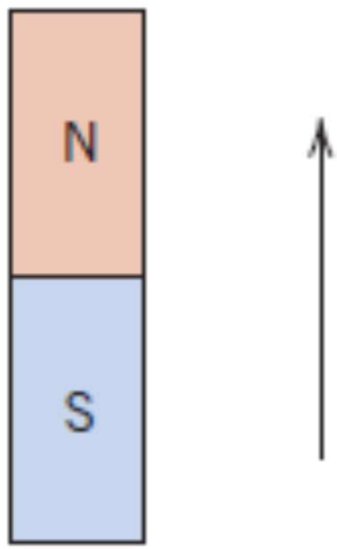
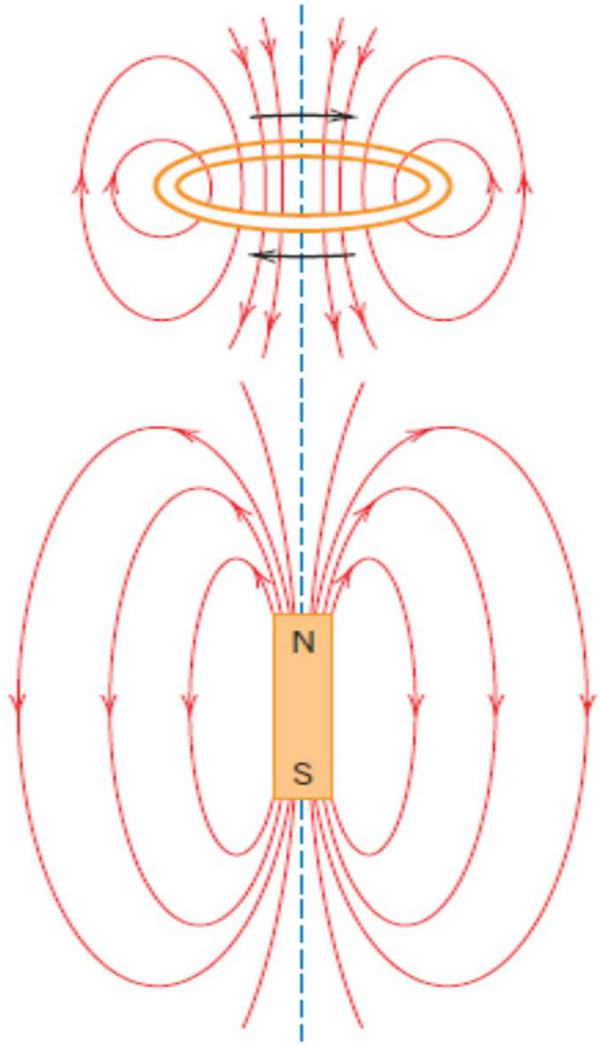
# Magnetic Materials

# Magnetism

Magnetic field around a current carrying conductor and a bar magnet.




Magnetic dipole – analogous to electric dipole



# Terminology and Notation

*H* – Magnetic field strength

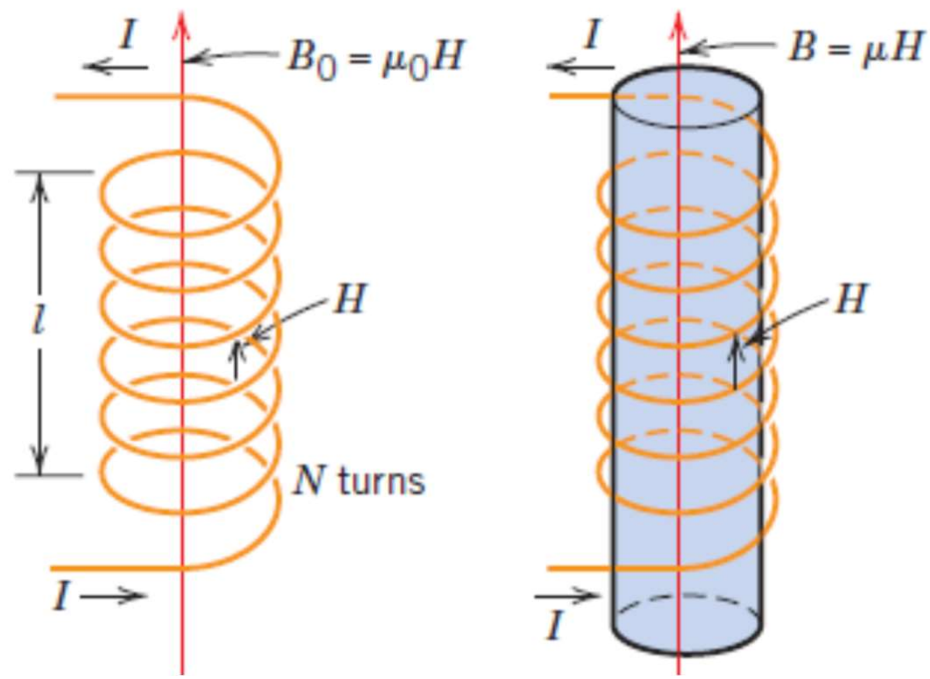
*B* – Magnetic Induction or Magnetic flux density

$$H = \frac{NI}{l}$$

*N* – Number of turns in a coil of length *l*, carrying current *I*.

Magnetic flux density in any medium is given by

$$B = \mu H$$




Where, $\mu$ is permeability of the medium

In vacuum $\mu = \mu_0 = 4\pi \times 10^{-7}$ Wb/(A.m)

# Magnetization (Analogous to Polarization)

$M$ – Magnetization

$$B = \mu_0 H + \mu_0 M$$

$$M = \chi_m H$$

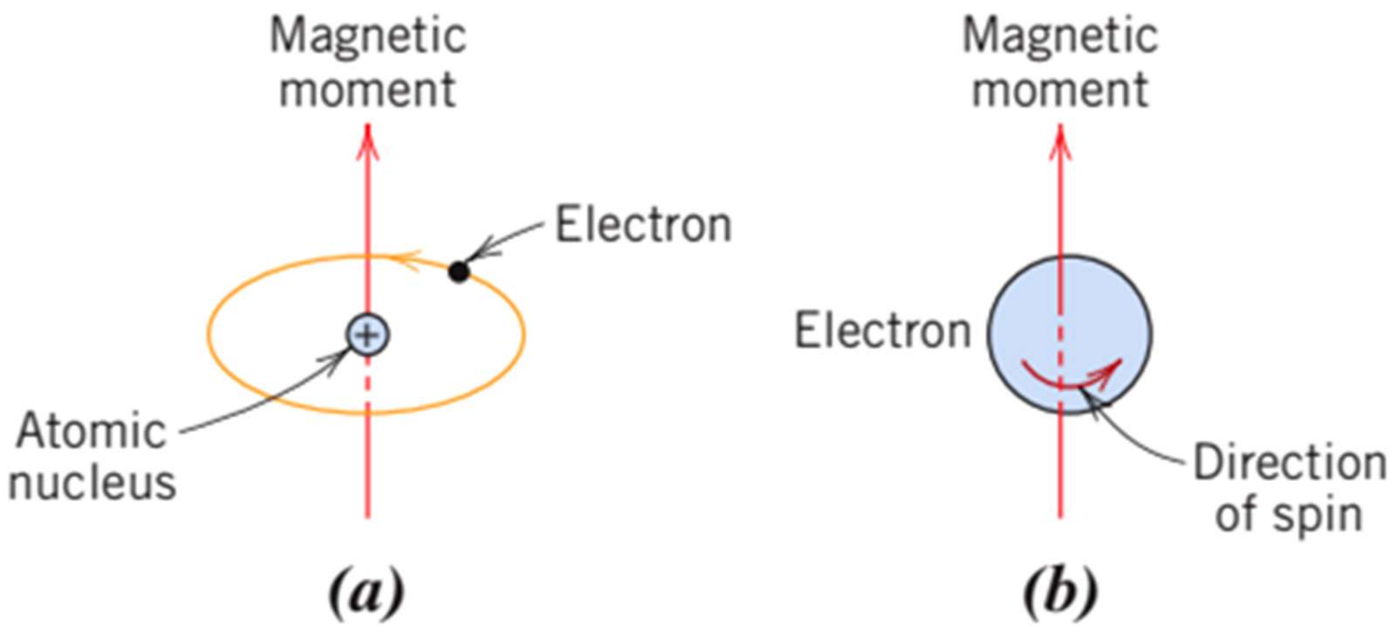
$\chi_m$ – Magnetic susceptibility

$$\chi_m = \mu_r - 1$$

# Magnetic Materials

## Origin of magnetism:

- The macroscopic magnetic properties of materials are a consequence of *magnetic moments* associated with individual electrons.
- Each electron in an atom has magnetic moments that originate from two sources.
- Magnetic moments arise from electron motions and the “spins” on electrons.




Magnetic moment associated with (*a*) an orbiting electron and (*b*) a spinning electron

Net atomic magnetic moment = sum of moments from all electrons.

