the force and move the charges a given distance apart. This ability of charged particle to do the works is called potential difference.
The unit of potential difference is volt.

Voltage is the driving force, sometimes called electromotive force or emf, in electric circuits and is what establishes current.

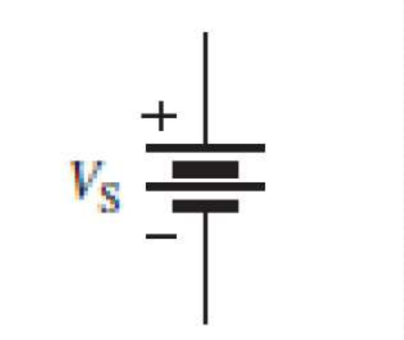


Potential Difference (Voltage) is defined as energy or work per unit charge.

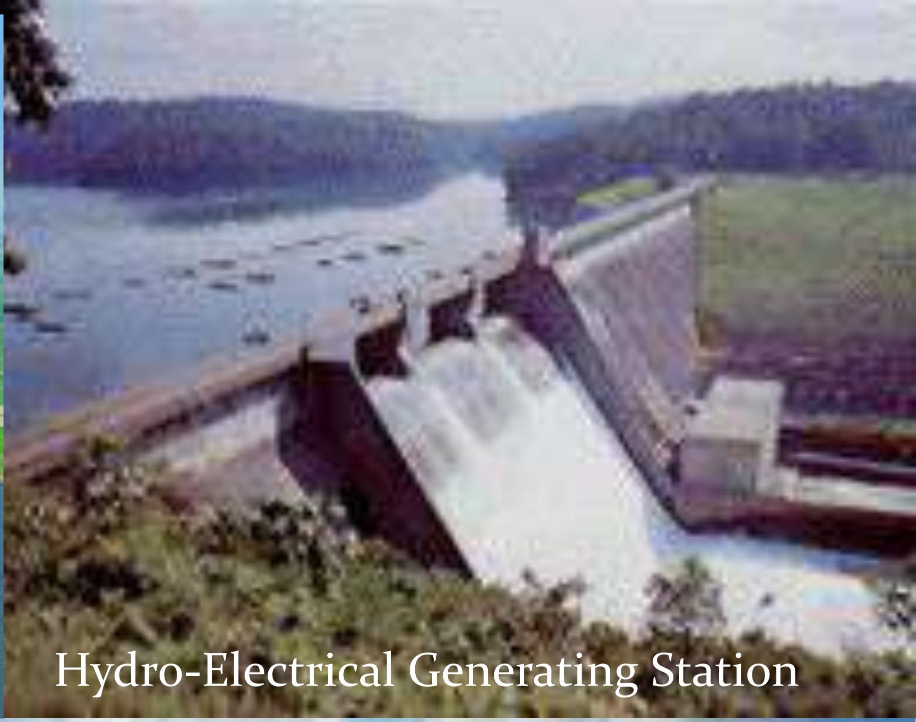
$$\text{Electrical Potential} = \frac{\text{Work done}}{\text{Charge}} = \frac{W}{Q} \quad \text{Volts}$$

One volt is the potential difference (voltage) between two points when one joule of energy is used to move one coulomb of charge from one point to the other.

Electro Motive Force (E.M.F) is the force which is required to drive the current from one point to another in an electrical circuit. E.M.F is denoted by a symbol (E) and its unit is volts (V).



Wind Energy



Hydro-Electrical Generating Station

Thermal / Nuclear Generating Station

Solar Energy

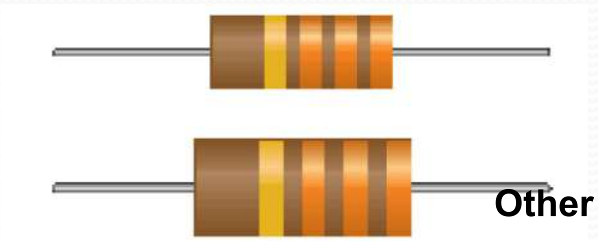
RESISTANCE

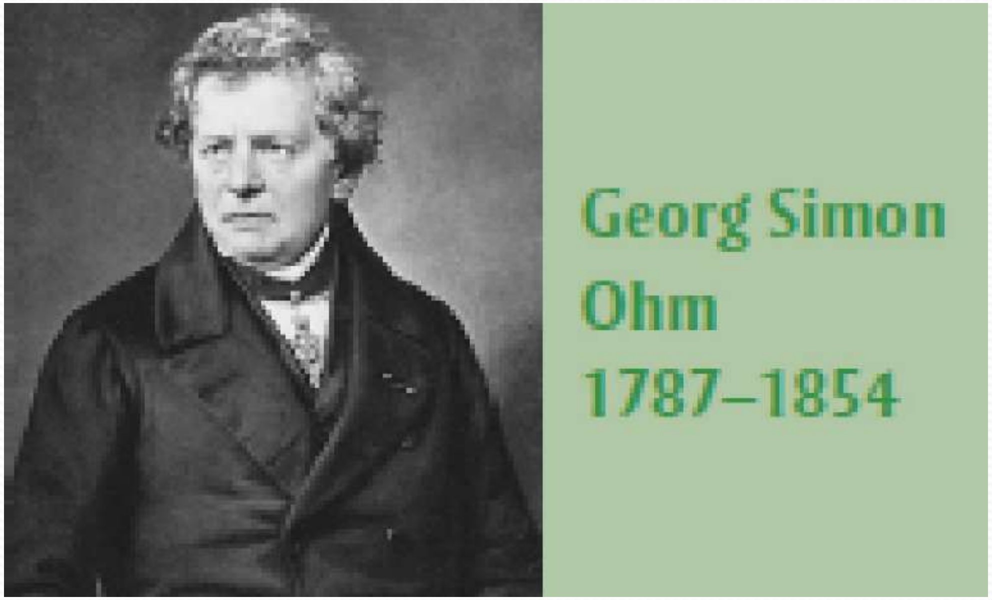
When there is current through a material, the free electrons move through the material and occasionally collide with atoms. These collisions cause the electrons to lose some of their energy, and thus their movement is restricted. The more collisions, the more the flow of electrons is restricted. This restriction varies and is determined by the type of material. **The property of a material that restricts the flow of electrons is called *resistance***, designated with *R*.

Resistance is the opposition to the flow of current.

Resistance is expressed in ohms, and represented by Greek letter omega (Ω).

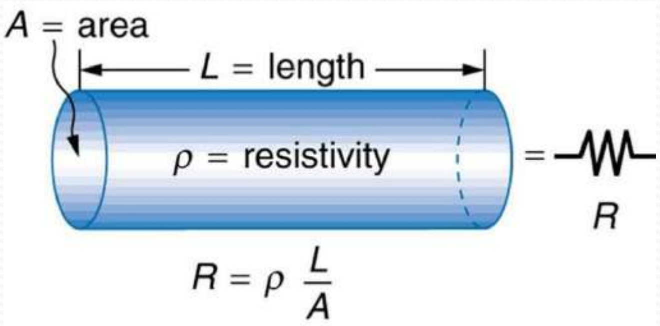
One ohm (Ω) of resistance exists if there is one ampere (1 A) of current in a material when one volt (1 V) is applied across the material.





Factors Governing the value of Resistance

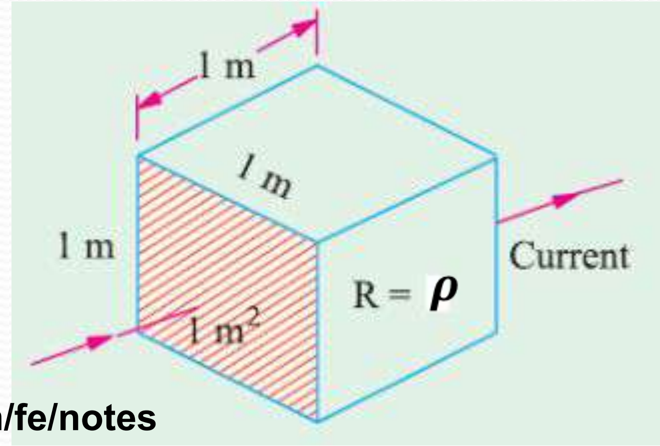
The resistance R offered by a conductor depends on the following factors :
(i) It varies directly as its length, l.
(ii) It varies inversely as the cross-section A of the conductor.
(iii) It depends on the nature of the material.
(iv) It also depends on the temperature of the conductor.



$$R = \frac{\rho l}{A} \quad \Omega$$

where ρ is a constant depending on the nature of the material of the conductor and is known as its *specific resistance or resistivity*.

If $l = 1$ m and $A = 1\ m^2$, then $R = \rho$
Hence, specific resistance of a material may be defined as the resistance between the opposite faces of a metre cube of that material.



Resistivity of the material is measured *in* $\Omega - \text{m}$

TABLE Resistivity of Some Materials

Type	Material	$\rho(\Omega \cdot m)$
Conductors (at 20°C)	Silver	16×10^{-9}
	Copper	17×10^{-9}
	Gold	24×10^{-9}
	Aluminum	28×10^{-9}
	Tungsten	55×10^{-9}
	Brass	67×10^{-9}
	Sodium	0.04×10^{-6}
	Stainless steel	0.91×10^{-6}
	Iron	0.1×10^{-6}
	Nichrome	1×10^{-6}
	Carbon	35×10^{-6}
	Seawater	0.25
Semiconductors (at 27°C or 300 K)	Germanium	0.46
	Silicon	2.3×10^{3}
Insulators	Rubber	1×10^{12}
	Polystyrene	1×10^{15}

Conductance and Conductivity

Conductance (G) : It is the easiness offered by material to the flow of current. Reciprocal of resistance is conductance. The unit of conductance is Siemens (S). Earlier, this unit was called mho (ʊ).

$$G = \frac{1}{R} = \frac{A}{\rho l} = \frac{1}{\rho}\frac{A}{l} = \sigma\frac{A}{l}$$

where σ $(Sigma)$ is called the ***conductivity*** or ***specific conductance*** of a conductor.

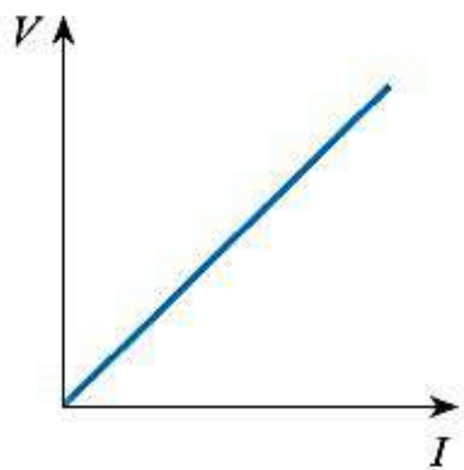
the unit of conductivity is Siemens/metre (S/m).

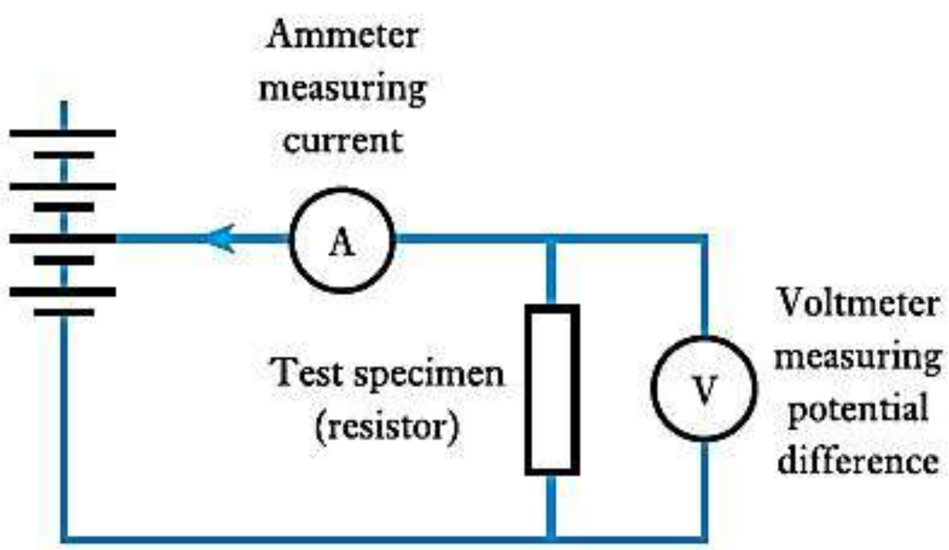
Ohms Law

The current following through a conductor is directly proportional to the potential difference across the conductor, provided temperature remains constant.

