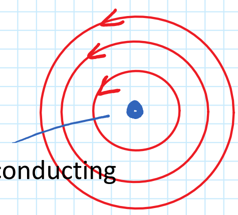
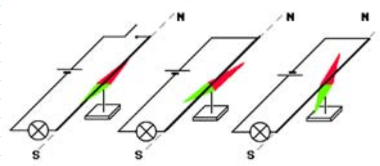
3.5 Generation of Magnetic Fields

3.5.1 Ampère's Circuital Law (quasi-stationary version)

Static B-fields: are generated by moving electric charges (electric currents, electric current densities), see experiments in video of introduction;
This constitutes the connection between electric and magnetic phenomena.



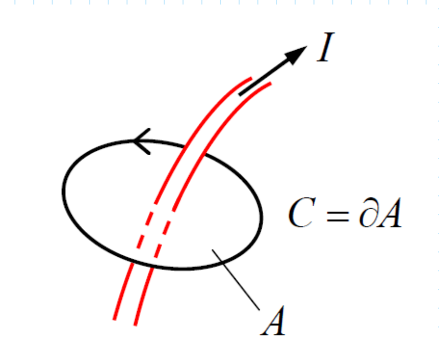
Current-conducting wire

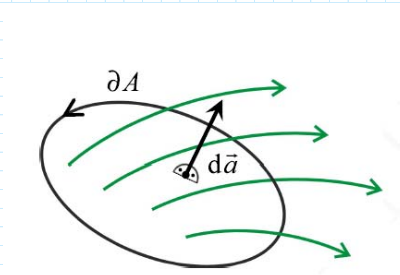


Oersted's experiment

Magnetic fields are different from electric fields, if you take a look at their structure:

- Electrostatic fields are conservative, have sources, Gauss' law is based on flux of displacement field (closed surface integral) and the charges as sources, where the field lines start (volume integral of charge density gives the total charges Q inside the volume)
- B-field: Closed field lines, field is source-free (solenoid)
- Structure is different -> closed curve/path integral around the surface A, where the current is flowing through





3.5.2 Magnetic Field Strenght $\vec{H}$

3.5.3 Magnetic fields in magnetizable material (permeability and susceptibility)

- External magnetic field (generated by a current density j): $\vec{B} = \mu \vec{H}$; $\vec{B} = \mu_0 \cdot \mu_r \cdot \vec{H}$

  Generates a magnetization inside a material
  - magnetization = current loops react to external B-field and are ordered (atomic current loops)
  - This can be seen from outside of the material and influences the B-field

  Magnetization : $\vec{M} = \chi_m \vec{H}$ $\qquad$ $\vec{H}$ = external field applied

  χ_m = material parameter = magnetic susceptibility ("χ" = chi)

  $\Rightarrow$ $\vec{B}$ - field inside material = sum of external field + magnetization

  $$\vec{B} = \mu_0 \vec{H} + \mu_0 \vec{M} = \underbrace{\mu_0 \vec{H}}_{\text{external field generated by } \vec{J}} + \underbrace{\mu_0 \chi_m \vec{H}}_{\text{magnetization of material}}$$

  $$\vec{B} = \mu_0 \vec{H} \underbrace{(1+\chi_m)}_{\mu_r} = \mu_0 \cdot \mu_r \vec{H} \quad \text{with } \boxed{\mu_r = 1 + \chi_m} \text{ relative permeability}$$

- See electrostatics: property of polarizable (i.e. dielectric) materials is described by electric permittivity (relativ dielectric constant):

  $$\vec{D} = \varepsilon_r \cdot \varepsilon_0 \vec{E} \quad ; \quad \varepsilon_r \geq 1 \Rightarrow \vec{E} = \frac{1}{\varepsilon_0 \varepsilon_r} \vec{D}$$

- In contrast to permittivity in electrostatics: μ_r can be smaller than one:

$\mu_r = 1 + \chi_m$ can not negative

and, hence:

$\vec{B} = \mu_0 \mu_r \cdot \vec{H}$; $\mu_r = 1 + \chi_m$

Classification of Materials:

diamagnetism

- Partly screening of external field by current loops

$\Downarrow$

$|\vec{B}|$ inside material is smaller than outside field

$$\boxed{\begin{array}{l}\mu_r < 1 \\ \chi_m < 0 \ ; \ |\chi_m| \ll 1\end{array}}$$

$$\vec{M} = \underbrace{\chi_m}_{<0} \cdot \vec{H}$$

paramagnetism

- Magnetic dipole moments are present
- These are ordered by external field

$\Downarrow$

$|\vec{B}|$ inside material is increased compared to outside field

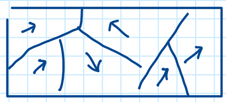
$$\boxed{\begin{array}{l}\mu_r > 0 \\ \chi_m > 0 ; \ |\chi_m| \ll 1\end{array}}$$

$$\vec{M} = \underbrace{\chi_m}_{>0} \cdot \vec{H}$$

ferromagnetisms

- Strong magnetic dipole moments are present
- They are partly ordered within certain domains already without external field (Weiß domains) → Weiss, or these regions of ordered dipoles already build up in a relatively small external field
- External field enlarges these domains
- magnetization is still present, although field is reduced to zero (remant magnetization)

→ Hysteresis



$\nearrow \ \vec{M} \neq 0$

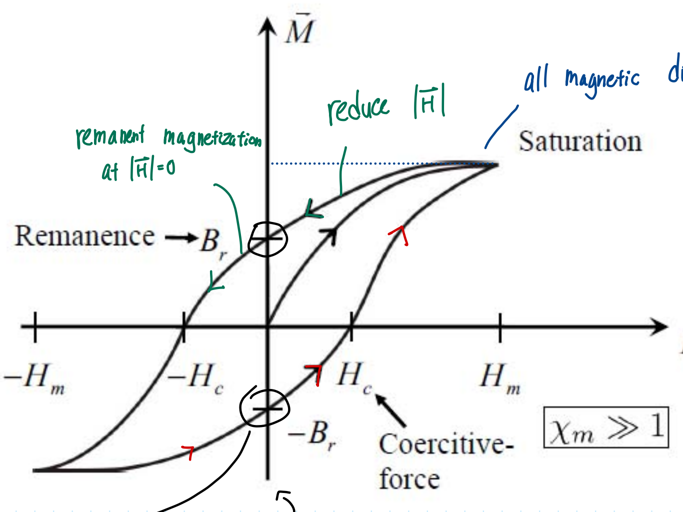
net magnetization exist inside Weiß - domains

→ $\vec{H}$ external field

$$\boxed{\mu_r \gg 1 \iff \chi_m \gg 1}$$

Hysteresis of ferromagnetic materials and Curie temperature:

$|\vec{M}| \sim |\vec{H}|$



all magnetic diapole aligned with $\vec{H}$

reduce $|\vec{H}|$

remanent magnetization at $|\vec{H}| = 0$

permanent magnet (ferromagnetic materials)

Hysteres curve : forward curve is not the same as backward curve

Magnetization can be removed / destroyed by heat for $T > T_C$

T_C = Curie Temperature

χ_m of ferromagnets = $10^4 \dots 10^5$