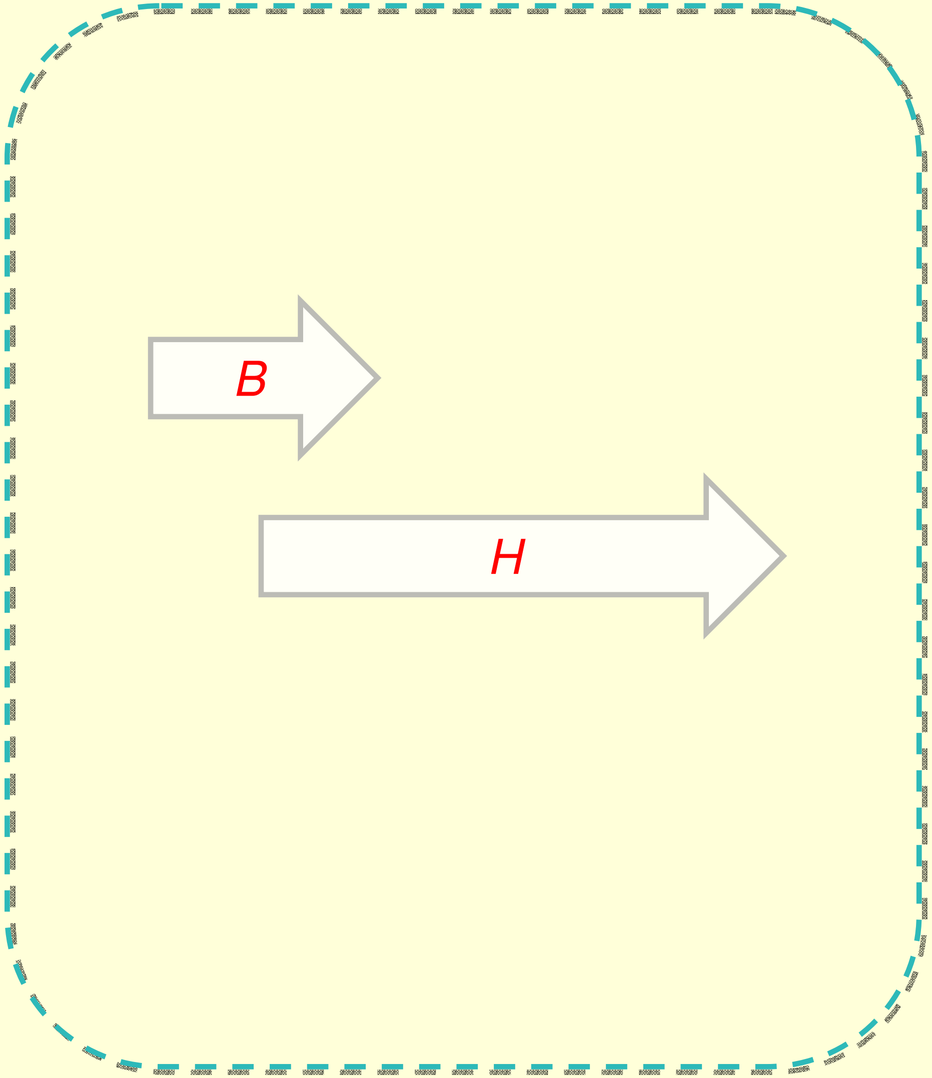
Ferromagnetism

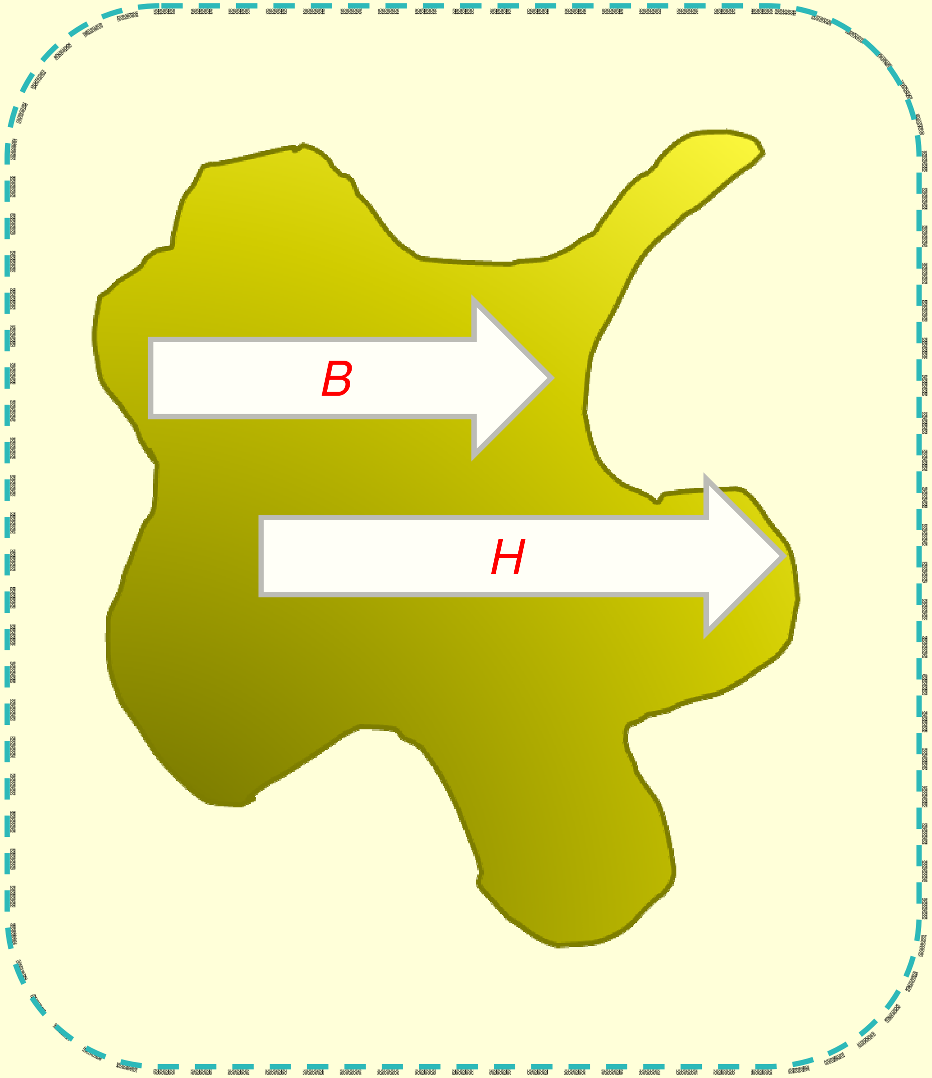


- In free space, the flux density and magnetizing field strength are related by the expression

$$\boxed{\vec{B} = \mu_0 \vec{H}}$$

- $\mu_0 = 4\pi \times 10^{-7}$ H.m^{-1}, the permeability of free space.

Ferromagnetism

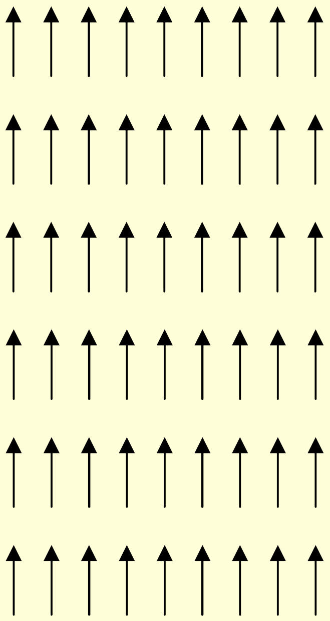


- For some materials we get more flux per ampere than for others. In *any* material, the expression is

