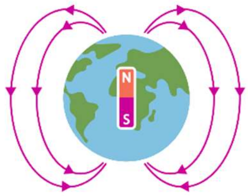


Chapter 5
Magnetism and matter

Introduction

A Greek Philosopher, Thales of Miletus had observed as long back as 600 B.C., that a naturally occurring ore of iron attracted small pieces of iron towards it. This ore was found in the district of Magnesia in Asia Minor in Greece. Hence the ore was named magnetite. The phenomenon of attraction of small bits of iron, steel, cobalt, nickel etc. towards the ore was called magnetism. The iron ore showing this effect was called a natural magnet. The structural formula of this natural ore was Fe_3O_4.

Atomic view of magnetism

What is the criteria that determines whether a material is magnetic or not? It is determined by the atomic structure of the atoms that makes up the material. In atomic view, there are electrons moving around the nucleus forming orbital currents. At the same time, electrons are also spinning about itself, forming spin currents. In most materials there are paired electrons spinning in the opposite directions. The field created by one moving charge is cancelled out by the other. As a result, no magnetic field is created. But some materials like iron, nickel, cobalt, etc. have unpaired electron or paired electrons spinning about the axis. In this case, the magnetic field created by one does not cancel by the other, resulting in the creation of an atomic sized magnet. According to the modified version of atomic theory of magnetism,

(i) Every molecule of a magnetic material is a complete magnet in itself possessing a north pole and a south pole.

(ii) In an unmagnetized substance, the molecular magnets are randomly aligned forming closed chains.

(iii) When the substance is magnetized, the molecular magnets get aligned such that the north poles of all molecular magnets get aligned in one direction.

Properties of magnets

(i) Magnets attract magnetic objects like iron, cobalt and nickel. The force of attraction of a magnet is maximum at the poles.

(ii) Like poles of two magnets repel each other (N – N and S – S), while opposite or unlike poles of two magnets attract each other (N – S and S – N).

(iii) If a bar magnet is suspended by a thread and is free to rotate, it will always align itself towards the geographical N-S line.

(iv) (iv) Magnetic monopole does not exist. Poles always exist in pairs (N – S). If it is tried to separate the two poles of a magnet by breaking it in the middle, we will obtain a new pair of magnets each with a north pole and a south pole.

(v) Both the poles of a magnet are equally strong.

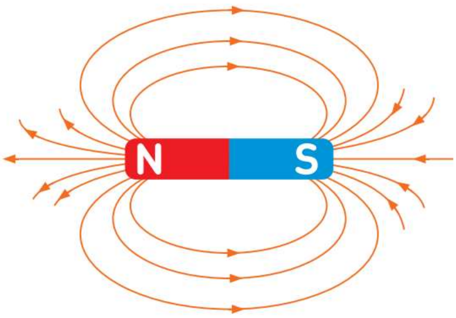
(vi) At high temperatures (more than curie temperature), magnetic properties of a magnet are lost.

Magnetic lines of force

Magnetic field lines as the path along which an isolated north pole would move, if it is free to do so.

Properties of Magnetic Lines

Following are some of the important properties of magnetic lines of force:

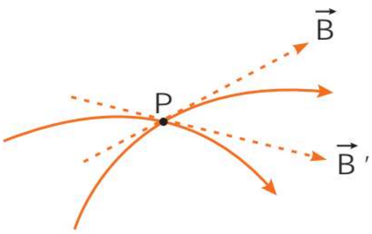


(i) Magnetic lines of force are closed continuous curves; we may imagine them to be extending through the body of the magnet.

(ii) Outside the body of the magnet, the direction of magnetic lines of force, is from north pole to south pole.

(iii) The tangent to magnetic line of force at any point gives the direction of magnetic field strength at that point.

(iv) No two magnetic lines of force can intersect each other because if they do there will be two directions of magnetic field at one point which is not possible.



(v) Magnetic lines of force contract longitudinally and they dilate laterally.

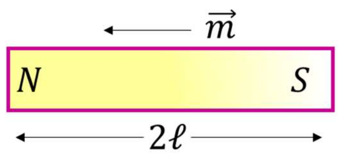
(vi) Crowding of magnetic lines of force represents stronger magnetic field and vice-versa.

