Atomic Mechanisms, Magnetization and Ferromagnetism

Recap on magnetic dipole and magnetization
Surface and volume magnetization currents
Diamagnetism & Paramagnetism
Ferromagnetism & History
Atomic level picture
B&H Macroscopic effects (non-linearity)

Chapter 5&6 – D.J.Griffiths

Magnetization

-) magnetic phenomena originates from electric charges in motion;

-) microscopically, all materials have tiny currents constituted by electrons orbiting the nuclei and electron spins;

-) For our purposes we can consider these as small magnetic dipoles;

-) In most cases these current loops are randomly oriented and hence cancel each other out

-) BUT when a field is applied, a net alignment of these dipoles produces a non zero magnetic field in response;

The medium is **magnetized** or magnetically polarized

In the case of E, the polarization is always aligned and in the same direction, but for magnetized medium you can have different cases:
        Same direction = paramagnets / Opposite direction = diamagnets

In some cases (ferromagnets) the material retains the net alignment after the field ceases to exist.
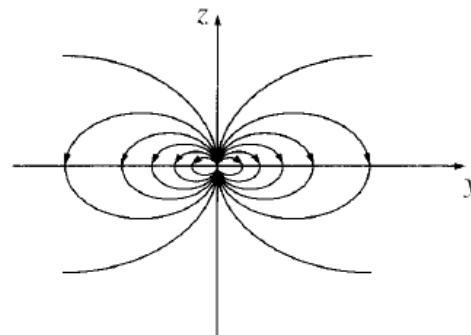
Multipole expansion

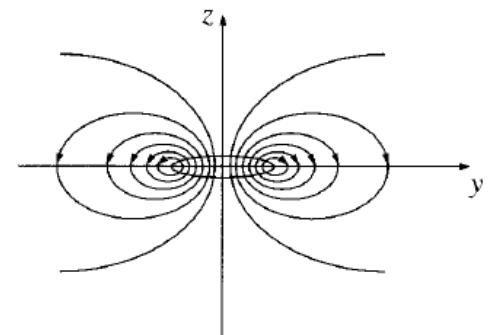$$\mathbf{m} \equiv I \int d\mathbf{a} = I\mathbf{a}$$

Suggests that the magnetic dipole moment is independent of the choice of origin. (true for the electric only when the total charge vanishes) – consistent.

The magnetic field of a pure dipole is easiest to calculate placing a dipole moment m at the origin, point along the "z" axis, so

$$\mathbf{A}_{\mathrm{dip}}(\mathbf{r}) = \frac{\mu_0}{4\pi} \frac{\mathbf{m} \times \hat{\mathbf{r}}}{r^2},$$

(a) Field of a "pure" dipole

(a) Field of a "physical" dipole

Becomes in spherical coordinates: $\mathbf{A}_{\mathrm{dip}}(\mathbf{r}) = \dfrac{\mu_0}{4\pi} \dfrac{m \sin\theta}{r^2} \, \hat{\boldsymbol{\phi}},$

So

$$\mathbf{B}_{\mathrm{dip}}(\mathbf{r}) = \nabla \times \mathbf{A} = \frac{\mu_0 m}{4\pi r^3} (2\cos\theta \, \hat{\mathbf{r}} + \sin\theta \, \hat{\boldsymbol{\theta}})$$

This is identical in structure to the field of an electric dipole, while up close, the field looks different from the field of a physical electric dipole.
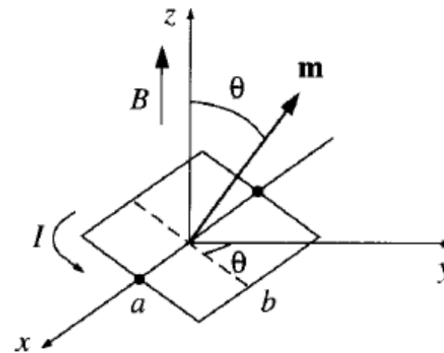
Torques on magnetic dipoles

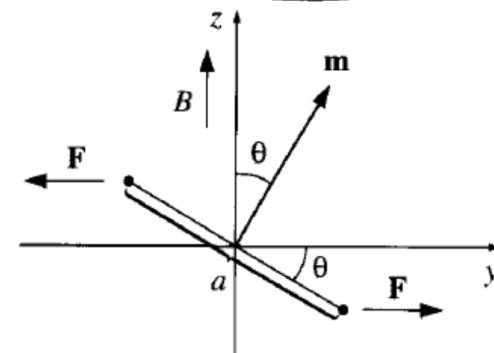Torque on a rectangular current loop in a uniform field **B**.

(a loop can be built up from infinitesimal rectangles the sides of which cancel with each other)

In the sketch you see a tilted loop.

The force on opposite sides cancel out in pairs. But the horizontal pair applies a torque:

$$\mathbf{N} = aF \sin\theta \, \hat{\boldsymbol{x}}$$

The magnitude of the force on each of these segments is

$$F = IbB$$

$$\mathbf{N} = IabB \sin\theta \, \hat{\boldsymbol{x}} = mB \sin\theta \, \hat{\boldsymbol{x}}$$

$$m = Iab \qquad \text{The magnetic moment of the loop}$$

$$\boxed{\mathbf{N} = \mathbf{m} \times \mathbf{B}}$$

This torque accounts for <u>paramagnetism</u>, which is dominant in atoms with an odd number of electrons.

4
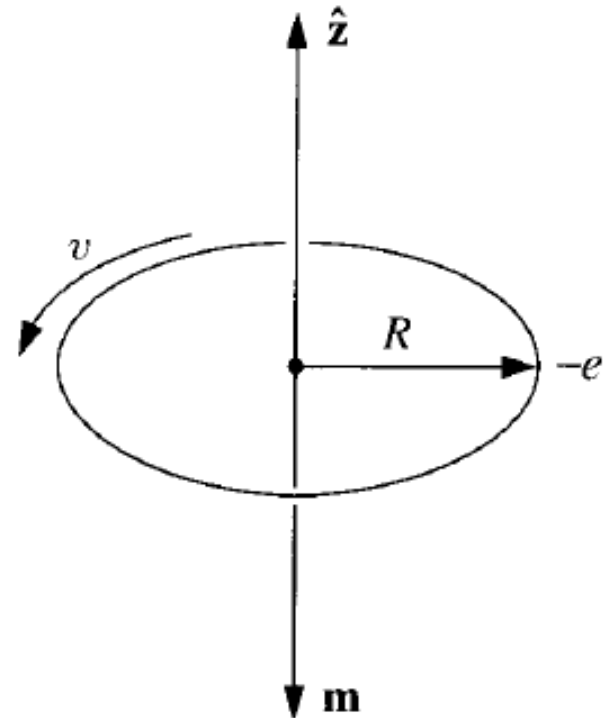
Microscale magnetic field

Consider the orbital motion that electrons perform around the nucleus.

This can be considered as a steady current

$$I = \frac{e}{T} = \frac{ev}{2\pi R}$$

The orbital dipole moment $I\pi R^2$ will then be
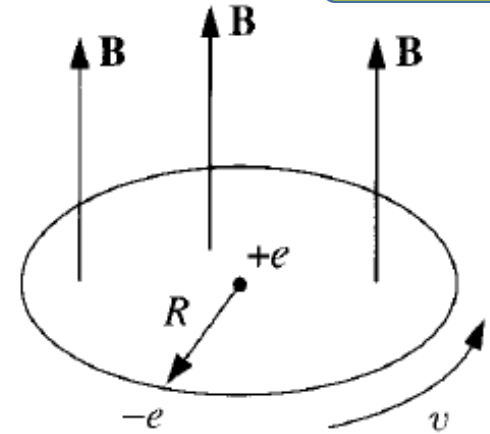
$$\mathbf{m} = -\frac{evR}{2}\hat{\mathbf{z}}$$

Microscale magnetic field

The largest consequence to the appearance of this magnetic moment is due to the force to which the electron is subject.

