Magnetic Susceptibility (χ) :→ It is the physical quantity which describes the amount & direction of the magnetisation acquired by the substance.
It is equal to the ratio of the magnetic field due to magnetisation to the induction of the magnetising field or equal to the ratio of the intensity of magnetisation to the magnetic intensity of the applied magnetising field.

$$\chi = \frac{\vec{B}_M}{\vec{B}_{ext} \text{ or } \vec{B}_0} \quad \text{—} ①$$

$$\because \vec{B}_{ext} \text{ or } \vec{B}_0 = \mu_0 \cdot \vec{H} \quad \text{—} ②$$

here : $\vec{H} = \frac{\vec{B}_0}{\mu_0}$ $A \cdot m^{-1}$; is magnetic Intensity which is a field vector.

$$\& \ \vec{B}_M = \mu_0 \cdot \vec{I} \quad \text{—} ③$$

from ①, ② & ③ :

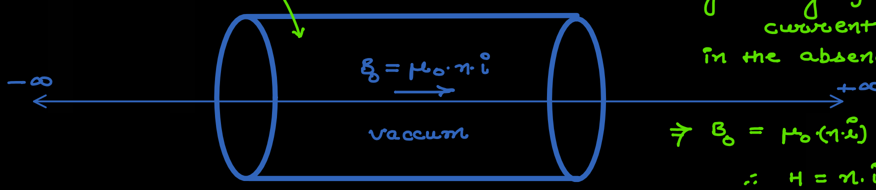
$$\chi = \frac{\mu_0 \cdot \vec{I}}{\mu_0 \vec{H}}$$

$$\therefore \chi = \frac{\vec{I}}{\vec{H}}$$

$$\Rightarrow \boxed{\chi = \frac{\vec{B}_M}{\vec{B}_0} = \frac{\vec{I}}{\vec{H}}} \text{ (unitless \& Dimensionless)} \quad \text{—} ④$$

Total magnetic field inside a solenoid :→ Total magnetic field inside a solenoid having a ferromagnetic core is mostly due to the magnetisation acquired by the core.

(Solenoid without a core)



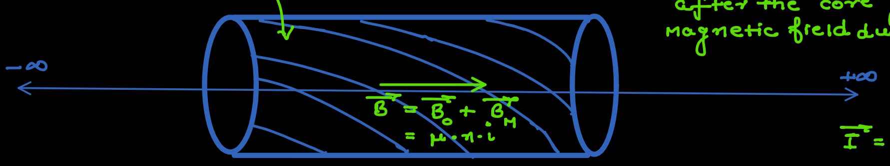
Magnetising field due to the current in the solenoid in the absence of core is B_0

$$\Rightarrow B_0 = \mu_0 (n \cdot i) = \mu_0 H$$

$$\therefore H = n \cdot i \quad \text{—} (*)$$

Magnetic intensity

{ Solenoid with Ferro-magnetic core }



after the core get magnetised magnetic field due to magnetisation is $\vec{B}_M$

so $\vec{B}_M = \mu_0 \cdot \vec{I}$

$\vec{I}$ = intensity of magnetisation

total magnetic field on the axis

$$\vec{B} = \vec{B}_0 + \vec{B}_M$$

$$\Rightarrow \vec{B} = \mu_0 \cdot \vec{H} + \mu_0 \cdot \vec{I}$$

$$\Rightarrow \vec{B} = \mu_0 \cdot (\vec{H} + \vec{I})$$

as $\vec{I} = \frac{\vec{M}}{V}$; (Difficult to Measure)

V = ?
M = ?

hence $\chi = \vec{I}$

as $\vec{I} = \frac{\vec{M}}{V}$; (difficult to measure)

