Types of Ferromagnetic Materials.

① **Hard ferromagnetic materials**: A ferromag. material which is not demagnetised easily is called hard ferromag. material. In a hard ferromag. material, magnetism remains even when the external magnetic field is removed. For ex: load stone, alnico etc. are hard ferromag. materials.
A compass needle is formed from hard ferromag. material.
A hard ferromag. material is used to make permanent magnets.

② **Soft ferromagnetic materials**: A ferromag. material which is demagnetised easily is called soft ferromag. material. A soft ferromag. material is demagnetised as soon as the external mag. field is removed. For ex: → Iron is a soft ferromag. material. Soft ferromag. materials are used to make the cores of transformers, electromagnets, magnetic tapes and computer disks.

* Curie's law for transition from Ferromagnetism to paramagnetism

The ferromag. property depends on temp. When a ferromag. material is heated, its magnetisation decreases gradually with rise in temp. At a particular ~~point~~ temp, ferromag. material changes over to paramag. material. This is because the domain structure disintegrates with rise in temp. The temp of transition from ferromagnetism to paramagnetism is called the "Curie temperature". It is different for different ferromag. materials.

Curie temp of some ferromagnetic materials

Material	Curie temperature
Cobalt	1394 K
Iron	1043 K
Fe_2O_3	893 K
Nickel	631 K
Gadolinium	317 K

T_c

Imp

* In case of ferromagnetic substance, mag. susceptibility is related to its absolute temp T as

$$\boxed{\chi_m = \frac{C}{T - T_c}}$$

where $T > T_c$
$C \rightarrow$ Curie's constant
$T_c \rightarrow$ Curie temp of the given material (material dependent – See table)

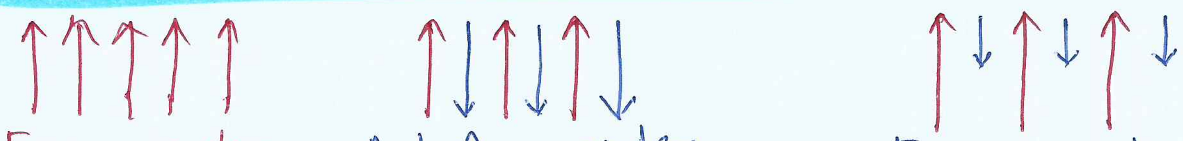
* When a given ferromag. material is heated, its temp rises (T rises). When T of that material becomes $> T_c$ of the given material, the material behaves like a paramagnetic material.

* Example: Iron: $T_c = 1043\,K$, when T of Iron $< 1043\,K$ → Iron behaves as ferromag. material in presence of external field.
when T of Iron $> 1043\,K$ → Iron behaves as paramag. material.

Info only

Ferromagnetism / Anti-ferromagnetism / Ferrimagnetism.

The interaction due to exchange forces produce large internal fields and the neighbouring magnetic dipoles (i.e. atoms) tend to align in the same direction, giving rise to ferromagnetism as shown below (Fig A)



Ferromagnetism fig (A) | Anti-ferromagnetism fig (B) | Ferrimagnetism Fig (C)

However, if the distance betw the interacting atoms (i.e. dipoles) is very small, then the exchange forces produce a tendency in the dipoles to align in antiparallel direction, giving rise to anti-ferromagnetism (fig B). MnO shows antiferromagnetism.

The materials in which the mag. moments of two neighbouring sublattices are of ~~a~~ unequal magnitude and are aligned in antiparallel direction due to mutual interaction show "ferrimagnetism" (fig c). They are also called Ferrites