# Magnetic Materials

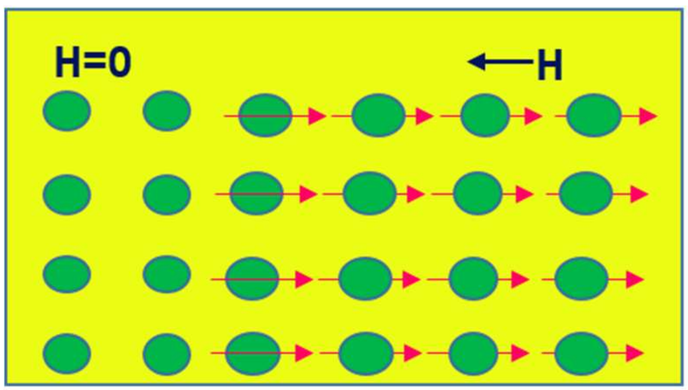
## Classification of materials:

The materials can be classified on the basis of their behavior in a magnetic field into three broad categories

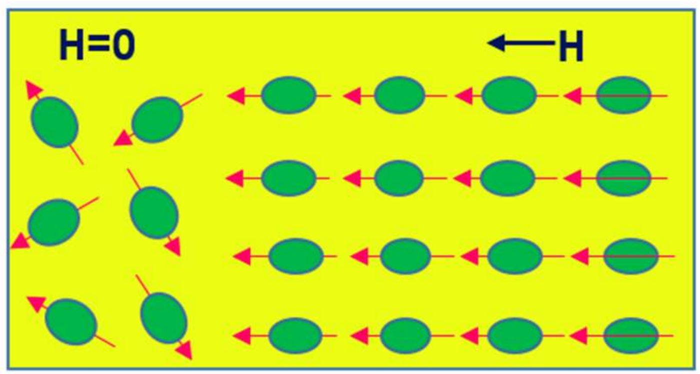
i. Diamagnetic materials

ii. Paramagnetic materials

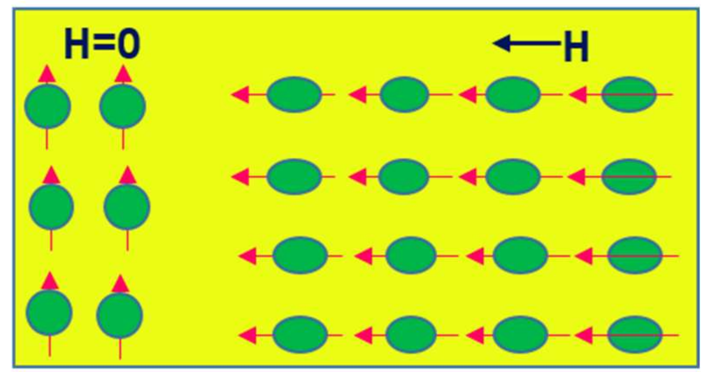
iii. Ferromagnetic materials




Diamagnetisms



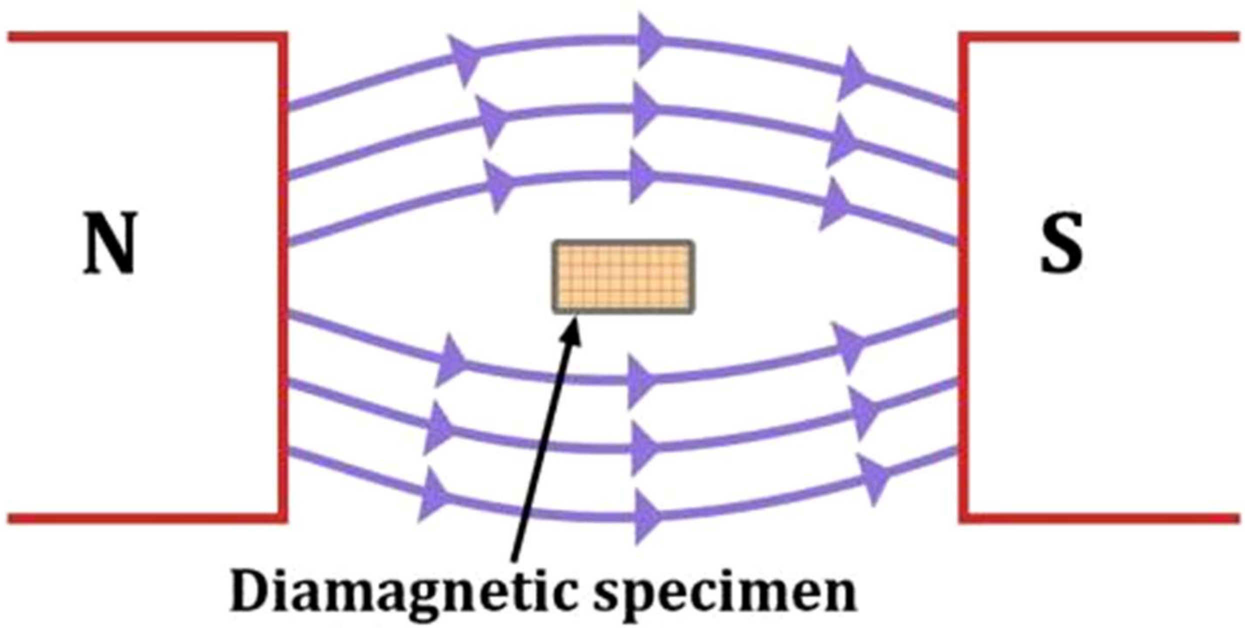

paramagnetisms




Ferromagnetisms

## Diamagnetic substances:

- Diamagnetic substances are those substances which get feebly magnetized in the opposite direction of the magnetizing field.
- Such substances are feebly repelled by magnets and tend to move from stronger to weaker part of the magnetic field.
- Examples of diamagnetic substances are Bismuth, copper, lead, zinc, tin, gold, silicon, nitrogen and silver.

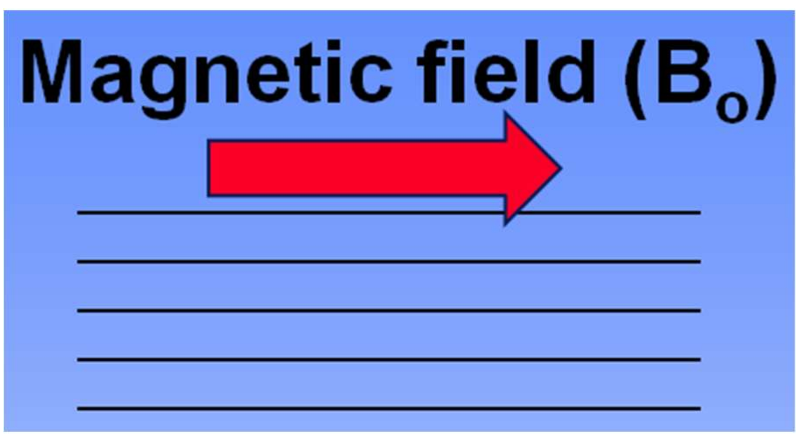


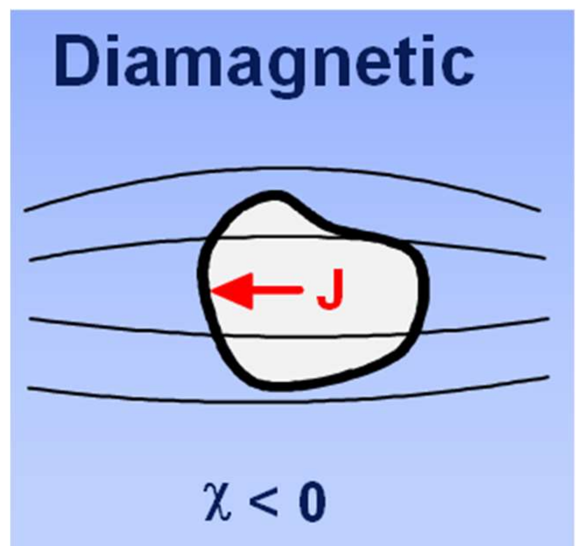
# Magnetic Materials

## Basis of diamagnetism:

- Electrons in an atom orbiting around nucleus possess orbital angular momentum.
- These orbiting electrons are equivalent to current-carrying loop and thus possess orbital magnetic moment.
- Diamagnetic substances are the ones in which resultant magnetic moment in an atom is zero.

- *All substances are diamagnetic*: The strong external magnetic field speeds up or slows down the electrons orbiting in atoms in such a way as to oppose the action of the external field.

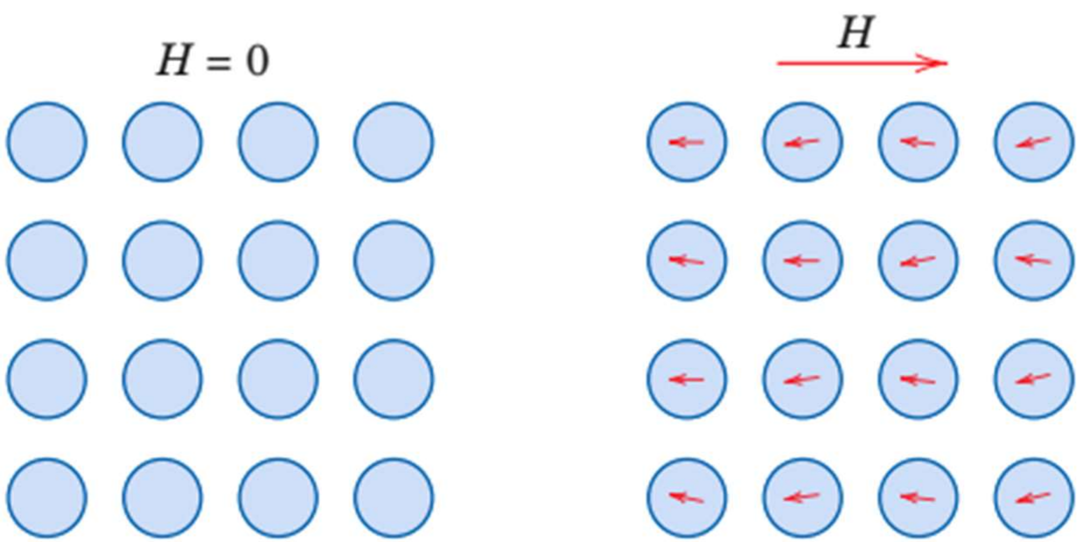


# Magnetic Materials

## Basis of diamagnetism:

- When an external magnetic field is applied, across a diamagnetic material, those electrons having orbital magnetic moment in the same direction slow down and those in the opposite direction speed up.
- This happens due to induced current in accordance with Lenz's law.
- For diamagnetic materials the value of the susceptibility (a measure of the relative amount of induced magnetism) is always negative
- Thus, the substance develops a net magnetic moment in direction opposite to that of the applied field and hence repulsion.

