5. Magnetic Properties

5A. Magnetization of Matter
5B. Classification of Magnetic Materials
5C. Magnetic Domains in Ferromagnetic Materials
5D. Ferromagnetic Hysteresis
5E. Magnetoresistance

The magnetic and electrical properties are intimately connected, but they are quite distinct from each other. This is mainly because **magnetic** properties essentially derive from the **electron spin** while the **electrical** properties are related to the **electron charge**.

5A. Magnetization of Matter

Magnetic Dipole Moment
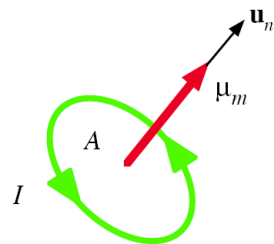
I — **Current**

μ_m — **Magnetic Moment**

$\mathbf{u}_n$ — **Unit Vector Normal to the Surface**

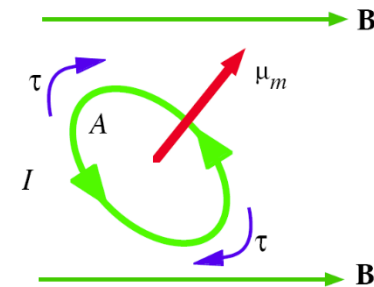A — **Area Circled by Current**
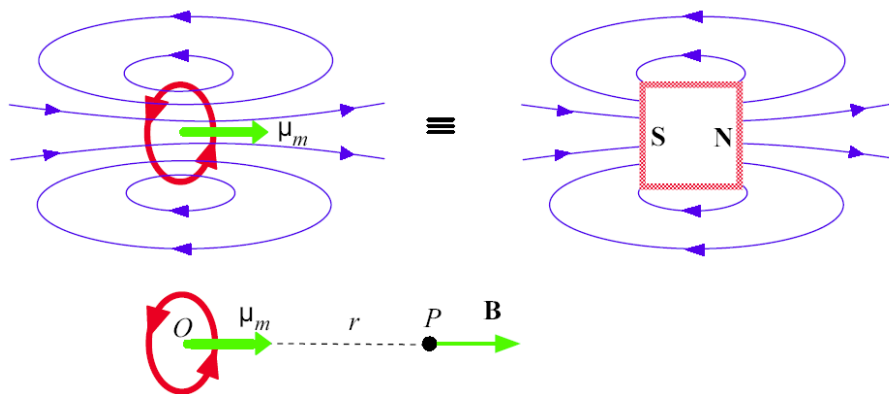
The energy of the magnetic dipole is given by

$$E = -\mu_m \cdot \mathbf{B}$$

where **B** is the magnetic field at the position of the magnetic dipole.

A magnetic dipole moment in an external field experiences a torque to align along **B**.

A magnetic dipole moment puts out a magnetic field **just like bar magnet**. The field **B** depends on μ_m.

Polarization P

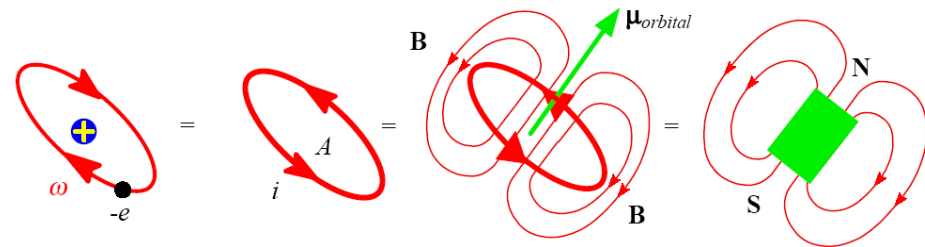$$\mathbf{P} = \frac{1}{V}\,[\mathbf{p}_1 + \mathbf{p}_2 + \ldots + \mathbf{p}_N]$$

$$D = E + 4\pi P$$

Magnetic dipole moment of the electron

The orbiting electron is equivalent to a current loop that behaves like a bar magnet. The resulting magnetic moment is called the orbital magnetic moment ($\boldsymbol{\mu}_{\text{orbital}}$) is given by

$$\boldsymbol{\mu}_{\text{orbital}} = -\frac{e}{2m_e}\mathbf{L}$$

Likewise, the spinning electron can be imagined to be equivalent to a current loop. This current loop behaves like a bar magnet, just as in the orbital case. This produces the spin magnetic moment. ($\boldsymbol{\mu}_{\text{spin}}$)

$$\boldsymbol{\mu}_{\text{spin}} = -\frac{e}{m_e}\mathbf{S}$$
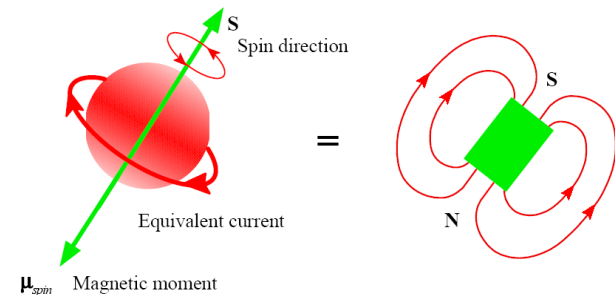
The total magnetic moment is

$$\boldsymbol{\mu}_{\text{tot}} = \boldsymbol{\mu}_{\text{orbital}} + \boldsymbol{\mu}_{\text{spin}} = -\frac{e}{2m_e}(\mathbf{L} + 2\mathbf{S})$$

We define a convenient unit for atomic-scale magnetic moment called Bohr magneton (μ_{B}).

$$\mu_{\text{B}} = \frac{e\hbar}{2m} = 9.27 \times 10^{-24} \text{ Am}^2 \text{ or JT}^{-1}$$

The electron spin has the magnitude of Bohr magneton.

3

5B. Classification of Magnetic Properties

$$\vec{H} = \vec{B} - 4\pi\vec{M}$$

$$\vec{M} = x_m\vec{H}$$

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

Type	χ_m (typical values)	χ_m versus T	Comments and Examples
Diamagnetic	Negative and small (-10^{-6}) *magnetic susceptibility*	T independent	Atoms of the material have closed shells. Organic materials, *e.g.*, many polymers; covalent solids, *e.g.*, Si, Ge, diamond; some ionic solids, *e.g.*, alkalihalides; some metals, *e.g.*, Cu, Ag, Au.
	Negative and large (-1)	Below a critical temperature	Superconductors
Paramagnetic	Positive and small $(10^{-5}-10^{-4})$	Independent of T	Due to the alignment of spins of conduction electrons. Alkali and transition metals.
	Positive and small (10^{-5})	Curie or Curie–Weiss law, $\chi_m = C/(T - T_C)$	Materials in which the constituent atoms have a permanent magnetic moment, *e.g.*, gaseous and liquid oxygen; ferromagnets (Fe), antiferromagnets (Cr), and ferrimagnets (Fe$_3$O$_4$) at high temperatures.
Ferromagnetic	Positive and very large	Ferromagnetic below and paramagnetic above the Curie temperature	May possess a large permanent magnetization even in the absence of an applied field. Some transition and rare earth metals, Fe, Co, Ni, Gd, Dy.
Antiferromagnetic	Positive and small	Antiferromagnetic below and paramagnetic above the Néel temperature	Mainly salts and oxides of transition metals, *e.g.*, MnO, NiO, MnF$_2$, and some transition metals, α–Cr, Mn.
Ferrimagnetic	Positive and very large	Ferrimagnetic below and paramagnetic above the Curie temperature	May possess a large permanent magnetization even in the absence of an applied field. Ferrites.

Most industrial applications are based on the **ferromagnetic** and ferrimagnetic materials.

Strictly speaking, this is the classification on magnetic properties. A material may exhibit different magnetism, for instance, **depending on the temperature**. (Most metals become diamagnetic below superconducting transition temperature.) Nevertheless, we often call "***xxx***magnetic material" according to its magnetism at room temperature.
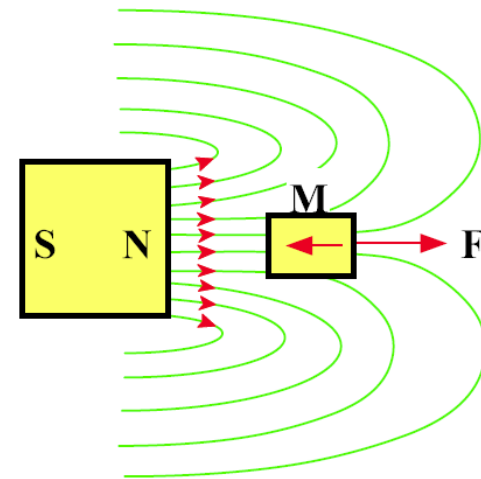
5B.1. Diamagnetism

A substance exhibits diamagnetism whenever the constituent atoms in the material have closed subshells and shells. This means that each constituent atom has **no permanent magnetic moment** in the absence of an applied field. Covalent crystals and many ionic crystals are typical diamagnetic materials because the constituent atoms have **no unfilled subshells**.

- $\vec{B} = \mu \vec{H}$
- $\vec{B} = \vec{H} + 4\pi \vec{M}$
- $\vec{M} = x_m \vec{H}$

The origin of diamagnetism is Lenz's law which states that when the flux through an electrical circuit is changed, an induced current is set up in such a direction as to oppose the flux change.

A diamagnetic material placed in a non-uniform magnetic field experiences a force towards smaller fields. This repels the diamagnetic material away from a permanent magnet.
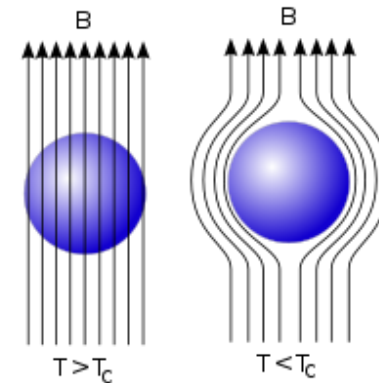
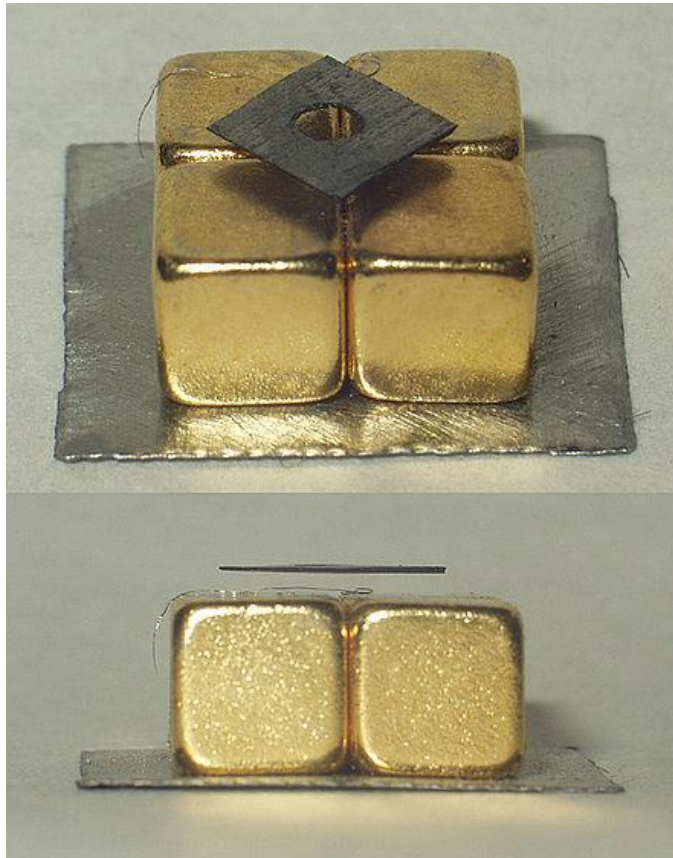## Superconductors

Of particular interests are superconductors that are **perfect diamagnets with $\chi_m = -1/4\pi$,** and totally expel the applied field from the material (Meissner effect).