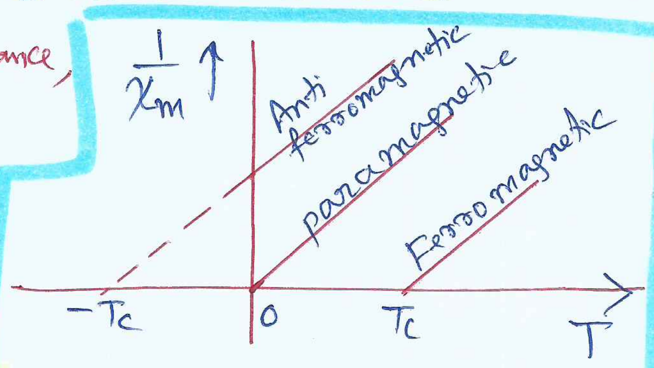
The chemical formula ~~for~~ a ferrite is xy_2z_4, where x is ~~+~~ a divalent -ve ion, 'y' is Fe^{3+} and z is the divalent oxygen ion O^{2-}.

Example of ferrite is magnetite (Fe_3O_4 or $Fe^{2+}Fe_2^{3+}O_4^{2-}$).

Ferrites are used as core materials in transformers.

* In ~~as~~ case of antiferromag. substance, χ_m is related to T as

$$\chi_m = \frac{C}{T+T_c}$$



* Variation of $(1/\chi_m)$ with T of the paramagnetic, ferromagnetic and anti-ferromagnetic substances is shown above.

NCERT

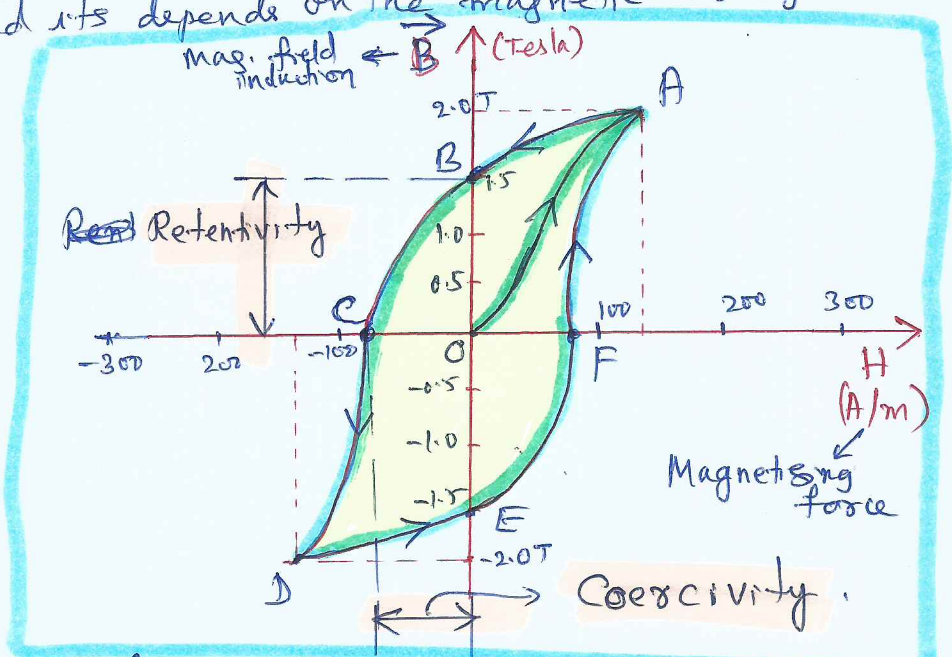
IMP

The magnetic Hysteresis loop (B-H curve for Ferromagnetic materials) (Retentivity and coercivity)

The relation betⁿ $\vec{B}$ and $\vec{H}$ in ferromagnetic materials is complex. It is often not linear and its depends on the magnetic history of the sample.

(Note: fig. is plot of $\vec{B}$ Vs $\vec{H}$. The shape of $\vec{M}$ Vs $\vec{H}$ is also identical for a given material)

The curve OABCDEFA depicts the behaviour of a given material as it is taken thro' a cycle of magnetisation. ~~and~~



- Suppose the ferromag. material (say iron core) is unmagnetised initially. $\Rightarrow$ $\vec{B}=0$, and $\vec{H}=0$. (This state is represented by origin O). Place the material in a solenoid and increase the current thro' the solenoid gradually. $\Rightarrow$ we are gradually increasing $\vec{H}$, then we observe $\vec{B}$ also increasing and saturates as depicted by curve OA. This behaviour represents alignment and merger of the domains of ferromag. material until no further enhancement ~~is possible~~ in $\vec{B}$ is possible. Therefore, there is no use of increasing solenoid current (hence $\vec{H}$) beyond this.

