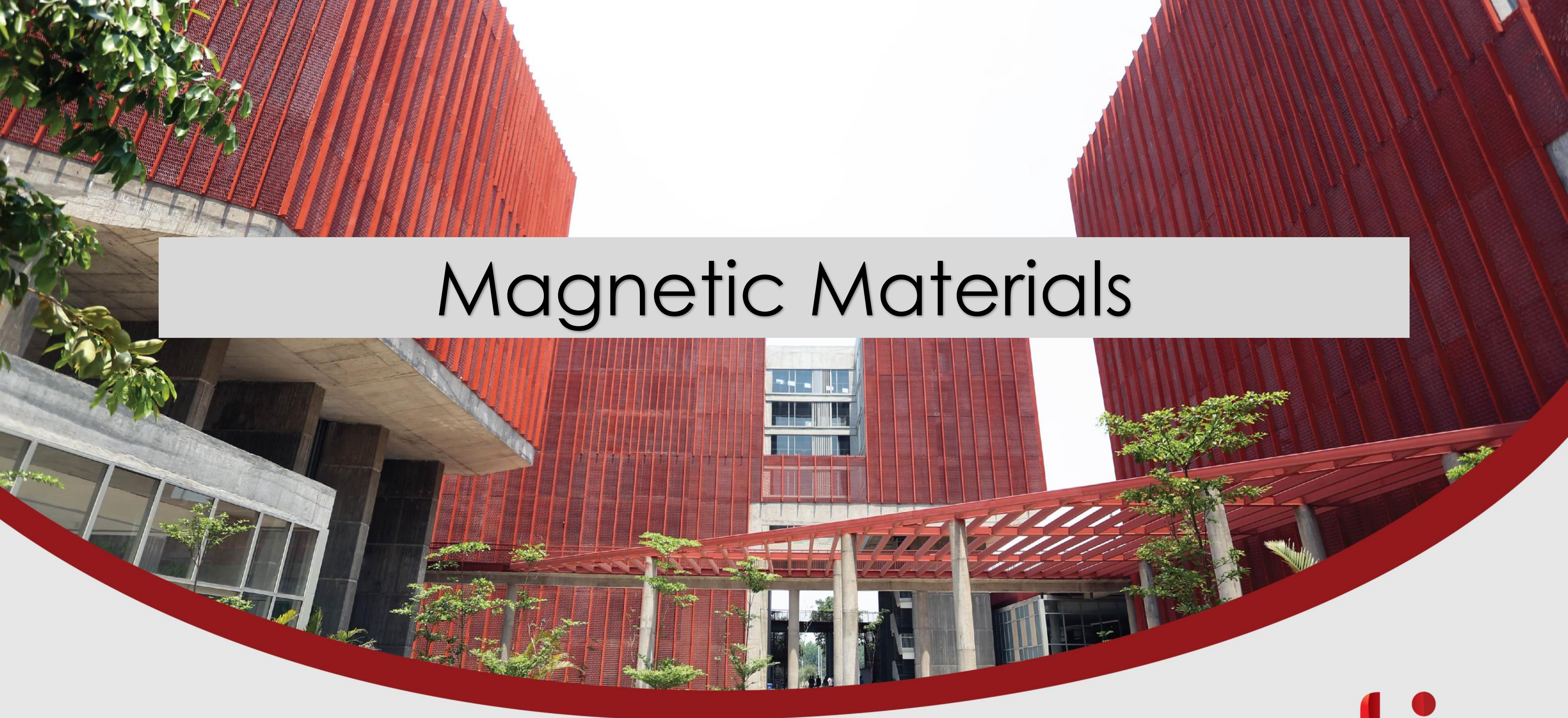
Magnetic Materials



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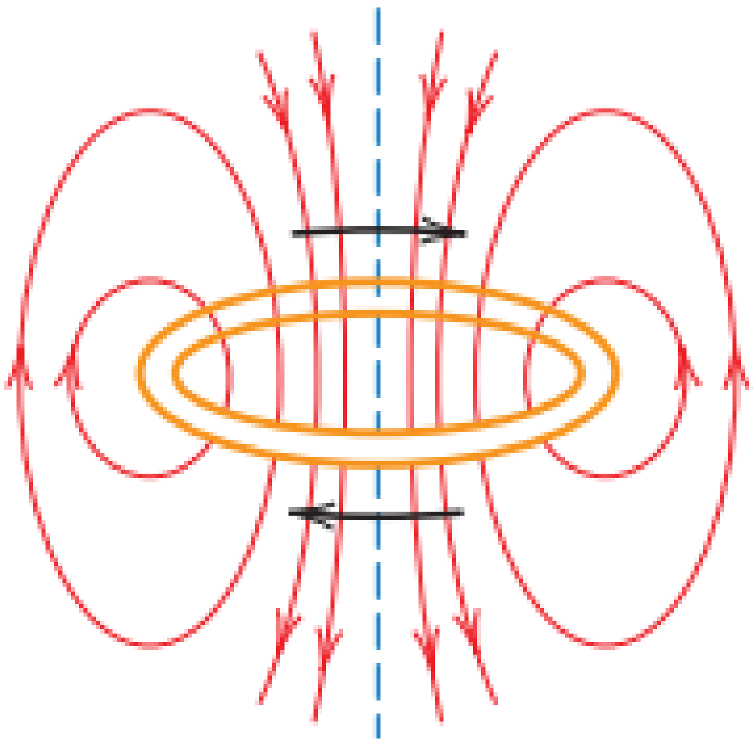
Origin of magnetism



Origin of Magnetism

Macroscopic (Charge currents)

Microscopic (Atomic scale)

- If a loop of area A is carrying a current I, the intrinsic intensity of the magnetic field is given by the magnetic moment vector (**m** or $\boldsymbol{\mu}$) directed from the north pole to the south pole; such that the magnitude of **m** is given by: $m = IA$ (units: [Am^2]).

- The magnetic moment is the measure of the strength of the magnet and is the ability to *produce (and be affected by)* a magnetic field.

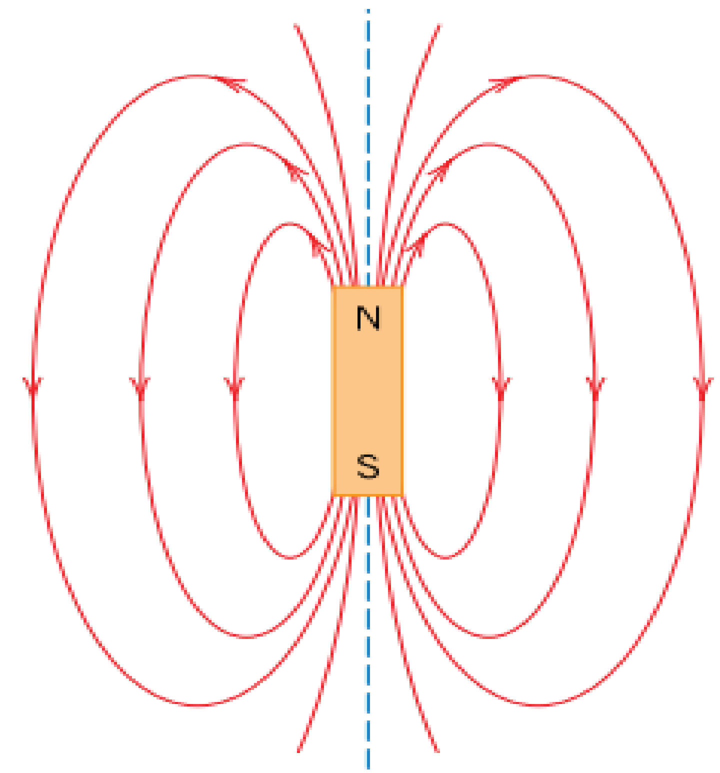
Magnetic dipoles

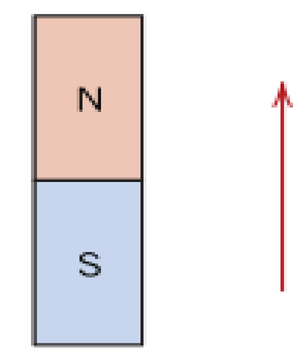
Magnetic forces are generated by moving electrically charged particles.

Imaginary lines of force may be drawn to indicate the direction of the force at positions in the vicinity of the field source.

The magnetic field distributions are indicated by lines of force.