$\therefore$ from; $\chi = \frac{\vec{I}}{\vec{H}}$

$$\vec{B} = \mu_0 \cdot (\vec{H} + \chi \cdot \vec{H})$$

$$\Rightarrow \vec{B} = \mu_0 \cdot (1+\chi) \cdot \vec{H}$$

here: $\boxed{1+\chi = \mu_r}$; ie; relative permeability of the substance

$\Rightarrow \vec{B} = \mu_0 \cdot \mu_r \cdot \vec{H}$ absolute permeability of the medium

also $\mu_r = \frac{\mu}{\mu_0}$; relative permeability

abs. perm. of vacuum

so $\vec{B} = \mu \cdot \vec{H}$

as $H = n \cdot i$

$\therefore$ $\boxed{B = \mu \cdot n \cdot i}$ T

here; μ = absolute permeability of the substance

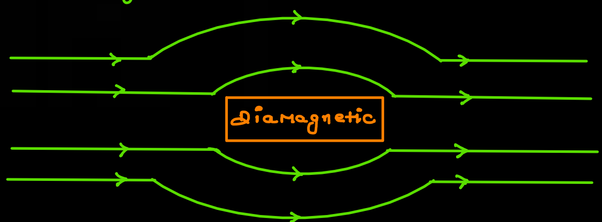
$\mu_0 n i << \mu n \cdot i$

Magnetic Properties of Materials :→ on the basis of the magnetisation acquired by the substance, materials are classified into following 3 catagories.

for Diamagnetic materials χ is b/w -1 & 0, which shows they get weakly magnetised opposite to the applied field, for paramagnetic materials χ is b/w 0 & 1, which shows they get weakly magnetised in the same direction of the applied field, & for ferro-magnetic substance χ is a large positive number which indicates they get strongly magnetised in the same direction of the applied field.

Diamagnetic	Paramagnetic	Ferromagnetic
$-1 \le \chi < 0$	$0 < \chi < 1$	$\chi >> 1$
$0 \le \mu_r < 1$	$1 < \mu_r < 2$	$\mu_r >> 1$
$\mu < \mu_0$	$\mu > \mu_0$	$\mu >> \mu_0$

Diamagnetism :→ Diamagnetic materials are such materials which have a tendency to move from stronger to the weaker field when kept in a non uniform magnetic field.
A magnet will always repel a diamagnetic substance.



if a piece of Diamagnetic substance is kept in an external field, field lines are repelled away from it.

Reason behind diamagnetism is, the increase in the magnetic moment opposite to the applied field. Diamagnetic molecules do not posses magnetic moment, we know the electrons in the orbitals have their spin in the opposite sense, when the field is applied, frequency of revolution of the $\bar{e}$s having magnetic moment along the field decreases & it increases for the $\bar{e}$s spinning in the opposite direction. Thus the substance develops a net magnetic moment in the opposite direction of the applied field.

Diamagnetism is present in all substances, but in some cases it is supressed by paramagnetism & ferromagnetism.

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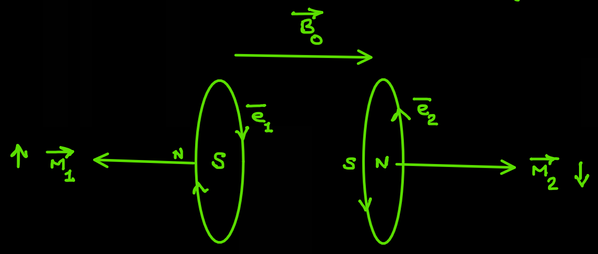
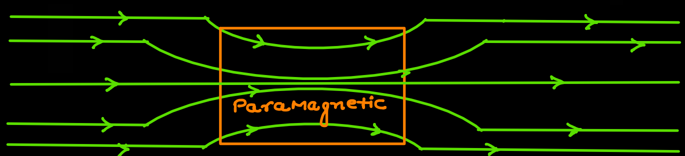


Eg: Bi, Cu, Pb, Si, N_2 (at STP), H_2O, NaCl etc.

when a diamagnetic substance is cooled upto very low temperature it achieves perfect diamagnetism & superconductivity too. in this case $\chi = -1$ & $\mu_r = 0$. This is called "Meissner Effect."