Consider B aligned orthogonal to the loop plane:

Equating all forces (centripetal, electrostatic and Lorentz)

$$\frac{1}{4\pi\epsilon_0}\frac{e^2}{R^2} + e\bar{v}B = m_e\frac{\bar{v}^2}{R}$$

The speed in question is greater than the one when B is zero.

$$\frac{1}{4\pi\epsilon_0}\frac{e^2}{R^2} + e\bar{v}B = m_e\frac{\bar{v}^2}{R} \qquad\qquad \frac{1}{4\pi\epsilon_0}\frac{e^2}{R^2} = m_e\frac{v^2}{R}$$

If the change is small:

$$\Delta v = \bar{v} - v$$
$$\bar{v} + v = 2\bar{v}$$

$$e\bar{v}B = \frac{m_e}{R}(\bar{v}^2 - v^2)$$
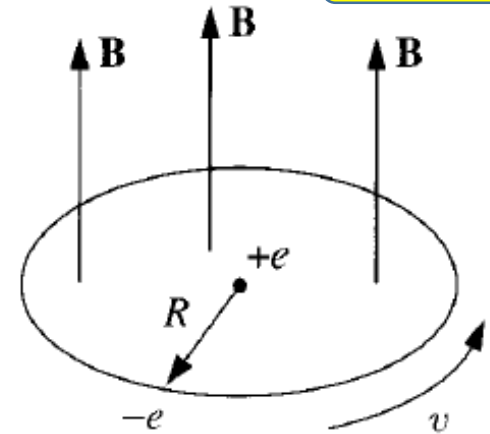
$$e\bar{v}B = \frac{m_e}{R}(2\bar{v})\Delta v$$

$$\boxed{\Delta v = \frac{eBR}{2m_e}}$$

6

Microscale magnetic field

A change in magnetic field implies a change in speed of the electron and a change in speed is equivalent to a change in the value of the current in the current loop.

$$\Delta v = \frac{eBR}{2m_e}$$

Change of magnetic dipole moment:

$$\Delta \mathbf{m} = -\frac{1}{2}e(\Delta v)R\,\hat{\mathbf{z}} = -\frac{e^2 R^2}{4m_e}\mathbf{B}. \qquad (6.8)$$

Change is opposite to **B**.

As the latter is calculated simply as a term affecting the loop currents from the electrons, this is present in all atoms and is the mechanism responsible for **diamagnetism**.

Magnetization

Diamagnetism It is generally much smaller than paramagnetism, but it becomes evident in those atoms (mostly with even number of electrons) where paramagnetism is usually absent.

The state of magnetic polarization is described by the vector quantity:

$\mathbf{M}$ = magnetic dipole moment per unit volume (or _Magnetization_)

Magnetic Intensity

As with the electric field, introducing a medium changes Maxwell's equations.

In the case of **E**, we introduced a new field **D** (the electric displacement) which included the effects of the medium implicitly.

Similarly for magnetic fields we can introduce a similar quantity… how do we go about doing this…

For **E**:

- We introduced the polarization of a dielectric material (**P** proportional to **E**)

- Similarly we introduce a quantity proportional to **B**: Magnetization **M**.

- **M** describes the response of a medium to magnetic induction

- Electrons can be modelled as moving loops around atoms: we can use the magnetic dipole to model the response

Magnetic Intensity

Now we use the theorem $\quad \displaystyle\int_V \boldsymbol{\nabla} \times \mathbf{F}\, dV = \int_S \mathbf{n} \times \mathbf{F}\, da$

$$
\begin{aligned}
\mathbf{A}(\mathbf{r}_1) &= \frac{\mu_0}{4\pi} \int_V \frac{\boldsymbol{\nabla}_2 \times \mathbf{M}(\mathbf{r}_2)}{r_{12}}\, dV_2 - \frac{\mu_0}{4\pi} \int_S \frac{\mathbf{n} \times \mathbf{M}(\mathbf{r}_2)}{r_{12}}\, da_2 \\
&= \frac{\mu_0}{4\pi} \int_V \frac{\boldsymbol{\nabla}_2 \times \mathbf{M}(\mathbf{r}_2)}{r_{12}}\, dV_2 + \frac{\mu_0}{4\pi} \int_S \frac{\mathbf{M} \times \mathbf{n}(\mathbf{r}_2)}{r_{12}}\, da_2
\end{aligned}
$$

This should look familiar…. and leads (as in the electrostatic case) to "current densities".

Magnetization Current Densities

$$
\mathbf{A}(\mathbf{r}) = \frac{\mu_0}{4\pi} \int \frac{1}{\imath}[\boldsymbol{\nabla}' \times \mathbf{M}(\mathbf{r}')]\, d\tau' + \frac{\mu_0}{4\pi} \oint \frac{1}{\imath}[\mathbf{M}(\mathbf{r}') \times d\mathbf{a}'].
$$

Potential of a   Potential of a
volume current   surface current

$$\boxed{\mathbf{J}_b = \boldsymbol{\nabla} \times \mathbf{M},} \qquad\qquad \boxed{\mathbf{K}_b = \mathbf{M} \times \hat{\mathbf{n}},}$$

Example – 6.1

Find the magnetic field of a uniformly magnetized sphere.

Choose M parallel to z:

$$\mathbf{J_b} = \boldsymbol{\nabla} \times \mathbf{M} = 0 \quad \text{and} \quad \mathbf{K_b} = \mathbf{M} \times \hat{\boldsymbol{n}} = M \sin\theta \, \hat{\boldsymbol{\phi}}$$

This is similar to the field of a uniformly magnetized sphere (example 5.11 on Griffiths),

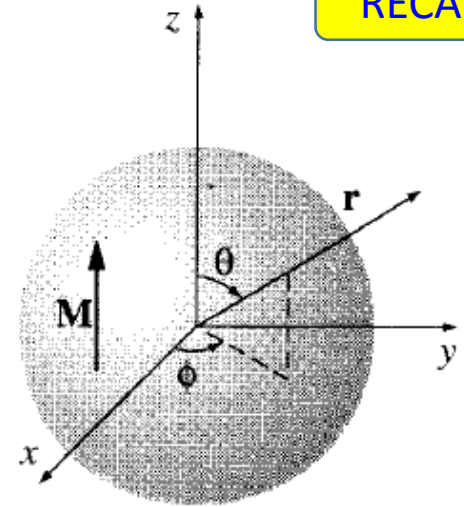$$\mathbf{K} = \sigma\mathbf{v} = \sigma\omega R \sin\theta \, \hat{\boldsymbol{\phi}}$$

with $\sigma\omega R \to M$

As the magnetic field produced by the rotating charged sphere is

$$\mathbf{B} = \boldsymbol{\nabla} \times \mathbf{A} = \frac{2\mu_0 R\omega\sigma}{3}(\cos\theta \, \hat{\mathbf{r}} - \sin\theta \, \hat{\boldsymbol{\theta}}) = \frac{2}{3}\mu_0\sigma R\omega\hat{\mathbf{z}} = \frac{2}{3}\mu_0\sigma R\boldsymbol{\omega}.$$

Ours will equivalently have $\mathbf{B} = \dfrac{2}{3}\mu_0\mathbf{M}$ inside the sphere

and outside that of a pure dipole $\mathbf{m} = \dfrac{4}{3}\pi R^3 \mathbf{M}$

Bound currents

Interpretation.

Magnetization M

Dipole moment $m = Mat$
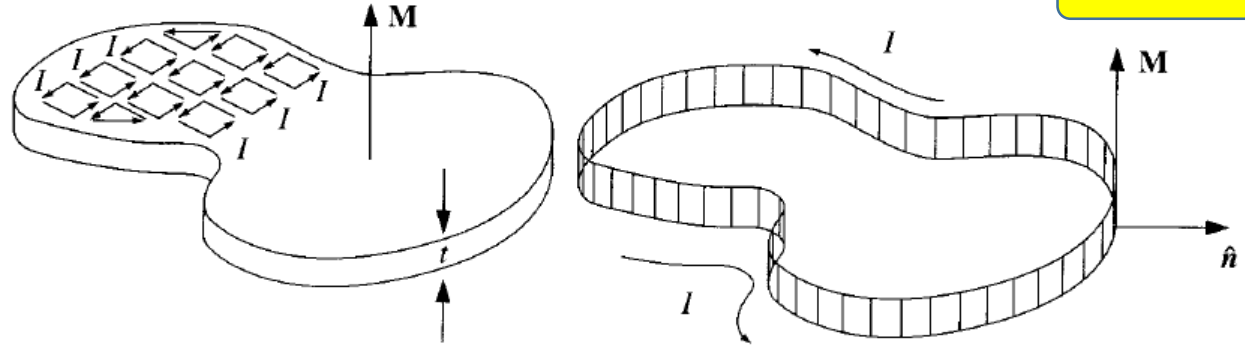
Current is I $m = Ia$

