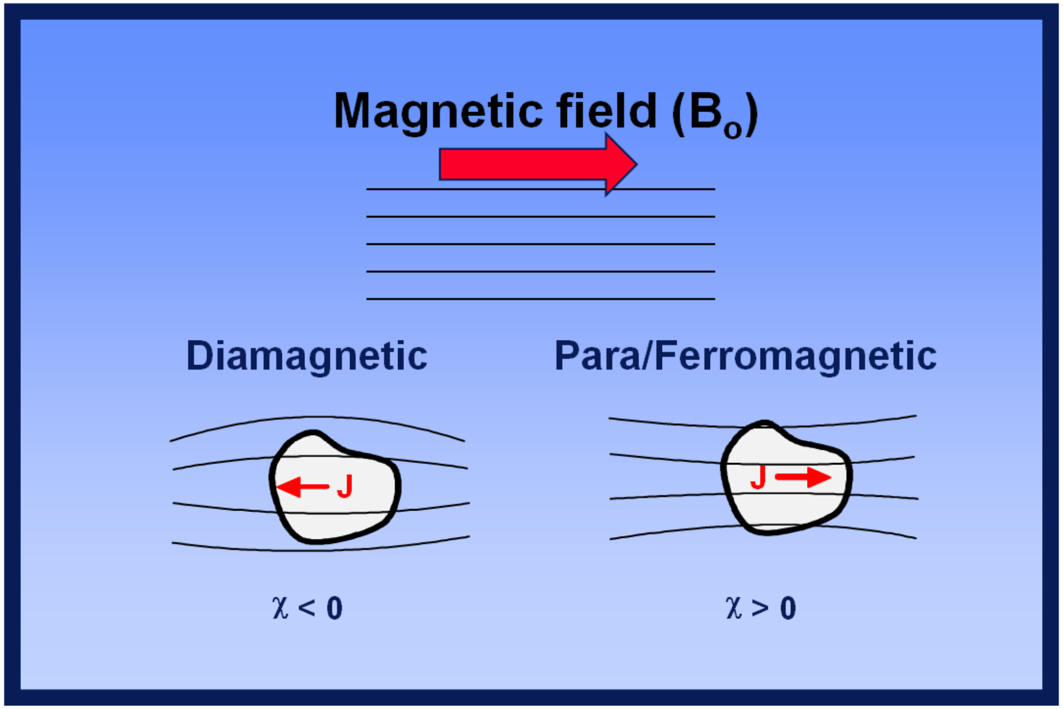
What is Diamagnetism?

$$\Delta\mathbf{m} \propto -\mathbf{B}$$

The induced net magnetic dipole moment is ***opposite*** to the field.

Origin: Lenz Law: Small ring currents are induced in the atomic orbitals which generate a magnetic moment antiparallel to the applied field direction.

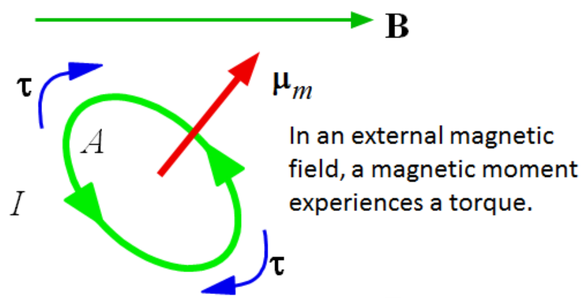
Present in any material!



What is Paramagnetism?

Inside matter there are a lot of ***tiny currents*** due to the electrons orbiting around the nuclei and intrinsic spins.

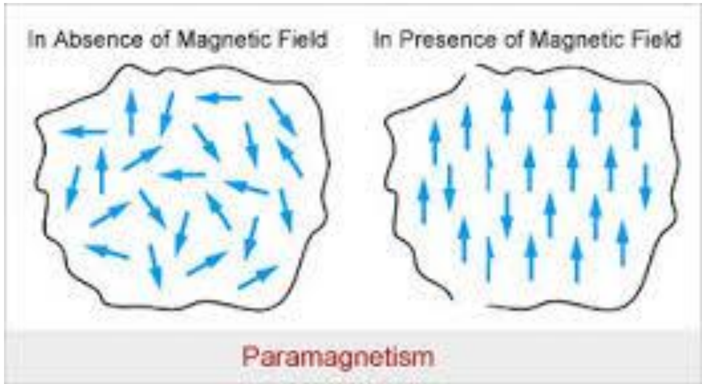
The scale of these small ***"current loops"*** are so small that the applied B-field can be considered uniform.



In a ***uniform*** B-field, $\mathbf{m}\cdot\mathbf{B}$ is ***constant*** and so

$$\mathbf{F}=\nabla(\mathbf{m}\cdot\mathbf{B})=0$$

The ***torque***, $\mathbf{N}=\mathbf{m}\times\mathbf{B}$, however, is ***non-zero*** & ***tends to align*** $\mathbf{m}$ ***in the same direction of*** $\mathbf{B}$



Quantum numbers

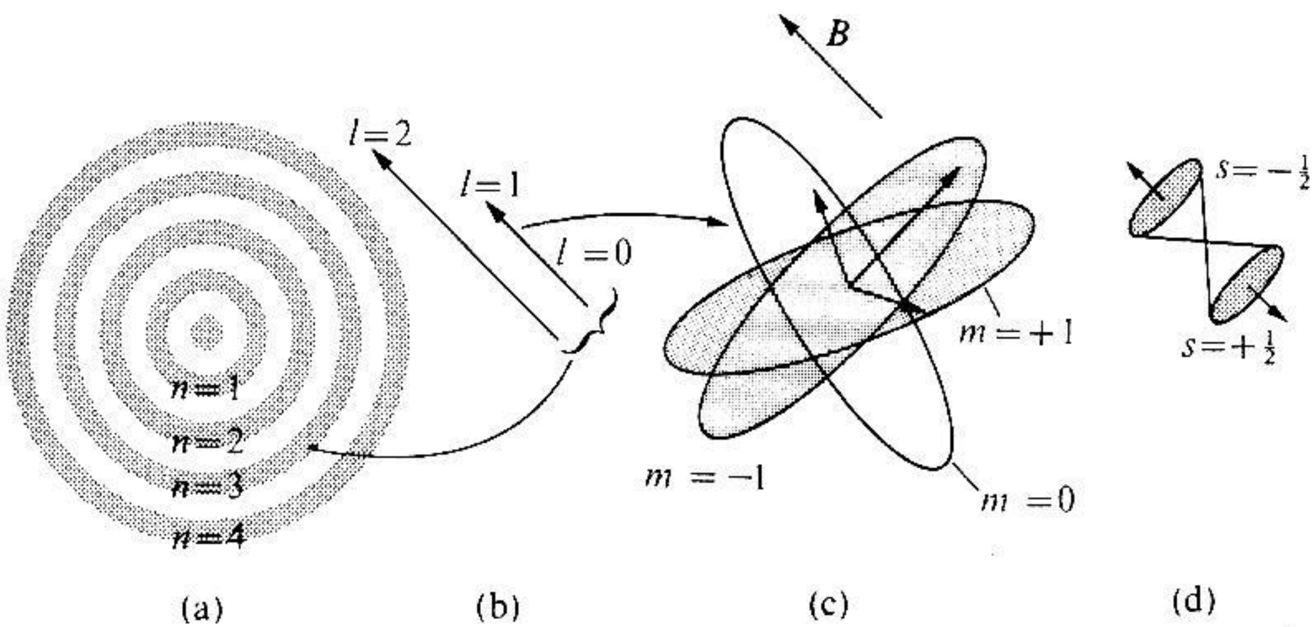
The motion of the electrons about a nucleus can be characterized by ***four quantum numbers n, l, m,* and *s***.