⊙ Next, we decrease the solenoid current (hence $\vec{H}$) till it reduces to zero. The curve follows AB, showing that when $\vec{H}=0$, $\vec{B}\neq 0$. Therefore, some magnetism is left in the specimen.

⊙ The value of $\vec{B}$ at $H=0$ is called ~~Ret~~ Retentivity or Remanence or "Residual magnetism" of the material. In fig, $B_r \simeq 1.5$ T, where subscript 'r' represents Retentivity. $\Rightarrow$ This shows the domains are not completely randomised even when the magnetising force $\vec{H}$ is removed.

~~⊙ Next, the current in the solenoid is~~ reversed ~~and increased slowly~~ ~~decreased~~, hence H ~~decreasing, $\vec{B}$ also decreases~~

⊙ Next the current in the solenoid is reversed and increased slowly, so that $\vec{H}$ acts in the opposite direction (say along -ve x-axis). Certain domains in the ferromagnetic material are flipped until the residual mag. field $\vec{B}$ in the specimen is reduced to zero. This is represented by curve BC

P.T.O →

Contd. from pre. page

- It means to reduce the residual magnetism (or retentivity) of the specimen to zero, we have to apply a magnetising force $\vec{H}$ (value OC) in the opposite direction. This value of magnetising force $\vec{H}$ is called "Coercivity" of the material.
  ∴ H = OC (See fig) needed to completely demagnetise the material is known as "Coercivity" of the material.
- As the reverse current in solenoid is increased in magnitude, we once again obtain saturation in the reverse direction at D. The variation is represented by curve CD.
- Next, the solenoid current is reduced → curve DE
- Further, the solenoid current is reversed and increased → curve EA.

→ The cycle repeats itself

→ From figure, Retentivity of the material $(\vec{B}) = 1.5\,T$ and Coercivity ~~~ $(\vec{H}) = -90\ A m^{-1}$

→ Note that initial curve OA will never get retraced again (by the above procedure) for that specimen. So, this specimen after undergoing this process keeps the history of its magnetic property.

→ It is clear that when a specimen of a mag. material is taken thro' a cycle of magnetisation, the magnetic flux density $\vec{B}$ (and also Intensity of magnetisation $\vec{M}$) lag behind the magnetising force $\vec{H}$. Thus, even if the magnetising force $\vec{H}$ is made zero, the values of $\vec{B}$ and $\vec{M}$ do not reduce to zero

⇒ the specimen tends to retain the magnetic properties.

Imp
- The phenomenon of lagging of $\vec{B}$ or $\vec{M}$ behind $\vec{H}$ when a specimen of a magnetic material is subjected to a cycle of magnetisation is called "Hysteresis".

OR (The phenomenon of lagging of Magnetic flux density $\vec{B}$ (or intensity of Magnetisation $\vec{M}$) behind the magnetising force $\vec{H}$ when a specimen of a mag. material is subjected to a cycle of magnetisation is called "Hysteresis".

- The closed curve ABCDEFA which represents a cycle of magnetisation of the substance is known as "Hysteresis curve" (or Hysteresis loop) of the substance. On repeating the process, the same closed curve ABCDEFA is traced again but the portion OA is never obtained.

P.T.O →

Contd. from pre. page.

From figure, we make the following observations:

(i) For a given value of $\vec{H}$; value of $\vec{B}$ (or $\vec{M}$) is not unique, but depends on previous history of the sample.

(ii) No segment OA, AB etc of the hysteresis curve is linear. Therefore, $\vec{B}$ or $\vec{M}$ is not proportional to $\vec{H}$ over any appreciable range.