So $I = Mt$

The surface current on the side is $K_b = \dfrac{I}{t} = M$

Using the outward going vector $\mathbf{K_b} = \mathbf{M} \times \hat{\boldsymbol{n}}$

(there is no current on the top and bottom surfaces)

Magnetic Intensity – Ampere's law in Magnetized materials   RECAP

As we did for the E field, let's combine al present magnetized currents, bound and free:

$$\mathbf{J} = \mathbf{J_M} + \mathbf{J_f}$$

Recall that J_f is due to motion of free charges and $\mathbf{J_M} = \nabla \times \mathbf{M}$

Ampere's law can then be written as

$$\nabla \times \mathbf{B} = \mu_0 (\mathbf{J_f} + \nabla \times \mathbf{M})$$

$$\mathbf{J_f} = \nabla \times \left(\frac{1}{\mu_0} \mathbf{B} - \mathbf{M} \right)$$

We define the quantity in parenthesis _Magnetic Intensity (or Auxiliary Field):_

$$\mathbf{H} = \frac{1}{\mu_0} \mathbf{B} - \mathbf{M}$$

The curl of H yields: $\nabla \times \mathbf{H} = \mathbf{J_f}$

The analogy here with **D** can be made on the purpose of the magnetic intensity so the response of the medium to magnetic induction can be written as

$$\int_S \nabla \times \mathbf{H} \cdot \mathbf{n} \, da = \int_S \mathbf{J_f} \cdot \mathbf{n} \, da$$

$$\oint_C \mathbf{H} \cdot d\mathbf{l} = \int_S \mathbf{J_f} \cdot \mathbf{n} \, da = I_f$$

Linear and non-linear media

As for the electric case, Magnetization (as for Polarization) is driven by the field **B**, and once this is removed, the material (whose magnetization is proportional to the field "should" return to its original state (and M should disappear).

This proportionality between **M** and **B** is given by the *magnetic susceptibility*.

$$\mathbf{M} = \chi_m \mathbf{H}$$

If this is case, such materials are referred to as "*linear media*".

Remember from our previous definition of **H**:

$$\mathbf{H} = \left(\frac{1}{\mu_0}\mathbf{B} - \mathbf{M}\right) = \left(\frac{1}{\mu_0}\mathbf{B} - \chi_m \mathbf{H}\right) \qquad\qquad (1 + \chi_m)\mathbf{H} = \frac{1}{\mu_0}\mathbf{B}$$

$$\mathbf{B} = \mu_0(1 + \chi_m)\mathbf{H} = \mu_0\mu_m\mathbf{H}$$

$$\mu = \mu_0\mu_m$$

Referred to as **permeability** of the material.

Magnetic susceptibility

So, in the way we defined different materials we have:

$$\chi_m < 0$$ Diamagnetic   ⟹   Magnetic levitation.
Superconductors have $\chi_m = -1$

$$0 < \chi_m < 1$$ Paramagnetic

$$1 \ll \chi_m$$ Ferromagnetic

Griffiths Table 6.1

Material	Susceptibility	Material	Susceptibility
Diamagnetic:		*Paramagnetic:*	
Bismuth	-1.6×10^{-4}	Oxygen	1.9×10^{-6}
Gold	-3.4×10^{-5}	Sodium	8.5×10^{-6}
Silver	-2.4×10^{-5}	Aluminum	2.1×10^{-5}
Copper	-9.7×10^{-6}	Tungsten	7.8×10^{-5}
Water	-9.0×10^{-6}	Platinum	2.8×10^{-4}
Carbon Dioxide	-1.2×10^{-8}	Liquid Oxygen ($-200°$ C)	3.9×10^{-3}
Hydrogen	-2.2×10^{-9}	Gadolinium	4.8×10^{-1}

Ferromagnetism

In ferromagnets, the alignment of the atomic dipoles, is "frozen in" and requires no external field to sustain magnetization.

One must look at an atomic-level picture as it is _the unpaired electron spins which give the direction of the moments_ and the strong force between neighbouring atoms will align the dipoles in the lowest energy configuration.

The lowest potential energy is with the spins aligned parallel.

The defining characteristic of ferromagnetism is the locality.

Such alignment occurs in small patches referred to as _domains._

The domains themselves can be randomly oriented and hence cancel out in most large scale metals.

Weiss mean field

Pierre-Ernest Weiss initially observed and suggested the existence of domains and suggested that the mean field be generally proportional to the overall magnetization M.

The typical size of these domains can vary but are originally (as in naturally) found at scales of 1 to 10 microns.
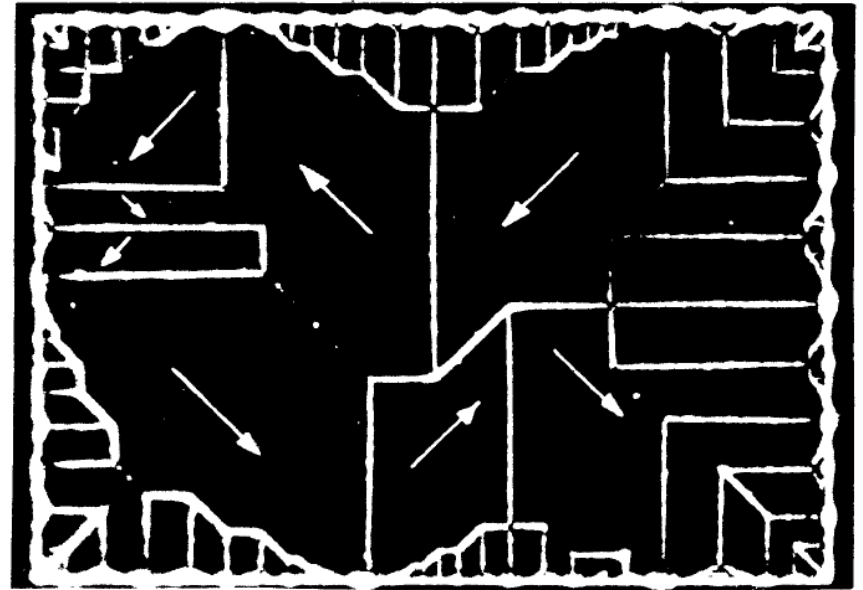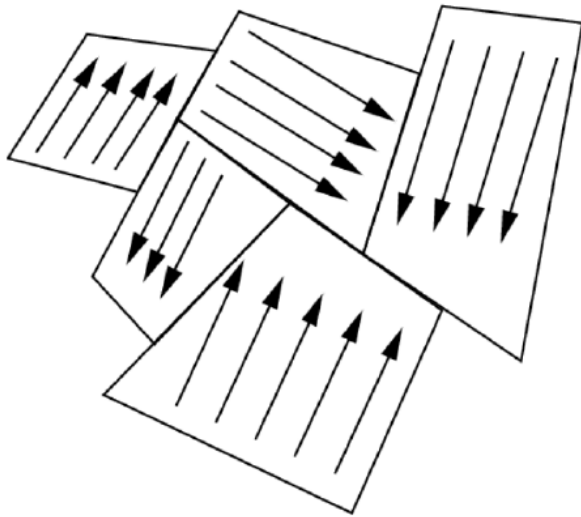
Ferromagnetic domains. (Photo courtesy of R. W. DeBlois)

Later on, quantum mechanics would explain that exchange interaction among neighbouring spins would favour co-alignment (ferromagnets).

17

Microscopic physics of domains

Exchange interaction

- Short range (1 atomic site)

- Keeps neighbouring dipoles aligned

Magnetic Force

- long range

- Has little net magnetic moment
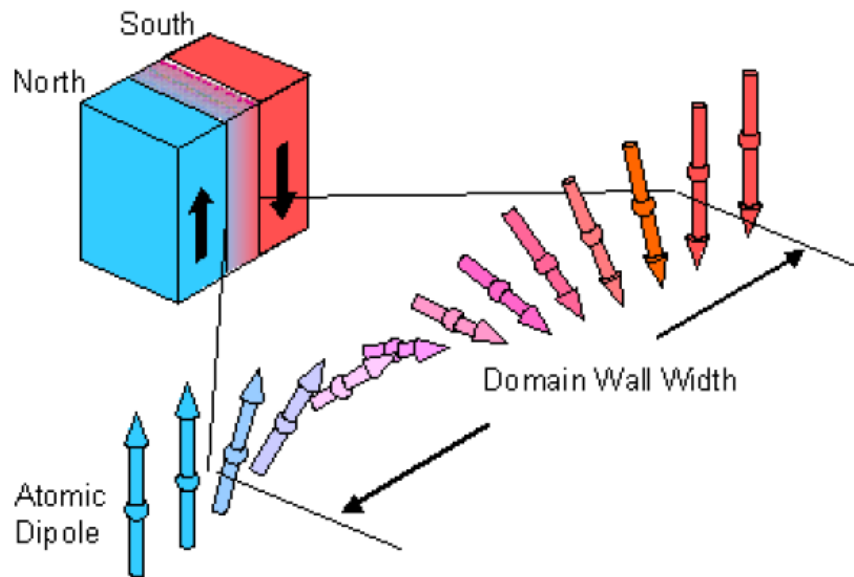
The long range magnetic energy is minimised and the exchange energy is sacrificed only in the region of the domain walls.