This means that $B = (1+4\pi\chi_m)H = 0.$

$\mu = 0$

5B.1. Diamagnetism

Pyrolytic carbon has one of the largest diamagnetic constants of any room temperature material. Here a pyrolytic carbon sheet is levitated by its repulsion from the strong magnetic field of Nd (neodymium) magnets.

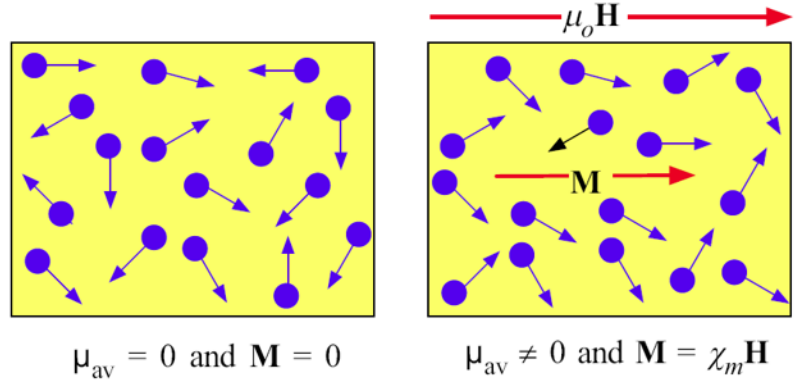$\mu = 0$

浮いた　土佐ノ海

TOSANOUMI
(Sumo Wrestler)

Height of Tosanoumi	186cm
Weight of Tosanoumi	142kg
Weight of disk	60kg
Total weight	202kg

As of February '98

協力：財団法人　日本相撲協会

Superconductor Levitation

5B.2. Paramagnetism

- $\vec{B} = \mu\vec{H}$
- $\vec{H} = \vec{B} - 4\pi\vec{M}$
- $\vec{M} = x_m\vec{H}$

Bound-Electron Paramagnetism

In a paramagnetic material, **each individual atom can possess a permanent magnetic moment that is contributed by <u>electron spin</u> or <u>orbital motions</u> of electrons (but mostly electron spin)**. It would be energetically favorable for them to align but due to *thermal agitation*, there is no average moment per atom and <u>***M = 0***</u>.

In the presence of an applied field, individual magnetic moments take alignments along the applied field, and ***M* is finite** and along ***B* (or *H*)**.

$\mu_{av} = 0$ and $\mathbf{M} = 0$ $\mu_{av} \neq 0$ and $\mathbf{M} = \chi_m\mathbf{H}$

$$\boldsymbol{\mu = 1}$$
$$\vec{M} = 0$$

$$\vec{M} \neq 0$$

A paramagnetic material placed in a non-uniform magnetic field experiences a force towards greater fields. This attracts the paramagnetic material (e.g. liquid oxygen) towards a permanent magnet.

Open shell structure

Strong magnet

Dewar

Liquid oxygen
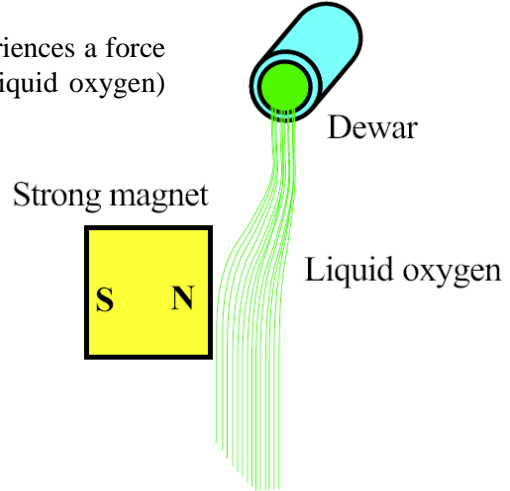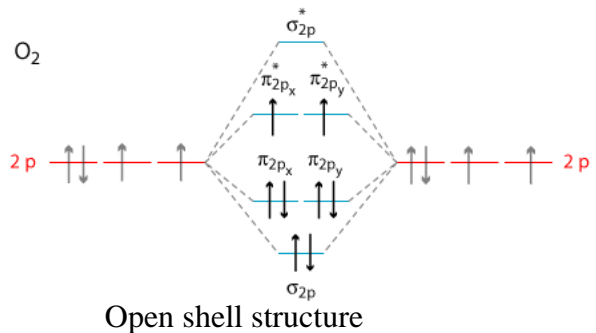
For simplicity, we consider an electron with $l = 0$ and $s = \frac{1}{2}$ such that the magnetic moment is $\mu_m = \mu_B$. Under the magnetizing field is H ($+z$ direction), the energy of spin-up and down will split:

$H = 0$ $H > 0$

$E = 0$

$\mu_B\mu_0 H$ — Spin up

$-\mu_B\mu_0 H$ — Spin down
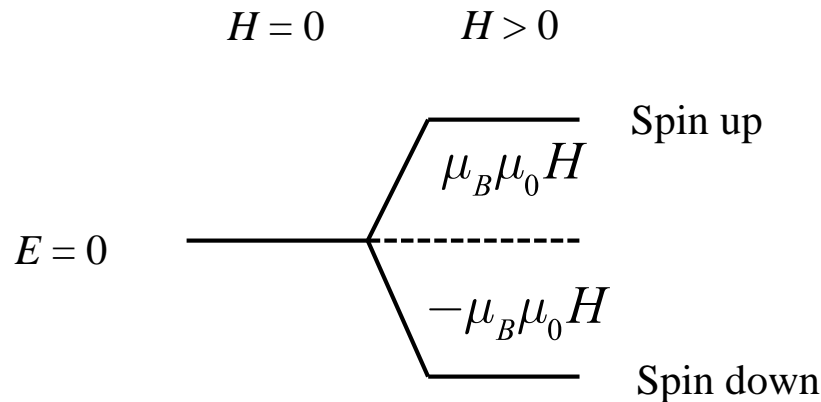
Note that the spin-up electron has the magnetic moment of $-\mu_B$ because of negative charge.

There are N such electrons in the unit volume and $N_\uparrow$ and $N_\downarrow$ are the numbers for up and down spin, respectively. The ratio between $N_\uparrow$ and $N_\downarrow$ is given by the Boltzmann factor since the magnetic moments are localized at each atomic site and so distinguishable.

$$\frac{N_\uparrow}{N_\downarrow} = e^{-2\mu_B\mu_0 H/kT} \rightarrow M = (N_\downarrow - N_\uparrow)\mu_B = N\mu_B\frac{e^{\mu_B\mu_0 H/kT} - e^{-\mu_B\mu_0 H/kT}}{e^{\mu_B\mu_0 H/kT} + e^{-\mu_B\mu_0 H/kT}} = N\mu_B\tanh(\frac{\mu_B\mu_0 H}{kT})$$

For small H, $\dfrac{\mu_B\mu_0 H}{kT} \ll 1$

$$\tanh(\frac{\mu_B\mu_0 H}{kT}) \simeq \frac{\mu_B\mu_0 H}{kT}$$

$$M = \frac{N\mu_B^2\mu_0 H}{kT} \Rightarrow \chi_{para} = \frac{N\mu_B{}^2\mu_0}{kT} = \frac{C}{T}$$

This is known as Curie's law and C is called the Curie constant. It is characterized by the inverse dependence on T.

Free-electron paramagnetism

For metals with free electrons, one contribution to the magnetic response comes from the interaction with the electron spins and the magnetic field known as Pauli paramagnetism.

$H = 0$

$H > 0$
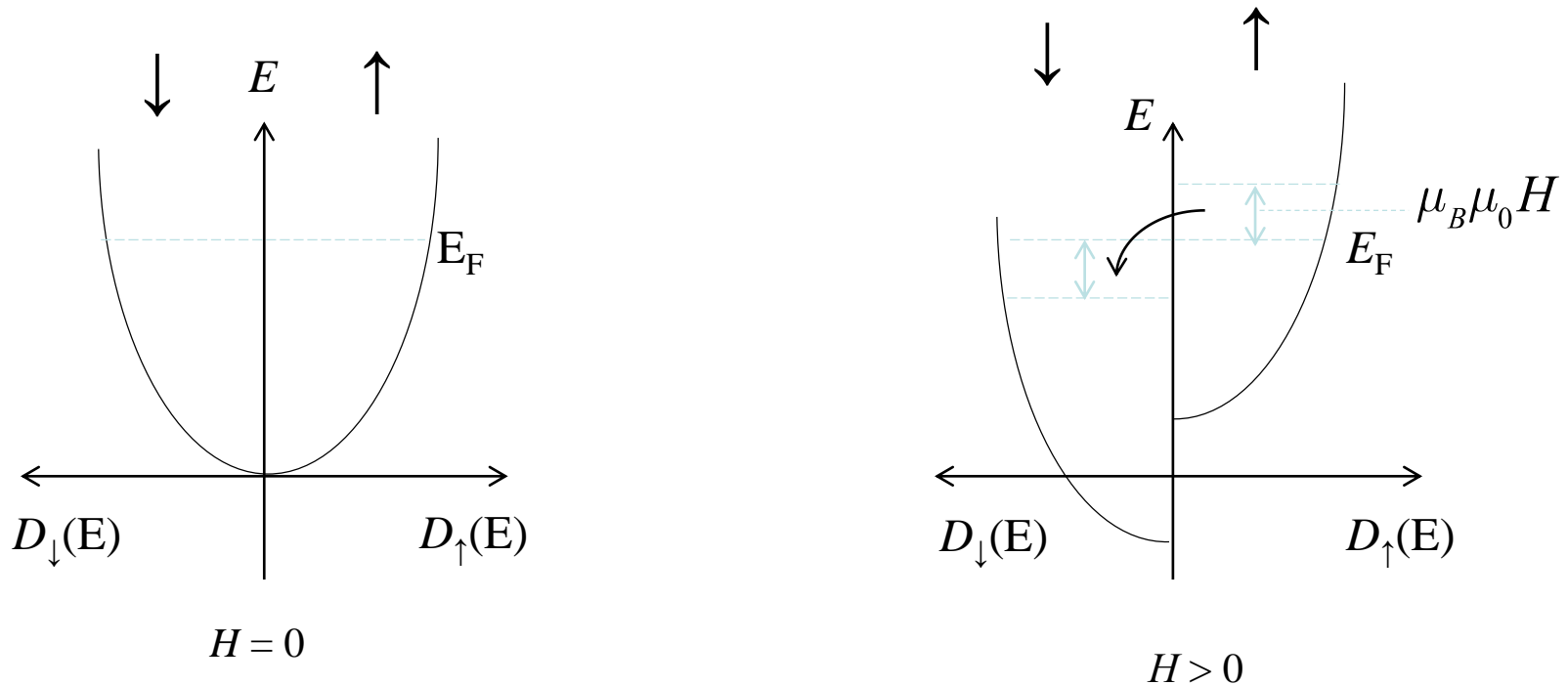
$\mu_B \mu_0 H \times D_\uparrow (E_F)$ changes the spin direction from up to down.

$$M = 2\mu_B^2 \mu_0 H D_\uparrow (E_F) \ \Rightarrow \ \chi_m = 2\mu_B^2 \mu_0 D_\uparrow (E_F) = \mu_B^2 \mu_0 D(E_F)$$
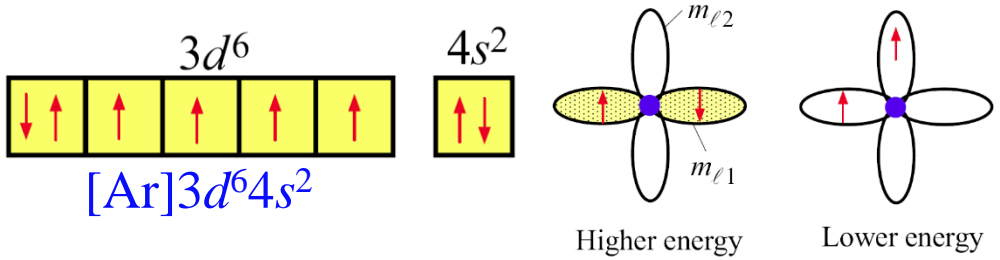
Since the Fermi level is almost temperature independent, so is the susceptibility for the Pauli paramagnetism.

