Magnetism and matter

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Introduction

Magnetism is the phenomenon due to which certain substances attract pieces of steel, iron, nickel etc.

Magnets are used in many devices like electric bell, telephone, radio, loud speaker, motors, fans, screw drivers, lifting heavy iron loads, super-fast trains especially in foreign countries, refrigerators etc.

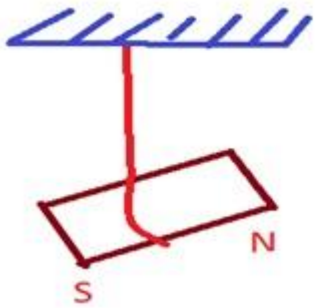
Magnetite is the world's first magnet. This is also called natural magnet. Though magnets occur naturally, we can also impart magnetic property on a substance. It would be an artificial magnet in that case.

History of magnets

- As early as 600 BC in Greece, shepherds observed that their wooden shoes which had iron nails struck at some places on the ground.
- An island in Greece called **magnesia** has magnetic ore deposits. The word magnet is derived from here.
- The technological use of magnet at around 400 BC by Chinese was remarkable. A thin piece of magnet when suspended freely always points towards North-South direction. This fact was utilized by a Chinese emperor Huang-ti to win a war.

Properties of magnets

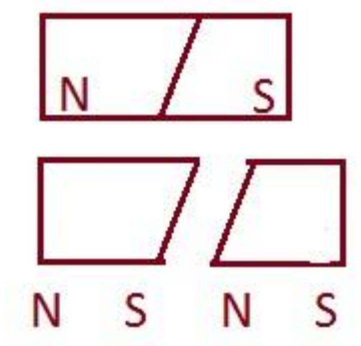
- Earth behaves as a magnet
- When a bar magnet is freely suspended, it points to the NS direction



- When two North poles are brought together, they repel each other. Similar effect is observed for South pole also

- However, when a North pole and South pole is brought together, they attract each other

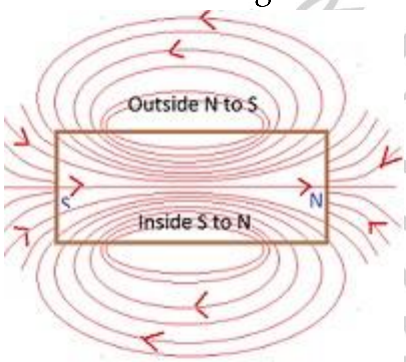
- Magnetic monopoles do not exists which means we cannot have a magnet with North pole alone or South pole alone
- If a bar magnet is broken in two halves, we get two similar bar magnets with weaker properties



- With the help of iron and its alloys, we can make magnets

Magnetic field lines

- When iron fillings are sprinkled on a sheet of glass placed over a short bar magnet, we observe a pattern. The pattern indicates that the magnet has two poles.
- This pictorially represents magnetic field lines. Thus, magnetic field lines are imaginary lines of magnetic field inside and around the magnet.

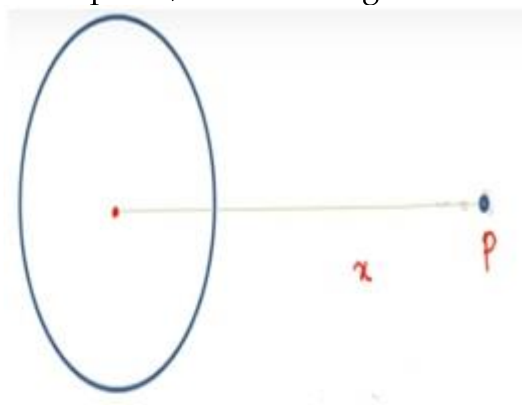


Some of the properties of the magnetic field lines are :

- The lines and continuous and outside the magnet, the field lines originate from the North pole and terminate at the South pole
- They form closed loops traversing inside the magnet. But here the lines seem to originate from the South pole and terminate at North pole to form closed loops.
- More number of close lines indicate stronger magnetic field
- The lines do not intersect each other
- The tangent drawn at the field line gives the direction of the field at that point.

Analogy – Circular Current loop and Current loop in uniform magnetic field

In chapter 1, Electric charges and fields, we studied about current carrying circular conductor.