Energy Dissipation due to Hysteresis (Hysteresis Loss)

We know that $BH = B\left(\frac{B}{\mu}\right) = \frac{B^2}{\mu_0 \mu_r}$ → has the dimensions of energy per unit volume. ∴ Area of B-H hysteresis loop represents energy dissipated per unit volume ~~of~~ in the material.

→ When a mag. material is taken thro' a cycle of magnetisation, some energy is spent in the process. The energy cannot be recovered and is dissipated as heat in the specimen. In fact, when a specimen is taken thro' a cycle of magnetisation, the molecular magnets (magnetic dipoles) in the specimen are oriented and reoriented time and again. This molecular motion within the specimen results in the production of heat.

→ It can be shown that the loss of energy per unit volume of specimen per cycle of magnetisation is equal to the area of B-H loop (in SI system) and equal to the area of M-H loop in CGS system.

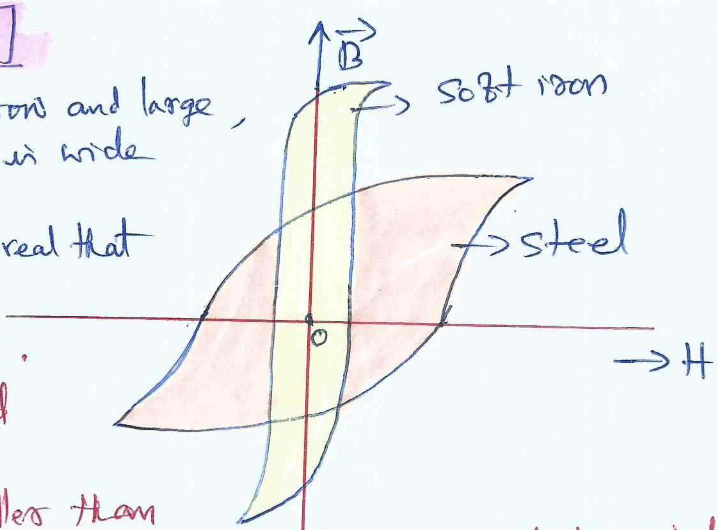
→ The exact shape and size of B-H (or M-H) loops depend on the nature of the material and history of the specimen.

→ ~~By studying~~ On just seeing B-H loops of various ferromag. materials, we can select the one which gives minimum hysteresis loss when put to a cycle of magnetisation.

→ By studying hysteresis loops of various mag. materials, we can study the difference in their properties → e.g. retentivity, coercivity, permeability, susceptibility and energy loss etc... Such studies enable us to select suitable materials for different applications — e.g. for electromagnets, for transformer cores, for permanent magnets etc...

Example :

- Hysteresis loop for "soft iron" is narrow and large, whereas the hysteresis loop for "steel" is wide and short.
- The hysteresis loops of soft iron & steel reveal that



(i) The Retentivity of soft iron is greater than the retentivity of steel.

(ii) soft iron more strongly magnetised than steel.

(iii) Coercivity of soft iron is smaller than that of steel. ⟹ soft iron loses its magnetism more rapidly than steel does.

(iv) → permeability of soft iron > that of steel.

(v) Area of B-H loop for soft iron < area of B-H loop for steel.
⟹ hysteresis loss in case of soft iron < that of steel.

Info only

Hysteresis loss (Nootan book). Only FYI

→ A ferromagnetic substance consists of local regions called "domains", each of which is spontaneously magnetised. In an unmagnetised substance, the directions of magnetisation in different domains are different so that, on an average, the resultant magnetization is zero.

→ When we magnetise the substance by placing it in an external magnetising field ($\vec{H}$), then those domains which are favourably oriented w.r.t. the external field grow in size, and also each domain rotates so that its direction of magnetisation becomes aligned with the field direction. During this process, the energy is taken by the substance.

→ When the external field is removed, the domain boundaries do not move completely back to their original positions ⇒ the substance retains some magnetisation (hysteresis effect)

→ Therefore, the energy supplied to the substance during magnetisation is not fully recovered. The balance energy left in the substance is lost as heat. This is called "hysteresis loss".