5B.3. Ferromagnetism

Transition metals (e.g., $_{26}$Fe, $_{27}$Co, $_{25}$Mn, and $_{28}$Ni) have <u>incomplete *d* shell,</u> and **<u>rare earth metals</u>** have **<u>incomplete *f* shell</u>**, such that **electrons are not fully paired**. The $3d$ and f electrons are fairly well localized at the atomic site so they can be regarded as the localized magnetic moment.

The <u>isolated Fe atom</u> has a spin magnetic moment of <u>$4\mu_B$</u>. In the <u>BCC structure</u>, the magnetic moment per Fe is <u>2.2 μ_B because of the bonding among the *d* orbitals</u>.

These spins tend to align parallel to each other so the material possess **permanent magnetization even <u>in the absence of external field *H*</u>**. These result in large χ_m and highly nonlinear relation between χ_m and H.

In solids, the orbital contribution to the magnetic moment is very small because valence electrons belong to the whole crystal in the band picture.

$3d^6$ $4s^2$

$[Ar]3d^6 4s^2$

$m_{\ell 2}$

$m_{\ell 1}$

Higher energy   Lower energy

Hund's rule for an atom with many electrons is based on the **<u>exchange interactions favoring spin alignment</u>**.

M

10
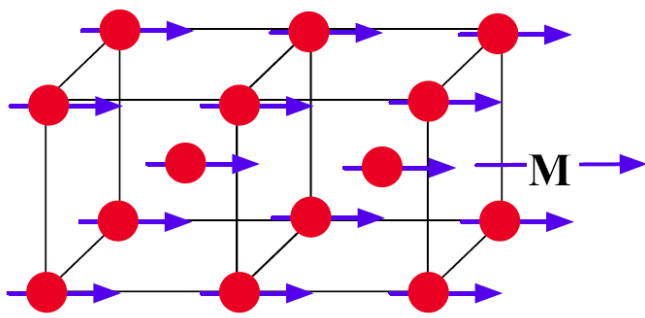
Below T_C, magnetization can exist with the support of the Weiss field, even without the external field, and the material becomes ferromagnetic. Following a similar procedure for paramagnetism under the external magnetic field, the magnetization is given by

$$M = N\gamma\mu_B \tanh(\frac{\gamma\mu_B\mu_0 H_{ex}}{kT}) = N\mu_B \tanh(\frac{\gamma\mu_B\mu_0\lambda M}{kT})$$

- $\vec{B} = \mu\vec{H}$
- $\vec{H} = \vec{B} - 4\pi\vec{M}$
- $\vec{M} = x_m\vec{H}$

where $\gamma\mu_B$ is the local magnetic moment.

This self-consistent equation can be numerically solved as shown in the right. The solution is the maximum magnetization that can be obtained at the given temperature, so it is called saturation magnetization $M_{sat}(T)$.

In reality, the **domain structure** (see later) reduce the magnetization and $M_{sat}(T)$ can be obtained only when high H field (the saturation field) is applied.

As $T \rightarrow 0$, $M \rightarrow N\gamma\mu_B$ that is the maximum magnetization that can be obtained for the given material.

This ferromagnetic transition is a **second-order (continuous) phase transition**.

$M(T)$

$\frac{M_{sat}(T)}{M_{sat}(0)}$

T / T_C

Saturation magnetization of Ni. The solid line is the mean-field result.
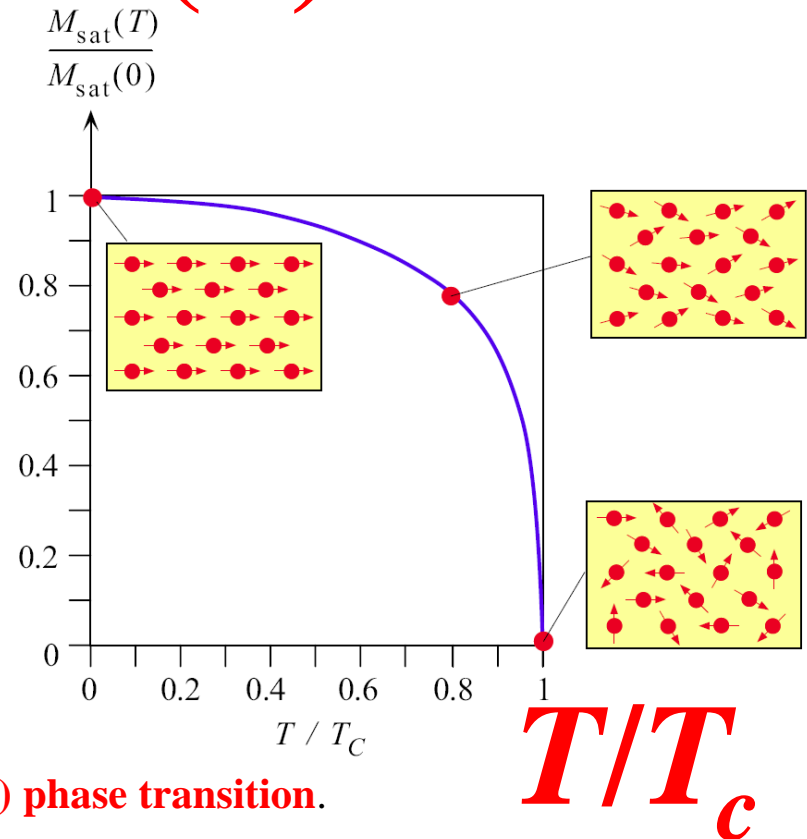
Table 1 Ferromagnetic crystals

Substance	Magnetization M_s, in gauss		$n_B(0\ K)$, per formula unit	Curie temperature, in K
	Room temperature	0 K		
Fe	1707	1740	2.22	1043
Co	1400	1446	1.72	1388
Ni	485	510	0.606	627
Gd	—	2060	7.63	292
Dy	—	2920	10.2	88
MnAs	670	870	3.4	318
MnBi	620	680	3.52	630
MnSb	710	—	3.5	587
CrO_2	515	—	2.03	386
$MnOFe_2O_3$	410	—	5.0	573
$FeOFe_2O_3$	480	—	4.1	858
$NiOFe_2O_3$	270	—	2.4	(858)
$CuOFc_2O_3$	135	—	1.3	728
$MgOFe_2O_3$	110	—	1.1	713
EuO	—	1920	6.8	69
$Y_3Fe_5O_{12}$	130	200	5.0	560

· **Order-Disorder Transition**

· **Ferro<u>magnetic</u> Transition**

· **Ferro<u>electric</u> Transition**

· **Fluid-Superfluid Transition**

· *· · · · ·*

*second-order phase transition
or
first-order phase transition*

Origin of ferromagnetism: exchange interaction

The localized *d* orbitals interact with *d* orbitals in other sites through exchange interaction, which originates from the Pauli exclusion principle. Simply put, when two electrons have the same spin, they tend to avoid each other spatially because occupying the same spin and same location violate the Pauli exclusion principle. As a result, the average distance between the electron increases, which reduces the Coulomb energy automatically. In reverse, the opposite spin means they can occupy the same position and so they tend to be close to each other compared to the parallel spin alignment. In conclusion, the exchange interaction favors the parallel spin configuration, and it is well described by the Heisenberg model.

$$E_{ex} = -J_e \mathbf{S}_1 \cdot \mathbf{S}_2$$

where $\mathbf{S}_1$ and $\mathbf{S}_2$ are the spin of the two local moments, and J_e is called the exchange integral. The sign and magnitude of J_e mainly depend on the atomic spacing.
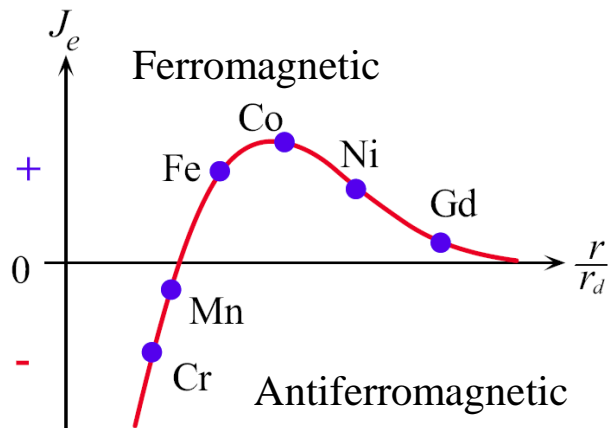
The exchange integral as a function of r/r_d, where r is the interatomic distance and r_d the radius of the *d*-orbit (or the average *d*-subshell radius. Cr to Ni are transition metals. For Gd, the *x*-axis is r/r_f where r_f is the radius of the *f*-orbit.

When the atomic spacing is small, the same spin is not favored because of Pauli exclusion principle.

Saturation magnetization and Curie temperature

Even though the ferromagnetic material favor parallel spin alignment, at high temperatures, the thermal energy of lattice vibration can overcome the potential energy of the exchange interaction, and the material behaves as being paramagnetic. The exchange interaction among magnetic moments can be effectively represented by the internal mean field (so called Weiss field) H_{ex} that is proportional to the magnetization: $H_{ex} = \lambda M$.

$$M = \chi_{para}(H + H_{ex}) = \chi_{para}(H + \lambda M) = \frac{C}{T}(H + \lambda M)$$

$$M = (\frac{C}{T - C\lambda})H = \frac{C}{T - T_C}H = \chi_m H$$

This is called the Curie-Weiss law and T_C is called the Curie temperature. This equation is only valid for $T > T_C$ in which the material is paramagnetic. It is noticeable that χ_m diverges at $T = T_C$. Such divergence is a characteristic of phase transition.

Compared to paramagnetic material, the spin-spin interaction is stronger in the ferromagnetic material such that M is larger than for typical paramagnetic material (paramagnetic at room T). This calls for the consideration of internal mean field.