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

$$\boxed{V = IR}$$



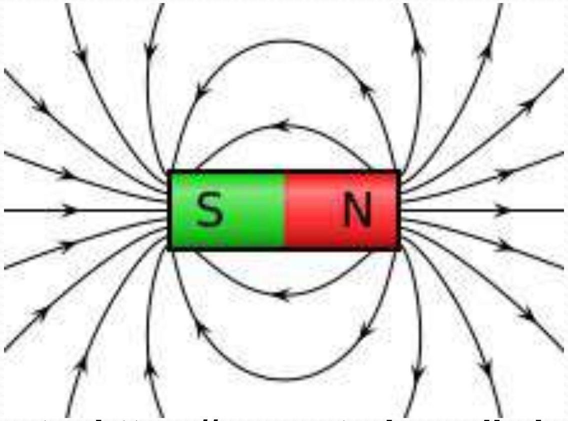


Unit - I
Electromagnetism

MAGNET : Substances that possess the property of attracting iron pieces are called magnets

- A magnet attracts magnetic materials towards itself.
- A freely suspended bar magnet always aligns in the north-south direction.
- Unlike poles attract each other and like poles repel each other.
- A magnet with a single pole does not exist. If a magnet is cut into two pieces each piece will behave like an independent magnet, with a north pole and a south pole.
- When a bar magnet is rubbed over an iron bar, it changes the iron bar into a magnet.

Al Ni Co



LAWS OF MAGNETISM

First law:

Like poles of a magnet repel each other and unlike pole attract each other.

Second Law :

the force between two magnetic poles placed in a medium is

(i) **directly proportional to their pole strengths**

(ii) **inversely proportional to the square of the distance between them and**

(iii) **depends upon medium surrounding the poles.**

$$F \ \alpha \ \frac{m_1 \, m_2}{d^2}$$

$$F = k \ \frac{m_1 \, m_2}{d^2}$$

$$F = \frac{1}{4 \, \pi\mu} \ \frac{m_1 \, m_2}{d^2}$$

$$F = \frac{1}{(4\pi\mu_0\mu_r)} \quad \frac{m_1\, m_2}{d^2}$$

m_1, m_2 $-Pole\ strenghts\ in\ weber$

d – distance between the poles in metres

F – force in Newton

μ_0 - *permeability of free space henry/metre*

$\mu_0 = 4\,\pi \times 10^{-7}$ *henry/metre*

μ_r - *relative permeability of the medium*

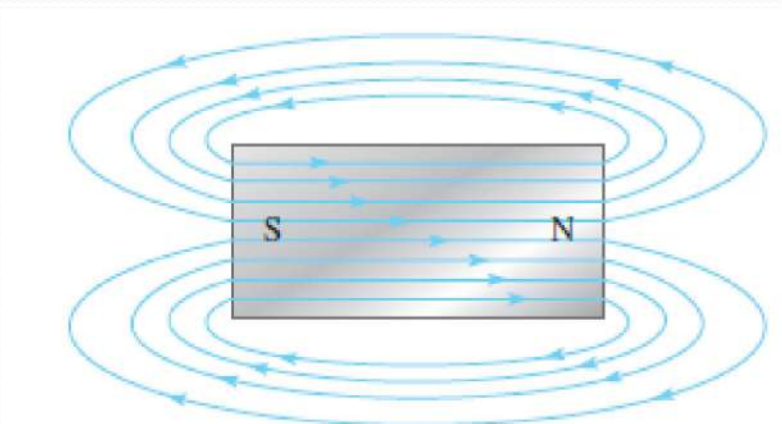
$$1\, wb = 10^8 \quad lines\ of\ force$$

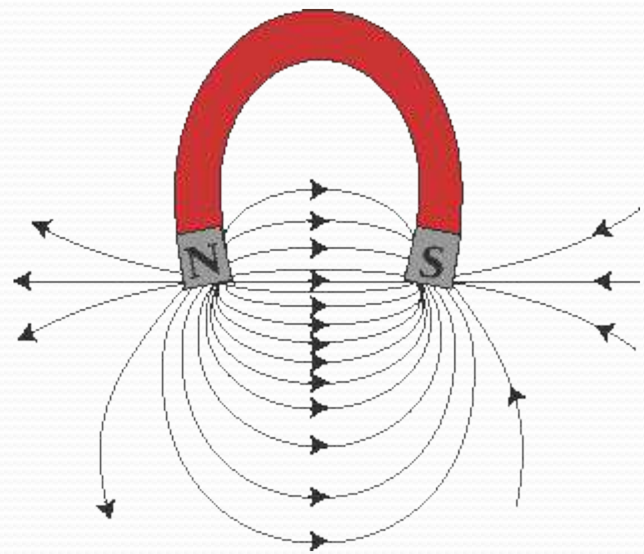
MAGNETIC FIELD

The space surrounding a magnet where another magnet experiences a force of attraction or repulsion is called magnetic field.

MAGNETIC LINES FORCE

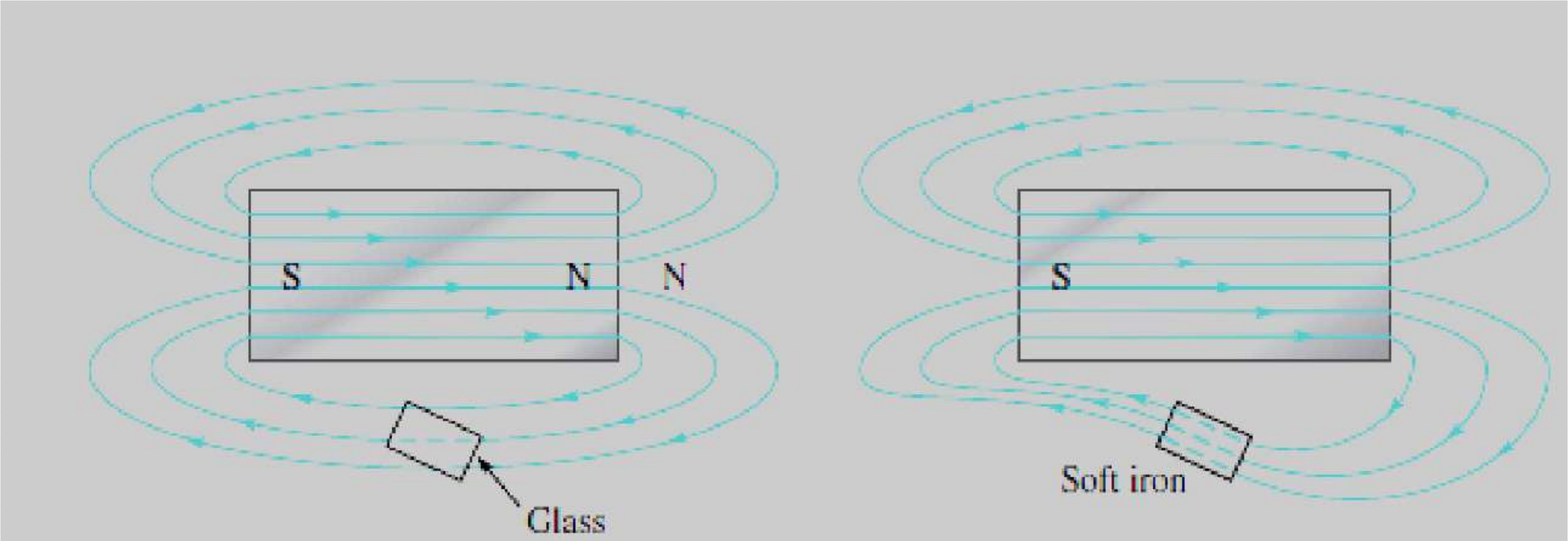
Magnetic field of a magnet is represented by *imaginary lines of Force. These line have no physical existence they are purely imaginary.*





Properties of lines of force

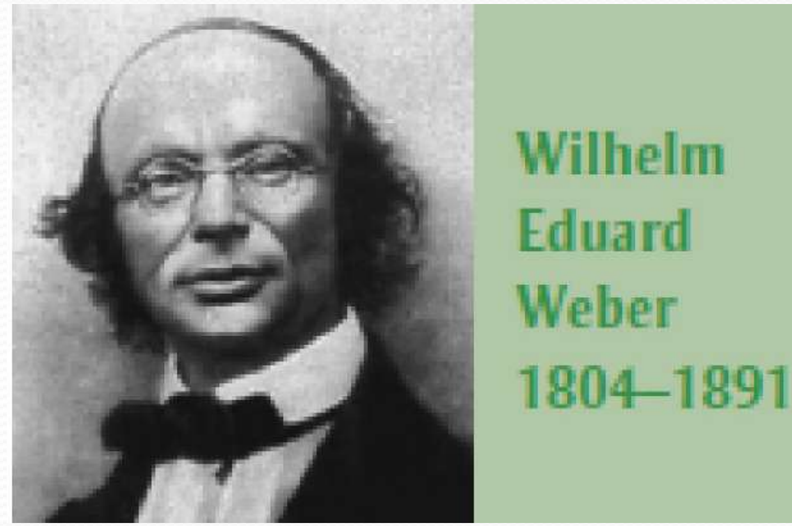
1. Lines of force always originate on N-pole and terminate on S-pole external to the Magnet.
2. Lines of force Forms a closed loop.
3. Lines of magnetic flux never intersect each other.
4. Lines of flux are like stretched rubber band, and always trying to contract in length.
5. Lines of magnetic flux which are parallel and acting in the same direction repel one another
6. Magnetic Lines of force always prefer the path of least opposition/ resistance path.



Magnetic Flux (φ).

The total number of line of force existing in a magnetic field is called magnetic flux. It is measured in *Weber.* denoted by the **φ** (Greek letter phi).

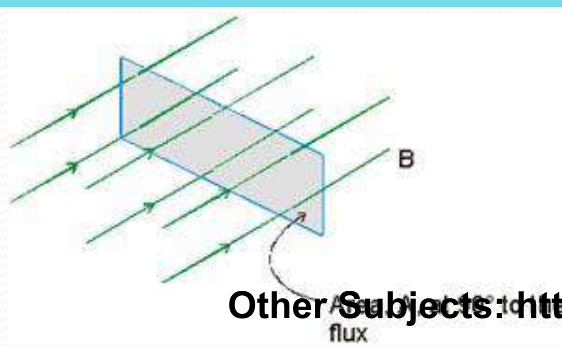
$$I = \frac{Q}{t} = \frac{dQ}{dt} = \frac{coulombs}{sec} = Ampere$$

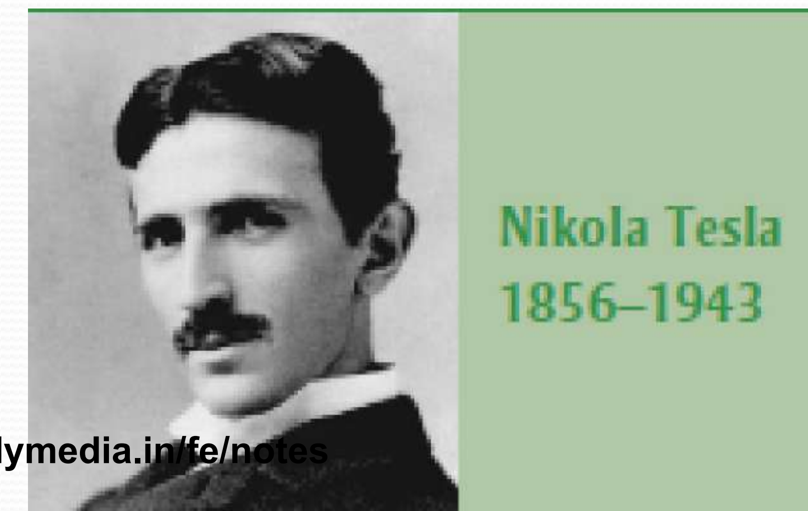


Magnetic Flux Density (B)

Magnetic flux per unit area measured in a plane perpendicular to the flux is called flux density. Denoted by B and measured in Tesla

$$Magnetic\ flux\ Density \quad B = \frac{\phi}{A} \quad Tesla = \frac{Wb}{m^2}$$





Magnetic Field Strength or **Magnetic Field Intensity** or **Magnetizing force(H)**

This quantity is used to measure the strength or weakness of the magnetic field. Magnetic field strength is defined as the *force* experienced by a *unit north pole* (North pole 1Wb pole strength) placed at that point in the magnetic field. unit of H is N/Wb

Permeability

The ease with which a magnetic field can be established in a given material is measured by the **permeability** of that material. The higher the permeability, the more easily a magnetic field can be established.

