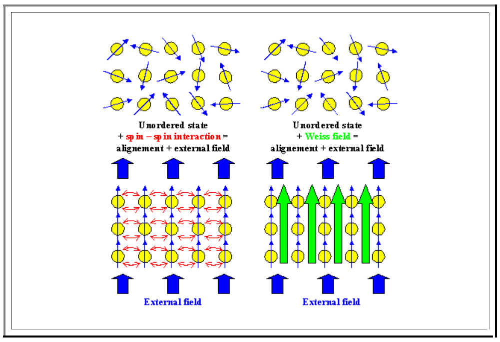
4.3.7 Summary to: Ferromagnetism

- In ferromagnetic materials the magnetic moments of the atoms are "correlated" or lined-up, i.e. they are all pointing in the same direction
  - The physical reason for this is a quantum-mechanical spin-spin interaction that has no simple classical analogue.
  - However, exactly the same result - complete line-up - could be obtained, if the magnetic moments would feel a strong magnetic field.
  - In the "mean field" approach or the "Weiss" approach to ferromagnetism, we simply assume such a magnetic field $\boldsymbol{H}_{\text{Weiss}}$ to be the cause for the line-up of the magnetic moments. This allows to treat ferromagnetism as a "special" case of paramagnetism, or more generally, "orientation polarization".



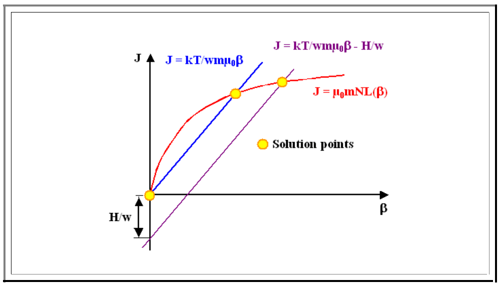
- For the magnetization we obtain ⇒
  - The term $\boldsymbol{w} \cdot \boldsymbol{J}$ describes the Weiss field via $\boldsymbol{H}_{\text{loc}} = \boldsymbol{H}_{\text{ext}} + \boldsymbol{w} \cdot \boldsymbol{J}$; the Weiss factor $\boldsymbol{w}$ is the decisive (and unknown) parameter of this approach.
  - Unfortunately the resulting equation for $\boldsymbol{J}$, the quantity we are after, cannot be analytically solved, i.e. written down in a closed way.

$$J \;=\; N \cdot m \cdot \mu_0 \cdot \mathrm{L}(\beta) \;=\; N \cdot m \cdot \mu_0 \cdot \mathrm{L}\left(\frac{m \cdot \mu_0 \cdot (H + w \cdot J)}{kT}\right)$$

- Graphical solutions are easy, however ⇒
  - From this, and with the usual approximation for the Langevin function for small arguments, we get all the major ferromagnetic properties, e.g.
    - Saturation field strength.
    - Curie temperature T_C.

$$T_C \;=\; \frac{N \cdot m^2 \cdot \mu_0^2 \cdot w}{3k}$$

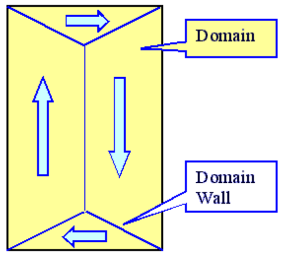
    - Paramagnetic behavior above the Curie temperature.
    - Strength of spin-spin interaction via determining $\boldsymbol{w}$ from T_C.
  - As it turns out, the Weiss field would have to be far stronger than what is technically achievable - in other words, the spin-spin interaction can be exceedingly strong!

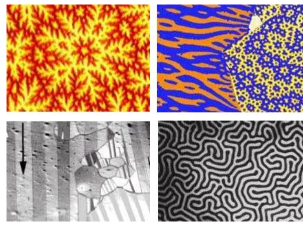


- In single crystals it must be expected that the alignments of the magnetic moments of the atom has some preferred crystallographic direction, the "easy" direction.

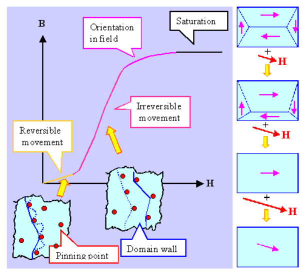
Easy directions:
Fe (bcc) <100>
Ni (fcc) <111>
Co (hcp) <001> (c-direction)

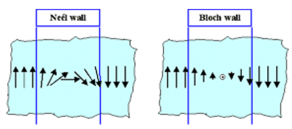
- A single crystal of a ferromagnetic material with all magnetic moments aligned in its easy direction would carry a high energy because:
  - It would have a large external magnetic field, carrying field energy.
- In order to reduce this field energy (and other energy terms not important here), magnetic domains are formed ⇒. But the energy gained has to be "payed for" by:
  - Energy of the domain walls = planar "defects" in the magnetization structure. It follows: Many small domains —> optimal field reduction —> large domain wall energy "price".
  - In polycrystals the easy direction changes from grain to grain, the domain structure has to account for this.
  - In all ferromagnetic materials the effect of magnetostriction (elastic deformation tied to direction of magnetization) induces elastic energy, which has to be minimized by producing a optimal domain structure.
- The domain structures observed thus follows simple principles but can be fantastically complicated in reality ⇒.



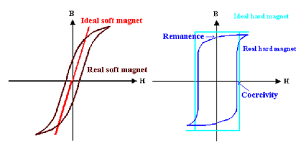


- For ferromagnetic materials in an external magnetic field, energy can be gained by increasing the total volume of domains with magnetization as parallel as possible to the external field - at the expense of unfavorably oriented domains.
  - Domain walls must move for this, but domain wall movement is hindered by defects because of the elastic interaction of magnetostriction with the strain field of defects.
  - Magnetization curves and hystereses curves result ⇒, the shape of which can be tailored by "defect engineering".
- Domain walls (mostly) come in two varieties:
  - Bloch walls, usually found in bulk materials.
  - Neél walls, usually found in thin films.





- Depending on the shape of the hystereses curve (and described by the values of the remanence M_R and the coercivity H_C, we distinguish hard and soft magnets ⇒.
- Tailoring the properties of the hystereses curve is important because magnetic losses and the frequency behavior is also tied to the hystereses and the mechanisms behind it.
  - Magnetic losses contain the (trivial) eddy current losses (proportional to the conductivity and the square of the frequency) and the (not-so-trivial) losses proportional to the area contained in the hystereses loop times the frequency.
  - The latter loss mechanism simply occurs because it needs work to move domain walls.
- It also needs time to move domain walls, the frequency response of ferromagnetic materials is therefore always rather bad - most materials will not respond anymore at frequencies far below **GHz**.



Questionaire
Multiple Choice questions to all of 4.3