External magnetic field influence

The application of an external magnetic field affects domains in a non-linear way.

Initially, a number of domains find themselves oriented randomly. As a magnetic field is introduced, Most dipoles will want to orient to align to it, but the torque is resisted due to the dipoles "staying" with the neighbouring spins.

This will be true throughout the material.
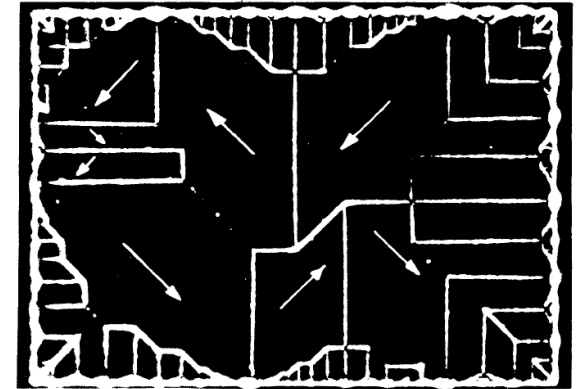
Ferromagnetic domains. (Photo courtesy of R. W. DeBlois)

In proximity to the domain boundaries, each dipole will find itself with competing neighbours at which point the influence of the external magnetic field will favour the neighbours which are aligned to the field therefore shifting progressively the boundary between domains.
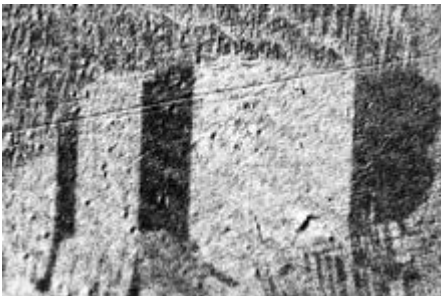
Moving domain walls in a grain of silicon steel caused by an increasing external magnetic field in the "downward" direction, observed in a Kerr microscope.

If the magnetic field is strong enough, one domain will take over and the iron is said to be saturated.

19

External magnetic field influence

This process of boundary shifting is not entirely reversible.

Consider an iron bar and a coil wrapped around it.
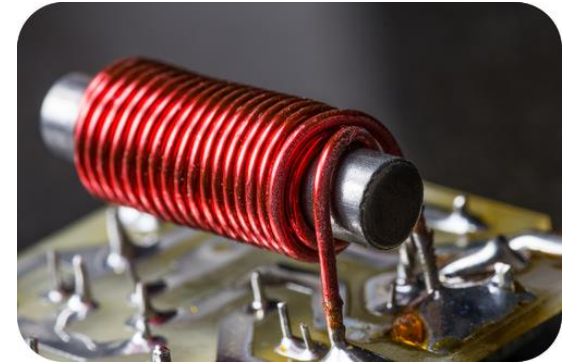
a) → b)

Raise the magnetic field level increasing the Magnetization up to a
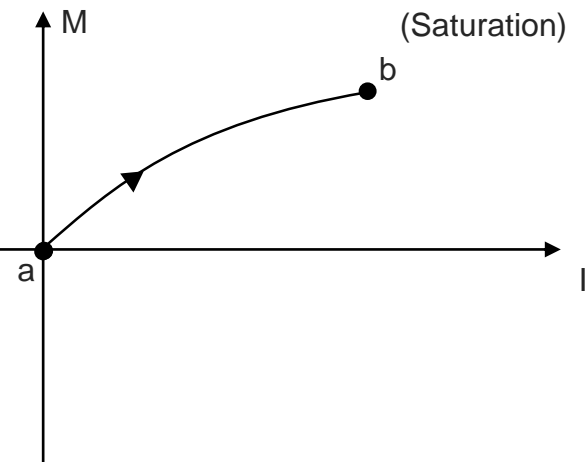point where further raising the field does not increase **M**.

$\mathbf{M}_S$ *Saturation magnetization*

$\mathbf{H}_S$ *Saturation intensity*

The magnetic intensity required to
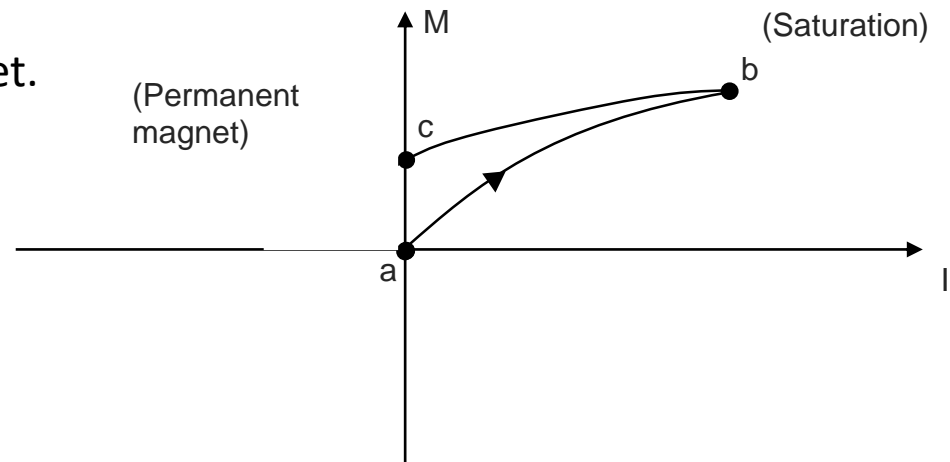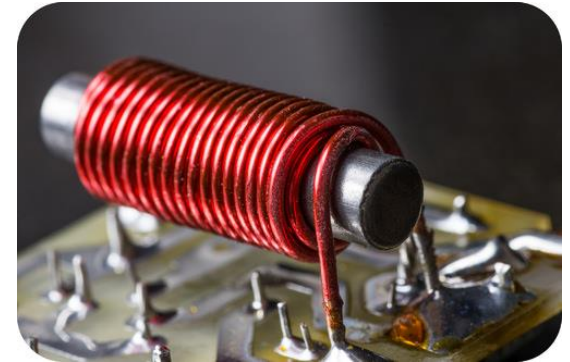reach saturation

$\mathbf{B}_S$ *Saturation induction*

Magnetic induction at saturation

External magnetic field influence

This process of boundary shifting is not entirely reversible.

b) → c)

Once the external field is switched off, some of the original domains are restored, but many retain the last magnetized direction.
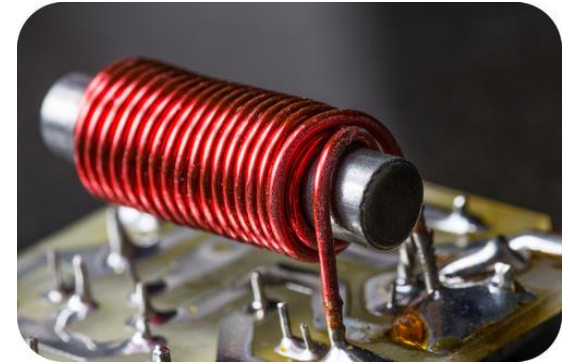
We now have a permanent magnet.