Weiss field in uniform magnetization:
Uniform magnetization is equal to surface currents so the internal field appears to be the same as M. However, the local field correction is needed.

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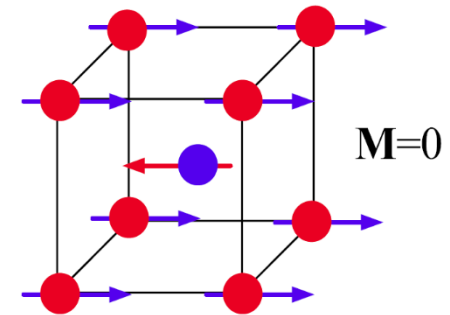# 5B.4. Antiferromagnetism

Antiferromagnetic BCC crystal

The antiferromagnetic materials have the same number of up and down spins, such that the total magnetization is zero. Usually, there are planes on which local moments are aligned in parallel way and the spin is alternating between the planes. Materials such as Mn, Cr, MnO, MnS, and NiO belong to this class.

$M=0$

Like ferromagnetic material, the antiferromagnetic material is also paramagnetic above a certain critical temperature called the Néel temperature (T_N).
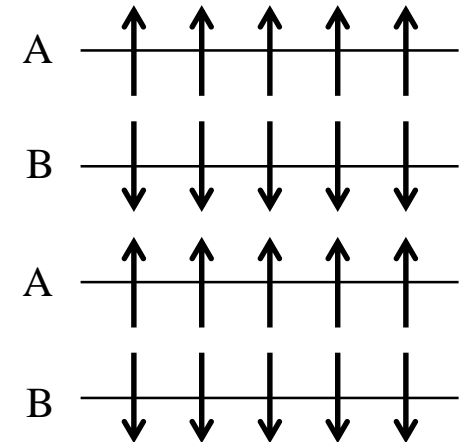
It can be theoretically shown that the susceptibility behaves as:

$$C_m = \frac{C\mathbb{C}}{T + T_N}$$
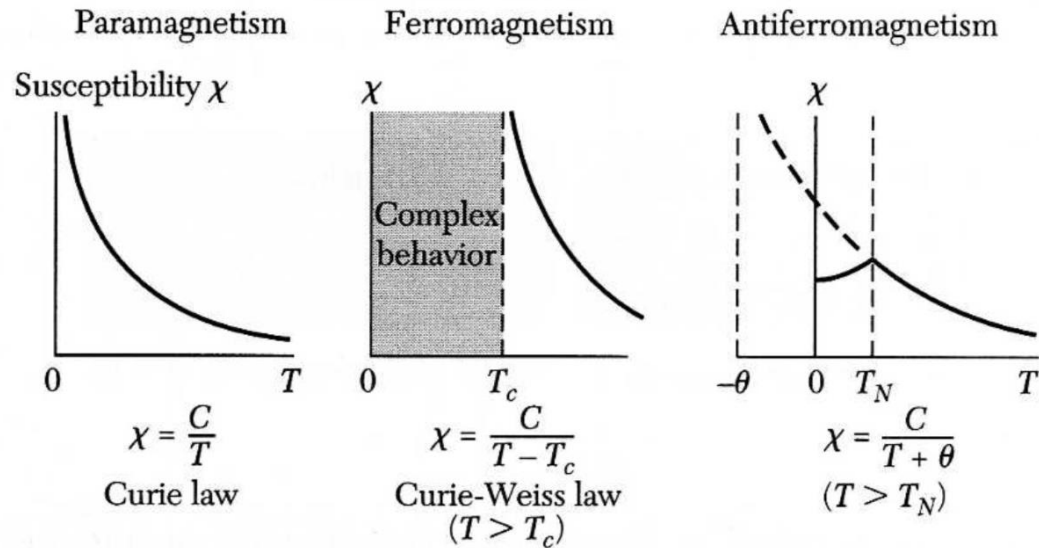
plane

A

B

A

B

Figure 20 Temperature dependence of the magnetic susceptibility in paramagnets, ferromagnets, and antiferromagnets. Below the Néel temperature of an antiferromagnet the spins have antiparallel orientations; the susceptibility attains its maximum value at T_N where there is a well-defined kink in the curve of χ versus T. The transition is also marked by peaks in the heat capacity and the thermal expansion coefficient.

Note that θ and T_N differ significantly.

| Substance	Paramagnetic ion lattice	Transition temperature, T_N, in K	Curie-Weiss θ, in K	$\dfrac{\theta}{T_N}$	$\dfrac{\chi(0)}{\chi(T_N)}$
MnO	fcc	116	610	5.3	$\frac{2}{3}$
MnS	fcc	160	528	3.3	0.82
MnTe	hex. layer	307	690	2.25	
MnF_2	bc tetr.	67	82	1.24	0.76
FeF_2	bc tetr.	79	117	1.48	0.72
$FeCl_2$	hex. layer	24	48	2.0	<0.2
FeO	fcc	198	570	2.9	0.8
$CoCl_2$	hex. layer	25	38.1	1.53	
CoO	fcc	291	330	1.14	
$NiCl_2$	hex. layer	50	68.2	1.37	
NiO	fcc	525	~2000	~4	
Cr	bcc	308			

5B.5. Ferrimagnetism

Ferrimagnetic materials such as ferrites (e.g., Fe_3O_4) exhibit magnetic behavior similar to ferromagnetism below T_C. Above T_C they become paramagnetic.

Magnetic structure on the right shows that all A atoms have their spins aligned in one direction and all B atoms have their spins aligned in the opposite direction. Unlike the antiferromagnetic case, the magnetic moment or the number of an A atom is greater than that of a B atom, and there is net magnetization M in the crystal.
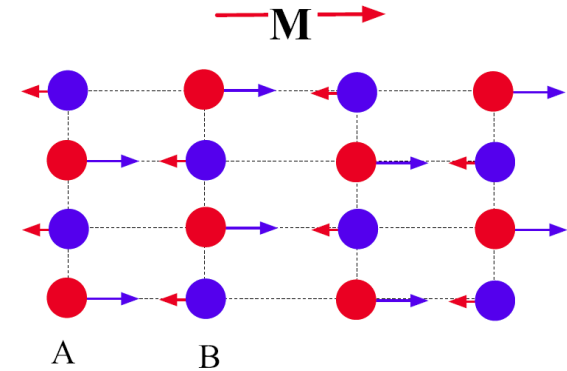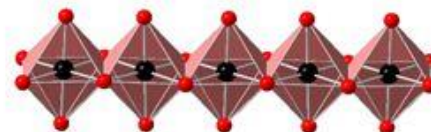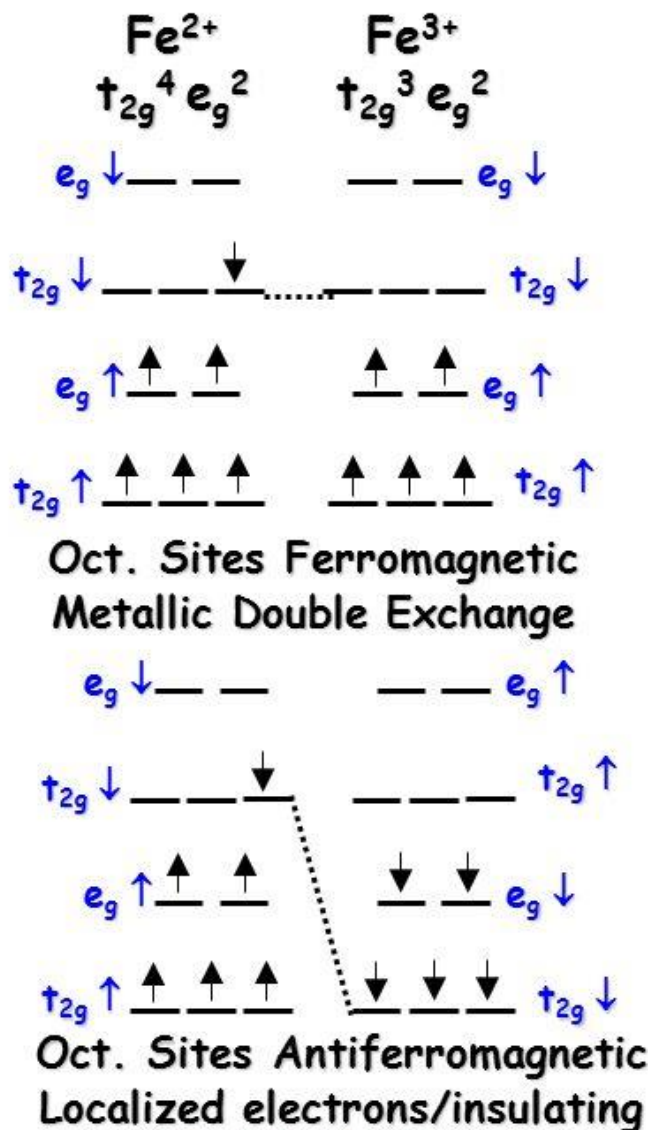
Since ferrimagnetic materials are typically nonconducting and therefore do not suffer from eddy current losses (induced currents from changing magnetic field are small), they are widely used in high-frequency electronics applications. (All useful magnetic materials in electrical engineering are invariably ferromagnetic or ferrimagnetic.)
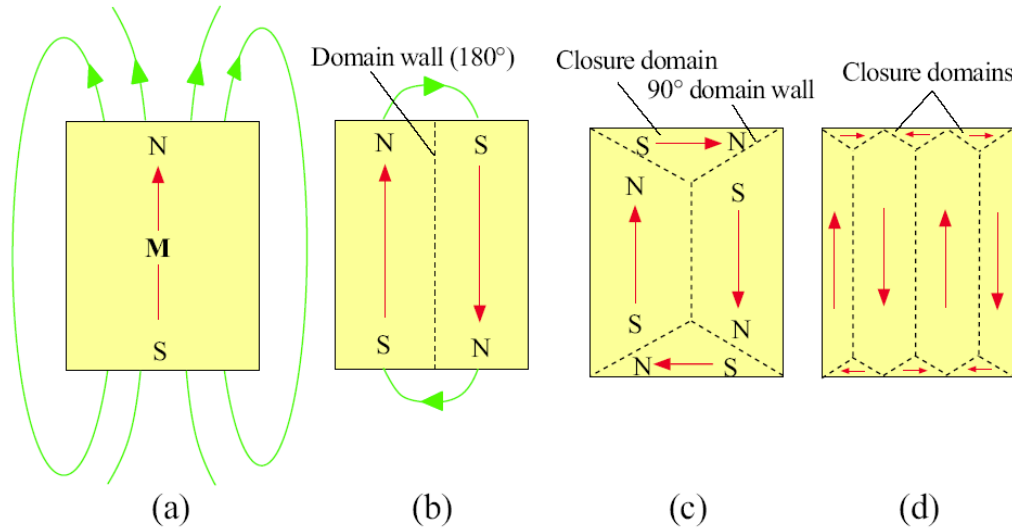
Double Exchange in Fe_3O_4
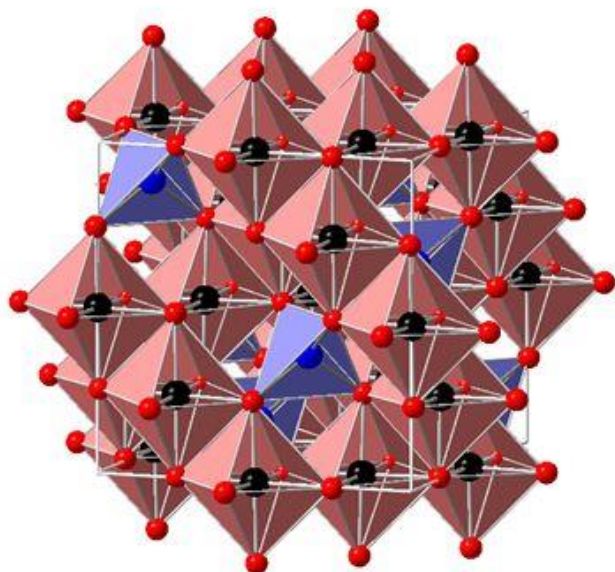
Fe_3O_4 is an inverse spinel, with Fe^{3+} on the tetrahedral sites and a 1:1 mixture of Fe^{2+}/Fe^{3+} on the octahedral sites. It is ferrimagnetic, with the octahedral sites and the tetrahedral sites aligned in different directions. The ferromagnetic alignment of the octahedral sites is necessary for delocalized carrier transport of the minority spin t_{2g} electron. This mechanism is called double exchange.