The **principal quantum number** ***n*** is an integer with values 1, 2, 3 … that characterizes the total energy.

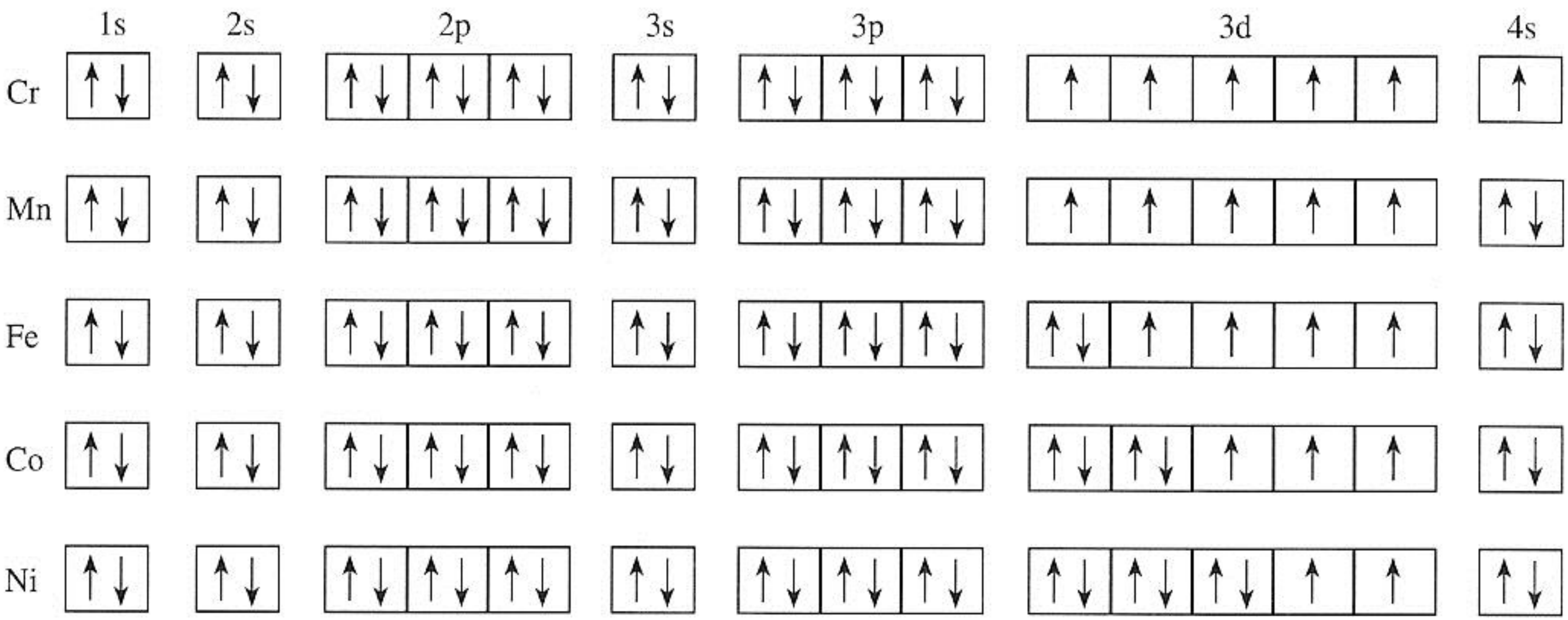
The orbital (angular momentum) quantum number ***l*** for a given ***n*** has values 0 to (n-1).

Magnetic quantum number ***m*** has values –l, …, 0, …, +l.

Spin quantum number ***s*** can only have two values, -½ and +½ .



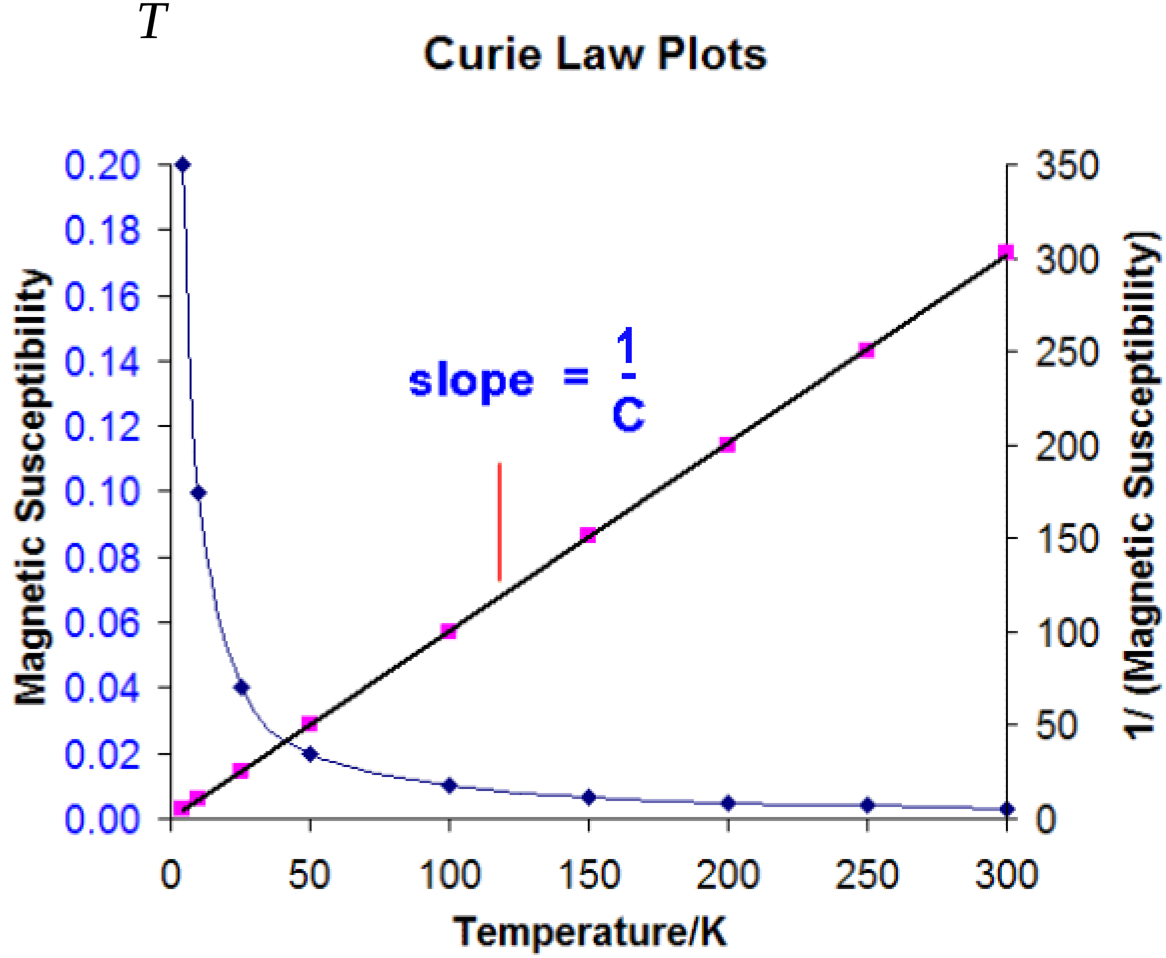
(3) The states of the atom or ion are characterized by a quantum number **J** which runs in steps **from L-S to L+S**. The ground state is given by **J = |L-S|** for a shell which is ***less than half full*** and by **J = L+S** for a shell which is ***more than half full***.