External magnetic field influence

This process of boundary shifting is not entirely reversible.

c) → d)

To remove the remaining magnetization, it will be necessary to reverse the current and force magnetization the opposite direction.
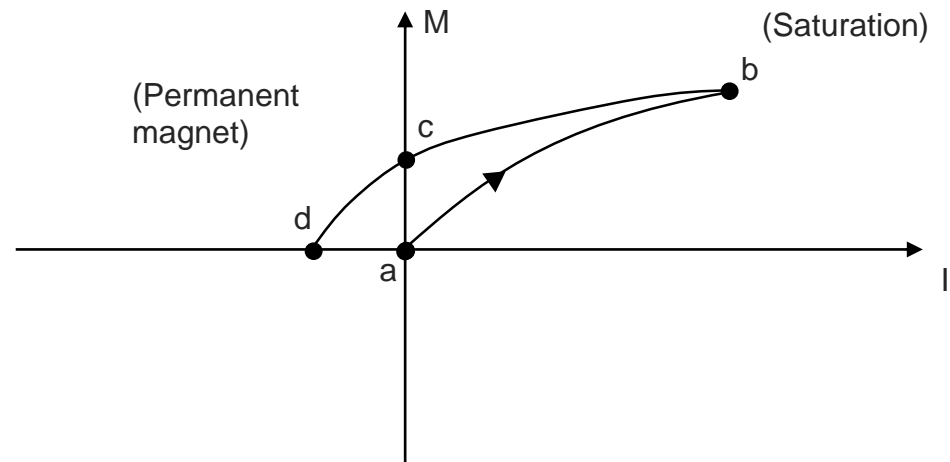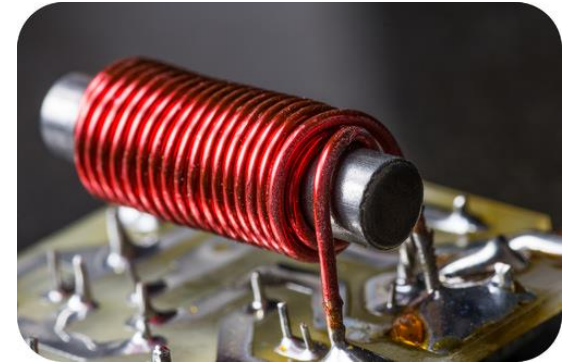
External magnetic field influence

This process of boundary shifting is not entirely reversible.

d) → e)
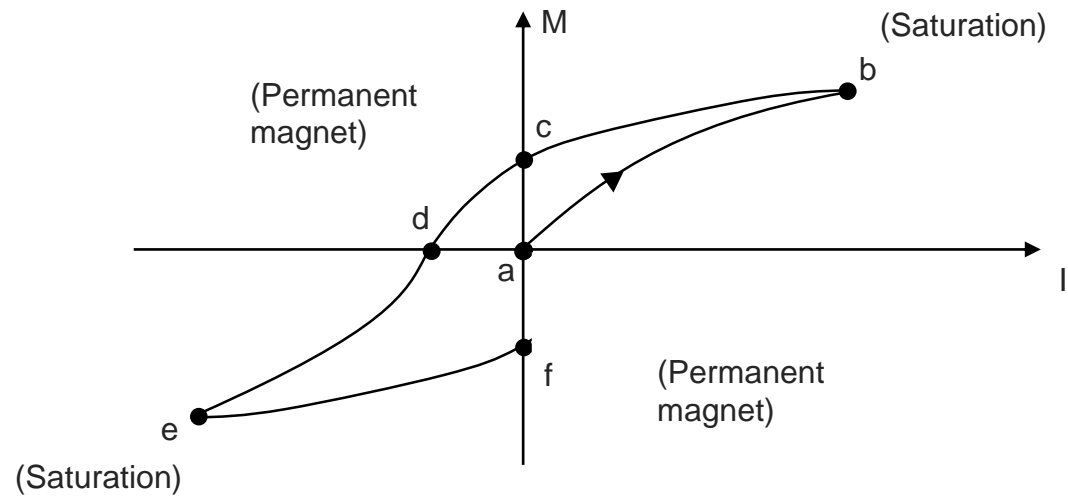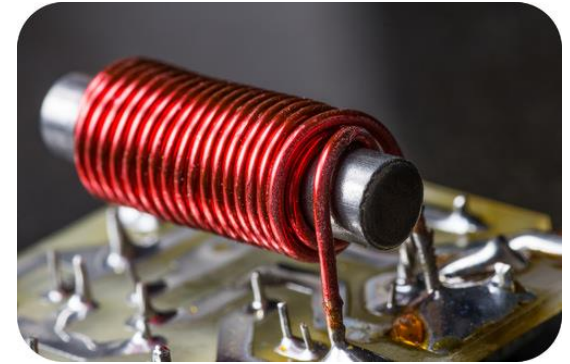
Continue raising the current up to the opposite saturation.
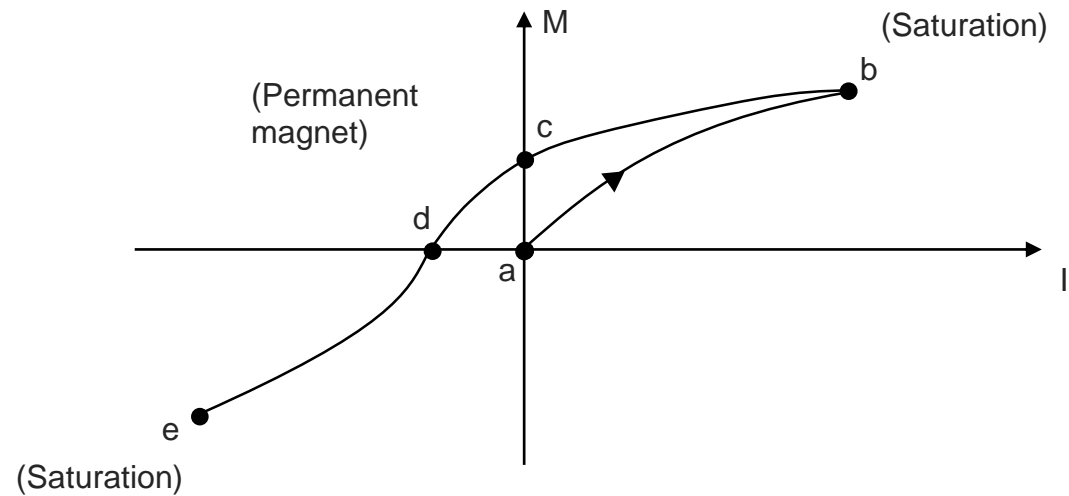
External magnetic field influence

This process of boundary shifting is not entirely reversible.

e) → f)

Switching the current off leaves the bar magnetized permanently in the opposite fashion.

# External magnetic field influence

This process of boundary shifting is not entirely reversible.

Once the external field is switched off, some of the original domains are restored, but many retain the last magnetized direction.

Consider an iron bar and a coil wrapped around it.

f) → g) and then b)

The loop can then be closed by raising the current as in the beginning to the saturation point (through the zero Magnetized point).

The path described is the **_hysteresis loop_**.
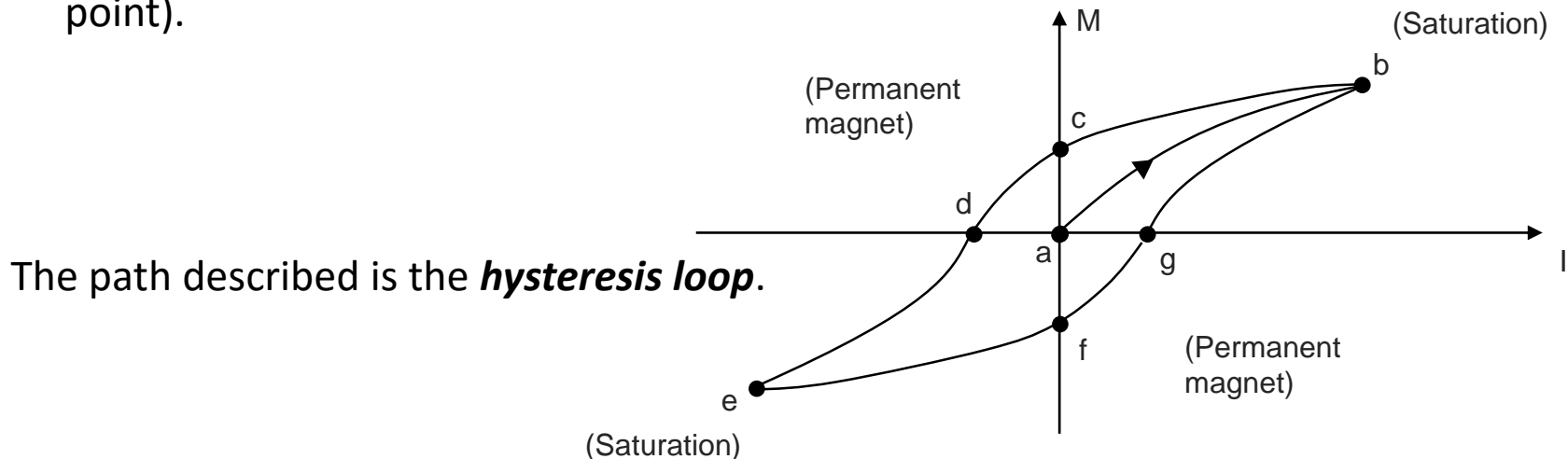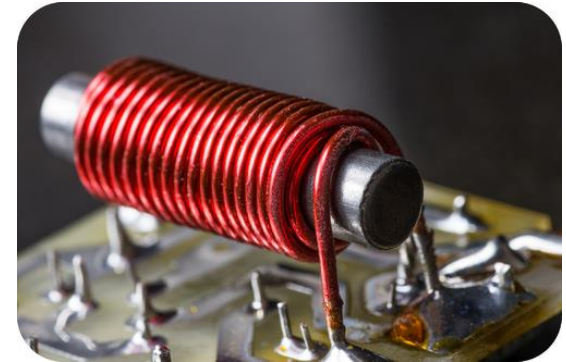
Microscopic analysis

