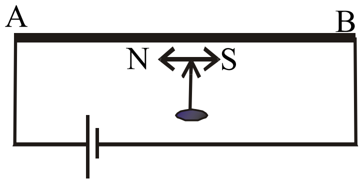
MAGNETIC EFFECT OF CURRENT AND MAGNETISM

Oersted's Experiment

In 1820, Oersted discovered that an electric current could produce a magnetic field. Stretch a wire AB over a pivoted magnetic needle NS placed below it, the length of the wire being parallel to the axis of the needle. On sending a current through the wire, the needle is found to get deflected. The needle tends to set itself at right angles to the wire. However it takes up a position slightly less than 90°. The deflection is caused by the action of two fields – one due to the magnetic field of the wire and other due to the earth's field. If current through AB is reversed, the needle will deflect in opposite direction.

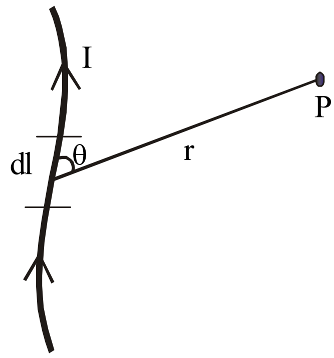


On reversing the current, the magnetic field is also reversed. *So Orested concluded that a magnetic field is associated with an electric current.*

**NB Biot – Savart law. OR Ampere's law.

Jean Baptiste Biot and Felix Savart experimentally obtained a relation for the magnetic field produced by a current carrying conductor.

According to Biot and Savart, the magnetic field dB at a point P due to a current I flowing through a small element of length dl of the conductor is (1) directly proportional to the length dl of the element and to the current I it carries. (2) inversely proportional to the square of the distance r between the current element and the point P; and (3) directly proportional to the sine of the angle θ between the current element and the line joining it with the point P under consideration.



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

OR $$dB = \frac{\mu_0}{4\pi}\frac{I\,dl\sin\theta}{r^2} \quad \text{.......................(1)}$$

Here μ_0 is called permeability of free space, whose value is $4\pi \times 10^{-7}$ wb/ A m.

In terms of vectors, (1) becomes $$\vec{dB} = \frac{\mu_0}{4\pi}\frac{I(\vec{dl}\times\vec{r})}{r^3} = \frac{\mu_0}{4\pi}\frac{I(\vec{dl}\times\hat{r})}{r^2}$$

Where $\hat{r}$ is a unit vector in the direction of $\vec{r}$.

The direction of magnetic field dB at P is perpendicular to the plane containing dl and r. This is **Biot – Savart law** for an element. It is also called *Laplace's law or Ampere's law.*

Note: 1) If the element is placed in a medium of relative permeability μ_r, then $dB = \frac{\mu_0\mu_r}{4\pi}\frac{I\,dl\sin\theta}{r^2}$

2) Value of μ_r is one for free space.

3) SI unit of magnetic field is tesla (T) named after the Yugoslav scientist Nikola Tesla.

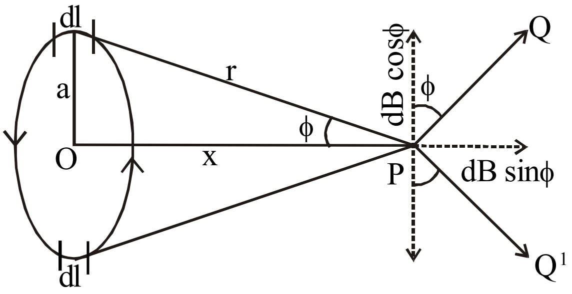
** Magnetic flux (ϕ_m)

The surface integral of magnetic field over a surface is called magnetic flux. Magnetic flux linked with a surface is defined as the product of area A and the component of field B normal to the area.

ie Magnetic flux ϕ_m = B A. The unit of magnetic flux is weber *(wb)*

**NB Magnetic field due to a circular coil or loop.

Consider a circular coil of wire of radius a, carrying a current I. Let P be a point on the axis of the coil at a distance x from the center O. Consider a small element dl of the loop carrying current. It is at a distance r from the point P.



Now according to Biot – Savart's law, the Magnetic field at P due to element dl is given by

$$dB = \frac{\mu_0}{4\pi}\frac{Idl\sin 90}{r^2}$$

Here q = 90° because for all elements around the loop, the distance r is perpendicular to dl.

$$dB = \frac{\mu_0}{4\pi}\frac{Idl}{r^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots(1)$$

The direction of dB is perpendicular to the plane containing dl and P – ie along PQ.

The field dB may be resolved into two components – dB sinϕ along the axis of the loop and dB cos f perpendicular to the axis.

If we consider a diametrically opposite element dl, the contribution of the magnetic field at P is same, but along PQ^1.

When we resolve the magnetic field along PQ^1, the perpendicular components due to the two elements being equal and opposite, cancel each other but the components along the axis get added up.

Now the current loop may be imagined to be made up of such pairs of elementary lengths, so that the magnetic field B at the point P is the sum of the components along the axis.

$$\text{i.e.} \quad B = \int dB\sin\phi = \int \frac{\mu_0}{4\pi}\frac{Idl\sin\phi}{r^2}$$

But from figure, $\sin\phi = \frac{a}{r}$

$$\therefore \; B = \frac{\mu_0}{4\pi}\frac{Ia}{r^3}\int dl$$

But $\int dl$ = perimeter of the loop = $2\pi a$.

$$\therefore \; B = \frac{\mu_0}{4\pi}\frac{Ia}{r^3}\,2\pi a$$

$$B = \frac{\mu_0}{2}\frac{Ia^2}{r^3} \quad \ldots\ldots\ldots\ldots\ldots(2)$$

But from figure; $r^2 = x^2 + a^2$.

Or $r^3 = (x^2 + a^2)^{3/2}$.

$$B = \frac{\mu_0 Ia^2}{2(x^2+a^2)^{\frac{3}{2}}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

If the loop has N turns, the magnetic field, $B = \frac{\mu_0 NIa^2}{2(x^2+a^2)^{\frac{3}{2}}}$ ....(4)

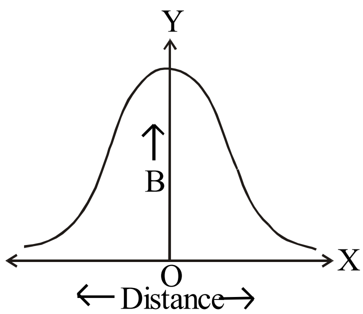
Case 1: At the center of the loop; $x = 0$.

$$B = \frac{\mu_0 NIa^2}{2a^3} = \frac{\mu_0 NI}{2a}$$

The field is perpendicular to the plane of the loop.

Case 2: If the distance x is very large, $x >>>> a$, then $a^2 <<<< x^2$.

$$B = \frac{\mu_0 NIa^2}{2x^3}$$



The variation of magnetic field with distance is as shown in figure.

Note: The direction of magnetic field is given by right hand palm rule: — If the direction of circular current is represented by the direction of the closed fingers of the right hand, then the stretched thumb will give the direction of magnetic field.