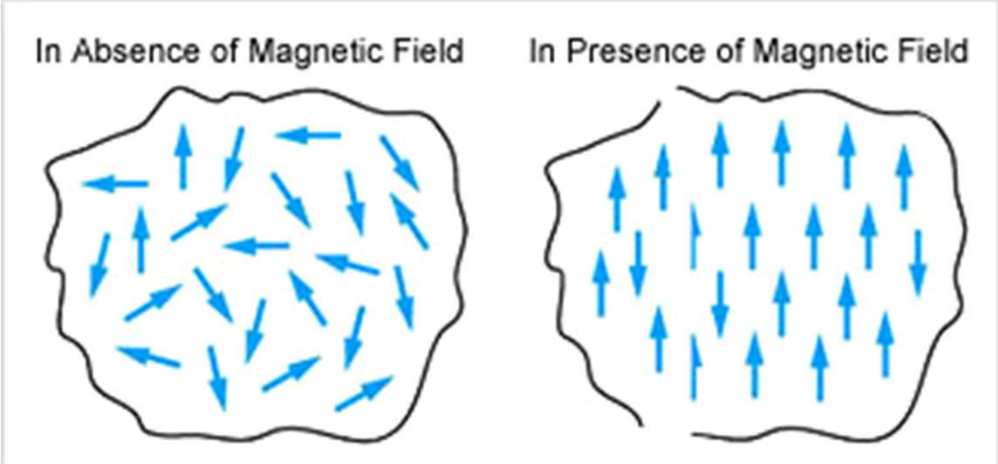



Atomic dipole configuration for a diamagnetic material with and without a magnetic field

# Magnetic Materials

## Paramagnetic substances:

- Paramagnetic substances are those which get weakly magnetized when placed in an external magnetic field.
- They have tendency to move from a region of weak magnetic field to strong magnetic field.
- They get weakly attracted to a magnet.



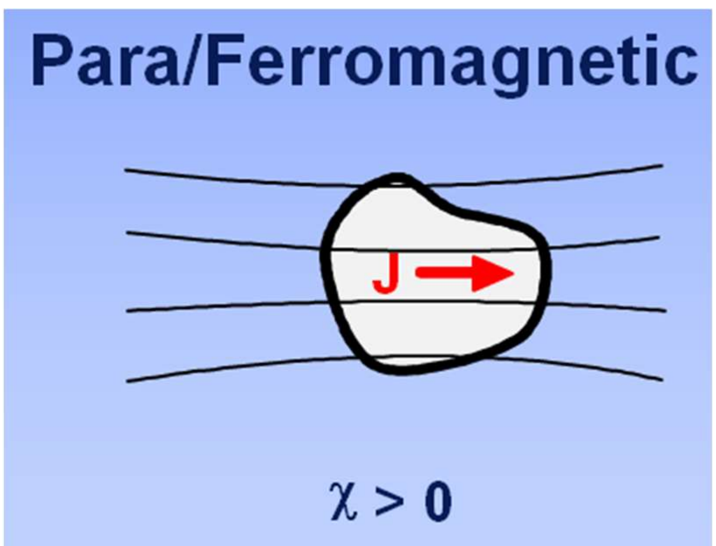
Paramagnetism

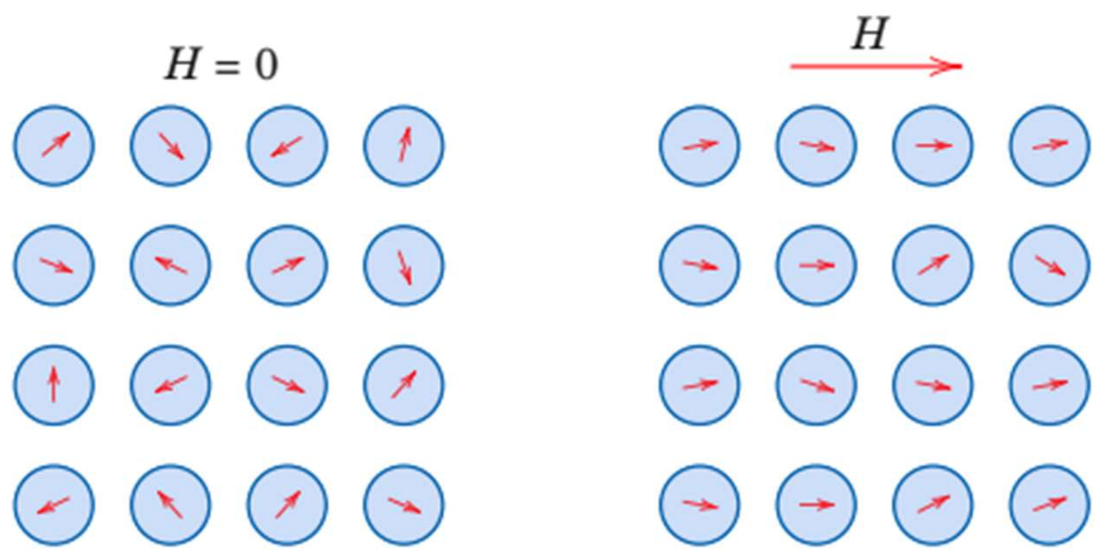
- Some examples of paramagnetic substances are manganese aluminium, chromium, platinum, sodium, copper chloride and oxygen at STP.

# Magnetic Materials

## Basis of Paramagnetism:

- The individual atoms (or ions or molecules) of a paramagnetic material possess a permanent magnetic dipole moment of their own.
- On account of the ceaseless random thermal motion of the atoms, no net magnetization is seen.
- In the presence of an external field, which is strong enough, and at low temperatures, the individual atomic dipole moment can be made to align and point in the same direction as the applied field.




Atomic dipole configuration with and without an external magnetic field for a paramagnetic material

# Magnetic Materials

## Ferromagnetic substances:

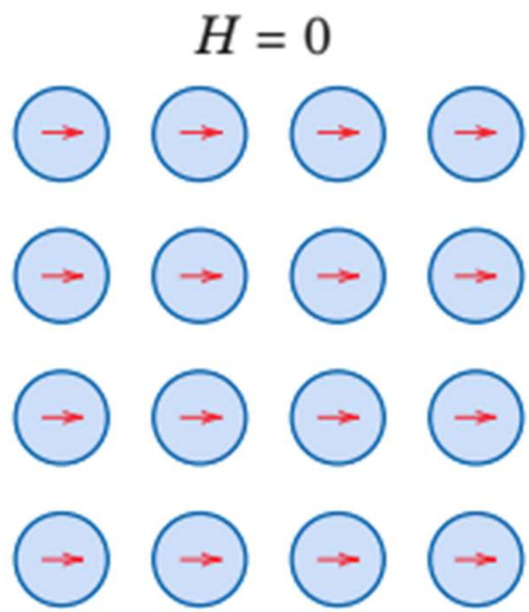
- Both dia- and para-magnetic materials are considered as non-magnetic because they exhibit magnetization only in presence of an external field.
- Ferromagnetic substances are those which get strongly magnetized when placed in an external magnetic field.
- They have tendency to move from a region of weak magnetic field to strong magnetic field.
- They get strongly attracted to a magnet.

- Few examples of ferromagnetic substances are iron, cobalt, nickel and some alloys

# Magnetic Materials

## Cause of ferromagnetism:

- The individual atoms (or ions or molecules) in a ferromagnetic material possess a dipole moment as in a paramagnetic material.
- However, they interact with one another 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.
- Typical domain size is 1 mm and the domain contains about $10^{11}$ atoms.
- In the first instant, the magnetization varies randomly from domain to domain and there is no bulk magnetization.
- When we apply an external magnetic field H, the domains orient themselves in the direction of H and simultaneously the domain oriented in the direction of H grow in size.