Fe^{2+}
$t_{2g}^4 e_g^2$

Fe^{3+}
$t_{2g}^3 e_g^2$

$e_g \downarrow$ — —   — — $e_g \downarrow$

$t_{2g} \downarrow$ — — ↓ .... — — — $t_{2g} \downarrow$

$e_g \uparrow$ ↑ ↑   ↑ ↑ $e_g \uparrow$

$t_{2g} \uparrow$ ↑ ↑ ↑   ↑ ↑ ↑ $t_{2g} \uparrow$

Oct. Sites Ferromagnetic
Metallic Double Exchange

$e_g \downarrow$ — —   — — $e_g \uparrow$

$t_{2g} \downarrow$ — — ↓   — — — $t_{2g} \uparrow$

$e_g \uparrow$ ↑ ↑   ↓ ↓ $e_g \downarrow$

$t_{2g} \uparrow$ ↑ ↑ ↑   ↓ ↓ ↓ $t_{2g} \downarrow$

Oct. Sites Antiferromagnetic
Localized electrons/insulating

5C. Magnetic Domains in Ferromagnetic Materials

Iron above T_c and cooled down does not show a net permanent magnetization. They rather form a magnetic domain with **different orientation** <u>**to reduce the total magnetostatic energy**</u>.

- ✓ Typical **thickness of domain wall** (Bloch wall): **~100 nm** for Fe.
- ✓ The creation of domain wall continues until reduction in field energy is equal to the **domain wall energy**.
- ✓ For iron particle with size of **~10 nm**, the domain wall energy is very costly and they are always magnetized.

(a) Magnetized bar of ferromagnet in which there is only one domain and hence an external magnetic field.

(b) Formation of two domains with opposite magnetizations reduces the external field and so magnetostatic energy. There are, however, field lines at the ends. The domain wall is formed between different magnetic orientations.

(c) Domains of closure fitting at the ends eliminates the external fields at the ends.

(d) A specimen with several domains and closure domains. There is no external magnetic field and the specimen appear unmagnetized.

All the practical ferromagnetic materials consist of **magnetic domains** in the absence of an applied magnetic field.
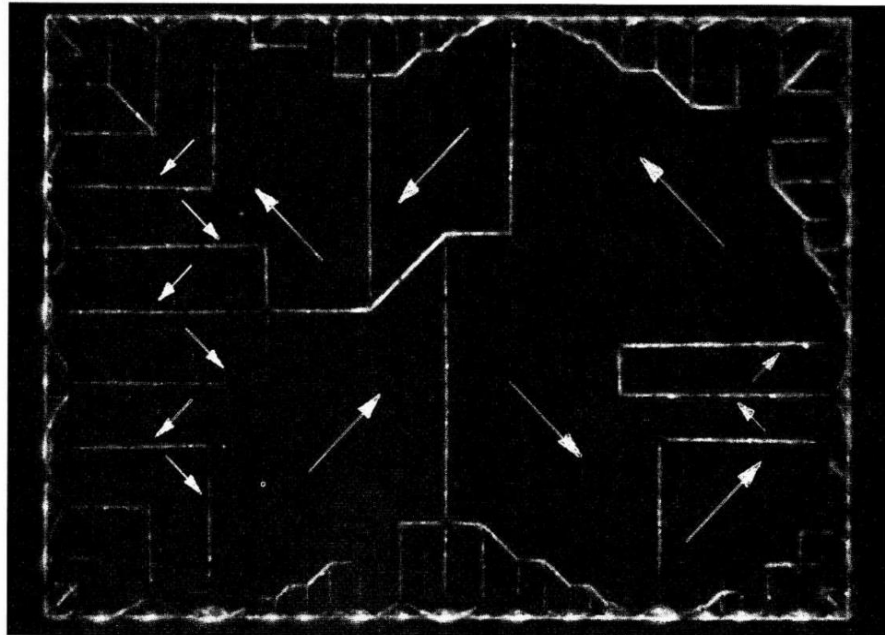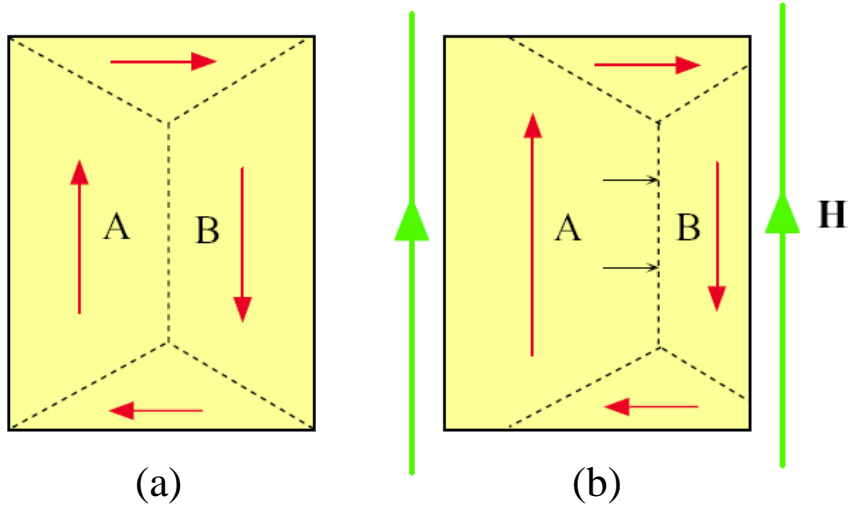

Figure 24 Ferromagnetic domain pattern on a single crystal platelet of nickel. The domain boundaries are made visible by the Bitter magnetic powder pattern technique. The direction of magnetization within a domain is determined by observing growth or contraction of the domain in a magnetic field. (After R. W. De Blois.)

(a) An unmagnetized crystal of iron in the absence of an applied magnetic field. Domains A and B are the same size and have opposite magnetizations.

(b) When an external field is applied the domain wall migrates into domain B which enlarges A and B. The result is that the specimen now acquires net magnetization. Spins in the domain experience a torque that rotates the spin orientation.

- $\vec{B} = \mu \vec{H}$
- $\vec{H} = \vec{B} - 4\pi \vec{M}$
- $\vec{M} = x_m \vec{H}$

Domain Walls

The change of magnetization direction is achieved by **gradually changing the direction of magnetization**. The region in the domain wall over which the rotation occurs is called the Bloch wall. In a Bloch wall the neighboring spin magnetic moments rotate gradually and it takes several hundred atomic spacings to rotate the magnetic moment by 180°.

Optimum Domain-Wall Thickness

~100 nm
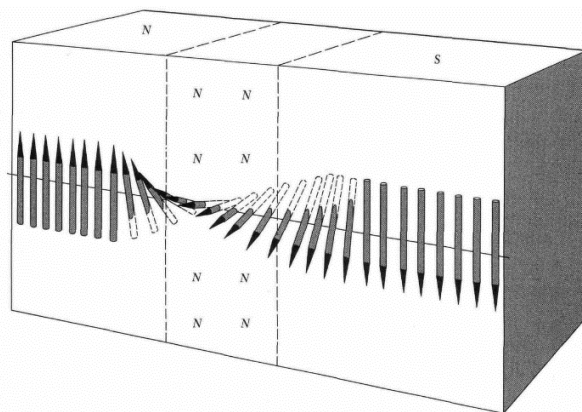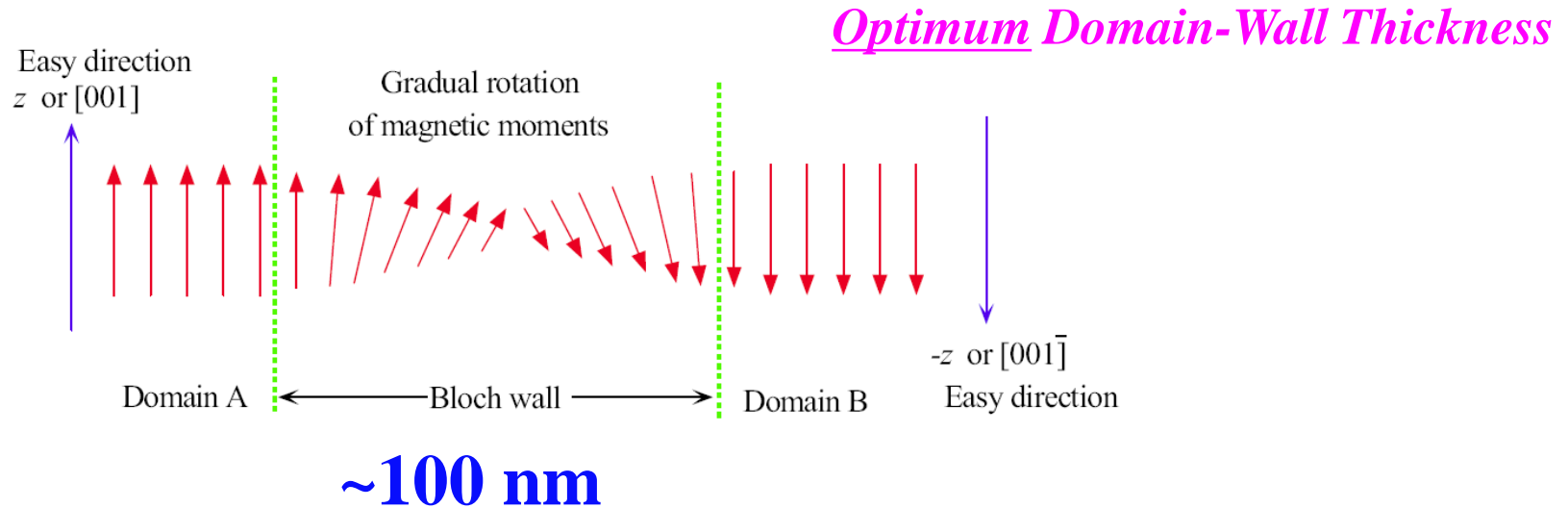
· **Order-Disorder Transition**

· **Ferromagnetic Transition**

· **Ferroelectric Transition**

· **Phase Separation**

· **Fluid-Superfluid Transition**

· .....