→ It can be proved that the energy lost per unit volume of a substance in a complete cycle of magnetisation is equal to the area of the hysteresis loop (B-H loop).

→ This knowledge has practical applications. On seeing the B-H loops of various ferromagnetic materials, we can select the one which gives minimum hysteresis loss when put to a cycle of magnetization. This material will be most suitable for constructing the cores of the transformers and the armature of dynamos and motors.

→ Besides this, an idea of the other magnetic properties of the material such as retentivity and coercivity can be obtained from the hysteresis curve. This helps us in selecting the proper magnetic material for a particular purpose.

NCERT

Uses of Ferromagnetic Materials

→ (1) permanent magnets
(2) Electromagnets

Important properties of ferromagnetic materials mentioned below help us in the proper selection of materials for various applications.

→ permeability (μ)
→ Susceptibility (χ_m)
→ Retentivity (B_r)
→ Coercivity (H_c)
→ Energy loss (Hysteresis loops)

(1) permanent magnets:

The substances which retain their ferromagnetic properties for a long time at room temp^re are called permanent Magnets.

The material chosen should have

(i) High ~~permeability~~ Retentivity (B_r) so that the magnet is strong.

(ii) High Coercivity (H_c) so that the magnetisation is not wiped out by stray external magnetic fields, mechanical ill-treatment and temp^r changes.

(iii) High permeability (μ) so that it can be easily magnetised.

(iv) → The hysteresis loss is immaterial in this case because the material is never put to cyclic changes of magnetisation.

From these considerations permanent magnets are made of "steel". Though ~~Ret~~ ~~Rt~~ Retentivity (B_r) of steel is slightly smaller than that of "soft iron", ~~yet its "coercivity" (H_c)~~ but its (steel's) coercivity outweighs much smaller coercivity of soft iron.

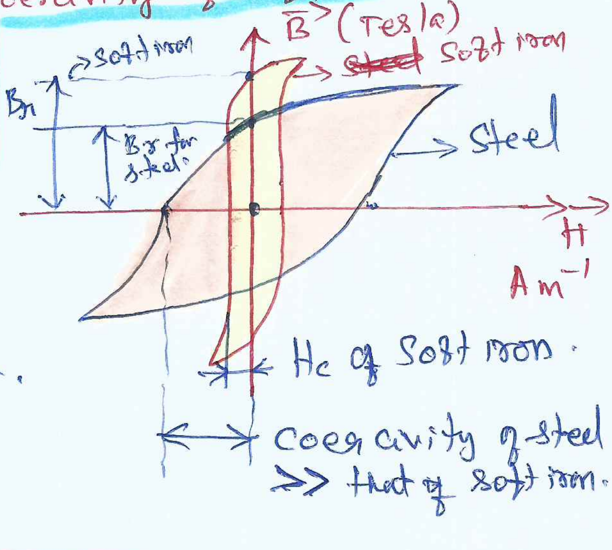
From figure, it is clear that

$(B_r)_{steel} < (B_r)_{soft\ iron}$, however

$(H_c)_{steel} \gg (H_c)_{soft\ iron}$ →

⟹ Soft iron is very easy to demagnetise by stray ~~fields~~ weak ~~fields~~ mag. fields, temp^r variation and mechanical ill-treatment.

→ ∴ Steel is preferred for making permanent magnets.

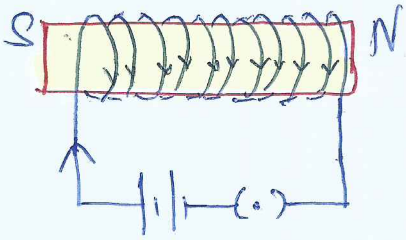


Many alloys are also used to make Permanent magnets.

(i) cobalt steel → It contains cobalt, tungsten, carbon, iron
(ii) Alnico → It contains Aluminium, nickel, cobalt, Cu, iron. It is brittle.
(iii) Ticonal → It contains tin, cobalt, nickel and aluminium.

