4.1.4 Summary to: Magnetic Materials - Definitions and General Relations

- The **relative permeability** μ_r of a material "somehow" describes the interaction of magnetic (i.e. more or less all) materials and magnetic fields ***H***, e.g. vial the equations ⇒
  - ***B*** is the **magnetic flux density** or **magnetic induction**, sort of replacing ***H*** in the Maxwell equations whenever materials are encountered.
  - ***L*** is the inductivity of a linear solenoid (also called coil or inductor) with length ***l***, cross-sectional area ***A***, and number of turns ***t***, that is "filled" with a magnetic material with μ_r.
  - ***n*** is *still* the index of refraction; a quantity that "somehow" describes how electromagnetic fields with extremely high frequency interact with matter.
    For all practical purposes, however, $\mu_r = 1$ for optical frequencies

$$B = \mu_0 \cdot \mu_r \cdot H$$

$$L = \frac{\mu_0 \cdot \mu_r \cdot A \cdot w^2}{l}$$

$$n = (\epsilon_r \cdot \mu_r)^{1/2}$$

- Magnetic fields inside magnetic materials polarize the material, meaning that the vector sum of magnetic dipoles inside the material is no longer zero.
  - The decisive quantities are the *magnetic* dipole moment ***m***, a vector, and the *magnetic* Polarization ***J***, a vector, too.
  - Note: In contrast to dielectrics, we define an additional quantity, the **magnetization *M*** by simply including dividing ***J*** by μ_0.
  - The magnetic dipoles to be polarized are either already present in the material (e.g. in **Fe, Ni or Co**, or more generally, in all **paramagnetic** materials, or are induced by the magnetic fields (e.g. in **diamagnetic** materials).
  - The dimension of the magnetization ***M*** is **[A/m]**; i.e. the same as that of the magnetic field.

$$B = \mu_0 \cdot H + J$$

$$\underline{J} = \mu_0 \cdot \frac{\Sigma \underline{m}}{V}$$

$$M = \frac{J}{\mu_0}$$

- The magnetic polarization ***J*** or the magnetization ***M*** are *not* given by some magnetic surface charge, because ⇒.

There is no such thing as a *magnetic monopole*, the (conceivable) counterpart of a negative or positive electric charge

- The equivalent of "Ohm's law", linking current density to field strength in conductors is the *magnetic* Polarization law:
  - The decisive material parameter is $\chi_{mag} = (\mu_r - 1)$ **= magnetic susceptibility**.
  - The "classical" induction ***B*** and the magnetization ***M*** are linked as shown. In essence, ***M*** only considers what happens in the material, while ***B*** looks at the total effect: material plus the field that induces the polarization.

$$M = (\mu_r - 1) \cdot H$$

$$M := \chi_{mag} \cdot H$$

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

- Magnetic polarization mechanisms are formally similar to dielectric polarization mechanisms, but the physics can be entirely different.

Atomic mechanisms of magnetization are not directly analogous to the dielectric case

Magnetic moments originate from:

- The intrinsic magnetic dipole moments ***m*** of elementary particles with spin is measured in units of the Bohr magneton m_{Bohr}.
- The magnetic moment m^e of the electron is ⇒
- Electrons "orbiting" in an atom can be described as a current running in a circle thus causing a magnetic dipole moment; too

$$m_{Bohr} = \frac{h \cdot e}{4\pi \cdot m^*_e} = 9.27 \cdot 10^{-24}\ \mathrm{Am}^2$$

$$m^e = \frac{2 \cdot h \cdot e \cdot s}{4\pi \cdot m^*_e} = 2 \cdot s \cdot m_{Bohr} = \pm m_{Bohr}$$

The total magnetic moment of an atom in a crystal (or just solid) is a (tricky to obtain) sum of all contributions from the electrons, and their orbits (including bonding orbitals etc.), it is either:

- **Zero** - we then have a **diamagnetic material**.

Magnetic field induces dipoles, somewhat analogous to elctronic polarization in dielectrics.
Always very weak effect (except for superconductors)
Unimportant for technical purposes

- In the order of a few Bohr magnetons - we have a essentially a **paramagnetic material**.

Magnetic field induces some order to dipoles; strictly analogous to "orientation polarization" of dielectrics.
Always very weak effect
Unimportant for technical purposes

In some **ferromagnetic** materials spontaneous ordering of magnetic moments occurs below the Curie (or Neél) temperature. The important families are

- Ferromagnetic materials ⇑⇑⇑⇑⇑⇑⇑
  large **μ_r, extremely important**.
- Ferrimagnetic materials ⇑⇓⇑⇓⇑⇓⇑
  still large **μ_r, very important**.
- Antiferromagnetic materials ⇑⇓⇑⇓⇑⇓⇑
  $\mu_r \approx 1$, unimportant

Ferromagnetic materials:
Fe, Ni, Co, their alloys
"AlNiCo", Co_5Sm, $Co_{17}Sm_2$, "NdFeB"

There is characteristic temperature dependence of **μ_r** for all cases

Questionnaire

Multiple Choice questions to all of 4.1