Q1. A circular coil consists of closely wound coils of 50 turns with a radius 5.0 cm and carries a current of 3.0 A. Find the magnetic flux density B at the centre of the coil. [1.88×10^{-3}T]
Q2. Find the magnetic field due to a circular coil of 50 turns and radius 10 cm, carrying a current of 10 A at a point on its axis distant 5 cm from the centre of the coil. [2.25×10^{-3} T]

**NB Ampere's Circuital theorem.

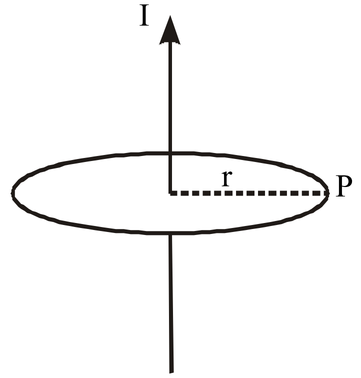
Ampere's Circuital theorem states that the line integral of the magnetic field around any closed path in free space is equal to μ_0 times the net current enclosed by the path.

Applications of Ampere's circuital theorem

1) Magnetic field due to a long straight conductor.

Consider a long straight conductor carrying a current I. Let B be the magnetic field at a point P, distant r from the long conductor. Now with r as radius and the conductor as center, draw a circle.

Now by Ampere's circuital theorem,



$$\int \vec{B} \bullet d\vec{l} = \mu_0 I$$
$$\int B\,dl = \mu_0 I$$
$$B \int dl = \mu_0 I$$
$$B\, 2\pi r = \mu_0 I$$
$$\text{or} \quad B = \frac{\mu_0 I}{2\pi r}$$

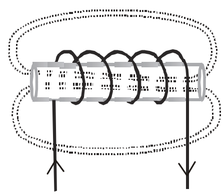
.**NB Magnetic field due to a solenoid

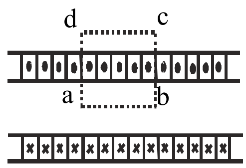
A solenoid consists of a long insulated wire wound closely and uniformly over a hollow cylindrical nonconducting core.

The number of turns per unit length $n = \frac{N}{l}$

(where N is the number of turns in a length l)

In the case of an ideal solenoid if length is much larger than the diameter, then the field outside the solenoid is zero and that inside the solenoid is uniform.





ab=cd=l
ad=bc=h

Consider a solenoid having n turns per unit length carrying current I. In order to find the magnetic field due to this solenoid we apply Ampere's circuital law to a loop abcd

$$\int_{abcd} \vec{B} \bullet d\vec{l} = \int_a^b \vec{B} \bullet d\vec{l} + \int_b^c \vec{B} \bullet d\vec{l} + \int_c^d \vec{B} \bullet d\vec{l} + \int_d^a \vec{B} \bullet d\vec{l} = Bl + 0 + 0 + 0 = Bl$$

(The second and fourth integrals are zero because B and dl are perpendicular. The 3rd integral is zero because B is zero outside the solenoid.)

According to Ampere's law

$$\int \vec{B} \bullet d\vec{l} = \mu_0 I \qquad \text{i.e., } B\,l = \mu_o\, n\, l\, I$$

$\mathbf{B = \mu_o n I}$ (since in a length l there are nl turns. Each turn carries current I. Total current enclosed by the loop n l I)

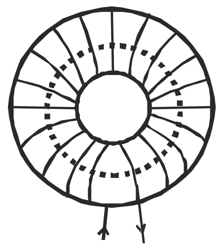
If a solenoid of length ℓ consists of N number of turns, then $n = \frac{N}{\lambda}$ $\therefore\ B = \frac{\mu_0 NI}{\ell}$

Here N = total number of turns of solenoid.

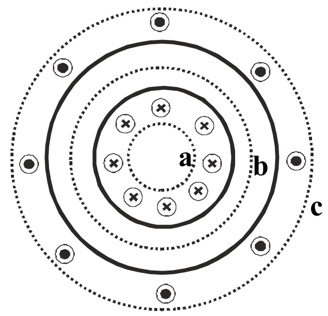
Now field at one end of solenoid, $\therefore\ B = \frac{\mu_0 nI}{2} = \frac{\mu_0 NI}{2\ell}$

Toroid

The toroid is a hollow circular ring on which a large number of turns of wire are closely wound. It can be considered as a solenoid bent into a circular shape.



We can apply Ampere's circuital law to find magnetic field due to a current carrying toroid. We consider a horizontal cross section of the toroid as shown in the figure below. We want to find the field at 3 regions a) inside the toroid (b) Inside the core of the toroid (c) outside the toroid. For this we consider 3 amperean loops a,b and c for the 3 regions respectively. Applying Ampere's circuital law to loop **a** we get.



$B_1 \times 2\pi r_1 l = \mu_o \times 0$

ie., $B_1 = 0$

Here r_1 is the radius of the circular loop. Thus the magnetic field at any point P in the open space inside the toroid is zero.

For loop **c** of radius r_3, applying Ampere's circuital law we get.

$B_3 \times 2\pi r_3 l = \mu_o \times 0$

The net current enclosed by the loop is zero because the algebraic sum of currents passing through the loop in both directions is zero. Thus the field outside the toroid at any point is also zero.

Consider the loop **b**, inside the core of the toroid. The magnetic field has the same magnitude B every where inside the core of the toroid because of symmetry. Applying toroid because of symmetry. Applying Ampere's circuital law to the loop of radius r we get

$B \times 2\pi r = \mu_o\, i\, (2\pi r n)$

where 'n' is the number of turns per unit length $\therefore$ $\mathbf{B = \mu_o n i}$.

Q3. A long straight conductor carries a current of 5 A. Find the magnetic field at a distance 1 m from it. [10^{-6}T]

Q4. A horizontal power line carries a current of 100 A in the south to north direction. What is the direction and magnitude of magnetic field 1 m below the line? [2×10^{-5}T]

Q5. A long conductor of radius 2 cm carries 30 A current. Find the magnetic induction on the surface of the conductor. [3×10^{-4} T]

Q6. Calculate the magnetic field at the centre of a circular loop carrying current 1A. The radius of the loop is 1 cm. Also calculate the magnetic field at a distance 5 cm from its centre on its axis. [$2\pi \times 10^{-5}$T, 4.74×10^{-7}T]

##NB Force on a moving charge in a magnetic field.

We know that moving charges can produce magnetic field. So when a charge moves through a magnetic field, it will interact with the field and hence experience a force. The force F acting on a charge q moving with a velocity v in a magnetic field of flux density B is given by

$$\vec{F} = q\,(\vec{v} \times \vec{B}) \qquad \text{..........................} \quad (1)$$

This force is known as magnetic Lorentz force.

From (1); $\mathbf{F = q\, v\, B \sin\theta}$ .... (2) ; where θ is the angle between $\vec{v}$ and $\vec{B}$.

The direction of magnetic Lorentz force is perpendicular to the plane containing $\vec{v}$ and $\vec{B}$.

Note: Lorentz force, $F = q\,v\,B\,\text{Sin}\,\theta$.

1) If charge is moving parallel to the field, $\theta = 0$. $\therefore$ F = 0.