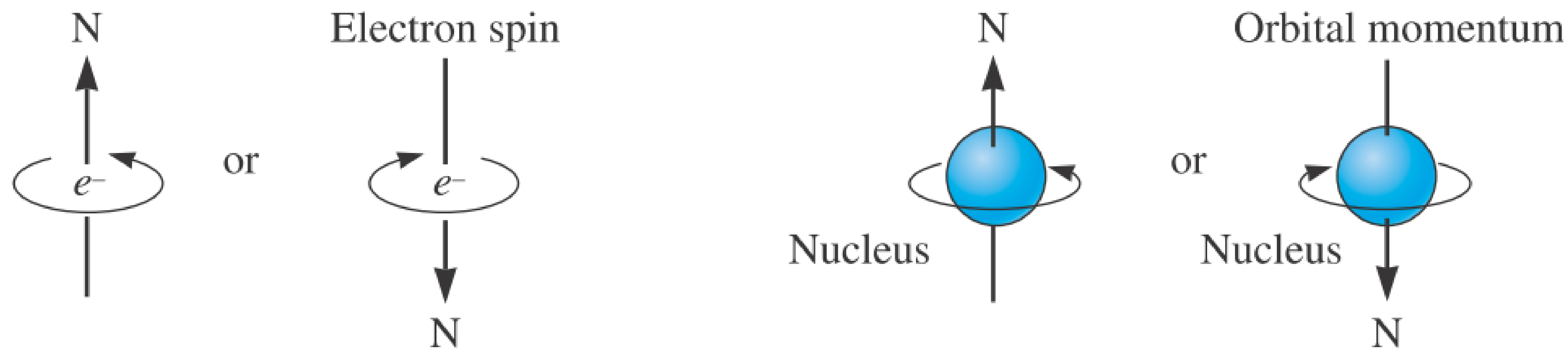
These field lines can be drawn from N to S.





Atomic origin of magnetic moments

A moving electric charge is responsible for Magnetism



Origin of Magnetism

Nuclear spin → Weak effect

Spin of electrons → Unpaired electrons required for net Magnetic Moment

Orbital motion of electrons

Magnetic Moment resultant from the spin of a single unpaired electron
Bohr Magnetron = 9.27×10^{-24} Am^2

Important quantities in magnetism

Magnetic Moment Vector (**m** or **μ**)

Measure of the strength of the magnet.

$$m = IA,$$

Units: [Am^2] or equivalently [Joule/Tesla].

Magnetization (**M**)

The materials response to the applied field H.

Magnetization induced by the applied external field H.

Magnetic moment (**m**) per unit volume (V).

Units: [A/m]

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

Magnetic field strength/Magnetizing force (**H**)

Measure of the strength of the externally applied field.

Units: [A/m]

Important quantities in magnetism

Magnetic induction/Magnetic flux density (**B**)

B is the magnetic flux density inside the material.
Magnetic flux per unit area.
Units: [Tesla = Weber/m^2]

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

(μ_0 is the magnetic permeability of vacuum = H/m = Wb/A/m = mKg/s^2A^2)

Permeability (μ) Units: [dimensionless]

Ability of the material to permeate magnetic field.

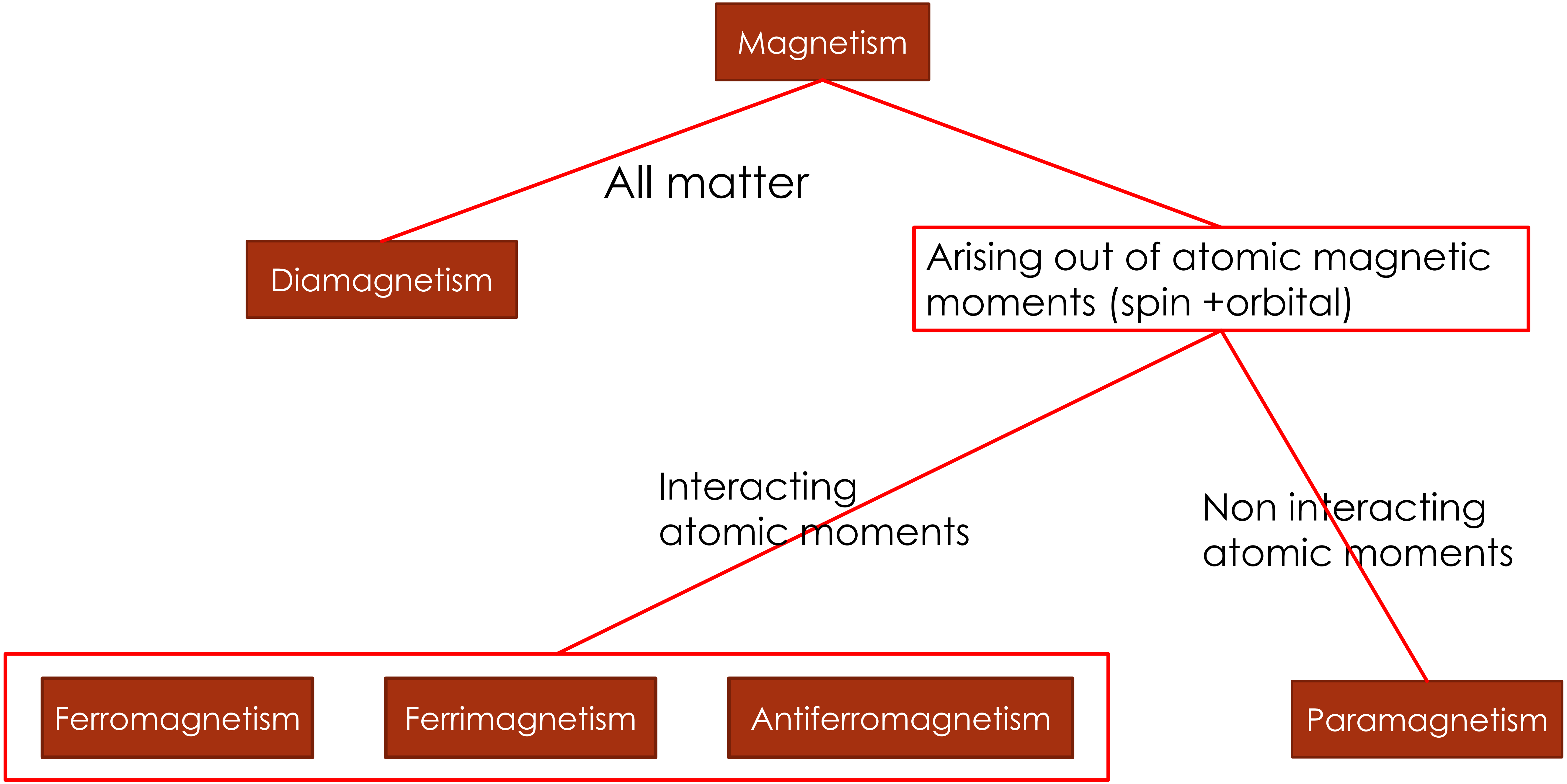
$$\mu = \frac{B}{H}$$

Magnetic susceptibility (χ) Units: [dimensionless]

How much magnetic field it can hold. Also tells whether it attracts or repel.
Susceptibility is a better quantity to get a 'feel' and 'physical picture' of the type of magnetism involved.