$$\boxed{\vec{B} = \mu \ \vec{H}}$$

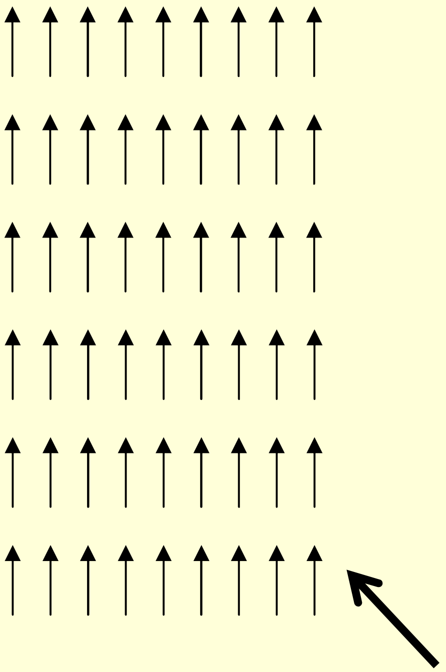
where $\mu=\mu_0\mu_r$, in analogy with the case in the electric field strength and ε.

Ferromagnetism



- In a class of materials including Fe, Ni and Co, the value of μ_r is large, and after exposure to an external magnetizing field, *H*, there remains a flux density – these are permanent magnets.

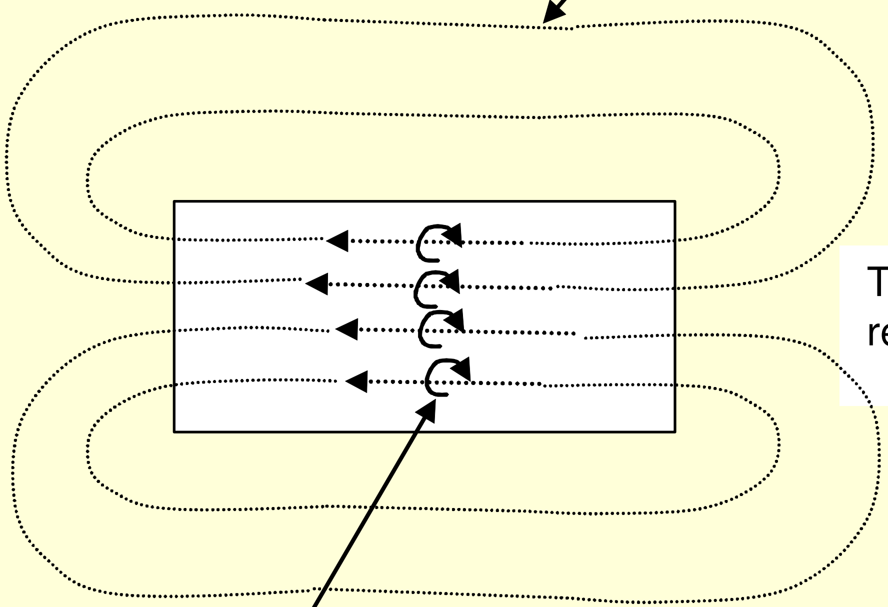
Ferromagnetism



Atomic “spins”