There are two competing factors that determine the energy of domain wall.

i) The exchange energy, which would keep the spins oriented as in the respective domains, tends to widen the Bloch wall so as to make the difference in spin orientation between neighboring spins a minimum. If the interatomic spacing is a, then there would be $N = \delta/a$ atomic layers in the wall. Since the spin moment angle changes by 180° across δ, we can calculate the relative spin orientations (180°/N) of adjacent atomic layers.

Potential energy

Domain wall energy, U_{wall}

Anisotropy energy, $U_{\text{anisotropy}}$

Exchange energy, U_{exchange}

δ

Domain wall thickness, δ

ii) The anisotropy energy, which would keep spins out of orientations not corresponding to the easy directions of magnetization, lead to narrowing of the Bloch wall so as to make the number of spins with nonpreferred orientation a minimum.
The domain thickness is determined by the condition of the minimum wall energy.
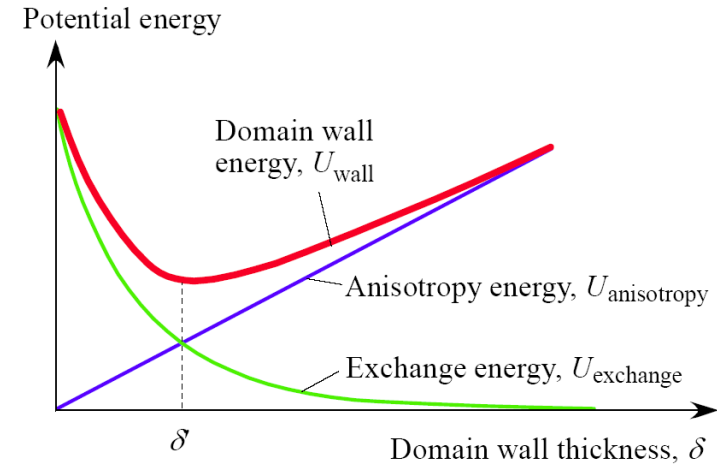
$$\diagdown U_{\text{wall}} \gg \frac{\rho^2 E_{\text{ex}}}{2a d} + K d \qquad \frac{dU_{\text{wall}}}{d\delta} = -\frac{\pi^2 E_{\text{ex}}}{2a\delta^2} + K = 0 \longrightarrow d' = \left(\frac{\rho^2 E_{\text{ex}}}{2ad}\right)^{1/2}$$

For Fe, Since $T_C = 1043$ K, $E_{\text{ex}} = kT_C = (1.38 \times 10^{-23}$ J K$^{-1})(1043$ K$) = 1.4 \times 10^{-20}$ J, so that

$$\delta' = \left(\frac{\pi^2 E_{\text{ex}}}{2aK}\right)^{1/2} = \left[\frac{\pi^2(1.4 \times 10^{-20})}{2(0.3 \times 10^{-9})(50,000)}\right]^{1/2} = 6.8 \times 10^{-8} \text{ m} \quad \text{or} \quad 68 \text{ nm}$$

$$U_{\text{wall}} = \frac{\pi^2 E_{\text{ex}}}{2a\delta'} + K\delta' = \frac{\pi^2(1.4 \times 10^{-20})}{2(0.3 \times 10^{-9})(6.8 \times 10^{-8})} + (50 \times 10^3)(6.8 \times 10^{-8})$$

$$= 0.007 \text{ J m}^{-2} \quad \text{or} \quad 7 \text{ mJ m}^{-2}$$

Magnetocrystalline anisotropy

The strength of exchange interaction depends on the direction along which the spins are aligned. The direction with largest J_e is called the easy axis because spins are easily aligned along that direction. The one with the smallest is called the hard axis.
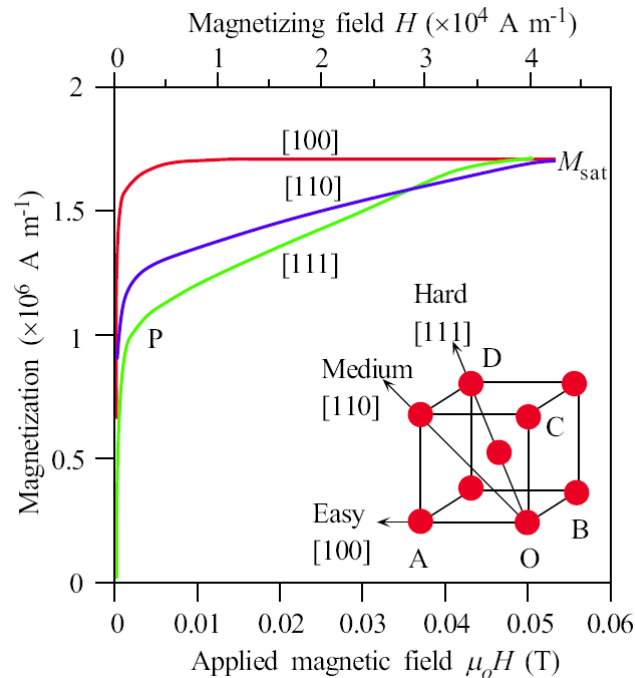
- Magnetocrystalline anisotropy in a single iron crystal. *M* vs. *H* depends on the crystal on the crystal direction and is easiest along [100] and hardest along [111]
- From 0 to P, magnetization along easy axis is maintained and they just align along OA, OB, and OC. From P onwards, the spin direction should move away from the easy axis.
- In typical samples, therefore, the magnetization direction is always along the easy axis.

The excess energy required to magnetize a unit volume of a crystal in a particular direction with respect to that in the easy direction is called the magnetocrystalline anisotropy energy (K).

Table 8.4 Exchange interaction, magnetocrystalline anisotropy energy K, and saturation magnetostriction coefficient λ_{sat}

Material	Crystal	$E_{\text{ex}} \approx kT_C$ (meV)	Easy	Hard	K (mJ cm^{-3})	λ_{sat} ($\times 10^{-6}$)
Fe	BCC	90	<100>; cube edge	<111>; cube diagonal	48	20 [100] −20 [111]
Co	HCP	120	// to c axis	$\perp$ to c axis	450	
Ni	FCC	50	<111>; cube diagonal	<100>; cube edge	5	−46 [100] −24 [111]

NOTE: K is the magnitude of what is called the first anisotropy constant (K_1) and is approximately the magnitude of the anisotropy energy. E_{ex} is an estimate from kT_C, where T_C is the Curie temperature. All approximate values are from various sources. (Further data can be found in Jiles, D., *Introduction to Magnetism and Magnetic Materials*, London, England: Chapman and Hall, 1991.)

5D. Ferromagnetic Hysteresis

Schematic illustration of magnetic domains in the grains of an unmagnetized polycrystalline iron sample. Very small grains can have single domains.
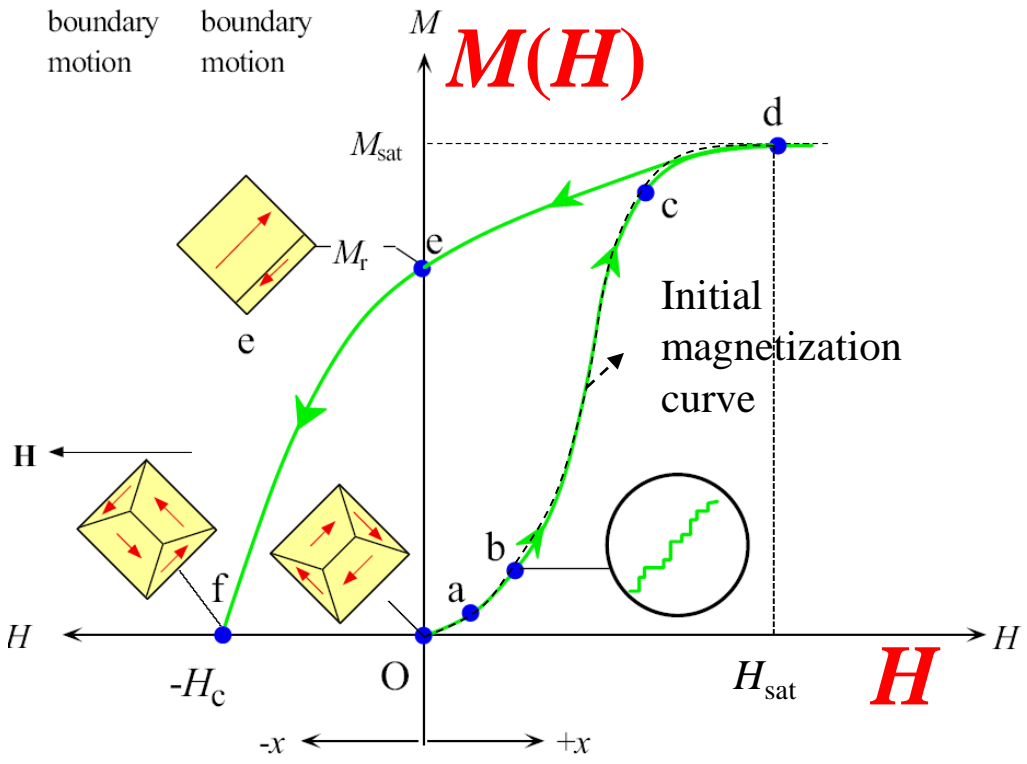
Small grain with a single domain

