# ELEC 315:
# Magnetic Materials

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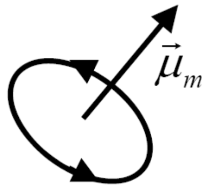
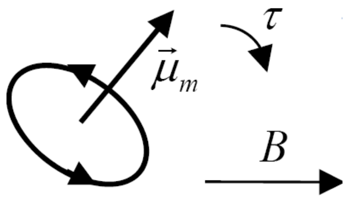
# Magnetic Moment

If we consider a current loop as shown in the figure below (similar to a coil carrying a current), then a magnetic moment can be defined for this current loop as:

$$\vec{\mu}_m = IA\hat{n}$$

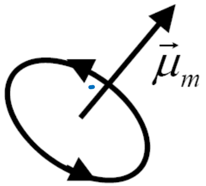



In the presence of an external magnetic field, a magnetic moment experiences a torque that tries to process the magnetic moment around the direction of magnetic field:




The magnetic moment also generates a magnetic field around it like a coil:

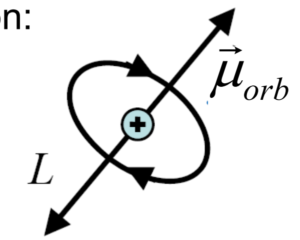
$$B \propto |\vec{\mu}_m| / r^3$$



# Magnetic Moment of Atoms

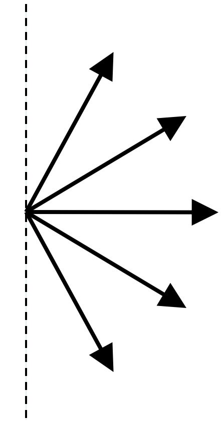
In classical physics, an electron orbiting an atom behaves like a current loop and has a magnetic moment that is proportional to the angular momentum of the electron:

$$\vec{\mu}_{orb} = -\frac{q}{2m_e}\vec{L}$$




The magnitude of angular momentum of electron, when quantum physics is used to calculate orbitals, is quantized and has different values for different orbitals:

$$L = \hbar\sqrt{l(l+1)}$$



For example, for s orbital

The component of angular momentum in the direction of an external magnetic field (z) is also quantized: $L_z = \hbar m_l$

The total magnetic moment of an electron is given by adding the magnetic moment due to angular momentum to magnetic moment due to the spin of electron: $\vec{\mu}_{spin} = -\frac{q}{m_e}\hbar s \qquad s = \pm 1/2$

$$\vec{\mu}_{total} = \vec{\mu}_{spin} + \vec{\mu}_{orb}$$

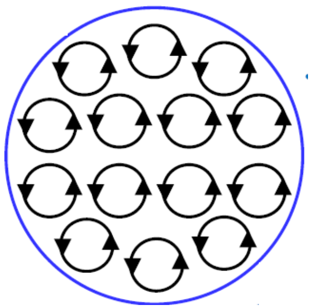
# Magnetization Vector

To calculate the magnetic moment for atoms with more than one electron, we need to add all the magnetic moments of each electron to calculate the total moment. This equals to zero for complete atomic shells, since orbital and spin moments of opposite signs have the same number and cancel each other.

For example, for a metal with a single final electron in 3s orbital (Na), the magnetic moment of the atom is only due to this final electron in 3s orbital, which is only due to its spin.

To calculate the *macroscopic* magnetic moment generated by all magnetic moments of different atoms and molecules we need to add all these *microscopic* magnetic moments:

$$\vec{M} = \frac{\sum \vec{\mu}_m}{V}$$



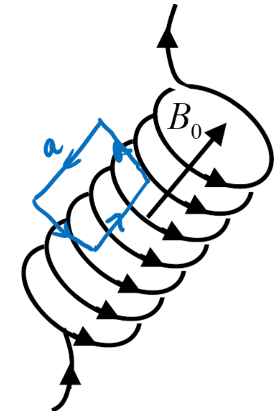
In most non-magnetic materials this adds up to be zero, however, specific properties of magnetic materials such as iron leads to an effective alignment of magnetic moments for creation of a permanent magnetization vector M. It can be shown that this vector equals to surface current:

$$M = I_m$$

# Magnetic Field and Permeability

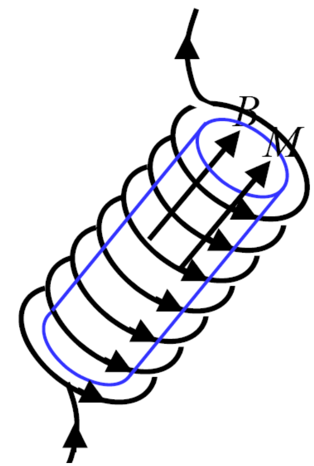
If we assume to have a solenoid with *n* turns per unit length carrying a current I, the magnetic field inside the solenoid is:

$$B_0 = \mu_0 nI$$




Now if we place a magnetic material in the solenoid, the atomic magnetic moments of the material align in the direction of external magnetic field, thus generating a magnetization vector. The resulting total magnetic field will be:

$$B = \mu_0 (nI + I_m) = B_0 + \mu_0 M \qquad H = nI$$




The magnetic permeability of the material is then defined by

$$\mu = \frac{B}{H} = \mu_r \mu_0 \qquad \mu_r = \frac{\mu}{\mu_0} = \frac{B}{B_0}$$

The magnetic susceptibility is defined by

$$\chi_m = \frac{M}{H} = \mu_r - 1$$

# Magnetic Material Classification

1. **Diamagnetism:**

   Diamagnetic materials have a small and negative susceptibility ($-10^{-6}$). These materials repel the magnetic field. Examples include Si, Ge, Cu, Au, Ag, water, organic materials and polymers.

   The magnetization vector is in the opposite direction of that of the applied magnetic field.

   The atoms have closed and filled shells and sub-shells (No permanent magnetic moment).

2. **Paramagnetism:**

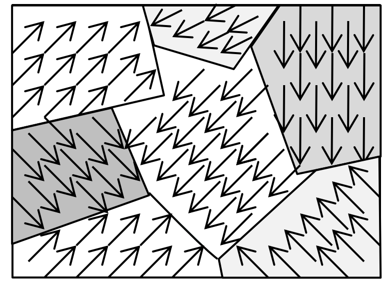
   Paramagnetic materials have a small and positive susceptibility, due to presence of some unpaired electrons. Examples: oxygen and most metals including Li, Mg, Mo. The atoms have small but permanent magnetic moments that align with field.

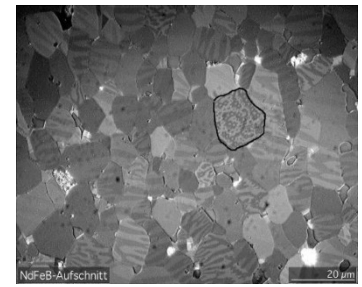
3. **Ferromagnetism:**

   Ferromagnetic materials like Fe, Co, Ni can have large magnetization even in the absence of magnetic field. The high magnetic properties is due to the presence of magnetic domains. The relationship between H-B are highly non-linear and saturates at high fields.

# Magnetic Domains and Hysteresis

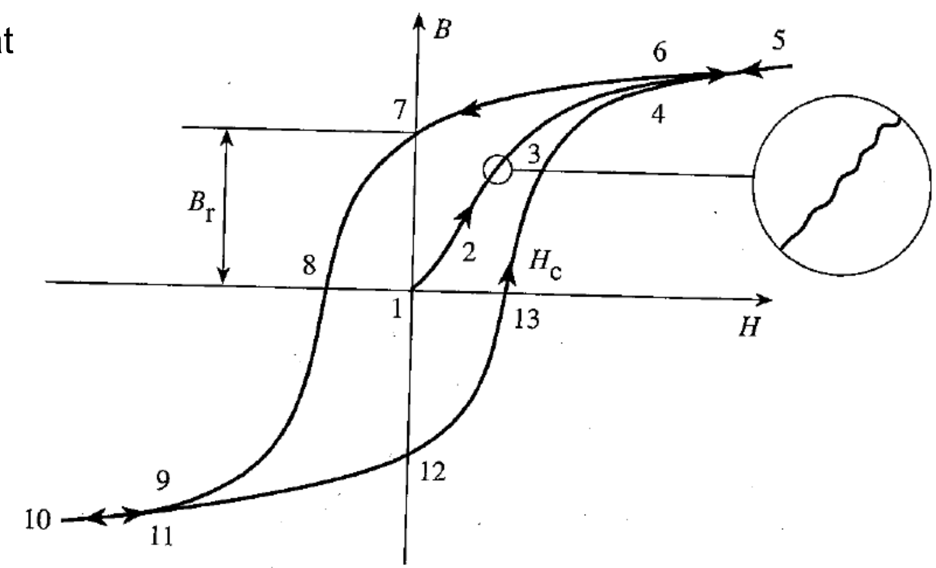
Ferromagnetic materials gain their magnetic properties from domains with aligned magnetic moments. When the material solidifies from a melt, the domains with aligned magnetic moments are formed.