Mutual alignment of atomic dipoles for a ferromagnetic material, even in the absence of an external magnetic field

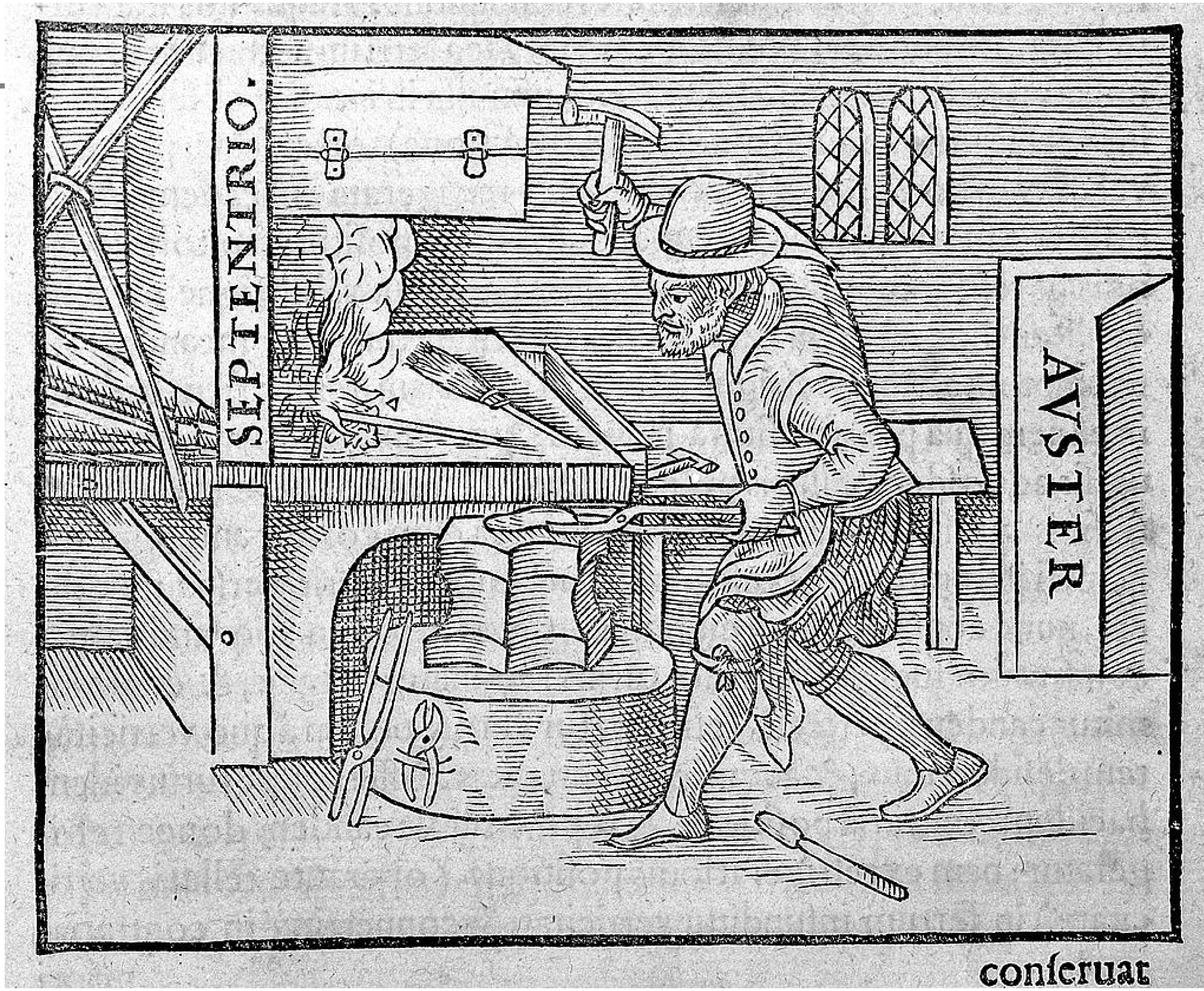
# Magnetic Materials

## Temperature dependence of ferromagnetism:

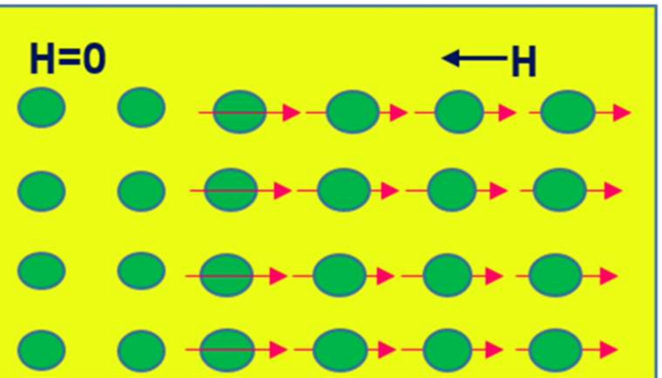
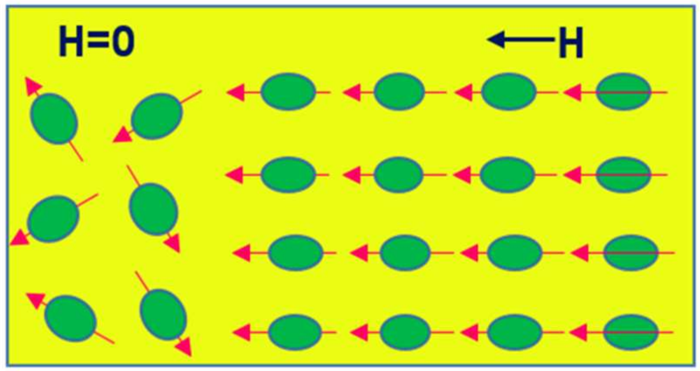
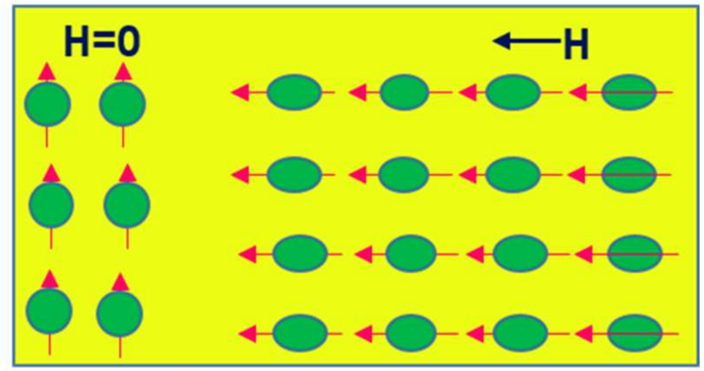
- The ferromagnetic property depends on temperature.
- At high enough temperature, a ferromagnet becomes a paramagnet.
- The domain structure disintegrates with temperature.
- This disappearance of magnetization with temperature is gradual.
- It is a phase transition reminding us of the melting of a solid crystal.
- The temperature of transition from ferromagnetic to paramagnetic is called the Curie Temperature $T_c$.

- The *susceptibility* above the Curie temperature, i.e., in the paramagnetic phase is described by,

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




An illustration from Gilbert's 1600 *De Magnete* showing one of the earliest methods of making a magnet. A blacksmith holds a piece of red-hot iron in a north–south direction and hammers it as it cools. The magnetic field of the Earth aligns the domains, leaving the iron a weak magnet.


H=0
H

H=0
H

H=0
H

# Magnetic Materials

## Differences of dia-, para-, and ferro- magnetic materials:

| *Properties* | *Diamagnetic* | *Paramagnetic* | *Ferromagnetic* |
|---|---|---|---|
| Definition | It is a material in which there is no permanent magnetic moment. | It has permanent magnetic moment. | It has enormous (more) permanent magnetic moment. |
| Spin or magnetic moment or dipole alignment. | No spin alignment. | Random alignment | Parallel and orderly alignment. |
| Behavior | Repulsion of magnetic lines of force from the centre of the material. | Attraction of magnetic lines towards the centre. | Heavy attraction of lines of force towards the centre. |
| Magnetized direction | Opposite to the External magnetic field. | Same direction as the External magnetic field. | Same direction as the External magnetic field. |
| Permeability | It is very less | It is high | It is very high |
| Relativity permeability | $\mu_r < 1$ | $\mu_r > 1$ | $\mu_r >> 1$ |
| Susceptibility | Negative | Low positive | High positive |

# Magnetic Materials

## Sub-classes of ferromagnetism:

Ferromagnets are very strong; dipoles line-up permanently upon application of external field.

It has two sub-classes:

- **Anti- Ferromagnetism:**
- **Ferri-magnetism:**

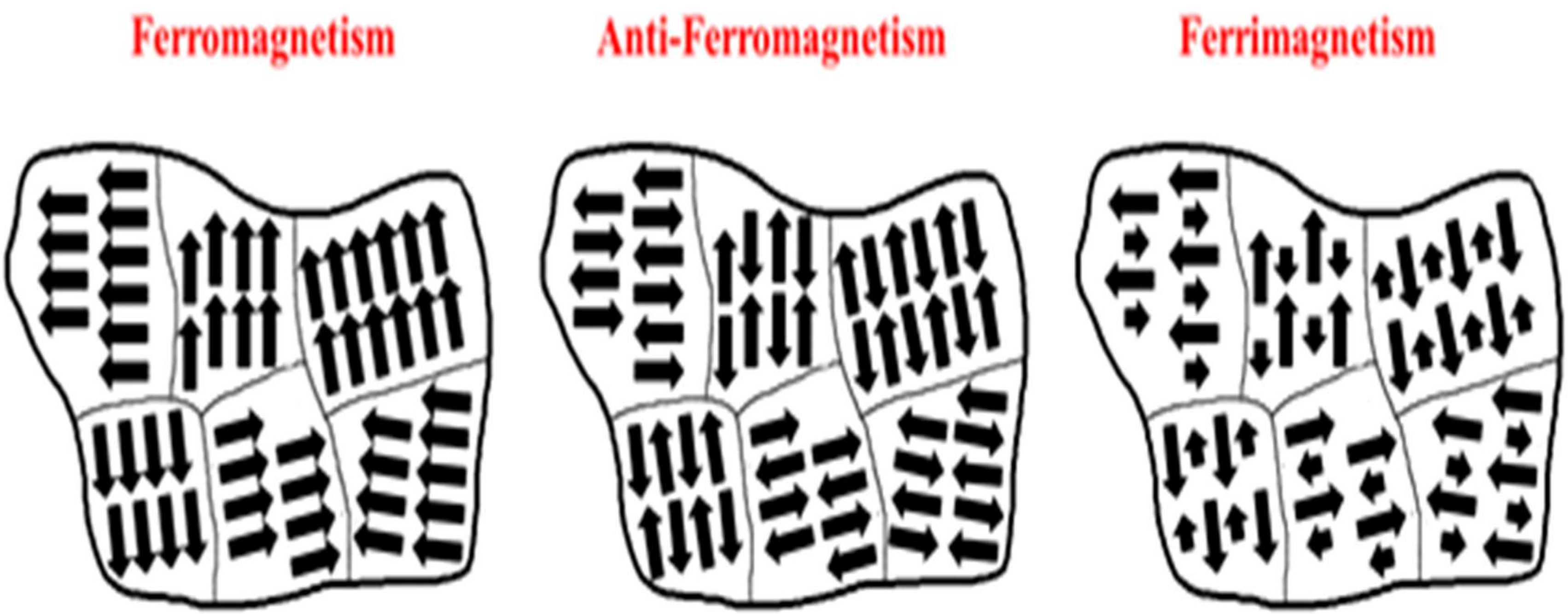



**Fig:** Domain alignments in Ferro, anti-Ferro, and Ferro-magnetism

# Magnetic Materials

## Anti-Ferromagnetism:

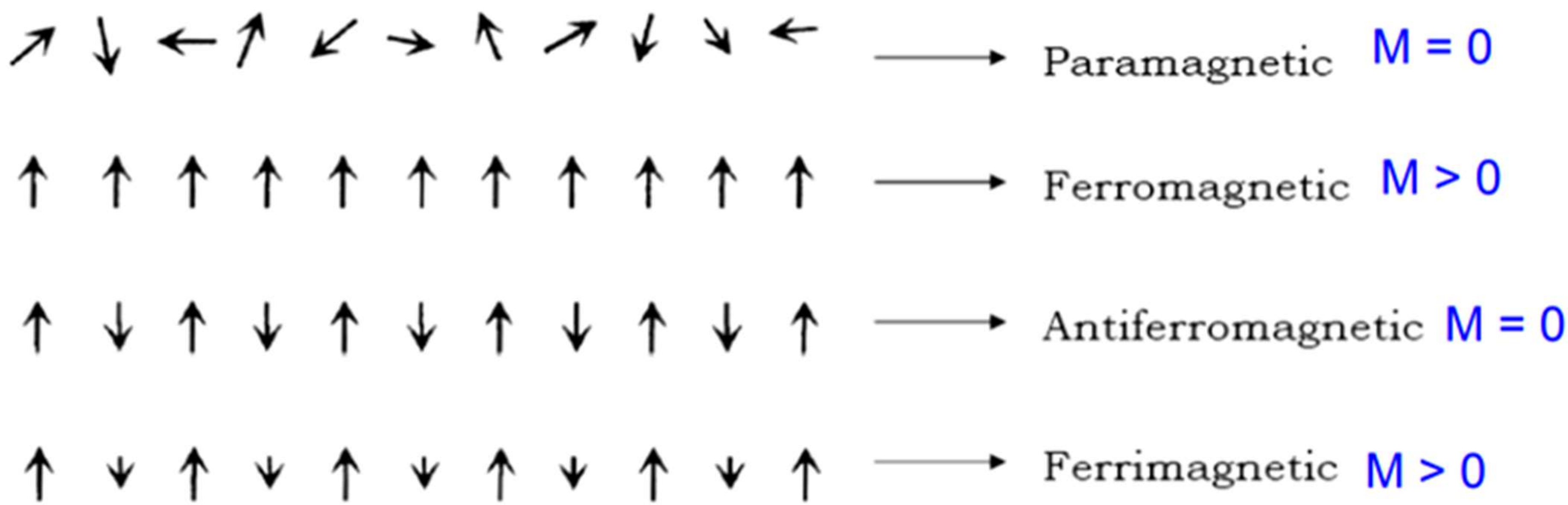
- Dipoles line-up, but in opposite directions, resulting in zero magnetization.
- Eg: Mn, Cr, MnO, NiO, CoO, $MnCl_2$
- Exchange interaction which is responsible for parallel alignment of spins is extremely sensitive to inter-atomic spacing and to the atomic positions.
- This sensitivity causes anti-parallel alignment of spins.
- One noticeable characteristic of anti-Ferromagnets is they attain *maximum susceptibility at a critical temperature* called ***Neel temperature***.
- At temperatures *above Neel temperature*, *anti-Ferromagnets* → *para-magnetic*.

## Ferri-magnetism:

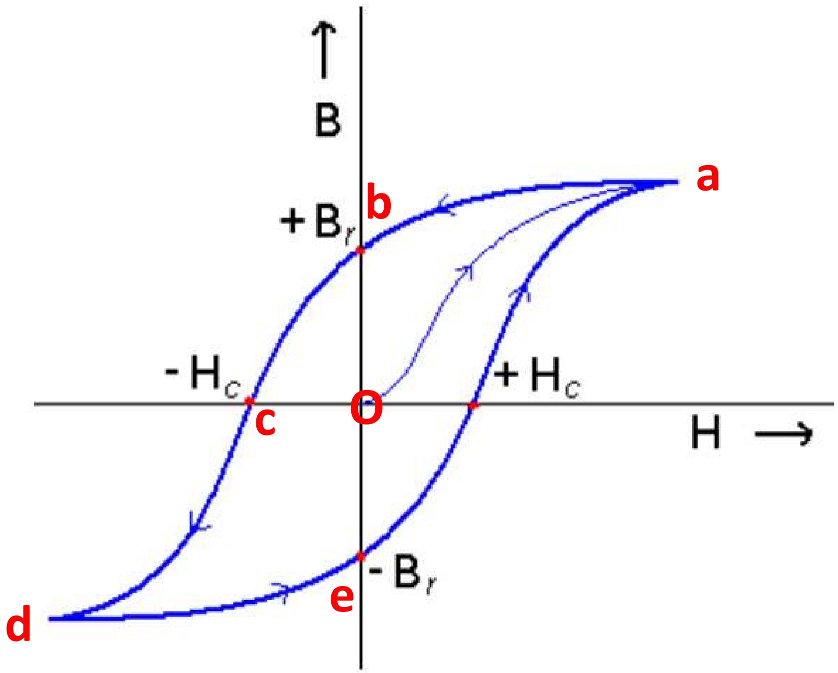
- In a magnetic field, the dipoles of a cation may line up with the field, while dipoles of other cation may not.
- Eg: $Fe_3O_4$, $NiFe_2O_4$, $(Mn.Mg)Fe_2O_4$, $PbFe_{12}O_{19}$, $BaFe_{12}O_{19}$
- Ferri-magnetism is similar to *anti-Ferromagnetism* in that the spins of different atoms or ions line up anti-parallel.
- *Below the Neel temperature*, *ferrimagnetic materials* →*ferromagnetic materials* & above the Neel temperature *ferrimagnetic* → *paramagnetic*.

