MAGNETISM AND MATERIALS

A substance which can attract small pieces of iron, steel, nickel, cobalt etc. and rests in the North-South direction when freely suspended is called a **magnet**.

A naturally occurring ore of iron, magnetite attracts small pieces of iron towards it. The phenomenon of attraction of small bits of iron, steel, cobalt, nickel, etc., towards the ore, is called **magnetism**.

A magnet is a material or an object that produces a magnetic field. The magnetic field is invisible but is responsible for most notable property of a magnet.

Magnets are of two types:

i. **Natural Magnets:** A natural magnet is a magnet that occurs naturally in nature. All natural magnets are permanent magnets, meaning they will never lose their magnetic power. The strongest natural magnet material is lodestone, also called magnetite. Natural magnets are generally irregular in shape and weak in strength.

ii. **Artificial Magnets:** Man magnet magnets are known as artificial magnets. Artificial Magnets have desired shape and desire strength. Examples: A bar magnet, a horse shoe magnet, compass needle, etc.

Force between two magnetic poles:

The force of attraction or repulsion F between two magnetic poles of strength m_1 and m_2 separated by a small distance r is directly proportional to the product of pole strengths and inversely proportional to the square of the distance between their centres, i.e.

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

or $$F = K\frac{m_1 m_2}{r^2}$$

where, K is magnetic force constant.

In SI units,

$$K = \frac{\mu_o}{4\pi} = 10^{-7} WbA^{-1}m^{-1}$$

where, μ_o is absolute magnetic permeability of free space (air/vacuum).

$$F = \frac{\mu_o}{4\pi} \cdot \frac{m_1 m_2}{r^2} \qquad \text{... (1)}$$

This is called Coulomb's law of magnetic force. SI unit of magnetic pole strength is ampere-metre.

Suppose, $m_1 = m_2 = m$ (say),

$r = 1m$

and $F = 10^{-7}$ N

From eqn. (1), we have

$$10^{-7} = 10^{-7} \times \frac{(m)(m)}{1^2}$$

or $m_2 = 1$

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or $m = \pm 1 A - m$

Therefore, strength of a magnetic pole is said to be one ampere-metre, if it repels an equal and similar pole, when placed in vacuum (or air) at a distance of one metre from it, with a force of 10^{-7} N.

The Bar Magnet:

The bar magnet has two poles similar to the positive and negative charges of an electric dipole. One pole is designated a North pole and the other as South pole. When a bar magnet is suspended freely, these poles point approximately towards the geographic North and South poles, respectively.

Like magnetic poles repel each other and unlike magnetic poles attract each other. If a bar magnet is dropped into a pile of iron-fillings, then the maximum amount of fillings get deposited near the ends of the magnet and almost nil in the middle.

The pattern suggests that attraction is maximum at the two ends of the bar magnet. These ends are called poles of the magnet. The poles of a magnet can never be separated.

The Magnetic Field Lines:

The magnetic field lines are visual and intuitive realisation of the magnetic field. The magnetic field lines in a magnetic field are those imaginary lines which continuously represent the direction of the magnetic field. The tangent drawn at any point on magnetic field line shows the direction of the magnetic field at that point.

Their properties are given below:

i. The magnetic field lines of a magnet (or a solenoid) form continuous closed loops. This is unlike the electric dipole, where these field lines begin from a positive charge and end on the negative charge or escape to infinity.
ii. The tangent to the field line at a given point represents the direction of the net magnetic filed B at that point.
iii. The larger the number of filed lines crossing per unit area, the stronger is the magnitude of the magnetic field B.
iv. The magnetic field lines do not intersect, for if they did, the direction of the magnetic field would not be unique at the point of intersection.

Magnetic Dipole: A magnetic dipole consists of a pair of magnetic poles of equal and opposite strength separated by a small distance.

e.g. a bar magnet, a compass needle, etc., are magnetic dipoles.

The two poles of a magnetic dipole (or a magnet), called North pole and South pole, are always of equal strength and of opposite nature. Further, such two magnetic poles always exist in pair.

Magnetic length of a magnet is defined as the distance between two poles of a bar magnet. It is a vector from S-pole of the magnet to its N-pole and it is represented by 2l.

Magnetic dipole moment is defined as the product of the pole strength of either pole and distance between the poles. It is represented by **M**.

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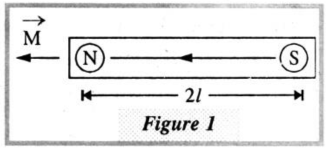

Figure 1

The direction of magnetic dipole moment is same as that of 2l. Let m be the pole strength of each pole then magnetic dipole moment is given by

$$M = m(2l)$$

M is a vector quantity so it can be written as

$\vec{M} = m\left(2\vec{l}\right)$, where $2\vec{l}$ is the magnetic length directed from South to North pole. Thus direction of magnetic dipole moment is from south to north pole.

SI unit of magnetic dipole moment is ampere-metre^2 (Am^2).

CURRENT LOOP AS MAGNETIC DIPOLE:

Let a circular wire carry current in clockwise direction, then direction of magnetic field will be such that lower face will acts as North pole and upper face will act as South pole. Thus a current loop behaves as a magnet i.e. magnetic dipole as shown in figure 2.

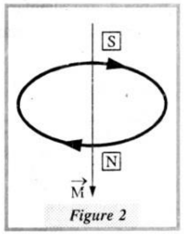

Figure 2

Magnetic dipole moment (M) of the current loop.

Torque acting on a current carrying loop placed in the magnetic field $\vec{B}$ is given by

$$\vec{\tau} = IAB\sin\theta \qquad \text{... (1)}$$

Where, I = Current flowing in the loop, A = Area of the loop, θ is the angle between $\vec{B}$ and normal to the plane of the loop.