A magnetic dipole consists of two unlike poles of equal strength and separated by a small distance. For example, a bar magnet, a compass needle etc. are magnetic dipoles. We shall show that a current loop behaves as a magnetic dipole. An atom of magnetic material behaves as a dipole due to electrons revolving around the nucleus. 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 and cannot be separated from each other. The distance between the two poles of a bar magnet is called the magnetic length of the magnet. It is a vector directed from S-pole of magnet to its N-pole, and is represented by $2\vec{\ell}$.

Magnetic dipole moment

Magnetic dipole moment is the product of strength of either pole (q_m) and the magnetic length (2l) of the magnet. It is represented by m.

Magnetic dipole moment = strength of either pole × magnetic length



$\boxed{m = q_m \times 2\ell}$

It is a vector quantity.

Its SI unit is Am^2.

We shall show that S.I. units of M are joule/tesla or ampere/metre^2.

$\therefore$ SI unit of pole strength is Am.

Note that the direction of magnetic moment (m) of a magnetic dipole is from south to north. This corresponds to the electric dipole moment (p) of an electric dipole from negative charge to positive charge.

Every formula in magnetism can be obtained from corresponding formula from electrostatics by making the substitutions shown in table below:

S.No.	Quantity in electrostatics	Magnetic analogue
1	Charge (q)	Pole strength (q_m)
2	+ve charge	North pole
3	-ve charge	South pole
4	$\frac{1}{\varepsilon_o}$	μ_o
5	$\frac{1}{4\pi\varepsilon_o}$	$\frac{\mu_o}{4\pi}$
6	Electric dipole moment (p)	Magnetic dipole moment (m)
7	Electric field intensity (E)	Magnetic field intensity (B)

Below are various formulae in magnetism that have been derived directly from formulae of electrostatics by direct substitution.

Coulomb's law in magnetism

When two poles of pole strengths q_{m_1} and q_{m_2} and kept r apart, then force of attraction or repulsion between them is given by

$$\boxed{F = \frac{\mu_o}{4\pi}\frac{q_{m_1} \times q_{m_2}}{r^2}}$$

Magnetic field intensity at a point

$$\boxed{\vec{B} = \lim_{m_o \to 0} \frac{\vec{F}}{q_{m_o}}}$$

Where F is the force acting on an imaginary isolated north pole of pole strength q_{m_o} .

Magnetic field due to a magnetic pole

Magnetic field intensity at a distance r due to magnetic pole of pole strength q_m is

$$\boxed{B = \frac{\mu_o}{4\pi}\frac{q_m}{r^2}}$$

Magnetic dipole moment of a magnet

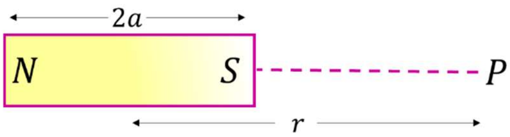
of length 2a having pole strength m (of each pole) is

$$\boxed{M = m \times 2a}$$

Magnetic field at axial line

of an electric dipole at a distance r from centre of the dipole is given by

$$\boxed{B_{axial} = \frac{\mu_o}{4\pi}\frac{2Mr}{\left(r^2 - a^2\right)^2}}$$

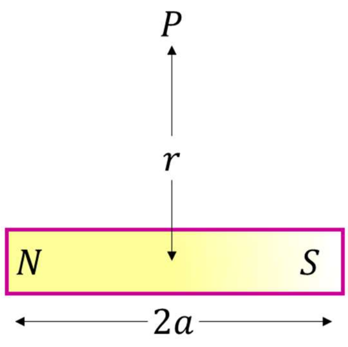


For short dipole (a<<r) this result reduces to

$$\boxed{B_{axial} = \frac{\mu_o}{4\pi}\frac{2M}{r^3}}$$

Magnetic field at equatorial line

of an electric dipole at a distance r from centre of the dipole is given by



$$\boxed{B_{eq} = \frac{\mu_o}{4\pi} \frac{M}{\left(r^2 + a^2\right)^{\frac{3}{2}}}}$$

For short dipole (a<<r) this result reduces to

$$\boxed{B_{eq} = \frac{\mu_o}{4\pi} \frac{M}{r^3}}$$

Torque acting on a magnetic dipole

When a magnetic dipole of dipole moment M is placed in external magnetic field B such that angle between $\vec{M}$ and $\vec{B}$ is θ, then torque acting on the dipole is given by

$$\boxed{\tau = MB\sin\theta}$$

in vector form

$$\boxed{\vec{\tau} = \vec{M} \times \vec{B}}$$

Work required to rotate dipole

Work done to rotate a dipole from angle θ_1 to θ_2 in an external magnetic field against its natural direction of rotation is

$$\boxed{W = -MB\left(\cos\theta_2 - \cos\theta_1\right)}$$

which is stored in the dipole in the form of **magnetic potential energy.**

Gauss law in magnetism

Gauss's law for magnetism is: **The net magnetic flux through any closed surface is zero.**