Absolute Permeability (μ)

The ratio of Magnetic flux density in a medium to magnetic Field Strength which Produces that flux density.

$$Permeability\ \mu = \frac{B}{H} \qquad Henries/meter$$

Permeability of free space / Vacuum or Magnetic Space constant (μ_0)

The ratio of Magnetic flux density in a air or vacuum to magnetic Field Strength which Produces that flux density.

$$Permeability\ of\ free\ space\ \ \boldsymbol{\mu_0} = \frac{B_0}{H} = 4\pi \times 10^{-7} \quad H/m$$

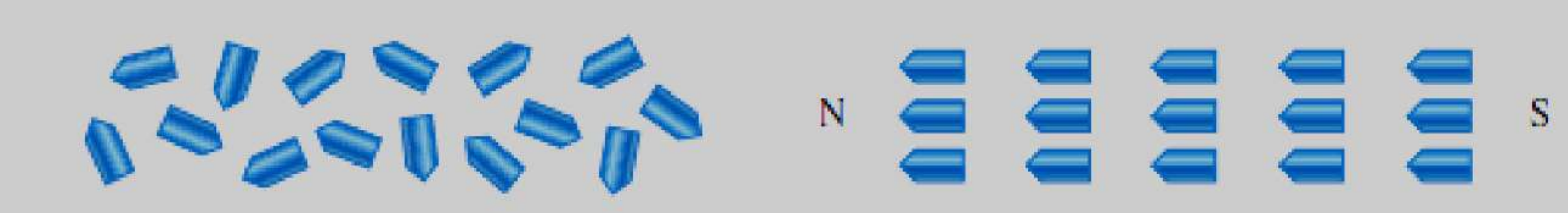
Relative Permeability ($\boldsymbol{\mu_r}$)

The ratio of Magnetic flux density in a medium to magnetic Flux Density in vacuum by same field Intensity under identical conditions.

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

How Materials Become Magnetized

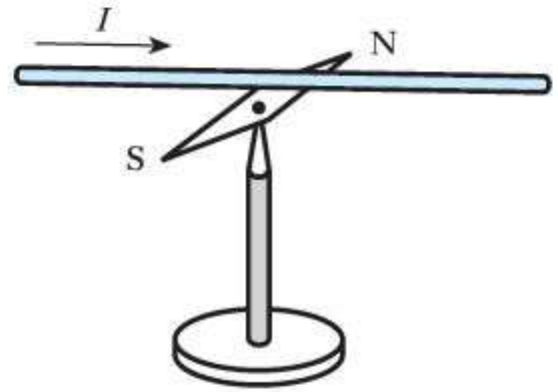
Ferromagnetic materials such as iron, nickel, and cobalt become magnetized when placed in the magnetic field of a magnet. Under the influence of the permanent magnetic field the materials aquires the properties of the magnet. When removed from the magnetic field, the object tends to lose its magnetism. Ferromagnetic materials have minute magnetic domains created within their atomic structure. These domains can be viewed as very small bar magnets with north and south poles. When the material is not exposed to an external magnetic field, the magnetic domains are randomly oriented, as shown in Figure (a). When the material is placed in a magnetic field, the domains align themselves as shown in figure (b). Thus, the object itself effectively becomes a magnet.



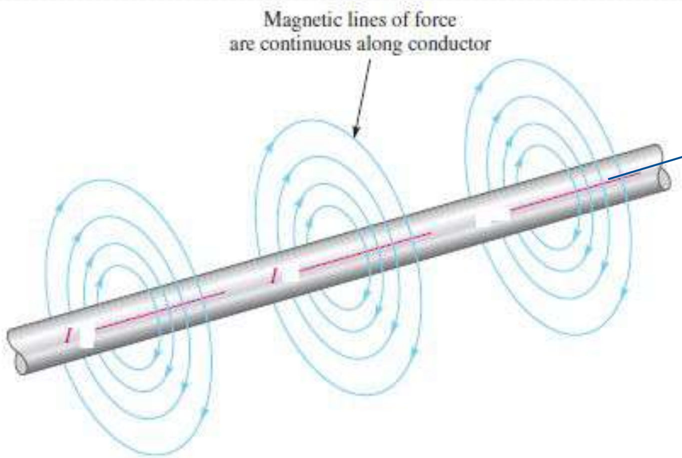
(a) The magnetic domains (N S) are randomly oriented in the unmagnetized material.

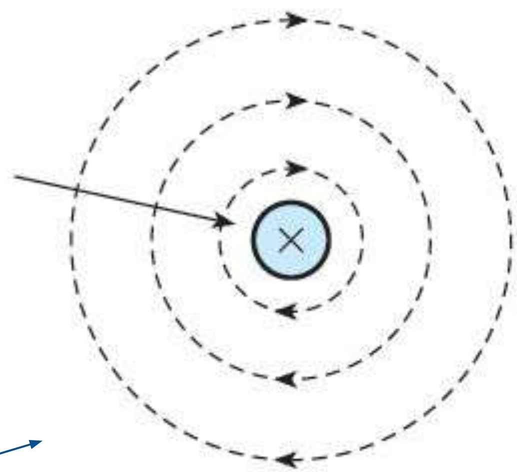
(b) The magnetic domains become aligned when the material is magnetized.

Magnetic effect of an electric current

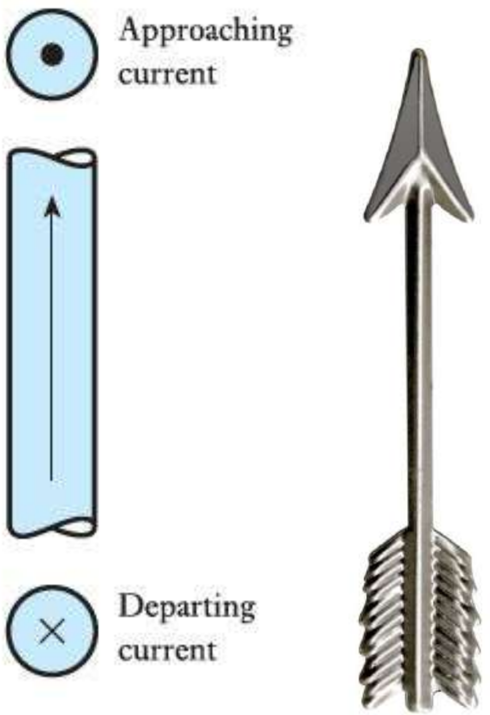


Oersted's experiment



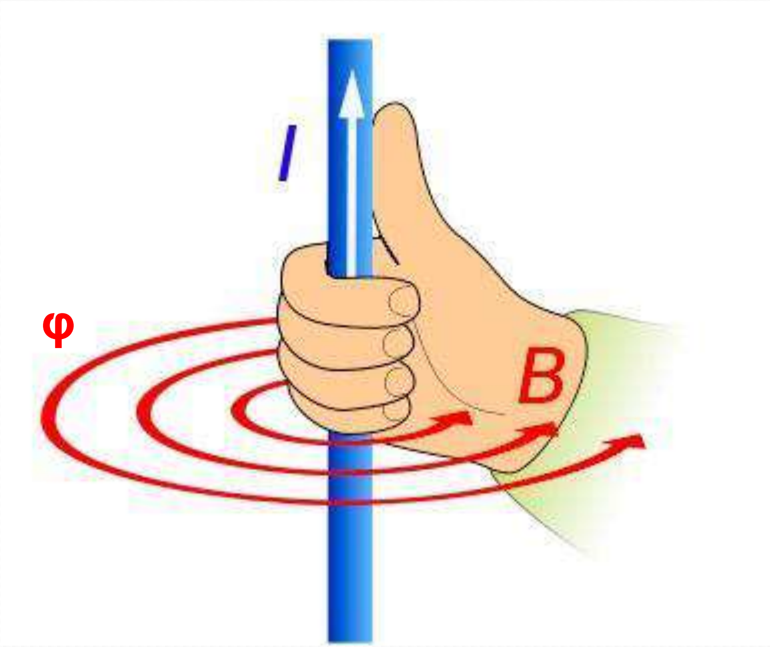


Magnetic flux due to current in a straight conductor

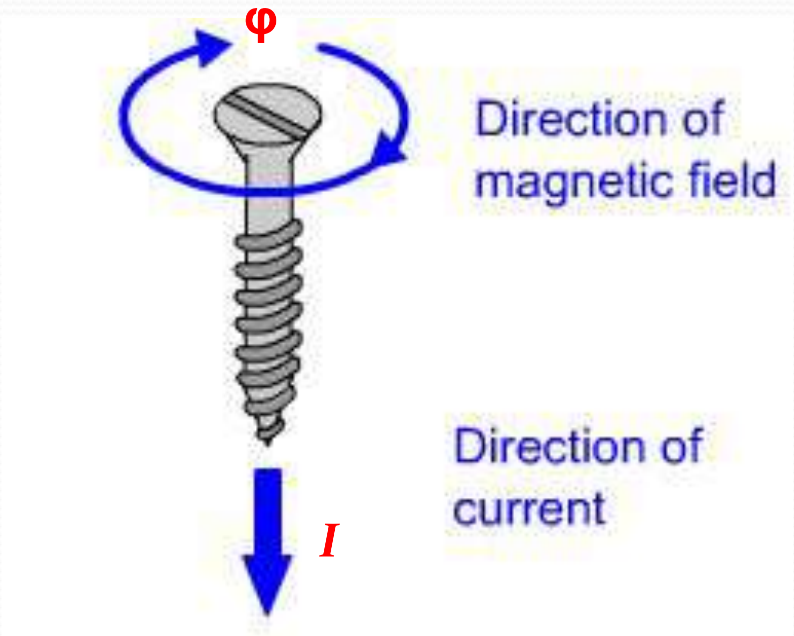


Current conventions

Electromagnetism is the production of a magnetic field by current in a conductor.