But, the torque acting on a magnetic dipole placed in the magnetic field $\vec{B}$ is given by

$$\tau = MB\sin\theta \qquad \text{... (2)}$$

Comparison of eqn. (1) and (2) gives the magnetic dipole moment of current loop i.e.

$$M = IA \qquad \text{... (3)}$$

If the loop has n turns, then M = n IA

where n is number of turns of loop, I is the current and A is the area of loop.

In vector form

$$\vec{M} = nI\vec{A}$$

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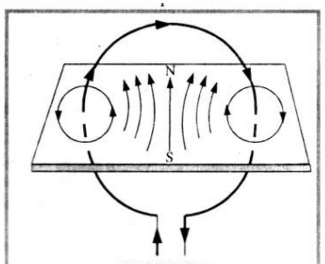

Figure 3

The magnetic lines of force due to a current loop are shown in figure 3. It is clear from figure that

i. Magnetic lines of force at the centre of the current loop are straight. It means that the magnetic field at the centre of the loop is uniform.
ii. The face of the current loop in which current flows clockwise, acts as South pole and the face of the loop acts as North pole. Thus, a current loop has two magnetic poles separated by a certain distance; therefore, current loop behaves as a magnetic dipole.

MAGNETIC DIPOLE MOMENT OF A REVOLVING ELECTRON (ATOM AS A MAGNETIC DIPOLE)

In an atom, electrons revolve around the nucleus in a circular orbit. The movement of the electron in circular orbit around the nucleus in anticlockwise is equivalent to the flow of current in the orbit in clockwise direction. Thus, the orbit of electrons is considered as tiny current loop.

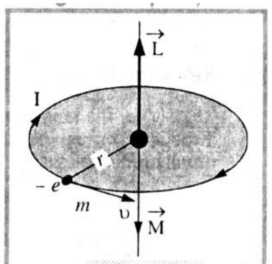

Figure 4

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If an electron revolves in anti-clockwise direction as shown in figure 4, the angular momentum vector $\vec{L}$ acts along the normal to the plane of orbit in upward direction and its magnitude is

$$L = mvr \qquad \text{or} \qquad vr = \frac{L}{m} \qquad \dots (1)$$

where, m is the mass of electron, v is the velocity and r is the radius of orbit.

Orbital motion of electron is taken as equivalent to the flow of conventional current in clockwise direction.

$$\therefore I = \frac{e}{T}$$

where, e is the charge on an electron and T is the period of orbital motion.

But $$T = \frac{2\pi r}{v} \qquad \left(\because v = \frac{Circumference}{Time - period} \right)$$

$$\therefore I = \frac{e}{2\pi r/v} = \frac{ev}{2\pi r}$$

Magnetic moment of a current loop,

$$M = I \times A = \frac{ev}{2\pi r} \times \pi r^2 = \frac{evr}{2}$$

Using (1) $\quad M = \frac{e}{2m} L \quad$ (orbital motion) $\quad$ ... (2)

In vector notation, $\vec{M} = -\left(\frac{e}{2m}\right)\vec{L}$

Negative sign shows that $\vec{M}$ and $\vec{L}$ are opposite to each other.

According to Bohr's Theory, angular momentum of electrons is given by

$\vec{L} = n\frac{h}{2\pi}$, where n = 1, 2, 3 ... and h is Planck's constant.

Then equation (2) becomes $\quad M = \frac{e}{2m}.\frac{nh}{2\pi} = n\left(\frac{eh}{4\pi m}\right)$

If n = 1 then $M_{least} = \frac{eh}{4\pi m}$, which is Bohr magneton denoted by μ_B.

It serves as natural unit of magnetic moment.

Bohr Magneton can be defined as the orbital magnetic moment of an electron circulating in the innermost orbit.

$$\mu_B = \frac{eh}{4\pi m} = \frac{1.6\times10^{-19}\times6.6\times10^{-34}}{4\times3.14\times9.1\times10^{-31}} = 9.27\times10^{-24}\,Am^2$$

<u>Main properties of a Bar Magnet are as under:</u>

1. **Property of attraction:** Poles of a magnet have ability to attract small pieces of magnetic material like iron, steel, cobalt, nickel etc. This ability of a magnetic pole is known as **'pole strength'**. In fact, the poles are not situated at the exact ends of a magnet but near the ends of the magnet.

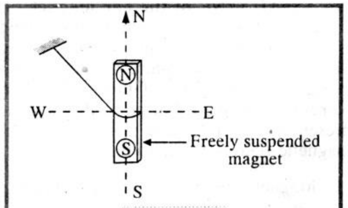

Figure 5

2. **Property of alignment:** A magnet when suspended freely comes to rest such that its North pole always points towards geographical North and South pole automatically aims towards geographic South pole.
   Line joining North and South poles of a magnet is called **magnetic axis** and a vertical plane passing through this line is called **magnetic meridian.**
3. **Unlike magnetic poles attracts each other:** If south pole of a magnet is brought near North pole of another magnet, attraction takes place. But when South pole of a magnet is brought near

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south pole of another magnet, repulsion takes place. Like poles repel each other but unlike poles attract each other.

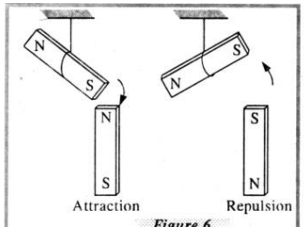

Figure 6

4. **Property of pairs:** Magnetic pole always exist in pairs whereas isolated electric charge exists. If a magnet is cut into two pieces it will result into two complete magnets each having both North as well as South poles. Magnetic monopoles do not exist.

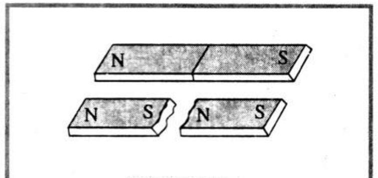

Figure 7

5. **Property of Testing:** A magnet attracts the iron piece as well as unlike pole of another magnet. Attractive property of a magnet cannot distinguish a magnetic material and a magnet. But if the polarity of the magnet is reversed then it will repel the like pole of the other magnet but attract the simple magnetic material. Thus repulsion is the surest test for distinguishing between an iron piece and a magnet.