The difference between the Gauss's law of magnetism and that for electrostatics is a reflection of the fact that isolated magnetic poles (also called monopoles) are not known to exist. There are no sources or sinks of B; the simplest magnetic element is a dipole or a current loop. So, if a closed surface is enclosing a source of magnetic field it has to have both poles – north and south. So the magnetic field lines leaving form north (+ ve magnetic flux) will be equal to number of magnetic field line entering south (- ve magnetic flux). Thus total flux will always be zero.

Consider a small vector area element ΔS of a closed surface S as in Fig. The magnetic flux is defined as

$\Delta\varphi = \vec{B}.\overrightarrow{\Delta S}$, where B is the field at ΔS. We divide S into many small area elements and calculate the individual flux through each. Then, the net flux is,

$$\varphi_B = \sum_{all} \Delta\varphi_B = \sum_{all} B.\Delta S = 0$$

Current loop as magnetic dipole

Consider a plane loop of wire carrying current, Figure below. Looking at the upper face current is anticlockwise. Therefore, it has a north polarity. Looking at the lower face of the loop, current is clockwise. Therefore, it has a south polarity. The current carrying loop thus behaves as a system of two equal and opposite magnetic poles and hence is a magnetic dipole.

The magnetic dipole moment of the current loop (m) is directly proportional to

(i) strength of current (I) through the loop and
(ii) area (A) enclosed by the loop.
(iii) Number of turns (N) in the loop.

Thus,

$$\boxed{m = NIA}$$

In vector form, we can rewrite equation as $\boxed{\vec{m} = NIA\hat{n}}$

where $\hat{n}$ is unit vector perpendicular to the plane of the loop in a direction given by right handed screw rule.

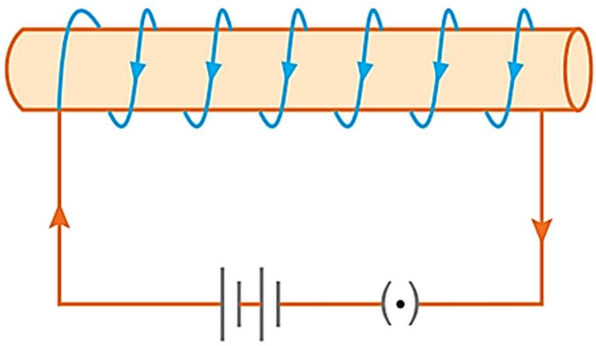
Magnetisation and magnetic intensity

We have seen that a circulating electron in an atom has a magnetic moment. In a bulk material, these moments add up vectorially and they can give a net magnetic moment which is non-zero.

Magnetisation

We define magnetisation M of a sample to be equal to its net magnetic moment per unit volume

$$\boxed{M = \frac{m}{V}}$$



- It's a vector quantity
- Its dimensions are $L^{-1}A$
- Its SI unit is Am^{-1}

Consider a long solenoid of n turns per unit length and carrying a current I. The magnetic field in the interior of the solenoid was shown to be given by

$B_o = \mu_o nI$

If the interior of the solenoid is filled with a material with non-zero magnetisation, the field inside the solenoid will be greater than B_o.

The net B field in the interior of the solenoid may be expressed as

$B = B_o + B_m$

where B_m is the field contributed by the material core. It turns out that this additional field B_m is proportional to the magnetisation M of the material and is expressed as

$B_m = \mu_o M$

Where μ_o is the same constant (permittivity of vacuum) that appears in Biot-Savart's law.

Magnetic intensity

Magnetic intensity is the measure of how strong or weak a particular magnetic field is.

It is represented by H and it's equal to product of no. of terms per unit length and current i.e.

$\boxed{H = nI}$

- H has the same dimensions as M and
- measured in units of Am^{-1}.
- It is a vector quantity.

Thus, the total magnetic field B is written as

$\boxed{B = \mu_o (H + M)}$

Also $B = \mu H$ where μ is the permeability of the medium placed in the core of the solenoid.