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

Types of magnetism

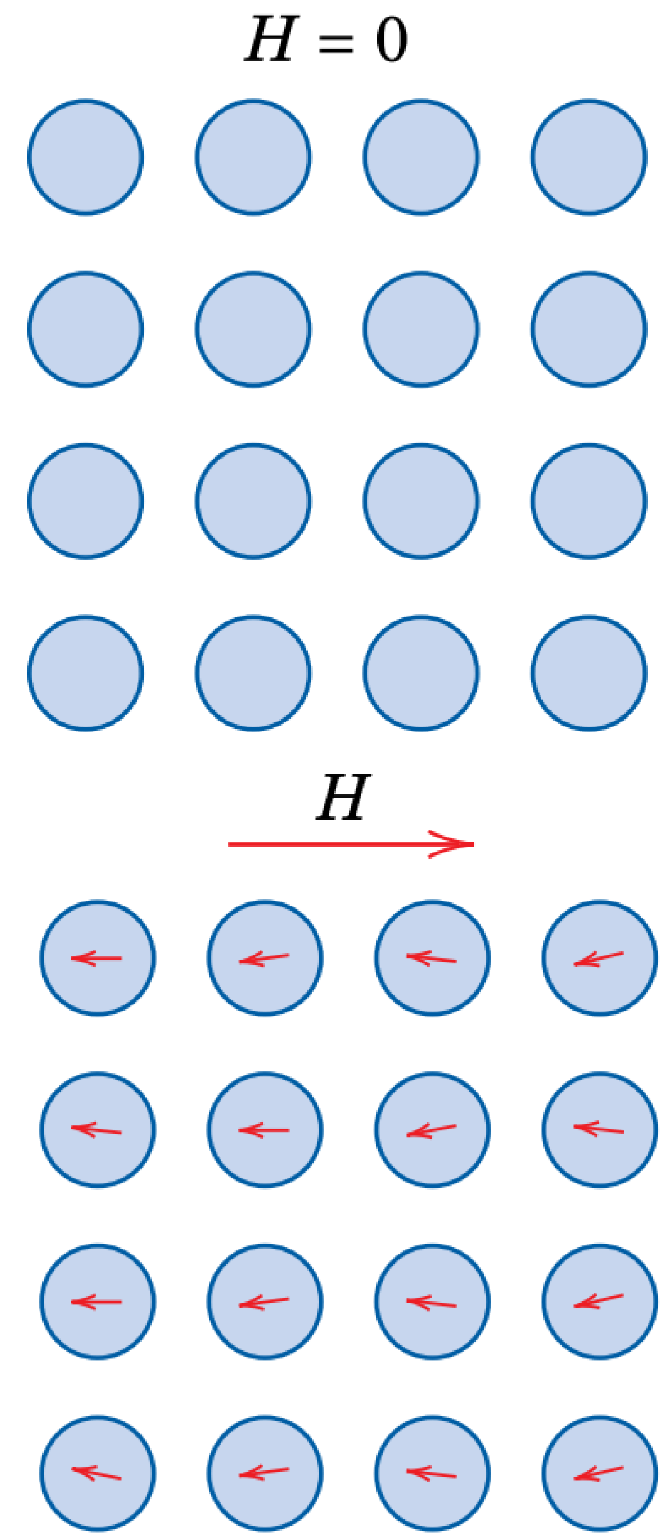


Diamagnetism

1. A very weak form of magnetism.
2. Nonpermanent and persists only while H is applied.
3. Closed shell electronic configuration leads to a net zero magnetic moment.
4. Induced by a change in orbital motion of electrons due to an applied magnetic field.
5. Magnitude of the induced magnetic moment is extremely small, and in opposite direction to **H**

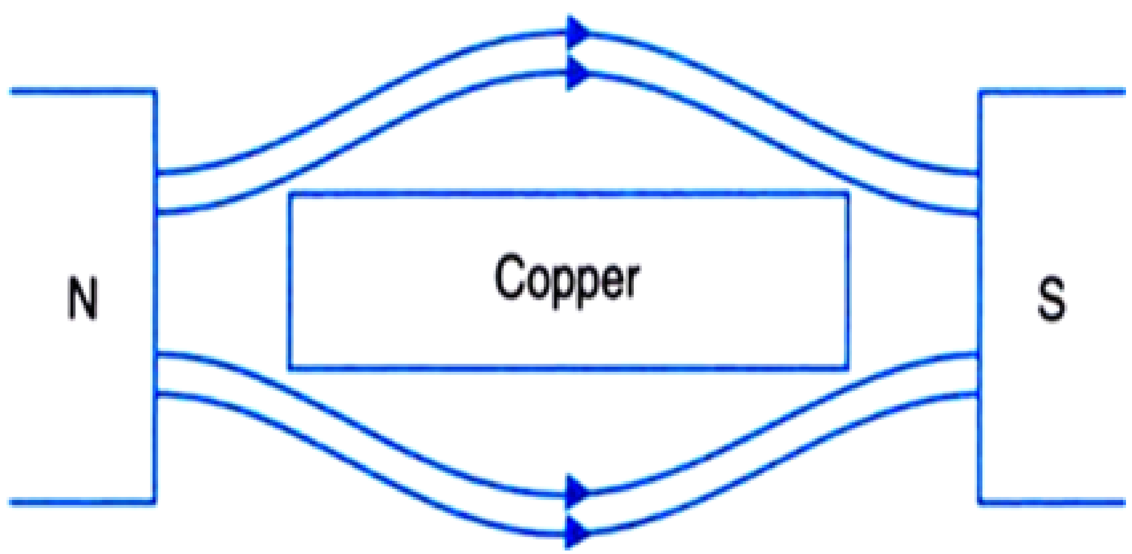
   B (inside diamagnetic solid) < B (vacuum).

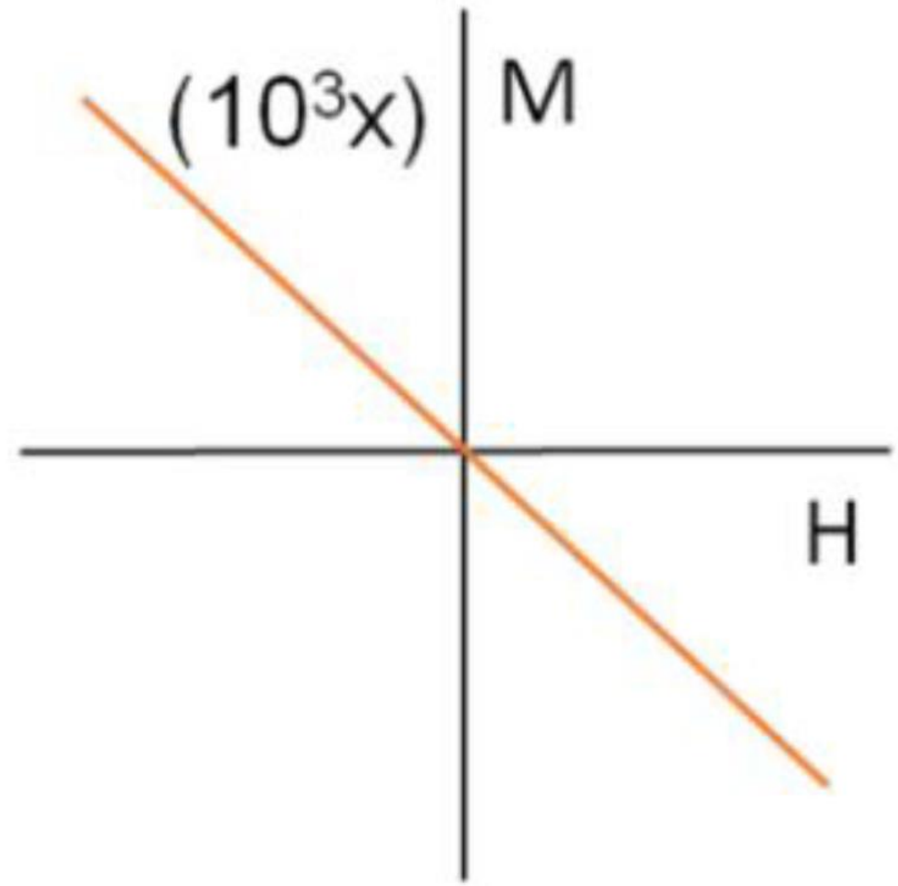
   $\chi < 0$ and $\mu_r < 1$.