The direction of magnetic moments inside a ferromagnetic material can be changed to align or join different domains by applying an external magnetic field.

- A maximum magnetization is achieved at
- If external field is reduced a residual field remains (retentivity)
- To reduce the field to zero, a negative external field is required (coercive field ).



# Soft and Hard Magnetic Materials

Based on B-H hysteresis curve of magnetic materials, they are categorized into soft and hard magnetic materials as shown in the figure.

**Hard magnetic** materials on the other hand require a high external magnetic field to magnetize or demagnetize. The coercive field for a hard magnetic material can be a million time larger than that for soft materials.

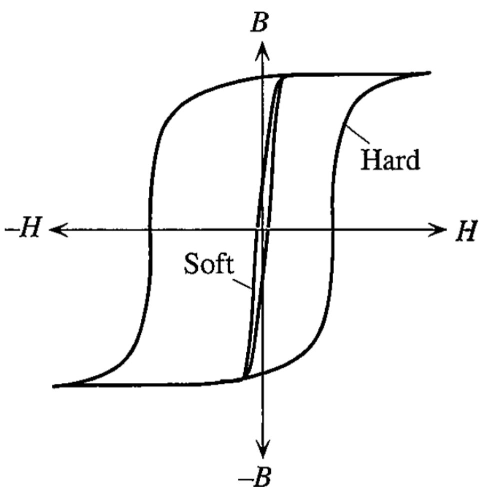



Table 8.6 Hard magnetic materials and typical values

| 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) | 0.19 | 0.9 | 50 | Wide range of permanent magnet applications. |
| Alnico (Columnar) | 0.075 | 1.35 | 60 | |
| Strontium ferrite (anisotropic) | 0.3–0.4 | 0.36–0.43 | 24–34 | Starter motors, dc motors, loudspeakers, telephone receivers, various toys. |
| Rare earth cobalt, *e.g.*, $Sm_2Co_{17}$ (sintered) | 0.62–1.1 | 1.1 | 150–240 | Servo motors, stepper motors, couplings, clutches, quality audio headphones. |
| NdFeB magnets | 0.9–1.0 | 1.0–1.2 | 200–275 | Wide range of applications, small motors (*e.g.*, in hand tools), walkman equipment, CD motors, MRI body scanners, computer applications. |
| Hard particles, $\gamma$-$Fe_2O_3$ | 0.03 | 0.2 | | Audio and video tapes, floppy disks. |

# Soft and Hard Magnetic Materials

**Soft magnetic** materials are easily magnetized and demagnetized, thus requiring low intensity for external magnetic field. These materials are suitable for applications where frequent magnetization and demagnetization is required, such as electric motors, inductors, and data storage.

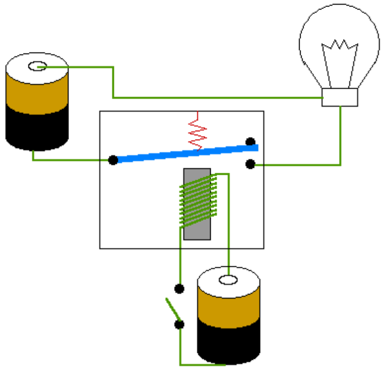
**Table 8.5** Selected soft magnetic materials and some typical values and applications