6. **Property of Induction:** When a piece of ordinary magnetic material is brought near a bar magnet, it acquires the property of a magnet without any actual physical contact. Such type of magnetism is called induced magnetism.

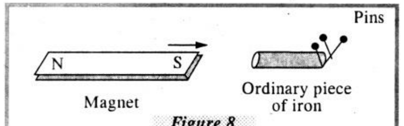

Figure 8

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MAGNETIC FIELD DUE TO A MAGNETIC DIPOLE (BAR MAGNET):

1. **Magnetic field at any point on the AXIAL LINE of the bar magnet:**

Let O be centre of a bar magnet with magnetic length 2l. P is a point on the axial line of the bar magnet at a distance r from the centre O. Let m be the pole strength of each pole of the magnet. Let a unit North pole be placed at point P. Assume that the presence of unit N-pole at P does not affect the magnetic field at P due to the bar magnet.

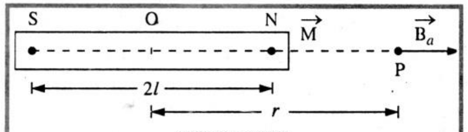

Figure 9

Magnetic field intensity at P due to North pole of the bar magnet,

$\vec{B}_1$ = Force experienced by unit N-pole at P = $\frac{\mu_o}{4\pi}\frac{m}{(r-l)^2}$ along NP.

Similarly, magnetic field intensity at P due to South pole of the bar magnet, $\vec{B}_2 = \frac{\mu_O}{4\pi}\frac{m}{(r+l)^2}$ along PS.

Therefore, net magnetic field intensity at P due to the bar magnet,

$$\vec{B}_a = \frac{\mu_O}{4\pi}\frac{m}{(r-l)^2} - \frac{\mu_o}{4\pi}\frac{m}{(r+l)^2} = \frac{\mu_o}{4\pi}m\left[\frac{(r+l)^2-(r-l)^2}{(r^2-l^2)^2}\right]$$

$$= \frac{\mu_o}{4\pi}m\left[\frac{(r+l+r-l)(r+l-r+l)}{(r^2-l^2)^2}\right] = \frac{\mu_o}{4\pi}m\left[\frac{2r\times 2l}{(r^2-l^2)^2}\right]$$

Since $m\times 2l = M$

$$\therefore B_a = \frac{\mu_o}{4\pi}\frac{2Mr}{(r^2-l^2)^2} \quad \text{along NP}$$

If the magnet is of very small length then $l^2 << r^2$

$$\therefore B_a = \frac{\mu_o}{4\pi}\frac{2M}{r^3}$$

Direction of $\vec{B}_a$ is along SN extended.

2. **Magnetic field intensity at a point on EQUATORIAL LINE of a bar magnet:**

Let the given point P lie on the equatorial line as shown in figure such that its distance from centre O is r. Magnetic field intensity at P due to N-pole of the bar magnet.

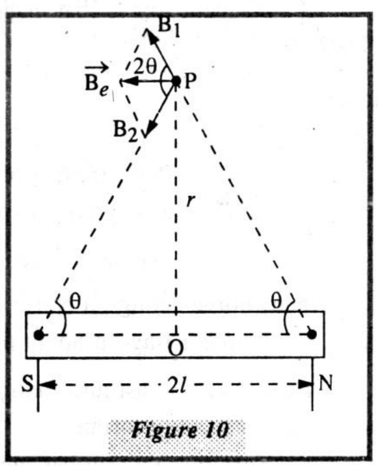

Figure 10

$$\vec{B}_1 = \frac{\mu_O}{4\pi}\frac{m}{\left(\sqrt{r^2+l^2}\right)2} \quad \text{along NP} \quad \dots (1)$$

$$= \frac{\mu_O}{4\pi}\frac{m}{(r^2+l^2)} \quad \text{along NP}$$

Magnetic field intensity at P due to S-pole of the bar magnet,

$$\vec{B}_2 = \frac{\mu_O}{4\pi}\frac{m}{(r^2+l^2)} \quad \text{along PS} \quad \dots (2)$$

$\vec{B}_1$ and $\vec{B}_2$ are inclined at angle 2θ. Therefore, the resultant of these two field intensities is given by

$$B_e = \sqrt{B_1^2 + B_2^2 + 2B_1B_2\cos 2\theta}$$

Since $B_1 = B_2$

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$$\therefore B_e = \sqrt{2B_1^2 + 2B_1^2 \cos 2\theta} = \sqrt{2B_1^2 (1 + \cos 2\theta)}$$

$$= \sqrt{2B_1^2 \times 2\cos^2 \theta}$$

$$= 2B_1 \cos\theta$$

Using eqn. (1), we get

$$B_e = 2 \times \frac{\mu_o}{4\pi} \frac{m}{(r^2 + l^2)} \cos\theta$$

From figure, $\cos\theta = \dfrac{l}{\sqrt{r^2 + l^2}}$

$$\because B_e = \frac{\mu_o}{4\pi} \frac{m \times 2l}{(r^2 + l^2)^{3/2}}$$

Since $m \times 2l = M$

$$\therefore B_e = \frac{\mu_o}{4\pi} \frac{M}{(r^2 + l^2)^{3/2}}$$

In case magnet is of very small length then $l^2 << r^2$

$$B_e = \frac{\mu_o}{4\pi} \frac{M}{r^3}$$

3. <u>Torque on a dipole (Bar Magnet) in a uniform Magnetic Field:</u>

If a magnetic dipole (bar magnet) is placed in a uniform magnetic field as shown in figure the North and South poles of the magnet will experience equal and opposite forces.