Grain boundary →

A grain with domains

$M(T)$

T
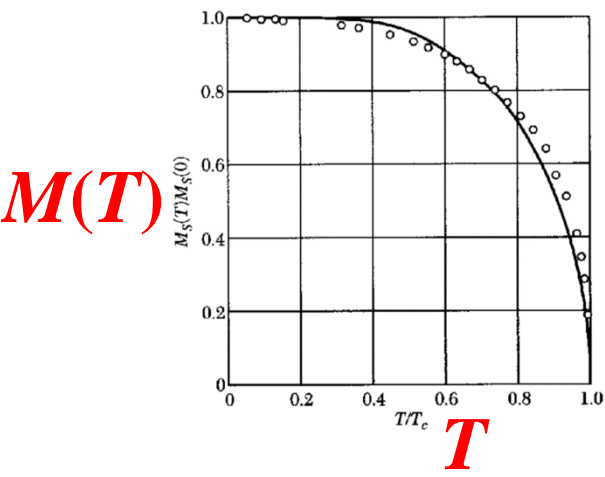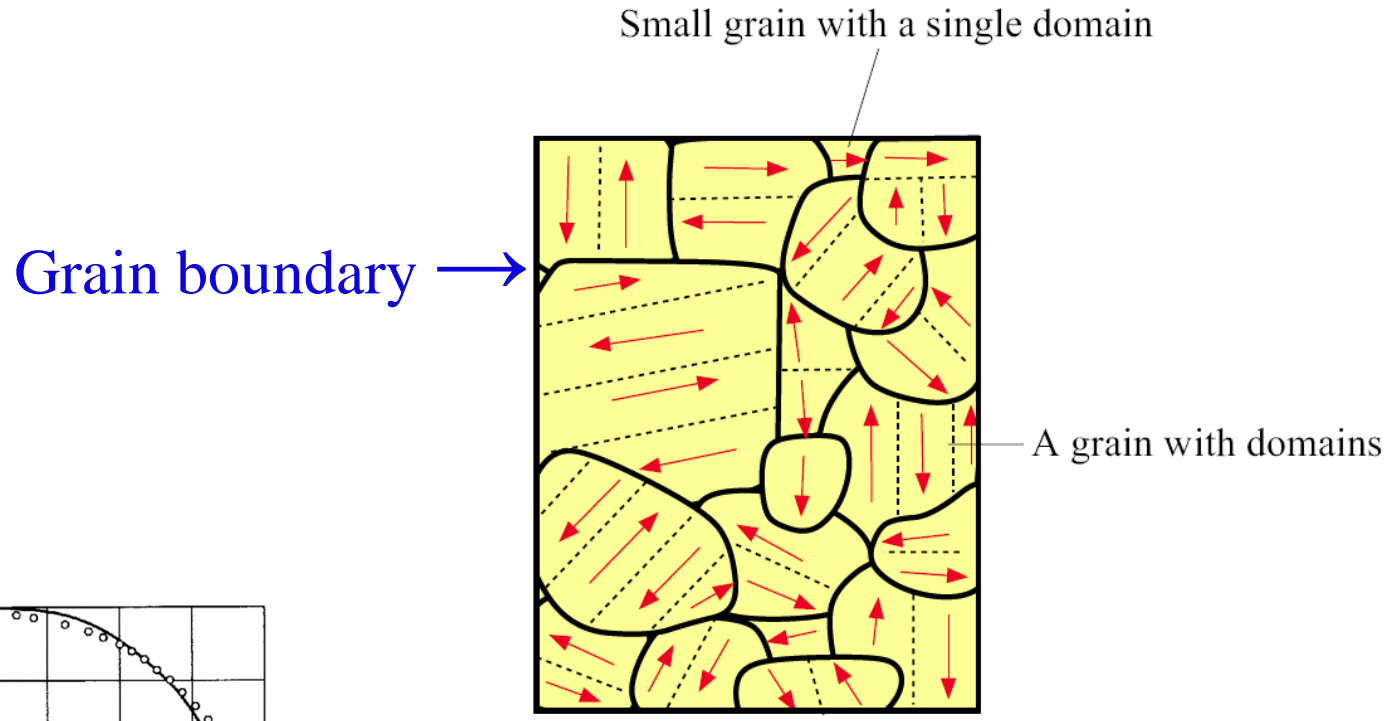
M vs. *H* **Behavior** of a previously unmagnetized polycrystalline iron specimen.

An example grain in the unmagnetized specimen is that at O.
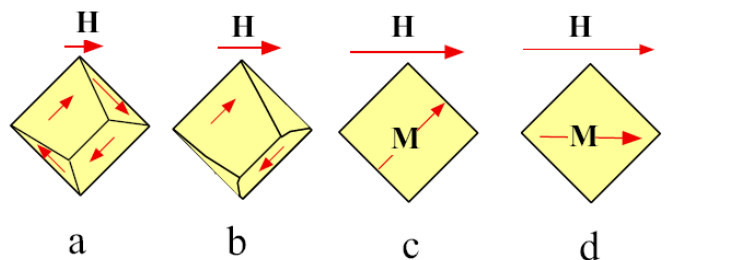
a — Reversible boundary motion
b — Irreversible boundary motion
c — Rotation of **M**
d — Saturation of **M**

M(*H*)

Initial magnetization curve

(a) Under very small fields, the domain boundary motion is **reversible**.

(b) The boundary motions are **irreversible** and occur in sudden jerks (Barkhausen effect). Heat generation from magnetostriction and Joule heating from eddy currents.

(c) **Nearly all the grains are single domains with saturation magnetizations** in the easy directions.

(d) Magnetizations in individual grains have to be rotated to align with the field *H*. The magnetization reaches at saturation magnetization. The saturation occurs at the **saturation field H_{sat}**.

(e) When the field is removed the specimen returns along d to e with **remnant or residual magnetization M_r**.

(f) To demagnetize the specimen we have to apply a magnetizing field of H_c (**coercive field or coercivity**) in the reverse direction. New domains should be nucleated and grown during demagnetization.
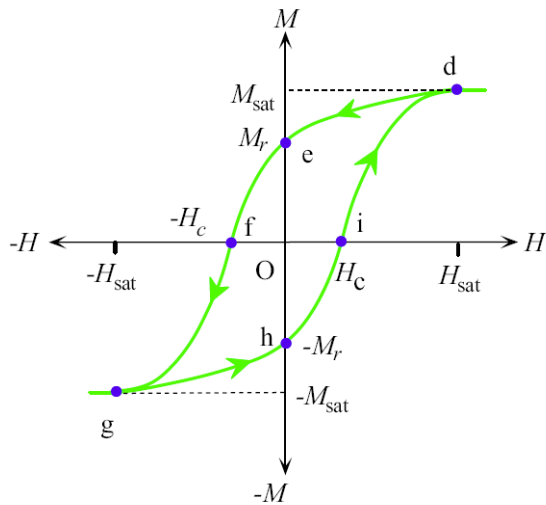
A typical M vs. H hysteresis curve
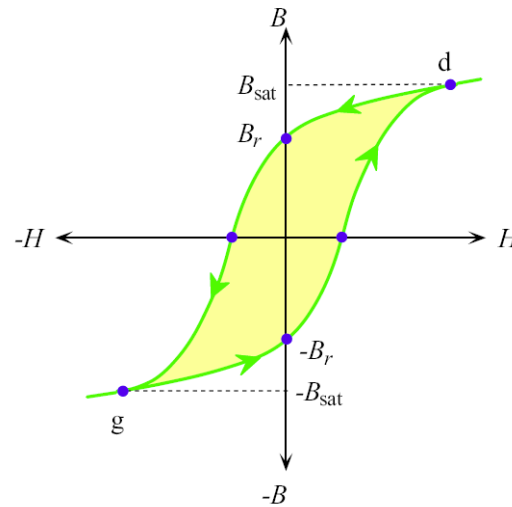
The corresponding B vs. H hysteresis curve. The shaded area inside the hysteresis loop is the energy loss per unit volume per cycle.
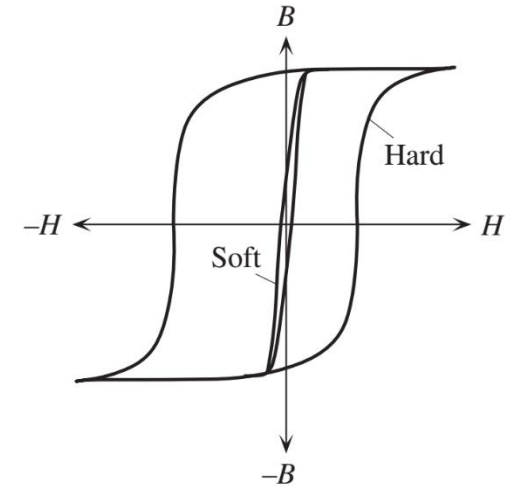
"Hard" magnetic materials
- High Mr, High Hc
- Many defects
- Useful as permanent magnet

"Soft" magnetic materials
- Area is small
- Few defects and inclusions
- Useful for transformer cores or for electromagnets

**Table 8.6** Selected hard magnetic materials and typical values

Magnetic Material	$\mu_o H_c$ (T)	B_r (T)	$(BH)_{max}$ (kJ m^{-3})	Examples and Uses
Ideal hard	Large	Large	Large	Permanent magnets in various applications.
Alnico (Fe–Al–Ni–Co–Cu)	0.05–0.1	1.0	40–50	Wide range of permanent magnet applications.
Alnico (Columnar)	0.075	1.35	60	
Strontium ferrite (sintered)	0.3–0.5	0.3–0.5	20–35	Starter motors, dc motors, loudspeakers, telephone receivers, various toys.
Rare earth cobalt, $e.g.$, Sm_2Co_{17} (sintered)	0.9–1.2	1.1	200–250	Servo motors, stepper motors, couplings, clutches, quality audio headphones.
NdFeB magnets	1.0–1.5	1.0–1.4	300–350	Wide range of applications, small motors ($e.g.$, in hand tools), audio equipment, hard drives, MRI body scanners.
Hard particles, γ-Fe_2O_3	0.03	0.2		Audio and video tapes, floppy disks.

Table 8.5 Selected soft magnetic materials and some typical values and applications

| Magnetic Material	$\mu_o H_c$ (T)	B_{sat} (T)	B_r (T)	μ_{ri}	$\mu_{r,max}$	W_h (J m^{-3})	Typical Applications
Ideal soft	0	Large	0	Large	Large	0	Transformer cores, inductors, electric machines, electromagnet cores, relays, magnetic recording heads.
Iron (commercial) grade, 0.2% impurities	$<10^{-4}$	2.2	<0.1	150	10^4	250	Large eddy current losses. Generally not preferred in electric machinery except in some specific applications ($e.g.$, some electromagnets and relays).
Silicon iron (Fe: 2–4% Si)	$<10^{-4}$	2.0	0.5–1	10^3	10^4–4×10^5	30–100	Higher resistivity and hence lower eddy current losses. Wide range of electric machinery ($e.g.$, transformers, motors, generators).
Supermalloy (79% Ni–15.5% Fe–5% Mo–0.5% Mn)	2×10^{-7}	0.7–0.8	<0.1	10^5	10^6	<0.5	High permeability, low-loss electric devices, $e.g.$, specialty transformers, magnetic amplifiers.
78 Permalloy (78.5% Ni–21.5% Fe)	5×10^{-6}	0.86	<0.1	8×10^3	10^5	<0.1	Low-loss electric devices, audio transformers, HF transformers, recording heads, filters, inductors.
Glassy metals, Fe–Si–B	2×10^{-6}	1.6	$<10^{-6}$	—	10^5	20	Low-loss transformer cores.
Ferrites, Mn–Zn ferrite.	10^{-5}	0.4	<0.01	2×10^3	5×10^3	<0.01	HF low-loss applications. Low conductivity ensures negligible eddy current losses. HF transformers, inductors ($e.g.$, pot cores, E and U cores), antenna rods, recording heads.

5E. Magnetoresistance

Magnetoresistance means the change in resistance under a magnetic field. In some materials, the magnetoresistance is anisotropic, which can be used in electronics. The origin of anisotropic magnetoresistance (AMR) is schematically explained in the below. When a magnetic field is applied, spins are aligned against the field direction. Due to the spin-orbit interaction, d-orbital is also aligned. The electrons traveling along the field experience more scattering than those traveling perpendicular to the field (a). As a result, resistivity depends on the current flow direction with respect to the applied magnetic field. The difference in the resistance is usually very small (only a few %).