- The origin of this effect is at the atomic level.
- Each atom can be considered to be giving rise to an atomic-scale electrical current, and in permanent magnets the direction of these atomic currents ***line up***.
- This occurs on a **very short length scale.**

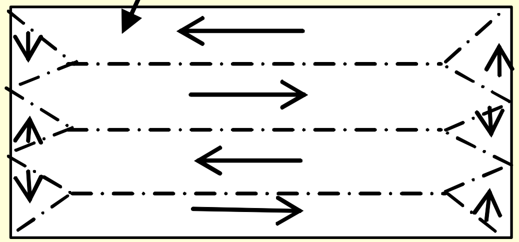
Ferromagnetic domains



Magnetic flux lines

Electron spins all in one direction – makes external magnetic field – high energy

Tends to relax to⇒

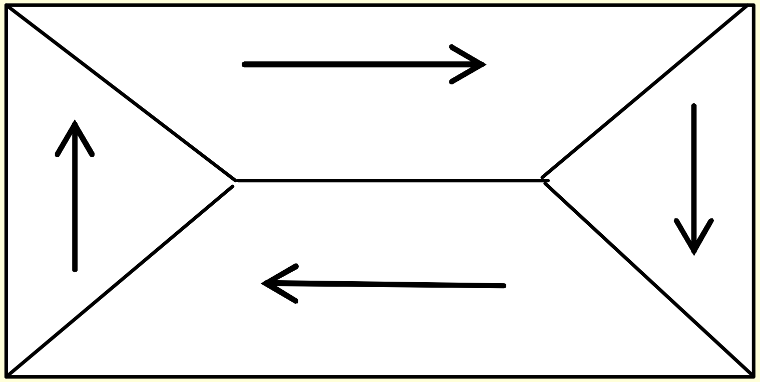


Domains in which electron spins are aligned

Electron spins rotate to form closed circuits – makes no external magnetic field – low energy

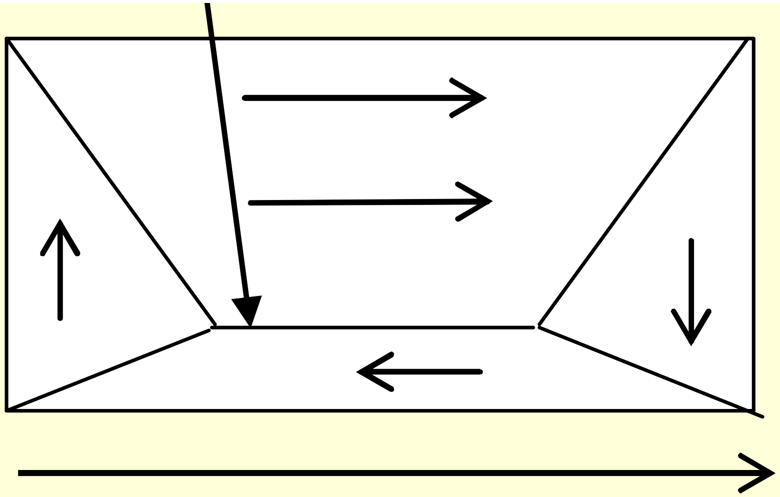
In iron the structure of the material allows the electron spins to line up in cubic directions i.e. along the edges of a cube hence the domain structure