2) If charge is moving $\perp^r$ to the field, $\theta = 90°$ $\therefore$ F = maximum = q v B.

3) If an electric field $\vec{E}$ is also present with the magnetic field, then the force on the charge due to the combined field is given by $\vec{F} = q\left[\vec{E} + (\vec{v} \times \vec{B})\right]$ and is known as *Lorentz force.*

NB **Special Case.**

**1) Charged particle moving at right angles to the magnetic field.

Consider a particle of charge q moving with a velocity v at right angles to a magnetic field of intensity B. Then the force F acting on the charge will be maximum and constant.

The force F = q v B.

This constant force will provide a centripetal force to the charged particle when it is launched perpendicular to the magnetic field. As a result, the particle describes a circular path of radius r, such that

$$qvB = \frac{mv^2}{r} \text{ ; where m = mass of the particle.}$$

$$\therefore \ r = \frac{mv}{qB}$$

This radius r is called cyclotron radius.

Now the period of rotation of the particle, T = distance/ velocity.

$$\text{ie} \ \ T = \frac{2\pi r}{v} = \frac{2\pi m v}{q vB} = \frac{2\pi m}{qB}$$

Or the frequency $\nu = \frac{1}{T} = \frac{q B}{2\pi m}$

This frequency is called cyclotron frequency.

** 2) Charged particle launched inclined to a magnetic field.

Let a charge q of mass m enter a uniform magnetic field of flux density B with a velocity v in a direction making an angle θ with the field. Now the velocity v can be resolved into two components – v cosθ in the direction of B and v sinθ perpendicular to B.

Due to v cosθ, the particle will move forward. At the same time due to v sinθ, it experiences a centripetal force q v B sinθ. Due to this, it will describe a circular path of radius r such that

$$qvB \sin\theta = \frac{mv^2 \sin^2\theta}{r}$$

$$\therefore \ r = \frac{mv \sin\theta}{qB} \ \ ....(1)$$

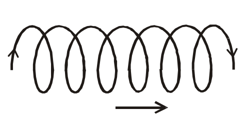
Due to these two motions, the particle moves in a *helical path or spiral path*, whose axis is in the magnetic field direction.

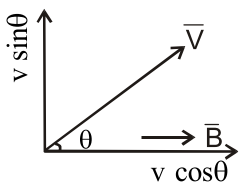
The time for one revolution of the particle,

$$T = \frac{2\pi r}{v \sin\theta} = \frac{2\pi m}{qB} \ \ ....(2)$$

During this time, the particle moves through a distance P in the direction of magnetic field B with a velocity v cosθ.

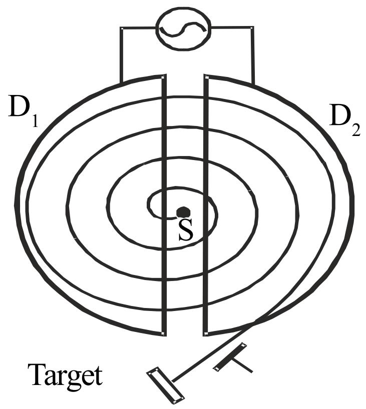
$$P = v\cos\theta \ T \quad \text{or} \quad P = \frac{2\pi m v\cos\theta}{q B}$$





Here P is called pitch of the helix.

NB Cyclotron



Cyclotron is a device in which Lorentz force is made use of in producing high-energy charged particles. It consists of two semi circular flat metal cylinders D_1 and D_2 called the dees. The dees have their diametric edges parallel and slightly separated from each other. The two dees are enclosed in an evacuated metal container. The arrangement is placed between the pole pieces of a powerful electromagnet so that a powerful uniform magnetic field is established perpendicular to the plane of the paper. A high frequency ac voltage is applied between the dees. So, there is an electric field between the dees but it is zero inside the dees. A source of ion 'S' is placed near the midpoint of the gap between the dees.

Consider an ion of charge +q and mass 'm' emitted from the source S at the instant when D_1 is negative. The ion is accelerated by the electric field in the gap between the dees and enters the electric field free region inside D_1 with a certain speed (v_1). Due to Lorentz magnetic force, the ion travels in a circular path of radius $r_1 = \frac{m v_1}{qB}$ By the time the ion completes a half cycle, the electric field gets reversed, and D_2 becomes negative. So the ion is again accelerated when it crosses the gap between the dees and will enter D_2 with greater velocity. So it will move in a circular path of larger radius within D_2. Though the speed increases, the cyclotron frequency, $\nu = \frac{q\,B}{2\pi\, m}$ of the particle remains the same.

Time taken to travel a semi circle in each D is same. If frequency of applied ac is same as the cyclotron frequency, the ion will be accelerated every time it crosses the dees. The process is repeated and finally the ion comes out of the cyclotron through the hole at the periphery of the dees. Since the source S continuously supply ions, a beam of high-energy ions is obtained from the cyclotron.

Theory: Let v_1 be the velocity of ion entering D_1 and r_1 be the radius of semicircular path.

Then, $$\frac{m v_1^2}{r_1} = q\, v_1\, B \qquad \text{Or} \qquad r_1 = \frac{m v_1}{qB}$$

Time to describe semicircular path, $$T = \frac{\pi r_1}{v_1} = \frac{\pi m}{qB}$$

Period of ac, $T = 2t = \frac{2\pi m}{qB}$ Now frequency of oscillator, $$\nu = \frac{1}{T} = \frac{qB}{2\pi m}$$

This is known as *cyclotron frequency or magnetic resonance frequency.*

Now if r_m is the maximum radius of path, then maximum velocity, $$v_m = \frac{q\,B\,r_m}{m}$$

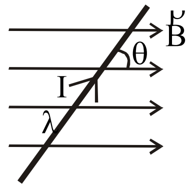
$\therefore$ Maximum kinetic energy acquired, $$E_m = \frac{1}{2} m v_m^2 = \frac{q^2 B^2 r_m^2}{2\, m}$$

NB Limitations of cyclotron OR demerits of cyclotron.

1) When velocity of ion becomes very large, its mass increases. This is known as *relativistic mass variation.* This affects the resonance condition. For electron, the mass variation is considerable due to its small mass and large velocity. So *electron cannot be accelerated by cyclotron.*
2) Chargeless particles cannot be accelerated using cyclotron.

NB Force acting on a current carrying conductor in a magnetic field.

When a charge moves in a magnetic field, it will experience a force. When a current carrying conductor is placed in a magnetic field, due to flow of charges, the conductor will experience a force.



Consider a conductor of length λ carrying a current I, placed in a uniform magnetic field B, inclined at an angle θ to the field direction.

Then the current through the conductor $I = n\,e\,a\,v_d$; where n = number of electrons per unit volume, e = electronic charge, A = area of cross-section of conductor and v_d is the drift velocity of electrons.