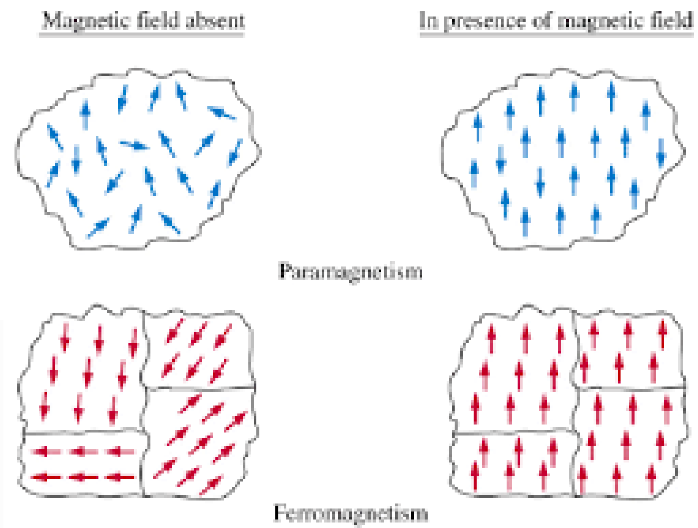
3d-shell	Cr	Mn	Fe	Co	Ni
S	5/2	5/2	2	3/2	1
L	0	0	2	3	3
J	5/2	5/2	4	9/2	4

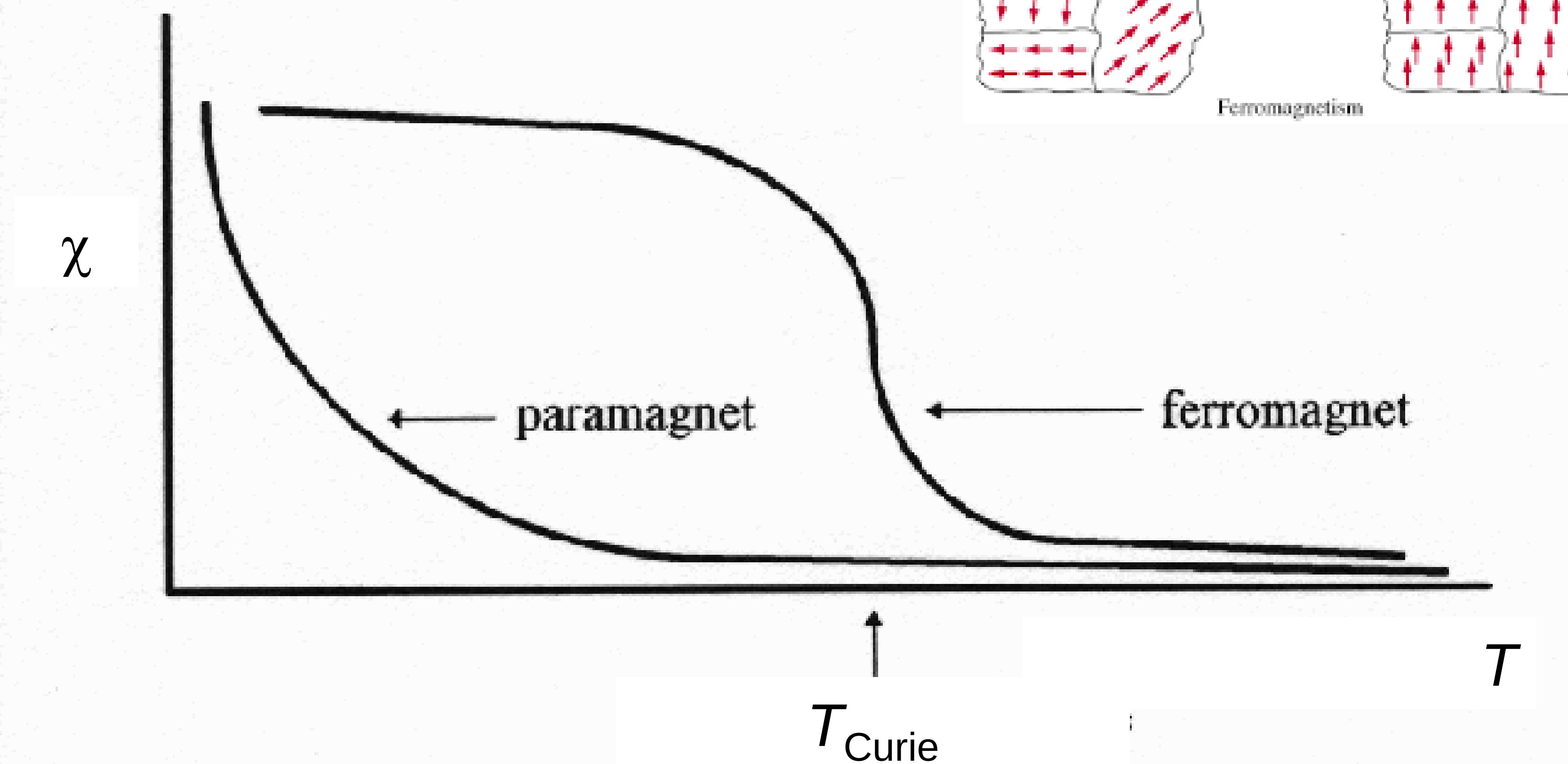
Curie's law

$$\chi_V = \frac{\mu_0 N_V g^2 \beta^2 J(J+1)}{3kT} = \frac{C}{T}$$



Ferromagnetism

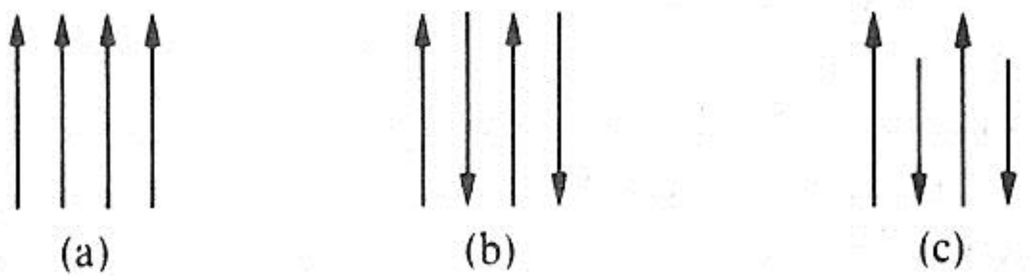




Ferromagnetism, Antiferromagnetism and Ferrimagnetism

Interactions between magnetic ions

The interactions between the magnetic ions can be strong enough to yield a mutual alignment of magnetic moments.



ferromagnetic antiferromagnetic ferrimagnetic

Dipole-dipole interactions: *the effect of the magnetic field of one dipole on its neighbor*.