Magnetization by boundary propagation.

Crystal imperfections and defects have their own associated energy.

The boundary between domain wall and imperfection is a local energy minimum.

In magnetizing, the energy to overcome this is provided by the magnetic field.

When this is switched off, the domain boundary will tend to remain pinned at the imperfection.

Hysteresis depends largely on the purity/impurity of the material.

B & H Macroscopic effects

Remember that **H** arises from *free* currents only (wires and coils…) $\boldsymbol{\nabla} \times \mathbf{H} = \mathbf{J_f}$
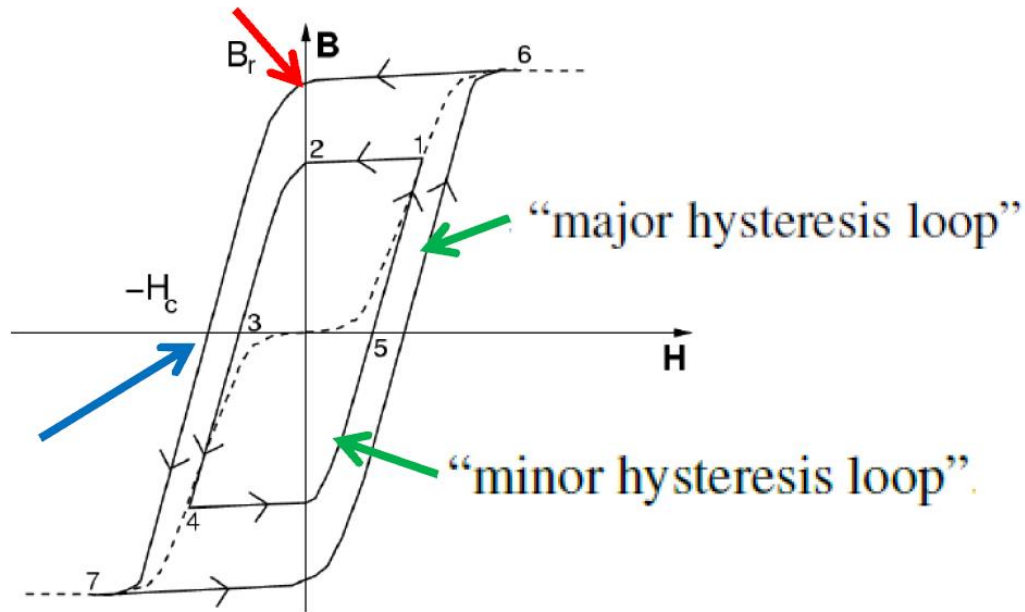
We can always impose a value of **H**…

… the result will be an induction **B** and a Magnetization **M**

As we change or vary **H** the magnetization will change and we can detect the results using Faraday's law to detect changes in **B**.

$$\mathbf{I} \;\rightarrow\; \mathbf{H}$$
$$\mathbf{M} \;\rightarrow\; \mathbf{B}$$

B-H curves for a ferromagnetic material

H_s *Saturation intensity*

The magnetic intensity required to reach saturation

B_s *Saturation induction*

Magnetic induction at saturation

B_r *Remanence*

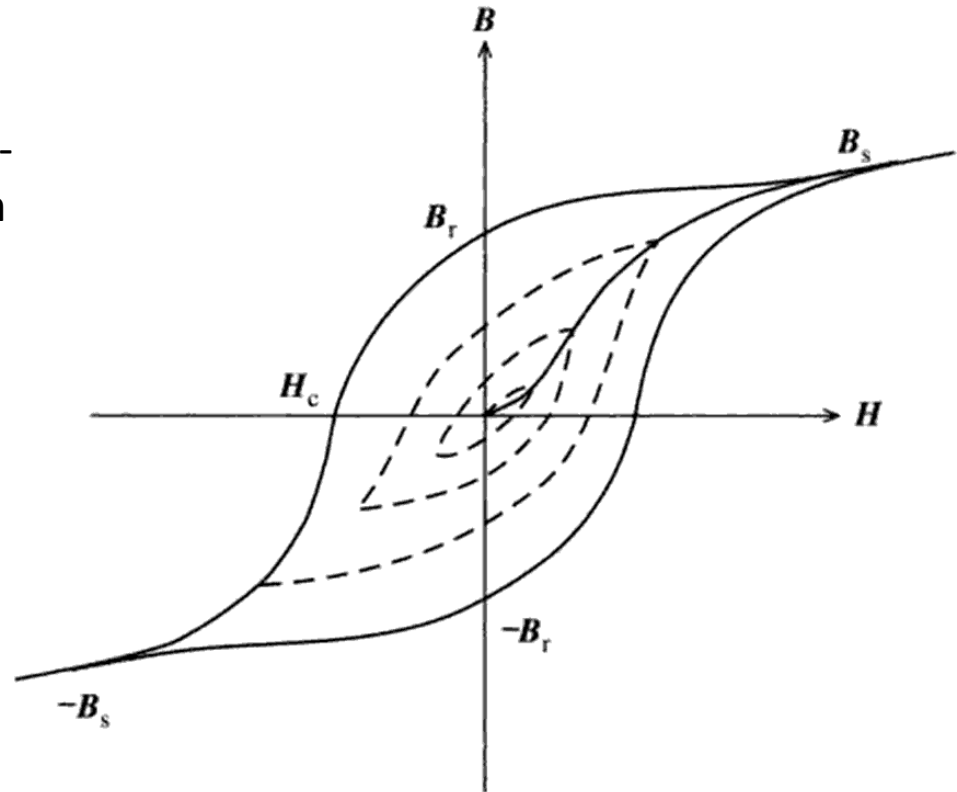Magnetic induction value when H is returned to zero.

H_c *Coercivity*

Value of magnetic intensity required to reduce B to zero after saturation.

Return to de-magnetized

To return the magnet to its original de-magnetized state, an iteration through minor hysteresis loops is required.

Crystals and Tensor susceptibility
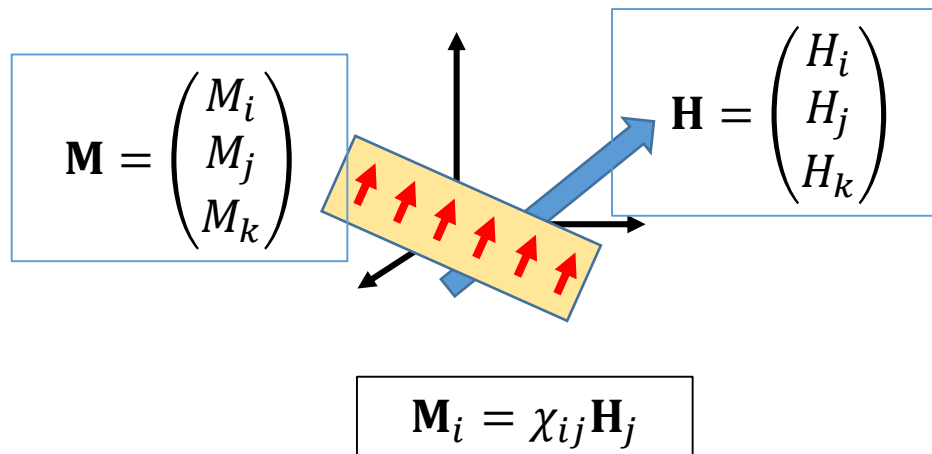
$$\mathbf{M} = \chi_m \mathbf{H}$$

In crystals, isotropy is replaced by oriented and clear directionality which presents a dependence of M on the axis of the crystal and the magnetic field present.