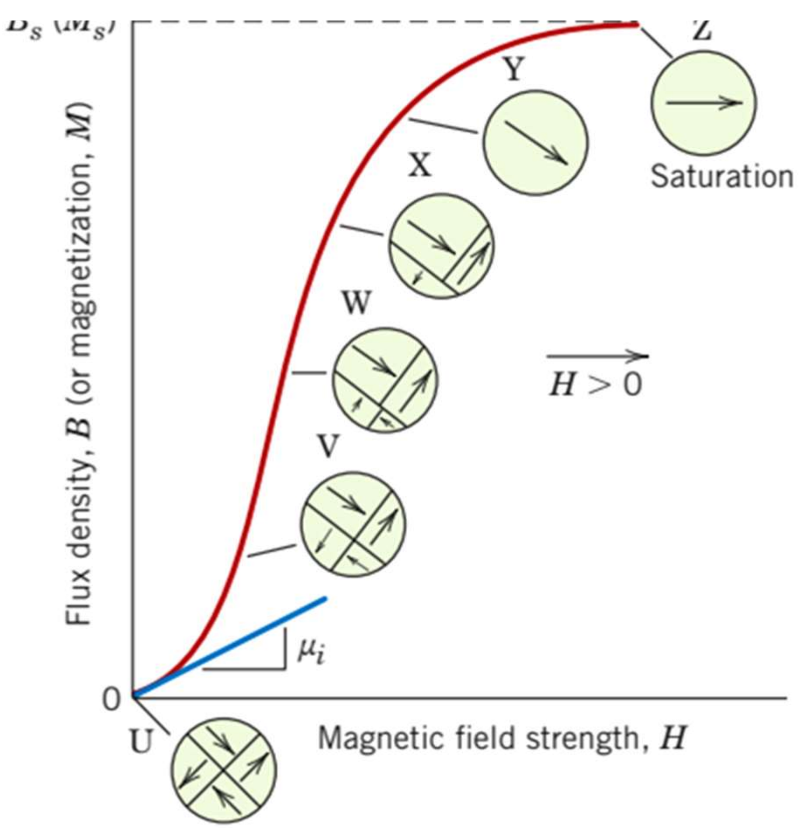
# Magnetic Materials

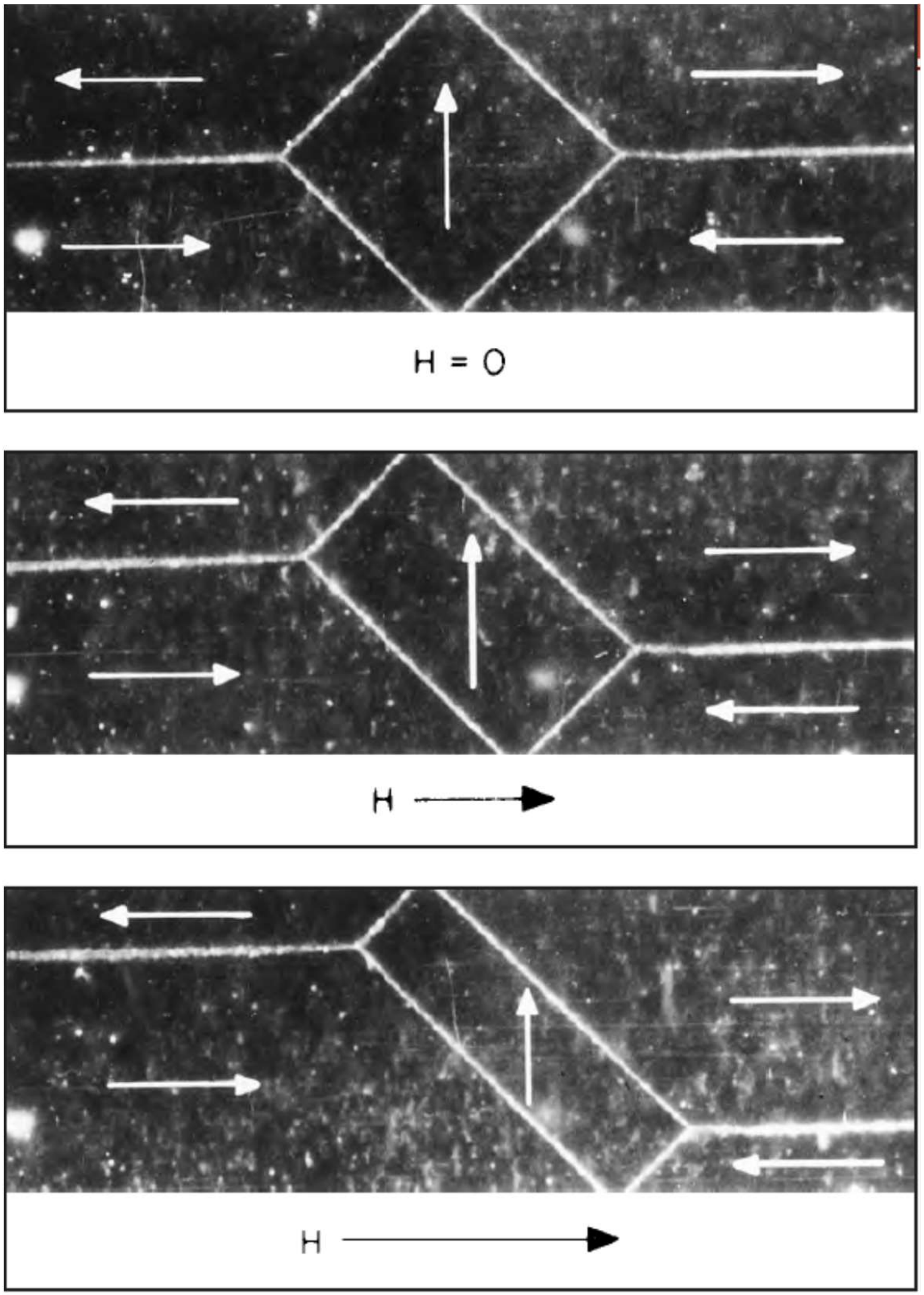
## Spin alignment for different magnetic substances with net magnetization



# Magnetic hysteresis

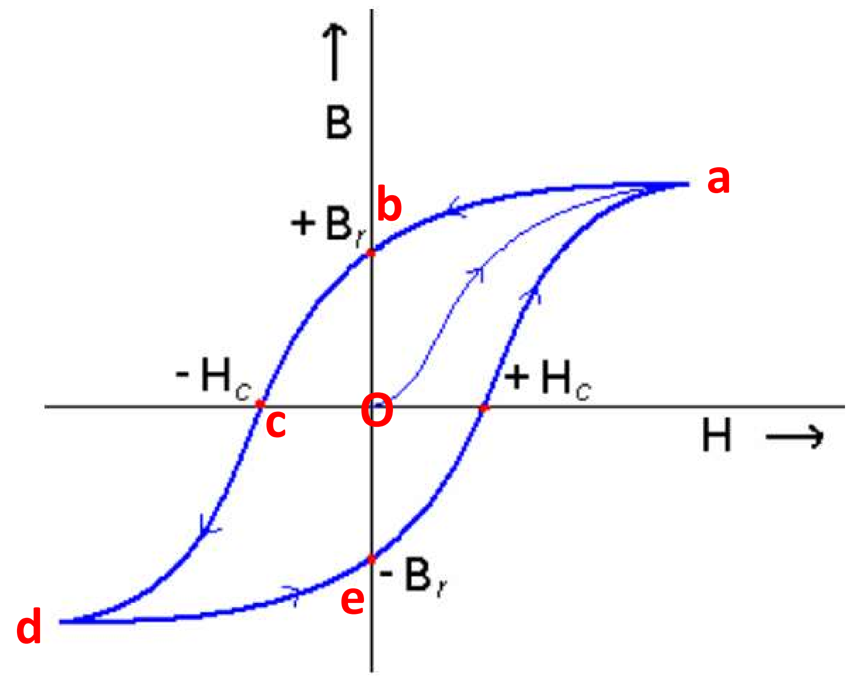


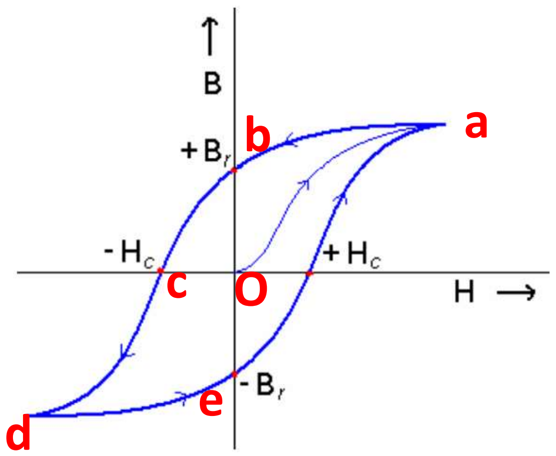



- Let the material be un magnetized initially.
- We place it in a solenoid and increase the current through the solenoid.
- The magnetic field B in the material rises and saturates as depicted in the curve 'Oa'.
- This behavior represents the alignment and merger of domains until no further enhancement is possible.
- It is pointless to increase the current (and hence the magnetic intensity H) beyond this.

- Next, we decrease H and reduce it to zero.
- At H = 0, B ≠ 0, this is represented by the curve $a_b$.
- The value of B at H = 0 is called retentivity or remanence, $B_r$.
- The domains are not completely randomized, even though the external driving field has been removed.

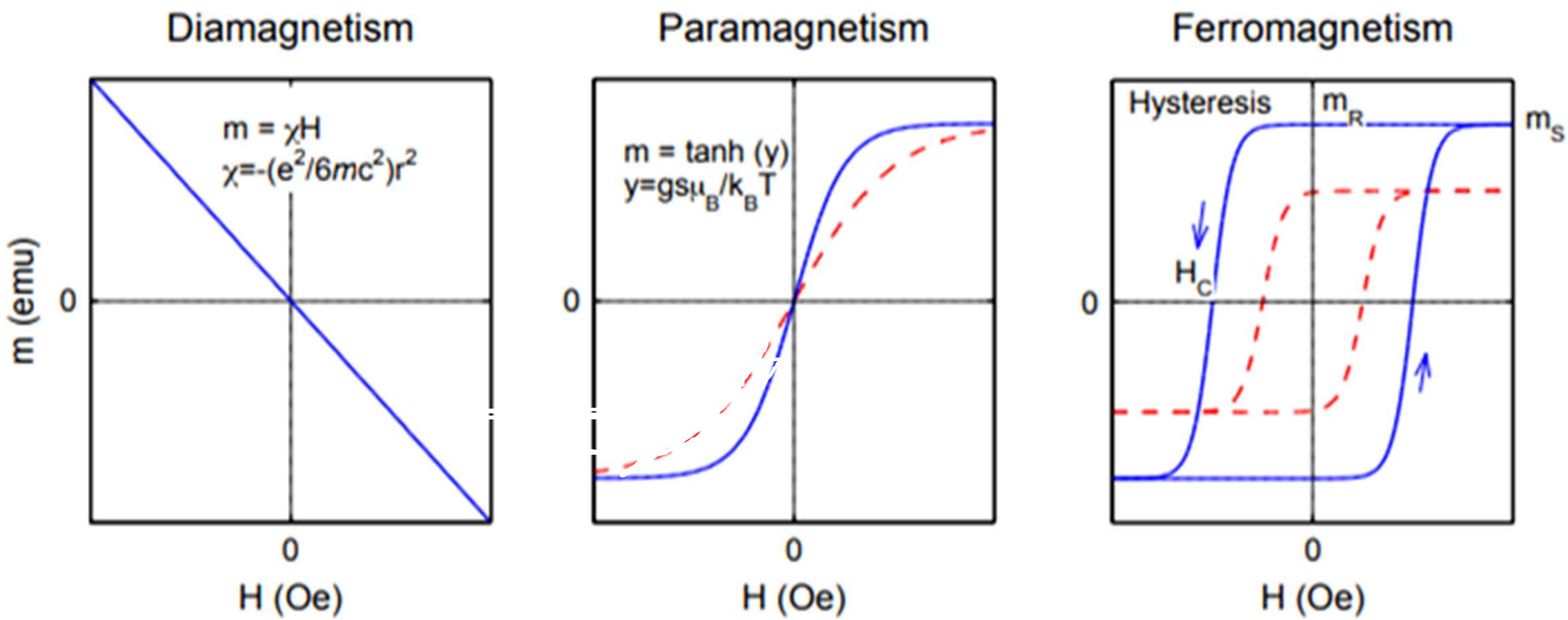


- Next, the current in the solenoid is reversed and slowly increased.
- Certain domains are flipped until the net field inside stands nullified.
- This is represented by the curve ‘bc’. The value of H at c is called **coercivity**, $H_c$.
- As the reversed current is increased in magnitude, we once again obtain saturation (curve ‘cd’).
- Next, the current is reduced (curve ‘de’) and reversed (curve ‘ea’).