The Lorentz force acting on a single electron, $f = e(\vec{v} \times \vec{B})$

∴ Total force acting on all the electrons or the total force acting on the conductor,

$$F = n\,A\,\ell\,f = n\,A\,\ell\,e(\vec{v} \times \vec{B}) \qquad \{\text{number of electrons in the conductor} = n\,A\,l\}$$

$$= n\,e\,A\,v\,(\vec{\ell} \times \vec{B})$$

Or $\vec{F} = I(\vec{\ell} \times \vec{B})$ .... (1)

Or $F = B\,I\,\ell\,\sin\theta$ .... (2)

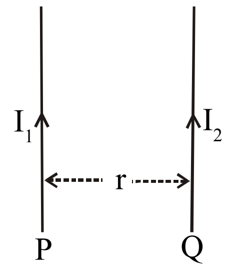
If the conductor is parallel to the field, θ = 0. Therefore force F = 0. If the conductor is perpendicular to the field, θ = 90°. Then force $F = B\,I\,\ell$ = maximum.

NB Fleming's left hand rule.

The direction of force acting on a conductor placed in a magnetic field is given by Fleming's left hand rule.

Stretch the forefinger, central finger (middle finger) and the thumb of the left hand so that they are mutually perpendicular. Now if the forefinger represents the direction of magnetic field, the central finger represents the current, then the thumb represents the direction of force.

NB Force between two parallel conductors carrying current.



Consider two infinitely long conductors P and Q parallel to each other and separated by a distance r. Let I_1 and I_2 be the currents through P and Q respectively. Now each conductor is in the magnetic field of the other and hence experiences a force.

The magnetic field produced by P at the conductor Q is given by

$$B = \frac{\mu_0 I_1}{2\pi r}$$

This magnetic field acts perpendicular to the conductor Q and is directed into the plane of the paper.

The force experienced per unit length of conductor Q, $F = I_2 B$

$$\text{ie } F = I_2 \frac{\mu_0 I_1}{2\pi r} \quad \text{Or} \quad F = \frac{\mu_0 I_1 I_2}{2\pi r}$$

Similarly, a force equal in magnitude but opposite in direction is exerted on P by the current carrying wire Q.

NB Note: *If the currents in the two conductors are in the same direction (parallel currents), the force between the conductors is attractive. If the currents are in opposite directions (anti parallel currents), the force is repulsive.*

NB Definition of Ampere.

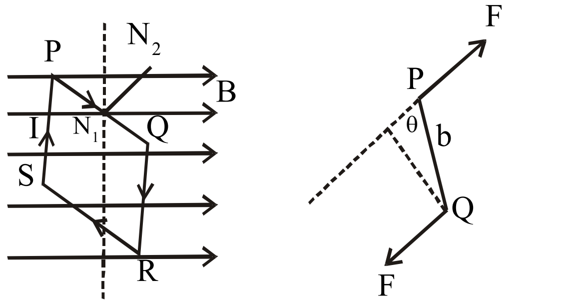
The force experienced per unit length between two infinitely long parallel conductors carrying currents I_1 and I_2 and separated by a distance r is given by $F = \dfrac{\mu_0 I_1 I_2}{2\pi r}$

If $I_1 = I_2 = 1A$ and $r = 1m$, then $F = \dfrac{\mu_0}{2\pi} = \dfrac{4\pi \times 10^{-7}}{2\pi} = 2 \times 10^{-7} N.$

Thus *"One Ampere is that current, which on flowing through two parallel straight conductors of infinite length and negligible area of cross section placed one metre apart in vacuum, will produce between them a force of 2×10^{-7} N per metre length".*

Q7. A beam of ions with velocity 2×10^5m/s enters normally into a uniform magnetic field of 0.40 T. If the specific charge of ion is 5×10^7C/kg, find the radius of the circular path described. [0.01 m]
Q8. The magnetic flux density applied in a cyclotron is 3.5 T. What will be the frequency of electric field that must be applied between the dees in order (a) to accelerate protons (b) alpha particles? mass of proton = 1.67×10^{-27} kg. [5.35×10^7Hz; 2.675×10^7Hz]
Q9. Two straight wires A and B of lengths 10 m and 16 m and carrying currents 4.0 and 5.0 A respectively in opposite directions, lie parallel to each other 4.0 cm apart. Compute the force on a 10 cm long section of the wire B near its centre. [10^{-5} N]

NB **Torque on a current loop in a magnetic field.



Consider a rectangular loop of wire PQRS of length a and breadth b placed in a uniform magnetic field B. It is free to rotate about an axis passing through the center and parallel to the length of the loop. N_1N_2 is normal to the plane of the loop, making an angle θ with the direction of B. Let a current I flow through the loop as shown in fig.

The force experienced by each of the sides PQ and RS is $I(\vec{b} \times \vec{B})$. These forces act in opposite direction (by Fleming's left hand rule) along the same line of action and hence they cancel each other.

The force F experienced by each sides PS and QR is given by $\vec{F} = I(\vec{a} \times \vec{B})$. Since these sides are perpendicular to the magnetic field, the magnitude of the force is 'I a B'. These forces acting on PS and QR are equal and opposite, but their lines of action do not coincide.

Hence a torque acts on the loop, and is given by

Torque, τ = force x perpendicular distance between forces.

ie $\tau = F \times QT = I\,a\,B \times b \sin\theta$

ie $\tau = B\,I\,A \sin\theta$. .... (1) ; where A = ab, the area of the loop. Here A is $\perp^r$ to the plane of the loop.

Now $\tau = I(\vec{A} \times \vec{B})$.

If the coil contains N number of turns, Torque, $\tau = B\,I\,A\,N \sin\theta$. .... (2)

Now magnetic moment m of the current loop, $m = N\,I\,A$.

$\therefore \quad \tau = m\,B \sin\theta$.

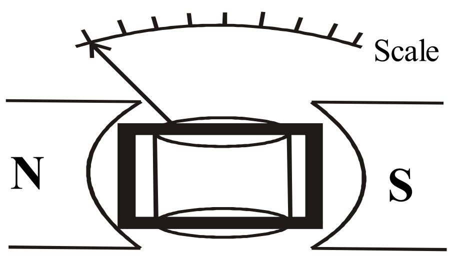
Or $\vec{\tau} = \vec{m} \times \vec{B}$ .... (3)

The direction of torque is such that it rotates the loop clockwise with respect to the axis.

The equation holds good for all plane loops of area A, whether they are rectangular or not.

Now, when θ = 90° ie *when the plane of the loop is parallel to the magnetic field, the torque is maximum* and is $\tau = B\,I\,A\,N$. When θ = 0°, ie *when the plane of loop is perpendicular to the magnetic field, the torque is zero.*

NB **Moving Coil Galvanometer



A moving coil galvanometer consists of a rectangular coil of insulated copper wire wound over a light aluminum frame. It is suspended between the pole pieces of a powerful horseshoe magnet.

The pole pieces are cylindrical in shape so as to have a *radial field*, the direction of magnetic field being always parallel to the plane of the coil.

Theory: Let I be the current through the rectangular coil of area A and number of turns N. Since the plane of the coil is parallel to the uniform magnetic field B, the torque acting on the coil, $\tau = BIAN$.

Due to this torque, the coil rotates. As coil rotates, the spring attached to it winds up. This will provide a restoring torque. If C is the *restoring torque per unit deflection (or couple per unit twist or torsional constant)* and θ is the deflection in the coil, then restoring torque (or restoring couple), $\tau = C\theta$.