This effect is very weak and can be completely disregarded, except at very low temperatures!

The magnitude of the magnetic energy due to dipole-dipole interaction can be estimated to have the order of $m_mB = \mu_0 m_m H = \mu_0 m_m^2 / (4\pi d^3)$

If m_m is the Bohr magneton (0.9×10^{-23} Am^2) and *d* is the interatomic spacing (0.3nm), this energy is ~ 3×10^{-25}J, equivalent to the thermal energy kT at $T = 10^{-2}$ K!

Exchange interaction:

A consequence of the quantum nature of the system.

If the ***wave functions of two atoms overlap***, then the electrons of atom 1 are to some extent also associated with atom 2, and vice versa. Thus some interaction must exist between two groups of electrons because they can exchange their roles. In particular, there is a correlation between their spins to reduce the system energy.

In **ferromagnetic materials** the resultant spin correlation is the **parallel orientation**. But for most materials it results in antiparallel alignment.

Ferromagnetism; the internal (or molecular) field

Ferromagnetic materials spontaneously acquire a permanent magnetic dipole moment below a critical temperature, called the Curie temperature T_c. Above T_c, they behave as ordinary paramagnets.

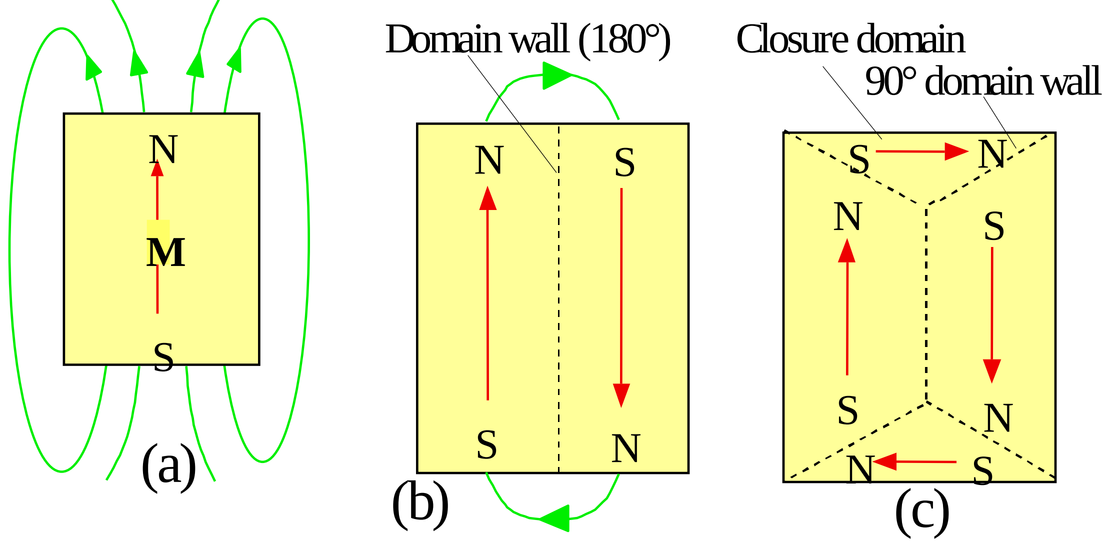
Alignment of the elementary dipoles is treated in terms of the exchange interaction:

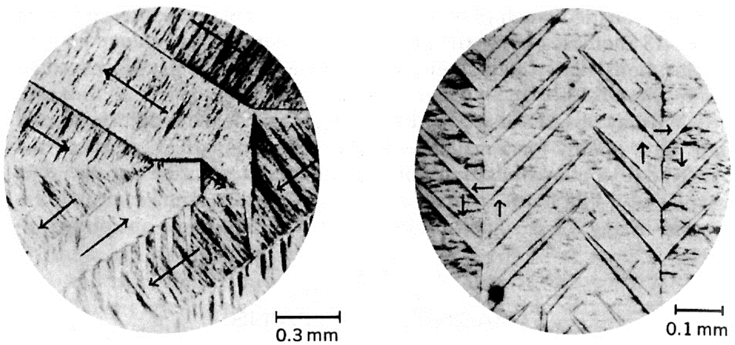
$$\boxed{E_{ex} = -S_i \sum_j J_{ij} S_j}$$

is the energy of ion *i* with spin S_i due to exchange interactions with its neighbors j_1, j_2, …, J_{ij} is the strength of the interaction. The summation is over all the j.

Ferromagnetic domains

A **magnetic domain** is a region of the crystal in which all the spin magnetic moments are aligned to produce a magnetic moment in one direction only.





The formation of domains induces **domain boundaries** (domain or Bloch walls), where the orientation of the moments changes. This ***requires energy***!

The creation of magnetic domains continues spontaneously until the energy gain is balanced by the energy increase.

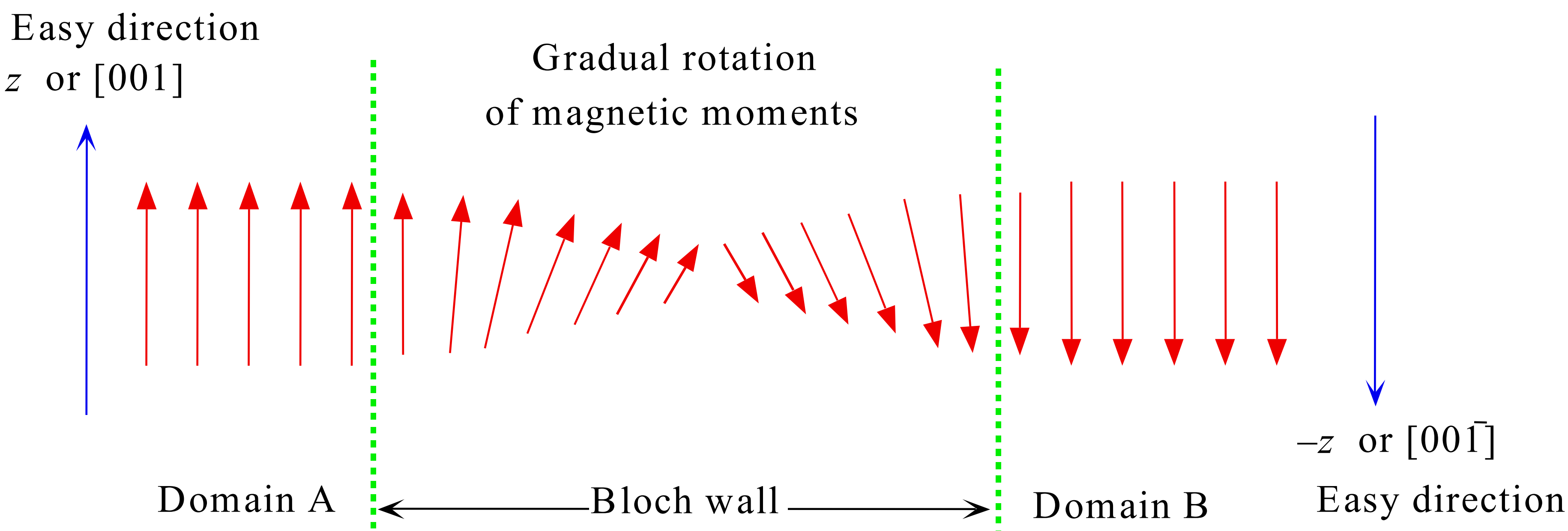
The specimen is then in equilibrium with no net magnetization macroscopically.