An efficient way to make a permanent magnet is to place a ferromag. rod in a solenoid and pass current through the solenoid. The magnetic field inside of the solenoid magnetises the rod.

Electromagnets:



Core of electromagnets are made of ferromagnetic materials, which have "high permeability" (or high susceptibility) specially at low magnetising force ($\vec{H}$) and "a low retentivity".

→ Soft iron is a suitable material for ~~this purpose~~ electromagnets.

→ When a soft iron rod is placed in a solenoid and current is passed through the solenoid, the magnetism of the solenoid is increased by a thousand fold. This increased magnetic strength due to soft iron rod will help in producing a much stronger electromagnet in lesser time.

~~when we switch off solenoid current, the magnetism of soft iron core is effectively switched off since the soft iron core has a very low retentivity (Hc)~~

→ When the solenoid current is switched off, the magnetism in soft iron core is removed instantly as coercivity (Hc) of soft iron is very low.

→ Briefly, when current in a solenoid is switched on, the soft iron rod placed inside it is magnetised at once. On the other hand, as soon as current in the solenoid is switched off, soft iron ceases to be a magnet.

IMP

* Material for making electromagnets should have
(i) High permeability (or high susceptibility) → to magnetize quickly
(ii) Low coercivity → to demagnetise quickly
(iii) Low Retentivity → Although "soft iron" has little high retentivity than steel, however very low coercivity of soft iron outweighs its little high retentivity than steel.

Cores of Generators, motors, transformers and telephone diaphragms are magnetised and demagnetised number of times, when AC flows thro' them. The material must therefore have a low hysteresis loss to have less dissipation of energy and hence a small heating of the material (otherwise the insulation of windings may break), a high permeability (to obtain a large flux density at low fields) and a high specific resistance (to reduce eddy current losses).

→ Soft iron is used for making these equipments.

→ More effective alloys have now been developed for transformer cores. They are permalloys, ~~m~~ mumetals etc ....

→ Electromagnets are used in electric bells, loudspeakers and telephone diaphragms, circuit breakers, relays, motor brakes.

→ Giant electromagnets are used ~~&~~ in cranes to lift machinery ~~etc~~ and bulk quantities of iron and steel.

Factors deciding the strength of an "electromagnet"

- As the strength of mag. field around a current-carrying wire is ∝ to the current in the wire, therefore, strength of an electromagnet is also dependent on current flowing thro' the coil. The mag. field produced by each loop of the coil is same as that produced by any other loop. As these fields ~~are in the~~ of the loop are in the same direction, increasing the number of loops in an electromagnet increases ~~the strength~~ its ~~&~~ strength.
- Further, the strength of an electromagnet can be increased by placing an iron rod or core inside the coil (solenoid). The field inside the solenoid magnetizes the core by induction.
- Therefore, the mag. strength of the core adds to that of the ~~co~~ coil to produce a much stronger electromagnet.

→ Hence, we conconclude that the factors deciding the strength of electromagnet are → Strong fields are required for strong electromagnets.

(i) No of loops in the coil (solenoid)

(ii) Strength of current passed → Magnetic field in a solenoid $B = \mu_0 n I$ depends on current. So high $\vec{B}$ is needed to produce strong electromagnets, which is achieved by large current thro' solenoid.

(iii) Nature of the core of electromagnet (Nature of material) → Soft iron is best suited for making electromagnets. Material should have thin & long hysteresis loop (to have low coercivity and low hysteresis loss). Material should have high permeability (μ) so that the material can be magnetised quickly when placed in the magnetizing field. → high ~~permeability also~~ susceptibility (χ_m) also leads to quicker magnetisation. Better to high low ~~reten~~ retentivity so that it can be demagnetised by opposite lower magnetic fields.

SI units and Dimensional formulae of some Physical quantities.