When the restoring torque becomes equal to the deflecting torque, the coil is said to be in equilibrium – ie it does not rotate further.

Then $C\theta = BIAN$.

Or $$I = \left(\frac{C}{BAN}\right)\theta$$

ie $I \propto \theta$ since C, B, A and N are constants.

Thus the deflection produced in a galvanometer is proportional to the current flowing through the galvanometer. This is the principle of galvanometer.

Also, $$I = \left(\frac{C}{BAN}\right)\theta$$

ie $I = k\theta$; where k = constant = $\frac{C}{BAN}$ called *galvanometer constant*.

** Current sensitivity of a galvanometer

Current sensitivity of a galvanometer is defined as the deflection produced in the coil for unit current flowing through it.

ie current sensitivity = $\frac{\theta}{I}$ $\frac{BAN}{C}$

** Voltage Sensitivity.

It is defined as the deflection produced per unit voltage applied to the coil of a galvanometer.

ie Voltage sensitivity = $\frac{\theta}{V} = \frac{\theta}{IG} = \frac{BAN}{CG}$

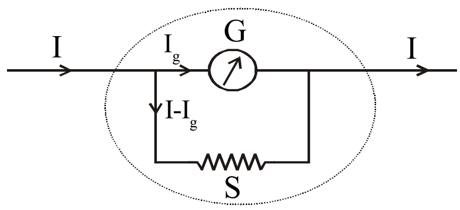
Where, V = voltage across the galvanometer coil and G = resistance of the galvanometer coil.

** Figure of merit: *The figure of merit of a galvanometer is the current required to produce a deflection of one mm on a scale placed at a distance of one meter from the mirror of the galvanometer.* As figure of merit decreases, the sensitivity of galvanometer increases. Unit: micro ampere per millimeter. [m A/ mm]

**NB Conversion of Galvanometer into Ammeter

A galvanometer can be converted into an ammeter by connecting a low resistance called shunt parallel to it.

Shunt is a very small resistance connected parallel to a large resistance so that majority of current flows through the shunt and only a very small current will flow through the galvanometer (large resistance). It helps to increase the range of the galvanometer.



Let G be the resistance of galvanometer and I_g be the current required for full-scale deflection of the galvanometer. In order to convert this galvanometer into an ammeter to read up to a current I, connect a shunt S in parallel such that when the current in the main circuit is I, the current through the galvanometer should be I_g.

Now let I_g and I_s be the current through galvanometer and shunt, Then $I = I_g + I_s$.
Since G and S are parallel, pd across G = pd across S

ie $I_g G = I_S S$

ie $I_g G = (I - I_g)\ S$ {because $I_S = I - I_g$ }

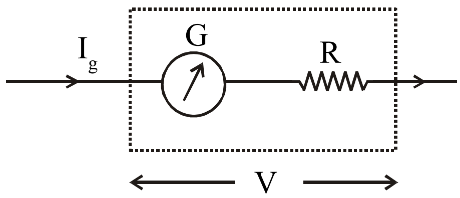
ie $I_g G = I \times S - I_g S$

ie $I_g\ (G + S) = I \times S$

$$I_g = \frac{I \times S}{G+S} \quad \text{Or} \quad I_s = \frac{I \times G}{G+S} \qquad \text{Also shunt resistance, } S = \frac{I_g \times G}{I - I_g}$$

From this, we can find the shunt to be connected.

**NB Conversion of galvanometer into a voltmeter.



A voltmeter is a device used to measure the pd between two points in an electrical circuit. For this the voltmeter is connected in parallel in a circuit. *To convert a galvanometer into a voltmeter, a high resistance is connected in series.*

Let G be the resistance of galvanometer and I_g be the current for full scale deflection. To convert this into a voltmeter to read up to V, connect a large resistance R in series with the galvanometer. The value of R should be such that when a pd of V volt is applied across the voltmeter, the current passing through the galvanometer is I_g.

For this, $V = I_g\ (G + R)$

$$\text{Or} \quad I_g = \frac{V}{G+R}$$

Now $V = I_g\ G + I_g\ R$

$$\text{Or} \quad R = \frac{V}{I_g} - G$$

From this we can calculate the value of R to be connected in series with the galvanometer.

Q10. A circular coil of 20 turns and radius 10 cm carries a current of 5 A. It is placed in a uniform magnetic field of 0.1T. Find the torque acting on the coil when the magnetic field applied (a) normal to the plane of the coil (b) in the plane of the coil. Also find out the total force acting on the coil. [0; 0.314 N m]

Q11. A galvanometer with a coil of resistance 12. 0 ohm shows a full scale deflection for a current of 2.5 mA. How it can be converted into an ammeter of range 7.5 A? What will be the resistance of ammeter formed? [4×10^{-3} ohm; 4×10^{-3} ohm]

Q12. A galvanometer with a coil of resistance 12 ohm shows a full scale deflection for a current of 2.5 mA. How will you convert it into a voltmeter of range 7.5 V? Also find the total resistance of voltemter formed. [2988 ohm; 3000 ohm]

MAGNETISM

Magnets:

The term magnet is derived from the word magnetite, found plenty in Magnesia, the upper part of Greece. Magnetite can attract small pieces of iron, steel etc and is called a natural magnet. Magnets produced artificially using various methods are called artificial magnets. For eg; an artificial magnet can be made by repeatedly hammering a steel rod placed in the north – south direction.

Chinese discovered that when a piece of magnetite is suspended freely, it would come to rest always in the geographical north – south direction. *This is the basic principle used in compass box.* Later, William Gilbert suggested that the earth itself could be considered as a huge magnet. It is due to this magnetisation exhibited by earth that a magnetic needle sets along the north – south direction.

Bar Magnet.

A bar magnet is a permanent magnet made by materials like steel, alnico etc. It is usually in the form of a rectangular bar or cylindrical rod.

Properties of bar magnet.

1) The two ends of a magnet are called the North Pole (N) and the South Pole (S). North pole is the pole which point towards the geographical North and South Pole is the pole, which points towards the geographical South, when a magnet is suspended freely. The distance between the two poles is called magnetic length (2l) of the magnet.

2) A magnet can attract magnetic substances like iron, steel, cobalt nickel etc. The power of attraction is maximum at poles. The poles are not situated exactly at the ends of the magnet. Hence the magnetic length of a magnet is slightly less than its geometric length.

3) A freely suspended magnet will always come to rest approximately in the geographic north – south direction. This is called the *directive property of a magnet.*

4) Isolated magnetic poles do not exist. Hence a magnet always has two poles – the N pole and the S pole.

5) Like poles of magnet repel and unlike poles attract each other.

Note: 1) If a magnet is cut into two equal pieces perpendicular to its axis, each of the two pieces is found to be still magnets. The pole strength of either part is found exactly the same as that of the magnet. If the magnet is cut exactly into two halves by cutting it parallel to its axis, the pole strength of each part is exactly half of the pole strength of original magnet.

2) In electricity, isolated charges exist but in magnetism, isolated poles do not exist.