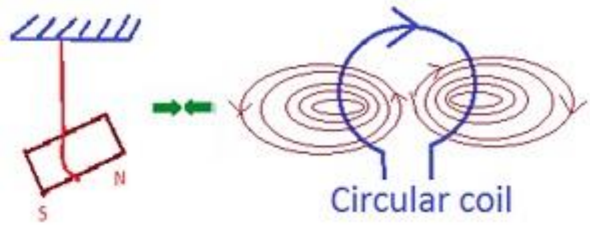


The current carrying circular loop of N turns is analogous to magnetic dipole. In a current carrying loop, if we view from one side, say right side, the current appears to move in clockwise

direction. This is like South polarity. If we view it from the other side, say left side, the current appears to move in the anticlockwise direction which is like North polarity.
Magnetic dipole moment of a current carrying loop is given by M = IA where

- Current – I
- Area of cross-section of the coil - A

For N such turns of the coil, Magnetic dipole moment M = NIA
The expression for moment in the case of current carrying loop having N turns is similar to rectangular loop placed in uniform magnetic field with area vector A. In both cases, m = NIA

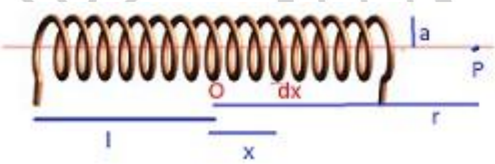


Analogy – Solenoid and Bar magnet
Before the analogy, let is find out **<u>the magnetic field at a far axial point of a solenoid</u>**:
Let the consider the following

- Length of the solenoid – 2l
- Radius of the solenoid – r
- Number of turns / unit length – n

Also, consider,

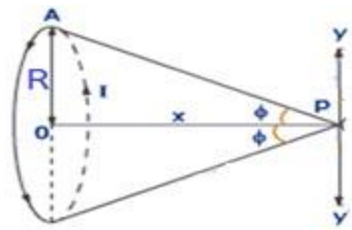
- dx - a small element dx in the solenoid
- x - distance of dx from the centre of the solenoid
- r –distance of the point P from the centre of the solenoid O



As the magnetic field on the axis of a circular loop is

$$B = \frac{\mu_0}{2}\frac{IR^2}{(x^2+R^2)^{\frac{3}{2}}}$$

where R is the radius and x is the distance of the point from the centre of the circular loop



Re-writing the above equation, for a small element dx,

$$dB = \frac{\mu_0 I a^2}{2(a^2+(r-x)^2)^{3/2}} * n * dx$$

Integrating the above expression and apply limits as l varies from +l to –l

$$B = \frac{n\mu_0 I a^2}{2} \int_{-l}^{+l} \frac{dx}{(a^2 + (r-x)^2)^{3/2}}$$

For a far axial point, r >> x ; r >> a

Hence, $a^2 + (r-x)^2 = a^2 + r^2 = r^2$

Hence, denominator is $(r^2)^{3/2} = r^3$

$$B = \frac{n\mu_0 I a^2}{2} \int_{-l}^{+l} \frac{dx}{r^3}$$

$$B = \frac{n\mu_0 I a^2}{2r^3} \int_{-l}^{+l} dx$$

$$B = \frac{n\mu_0 I a^2}{2r^3} [x]^{l}_{-l}$$

$$B = \frac{n\mu_0 I a^2}{2r^3} [2l]$$

$$B = \frac{n\mu_0 I l a^2}{r^3}$$

Magnetic moment of the solenoid is given by (total number of turns * current * cross-sectional area) which is

$$n * 2l * \pi a^2$$

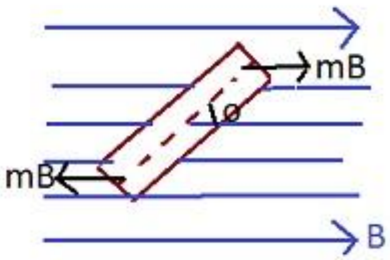
$$B = \frac{\mu_0 2m}{4\pi r^3}$$

A bar magnet may be considered as a large number of circulating currents analogous to a solenoid.

S.No.	**Bar magnet**	**Solenoid**
1	The field lines of bar magnet are similar to Solenoid	Continuous field lines like bar magnet
2	Cutting a bar magnet into two pieces results in smaller bar magnets but monopoles are not possible	Cutting of solenoid results in smaller solenoid of slightly weaker fields
3	Cutting a bar magnet into two pieces results in smaller bar magnets but monopoles are not possible	Cutting of solenoid results in smaller solenoid of slightly weaker fields

4	Magnetic field at a far axial point is same
5	Magnetic moment is the same

Dipole in a uniform magnetic field



<u>Expression for finding the value of magnetic field:</u>

Take a compass with known value of magnetic moment m and moment of Intertia I . Allow the needle to oscillate in a magnetic field of value B.