(a) If the whole specimen is magnetized in one direction, like a bar magnet, there is a large amount of magnetic energy stored in the field outside.

(b) This energy can be greatly reduced by dividing the material into two domains magnetized in opposite directions.

(c) This energy is further reduced by closure domains at the ends of the crystal with magnetizations at 90º.

Domain walls: a domain wall is not simply one atomic spacing wide. Exchange forces between neighboring atomic spins favor very little relative rotation, demanding a very thick wall. On the other hand, magnetic moments orientated away from the easy direction possess excess energy, i.e. anisotropy energy, demanding a very thin wall. In reality, the wall thickness is a compromise to get minimum total energy. In a domain wall, the neighboring spin magnetic moments rotate gradually, and it takes several hundred atomic spacings to rotate the magnetic moment by 180º.



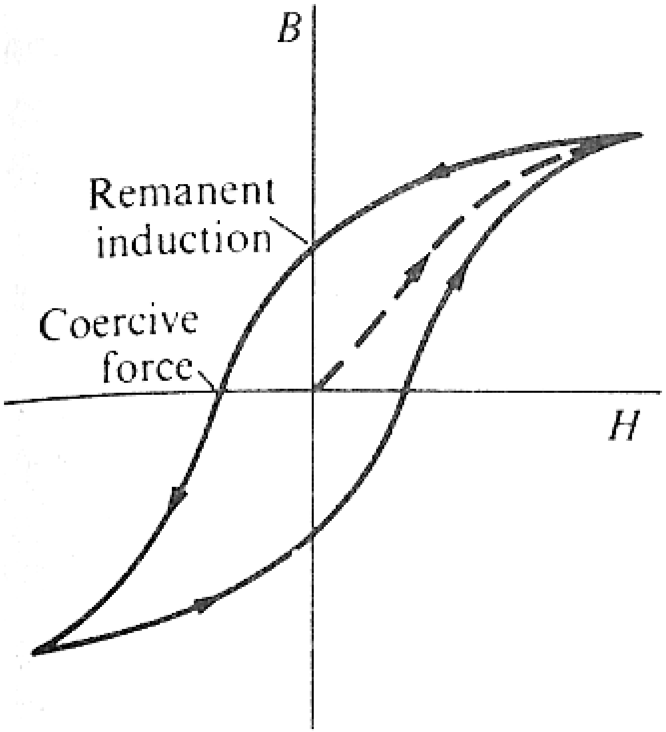
The hysteresis curve

$$\mathbf{B} = \mu_0\mathbf{M} + \mu_0\mathbf{H}$$

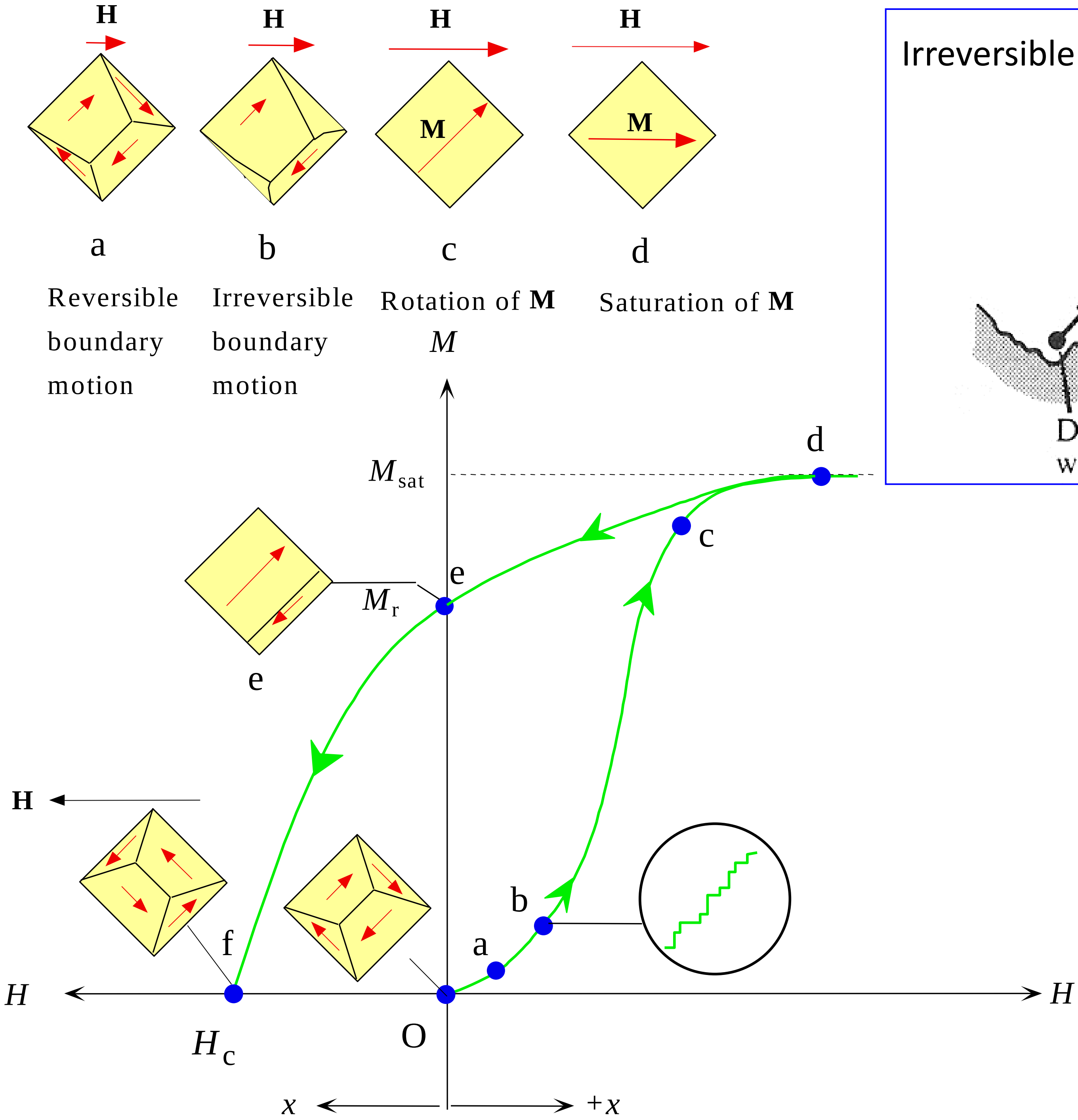
When a ferromagnet is placed in a cyclic magnetic field, the magnetization and the value of B within the material follow a typical **hysteresis curve**.