**NB Magnetic dipole: *Two equal and opposite poles separated by a certain distance is called magnetic dipole.* The distance (2l) between the two poles is called magnetic length or dipole length

Moment of a magnet (m) OR Magnetic dipole moment.

Moment of a magnet is the product of pole strength and distance between the poles.

Thus moment, m = P x 2l ; where P = pole strength and 2l =length of magnet.

Unit of dipole moment is A m^2.

Current loop as a magnetic dipole.

A current loop can be considered as a magnet.

Consider a circular loop of radius a carrying a current I. Then magnetic flux density at a distance x from its center,

$$B = \frac{\mu_0 I a^2}{2x^3}, \qquad B = \frac{\mu_0}{4\pi}\frac{2(\pi a^2) I}{x^3} \qquad \text{ie } B = \frac{\mu_0}{4\pi}\frac{2AI}{x^3} \quad \text{.................(1)}$$

Where $A = \pi a^2$, the area of the loop. The magnetic flux density along the axis of a magnetic dipole of moment 'm' at a distance 'd' from its center is given by

$$B = \frac{\mu_0}{4\pi}\frac{2m}{d^3} \quad \text{......................(2)}$$

Comparing (1) and (2), dipole moment m = A I.

If the coil has N loops, moment, m = N A I.

.

Magnetic dipole as current loop.

Magnetism is an effect produced by electric charges is motion. Ampere suggested that elementary atomic magnets in materials were tiny circulating currents. Thus in a bar magnet, all atomic magnets are aligned in the same direction. Here in addition to orbital motion of electrons, spin motion of electrons also contribute to atomic magnetism.

A small loop of current behaves like a magnetic dipole. The magnitude of dipole moment is m = A I and direction is the direction of flow of current.

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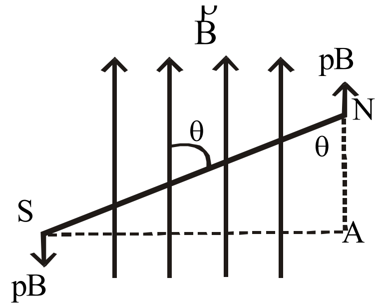
**NB Torque acting on a magnetic dipole placed in a uniform magnetic field.

Consider a magnetic dipole NS of moment m = p (2l) placed in a uniform magnetic field B inclined at an angle q to the field direction. Then the N pole will experience a force pB in the direction of magnetic field and S pole will experience a force pB opposite to the direction of field. Due to these forces, the dipole will experience a torque,

τ = One of the forces x perpendicular distance between the forces.

ie $\tau = p B \times SA$ .... (1)



But from fig, $\sin\theta = \frac{SA}{SN} = \frac{SA}{2\ell}$

$\therefore SA = 2\ell \sin\theta$

Substuting in (1), torque, $\tau = p B 2\ell \sin\theta$

ie $\tau = m B \sin\theta$; where $m = p(2\ell)$.

In vector notation, $\vec{\tau} = \vec{m} \times \vec{B}$

The direction of t is $\perp^r$ to the plane containing m and B.

Now we have $\tau = m B \sin\theta$ If $\theta = 90°$ and B = 1 T; $\tau = m$.

Thus dipole moment of a magnetic dipole is numerically equal to the torque acting on it, when it is placed perpendicular to a uniform magnetic field of unit strength.

Note: 1) If q = 0, $\tau = 0$. ie when dipole is parallel to the magnetic field, the torque acting on it is zero. This is why a freely suspended or pivoted magnetic needle always comes to rest along the geographical N – S direction.

2) If the dipole is placed in a uniform magnetic field, it experiences a torque but the net translatory force acting on it is zero. But when it is placed in a nonuniform magnetic field, the forces acting on the two poles are different. *Hence the dipole experiences both torque and translatory force.*

**NB Magnetic field lines

The space around a magnet or a current carrying conductor where its magnetic force is experienced is called a magnetic field.

A magnetic field line e in a magnetic field is a curve, the tangent to which at any point gives the direction of the magnetic field at that point.

In case of bar magnet, lines of force is assumed to emerge from the N pole, passes through the surrounding medium, enters the S pole and goes within the magnet from S to N pole. *Thus magnetic lines of force are always closed. But electric lines of force will always start from a +ve charge and end in negative charge.*

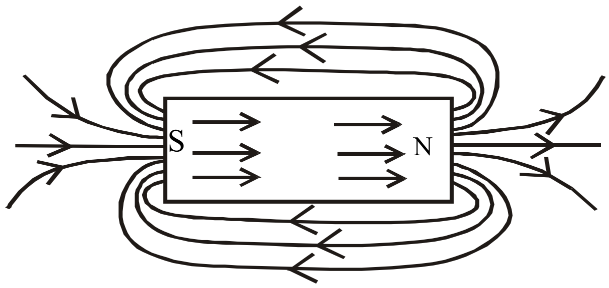
NB: Characteristics of magnetic field lines

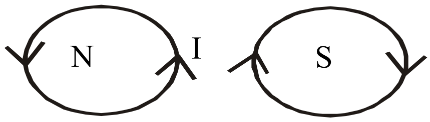
1) The magnetic field lines are always closed.
2) The tangent at any point on a field line gives the direction of magnetic field at that point.
3) In a uniform magnetic field, the field lines are parallel to each other.
4) No two field lines will intersect each other. If they intersect, the magnetic field will be having two directions at that point, which is impossible.
5) The number of field lines passing normally through unit area taken around a point gives the intensity of the magnetic field (magnetic flux density) at that point.

Bar magnet and solenoid

When a current is passed through a solenoid, it behaves like a bar magnet. At the two ends, N pole and S pole are developed. When we look at one end of the solenoid, if the current flows in anti clockwise direction, then that end is N pole. If the current flows in clockwise direction, that end is the S pole. If a current I flows through a solenoid having an area of cross-section A and number of turns N, then Magnetic moment of solenoid, m = N A I.

The lines of force around a bar magnet is as shown:





Gauss's Theorem in magnetism.

Gauss's theorem states that the surface integral of magnetic field over a closed surface is zero.

ie $\int B \bullet dS = 0$; where B = Magnetic field.

Earth's magnetic field.

A freely suspended or pivoted magnetic needle always comes to rest in the geographical north – south direction. This shows that earth acts as a magnet. A huge magnet is imagined to be situated inside the earth. The north pole of this imaginary magnet points towards geographic south and south pole points towards geographic north. The magnetic axis of earth makes an angle about 20° with the geographic axis. Experimentally it has been found that this angle does not remain constant, since the positions of magnetic poles of earth gradually change. At present, the south pole of the imaginary magnet is located in far northern Canada, while the north pole is located diametrically opposite in the southern hemisphere.

A circle on earth's surface, whose plane is perpendicular bisector of magnetic axis of earth, is called the magnetic equator. It passes through Thiruvananthapuram.

(a) Geographic meridian: *The vertical plane passing through the geographic north – south direction is called geographic meridian.*

(b) Magnetic meridian*: The vertical plane passing through the north – south direction as indicated by the freely suspended magnet is called magnetic meridian.*

**NB Magnetic elements of earth.

The earth's magnetic field at a particular place can be specified by three quantities namely declination, dip or inclination and horizontal intensity. These three quantities are together called magnetic elements.