29
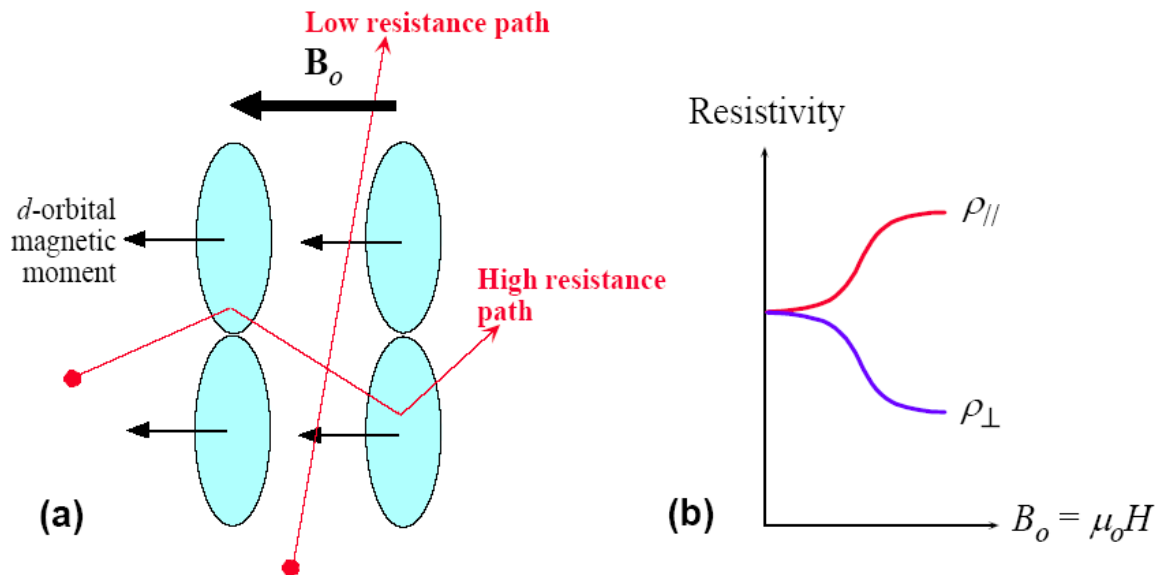
Giant Magnetoresistance (GMR)

In some multilayer structures of metals, the magnetoresistance can be more than 10%. It is used in reading the magnetic information in hard disk drive.
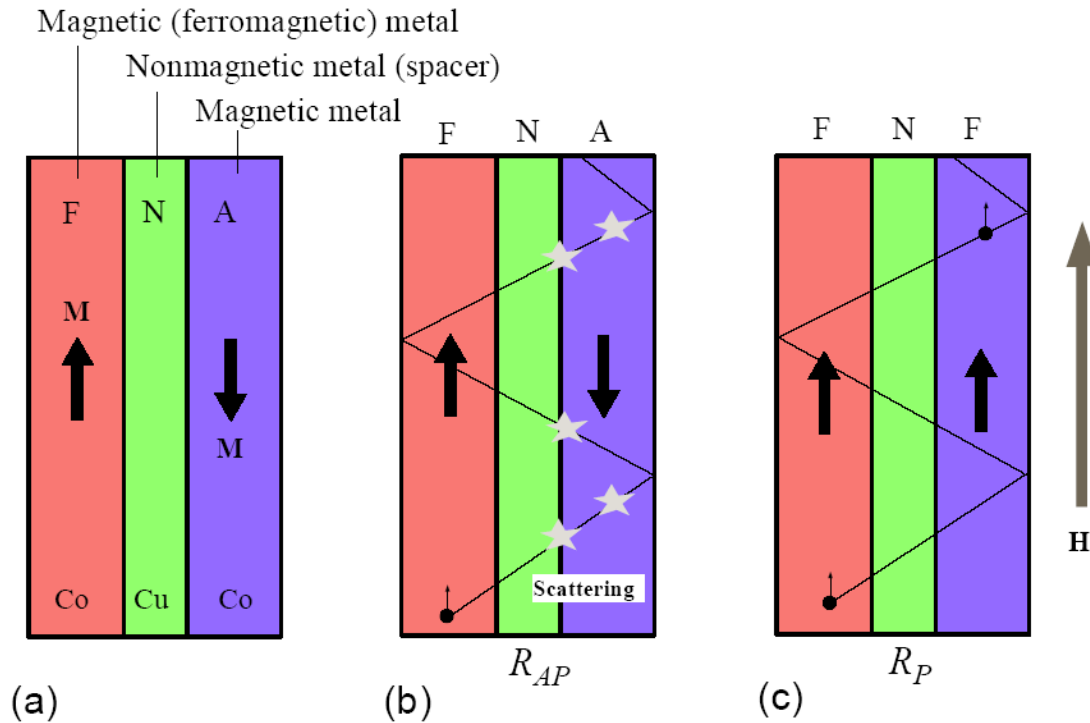
A highly simplified view of the principle of the giant mangetoresistance effect.
(a)   The basic trilayer structure.
(b)   Antiparallel magnetic layers with high resistance R_{AP}.
(c)   An external field aligns layers, parallel alignment has a lower resistance R_P.

Application of GMR: spin valve
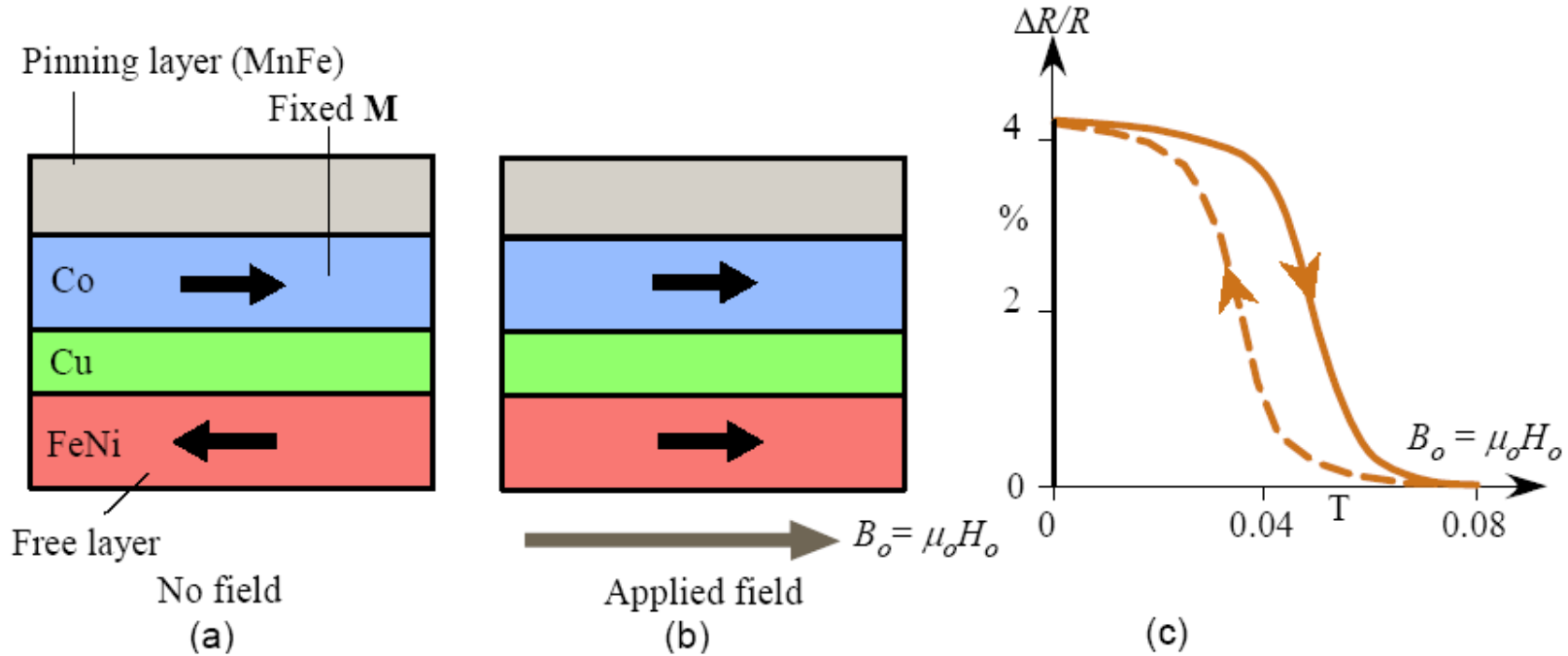
Principle of the spin valve (a) No applied field. (b) Applied field has fully oriented the free layer magnetization. (c) Resistance change vs. applied field magnetic field (schematic) for a FeNi/Cu/FeNi spin valve.

Science vs. Art
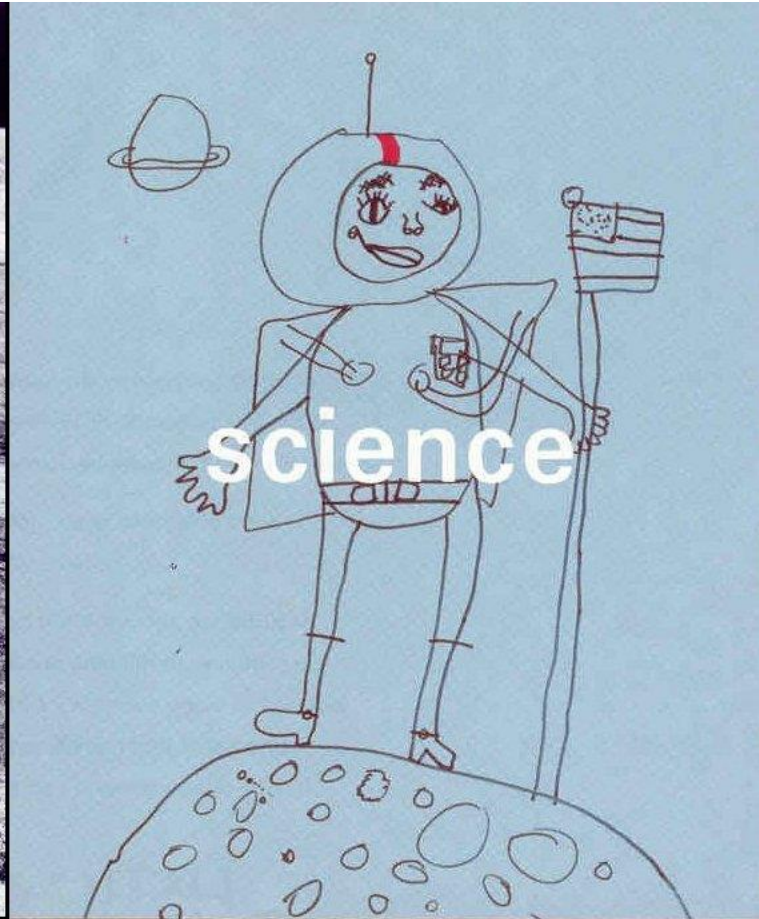
College of Arts and Sciences

Physics, Mathematics, Psychology, Music, etc.

Prof. John Nash
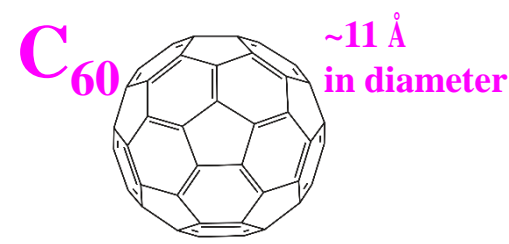# A Beautiful Mind

Born	June 13, 1928 Bluefield, West Virginia, U.S.
Died	May 23, 2015 (aged 86) Monroe Township, Middlesex County, New Jersey, U.S.
Nationality	American
Fields	•Mathematics •Economics
Institutions	•Massachusetts Institute of Technology •Princeton University

Spent several years at psychiatric hospitals.

Humanity's Top Ten Problems for the Next 50 Years

C_{60} ~11 Å in diameter

1. ENERGY
2. WATER
3. FOOD
4. ENVIRONMENT
5. POVERTY
6. TERRORISM & WAR
7. DISEASE
8. EDUCATION
9. DEMOCRACY
10. POPULATION

Prof. R. E. Smalley (1943 – 2005)

2021   7.9 Billion People
2100   ~11 Billion People

Earth shown
for size comparison