Diamagnetism

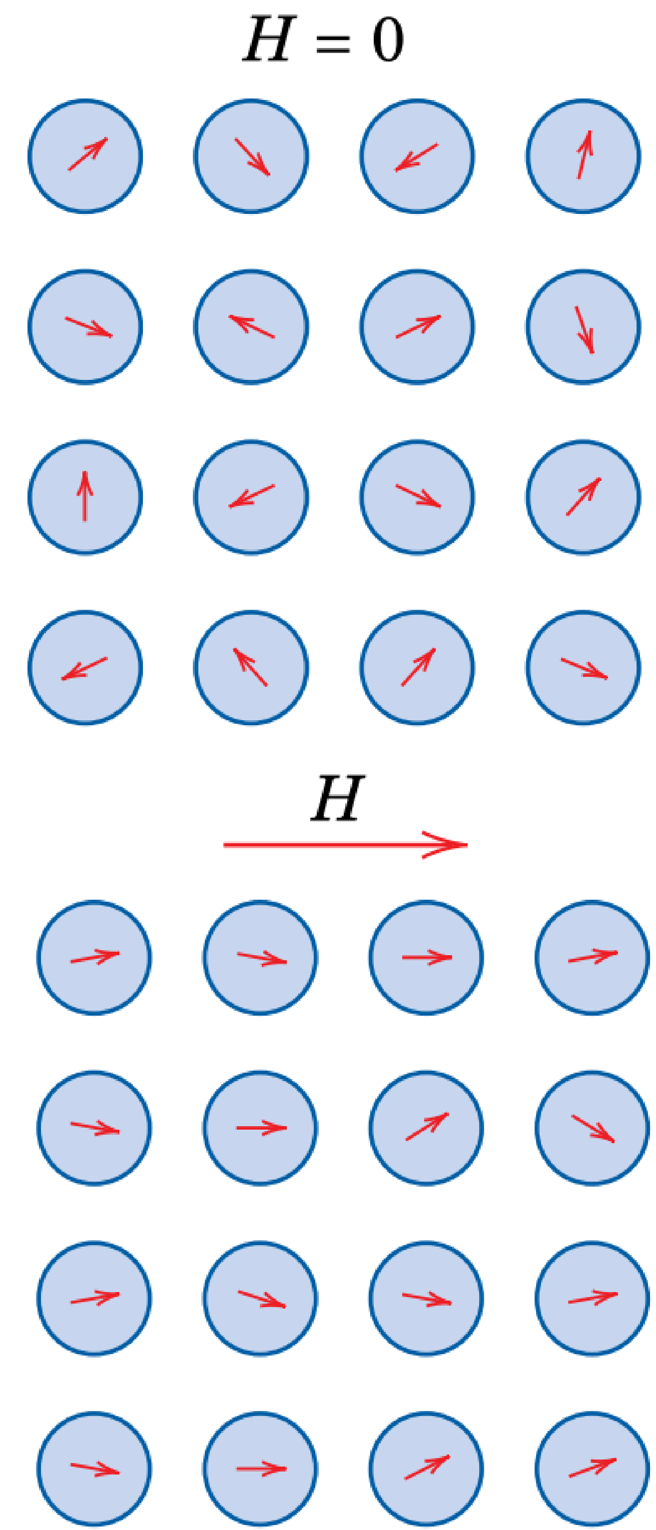
1. Repels the applied magnetic field.
2. Volume susceptibility χ_m is of order of -10^{-5}.
3. e.g. Cu, Au, Ag, Hg, Si, Zn, Al_2O_3





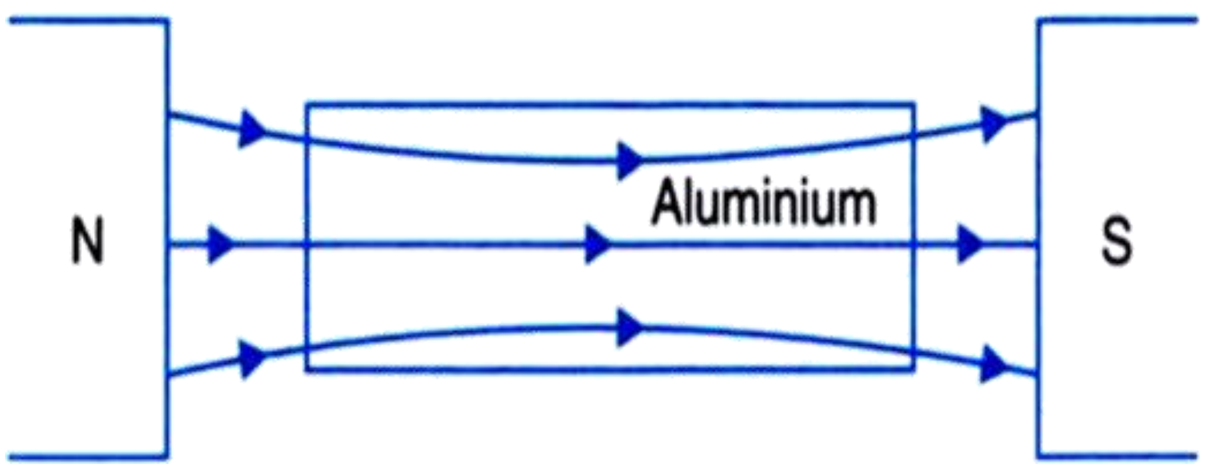
Paramagnetism

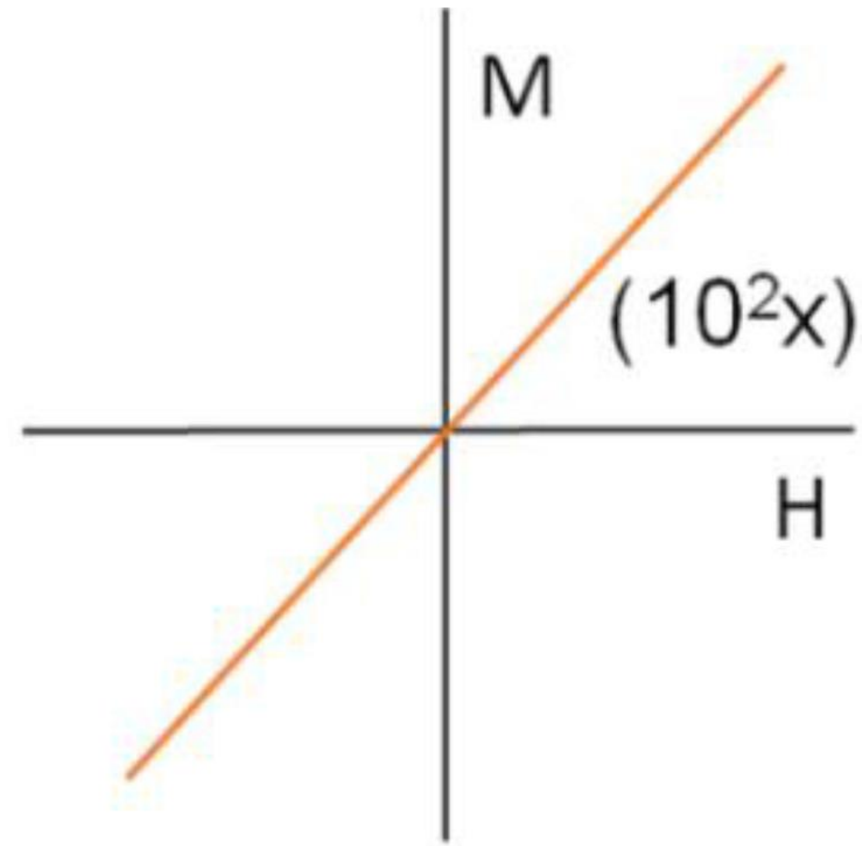
1. Arising when the atom/molecule has a net a magnetic moment.
2. Incomplete cancellation of electron spin and/or orbital magnetic moments → permanent dipole moment of each atom.
3. When **H** = 0, atomic magnetic moments are randomly oriented, → no net macroscopic magnetization.
4. When **H** is applied, these atomic dipoles preferentially align, by rotation, with **H** → **paramagnetism**
5. As the dipoles align with the external field, they enhance it, $\mu_r > 1$ and $\chi_m > 0$.



Paramagnetism

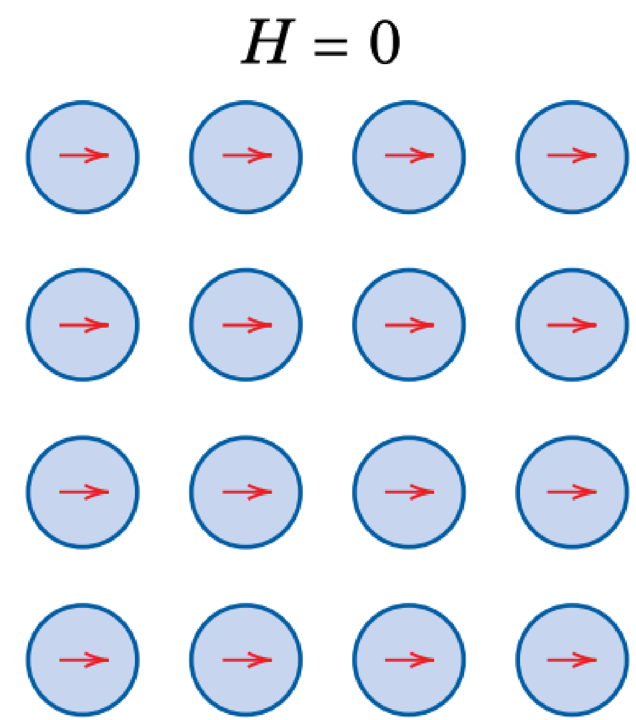
1. Weakly attracts the applied magnetic field.
2. χ_m is in the range from 10^{-5} to 10^{-2}.
3. e.g. Al, Cr, Na, Ti,Zr, Mo