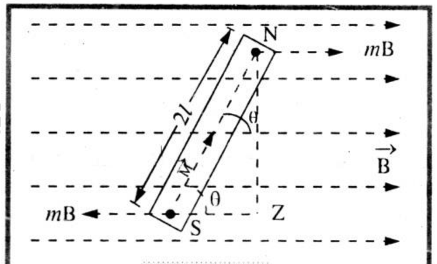

Figure 11

Let

i. Magnetic length of magnet = 2l
ii. Pole strength of each pole = m
iii. Strength of magnetic field = B
iv. Angle between $\vec{M}$ and $\vec{B}$ = θ

then, Force acting on North pole = mB along $\vec{B}$

Force acting on South pole = mB opposite to $\vec{B}$

These forces constitute a couple which tends to rotate the magnet in the direction of $\vec{B}$. Thus the magnet experiences a torque.

$\therefore$ Torque acting on bar magnet is

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$$\tau = \text{Force} \times \perp \text{distance between forces}$$

$$= mB \times ZN = mB\,(SN \sin\theta) = mB\,(2l \sin\theta)$$

$$\left(\because in - \Delta SZN, \sin\theta = \frac{ZN}{SN} or ZN = SN \sin\theta\right)$$

$$= (m \times 2l) B \sin\theta$$

or $$\tau = MB \sin\theta$$

($\because$ m × 2l = M, the magnetic dipole moment)

In vector form $$\vec{\tau} = \vec{M} \times \vec{B}$$

When B = 1 unit and θ = 90° then τ = M $\left(\because \sin 90^o = 1\right)$

Thus, magnetic dipole moment can be defined as the torque acting on a magnetic dipole placed normal to a uniform magnetic field of unit strength.

<u>COMPARISION OF MAGNETIC DIPOLES (BAR MAGNET AND SOLONOID):</u>

A current carrying straight solenoid behaves like a bar magnet.

A study of magnetic lines of force around a solenoid carrying current and magnetic lines of force around a bar magnet shows that the solenoid acts like a bar magnet. All properties of bar magnet are applicable in case of solenoid also. Figure A and B shows the comparison of magnetic lines of force in the case of a solenoid and a bar magnet respectively.

Magnetic field inside a solenoid is stronger than inside of a bar magnet. If a magnetic material is placed inside a hollow solenoid then the same is readily magnetised. Magnetic field outside a solenoid is very weak. Magnetic field inside a solenoid is uniform, while outside the solenoid it is non-uniform.

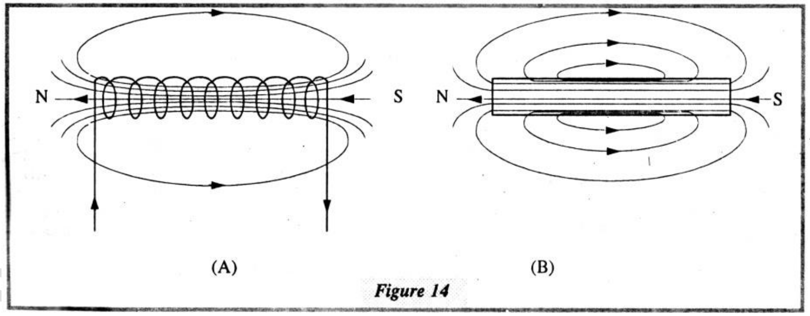

Figure 14

<u>CLOCK RULE:</u> The polarity of a solenoid can be determined with the help of clock rule. Figure A and B show that anti-clockwise current in a face of the solenoid gives north polarity to it and clockwise current gives South polarity.

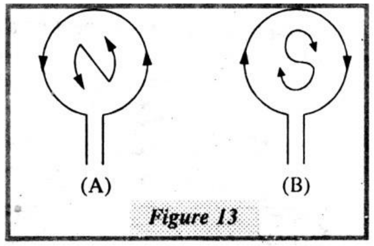

Figure 13

<u>RIGHT HAND MOMENT RULE:</u> Magnetic dipole moment of a solenoid can be determined by applying right hand moment rule.

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According to this rule, thumb of the right hand gives the direction of magnetic dipole moment when fingers curl in the direction of current. Figure makes the application of rule amply clear.

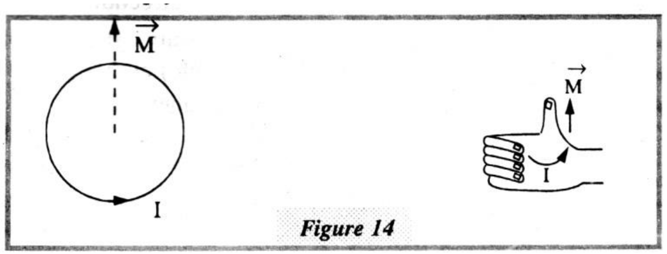

Figure 14

MAGNETIC FIELD: Magnetic field is the space around a magnet (or a current carrying wire) within which its effect can be experienced. Magnetic field can be represented with the help of a set of lines or curves called **magnetic field lines**. These lines are not real but can be drawn to simply visualize the magnetic field.

UNIFORM MAGNETIC FIELD: Magnetic field in a region is uniform if it has same strength at all the points in the region.

Examples: Magnetic field of Earth and Magnetic field inside a long current carrying solenoid.

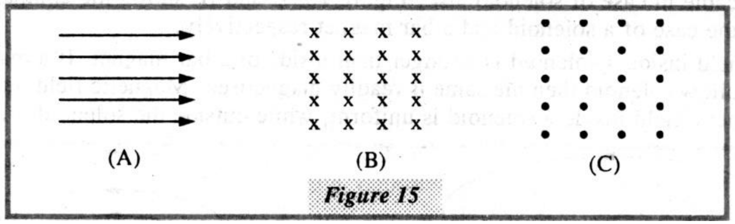

Figure 15

NON-UNIFORM MAGNETIC FIELD: Magnetic field in a region is non-uniform if it has different strength at different points in the region.