1) Magnetic declination (δ)

Declination at a place is the angle between magnetic meridian and geographical meridian at that place.

2) Dip or inclination (θ)

It is the angle which the earth's magnetic field B at a particular place makes with the horizontal line.

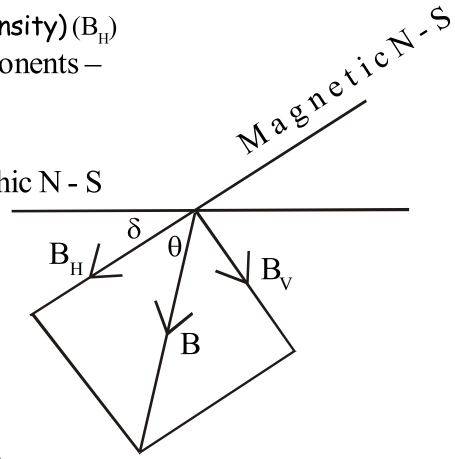
3) Horizontal component of earth's magnetic field (Horizontal intensity) (B_H)

The earth's magnetic field B can be resolved into two components – B_V in the vertical direction and B_H in horizontal direction.

Now from fig; $B_H = B\cos\theta$ and $B_V = B\sin\theta$

Or $\tan\theta = \dfrac{B_V}{B_H}$

$\therefore \theta = \tan^{-1}\left(\dfrac{B_V}{B_H}\right)$ And $B = \sqrt{B_H^2 - B_V^2}$



At equator, angle of dip, $\theta = 0$. $\therefore$ Horizontal intensity B_H is maximum.

At poles, $\theta = 90°$ $\therefore B_H = 0$ and B_V = maximum.

The strength of earth's field is of the order of 10^{-4} T, which is 1 gauss. ie $1G = 10^{-4}$ T. A gauss is often called an oersted. *Thus the earth's magnetic field is about 1 oersted.*

##NB **Magnetic properties of materials.**

1) Magnetising field (H)

When a magnetic material is placed in a magnetic field, it becomes magnetized. The ability of the applied field to magnetise the substance is measured by the quantity - magnetising field denoted by the letter H.

The magnetizing field along the axis of a solenoid having n turns per unit length and carrying a current I is given by $H = n I$.

2) Permeability (μ)

The ratio of magnetic flux density B in a material to the magnetising field is called the absolute permeability (μ) of the medium.

ie $\mu = \dfrac{B}{H}$ Or $B = \mu H$; Here $\mu = \mu_0 \mu_r$. For free space, $\mu = \mu_0$ $\therefore$ $B = \mu_0 H$

3) Intensity of magnetization (M)

Intensity of magnetization is defined as the magnetic moment developed per unit volume of the specimen when subjected to a magnetic field.

ie $M = \dfrac{m}{V} = \dfrac{P\,2\ell}{a\,2\ell} = \dfrac{P}{a} = \dfrac{\text{Pole strength}}{\text{area}}$

4) Susceptibility (χ_m)

Magnetic susceptibility is the ratio of intensity of magnetization produced in a material to the magnetizing field. ie $\chi_m = \dfrac{M}{H}$

**NB Hysteresis

When a magnetic material is magnetised or is subjected to cycles of magnetization, intensity of magnetization M and magnetic induction B lag behind the applied magnetizing field H. Thus if magnetic field is made zero, the values of M and B are not zero, and there is a tendency in the material to retain its magnetic properties.

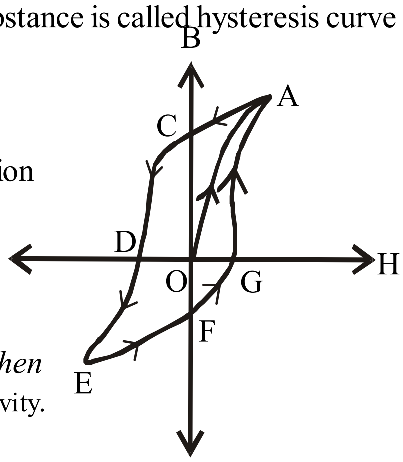
This phenomenon of lagging of intensity of magnetization M and magnetic flux density B behind the magnetising force H in a magnetic material subjected to cycles of magnetization is known as hysteresis.

Coercive force or coercivity.

When the magnetising field H is reversed, for certain value of it, magnetic flux density B becomes zero. *This value of reverse magnetising field required to demagnetize the specimen completely is called* coercivity *of the specimen.*

NB Hysteresis curve OR Hysteresis loop

A curve showing the variation of B with H for a magnetic substance is called hysteresis curve or hysteresis loop.



Let an iron bar be magnetised slowly. When the magnetising field H is gradually increased, the magnetic flux density, B increases along OA. At A, the magnetic flux density B and intensity of magnetization M reaches a saturation value.

Now, let H be decreased. Then B also decreases along AC but lags behind H. When H becomes zero, B does not become zero ie the substance retains some magnetism denoted by OC.

This value of magnetic flux density in the specimen even when the magnetising field is reduced to zero is called remanence or rententivity.

If H is increased in the reverse direction, the value of B further decreases, still lagging behind H. For value of H denoted by OD, B becomes zero. OD is called coercivity of the specimen.

When H is reversed further, in the reverse direction, B increases in the opposite direction till a point E is reached.

When the field is reduced to zero, EF portion is obtained. When H is reversed and increased to initial value, the portion of curve FGA is obtained.

From the curve, we can find that the magnetic flux density B always lags behind the magnetising field H. The closed curve ACDEFGA is called hysteresis loop. The area of hysteresis loop represents the energy loss per unit volume per cycle of magnetization of the specimen.

**NB Magnetic materials

On the basis of magnetic properties, magnetic materials are classified into three – dia, para and ferro magnetic materials.

Diamagnetic substances.

They are substances, which are repelled feebly by magnets.

Eg: Antimony, bismuth, gold, mercury, water, zinc etc.

Properties:

1) The atoms of diamagnetic substance possess no magnetic moment.
2) When suspended freely in a uniform field, a diamagnetic substance set itself at right angles to the field.
3) When placed in a non-uniform magnetic field, they move from stronger to weaker parts of the field.
4) The relative permeability of diamagnetic substance is less than one.
5) Susceptibility is negative.
6) Susceptibility is independent of temperature.
7) When diamagnetic substance is placed in a magnetic field, the magnetic lines of force prefer to pass through surrounding air than through the substance.
8) When magnetizing field is removed, diamagnetic substances loses its magnetism.

** Paramagnetic substances.

They are substances, which are feebly attracted by magnets.

Eg: Aluminum, platinum, manganese, chromium etc.

1) They are weakly magnetized in the direction of applied field.
2) They have small magnetic moment.
3) When suspended in a uniform field, they will set themselves in a direction parallel to the field.
4) Here the lines of force prefer to pass through the material than through air, when placed in a magnetic field.
5) When placed in a non-uniform field, paramagnetic substances will move from weaker to stronger part of field.
6) Relative permeability is greater than one.
7) Susceptibility is small but positive.
8) Susceptibility of paramagnetic substance is inversely proportional to temperature (absolute temperature). This is called Curie's law.
9) When field is removed, they will lose their magnetism.