Ferromagnetic domains



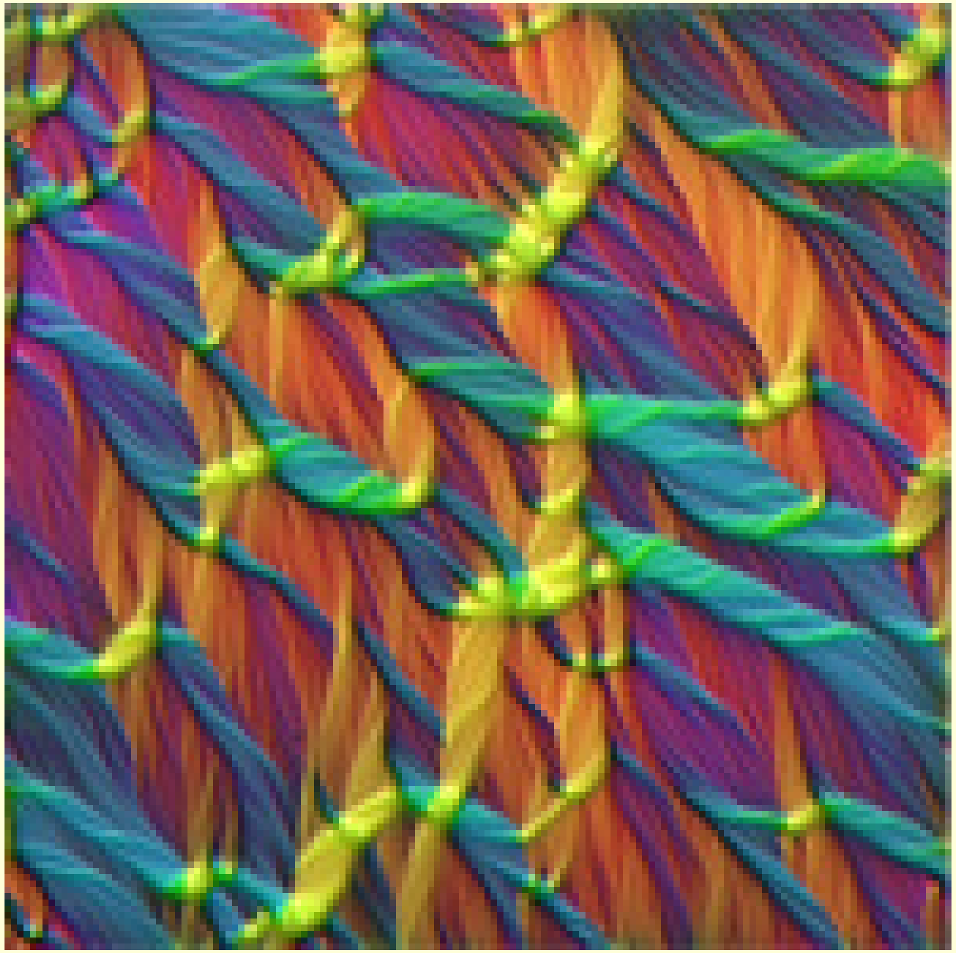
No external magnetisation, no external field

Electron spins flip over and domain wall moves downwards

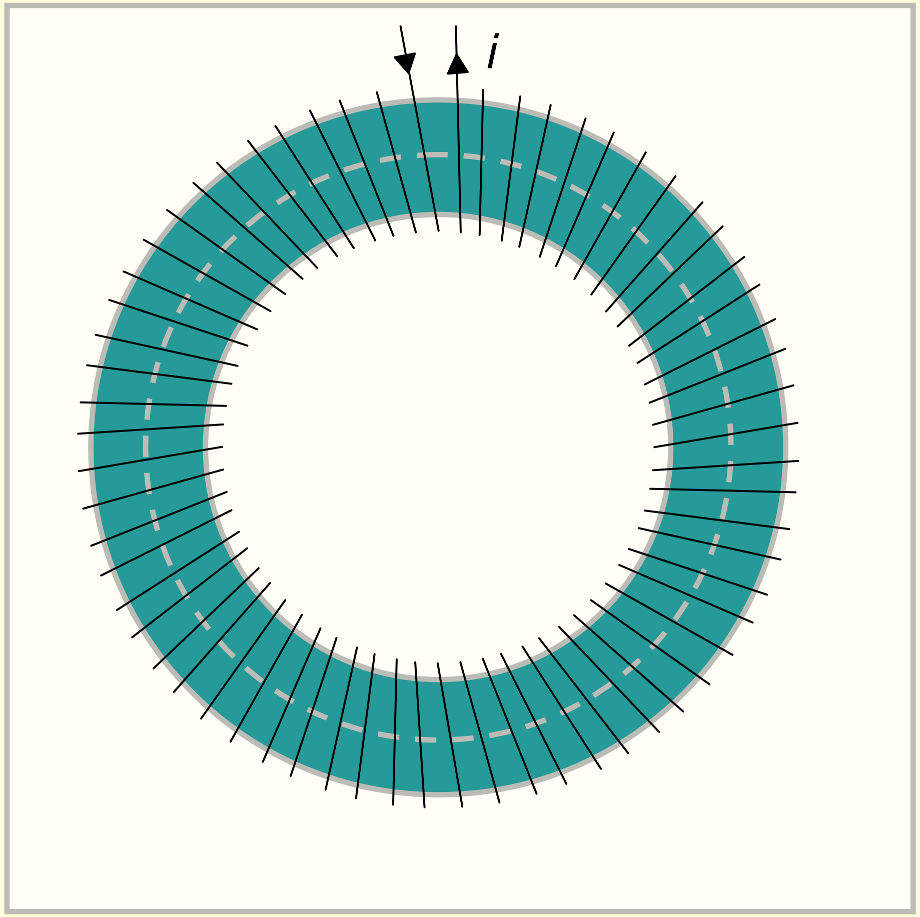


External magnetisation, domains shift and net magnetisation in line with applied field results

