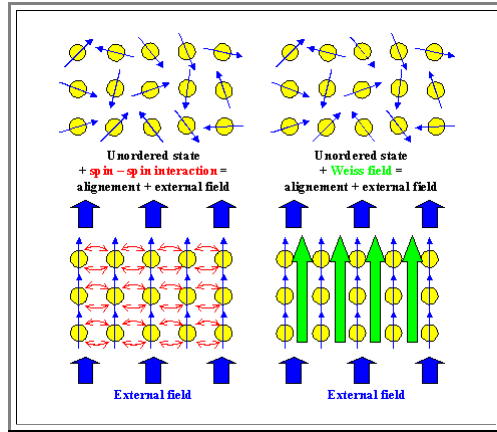


### 4.3.7 Summary to: Ferromagnetism

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  $H_{\text{Weiss}}$  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  $\Rightarrow$

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

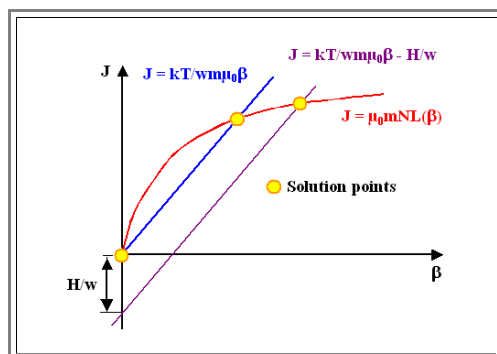
$$J = N \cdot m \cdot \mu_0 \cdot L(\beta) = N \cdot m \cdot \mu_0 \cdot L\left(\frac{m \cdot \mu_0 \cdot (H + w \cdot J)}{kT}\right)$$

Graphical solutions are easy, however  $\Rightarrow$

- 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  $w$  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)  $\langle 100 \rangle$   
**Ni** (fcc)  $\langle 111 \rangle$   
**Co** (hcp)  $\langle 001 \rangle$  (c-direction)

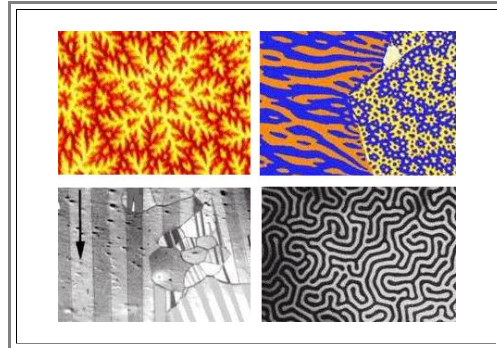
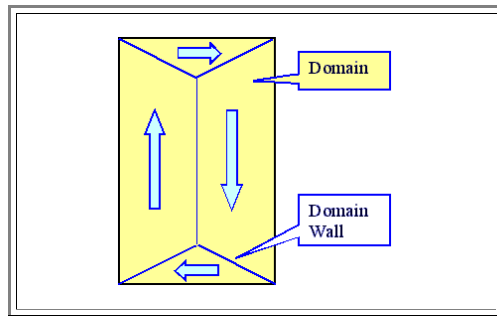
A single crystal of a ferromagnetic material with all magnetic moments aligned in its easy direction would carry a high energy because:

- 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  $\Rightarrow$ . 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  $\rightarrow$  optimal field reduction  $\rightarrow$  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  $\Rightarrow$ .

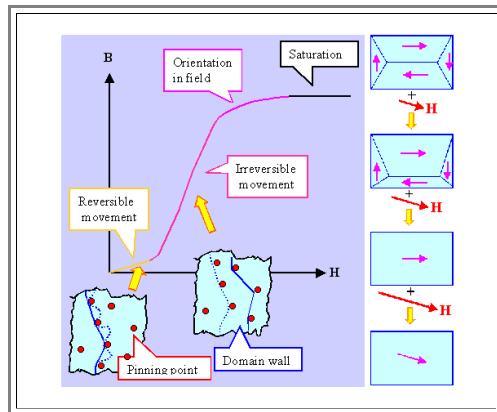
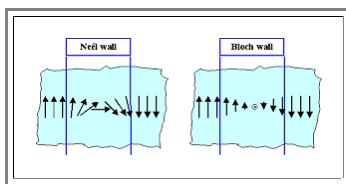


For ferromagnetic materials in an external magnetic field, energy can be gained by increasing the total volume of domains with magnetization as parallel as possible to the external field - at the expense of unfavorably oriented domains.

- 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  $\Rightarrow$ , the shape of which can be tailored by "defect engineering".

Domain walls (mostly) come in two varieties:

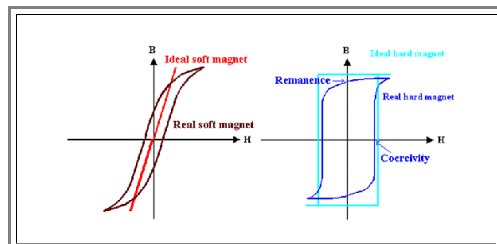
- Bloch walls, usually found in bulk materials.
- Neél walls, usually found in thin films.



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  $\Rightarrow$ .

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**.

## Questionnaire

Multiple Choice questions to all of 4.3