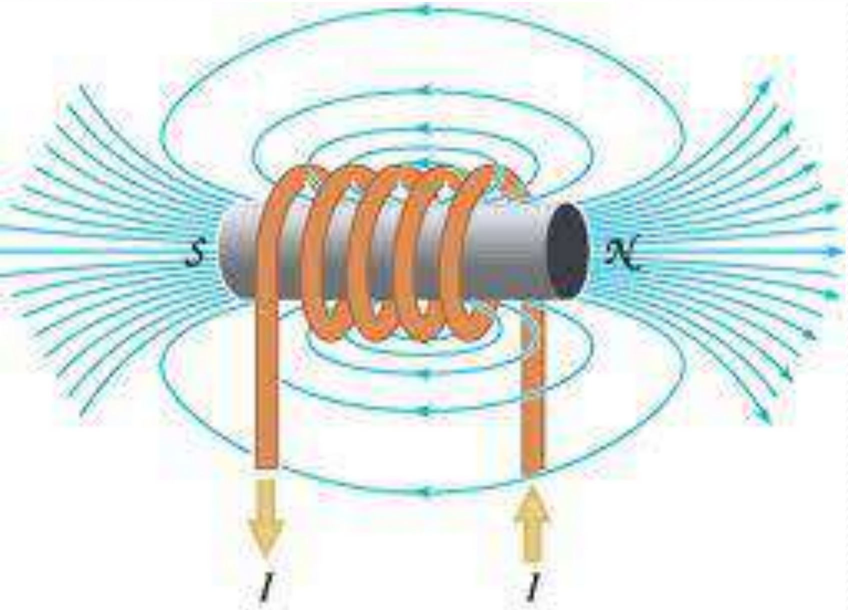


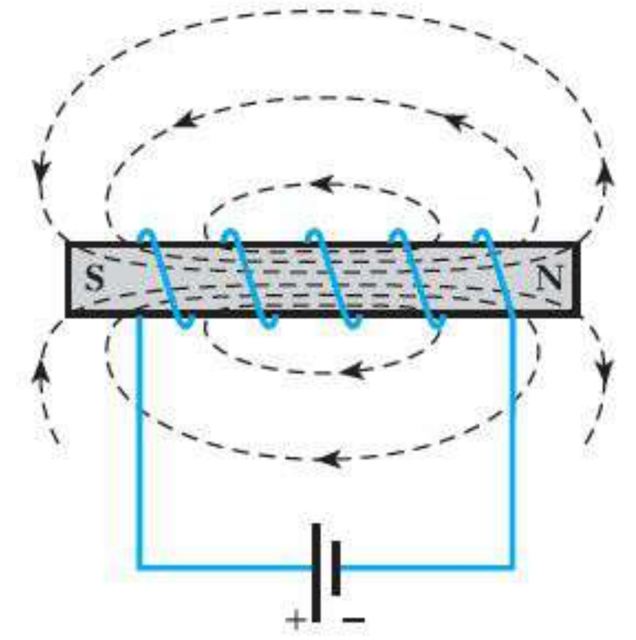
Right hand Grip / Thumb Rule



Corkscrew Rule

Magnetic field due to circular conductor or solenoid

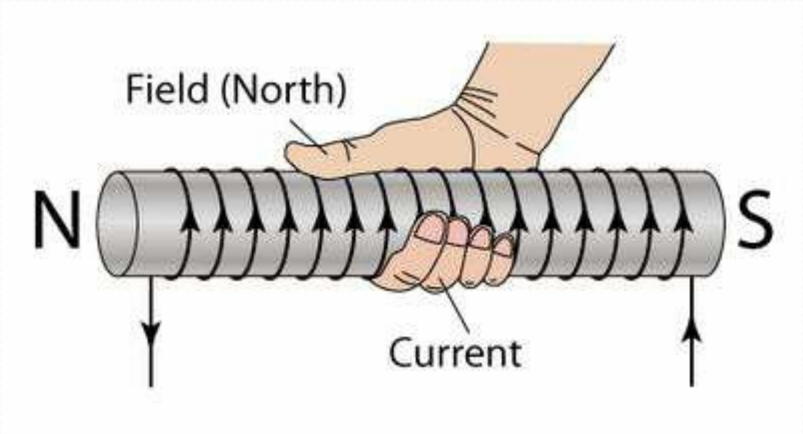




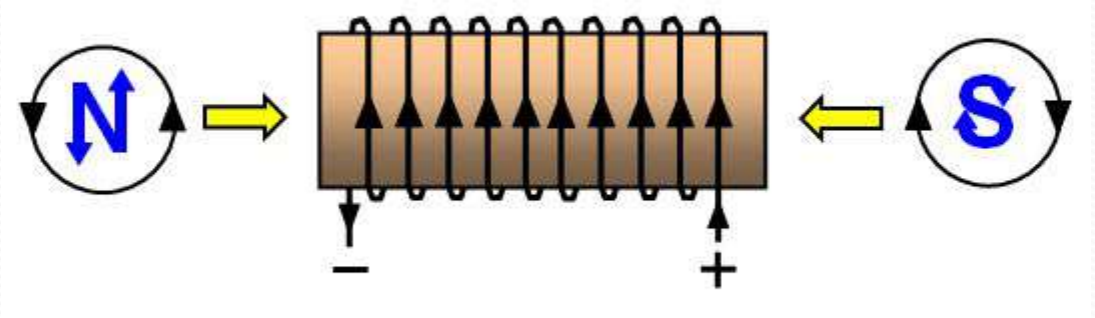
Solenoid with a steel core

If a coil is wound on a steel rod, as in Fig. and connected to a battery, the steel becomes magnetized and behaves like a permanent magnet.

Right hand thumb rule



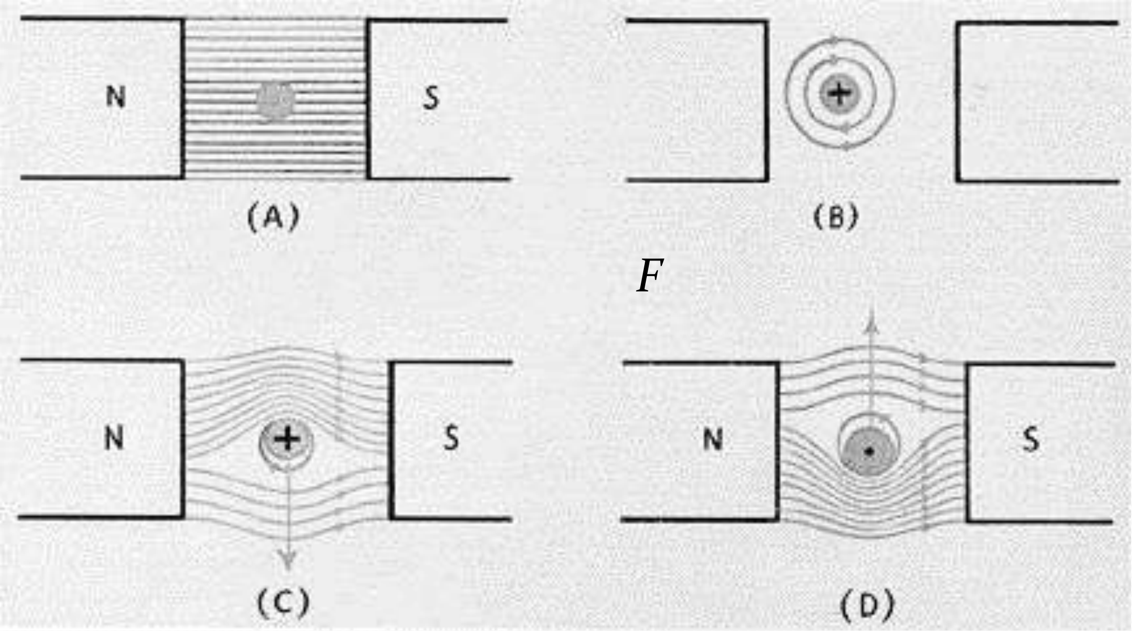
End rule



Magnetic field strength inside a solenoid

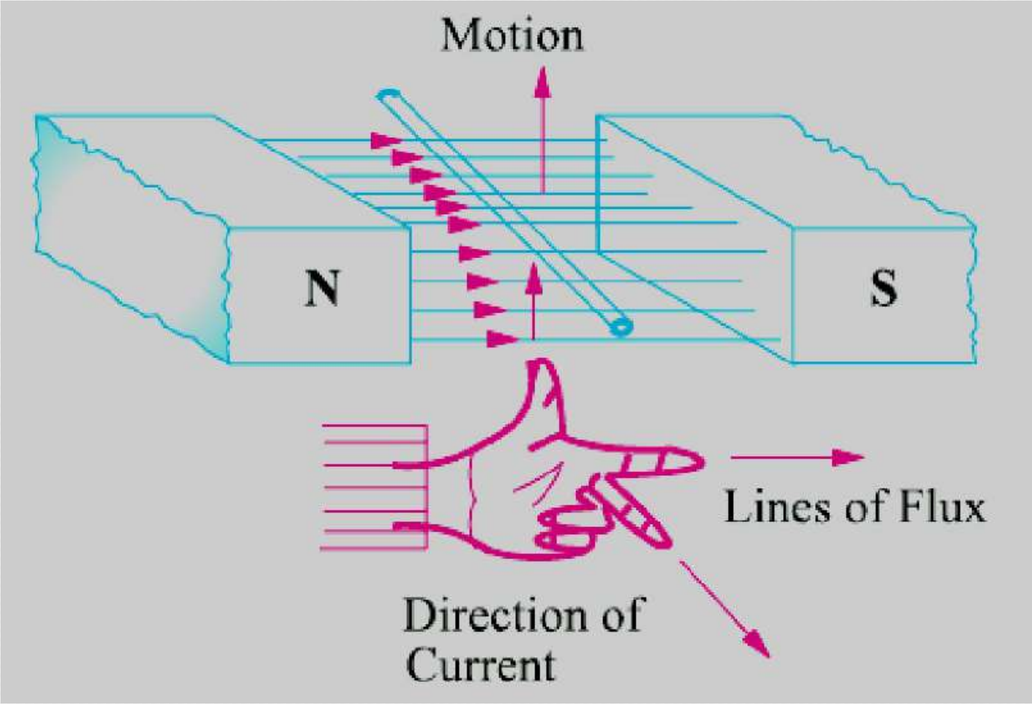
$$Magnetic\ field\ strenght \quad H = \frac{NI}{l} = \frac{\text{Ampere . Turns}}{metre} \qquad AT/m\ (Newton/Weber)$$

Force on current carrying conductor placed in magnetic field



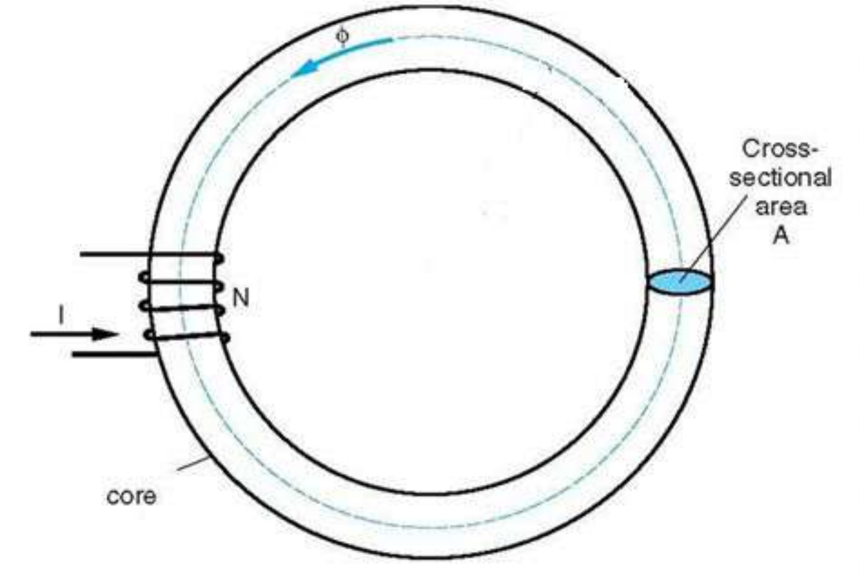
$$F = B\,I\,l\ sin(\theta)$$

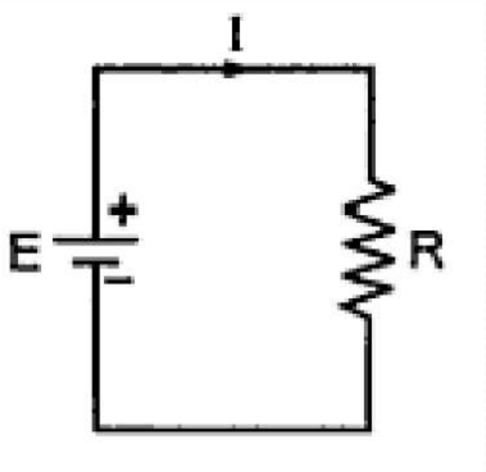
Flemings Left Hand Rule



Fore Finger : Magnetic Field
mIddle : Current I
thuMb : Motion

Toroid





N- Number of Turns
I – Current in the coil Amp
Φ – Flux in the core in wb
A- Area of the core in m²
l- lenghth of the magnetic path in m
μ - Absolute permeability of core

$$Magnetic\ field\ strenght\ inside\ the\ solenoid \quad H = \frac{\text{NI}}{l}$$

$$Magnetic\ flux\ Density \quad B = \frac{\Phi}{A}$$

Flux density $B = \mu H$

$$B = \mu \frac{\text{NI}}{l}$$

$$flux \quad \Phi = \frac{N\,I\,A\,\mu}{l}$$

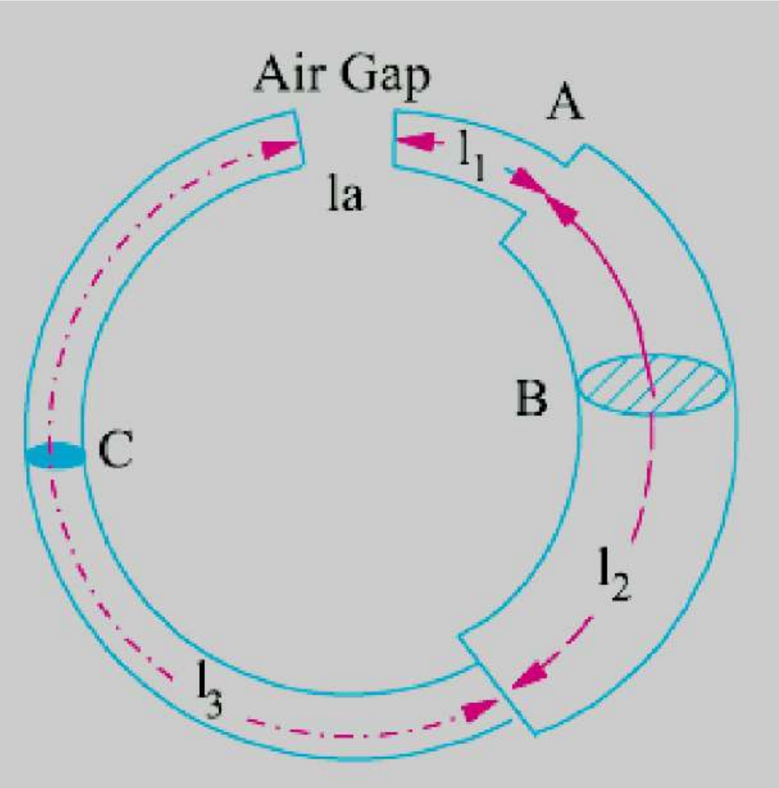
$$\Phi = \frac{\frac{N\,I}{l}}{\mu\,A} = \frac{N\,I}{\frac{l}{\mu_0\,\mu_r\,A}} = \frac{mmf}{Reluctance} = \frac{F}{S}$$