After a cycle is completed and H is again zero, the material retains some magnetization and this is called the **remanence**.

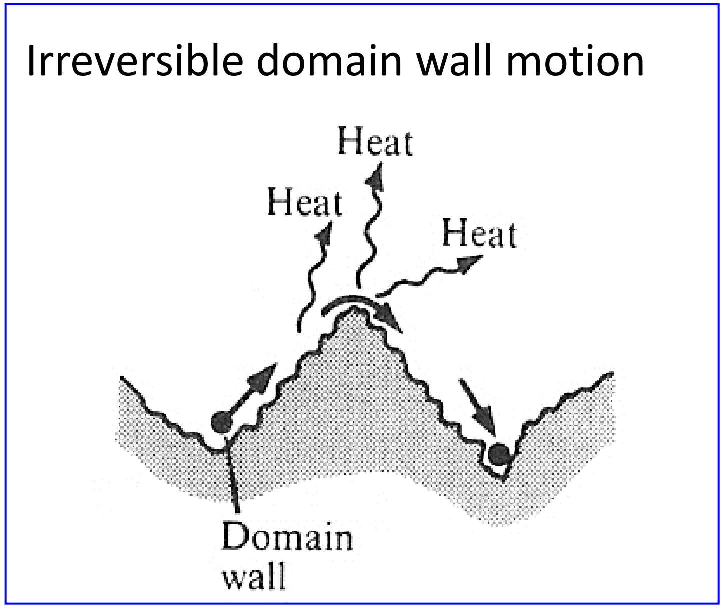
In order to reduce B to zero, a reverse intensity, the **coercive force** is required.



The energy dissipated during the cycle is equal to the area enclosed by the curve.



H
H
H
H
M
M
a
b
c
d
Reversible boundary motion
Irreversible boundary motion
Rotation of M
Saturation of M
M
d
M_{sat}
c
e
M_r
e
H
b
f
a
H
H
H_c
O
x
+x



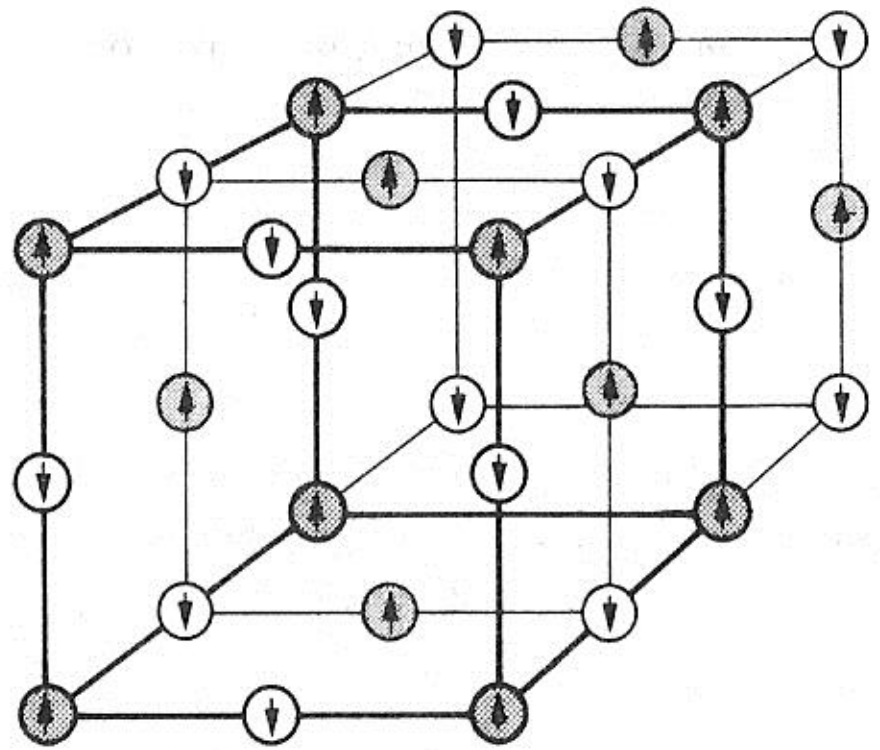
Irreversible domain wall motion
Heat
Heat
Heat
Domain wall

Antiferromagnetism

In most cases the exchange energy is minimized when *neighboring spins are antiparallel* forming *antiferromagnetic ordering*. The alignment of spins in an antiparallel array is also a cooperative transit and it occurs at a temperature known as the Neel temperature, T_N.

The antiferromagnetic ordering can be considered as two interpenetrating sub-lattices which are magnetized in opposite directions.

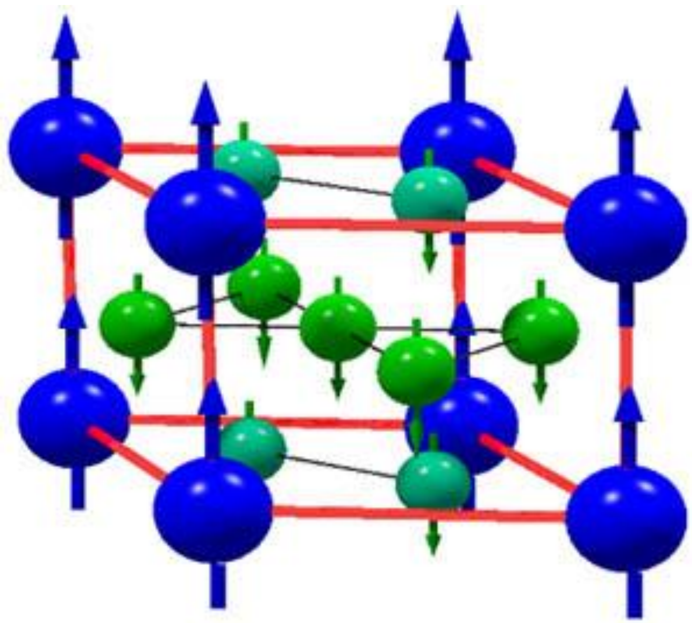
No net magnetization!