2) <u>Paramagnetism</u>:→ These are the materials which have a tendency to move from the weaker to the stronger field when kept in an external non-uniform magnetic field.
when they are brought near any magnet. they are weakly attracted towards the magnet.



Paramagnetic materials slightly posses some magnetic moment when at low temperature, sufficient magnetising field is applied individual magnetic dipole get aligned along the field & the material acquires a net magnetic moment.
when a piece of paramagnetic substance is kept in an external field, the field it get enhanced.

Eg: Al, Na, Ca, O_2 (at STP), CuCl etc.

Experimentally it is found that magnetisation of paramagnetic substance is inversely proportional to their absolute temperature.

ie; $\downarrow \chi_{para} \propto \frac{1}{T} \uparrow$

$$\Rightarrow \boxed{\chi_{para} = \frac{\mu_0 \cdot C}{T}} \longrightarrow (*)$$

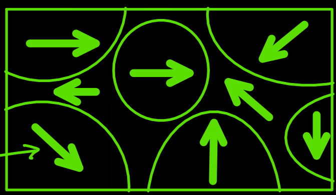
here; C = curie's const.

<u>Ferro-magnetism</u>:→ Ferromagnetic substances are those who get strongly magnetised in the same direction of the applied field. They move rapidly from the weaker to the stronger field when kept in a non-uniform magnetic field.
The individual atoms, ions or molecules in a ferromagnetic material have a dipole moment as in a paramagnetic substance. However they interact with each other in such a way that they spontaneously align themselves in a common direction over a macroscopic volume called "Domain". Each domain has a net magnetisation its size is approx $1\,mm^3$ & contains approx 10^{11} atoms. Without the external magnetising field their individual

"Domain". Each domain has a net magnetisation its size is approx $1\,mm^3$ & contains approx 10^{11} atoms. Without the external magnetising field their individual magnetisation varies from domain to domain hence their is not net magnetisation.

As we apply external magnetic field $\vec{B_0}$, the domains orient themselves along $\vec{B_0}$ & hence they grow is size hence magnetisation increases upto large extent.

$\vec{B_0} = 0$

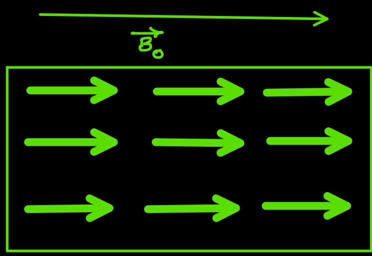


Domains

i) unmagnetised ferro-magnetic Materials

(Randomly aligned Domains)

$\vec{B_0}$



ii) Magnetised ferromagnetic Material

(aligned Domains)

In ferromagnetic materials magnetic field lines become highly concentrated. Even after removal of the external magnetising field, magnetisation persists in the material, such materials are called hard ferro-magnet. ALNICO, an alloy of Fe, AL, Ni, Co & Cu & Loadstone are such materials. They are used to called permanent magnets. On the other hand some ferromagnetic materials become completely demagnetised after removal of external magnetising field, such materials are called "Soft Ferromagnets" like soft iron.

Some ferro-magnetic materials are;

Fe, Co, Ni, Al, Gd etc.

Ferromagnetism depends upon temperature, at a sufficiently high temperature a ferromagnetic substance becomes paramagnetic. At high temperature domains disintegrates. The temperature at which the ferromagnetic substance becomes paramagnetic is called "Curie's temperature."

susceptibility of a ferromagnetic substance when it gains paramagnetism above curie's temperature.

$$\boxed{\chi = \frac{C}{T - T_C}} \quad (\text{here } T > T_C)$$

Magnetic Hysteresis:→

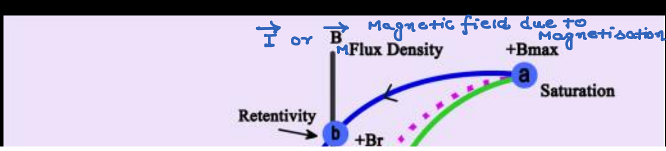
Ferromagnetic Materials when once get magnetised do not easily get demagnetised, this defect of ferromagnetic Materials is called "Magnetic Hysteresis."