Real domains: Cobolt

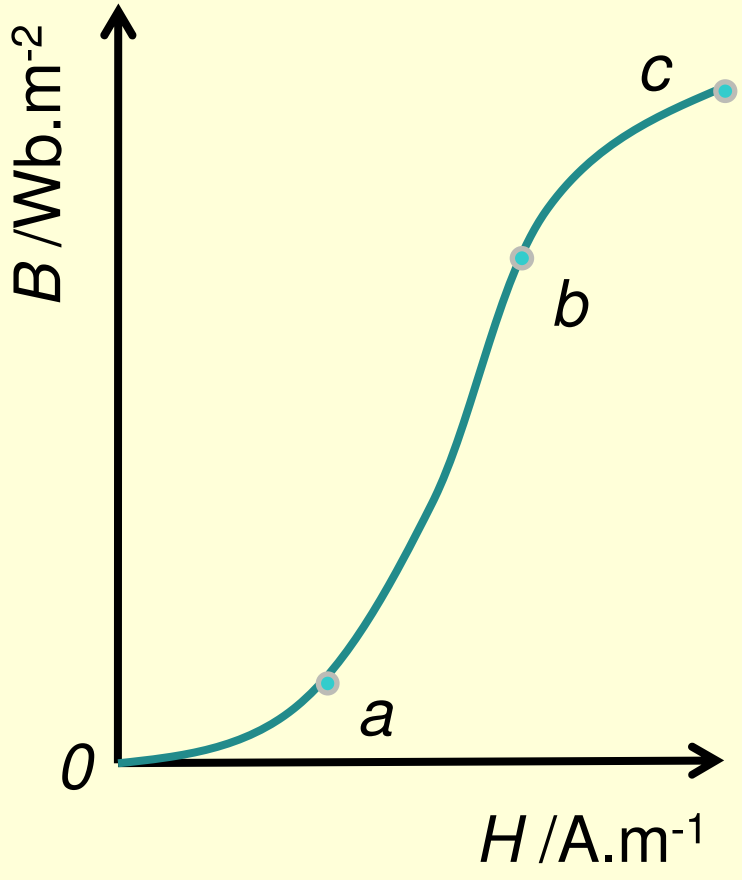


Idealised magnetisation process



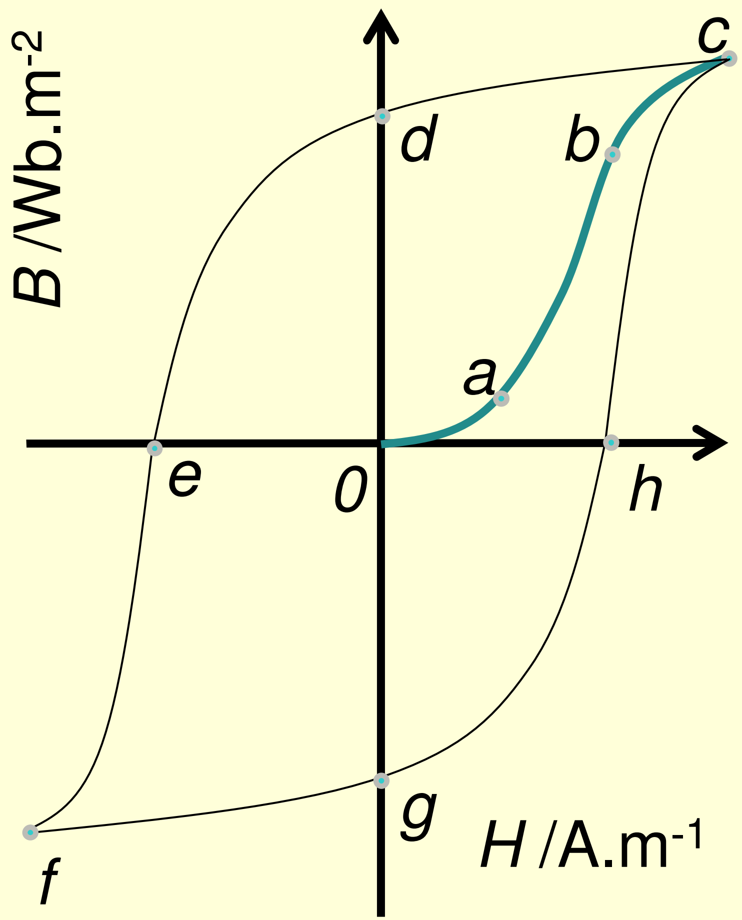
- A magnetically susceptible material is placed into an external magnetizing field, *H*.
- Individual domains in the core are aligned to the applied field…

Initialisation



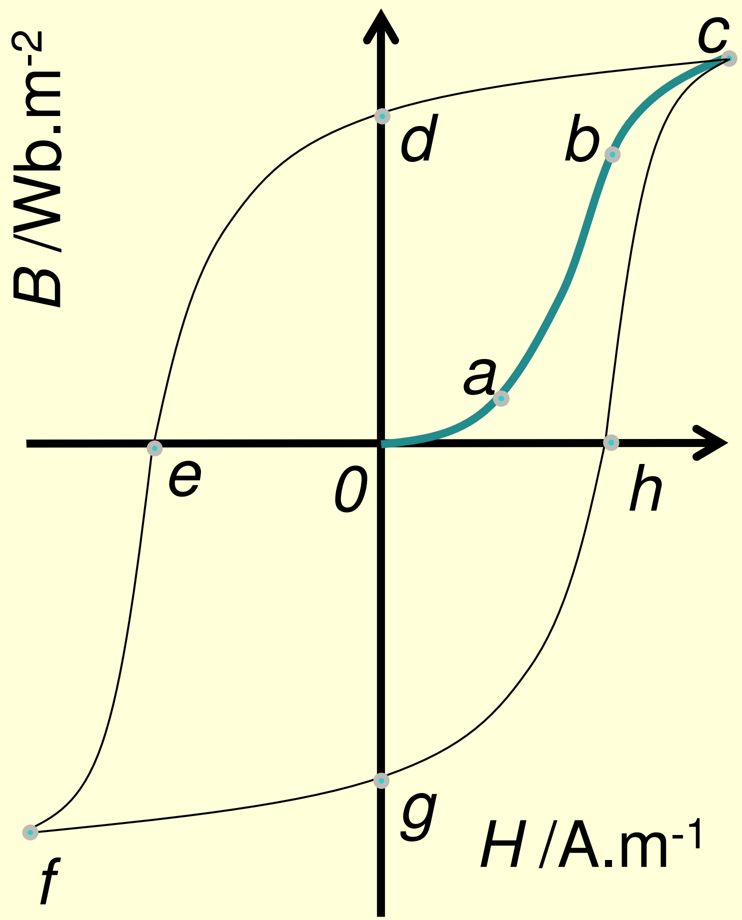
- At “0”, domains are randomly aligned and there is no net magnetic flux density from the core.
- “0-*a*”, some domains are *switched* to align with the *H*-field
- “*a-b*” is where many domains are switching to applied field direction: large μ_r.
- “*b-c*” is where the domains are all parallel, so the remaining variations of B are small.
- Further increases in B with H is linear and reversible: this is the saturation limit.