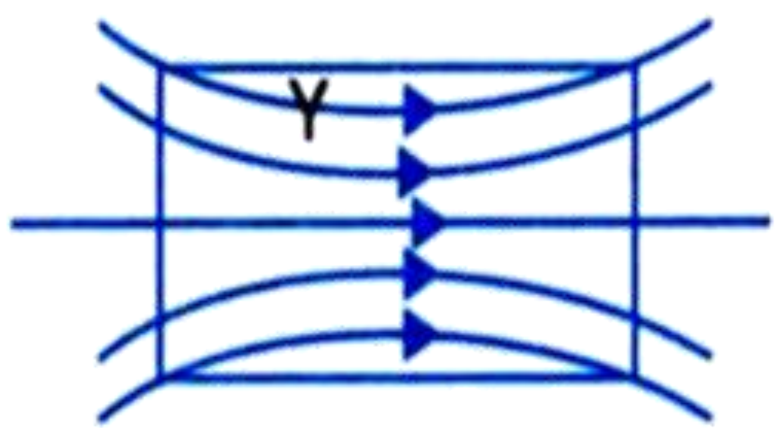


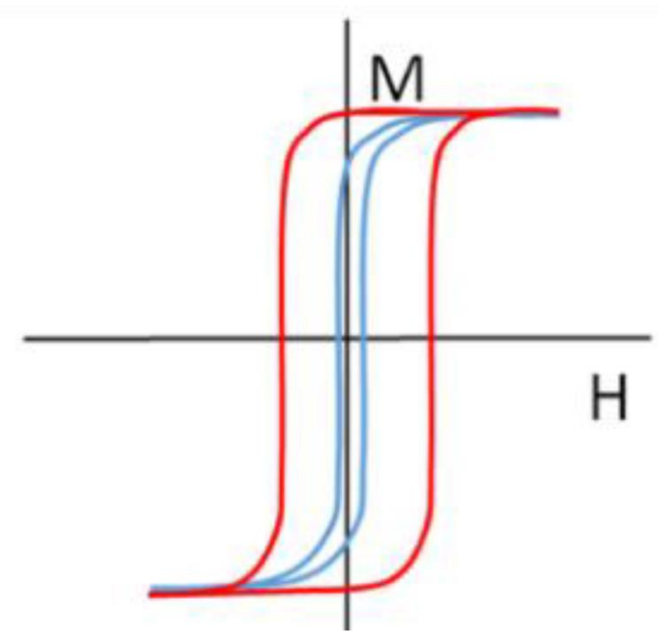


Ferromagnetism

1. The bands must have vacant levels (e.g. 3d bands in Fe, Co, Ni) for unpaired electrons.
2. Certain metallic materials possess a permanent magnetic moment even when **H = 0**, and show very large and permanent magnetizations → **ferromagnetism**
3. Strongly attracts magnetic field.
4. Very high value of χ_m is possible ($\sim 10^6$)
5. Ex: transition metals Fe (as BCC α-ferrite), Co, Ni, Gd etc.







Origin of Ferromagnetism

1. Involve the way in which magnetic moments are coupled (arranged).
2. Coupling interactions cause net spin magnetic moments of adjacent atoms to align with one another, even when **H** = 0.
3. There is also an orbital magnetic moment contribution (smaller than the spin moment).
4. Uncancelled electron spins → atomic magnetic moments → Permanent magnetic moments.
5. Assuming direct exchange, the interatomic distance should be correct for exchange forces to be operative (leading to parallel alignment).
6. This mutual parallel spin alignment exists over large-volume regions (called as **domains**)

DOMAINS: Collection of spins form to minimize energy.

How ?

Why?

Origin of Ferromagnetism

1. If 3d orbital overlaps with neighboring atoms ➔ Spins alignment ➔ Ferromagnetism.
2. If all electrons in 3d orbital are paired ➔ Antiferromagnetism.
3. There is electrons exchange integral (J_{ex} i.e. Relative proximity of electrons.)

$(J_{ex}) = E_{unmagnetized} - E_{emagnetize}$ state

$E_{ex} = -J_{ex} S_1.S_2$; S_1 and S_2 are the spins angular momenta of individual atoms.

J_{ex} is positive for Ferromagnetic materials, E_{ex} is negative.

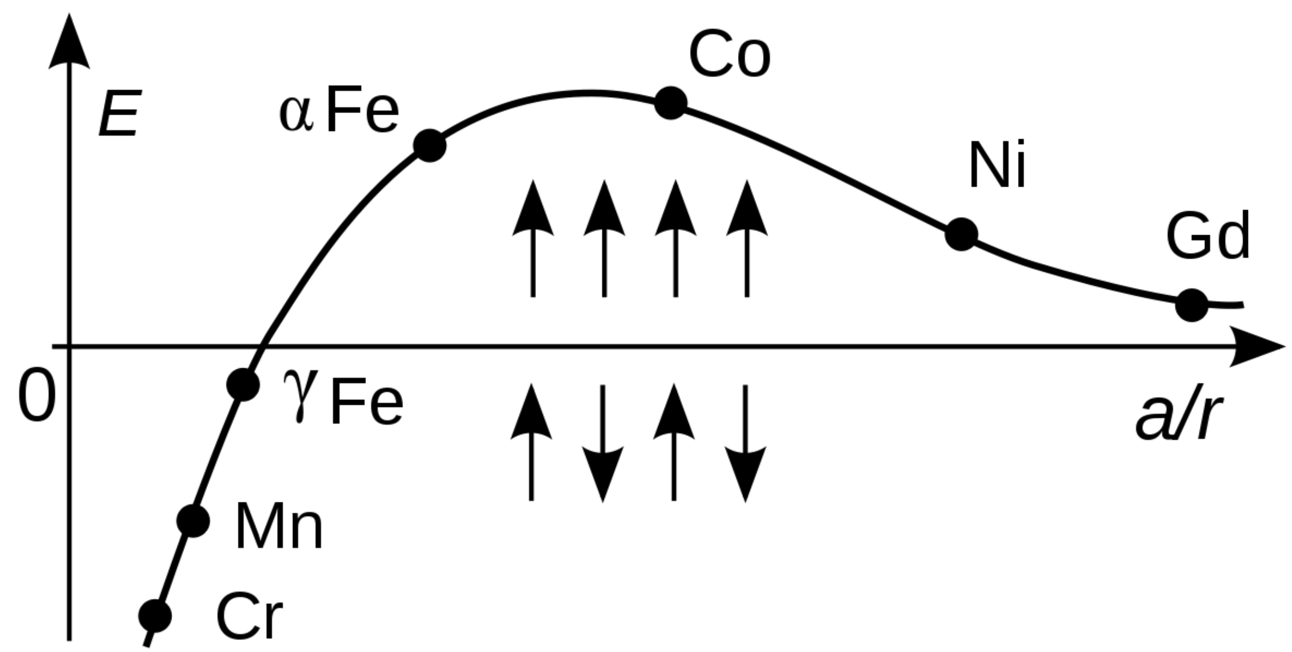
J_{ex} is negative for antiferromagnetic materials, E_{ex} is positive.

J_{ex} is a function of $d_{atomic}/d_{3d\ orbital}$

Origin of Ferromagnetism

Element	Ti	Cr	Mn	Fe	Co	Ni
$d_{atomic}/d_{3d\ orbital}$	1.12	1.18	1.47	1.63	1.82	1.98