In fact, given a magnetic intensity H aligned with one axis (x,y or z), it is possible for the crystal sample to align to any of the axes… as such we can write

$$\mathbf{M}_i = \chi_{ij}\mathbf{H}_j$$

with "i" and "j" two of the three axes.

So this expression of susceptibility is a 3x3 tensor describing the magnetization

$$\mathbf{M} = \begin{pmatrix} M_i \\ M_j \\ M_k \end{pmatrix} \qquad \mathbf{H} = \begin{pmatrix} H_i \\ H_j \\ H_k \end{pmatrix}$$

$$\mathbf{M}_i = \chi_{ij}\mathbf{H}_j$$

30

Materials that have the population of atoms with magnetic dipoles alternately opposite
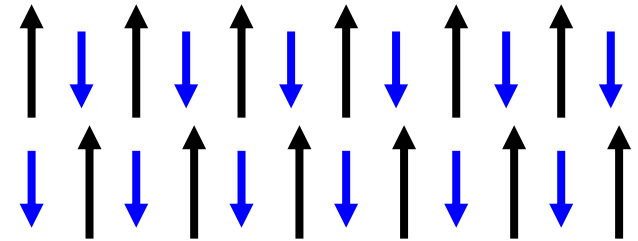
Anti-ferromagnetism

In these materials, the magnetic moments are distributed in a specific way with alternate alignments (opposite) thereby cancelling out most of the Magnetization.
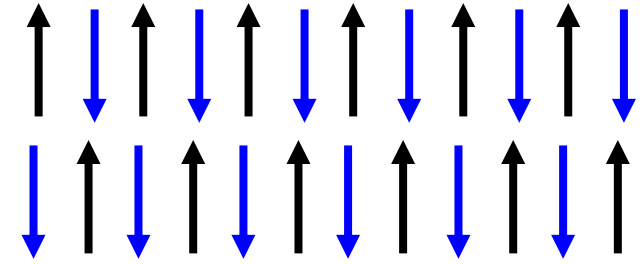
Ferrimagnetism

Composed of two different ions or materials, as in the anti-ferromagnetic, but the dipoles do not cancel out producing reisudal magnetism.

A historical soundbite

Magnetism in history…

Lodestone, Thales 600BC

Heisenberg, 1928

A historical soundbite

Magnetism in history…

Two naturally occurring materials which showed electromagnetic effects:
Amber (greek: electron)
Lodestone (greek: Magnes lithos)

As well as natural manifestations through weather (lightning, static) and animals (eels).

There are many reports of "first usage" (Egypt, China, Greece, Olmec (central America).

Philosophy (early science) however starts with…

Writing and experimenting on static electricity.

History of (electro)magnetism

Magnetism experiments stemming from compass needles

Figure 9.1 The portrait of Shen Kua, a great scholar of Song Dynasty (A.D. 960-1127).

Shen Kuo (Chinese scientist – Song Empire), wrote on the properties of the magnetic needle compass and the "True North".

But then there are many single accounts of observations of magnetic behaviour (of the same nature as the compass) and of static electricity and its origin throughout the medieval period (Europe, Middle-East,…)
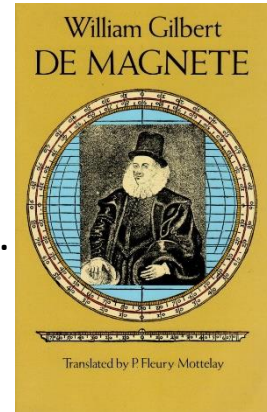
Alexander Neckham (1157-1231)

Petrus Peregrinus de Maricourt (XIII cen.) – scientific account and the use of the word "pole".

Existing records in Italy of a perfected compass with enclosure (1300s)

More in detail when it comes to magnetism…

William Gilbert (1544 – 1603) "Father of the electrical science"

Much experimentation on different materials, relation to heat…

1895 – Curie proposed the Curie Law

1905 – Langevin formulated the theory which described paramagnetism and diamagnetism

Almost the same year Wiess proposed the theory for Ferromagnetism

Subsequently, magnetism benefit from the development of quantum mechanics and the introduction of electron spin and exchange interactions.

Magnetism   (derivation)

Last year, you had the following statement:

It can be shown that the magnetisation varies as:

$$M = N\langle\mu\rangle = N\mu \tanh\left(\frac{\mu B}{k_B T}\right)$$

Energy of a magnetic dipole:

$$E = -mB\cos\theta$$

Number of dipoles with energies in the interval $[E, E + dE]$

$$dn = ce^{(-E/kT)}dE \qquad\qquad dE = mB\sin\theta\, d\theta$$

Which becomes

$$dn = ce^{(mB\cos\theta/kT)}mB\sin\theta\, d\theta$$

Which is the number of dipoles with orientation $[\theta, \theta + d\theta]$

Magnetism   (derivation)

Consider the resolved component of the magnetisation $m \cos \theta$
and integrate over all atoms such that we can write

$$M = N\langle m \rangle = \int m \cos \theta \, dn$$

N is the total number of dipoles and <m> the average dipole field.

(note the integral is on the population (distribution) which has that particular orientation… "m" can be taken out.

As such we can express the ratio of the average magnetic dipole with the

$$\frac{\langle m \rangle}{m} = \frac{\int_0^N \cos \theta \, dn}{\int_0^N dn}$$

We can write $x = \dfrac{mB \cos \theta}{kT} = a \cos \theta$ $dn = c e^{(mB \cos \theta / kT)} mB \sin \theta \, d\theta$
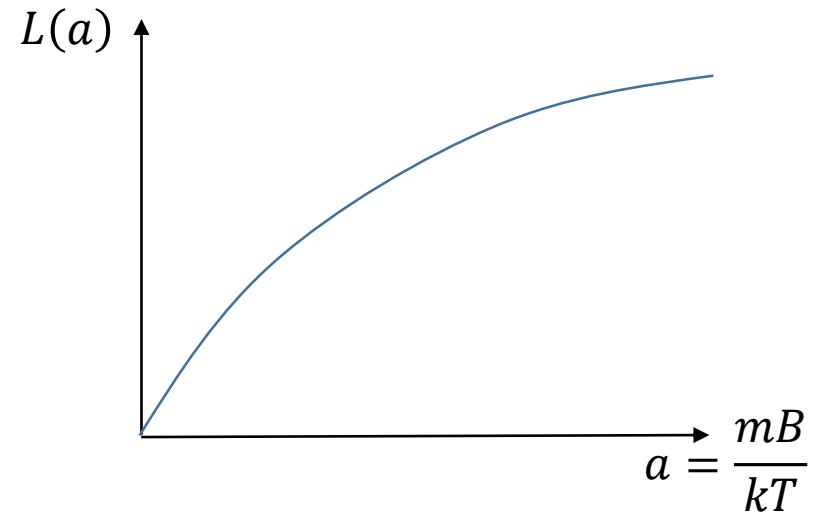
And solve: $\dfrac{\langle m \rangle}{m} = \dfrac{1}{a} \dfrac{\int_{-a}^{a} x e^x dx}{\int_{-a}^{a} e^x dx} = \dfrac{e^a + e^{-a}}{e^a - e^{-a}} - \dfrac{1}{a}$

Magnetism   (derivation)

$$L(a) = \frac{\langle m \rangle}{m} = \frac{e^a + e^{-a}}{e^a - e^{-a}} - \frac{1}{a}$$

$L(a)$

$a = \dfrac{mB}{kT}$

L(a) is the Langevin function

$$M = NmL(a)$$

Magnetization increases as:

-) The field increases

-) The temperature decreases

IF $mB \ll kT$ then $a \ll 1$

Magnetism   (derivation)

L(a) can be expanded in powers of "a":

$$L(a) = \frac{e^a + e^{-a}}{e^a - e^{-a}} - \frac{1}{a} \cong \frac{a}{3} + \frac{a^2}{45} + \cdots$$

So then

$$M = NmL(a) \approx \frac{Nma}{3} \approx \frac{Nm^2 B}{3kT} \approx \frac{Nm^2 \mu_0 H}{3kT}$$

Our susceptibility becomes:

$$\chi = \frac{M}{H} \approx \frac{Nm^2 \mu_0}{3kT}$$

This is Curie's Law and the quantity $C = \dfrac{Nm^2 \mu_0}{3k}$

Also referred to as Curie's constant

Curie temperature

As one raises the temperature, a permanent magnet (ferromagnet) loses its magnetic moment caused by the added disorder of the dipoles .