Magnetic susceptibility (χ)

It is ratio of M to H i.e.

$$\boxed{\text{magnetic susceptibility} = \frac{\text{Magnetisation}}{\text{Magnetic intensity}}}$$

$$\chi = \frac{M}{H}$$

It is a unit less and dimensionless quantity.

- It is a measure of how a magnetic material responds to an external field.

- Susceptibility is small and positive for materials, which are called paramagnetic.
- It is small and negative for materials, which are termed diamagnetic.

Relative magnetic permeability

Relative magnetic permeability, often denoted as μ_r, is a dimensionless measure that indicates how easily a material can become magnetized when exposed to an external magnetic field. It is a ratio that compares the permeability of a specific material to the permeability of free space (vacuum), which is denoted as μ_0.

Mathematically, relative magnetic permeability is defined as:

$$\boxed{\mu_r = \frac{\mu}{\mu_o}}$$

Where:

- μ_r is the relative magnetic permeability of the material.
- μ is the absolute permeability of the material (its ability to support the formation of a magnetic field within itself).
- μ_0 is the magnetic permeability of free space or vacuum, which is a constant value approximately equal to $4\pi \times 10^{-7}\,\text{TmA}^{-1}$ (Tesla meter per Ampere).

Relation between susceptibility and relative magnetic permeability

As $B = \mu_o (H + M)$

$$\Rightarrow \mu H = \mu_o (H + M)$$

$$\Rightarrow \frac{\mu H}{H} = \mu_o \left(\frac{H}{H} + \frac{M}{H}\right)$$

$$\Rightarrow \frac{\mu}{\mu_o} = \left(1 + \frac{M}{H}\right)$$

$$\Rightarrow \mu_r = 1 + \chi$$

Magnetic properties of materials

Classification Basis: The magnetic properties of materials are classified based on their magnetic susceptibility. This property determines how materials respond to external magnetic fields.

Categories:

- **Diamagnetic Materials:** Characterized by a negative susceptibility.

- **Paramagnetic Materials:** Display a positive but small susceptibility.
- **Ferromagnetic Materials:** Identified by their large and positive susceptibility.

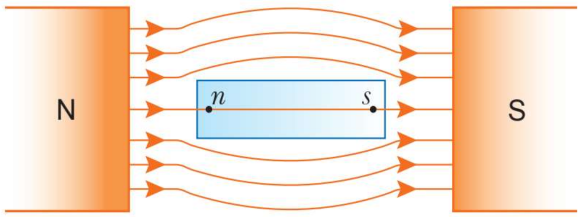
Diamagnetism

Diamagnetic substances inherently move from stronger parts to weaker parts of an external magnetic field.

Unlike magnets that attract ferromagnetic materials like iron, diamagnetic substances are repelled.

Interaction with Magnetic Field:

- **Field Line Dynamics:** In the presence of a diamagnetic material, the magnetic field lines are either repelled or expelled, leading to a reduced magnetic field within the material itself.



- **Magnitude of Reduction:** Typically, the reduction in the magnetic field is quite minimal, about one part in 105.
- **Behaviour in Non-uniform Fields:** These materials exhibit a tendency to move from regions of high magnetic field intensity to areas with lower field strength.

Theoretical Explanation of Diamagnetism

- The electrons orbiting around the nucleus possess this momentum, contributing to the overall magnetic characteristics of the atom.
- These orbiting electrons can be likened to current-carrying loops, endowing them with an orbital magnetic moment.
- In diamagnetic substances, the overall magnetic moment of an atom is zero.
- Upon the application of an external magnetic field, electrons with a magnetic moment aligned in the same direction as the field slow down, while those in the opposite direction accelerate.
- This phenomenon is a result of induced currents, which will be further explored in Chapter 6, and leads to the development of a net magnetic moment opposite to the direction of the applied field, causing repulsion.

Examples and Special Cases of Diamagnetic Materials

Common Examples: Some typical diamagnetic materials include bismuth, copper, lead, silicon, nitrogen (at standard temperature and pressure), water, and sodium chloride.

Universal Presence: Diamagnetism is a property present in all substances, though often overshadowed by stronger magnetic effects like paramagnetism and ferromagnetism.