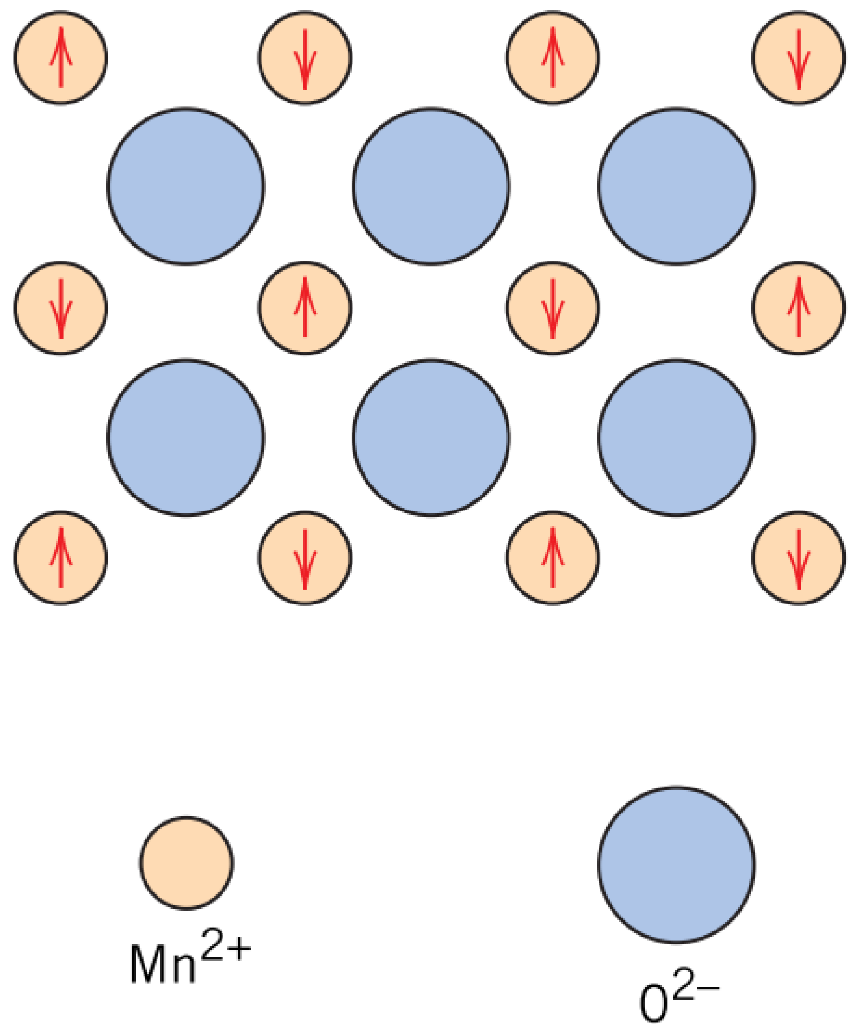
If the ratio of $d_{atomic}/d_{3d\ orbital}$
<1.5 Antiferromagnetic
1.5 – 2 Ferromagnetic



We can change $d_{atomic}/d_{3d\ orbital}$ by alloying
e.g.
Mn → Antiferromangetic
Doping of suitable ion → Increases Mn-Mn distance (diameter)
Heusler alloys → Cu_2MnSn and Cu_2MnAl are ferromagnetic.

Antiferromagnetism

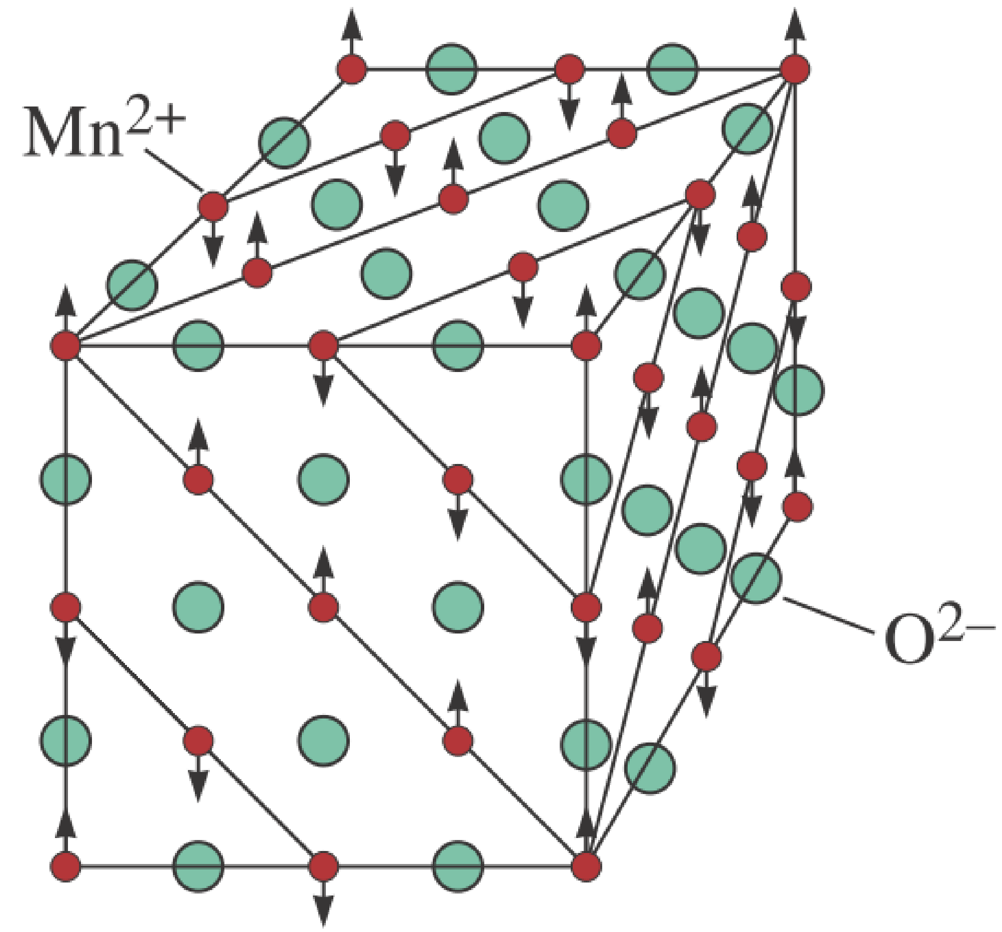
1. Magnetic moment coupling between adjacent atoms or ions results in an antiparallel alignment;
2. the alignment of the spin moments of neighboring atoms or ions in exactly opposite directions is termed ANTIFERROMAGNETISM.
3. e.g. Cr, MnO, FeO



Antiferromagnetism

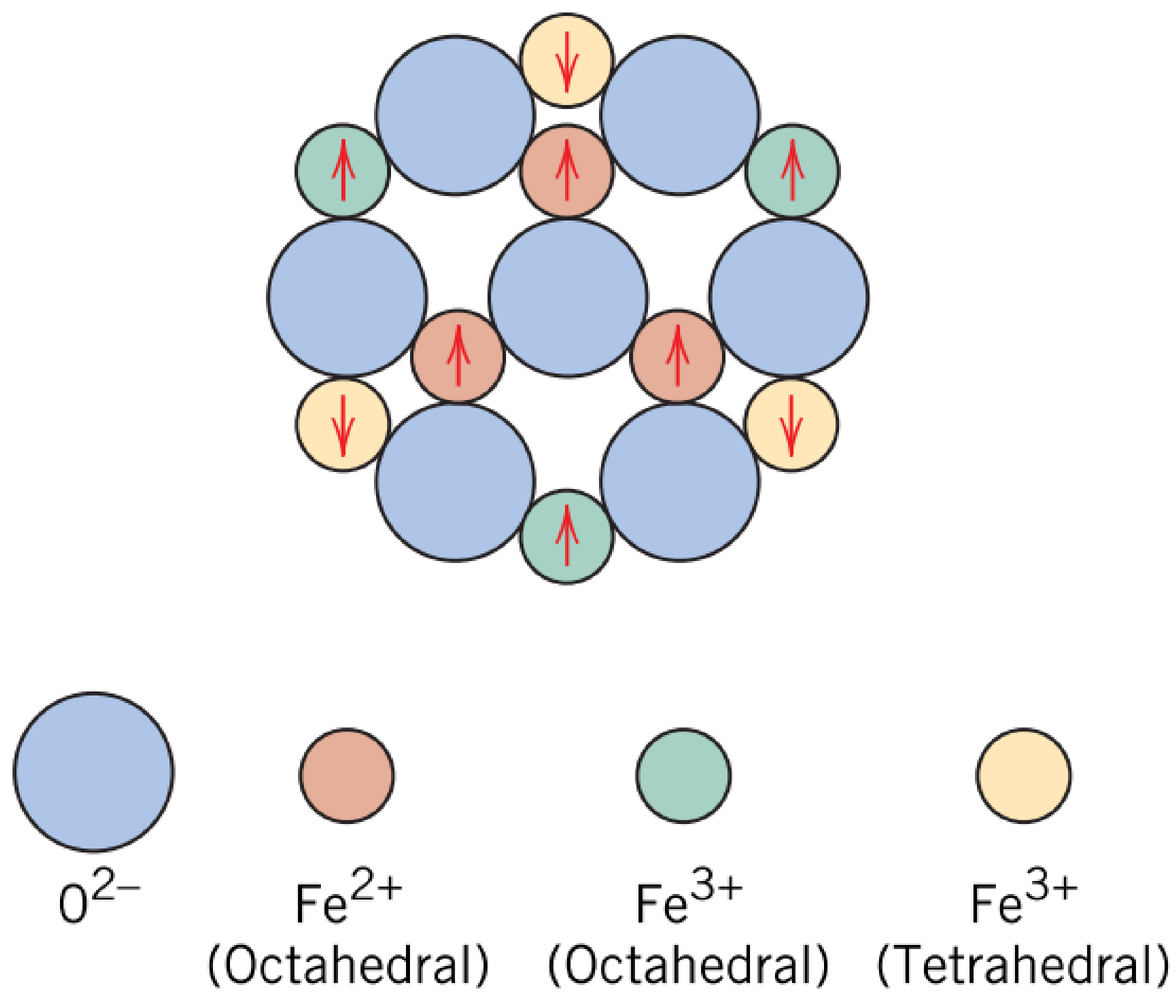
CASE STUDY: MnO

- Mn^{2+} ions possess a net magnetic moment (spin origin).
- O^{2-} ions has no magnetic moment due to cancellation of spin and orbital moments.
- These Mn^{2+} ions are arrayed in the crystal structure such that the moments of adjacent ions are antiparallel.
- The opposing magnetic moments cancel one another, consequently, the solid do not possesses net magnetic moment.