Reversal of applied field



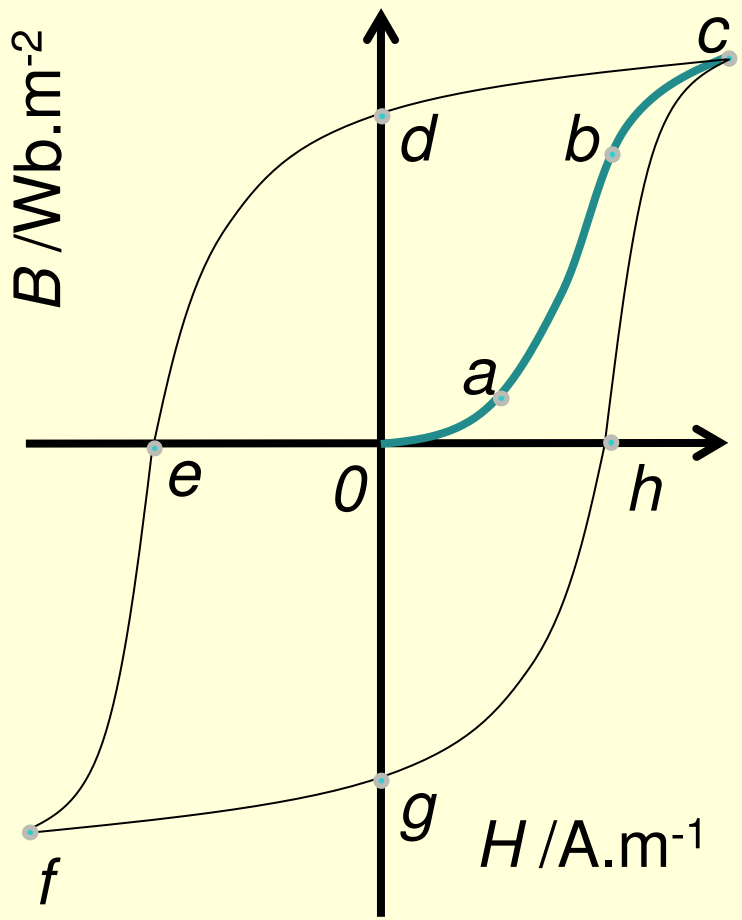
- "*c-d*" is where the applied field is removed and **some of the aligned domains flip back.**
- At *d* the flux density value is termed the ***remnent flux density***, B_r.
- It is the remnent flux density that represents the **permanent magnetism** of a magnetized material.

Reversal of applied field



- “*d-e*”: as the applied field starts to point in the direction opposed to the remnent flux, the domains begin to flip, with a rapid increase in rate where the majority of domains switch orientation.
- At *e* the flux density from the magnetised material is exactly balanced by the induced polarisation from the applied field.
  - This is the ***coercive field***.
- Beyond the coercive field, the material rapidly polarised akin to “*a-b*”, eventually **saturating** at *f*.