The torque on the needle is given by

$\tau = \vec{m} \times \vec{B} = -mB\sin\Theta$ where τ is restoring torque

Θ is angle between m and B

By Newton's second law,

Restoring torque = I α where I is moment of inertia

A is angular acceleration

$= I\frac{d\omega}{dt}$

$= I\frac{d^2}{dt^2}\theta$

$-mB\sin\Theta = I\frac{d^2}{dt^2}\theta$

For small values of Θ, sin Θ = Θ,

$-mB\Theta = I\frac{d^2}{dt^2}\theta$

$\frac{d^2}{dt^2}\theta = -\frac{mB}{I}\Theta$

This resembles simple harmonic motion, $\frac{d^2}{dt^2}x = -\omega^2 x$

Hence, $\omega^2 = \frac{mB}{I}$; $B = \frac{\omega^2 I}{m}$

As, $\omega = \frac{2\pi}{T}$, $B = (\frac{2\pi}{T})^2\frac{I}{m}$

$$\boxed{B = \frac{4\pi^2 I}{mT^2}}$$

Expression for finding the value of magnetic potential energy :

In the above case, the magnetic potential energy (U_m) is the work done in taking the magnetic needle (NS) in the magnetic field B from the initial position to the final position.

$$U_m = \int \tau \, d\theta$$

$$= \int mB \sin\theta \, d\theta$$

$$= -mB \cos\theta = \vec{m}.\vec{B}$$

Numericals: A short bar magnet placed with its axis at 30^0 with a uniform external magnetic field of 0.25 T experiences a torque of magnitude equal to $4.5 * 10^{-2}$ What is the magnitude of magnetic moment of the magnet?

Given B = 0.25T, $\tau = 4.5 * 10^{-2}$ J , $\Theta = 30^0$, M = ?

τ = MB sinΘ

M = τ / B sinΘ

= $4.5 * 10^{-2}$ / 0.25 * sin 30 = 0.36 J/T

Numericals: A short bar magnet of moment 0.32 JT^{-1} is placed in a uniform external magnetic field of 0.15 T. If the bar is free to rotate in the plane of the field, which orientation would correspond to its (a) stable (b) unstable equilibrium? What is the potential energy of the magnet in each case?

Given M = 0.32 JT^{-1}

B = 0.15 T

- In stable equilibrium, the bar magnet would be aligned along the magnetic field and $\theta = 0^0$

P.E = - MBCosθ = - 0.32 * 0.15 * cos 0^0 = $-4.8 * 10^{-2}$ J

- In unstable equilibrium, the bar magnet would make and angle 180^0 with the magnetic field and $\theta = 180^0$

P.E = - MBCosθ = - 0.32 * 0.15 * cos 180^0 = $4.8 * 10^{-2}$ J

Numericals : A circular coil of 16 turns and radius 10cm carrying a current of 0.75 A rests with its plane normal to an external field of magnitude $5.0 * 10^{-2}$ When the coil is turned slightly and released, it oscillates about its stable equilibrium with frequency of 2.0 s^{-1} . What is the moment of inertia of the coil about its axis of rotation?

Given n = 16 turns

a = $10 * 10^{-2}$ m

I = .75 A

B=$5.0 * 10^{-2}$ T

υ=2.0 s^{-1}

I = ?

M = nIA = 16 * .75 * 3.14 * $(10 * 10^{-2})^2$ = 0.377 J/T

$$\omega^2 = \frac{MB}{I}$$

Hence, $(2\pi \upsilon)^2$ = MB / I

= 0.377 * 5.0 * 10^{-2} / 4 * 3.14 * 3.14 * 2 * 2

= $1.2 * 10^{-4}$ kg m^2

Numericals : A magnetic dipole is under the influence of two magnetic fields. The angle between the field directions is 600 and one of the field has a magnitude of 1.2 * 10-2T. If the dipole comes to a stable equilibrium at an angle of 150 with this field, what is the magnitude of the other field?

$B_1 = 1.2 * 10^{-2}$ T

$B_2 = ?$

Angle between the two fields B_1 and B_2, $\theta = 60^0$

Angle between dipole and field B_1, at stable equilibrium = $\theta_1 = 15^0$

Angle between dipole and field B_2,at stable equilibrium = $\theta_2 = \theta - \theta_1$

$= 60^0 - 15^0 = 45^0$

At rotational equilibrium, torque due to both fields should balance.