Example: Magnetic field of a bar magnet.

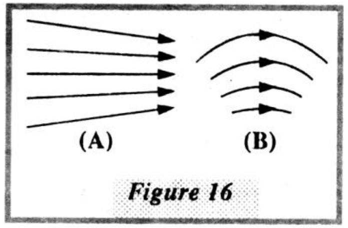

Figure 16

**** A strong magnetic field is represented by closely spaced lines whereas weak magnetic field is represented by widely spaced lines.*

PROPERTIES OF MAGNETIC FIELD LINES:

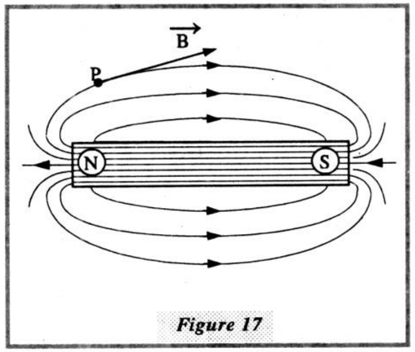

Figure 17

i. Magnetic field lines are continuous and closed curves travelling from North pole to South pole outside the magnet and from South pole to North pole inside the body of the magnet.
ii. The tangent at any point on the magnetic field line gives the direction of magnetic field at that point.
iii. No two magnetic field lines do not intersect or cross each other. If they cross each other, then at the point of intersection there will be two directions of the magnetic field which is impossible.
iv. Widely spaced lines represent weak magnetic field and closely spaced lines represent strong magnetic field.
v. Magnetic field lines dilate laterally but they contract longitudinally.
vi. Although magnetic lines are not real yet they represent a magnetic field which is real.

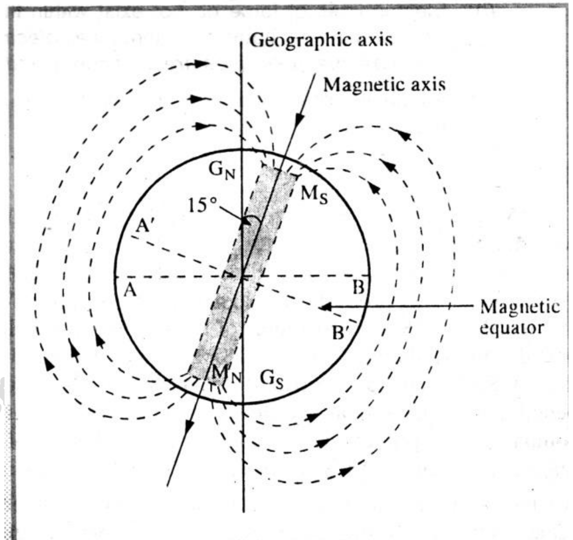

Figure 19

MAGNETISM OF EARTH

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GEOGRAPHIC AXIS: An imaginary line joining the geographic poles of the earth (G_N and G_S) is known as geographic axis.

MAGNETIC AXIS: Magnetic axis is the line joining the magnetic poles of the earth.

Geographic axis and magnetic axis do not coincide with each other. The magnetic axis makes an angle of about 15^o with the geographic axis.

GEOGRAPHIC MERIDIAN: A vertical plane which passes through the geographic axis is called geographic meridian.

MAGNETIC MERIDIAN: A vertical plane which passes through the magnetic axis is called magnetic meridian.

GEO-MAGNETIC EQUATOR: A great circle (having diameter $A'B'$ in figure) on the earth's surface perpendicular to the magnetic axis (M_SM_N) is known as geo-magnetic equator or simply magnetic equator.

*** The magnetic field lines of force due to earth's magnetism are parallel to the earth's surface near the magnetic equator and perpendicular to the earth's surface near the magnetic poles of the earth.

The magnitude of the earth's magnetic field is 0.3 G to 3×10^{-5}T.

The magnetic field of the earth changes from place to place on the surface of the earth. Moreover, it changes with time at a given place on the earth.

MAGNETIC ELEMENT OF THE EARTH: The magnitude and direction of the magnetic field of the earth at a place are completely given by certain quantities known as magnetic elements.

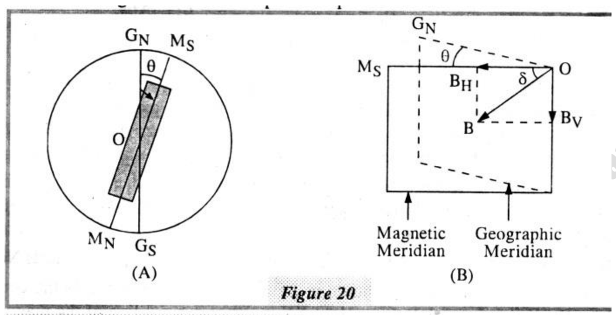

Figure 20

1. **Magnetic Declination (θ):** Magnetic declination at a place is defined as the angle between geographic meridian and magnetic meridian at a place.
   Figure A shows the top view of the earth where planes through G_N-G_S and M_N-M_S appear to be geographic and magnetic meridians respectively. The angle $G_NOM_S = \theta$ is magnetic declination. Figures B shows the meridian clearly.