$$Magneto\ Motive\ Force \quad mmf = N\,I = H\,l = S\,\Phi \quad \text{Amper . Turns (AT)}$$

$$Reluctance\ \ S = \frac{l}{\mu A} = \frac{l}{\mu_0 \mu_r A} \quad \text{AT/wb}$$

$$Permeance = \frac{1}{Reluctance}$$

Series Magnetic Circuit

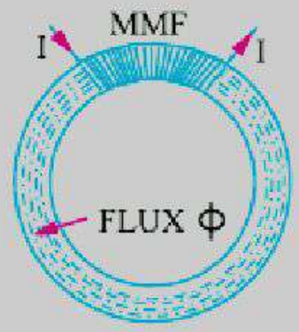
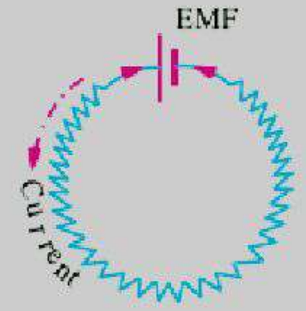


$$\text{total reluctance} = \sum \frac{l}{\mu_0 \mu_r A}$$

$$= \frac{l_1}{\mu_0 \mu_{r_1} A_1} + \frac{l_2}{\mu_0 \mu_{r_2} A_2} + \frac{l_3}{\mu_0 \mu_{r_3} A_3} + \frac{l_a}{\mu_0 A_g}$$

Comparison Between Magnetic and Electric Circuits.

SIMILARITIES

Magnetic Circuit	Electric Circuit
 Fig. 6.27	 Fig. 6.28
1. Flux = $\frac{\text{m.m.f.}}{\text{reluctance}}$	Current = $\frac{\text{e.m.f.}}{\text{resistance}}$
2. M.M.F. (ampere-turns)	E.M.F. (volts)
3. Flux Φ (webers)	Current I (amperes)
4. Flux density B (Wb/m^2)	Current density (A/m^2)
5. Reluctance $S = \frac{l}{\mu A}\left(= \frac{l}{\mu_0 \mu_r A}\right)$	resistance $R = \rho \frac{l}{A} = \frac{l}{\rho A}$
6. Permeance (= 1/reluctance)	Conductance (= 1/resistance)
7. Reluctivity	Resistivity
8. Permeability (= 1/reluctivity)	Conductivity (= 1/resistivity)
9. Total m.m.f. = $\Phi S_1 + \Phi S_2 + \Phi S_3 + \ldots$	9. Total e.m.f. = $IR_1 + IR_2 + IR_3 + \ldots$

DIFFERENCES

1. Strictly speaking, flux does not actually ‘flow’ in the sense in which an electric current flows.
2. If temperature is kept constant, then resistance of an electric circuit is constant and is independent of the current strength (or current density). On the other hand, the reluctance of a magnetic circuit does depend on flux (and hence flux density) established in it. It is so because μ (which equals the slope of *B*/*H* curve) is not constant even for a given material as it depends on the flux density *B*. Value of μ is large for low value of *B* and ***vice-versa***. Hence, reluctance is small ($S = \frac{l}{\mu A}$) for small values of *B* and large for large values of *B*.
3. Flow of current in an electric circuit involves continuous expenditure of energy but in a magnetic circuit, energy is needed only creating the flux initially but not for maintaining it.

Example 1 :

An iron ring has a mean circumference of 180 cm. It carries a current Of 1.5 Amp and has 600 turns of coil wound over it. The relative Permeability of the iron is 1200. Calculate 1) MMF 2) Field strength and 3) flux density.

Length of magnetic path $l = 180cm = 1.8\ m$ $\quad$ $No.\,of\ turns\ N = 600$

$$current\ through\ the\ coil\ = 1.5\ A$$

$$relative\ permeability\ of\ iron\ \ \mu_r = 1200$$

$$Magneto\ Motive\ Force\quad mmf = NI = 600 \times 1.5 = \mathbf{900}\ \ \text{Amper . Turns (AT)}$$

$$Magnetic\ field\ strenght\quad H = \frac{\text{NI}}{l} = \frac{900}{1.8} = \mathbf{500}\ AT/m$$

$$\mu = \mu_0 \mu_r = \frac{B}{H}$$

$$Flux\ Density\ B = \mu_0 \mu_r H$$

$$B = 4\pi \times 10^{-7} \times 1200\ \times 500$$

$$\boldsymbol{B = 0.754\ T}$$

Example 2 :

An iron ring has a mean circumference of 50 cm has an air gap of 2mm cut in it . It has circular cross section of area 5 cm2. It carries a coil wound with 600 turns wound uniformly. The relative Permeability of the iron is 580. If the coil carries a current of 2A . Find the flux in the air gap.

Solution:

Length of magnetic path $l = 50cm = 0.5m$

Air gap Length $l_a = 2mm = 2 \times 10^{-3}\ m$

Length of iron $l_i = 0.5 - 2 \times 10^{-3} = 0.498m$

$$area\ of\ cross\ section\ a = 5\ cm^2 = 5 \times 10^{-4}\ m^2$$
$$No.of\ turns\ N = 600$$

$$current\ through\ the\ coil = 2\ A$$

$$relative\ permeability\ of\ iron\ \mu_r = 580$$
$$relative\ permeability\ of\ Air\ \mu_a = 1$$

$$Magneto\ Motive\ Force\quad mmf = NI = 600 \times 2 = \mathbf{1200}\ \text{AT}$$

$$Reluctance\ of\ Iron\ \ S_i = \frac{l_i}{\mu_0 \mu_r a} = \frac{0.498}{4\pi \times 10^{-7} \times 580 \times 5 \times 10^{-4}} = \mathbf{1366537\ AT/wb}$$

$$Reluctance\ of\ Air\ gap\ \ S_g = \frac{l_g}{\mu_0 \mu_r a} = \frac{2 \times 10^{-3}}{4\pi \times 10^{-7} \times 1 \times 5 \times 10^{-4}} = \mathbf{3183098\ AT/wb}$$

$$Total\ Reluctance\ of\ magnetic\ path\ \ S_t = S_i + S_g$$

$$S_t = 1366537 + 3183098$$

$$S_t = \mathbf{4549636\ AT/wb}$$

$$Flux\ in\ the\ air\ gap\ \varphi = \frac{mmf}{total\ Reluctance}$$

$$\varphi = \frac{NI}{S_t} = \frac{1200}{4549636} = \mathbf{0.263}\ mwb$$

Example 3 :

A coil of N turns is wound on a cast iron ring which has a mean length of 50 cm and its cross section is of 4 cm diameter. The current flowing through the coil is 2A . which produces flux of 6 mwb in the air gap of 2mm length The relative Permeability of the iron is 1000.Calculate the number of turns N.

Length of magnetic path $l = 50cm = 0.5m$

Air gap Length $l_a = 2mm = 2 \times 10^{-3}\ m$

Length of iron $l_i = 0.5 - 2 \times 10^{-3} = 0.498m$

Diametre of the core d $= 4cm$

$$area\ of\ cross\ section\ a = \pi r^2 = 12.56 \times 10^{-4}\ m^2$$

$$Flux\ in\ the\ air\ gap\ \varphi = 6mwb$$

$$current\ through\ the\ coil\ = 2\ A$$

$$relative\ permeability\ of\ iron\ \mu_r = 1000$$

$$relative\ permeability\ of\ Air\ \mu_a = 1$$

$$Reluctance\ of\ Iron\ S_i = \frac{l_i}{\mu_0 \mu_r a} = \frac{0.498}{4\pi \times 10^{-7} \times 1000 \times 12.56 \times 10^{-4}}$$

$$= 315522.14\ AT/wb$$

$$Reluctance\ of\ Air\ gap\ S_g = \frac{l_g}{\mu_0 \mu_r a} = \frac{2 \times 10^{-3}}{4\pi \times 10^{-7} \times 1 \times 12.56 \times 10^{-4}}$$

$$= 1267157.19\ AT/wb$$

$$Total\ Reluctance\ of\ magnetic\ path\ S_t = S_i + S_g$$

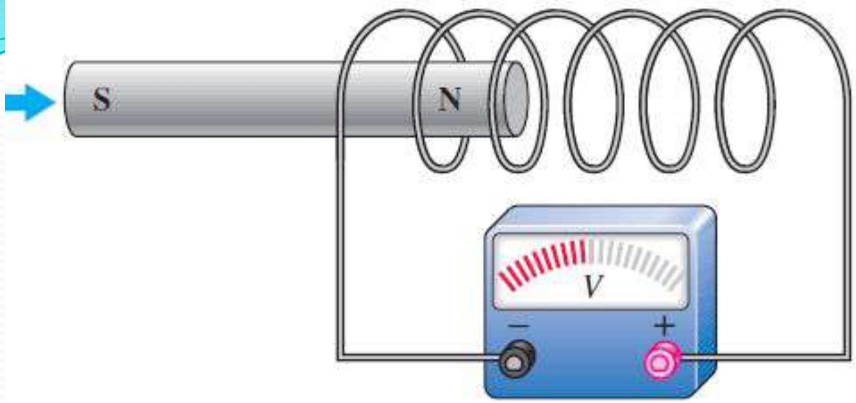
$$S_t = 315522.14 + 1267157.19$$

$$S_t = 1582679.33\ AT/wb$$

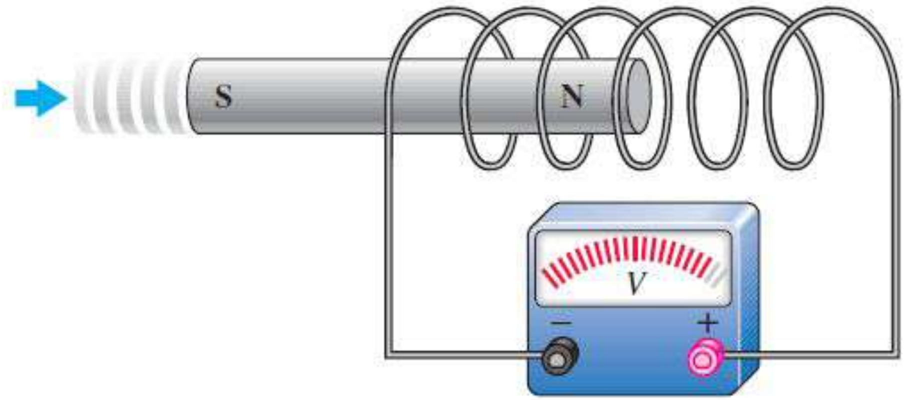
$$Flux\ in\ the\ air\ gap\ \varphi = \frac{mmf}{total\ Reluctance} = \frac{NI}{S_t}$$