Hence,

Torque due to field B_1 = Torque due to field B_2

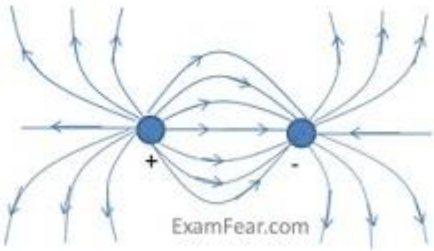
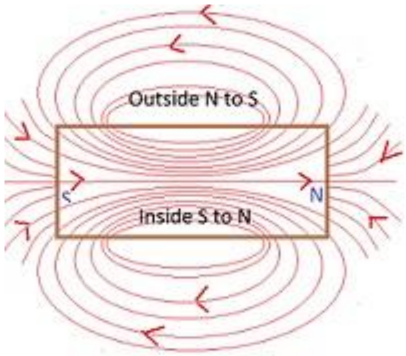
$MB_1 \sin \theta_1 = MB_2 \sin \theta_2$

$B_2 = B_1 \sin \theta_1 / \sin \theta_2$

$= 1.2 * 10^{-2} * \sin 15 / \sin 45$

$= 4.39 * 10^{-3}$ T

Electrostatics & Magnetism – Dipole Analogy

Feature	**Electrostatics**	**Magnetism**
Field Lines	Field lines are not continuous 	Field lines are continuous 

Dipole moment	Symbol – p	Symbol - m
Equatorial field	$\frac{1}{4\pi\epsilon_0}\frac{p}{r^3}$	$\frac{-\mu_0}{4\pi}\frac{m}{r^3}$
Axial field	$\frac{1}{4\pi\epsilon_0}\frac{2p}{r^3}$	$\frac{\mu_0}{4\pi}\frac{2m}{r^3}$
Torque in external field	$\vec{p} \times \vec{E}$	$\vec{m} \times \vec{B}$
Energy in external field	$-\vec{p} \cdot \vec{E}$	$-\vec{m} \cdot \vec{B}$

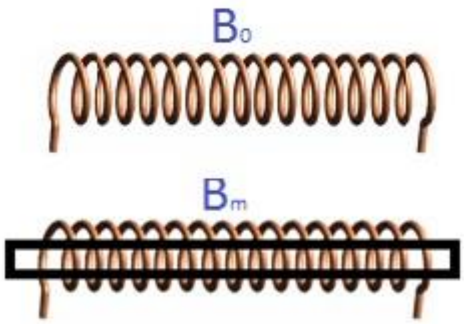
Terms used in Magnetism:-

<u>Magnetization M :</u> As we know, the nucleus of the atom consists of Neutrons and positively charged protons. The electrons which are negatively charged revolve around. Thus, the circulating electron in an atom has a magnetic moment.

In a material made of many atoms, these magnetic moments add up vectorially and give a net magnetic moment which is non-zero.
Hence, Magnetisation M = m_{net} / V which is net magnetic moment per unit volume. Its unit is A/m^2

<u>Magnetic Intensity / Magnetising force H</u>:

Consider a solenoid of n turns per unit length and carrying a current I. Hence,
$B_0 = \mu_0 n I$
The interior of the solenoid is filled with a material of non-zero magnetisation (M).



$B = B_0 + B_m$
$= B_0 + \mu_0 M$
Dividing by μ_0, $B / \mu_0 = B_0 / \mu_0 + M$
$B / \mu_0 = H + M$ [$H = B_0 / \mu_0$, the variation of magnetic field with permeability Is called Magnetic intensity]
$B = \mu_0 (H + M)$
H depends on external factors like current flowing etc. Its unit is A/m^2
M depends on the material inside the solenoid

<u>Susceptibility</u> χ <u>:-</u>

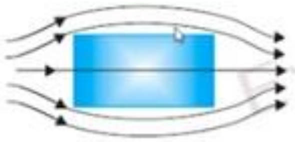
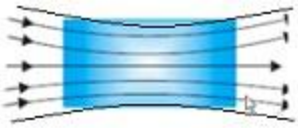
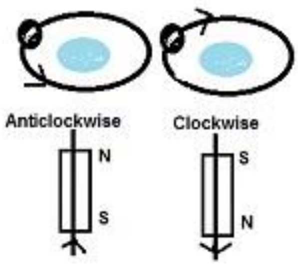
In the expression, $B = \mu_0 (H + M)$
M can also depend on external factors. Hence, $M = \chi H$
where the χ dimensionless quantity is called Susceptibility It gives how a magnetic material responds to an external field. It is dimensionless quantity.