The temperature at which the transition from Ferromagnetic to Paramagnetic is called:
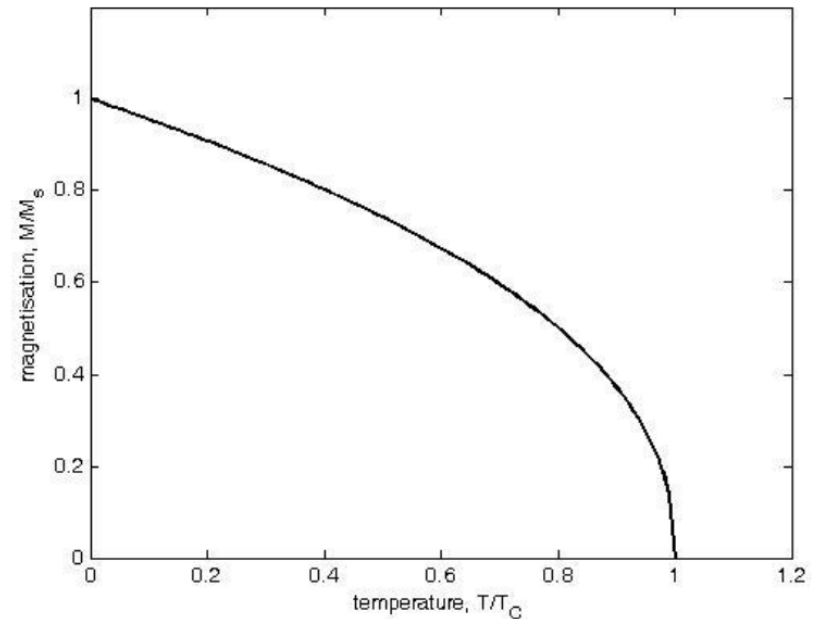
Curie temperature

For $T > T_C$:

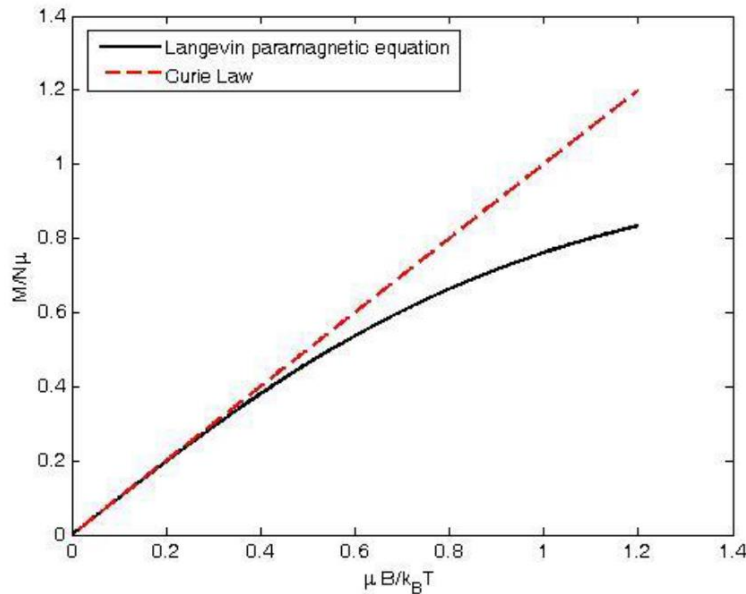$$\frac{M}{M_S} \propto \frac{1}{T - T_C}$$

For $T < T_C$:

$$\frac{M}{M_S} = \left(\frac{T_C - T}{T_C}\right)^\gamma$$

$$\gamma \approx 0.36 - 0.39$$

Curie temperature

A material is paramagnetic
above its Curie temperature

A list of Curie temperatures (Wikipedia*)

Material	Curie temperature (K)
Iron (Fe)	1043
Cobalt (Co)	1400
Nickel (Ni)	627
Gadolinium (Gd)	292
Dysprosium (Dy)	88
Manganese bismuthide (MnBi)	630
Manganese antimonide (MnSb)	587
Chromium(IV) oxide (CrO_2)	386
Manganese arsenide (MnAs)	318
Europium oxide (EuO)	69
Iron(III) oxide (Fe_2O_3)	948
Iron(II,III) oxide ($FeOFe_2O_3$)	858
$NiO–Fe_2O_3$	858
$CuO–Fe_2O_3$	728
$MgO–Fe_2O_3$	713
$MnO–Fe_2O_3$	573
Yttrium iron garnet ($Y_3Fe_5O_{12}$)	560
Neodymium magnets	583–673
Alnico	973–1133
Samarium–cobalt magnets	993–1073
Strontium ferrite	723

(*) values from Buschow 2001, p5021, table 1
Jullien 1989, p. 155 and Kittel 1986

41

Temperature effects

Anti-ferromagnetism

These materials also have a critical temperature which is the Néel (Louis Néel, nobel prize 1970) temperature above which these materials become paramagnetic.

Ferrimagnetism

Similarly to ferromagnetic, they are such only below the Curie T. Otherwise revert to paramagnetic.

substance	Néel temperature, in Kelvin
MnO	116
MnS	160
MnTe	307
MnF_2	67
FeF_2	79
$FeCl_2$	24
FeI_2	9
FeO	198
FeOCl	80
$CoCl_2$	25
CoI_2	12
CoO	291
$NiCl_2$	50
NiI_2	75
NiO	525
Cr	308
Cr_2O_3	307
Nd_5Ge_3	50

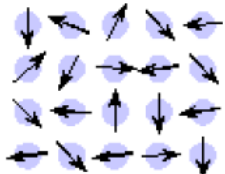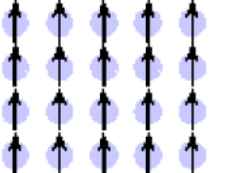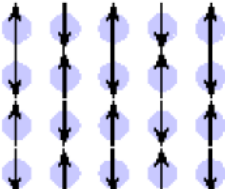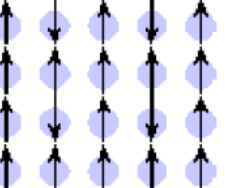# Microscopic physics of domains

two different types of magnetic materials:

soft ones (always have a low coercivity, and sometimes a low remanence but high μ_{r-eff}) which are easy to magnetise and demagnetise and so are used in transformers (frequent changes in magnetization) of in shielding;

and **hard** ones (large coercivity and remanence) which are hard to demagnetise once magnetised and are used as permanent magnets.
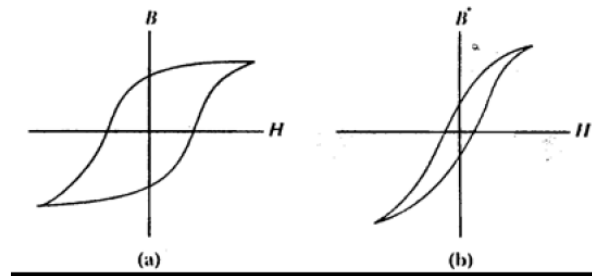
Summary of Type of Magnetism

Type of Magnetism	Susceptibility	Atomic / Magnetic Behaviour		Example / Susceptibility
Diamagnetism	Small & negative.	Atoms have no magnetic moment		Au -2.74×10^{-6} Cu -0.77×10^{-6}
Paramagnetism	Small & positive.	Atoms have randomly oriented magnetic moments		β-Sn 0.19×10^{-6} Pt 21.04×10^{-6} Mn 66.10×10^{-6}
Ferromagnetism	Large & positive, function of applied field, microstructure dependent.	Atoms have parallel aligned magnetic moments		Fe ~100,000
Antiferromagnetism	Small & positive.	Atoms have mixed parallel and anti-parallel aligned magnetic moments		Cr 3.6×10^{-6}
Ferrimagnetism	Large & positive, function of applied field, microstructure dependent	Atoms have anti-parallel aligned magnetic moments		Ba ferrite ~3

44

Summary of Type of Magnetism

At room temperature:

Microscopic physics of domains