- The cycle repeats itself. Note that the curve ‘Oa’ does not retrace itself as H is reduced.
- For a given value of H, B is not unique but depends on previous history of the sample. This phenomenon is called **hysteresis**.
- The word hysteresis means lagging behind and not ‘history’.
- The hysteresis curve allows us to select suitable materials for permanent magnets.

## Magnetic hysteresis of different magnetic substances:



## Soft Magnetic Materials

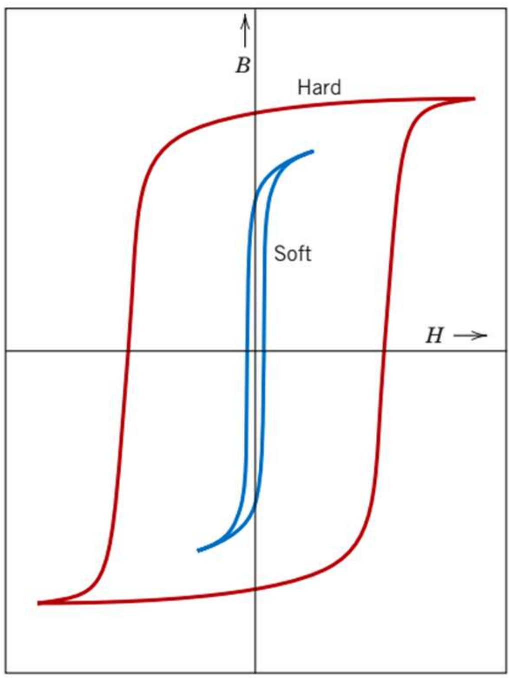
- Both ferro- and ferrimagnetic materials are classified as either *soft* or *hard* on the basis of their hysteresis characteristics.
- **Soft magnetic materials** are used in devices that are subjected to alternating magnetic fields and in which energy losses must be low (Ex: transformer cores).

➢ For this reason, the relative area within the hysteresis loop must be small and it is characteristically thin and narrow, as represented in Fig.

➢ A soft magnetic material must have a high initial permeability and a low coercivity.

➢ A material possessing these properties may reach its saturation magnetization with a relatively low applied field and have low hysteresis energy losses.

- A soft magnetic material must be free of structural defects (particles of a nonmagnetic phase or voids in the magnetic material).
- **Eddy currents:** The energy losses may result from electrical currents that are induced in a magnetic material by a magnetic field that varies in magnitude and direction with time. (*Required to minimize these energy losses*)
- These are used in generators, motors, dynamos, and switching circuits.



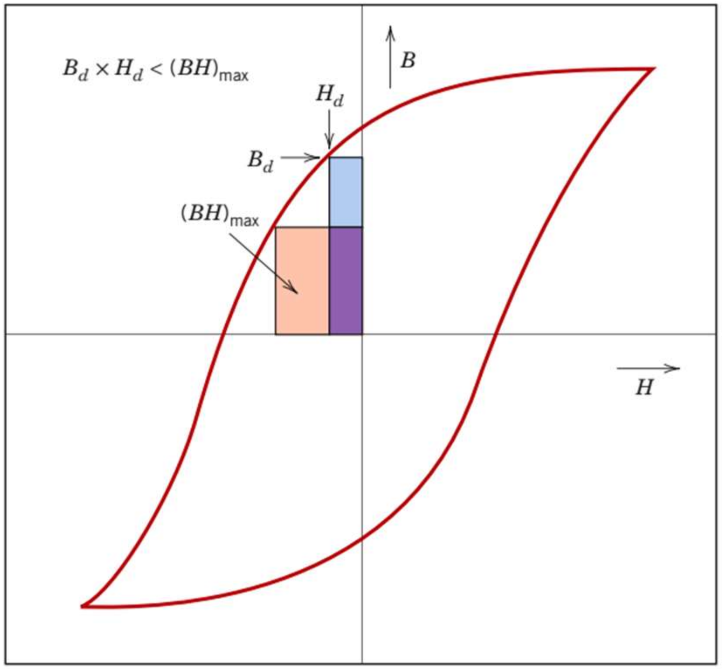
# Hard Magnetic Materials

- Hard magnetic materials are used in permanent magnets, which must have a high resistance to demagnetization.
- **Hard magnetic materials** has high remanence, coercivity, and saturation flux density, as well as low initial permeability and high hysteresis energy losses.
- The two most important characteristics relative to applications for these materials are the *coercivity* and the *energy product*, designated as $(BH)_{max}$.

➢ $(BH)_{max}$ corresponds to the area of the largest *B-H* rectangle that can be made within the second quadrant of the hysteresis curve (Fig).

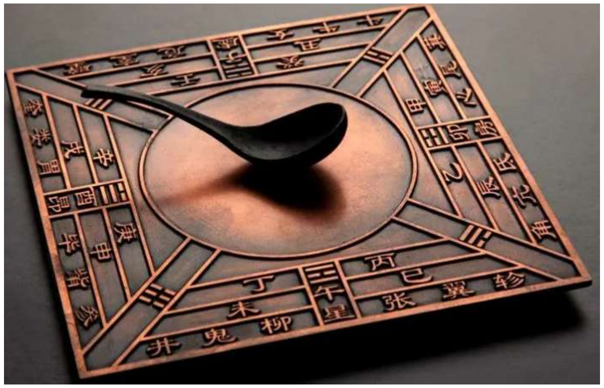
➢ The larger $(BH)_{max}$, the harder the material in terms of its magnetic characteristics.

- **Conventional HMM:** $(BH)_{max}$ range: 2 and 80 kJ/m$^3$.
- Ex: Magnet steels, Cu–Ni–Fe alloys, and Al–Ni–Co alloys
- **High energy HMM:** $(BH)_{max}$ range: > 80 kJ/m$^3$.
- Ex: $SmCo_5$, $Nd_2Fe_{14}B$
- Used in a host of different devices in a variety of technological fields.
- Such as cordless drills and screwdrivers, automobiles etc.

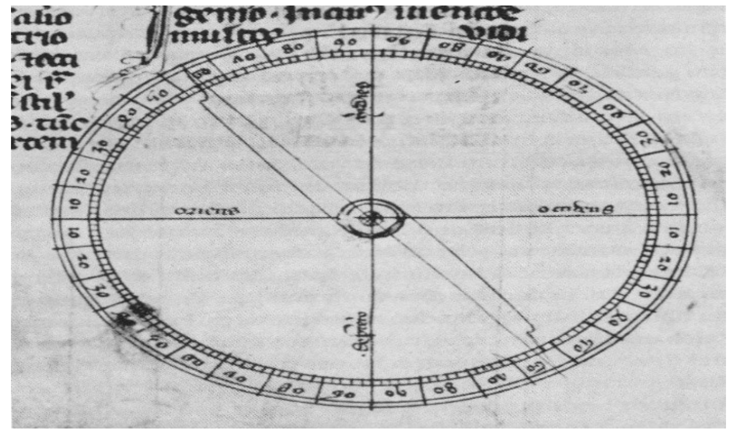


# Magnetic Materials Applications

1. Han Dynasty (2nd century BCE to 2nd century CE): Navigation-Compass



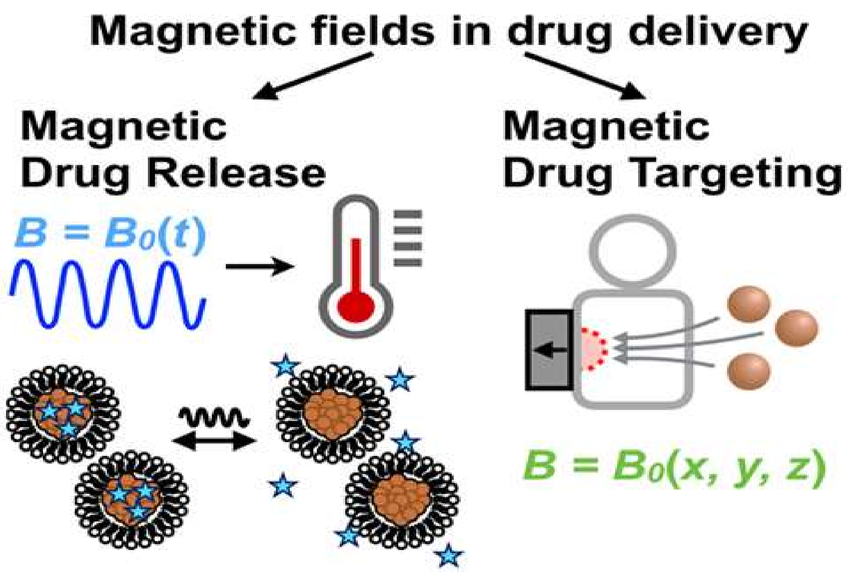
2. Pivoting compass needle: During 14th century