Reversal of applied field



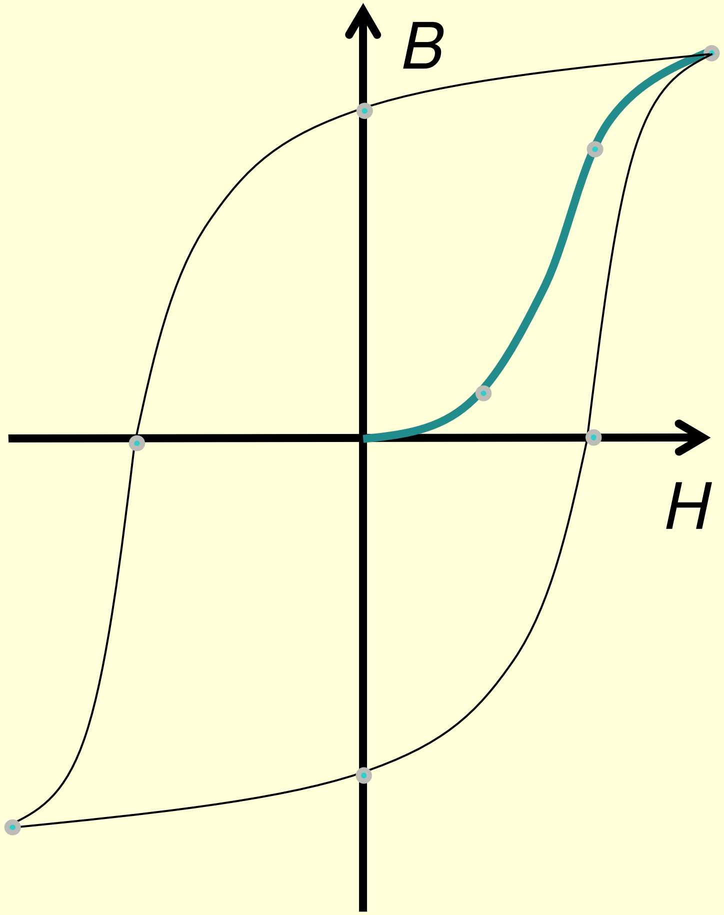
- "*f-g-h-c*" is the symmetric equivilent of "*c-d-e-f*", and the magnetisation of the material can be cycled around this loop over many field reversals.

Magnetisation energy density

- The energy (densty) stored in a magnetic field is given by

$$E = \int_{B_1}^{B_2} H \, dB$$

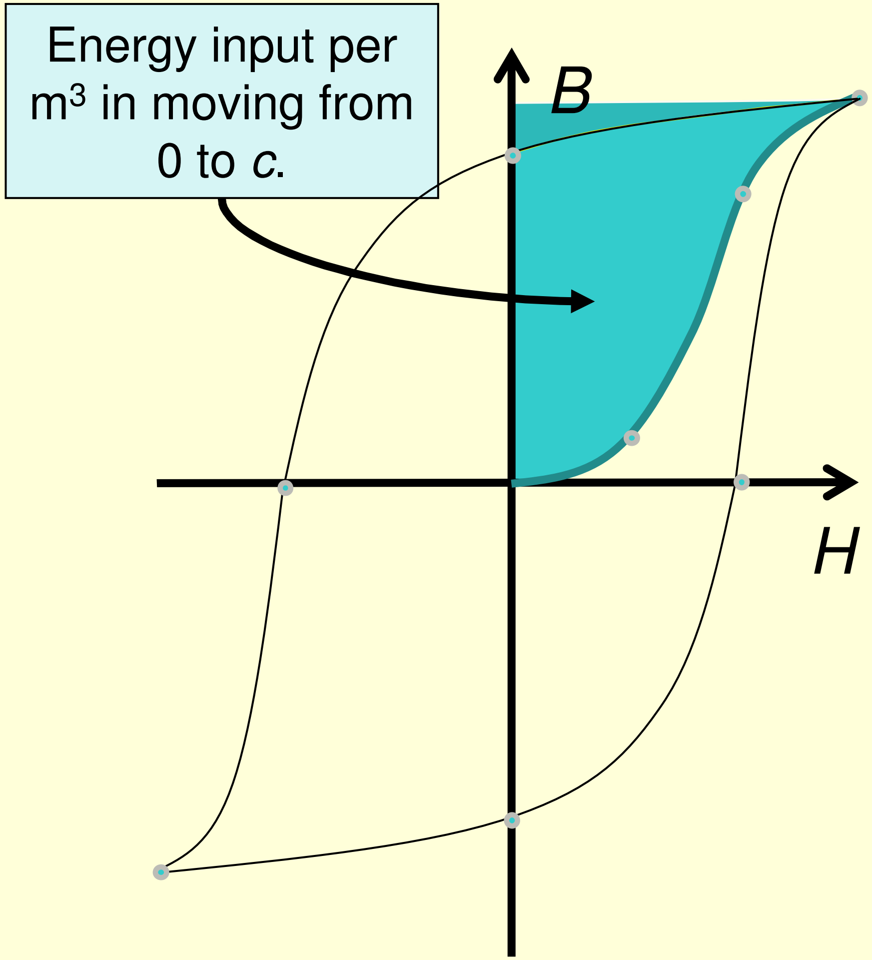
- Do the units add up?



Magnetisation energy density

$$\boxed{E = \int_{B_1}^{B_2} H \, dB}$$

- In the initial stage, energy is deposited in the magnetisation of the ferromagnetic core