Quantity	Symbol	Dimensional formula	SI unit
Magnetic Dipole moment	m	$[M^0L^2T^0I]$	$A\,m^2$ or $J\,T^{-1}$
pole strength	q_m	$[M^0L^1T^0I]$	$A\,m$
Horizontal component of magnetic field of earth	B_H	$[M^1L^0T^{-2}I^{-1}]$	Tesla (T)
Intensity of Magnetization	M	$[M^0L^{-1}T^0I]$	$A\,m^{-1}$
Intensity of Magnetizing field	H	$[M^0L^{-1}T^0I]$	$A\,m^{-1}$
permeability	μ	$[MLT^{-2}I^{-2}]$	$T\,A\,m^{-1}$
Susceptibility	χ_m	[no dimension]	~~no~~ no unit.

Electromagnet: One of the applications of the magnetic effects of electric current is the electromagnet. We have read that a current-carrying solenoid behaves like a bar magnet (fig A). If we place a soft iron rod in the solenoid, the magnetism of the solenoid increases thousand times (Fig B). Then the solenoid is called an "electromagnet". It is a temporary magnet.

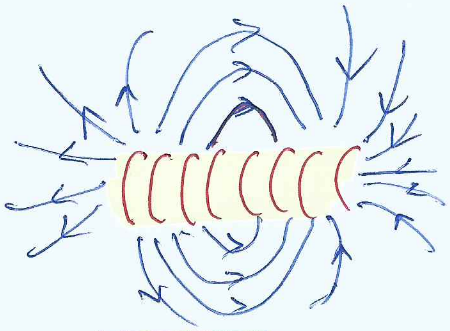


Fig A

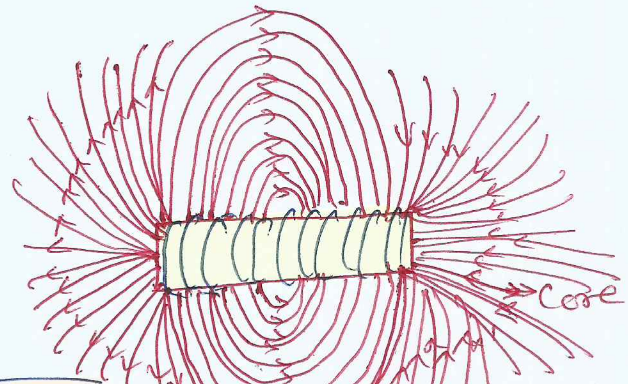


Fig B

An electromagnet is made by winding closely a number of turns of insulated copper wire over a soft-iron straight core (Fig C) or a horse-shoe rod (Fig D). On passing current thro' this solenoid, a mag. field is produced in the space within the solenoid. As a result, the domains in the iron-rod rotate and aligned so that the direction of their magnetisation coincides with the direction of the mag. field within the solenoid. So the rod becomes a magnet. On switching the current in the solenoid off, the rod is almost completely demagnetised.

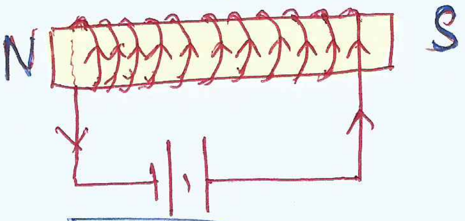


Fig C

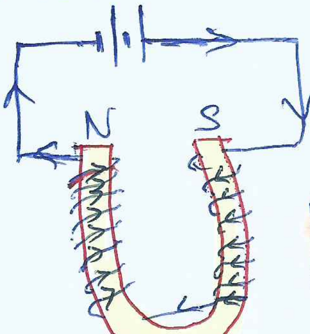
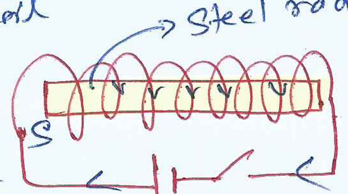


Fig D

The wires on the arms of the horse-shoe rod is so wound that current in the wire on the two arms be in opposite directions.