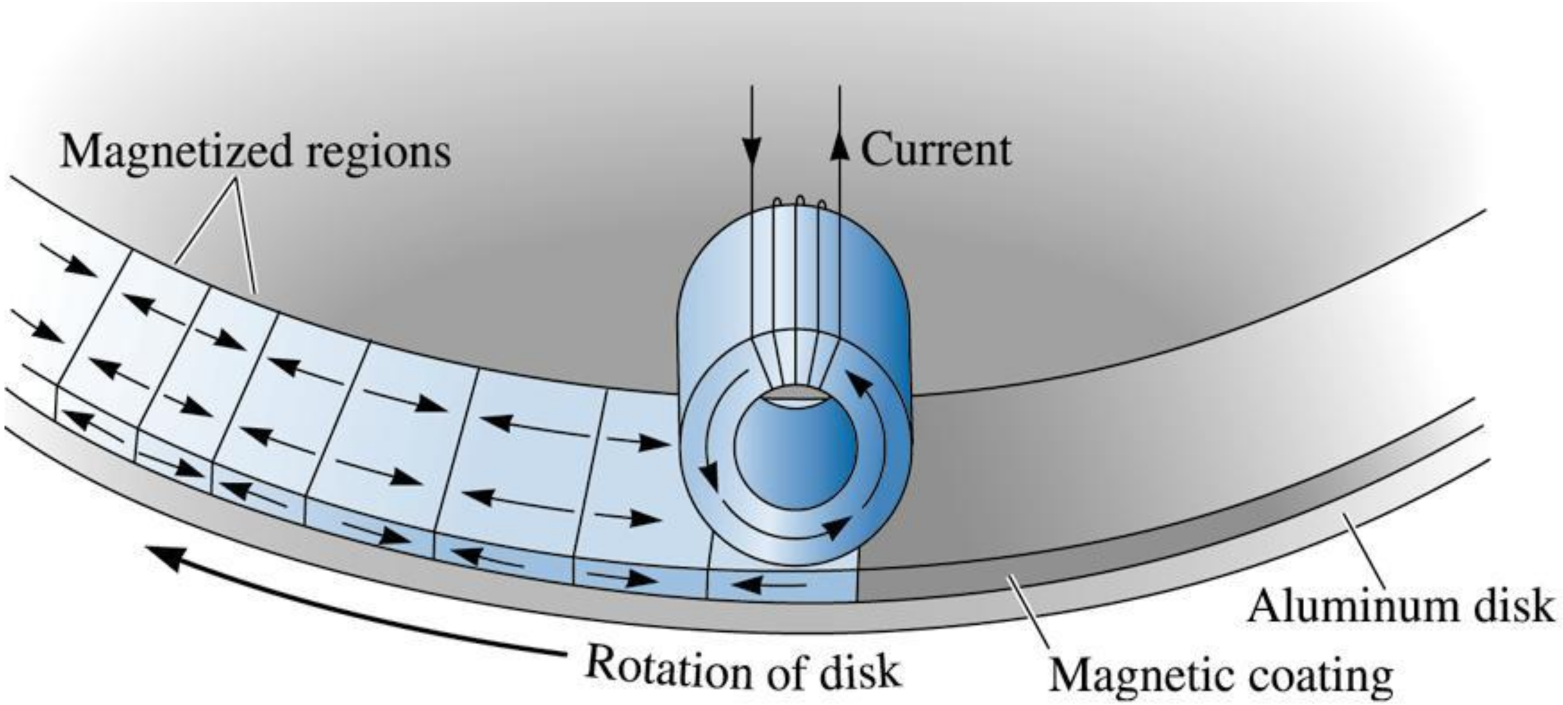
Ferrimagnetism

In some crystals the *magnitude of the magnetic moments on each of the two sub-lattices are not exactly the same*. When spontaneous antiparallel alignment occurs, the crystal has a *net permanent magnetization*. This phenomenon is known as ferrimagnetism.

When they are magnetized their behavior is very similar to that of ferromagnets. The also have a domain structure.



Applications of Magnetic Materials



Information can be stored or retrieved from a magnetic disk by use of an electromagnetic head. A current in the head magnetizes domains in the disk during storage; the domains in the disk induce a current in the head during retrieval.

Spintronics

Spintronics: (a neologism for "spin-based electronics"), also known as magnetoelectronics, is an emerging technology which exploits the quantum spin states of electrons as well as making use of their charge state.

The electron spin itself is manifested as a two state magnetic energy system.

In order to make a spintronic device, the primary requirement is to have a system that can generate a current of spin polarized electrons, and a system that is sensitive to the spin polarization of the electrons.

Spintronics

- Conventional electronic devices ignore the spin property and rely strictly on the transport of the electrical charge of electrons

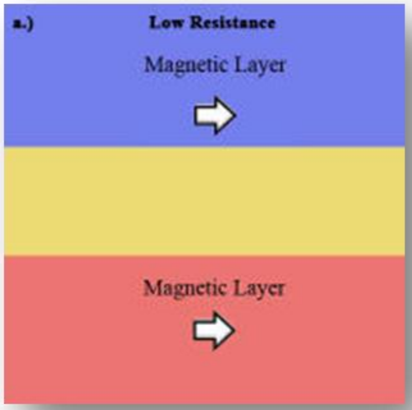
- Adding the spin degree of freedom provides new effects, new capabilities and new functionalities

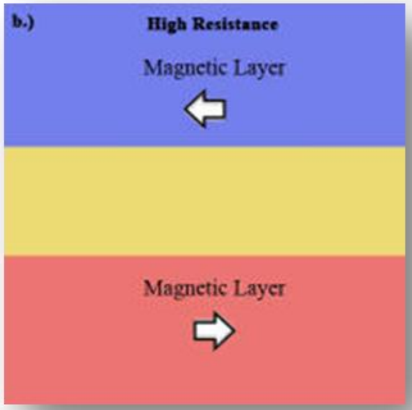
Advantages of Spin

- Information is stored into spin as one of two possible orientations
- Spin lifetime is relatively long, on the order of nanoseconds
- Spin currents can be manipulated
- Spin devices may combine logic and storage functionality eliminating the need for separate components
- Magnetic storage is nonvolatile
- Binary spin polarization offers the possibility of applications as qubits in quantum computers

GMR

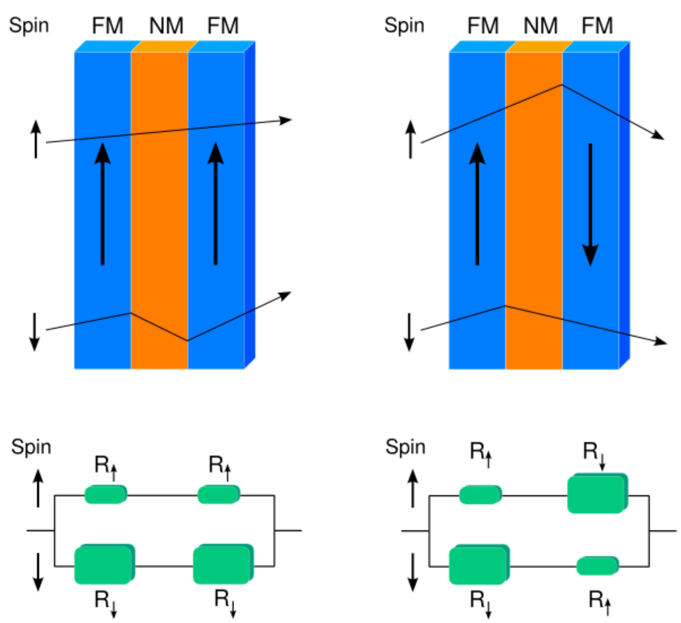
- 1988 France, GMR discovery is accepted as birth of spintronics
- A Giant Magneto-Resistive device is made of at least two ferromagnetic layers separated by a spacer layer
- When the magnetization of the two outside layers is aligned, lowest resistance
- Conversely when magnetization vectors are antiparallel, high R
- Small fields can produce big effects