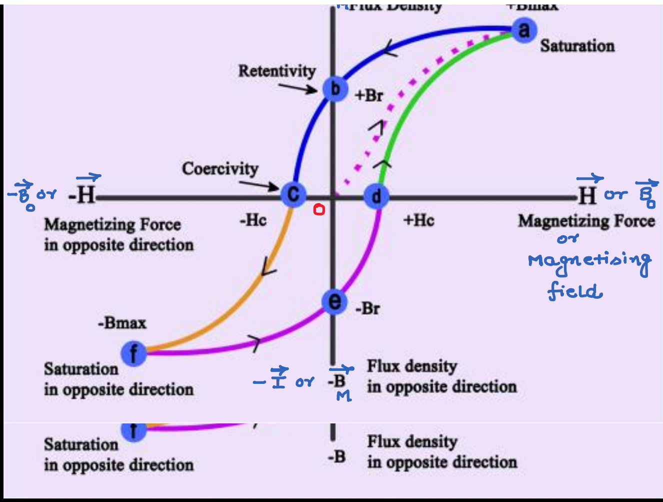
Considering a ferromagnetic core which initially do not posses any magnetisation is placed inside a solenoid & the current is increased which induces a magnetising field on the axis, the core get magnetised & the magnetisation of the core reaches to a saturated value ie B_{Max}. This is the stage when no further enhancement of the domains is possible. It becomes pointless to increase the magnetising field by increasing the current at this stage. (oa section of graph)

Now if we decrease the current to zero ie complete removal of the magnetising field, some residual magnetisa-

ob & oe = Retentivity

oc & od = coercivity





Now if we decrease the current to zero ie complete removal of the magnetising field, some residual magnetisation remain left in the substance (section ab) & the core attains a permanent magnetisation called "Retentivity" (ob).

To completely demagnetise the substance an opposite magnetising field must be applied (section bc). the opposite Magnetising field required to completely demagnetise the substance is called "coercivity" (oc)

As the reverse current is increased the magnetising field also increases in the opposite direction & the substance achieves max. magnetisation in the opposite direction (Section cf).

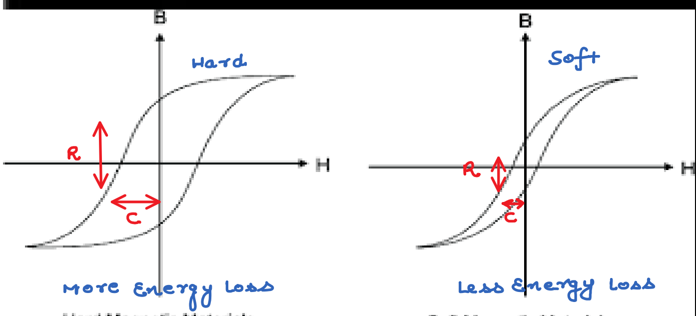
The cycle repeats itself again during the process of demagnetisation from this stage. The Graph b/w $\vec{B_M}$ vs $\vec{B_0}$ or $\vec{I}$ vs $\vec{H}$ found is called "Hysteresis loop".

Imp. Notes

1) slope of the tangent drawn at any point on Hysteresys loop is the susceptibility of the substance.

$$\boxed{\chi = \frac{dB_M}{dB_0} \text{ or } \frac{dI}{dH}}$$

2) Area enclosed by a hysteresis loop gives energy lost per cycle.



Hard Magnetic Materials

Soft Magnetic Materials

3) for Hard ferromagnets both retentivity & coercivity are high.

4) for soft ferromagnets both retentivity & coercivity are Low.

5) Soft ferromagnets are preferred to make cores of solenoids, toroids, Galvanometers, Transformers etc.