The end of the rod, looking towards which, the current in the solenoid appears anticlockwise, is the north pole N and the is south pole.

Permanent magnets: $\vec{B}$ inside a current-carrying coil is used commercially for making permanent magnets for use in motors, dynamos etc... Permanent bar-magnets of cobalt, steel or alnico can be made by placing a bar in a coil of thick wire and passing a large current (≈ 1000 A) thro' the coil. The current need only be instantaneous because, once the magnetising field is established the time for which it exists has no effect on the intensity of the magnetisation of the bar. A south pole is obtained at that end of the bar in which the current flows clockwise, and a north pole is obtained at the other end.

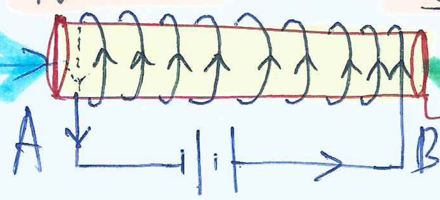


Imp

Identification of N and S poles in a solenoid

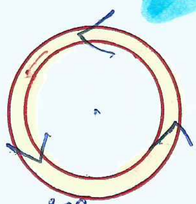
N → how?

S → how?



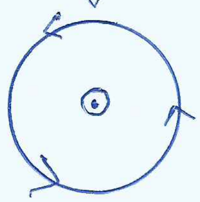
Look at this end and draw side view of what you are seeing

magnetic rod (eg. circular or cylindrical rod)



If you see current in anti-clockwise direction, it is N-pole

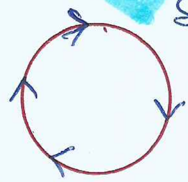
This is like



using Right hand thumb rule, $\vec{B}$ is $\perp^r$ to page and pointing upwards (out of the page)

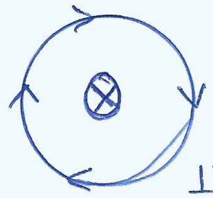
End A of Solenoid is N-pole
End B of Solenoid is S-pole

Side view

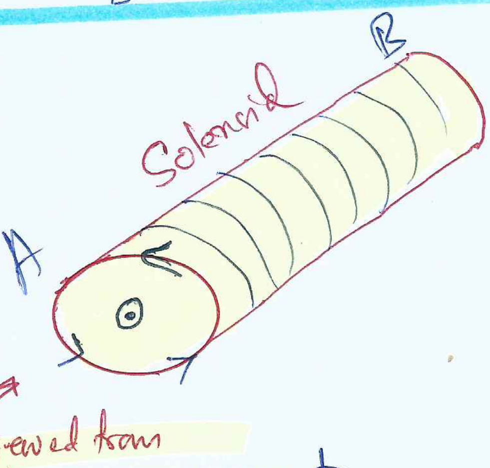


If you see current in clockwise direction, it is S-pole.

This is like

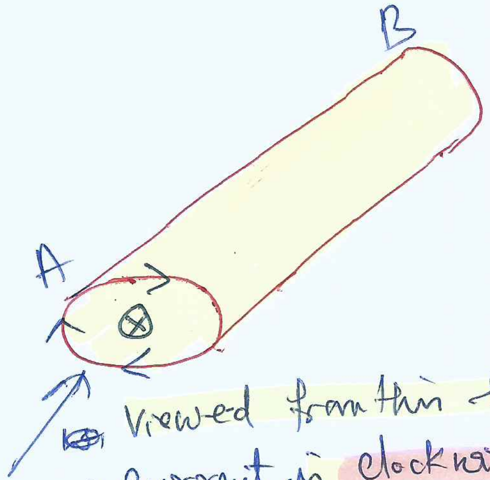


using Right hand thumb rule, $\vec{B}$ is $\perp^r$ to page and pointing downwards (into the page)



viewed from here → current is anti-clockwise.

As per RH thumb rule also,
End A is N-pole
end B is S-pole



Viewed from this side → current is clockwise.

As per RH thumb rule also,
end A is S-pole
end B is N-pole