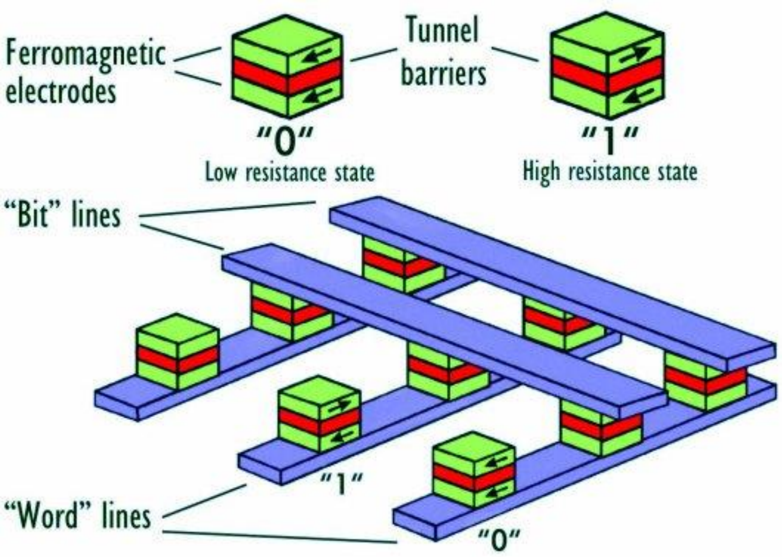
Spin Valve

- Simplest and most successful spintronic device
- Used in HDD to read information in the form of small magnetic fields above the disk surface

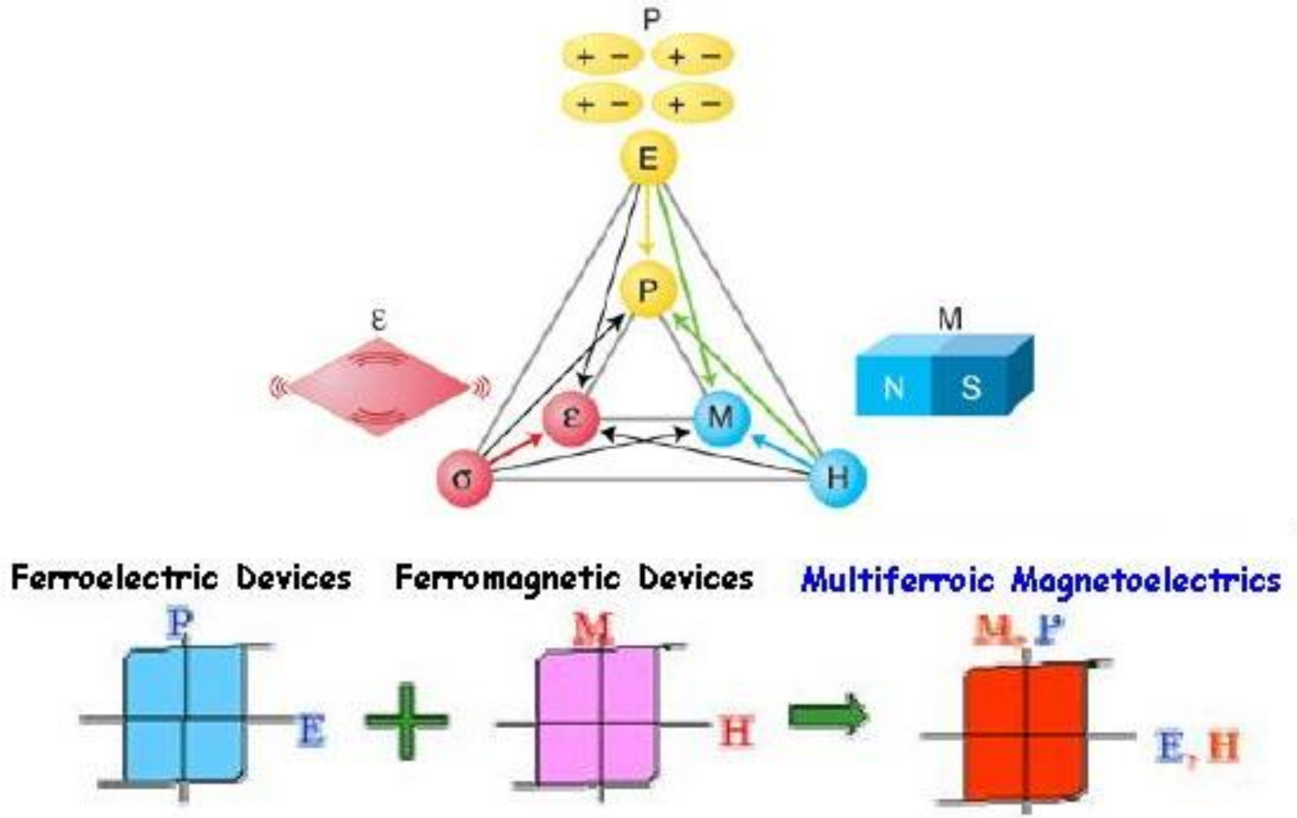


MRAM

- MRAM uses magnetic storage elements instead of electric used in conventional RAM
- Tunnel junctions are used to read the information stored in Magnetoresistive Random Access Memory, typically a ”0” for zero point magnetization state and “1” for antiparallel state



Multiferroics have been formally defined as materials that exhibit more than one primary ferroic order parameter simultaneously and the order parameters are coupled to each other.



Most promising: ferromagnetic-ferroelectric materials: magnetization can be controlled by electrical fields and polarization by magnetic fields. Ideal for data storage and sensors.

http://www.uic.edu/labs/AMReL/NIRT/index.html

Problem: Magnetism and Ferroelecticity mutually exclusive

Magnetism requires partially filled d or f-shells, ferroelectricity requires completely filled shells.

Most of the known single phase bulk magnetoelectric materials do not exhibit strong magnetoelectric coupling.

Large magnetoelectric effects have been discovered in composites, laminates and more recently in nanostructured materials.

But how to couple magnetism and ferroelectic order with each other in composite materials?

One solution: Use the strain associated with the magnetic and ferroelectric orders. Large interfaces required, for example magnetic and ferroelectric multilayers.