2. **Magnetic Inclination or Dip (δ):** Magnetic dip is the angle between the direction of total intensity of magnetic field of earth and horizontal line in the magnetic meridian. In Figure OB represents total intensity of magnetic field. OB makes an angle δ with a horizontal line OM_S in the magnetic meridian. This angle is called as Dip at that place.
3. **Horizontal Component of Earth's Magnetic field (B_H):** The component of total intensity of magnetic field of earth in the horizontal direction in magnetic meridian is called as horizontal component of earth's magnetic field.
   In the figure B, B_H is the horizontal component and B_V is the vertical component of intensity of magnetic field of earth**.** Then

$$B_H = B\cos\delta \quad \text{... (1)}$$

$$B_V = B\sin\delta \quad \text{... (2)}$$

Dividing (2) by (1) $\dfrac{B_V}{B_H} = \dfrac{B\sin\delta}{B\cos\delta} = \tan\delta$

or $\tan\delta = \dfrac{B_V}{B_H}$ ...(3)

Squaring and adding (1) and (2), we get

$$B_H^2 + B_V^2 = B^2\cos^2\delta + B^2\sin^2\delta = B^2(\cos^2\delta + \sin^2\delta) = B^2$$

or $B = \sqrt{B_H^2 + B_V^2}$

*****The value of B_H is different at different places. It is zero at poles and equal to total value of magnetic field intensity at equators.*

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VARIOUS TERMS RELATED TO MAGNETISM

MAGNETIC FLUX: The number of magnetic lines of force passing normally through a surface is defined as magnetic flux and is denoted by ϕ.

The SI unit of magnetic flux is weber (Wb).

MAGNETIC FLUX DENSITY:

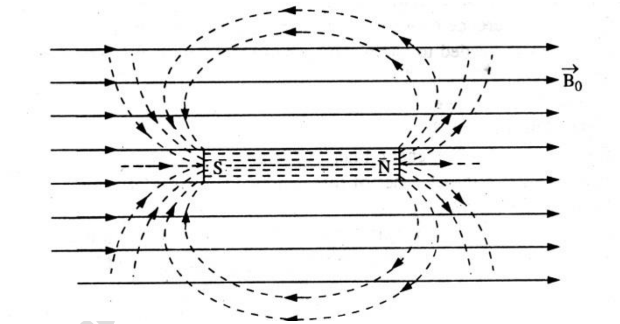
The number of magnetic lines of force passing normally through a unit area of a substance is defined as magnetic flux density denoted by B.

If ϕ is the flux passing normally through a substance of area A then flux density.

$$B = \frac{\phi}{A} \qquad \text{or} \qquad \phi = BA$$

In general $\phi = \vec{B}.\vec{A} = BA\cos\theta$

***When a magnetic substance is placed in the magnetising field (B_o), then the substance gets magnetised. The net magnetic field inside the magnetised substance is the sum of the magnetising filed (B_o) and the magnetic field due to the magnetisation of the substance (B_m). i.e. $B = B_O + B_m$



MAGNETIC PERMEABILITY: The degree or extent to which magnetic lines of force can enter a substance is known as magnetic permeability. It is denoted by μ.

Magnetic permeability of a substance is equal to the ratio of the magnitude of the magnetic induction (B) to the intensity of magnetising field (H).

i.e. $\mu = \frac{B}{H}$ or $B = \mu H$

SI unit of magnetic permeability $= \frac{unit-of-B}{unit-of-H} = \frac{T}{Am^{-1}} = TmA^{-1}$

RELATIVE MAGNETIC PERMEABILITY: The ratio of the flux density or magnetic induction in the material (or substance) to the flux density in vacuum (B_o) is known as relative magnetic permeability.

i.e. $$\mu_r = \frac{B}{B_O} = \frac{\mu H}{\mu_O H} = \frac{\mu}{\mu_O}$$

where μ_o is absolute permeability of vacuum or free space or $$\mu = \mu_o \mu_r$$

μ_r is dimensionless.

INTENSITY OF MAGNETISING FIELD OR MAGNETIC INTENSITY (H):

The magnetic field which magnetises a substance placed in it is called the magnetising field.

The degree or extend to which the magnetising field can magnetise a substance is known as the intensity of magnetising field. It is denoted by H.

Intensity of magnetising field is equal to the ratio of the magnetising field (B_o) to the permeability of free space (μ_o)

i.e. $$H = \frac{B_O}{\mu_O} \quad \text{or} \quad B_0 = \mu_o H$$

where $$\mu_o = 4\pi \times 10^{-7}\, TmA^{-1}$$

S.I. Unit of H $$= \frac{Unit-of-B_o}{Unit-of-\mu_o} = \frac{T}{TmA^{-1}} = Am^{-1}$$

Magnetic intensity H is also called magnetising force.

INTENSITY OF MAGNETISATION OR MAGNETISATION (I):

The degree or extent to which a substance is magnetised when placed in the magnetising field is called intensity of magnetisation. It is denoted by I.

When a magnetic substance is placed in the magnetising field, then this substance acquires magnetism. In other words, one end of the substance becomes N-pole and the other end becomes S-pole. Thus, the magnetised substance has a certain magnetic dipole-moment.

The magnetic dipole moment per unit volume of the substance is known as intensity of magnetisation.

If M be the magnetic dipole moment of the substance and V be its volume, then

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

Since $M = m \times 2l$ and $V = A \times 2l$

$$\therefore I = \frac{m \times 2l}{A \times 2l} = \frac{m}{A}$$

Thus, intensity of magnetisation is equal to the pole strength per unit area of cross-section of the substance.

$$S.I.-Unit-of-I = \frac{Unit-of-dipole-moment}{Unit-of-volume} = \frac{Am^2}{m^3} = Am^{-1}$$

MAGNETIC SUSCEPTIBILITY (χ_m): It is the property of a substance which shows how easily the substance can be magnetised when placed in the magnetising field. It is denoted by χ_m.

Magnetic susceptibility is equal to the ratio of intensity of magnetisation (I) to the intensity of magnetising field (H).

Phogendro Wangkhem (MEC Explorer Academy)

i.e. $\chi_m = \frac{I}{H}$

χm has no unit. It is just a number.