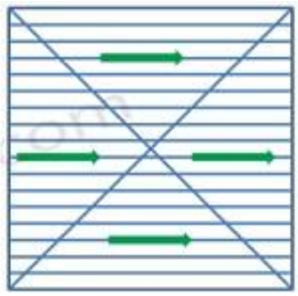
<u>Permeability μ:-</u>

$B = \mu_0 (H + M)$
$B = \mu_0 (H + \chi H)$
$B = \mu_0 (1 + \chi) H$
$= \mu_0 \mu_r H$ [$\mu = \mu_0 \mu_r = \mu_0 (1 + \chi)$]
μ is called magnetic permeability of the substance. μ_r is relative magnetic permeability of the substance. Its unit is Tm/A.

Diamagnetic, Paramagnetic and Ferromagnetic substances:-

Feature	**Diamagnetic**	**Paramagnetic**	**Ferromagnetic**
Nature	Individual constituents <u>do not have</u> net magnetic moment on their own	Individual constituents<u>have</u> net magnetic moment on their own	Individual constituents <u>have</u> net magnetic moment on their own

			and domain formation occurs
			
Field Lines	Field lines do not prefer to pass through	Field lines prefer to pass through	Field lines prefer to pass through closely
Examples	Antimony, Bismuth, Copper, Gold, Quartz, Mercury, Water, Alcohol, Air and Hydrogen	Aluminium, Platinum, Chromium, Manganese, Crown glass and Oxygen	Nickel, Iron, Cobalt and their alloys
Placed in uniform magnetic field (B_{ext})	Small magnetic moment is produced in each atom / molecule proportional to B_{ext} but opposite in direction	Individual dipole moment align along with B_{ext} and the substance is weakly magnetised	Magnetic moments of different domains are aligned with B_{ext} and the substance gets strongly magnetised
Electron theory	The orbital and spin motion of electron for each atom cancels with the other **<u>Presence of magnetic field</u>** : The atom gets magnetised due to induced dipole moment  	The atoms are randomly oriented but each atom has its own magnetic moment **<u>Presence of magnetic field</u>** : The atom gets oriented in a orderly fashion 	 Each atom has a magnetic moment. Many atoms together form a domain. Each domain behaves like a magnet **<u>Presence of magnetic field</u>** :

			 The domain which was in the direction of the magnetic field increased in size. The other domains which are not in the direction of the magnetic field rotate and try to align itself in the field direction  The domains and their magnetic moments are aligned in the direction of the applied magnetic field
Placed in Non uniform magnetic field	Tends to move from high to low field	Tends to move from weak to strong field	Tends to move towards high field
Susceptibility	Small and negative $-1 < \chi_m < 0$	Small and positive $0 < \chi_m < a$ a – small +ve number	Very large and positive $\chi_m > 1000$
Effect of temperature	Independent of temperature	χ_m proportional $1/T$	χ_m proportional to $1 / T - Tc$

Relative permeability	Positive and less than 1 $0 < \mu_r < 1$	Positive and greater than 1 $1 < \mu_r < 1 + a$ where a is small number	Large $\mu_r > 1000$
Variation of I and H	Linear change and saturable low temperature	Linear change	Non linear change

Key effects

<u>Meissner's effect</u> :

- Superconductors are diamagnetic and hence repel and are also repelled by magnets
- When cooled to very low temperature, it exhibits perfect conductivity and diamagnetism
- This phenomenon is called **<u>Meissner effect</u>**
- Hence used in levitated superfast trains

<u>Curie's law :</u>

- Magnetisation of paramagnetic substances is inversely proportional to absolute temperature
- $M = C\, B_0/T$ which is equivalent to

$\chi = C\, \mu_0 / T$ known as **<u>Curie's law</u>**

Hence, the value of μ and χ depends not only on the material but also on the temperature

- As field is increased or temperature is lowered (B /T), the magnetisation increases and reaches saturation M_s.
- Beyond this point M_s, Curie's law is not obeyed

<u>Curie Weiss's law :</u>

- The Curie–Weiss law describes the magnetic susceptibilityχ of a ferromagnet in the paramagnetic region above the Curie point
- At high temperature, Ferro magnet becomes paramagnet. The domain structure disintegrates with temperature
- This transition temperature is called Curie temperature T_c
- $\chi = C / (T - T_c)$ for temperature above Curie temperature