| Magnetic Material | $\mu_o H_c$ (T) | $B_{sat}$ (T) | $B_r$ (T) | $\mu_{ri}$ | $\mu_{r,max}$ | $W_h$ | 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 | $10^3$ | $10^4$– $4 \times 10^5$ | 30–100 | Higher resistivity and hence lower eddy current losses. Wide range of electric machinery (*e.g.*, transformers). |
| Supermalloy (79% Ni–15.5% Fe–5% Mo–0.5% Mn) | $2 \times 10^{-7}$ | 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) | $5 \times 10^{-6}$ | 0.86 | <0.1 | $8 \times 10^3$ | $10^5$ | <0.1 | Low-loss electric devices, audio transformers, HF transformers, recording heads, filters. |
| Glassy metals, Fe–Si–B | $2 \times 10^{-6}$ | 1.6 | $<10^{-6}$ | — | $10^5$ | 20 | Low-loss transformer cores. |
| Ferrites, Mn–Zn ferrite | $10^{-5}$ | 0.4 | <0.01 | $2 \times 10^3$ | $5 \times 10^3$ | <0.01 | HF low-loss applications. Low conductivity ensures negligible eddy current losses. HF transformers, inductors (*e.g.*, pot cores, E and U cores), recording heads. |

# Example

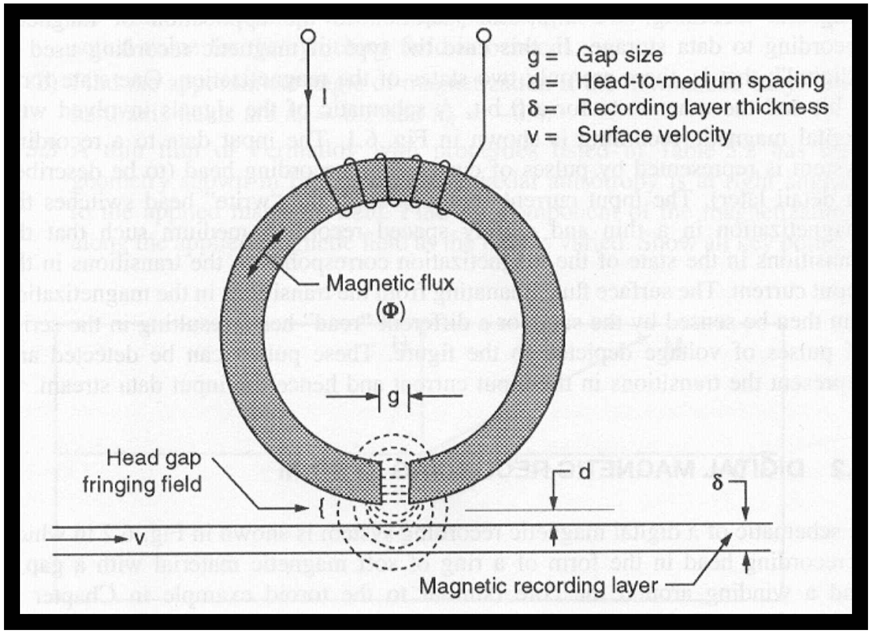
A cylindrical ferromagnet of length L and diameter d, (d<<L) has a uniform magnetization M along its axis. A current is passed in an empty solenoid of the same geometry. If the solenoid has N turns and an air core, how much current is required to generate the same magnetic field as is produced by the magnetized cylinder?

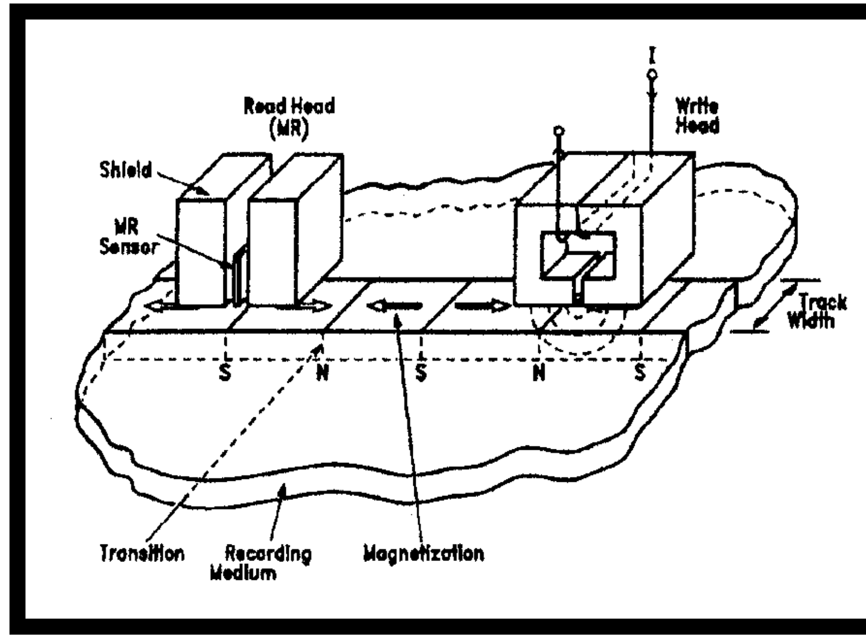
Explain how a relay works. What is the difference if we use a soft or hard magnetic material as the core in a relay?