Ferro magnetic substances

They are substances which when placed in a magnetic field are strongly magnetized in the direction of field. They are attracted by magnets and can be magnetized.

Eg: Iron, cobalt, nickel, steel etc.

1) The atoms of ferromagnetic materials possess small magnetic moments.
2) When suspended in a uniform field, it will set itself parallel to the field.
3) When placed in a magnetic field, the lines of force tend to crowd inside the ferromagnetic material.
4) When placed in non-uniform field, they move from weaker to stronger part of field.
5) Relative permeability is large compared to paramagnetic substance.
6) The susceptibility is +ve and has high value.

7) Susceptibility decreases with increase of temperature ie Curie's law is obeyed; up to a temperature called Curie temperature. Above this temp, a ferromagnetic substance becomes a paramagnetic substance.
8) They retain some magnetism even after the magnetizing field is removed.

NB **Electromagnets**

The materials used for making electromagnet should have large value of magnetization even in a small magnetizing field, high susceptibility for low fields and low hysteresis loss.

Soft iron possesses all these properties and hence is used for making electromagnets.

In case of cores of dynamos and transformers, they are subjected to a large number of cycles of magnetization. Hence the loss of energy due to hysteresis will be very large. So we use soft iron cores in transformers because soft iron has low hysteresis loss.

NB **Permanent magnets**

The materials used for making permanent magnets should have high residual magnetism, large coercivity and should be able to withstand mechanical ill treatment and temp changes and also large hysteresis loss. Steel possesses all these properties except that it has small residual magnetism. Hence steel is best for making permanent magnets. In actual practice, tungsten steel, alnico, vicalloy etc are used as permanent magnets. Vicalloy (iron, cobalt and vanadium) can be made into a tape and hence can be used for magnetic recording of sound.

Charges moving in perpendicular electric and magnetic fields. (Crossed electric and magnetic fields)

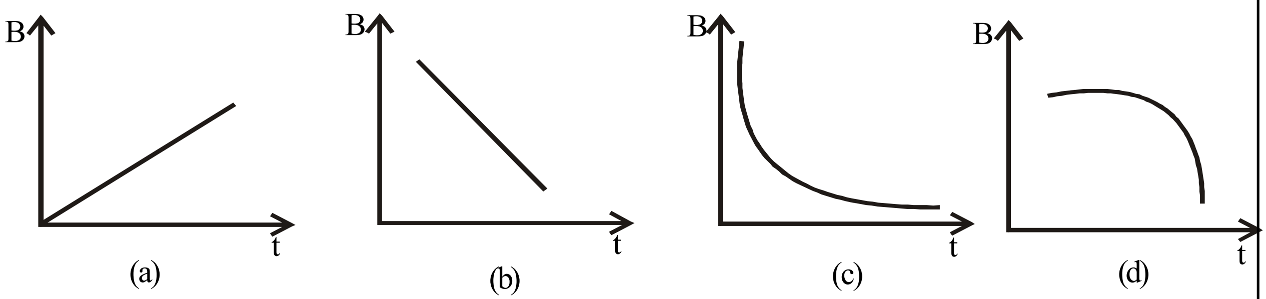
NB: Velocity Selector :

Consider a charge q moving with a velocity v perpendicular to an electric field E and magnetic field B which in turn are mutually perpendicular.

Now force on the charge due to electric field, $F_1 = q E$. Force due to magnetic field, $F_2 = q v B$.
Due to these two fields, the charge will get deflected. Now for the charge to move without any deviation, $F_1 = F_2$.
i.e, $q E = q v B$. or $v = E / B$.

Thus only charges moving with this velocity will pass through the fields undeviated. This is the principle used in selecting charged particles moving with constant velocity. This is the basic principle of **mass spectrometer.**

Q13. The horizontal component of earth's magnetic field at a place is 0.4×10^{-4}T. If angle of dip is 45^0, what are the values of vertical component and total intensity of earth's field? [0.4×10^{-4}T; $0.5656 \; 10^{-4}$T]
Q14. A toroidal solenoid has 3000 turns and a mean radius of 10 cm. It has a soft iron core of relative permeability 2000. Find the magnitude of the magnetic field in the core when a current of 1.0 A is passed through the solenoid. [12T]
Q15. Obtain the earth's magnetisation, assuming that the earth's field can be approximated by a gaint bar magnet of magnetic moment 8.0×10^{22} Am^2. The earth's radius is 6400 km. [72.8 A/m]
Q16. Which of the following graphs shows the variation of magnetic induction B with distance r from a long wire carrying current?



Q17. If a particle moving in a magnetic field, increases its velocity, then its radius of the magnetic field circle will.......(a) remain constant (b) decrease (c) increase (d) either b or c.
Q18. A magnetic field exerts no force on ......(a) a magnet (b) an unmagnetised iron bar (c) a moving charge (d) a stationary charge.
Q19. The vertical component of earths magnetic field is zero at.......(a) magnetic equator (b) magnetic poles (c) geographic poles (d) at 90^0 latitude.
Q20. The most suitable material for permanant magnet is .... (a) copper (b) aluminium (c) steel (d) iron.

Analogy between Electrostatics and Magnetism

Property/Law		Electrostatics	Magnetism
1	**Basic law for field**	Coulomb's law $E = \frac{1}{4\pi\varepsilon_0}\frac{q}{r^2}$	Biot Savart's law $dB = \frac{\mu_0}{4\pi}\frac{I\,dl\sin\theta}{r^2}$
2	**Source**	Charges – static(and moving)	Moving charges
3	**Dipole moment**	$P = q.2a$	$M = IA$
4	**Field on the equatorial line of (short) dipole**	$E = \frac{1}{4\pi\varepsilon_0}\frac{P}{r^3}$	$B = \frac{\mu_0}{4\pi}\frac{m}{r^3}$ (bar magnet)
5	**Axial field**	$E = \frac{1}{4\pi\varepsilon_0}\frac{2P}{r^3}$	$B = \frac{\mu_0}{4\pi}\frac{2m}{r^3}$
6	**Torque acting on external uniform field**	$\vec{\tau} = \vec{P} \times \vec{E}$	$\vec{\tau} = \vec{m} \times \vec{B}$
7	**Potential energy in external field**	$U = \vec{P} \bullet \vec{E}$	$U = \vec{m} \bullet \vec{B}$
8	**Field lines**	Begins from positive and ends on negative charges	Closed and continuous lines without beginning and end
9	**Expression for flux**	$\phi_E = \int \vec{E} \bullet d\vec{S}$	$\phi_B = \int \vec{B} \bullet d\vec{S}$
10		Gauss' theorem $\oint \vec{E} \bullet d\vec{S} = \frac{\Sigma q}{\varepsilon_0}$	Ampere's circuital law $\oint \vec{B} \bullet d\vec{\ell} = \mu_0 I$
11		Isolated charges can exist	Isolated monopoles cannot exist
12	**Law governing interactions**	$\vec{F} = q\vec{E}.$	$\vec{F} = q\left(\vec{v} \times \vec{B}\right)$