RELATION BETWEEN MAGNETIC PERMEABILITY AND MAGNETIC SUSCEPTIBILITY:

We know that total magnetic flux density (B) in a substance is the sum of the magnetic flux density in vacuum (B_o) and magnetic flux density due to the magnetisation of the substance (B_m).

i.e. $B = B_O + B_m$

Now $B_O = \mu_O H$ and $B_m = \mu_o I$ ... (1)

$\therefore B = \mu_O H + \mu_O I = \mu_O (H + I)$

Dividing both sides by H, we get

$$\frac{B}{H} = \mu_o \left(1 + \frac{I}{H}\right) \qquad \text{... (2)}$$

But $\frac{B}{H} = \mu$ and $\frac{I}{H} = \chi_m$

$\therefore$ eqn. (2) can be written as

$$\mu = \mu_o (1 + \chi_m) \qquad \text{... (3)}$$

or $\frac{\mu}{\mu_o} = 1 + \chi_m$

Since $\frac{\mu}{\mu_o} = \mu_r$ $\therefore \mu_r = 1 + \chi_m$ ... (4)

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MAGNETIC MATERIAL

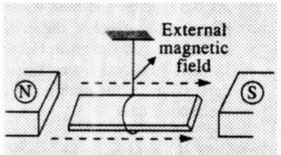
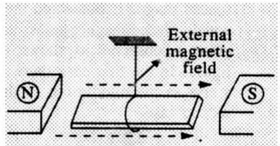
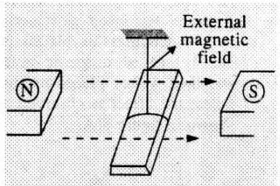
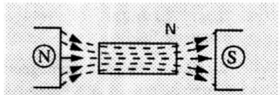
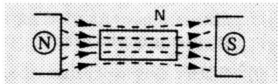
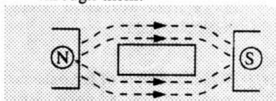
Faraday divided the materials in three classes according to their magnetic behaviour:

a. **Ferromagnetic Material:** ***The materials which are strongly magnetised in the direction of the applied magnetic field are known as Ferromagnetic Materials*. Examples**: Iron, steel, nickel, cobalt and alloys like alnico (aluminium + nickel + cobalt) are ferromagnetic materials. Ferromagnetic substances can be easily magnetised.
Ferromagnetic effect is noticed even in the presence of weak magnetic field. With the rise in temperature it becomes comparatively less easier to magnetise the ferromagnetic substance.
b. **Paramagnetic Material:** ***The materials which are weakly magnetised in the direction of applied magnetic field are known as Paramagnetic Materials***. Examples: Aluminium, chromium, manganese, platinum, antimony, sodium, copper chloride, salt solutions of iron and nickel, liquid oxygen, crown glass etc. are paramagnetic materials.

Paramagnetic materials tend to lose their magnetic behaviour with the rise in temperature. Paramagnetic materials cannot be easily magnetised.

c. **Diamagnetic Material: *The materials which are weakly magnetised in a direction opposite to the direction of applied magnetic field are known as Diamagnetic Materials***. Examples: Gold, silver zinc, lead, bismuth, mercury, marble, glass, quartz, water, alcohol, air, helium, argon hydrogen, salts like sodium chloride etc. are diamagnetic materials.

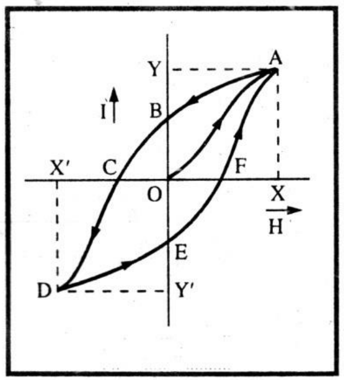
It is very difficult to magnetise a diamagnetic material. They require very strong magnetic fields to show magnetic properties. Their magnetic behaviour normally does not depend upon change in temperature.

Ferromagnetic Materials	Paramagnetic Materials	Diamagnetic Materials
(a) They are *strongly attracted* by a magnet.	*(a)* They are *weakly attracted* by a magnet.	*(a)* They are *weakly repelled* by a magnet.
(b) A freely suspended ferromagnetic rod *quickly sets itself along the direction of* external magnetic field as shown in figure 6(A).	*(b)* A freely suspended paramagnetic rod *slowly sets itself along the direction* of external magnetic field as shown in figure 6B.	*(b)* A freely suspended diamagnetic rod *slowly sets itself at right angle to the direction* of external magnetic field as shown in figure 6(C)
 *Figure 6(A)*	 *Figure 6(B)*	 *Figure 6(C)*
(c) When they are placed in a magnetic field, the *magnetic lines of force prefer to pass* through them.	*(c)* When they are placed in a magnetic field, *most of the magnetic lines of force prefer* to pass through them.	*(c)* When they are placed in a magnetic field, the *magnetic lines of force do not prefer to* pass through them.
 *Figure 7(A)*	 *Figure 7(B)*	 *Figure 7(C)*
This behaviour indicates that	This behaviour indicates that	This behaviour indicates that
(i) Field within the sample is much more than the magnetic intensity (figure 7A) *i.e. permeability* (μ) *is much more than unity.* ($B >> H$ or $\frac{B}{H} >> 1$ or $\mu >> 1$).	*(i)* Field within the sample is more than the magnetic intensity (figure 7B) *i.e. permeability* (μ) is *more than unity* ($B > H$ or $\frac{B}{H} > 1$ or $\mu > 1$).	*(i)* Field within the sample is decreased to a very small value (figure 7C) *i.e. permeability* (μ) *is always less than unity* ($B < H$ or $\frac{B}{H} < 1$ or $\mu < 1$)
(ii) Flux density (B) inside a ferromagnetic material is much larger than in air.	*(ii) Flux density* (B) inside a paramagnetic material is larger than in air.	*(ii) Flux density*(B) inside a diamagnetic material is less than in air.
(iii) The sample gets strongly magnetised in the direction of magnetising field.	*(iii)* The sample gets weakly magnetised in the direction of magnetising field.	*(iii)* The sample gets weakly magnetised in the direction opposite to the direction of magnetising field.