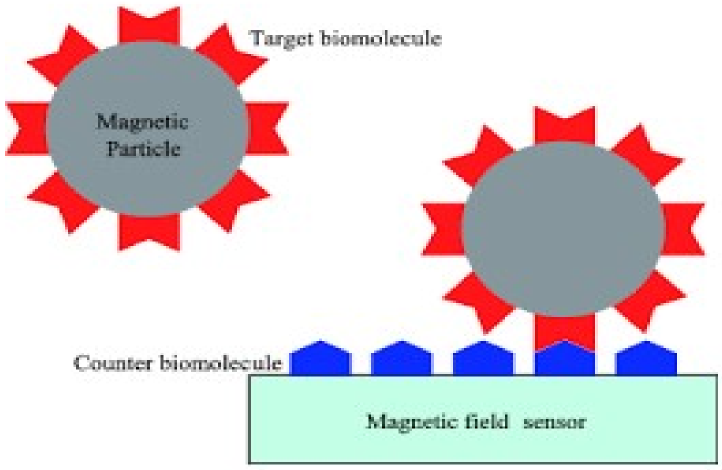
**Advanced Applications**:

- ✓ Computer technology
- ✓ Electrical distribution
- ✓ transformers
- ✓ Sensors, Motors

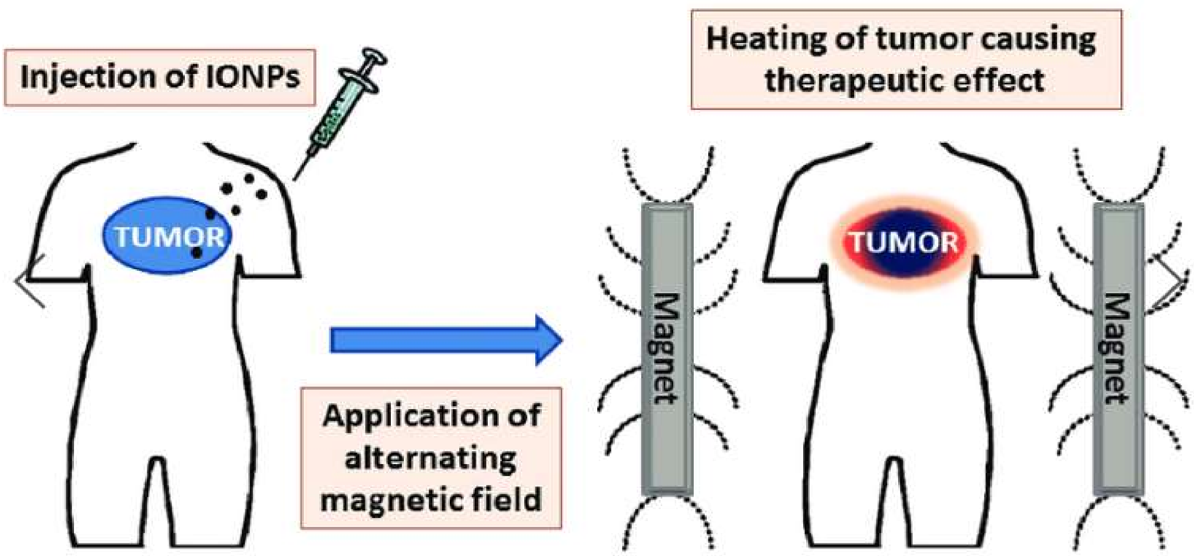
## Drug delivery




## Biosensors



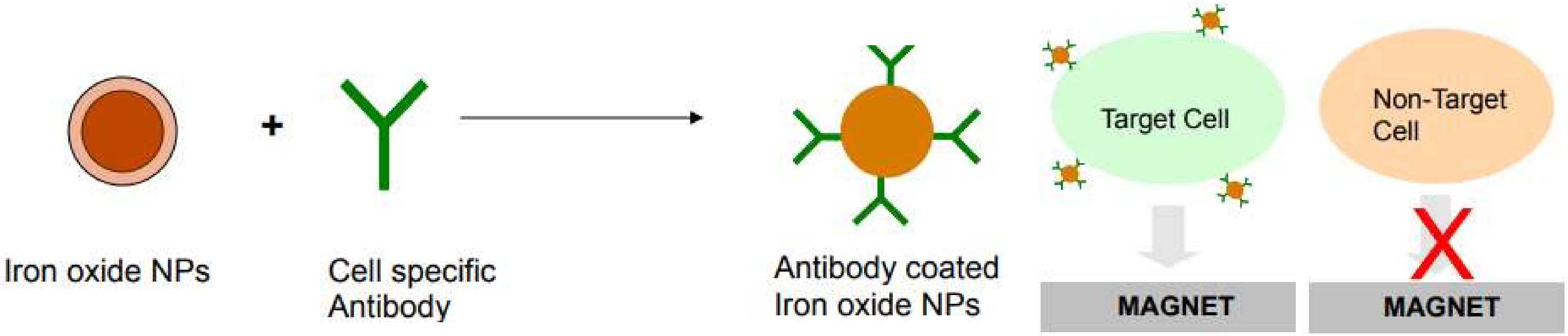

## Cancer therapies



## Medical Devices:

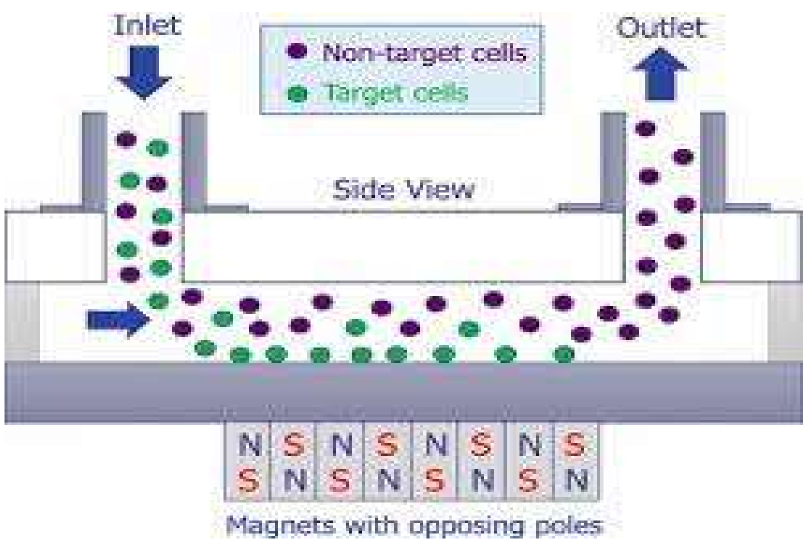
### Magnet in a Microfluidic Chamber

Surface modification of Iron NPs to target tumor cells and trap them in microfluidic chamber using magnetic fields

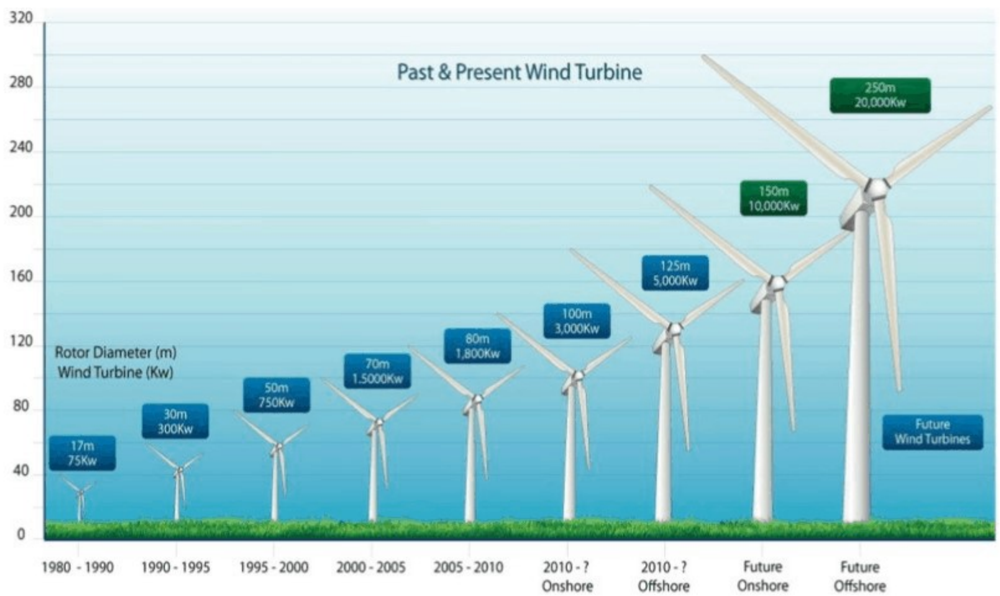



### Magnetic Cell Separation

Using MNPs as an agent for separation, a small number of cancer cells can be concentrated and collected for assaying.



## Magnets and Energy




## Magnets and the Military