Unique Case of Superconductors

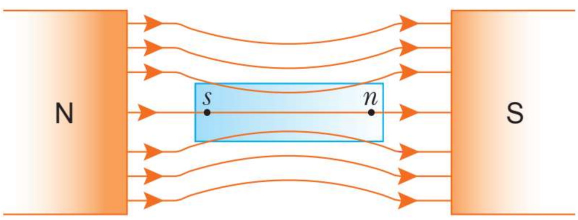
- **Defining Characteristics:** Superconductors exhibit both perfect conductivity and perfect diamagnetism, but only at very low temperatures.
- **Magnetic Field Interaction:** In superconductors, magnetic field lines are completely expelled. This is quantified by a susceptibility of -1 and a relative magnetic permeability of 0.
- **Meissner Effect:** This phenomenon, named after its discoverer, refers to the perfect diamagnetism observed in superconductors.

Practical Applications

A notable application of superconductors is in the development of magnetically levitated superfast trains.

Paramagnetism

- Paramagnetic substances are weakly magnetized in the presence of an external magnetic field, showing a slight attraction to magnets.
- Tend to move from regions of weak magnetic field to strong magnetic field.
- **Atomic Characteristics:**
  - **Permanent Magnetic Dipole Moment:** Individual atoms, ions, or molecules possess their own dipole moments.
  - **Random Thermal Motion:** This motion typically prevents net magnetization in the absence of an external magnetic field.
  - **Alignment in External Field:** Under a strong external magnetic field (B0), especially at low temperatures, the atomic dipole moments align with the field, enhancing the internal magnetic field of the material.
- **Magnetic Field Interaction:**
  - **Field Lines Concentration:** Field lines concentrate inside paramagnetic materials, slightly enhancing the internal field.

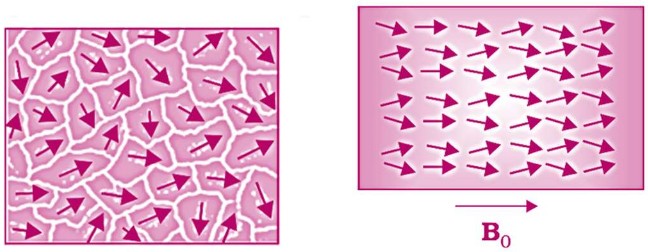


  - **Behaviour in Non-uniform Fields:** These substances move from areas of weaker to stronger magnetic fields.

- **Examples of Paramagnetic Materials:** Aluminium, sodium, calcium, oxygen (at STP), and copper chloride.
- **Dependence on Conditions:** The magnetic susceptibility (c) and relative magnetic permeability (mr) depend on both the material and the temperature.
- **Saturation Point:** Increased magnetization with stronger fields or lower temperatures until all dipoles align perfectly with the field (saturation).

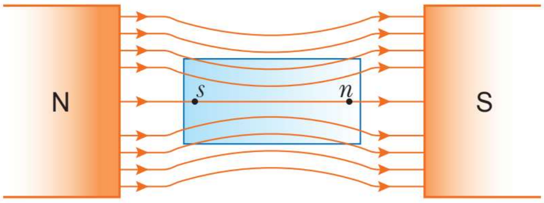
Ferromagnetism

- **Definition:** Ferromagnetic substances are strongly magnetized in an external magnetic field and exhibit a strong attraction to magnets.
- **Movement in Magnetic Fields:** Move from regions of weak to strong magnetic fields.
- **Atomic and Domain Characteristics:**
    - **Permanent Dipole Moment:** Similar to paramagnetic materials, but with a key difference in interaction.
    - **Domain Formation:** Atoms align spontaneously in a common direction within macroscopic volumes called domains.



(a) (b)

- **Domain Behaviour:**
    - **Random Orientation:** Initially, domains have random magnetization directions, resulting in no bulk magnetization.
    - **Alignment in External Field:** Under an external field (B_O), domains align and grow in the direction of B_O.
- **Magnetic Field Interaction:**
    - **Field Lines Concentration:** Highly concentrated in ferromagnetic materials.



- **Behaviour in Non-uniform Fields:** Tend to move towards areas of higher magnetic field strength.

- **Types of Ferromagnetic Materials:**
  - **Hard Magnetic Materials:** Retain magnetization after the external field is removed (e.g., Alnico, lodestone).
  - **Soft Magnetic Materials:** Lose their magnetization without the external field (e.g., soft iron).
- **Examples and Permeability:** Iron, cobalt, nickel, gadolinium, etc., with relative magnetic permeability >1000.
- **Temperature Dependence:** Ferromagnetism turns into paramagnetism at high temperatures as the domain structure disintegrates.