Bhogendro Wangkhem (ME

MAGNETISATION CURVE/ HYSTERESIS LOOP:

Consider a solenoid having ferromagnetic (Iron) core inside it. Current in it is to be increased and decreased in the following steps.



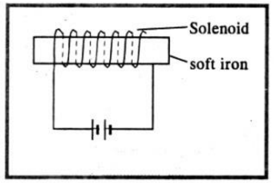
1. To start with, the iron core is initially unmagnetised (point O). Now increase the current which increases the intensity of magnetising field (H) from zero to X such that magnetisation (I) has value Y at position A. Further increase in current bringing increase in H does not change the value of I. Thus point A is known as saturation point corresponding to which I is maximum.
2. Reduce the current in solenoid such that (H) is again reduced to zero as shown by point B. Now the magnetism is core reduces along AB and not along previous curve AO. Thus, the value of intensity of magnetisation (I) corresponding to zero value of H is equal to OB.
3. Reverse the current in the solenoid and increase it until point D is reached.
4. Reduce the current again such that (H) becomes zero (shown by point E).
5. Change the polarity of the current again and increase it until point A is reached again.

Curve ABCDEF is known as Hysteresis loop which is the result of a cycle of magnetisation and demagnetisation. It is important to refer to OB and OE figure which clearly indicates that even when there is zero magnetic field intensity some magnetisation I is still there. ***The magnetism retained by the specimen even when magnetising field is reduced to zero is called residual magnetism of the material and this property of the magnetic material is known as Retentivity.***

To bring residual magnetism to zero, magnetising field intensity equal to OC and OF is to be applied in the opposite direction. ***The property of a magnetic material which depends upon the value of reverse magnetising field required to reduce the residual magnetism to zero is known as Coercivity.***

ELECTROMAGNETS: *An electromagnet is basically a coil of many turns of insulated wire wound over an iron core. When current is passed through the wire magnetic effect is produced.*

Bhogendro Wangkhem (MESI Explore Academy)



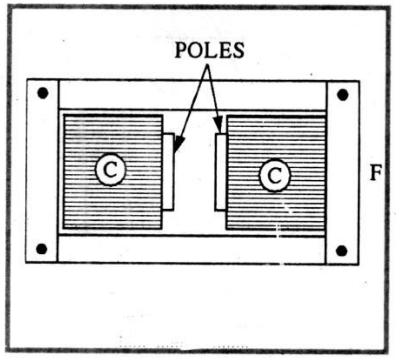


Figure shows an electromagnet in which coils are wound over ferromagnetic material to serve as magnetic poles and F is the iron frame. Cores of generators and motors can be considered as special electromagnets. Almost no hysteresis loss is a very important requirement of such materials. Electromagnets are usually found in lifting magnets, relays, controllers, circuit breakers, electric valves and motor brakes.

Silicon iron and mumetal are used to form cores of transformer. Following factors decide the strength of an electromagnet.

i. Nature of material: Soft iron is best suited for an electro-magnet. Material of an electromagnet should have thin and long hysteresis loop. They should have low retentivity. The material should magnetise quickly. They should have high permeability. Silicon, iron, and mumetal are also used to make electromagnet.
ii. Electric current: Strength of current in the solenoid gives the required magnetising force to an electromagnet. Weak currents may not magnetise the sample properly.
iii. Number of turns per unit length of solenoid: Higher the number of turns, higher is the magnetising field. High field is required for strong electromagnets.
iv. Temperature: Magnetism is lost at high temperatures. This fact was properly studied by Curie who gave a law to this effect. Curie's law is explained below.

<u>CURIE'S LAW</u>: *Curie's law can be stated as, magnetic susceptibility of a material varies inversely with temperature (in Kelvin) of the material.*

Curie discovered experimentally that intensity of magnetisation I of a magnetic material is directly proportional to magnetic field intensity B and inversely proportional to the temperature T (in Kelvin)

i.e. $I \propto \frac{B}{T}$ or $I \propto \frac{H}{T}$ $[\because B \propto H]$

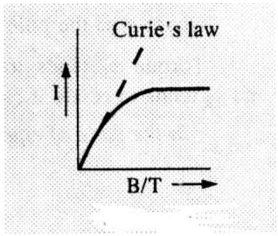
or $\frac{I}{H} \propto \frac{1}{T}$ or $\chi_m \propto \frac{1}{T}$ $\left[\because \frac{I}{H} = \chi_m\right]$

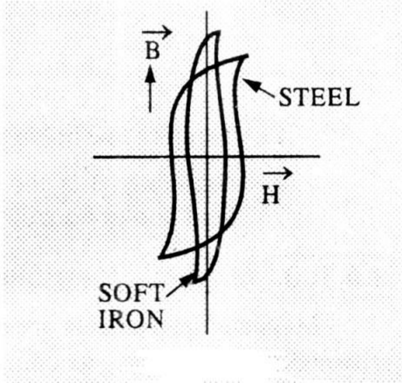
o $\chi_m = \frac{C}{T}$

where C is called Curie constant.

Increase in magnetisation (I) with decrease in temperature has a limit when the material becomes saturated. Figure shows a curve between

(I) and (B/T). Once saturation is achieved further decrease in temperature does not bring change in magnetisation.





PERMANENT MAGNETS:

Steel is a common material used to make permanent magnets. It has high residual magnetism (retentivity). It has very high coercivity i.e. hysteresis loop is wider. Although area of hysteresis loop for steel is large yet it is of no importance because a permanent magnet is supposed to retain the magnetism and is not required to undergo cycle of magnetisation and demagnetisation. Many alloys are also used to make permanent magnets:

i. Cobalt steel – It contains cobalt, tungsten, carbon and iron.
ii. Alnico – It contains aluminium, nickel, cobalt, copper and iron. It is brittle.

Bhogendro Wangkhem (MECI Explorer Academy)