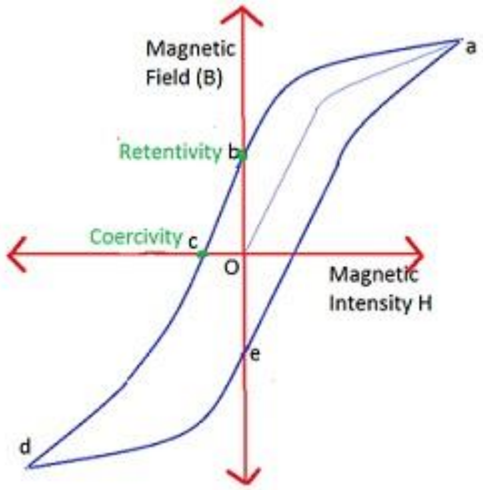
Types of Ferromagnets :-

<u>Hard Ferro magnets</u> – When external magnetic field is removed, magnetisation persists. These are called Hard ferromagnets Example – Alnico, Iodestone

<u>Soft Ferro magnets</u> – When external magnetic field is removed, magnetisation disappears. These are called Soft ferromagnets Example – Soft iron, Cobalt, Nickel, Gadolinium

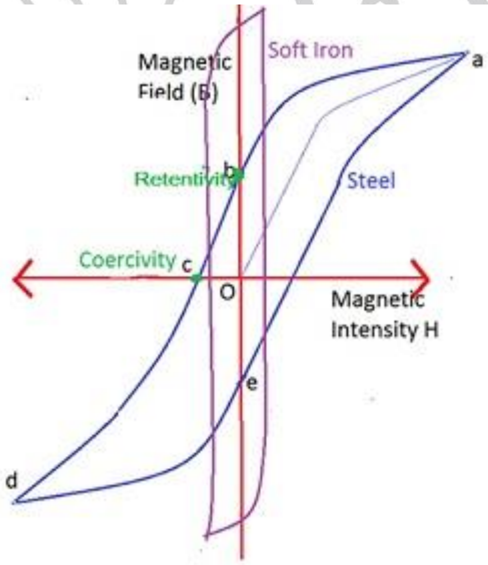
Hysterisis

The word hysteresis means lagging behind. The phenomenon of lagging of intensity of magnetisation (M) behind magnetic intensity (H), when a specimen of magnetic material is subjected to a cycle of magnetization is called hysteresis.



The curve shown would very for different materials like steel, soft iron etc.

- Place an unmagnetised material inside the solenoid and increase the current through the solenoid. This increases the magnetic intensity (H) which is shown in X-axis
- As H increases, the magnetic field B in the material increases and reaches saturation as depicted in the graph as Oa.
- When saturation is reached, there is no point in increasing the current further
- Therefore, decrease the current. So H magnetic intensity also decreases.
- At a point when H is equal to zero, B in Y-axis is not equal to zero. This is indicated by ab.
- The value of H at B=0 is called **retentivity or remanence**.
- Next reverse the current and slowly increase the same. This is represented by bc. The value of H at c(B=0) is called **coercivity**
- As current increases, once again saturation is reached. Curve cd depicts this
- Then the current is reduced (de) and then reversed (curve ea)
- Note the curve ea is obtained and it does not trace the old path Oa



Permanent magnets and Electromagnets

Feature	Permanent Magnet	Electromagnet
What is it?	Substances which retail ferromagnetic property for a long time at room temperature	In day to day applications, we need electro magnets

		which are again made of ferromagnetic materials Electric bells, loud speakers, Telephone Diaphragms, Cranes etc use electro magnets
Substances suitable	Steel, Alnico, Cobalt steel and ticonal	Soft Iron, Iron and Steel alloy
How can it be made?	· One of the method depicted in a 400 years old book is to hold an iron rod in NS direction and hammer it repeatedly · Hold a steel rod and stroke it with one end of a bar magnet many times always in the same direction · Place a ferro magnetic rod in a solenoid and pass current. The magnetic field of the solenoid magnetises the rod	Place a soft iron rod in a solenoid and pass current. Then switch off the solenoid current
Properties of the material	High retentivity – For the magnet to be strong High coercivity –Temperature fluctuation, minor mechanical action and stray magnetic fields nearby should not reduce the magnetic effect of the magnet High Permeability – so that it can be magnetised easily	High Permeability Low retentivity Narrow Hysteresis curve so that energy dissipated and heating should be small High resistivity – to lower losses due to eddy currents