# Magnetic Storage

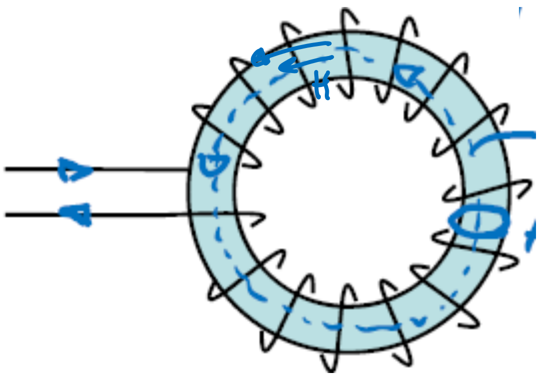
Toroidal shape magnets are used to write and read information on a piece of magnetic film.



# Example

Calculate the inductance of a toroidal coil with the length L and N turns.



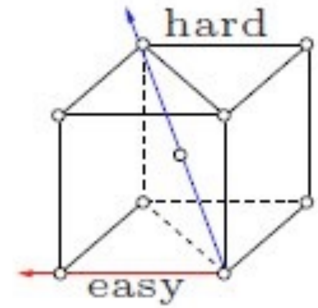
# Magnetocrystalline Anisotropy

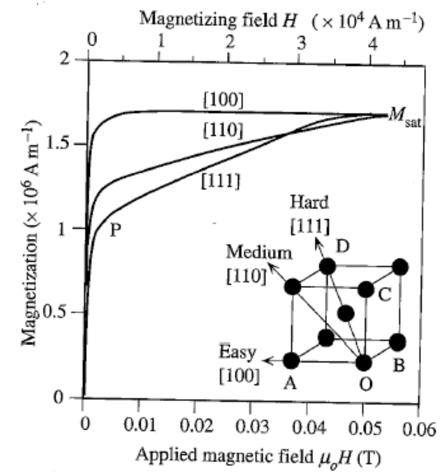
**Ferromagnetic** materials show magnetic anisotropy in different crystalline directions. In other words along some axes the material can get magnetize easier than other directions.

Iron for example has a BCC crystal and along [100] direction the spins of domains can be aligned much easier. There are six <100> directions giving iron crystal 6 easy axes. This can be as low as 0.01 T.

In contrast, magnetizing the crystal along direction [111] is hard and more external field is required.

The reason for having this anisotropy is the exchange interaction energy for spin and orbital of atoms in ferromagnetic materials such as Fe, Ni and Co.



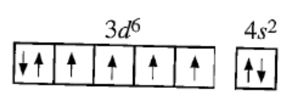




**Figure 8.18** The isolated Fe atom has four unpaired spins and a spin magnetic moment of $4\beta$.

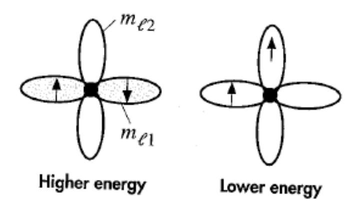
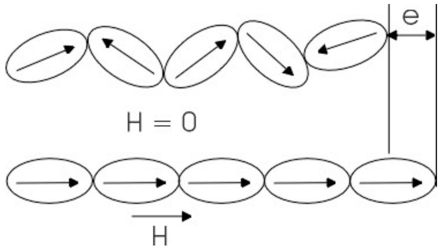



**Figure 8.19** Hund's rule for an atom with many electrons is based on the exchange interaction.

# Magnetostriction

If strain is applied to a ferromagnetic crystal in certain direction, the atomic distance changes in that direction and also in other directions. This will change the exchange interaction energy of atomic spins and magnetization properties of the material.

The reverse process also happens and applying an external field will cause the ferromagnet crystal to change its dimensions.




For example, when external field is applied to iron in direction [100], crystal gets longer in this direction and shorter in transverse [010] and [001] directions.

Magnetostrictive constant $\lambda$ denotes the longitudinal strain upon magnetization.