$$6.0 \times 10^{-3} = \frac{N \times 2}{1582679.33} \qquad \mathbf{N = 4748}$$

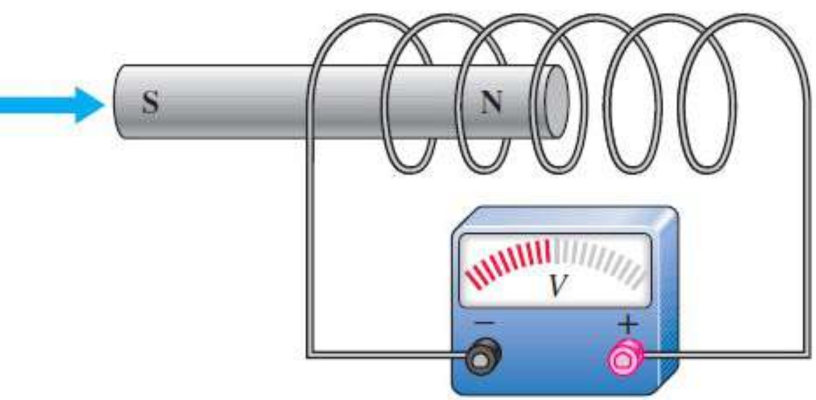
Faradays Experiment



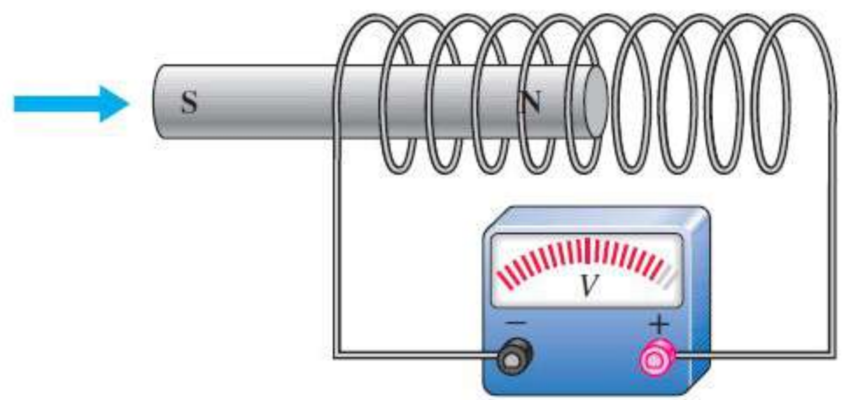
As the magnet moves slowly to the right, its magnetic field is changing with respect to the coil, and a voltage is induced.



As the magnet moves more rapidly to the right, its magnetic field is changing more rapidly with respect to the coil, and a greater voltage is induced.

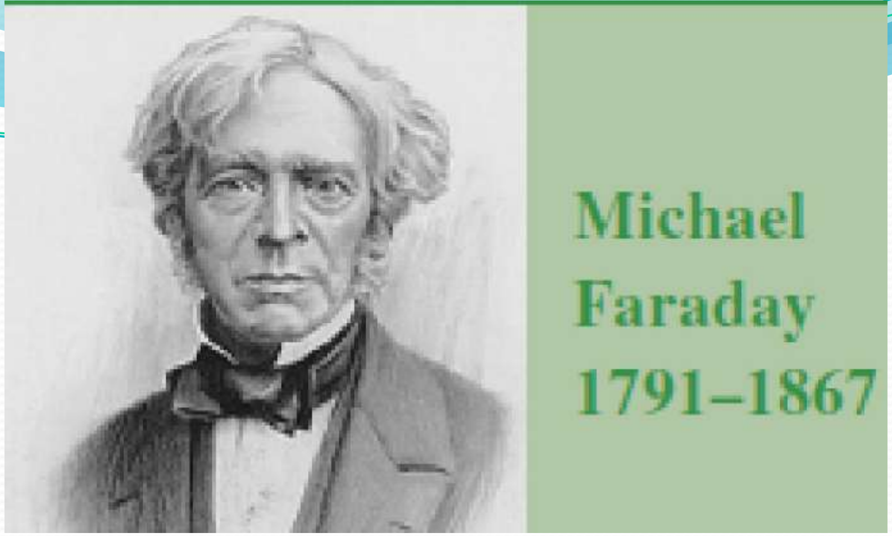


Magnet moves through a coil and induces a voltage.



Magnet moves at same rate through a coil with more turns
(loops) and induces a greater voltage.

Faraday's Laws of Electromagnetic Induction



First Law : Whenever a conductor cuts magnetic flux, an e.m.f. is induced in that conductor.

Second Law : The magnitude of the induced e.m.f. is equal to the rate of change of flux-linkages.

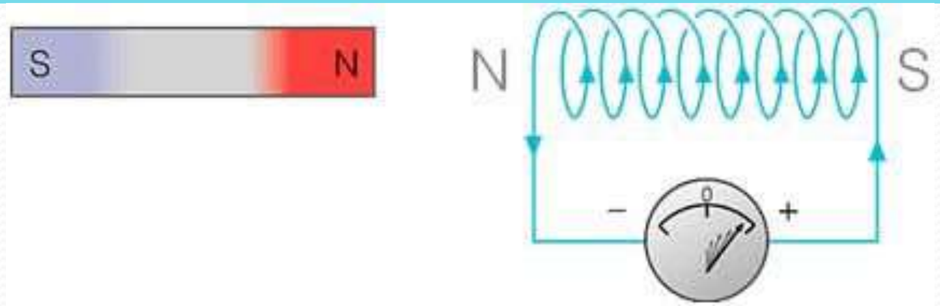
$$Flux\ linkages = flux \times No\ of\ turns\ of\ the\ coil = N \times \phi$$

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

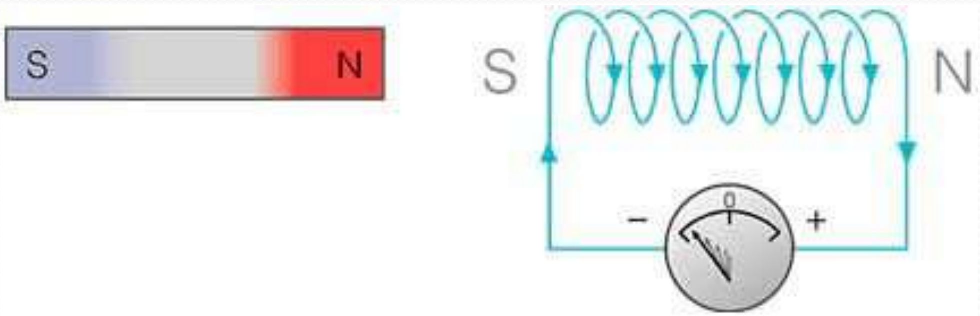
Lenz's Law

The direction of the induced emf is such that it opposes the cause producing it.

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



When a magnet is moving towards the coil.



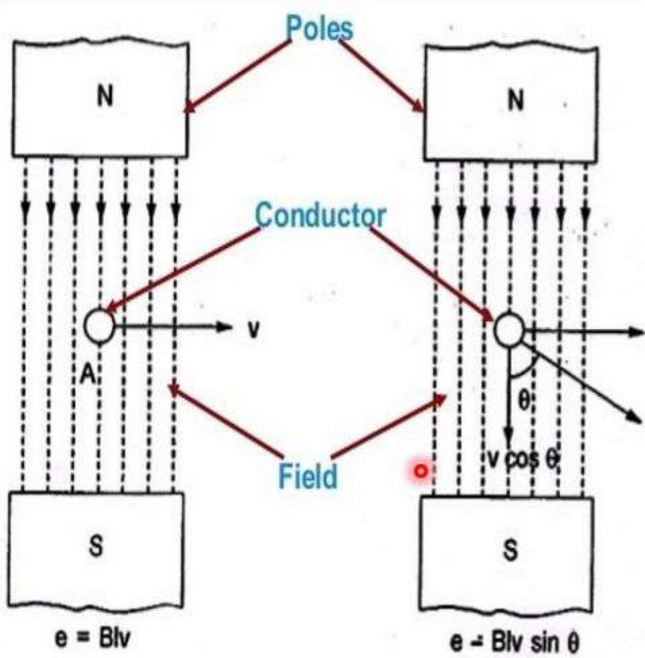
When a magnet is moving away from the coil

Heinrich Lenz
(1804-1865)

Dynamically induced emf : ***Emf induced in the conductor or the coil due to relative motion between the conductor and magnetic field.***

a conductor of length l *meter is moved in a magnetic field with flux density of* B *with a velocity of* v m/sec

Let this conductor is moved through distance ***dx*** **in small time** ***dt*** **then**



Area swept by the conductor = ***l dx***

Flux cut by the conductor d ϕ***=B l dx wb***

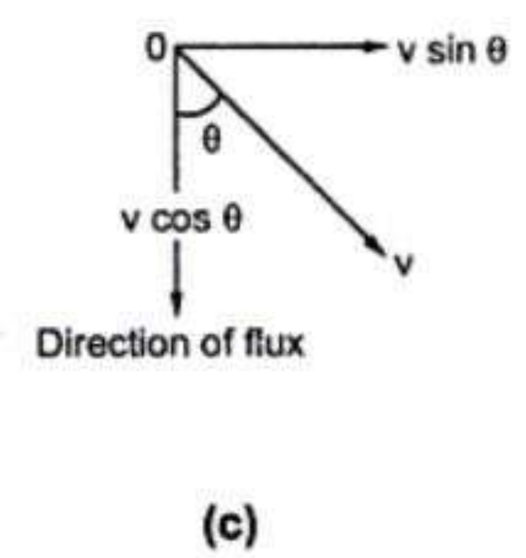
According to faradays law magnitude of the induced emf is proportional to the rate of change of flux

$$e = \frac{flux\ cut}{time} = \frac{d\,\phi}{dt}$$

$$e = \frac{B\,l\,dx}{dt}$$

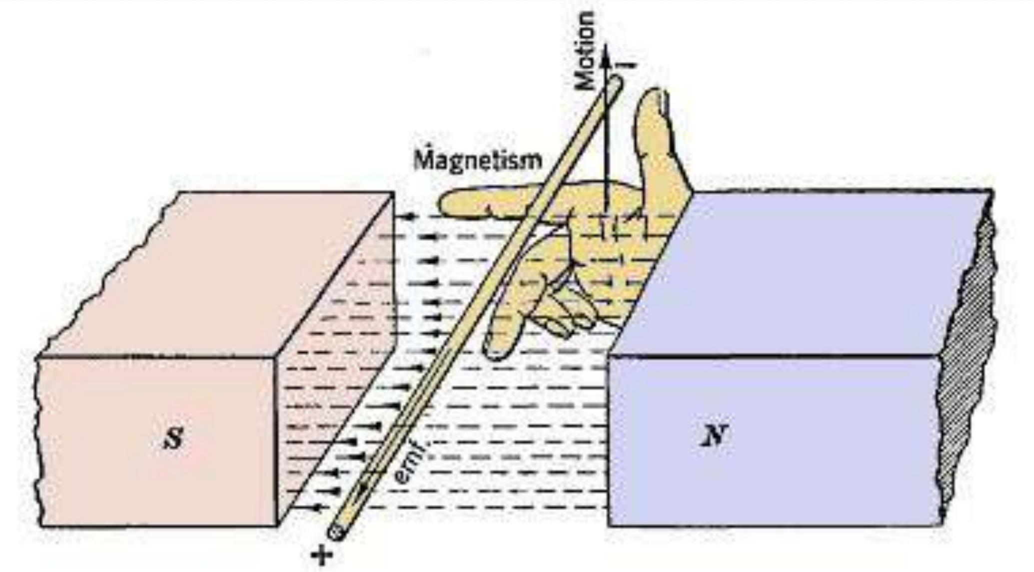
$$e = B\,l\,v \qquad volts$$

$if\ \theta\ is\ angle\ between\ conductor\ and\ flux$



$$e = B\ l\ v\ sin\theta \quad volts$$

Flemings Right Hand Rule. The direction of dynamically induced emf in the conductor is given by Flemings Right Hand Rule.