Ferrimagnetism

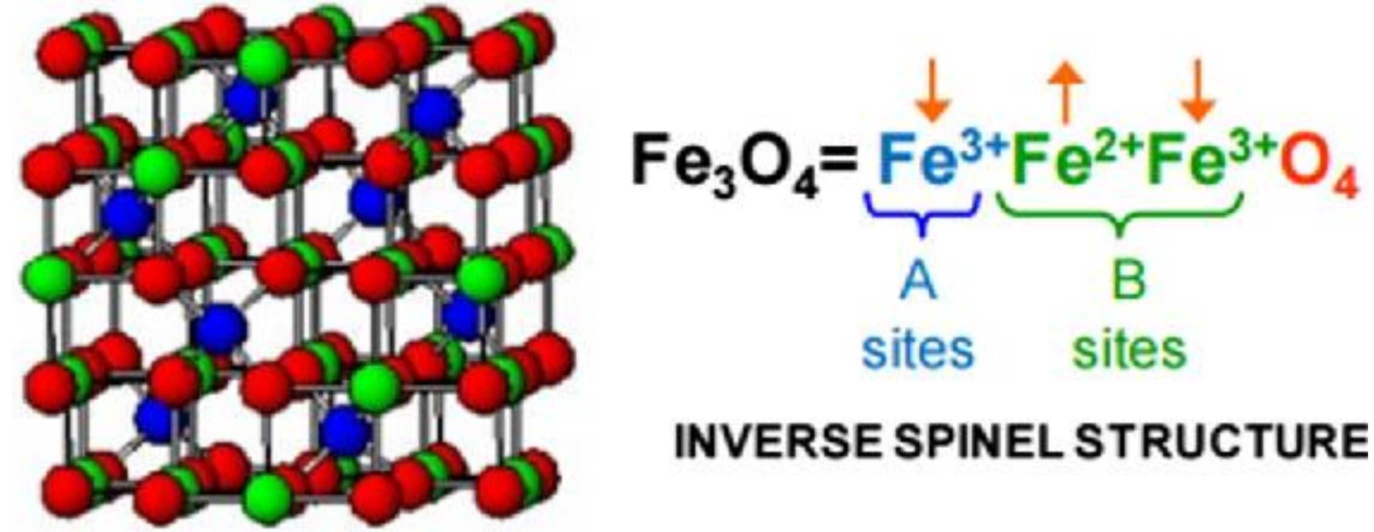
1. Constituent atoms may be antiferromagnetically coupled, but can have different magnetic moments.
2. Hence, there is some net magnetic moment in each coupling.
3. e.g. $MnFe_2O_4$, Fe_3O_4, $NiFe_2O_4$



Ferrimagnetism

Case study: Fe_3O_4

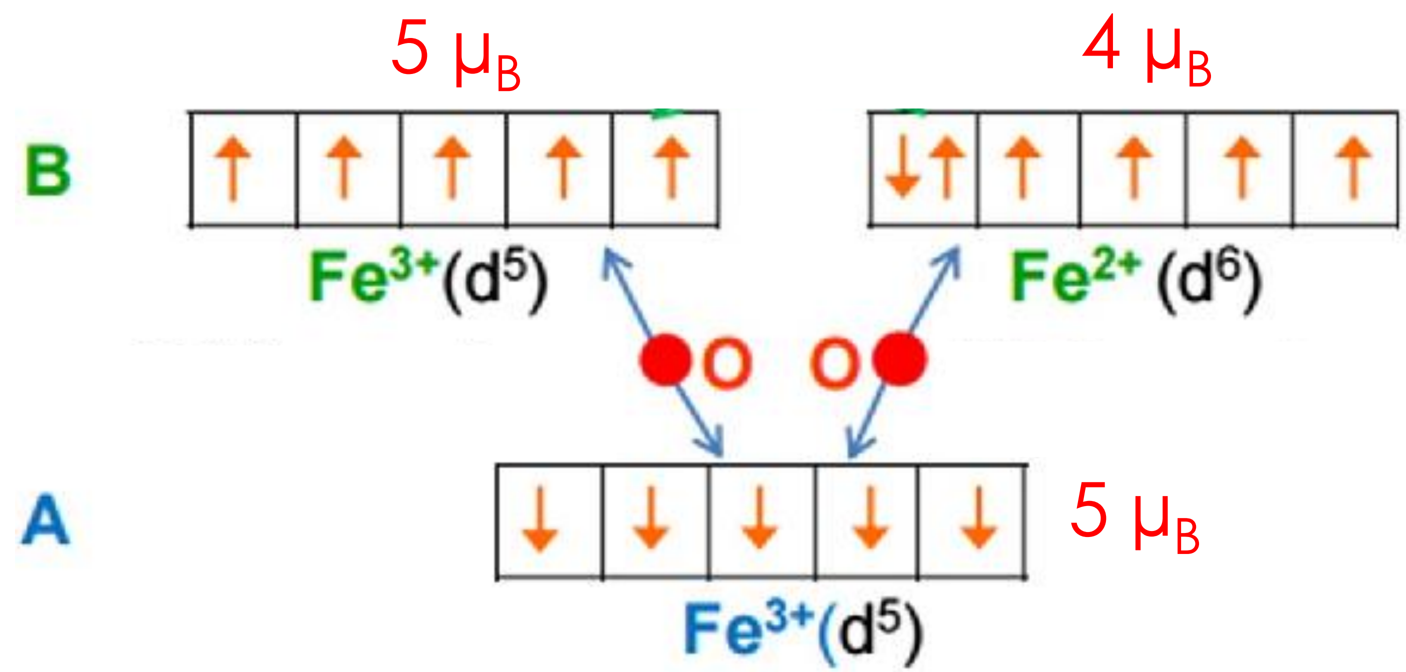
General formula is MFe_2O_4 (M is a bi-valent metal like Fe, Ni, Co, Zn, Mg, Mn, etc.); crystallizes in inverse spinel structure.



50% B - tetrahedral sites

A and 50% B - octahedral sites

O^{2-} ions are magnetically neutral.