Fore Finger : Magnetic Field
mIddle : Current I
thuMb : Motion

Example *A conductor of length 1 metre moves at right angles to a uniform magnetic field of flux density 1.5 Wb/m^2 with a velocity of 50 metre/second. Calculate the e.m.f. induced in it. Find also the value of induced e.m.f. when the conductor moves at an angle of 30° to the direction of the field.*

Solution. Here $B = 1.5\ \text{Wb/m}^2 \quad l = 1\ \text{m} \quad \upsilon = 50\ \text{m/s}\ ;\ e = ?$

Now $e = Bl\upsilon = 1.5 \times 1 \times 50 =$ **75 V.**

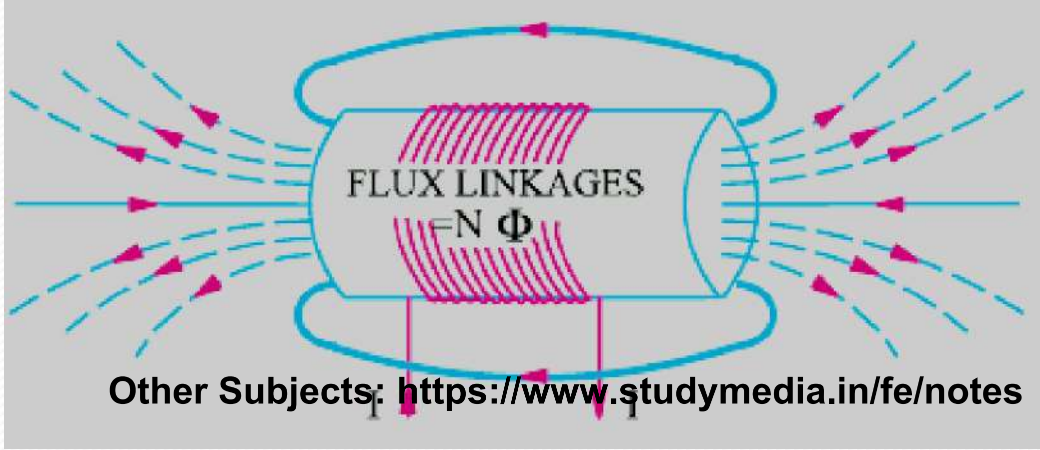
In the second case $\theta = 30°$ $\therefore \sin 30° = 0.5 \quad \therefore e = 75 \times 0.5 =$ **37.5 V**

Statically Induced E.M.F.

(a) self-induced e.m.f.

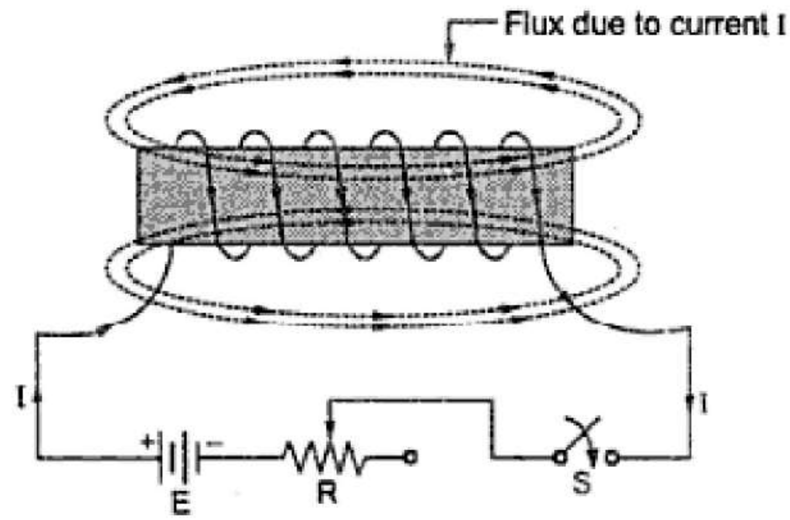
(b) Mutually induced e.m.f.

Self-induced e.m.f. **This is the e.m.f. induced in a coil due to *the change of its own flux linked with it.* If current through the coil is changed, then the flux linked with its own turns will also change, which will produce in it what is called *self-induced* e.m.f. The direction of this induced e.m.f. (as given by Lenz's law) would be such as to oppose any change of flux which is, in fact, the very cause of its production. Hence, it is also known as the opposing or counter e.m.f. of self-induction.**



Self-inductance

It is found that whenever an effort is made to increase current (and hence flux) through it, it is always opposed by the instantaneous production of counter e.m.f. of self-induction.If, now an effort is made to decrease the current (and hence the flux), then again it is delayed due to the production of self-induced e.m.f., this time in the opposite direction. This property of the coil due to which it opposes any increase or decrease of current or flux through it, is known as ***self inductance***.



It is quantitatively measured in terms of coefficient of self induction L.

Magnitude of self induced emf

From faradays law $e = -N\frac{d\varphi}{dt} \quad volts$

$$\varphi = \frac{\varphi}{I} \times \mathrm{I} = \frac{\text{flux}}{Amp} \times \mathrm{I}$$

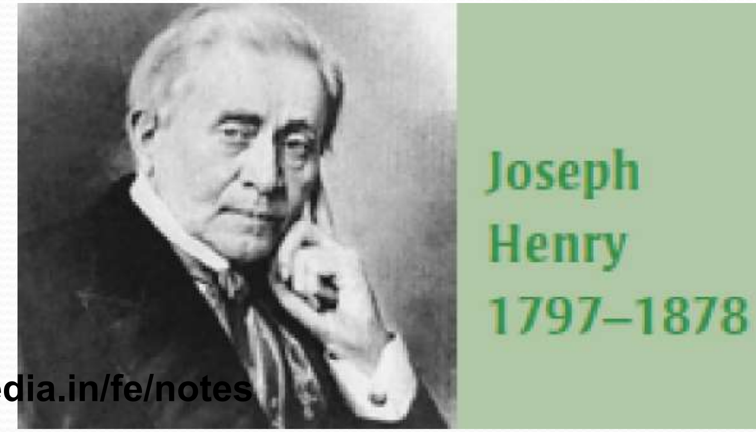
Rate of change of flux $= \frac{\varphi}{I} \times$ Rate of change of current

$$\frac{d\varphi}{dt} = \frac{\varphi}{I} \times \frac{dI}{dt}$$

$$e = -N\frac{\varphi}{I} \times \frac{dI}{dt}$$

The constant $\frac{N\varphi}{I}$ in the above expression is called co-efficient of self inductance or **self inductance** and is denoted by L

$$\boxed{\mathrm{L} = \frac{N\varphi}{I} \quad \text{Henry}}$$



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

Expressions for Coefficient of Self Inductance (L)

$$L = \frac{N\phi}{I}$$

But $$\phi = \frac{\text{m.m.f.}}{\text{Reluctance}} = \frac{NI}{S}$$

∴ $$L = \frac{N.NI}{I.S}$$

∴ $$\boxed{L = \frac{N^2}{S} \quad \text{henries}}$$

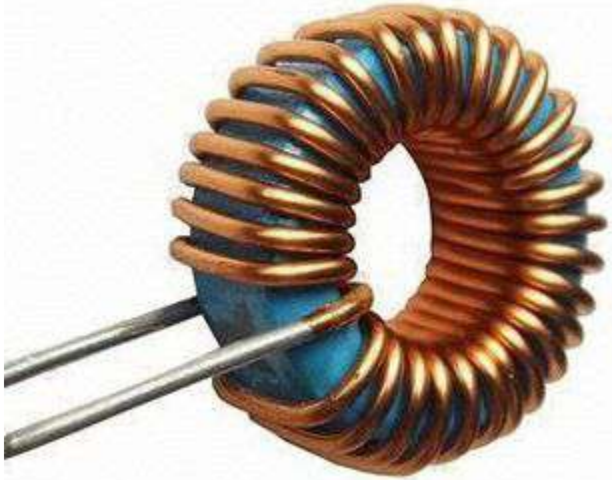
Now $$S = \frac{l}{\mu a}$$

$$L = \frac{N^2}{\left(\frac{l}{\mu a}\right)}$$

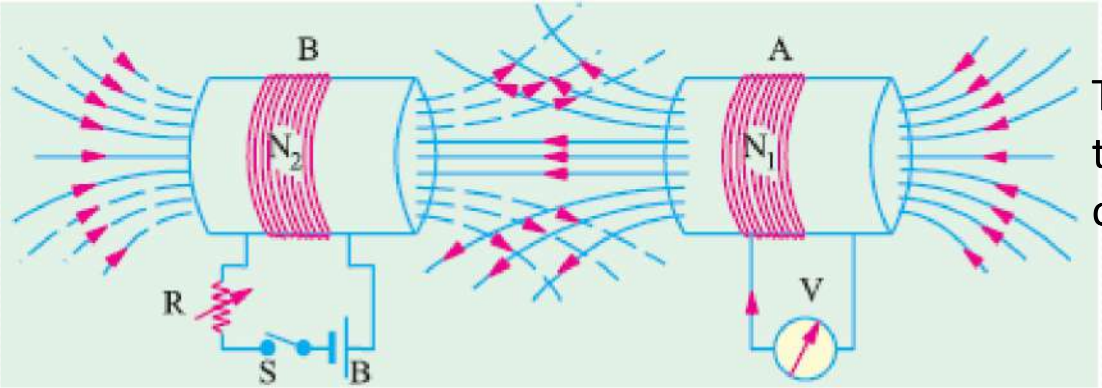
∴ $$\boxed{L = \frac{N^2 \mu a}{l} = \frac{N^2 \mu_0 \mu_r a}{l} \quad \text{henries}}$$

Where l = length of magnetic circuit

a = area of cross-section of magnetic circuit through which flux is passing.



Mutually Induced EMF



This is the emf induced in a coil due to change in current in the nearby coil.

Magnitude of Mutually Induced E.M.F.

Let N_1 = Number of turns of coil A

N_2 = Number of turns of coil B

I_1 = Current flowing through coil A

ϕ_1 = Flux produced due to current I_1 in webers.

ϕ_2 = Flux linking with coil B

According to Faraday's law, the induced e.m.f. in coil B is,

$$e_2 = -N_2 \frac{d\phi_2}{dt}$$

Negative sign indicates that this e.m.f. will set up a current which will oppose the change of flux linking with it.

Now $$\phi_2 = \frac{\phi_2}{I_1} \times I_1$$

If permeability of the surroundings is assumed constant then $\phi_2 \propto I_1$ and hence ϕ_2 / I_1 is constant.

$$\therefore \quad \text{Rate of change of } \phi_2 = \frac{\phi_2}{I_1} \times \text{Rate of change of current } I_1$$

$$\therefore \quad \frac{d\phi_2}{dt} = \frac{\phi_2}{I_1} \cdot \frac{dI_1}{dt}$$

$$\therefore \quad e_2 = -N_2 \cdot \frac{\phi_2}{I_1} \cdot \frac{dI_1}{dt}$$

$$\therefore \quad e_2 = -\left(\frac{N_2 \phi_2}{I_1}\right) \frac{dI_1}{dt}$$

Here $\left(\frac{N_2 \phi_2}{I_1}\right)$ is called coefficient of mutual inductance denoted by M.

$$\therefore \quad \boxed{e_2 = -M \frac{dI_1}{dt} \quad \text{volts}}$$

Coefficient of mutual inductance is defined as the property by which e.m.f. gets induced in the second coil because of change in current through first coil.

Expressions of the Mutual Inductance (M)

1)
$$\boxed{M = \frac{N_2 \phi_2}{I_1}}$$

2) ϕ_2 is the part of the flux ϕ_1 produced due to I_1. Let K_1 be the fraction of ϕ_1 which is linking with coil B.

$$\therefore \quad \phi_2 = K_1 \phi_1$$

$$\therefore \quad \boxed{M = \frac{N_2 K_1 \phi_1}{I_1}}$$

3) The flux ϕ_1 can be expressed as,

$$\phi_1 = \frac{\text{m.m.f.}}{\text{Reluctance}} = \frac{N_1 I_1}{S}$$

$$\therefore \quad M = \frac{N_2 K_1}{I_1}\left(\frac{N_1 I_1}{S}\right)$$

$$\boxed{M = \frac{K_1 N_1 N_2}{S}}$$

If all the flux produced by coil A links with coil B then $K_1 = 1$.

$$M = \frac{N_1 N_2}{S}$$

5) If second coil carries current I_2, producing flux ϕ_2, the part of which links with coil A i.e. ϕ_1 then,

$$\phi_1 = K_2 \phi_2 \quad \text{and} \quad M = \frac{N_1 \phi_1}{I_2}$$

$$M = \frac{N_1 K_2 \phi_2}{I_2}$$

Now $$\phi_2 = \frac{N_2 I_2}{S}$$

$$M = \frac{N_1 K_2 N_2 I_2}{I_2 S}$$

$$\boxed{M = \frac{K_2 N_1 N_2}{S}}$$

If entire flux produced by coil B_2 links with coil 1, $K_2 = 1$ hence,

$$M = \frac{N_1 N_2}{S}$$

Coefficient of Coupling or Magnetic Coupling Coefficient

We know that, $M = \frac{N_2 K_1 \phi_1}{I_1}$ and $M = \frac{N_1 K_2 \phi_2}{I_2}$