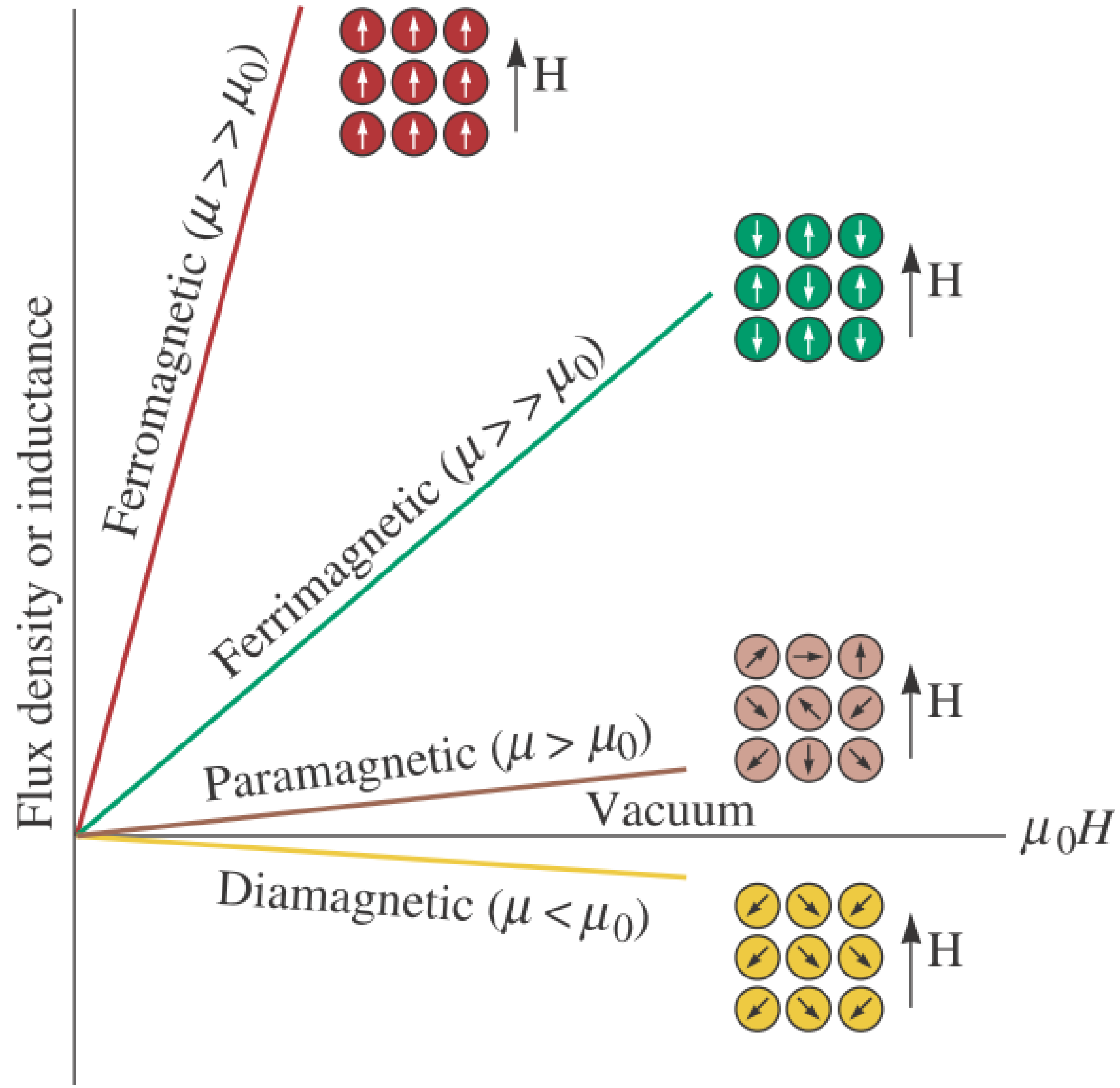
From the magnetism point of interest, the cations occupying tetrahedral sites have their spins oppositely oriented with respect to the cations on octahedral sites.

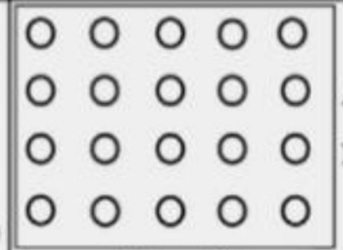
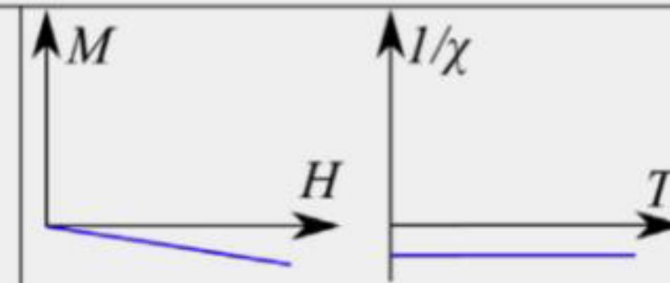
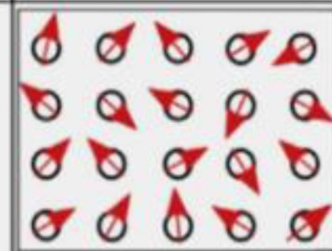
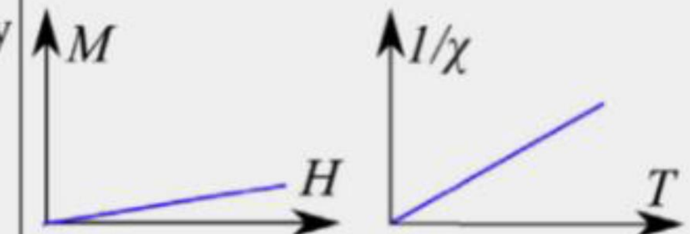
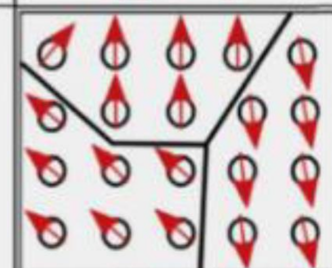
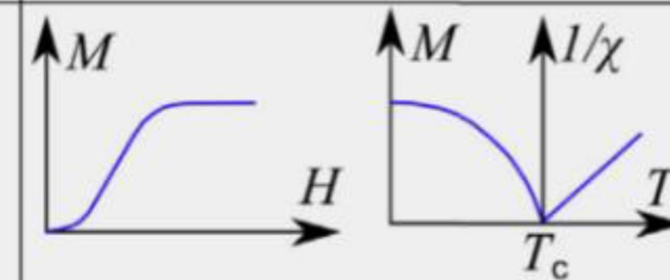
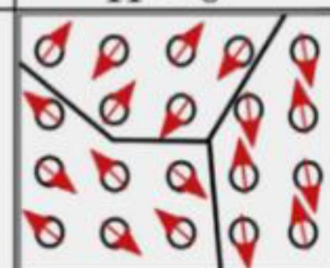
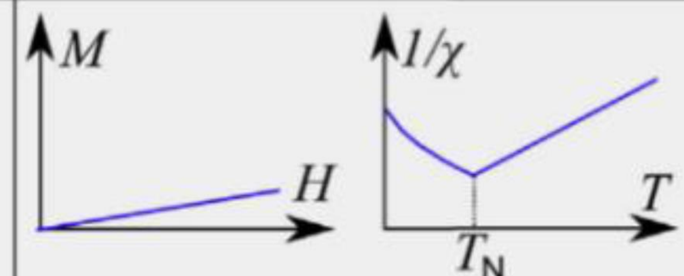
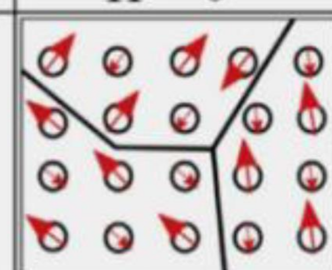
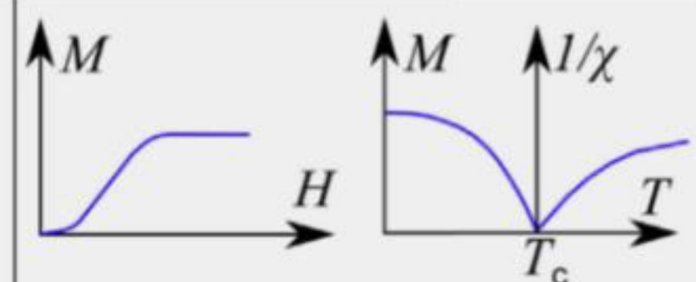
Net magnetic moment

$9\ \mu_B - 5\ \mu_B = 4\ \mu_B$

Summary

Relation of B and H in relation to the permeability.



Magnetism	Examples	Magnetic behaviour
Diamagnetism	Bi, Si, Cu, inert gases Susceptibility small and negative (-10^{-6} to -10^{-5})	 H = 0 Atoms have no magnetic moments. 
Paramagnetism	Al, O_2, MnBi Susceptibilty small and positive (10^{-5} to 10^{-3})	 H = 0 Atoms have randomly oriented magnetic moments. 
Ferromagnetism	Fe, Ni, Co, Gd Susceptibility large (generally > 100)	 H = 0 Atoms are organized in domains which have parallel aligned magnetic moments. 
Antiferromagnetism	Cr, MnO, FeO Susceptibilty small and positive (10^{-5} to 10^{-3})	 H = 0 Atoms are organized in domains which have antiparallel aligned moments. 
Ferrimagnetism	Fe_3O_4, $MnFe_2O_4$, $NiFe_2O_4$ Susceptibility large (generally > 100)	 H = 0 Atoms are organized in domains which have a mixture of unequal antiparallel aligned moments. 

Summary

1. Magnetism is produced by moving charges such as electrons in an atom.
2. Diamagnetic materials do not posses any intrinsic magnetic moment.
3. Diamagnetic materials shows very small and negative susceptibility.
4. Ferromagnetic materials shows large and positive susceptibility.
5. Domain is a cluster of alike spins forms to minimize energy.
6. In antiferromagnetic materials, there is complete cancellation of magnetic moments.