Multiplying the two expressions of M,

$$M \times M = \frac{N_2 K_1 \phi_1}{I_1} \times \frac{N_1 K_2 \phi_2}{I_2}$$

$$\therefore \quad M^2 = K_1 K_2 \left(\frac{N_1 \phi_1}{I_1}\right)\left(\frac{N_2 \phi_2}{I_2}\right)$$

But $\frac{N_1 \phi_1}{I_1}$ = Self inductance of coil 1 = L_1

$\frac{N_2 \phi_2}{I_2}$ = Self inductance of coil 2 = L_2

$$\therefore \quad M^2 = K_1 K_2 L_1 L_2$$

$$M = \sqrt{K_1 K_2} \cdot \sqrt{L_1 L_2} = K\sqrt{L_1 L_2}$$

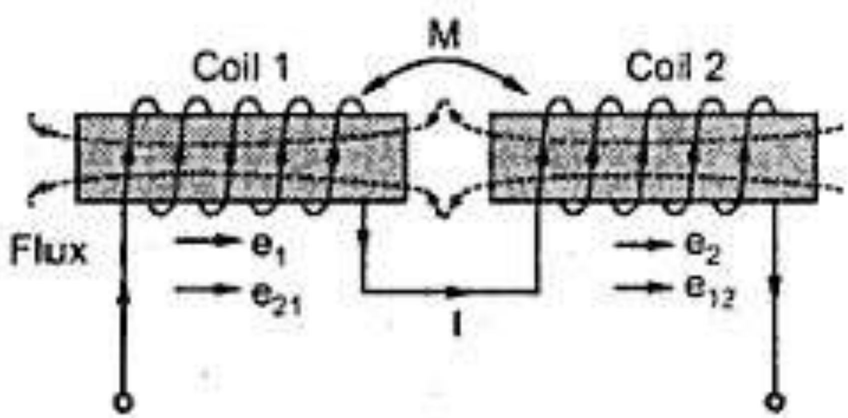
$$\boxed{K = \frac{M}{\sqrt{L_1 L_2}}}$$

Effective Inductance of Series Connection

Similar to the resistances, the two inductances can be coupled in series. The inductances can be connected in series either in series aiding mode called **cumulatively coupled connection** or series opposition mode called **differentially coupled connection.**

1 Series Aiding or Cumulatively Coupled Connection

Two coils are said to be cumulatively coupled if their fluxes are always in the same direction at any instant.



If current flow through the circuit is changing at the rate of $\frac{di}{dt}$ then total e.m.f. induced will be due to self induced e.m.f.s and due to mutually induced e.m.f.s.

Due to flux linking with coil 1 itself, there is self induced e.m.f.,

$$e_1 = -L_1 \frac{di}{dt}$$

Due to flux produced by coil 2 linking with coil 1 there is mutually induced e.m.f.,

$$e_{21} = -M\frac{di}{dt}$$

Due to flux produced by coil 1 linking with coil 2 there is mutually induced e.m.f.,

$$e_{12} = -M\frac{di}{dt}$$

Due to flux produced by coil 2 linking with itself there is self induced e.m.f.

$$e_2 = -L_2 \frac{di}{dt}$$

The total induced e.m.f. is addition of these e.m.f.s as all are in the same direction,

$$e = e_1 + e_{21} + e_{12} + e_2 = -L_1 \frac{di}{dt} - M\frac{di}{dt} - M\frac{di}{dt} - L_2 \frac{di}{dt}$$

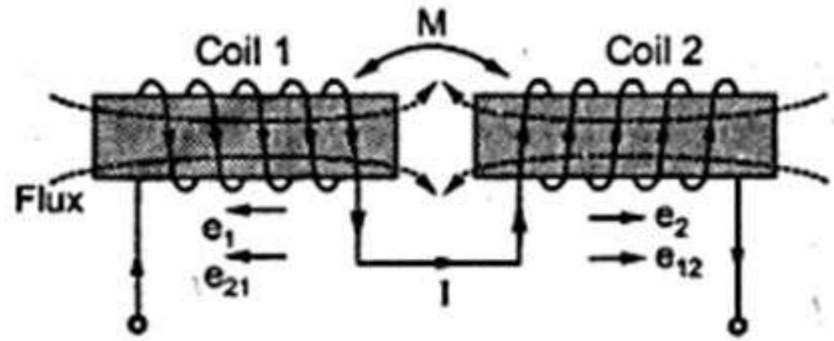
$$= -[L_1 + L_2 + 2M]\frac{di}{dt} = -L_{eq}\frac{di}{dt}$$

Where L_{eq} = Equivalent inductance

$\therefore$ $\boxed{L_{eq} = L_1 + L_2 + 2M}$

2 Series Opposition or Differentially Coupled Connection

Two coils are said to be differently coupled if their fluxes are always in the opposite direction at any instant.



$$e_1 = -L_1 \frac{di}{dt}, \qquad e_{21} = +M\frac{di}{dt}$$

$$e_{12} = +M\frac{di}{dt} \quad \text{and} \quad e_2 = -L_2 \frac{di}{dt}$$

the total e.m.f. is the addition of these four e.m.f.s,

$$e = e_1 + e_{21} + e_{12} + e_2$$

$$= -L_1 \frac{di}{dt} + M\frac{di}{dt} + M\frac{di}{dt} - L_2 \frac{di}{dt}$$

$$= -[L_1 + L_2 - 2M]\frac{di}{dt} = -L_{eq} \frac{di}{dt}$$

L_{eq} = Equivalent inductance of the differentially coupled connection.

$$\boxed{L_{eq} = L_1 + L_2 - 2M}$$

Example *Two coils with a coefficient of coupling of 0.5 between them, are connected in series so as to magnetise* **(a)** *in the same direction* **(b)** *in the opposite direction. The corresponding values of total inductances are for* **(a)** *1.9 H and for* **(b)** *0.7 H. Find the self-inductances of the two coils and the mutual inductance between them.*

Solution. (*a*) $L = L_1 + L_2 + 2M$ or $1.9 = L_1 + L_2 + 2M$ ...(*i*)

(*b*) Here $L = L_1 + L_2 - 2M$ or $0.7 = L_1 + L_2 - 2M$ ...(*ii*)

Subtracting (*ii*) from (*i*), we get

$$1.2 = 4M \qquad \therefore \quad M = 0.3 \text{ H}$$

Putting this value in (*i*) above, we get $L_1 + L_2 = 1.3$ H ...(*iii*)

We know that, in general, $M = k\sqrt{L_1 L_2}$

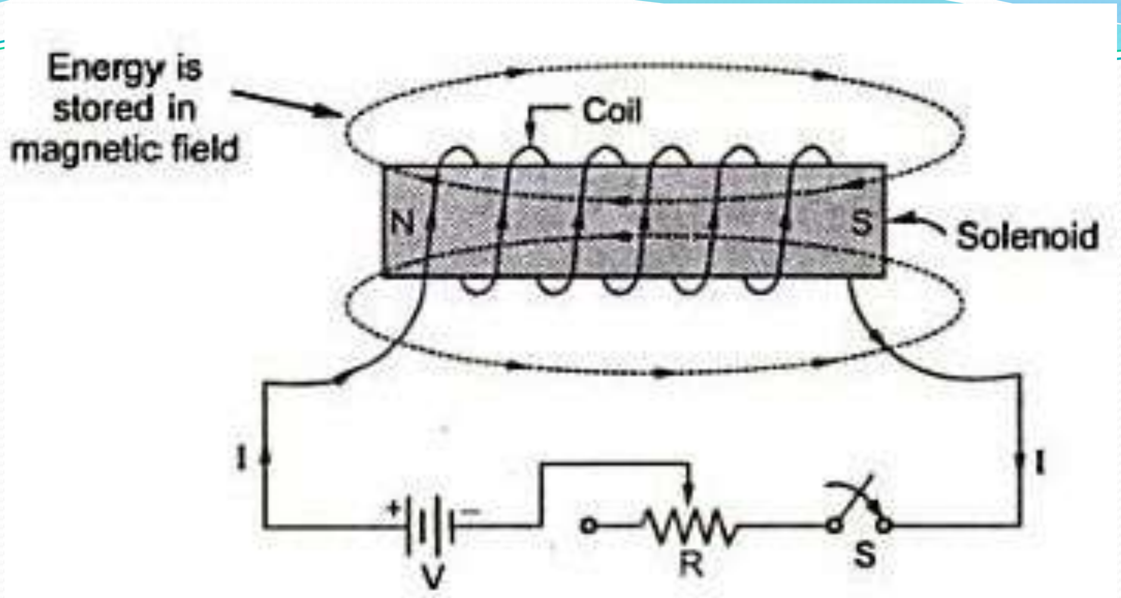
$$\therefore \quad \sqrt{L_1 L_2} = \frac{M}{k} = \frac{0.3}{0.5} = 0.6 \qquad \therefore \; L_1 L_2 = \mathbf{0.36}$$

From (*iii*), we get $(L_1 + L_2)^2 - 4L_1L_2 = (L_1 - L_2)^2$

$$\therefore \quad (L_1 - L_2)^2 = 0.25 \quad \text{or} \quad L_1 - L_2 = 0.5 \qquad \text{...}(iv)$$

From (*iii*) and (*iv*), we get $L_1 = \mathbf{0.9\ H}$ and $L_2 = \mathbf{0.4\ H}$

Energy Stored in a Magnetic Field



Let, at any instant,

i = instantaneous value of current ; e = induced e.m.f. at that instant = $L.di/dt$

Then, work done in time dt in overcoming this opposition is

$$dW = ei\,dt = L.\frac{di}{dt} \times i \times dt = Li\,di$$

Total work done in establishing the maximum steady current of I is

$$\int_0^W dW = \int_0^I Li.di \qquad \text{or} \quad W = \frac{1}{2} L\,I^2$$

This work is stored as the energy of the magnetic field $\therefore E = \frac{1}{2} L\,I^2$ joules

Energy Stored Per Unit Volume

It has already been shown that the energy stored in a magnetic field of length $l\ metre\ and\ of\ cross - section\ A\ m^2$ is

$$E = \frac{1}{2} L I^2 ----(1)$$

We know that

$$L = \frac{N^2 \mu_0 \mu_r A}{l} ----(2)$$

Substituting (2) in (1)

$$E = \frac{1}{2} \frac{N^2 \mu_0 \mu_r A}{l} I^2$$

$$E = \frac{1}{2} \mu_0 \mu_r A l \frac{N^2 I^2}{l^2}$$

$$E = \frac{1}{2} (\mu_0 \mu_r)(Al) H^2 \qquad \because H = \frac{NI}{l}$$

Now $volume\ of\ the\ magnetic\ core \quad v = Al$

$$E/m^3 = \frac{1}{2}\ (\mu_0\mu_r)\ H^2$$

We know that $\mu = \mu_0\mu_r = \frac{B}{H}$

$$\text{Energy stored per unit volume} = \frac{1}{2} B\ H = \frac{1}{2}\mu\ H^2 = \frac{1}{2}\frac{B^2}{\mu} \qquad Joule\,s/m^3$$

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Example *Reluctance of a magnetic circuit is known to be 10^5 AT/Wb and excitation coil has 200 turns. Current in the coil is changing uniformly at 200 A/s. Calculate* **(a)** *inductance of the coil* **(b)** *voltage induced across the coil and* **(c)** *energy stored in the coil when instantaneous current at $t = 1$ second is 1 A. Neglect resistance of the coil.*

Solution. (a) $L = N^2/S = 200^2/10^5 = \mathbf{0.4\ H}$

(b) $e_L = L\, dI/dt = 0.4 \times 200 = \mathbf{80\ V}$

(c) $E = \frac{1}{2} L I^2 = 0.5 \times 0.4 \times I^2 = \mathbf{0.2\ J}$

Example *An iron ring of 20 cm mean diameter having a cross-section of 100 cm² is wound with 400 turns of wire. Calculate the exciting current required to establish a flux density of 1 Wb/m² if the relative permeability of iron is 1000. What is the value of energy stored ?*

Solution. $B = \mu_0 \mu_r NI/l \text{ Wb/m}^2$

$\therefore \quad 1 = 4\pi \times 10^{-7} \times 1000 \times 400\, I/0.2\pi$ or $I =$ **1.25 A**

Now, $L = \mu_0 \mu_r AN^2/l = 4\pi \times 10^{-7} \times 10^3 \times (100 \times 10^{-4}) \times (400)^2/0.2\pi = 32.\text{H}$

$$E = \frac{1}{2} LI^2 = \frac{1}{2} \times 3.2 \times 1.25^2 = \mathbf{2.5\ J}$$