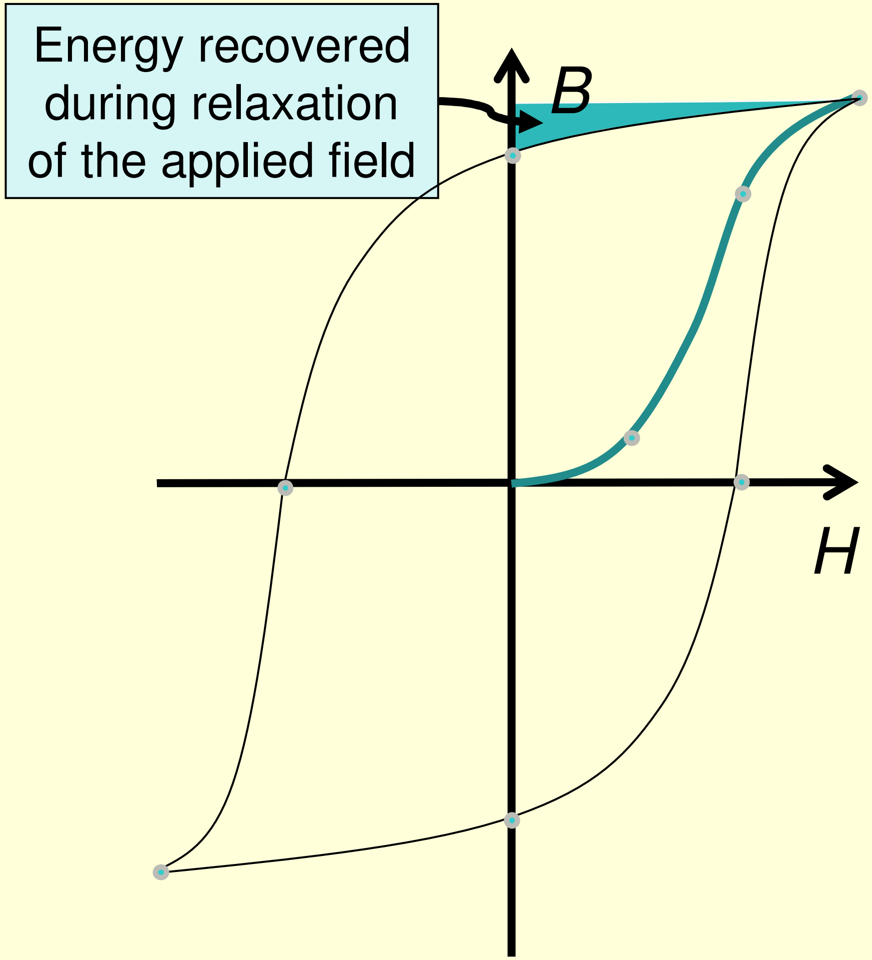


Energy input per m^3 in moving from 0 to *c*.

Magnetisation energy density

$$E = \int_{B_1}^{B_2} H \, dB$$

- Removal of the applied field allows some domains to rotate, and the stored energy is reduced.

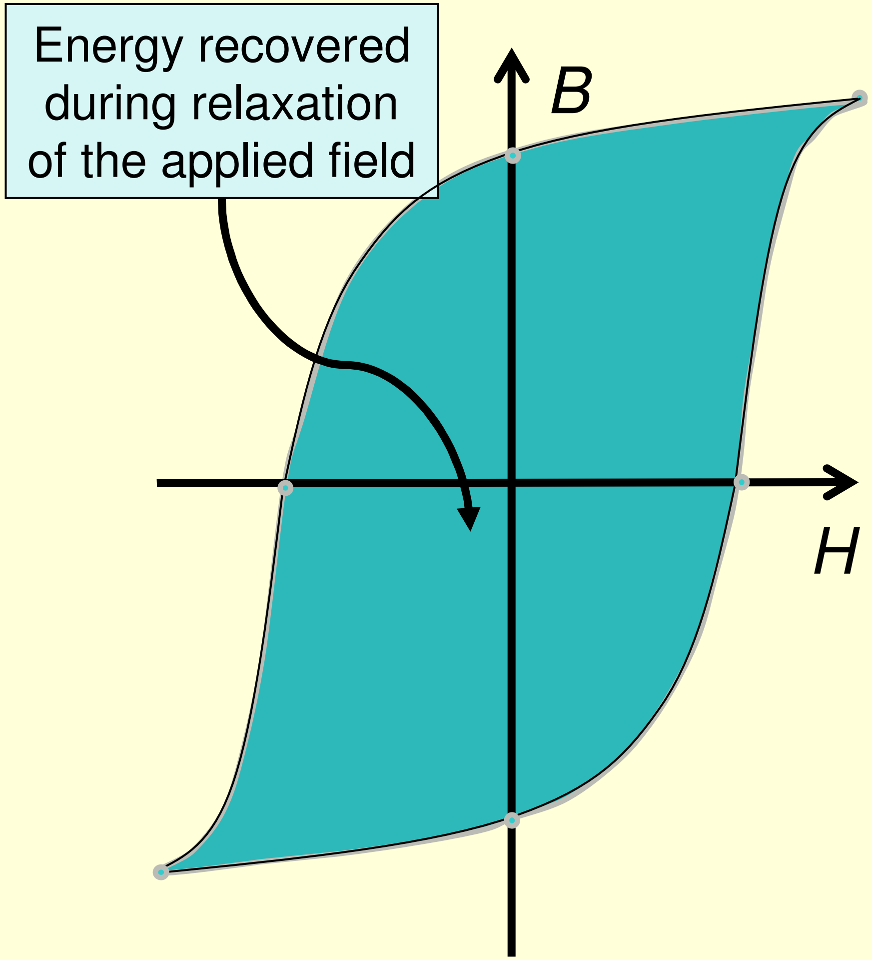


Energy recovered during relaxation of the applied field

Magnetisation energy density

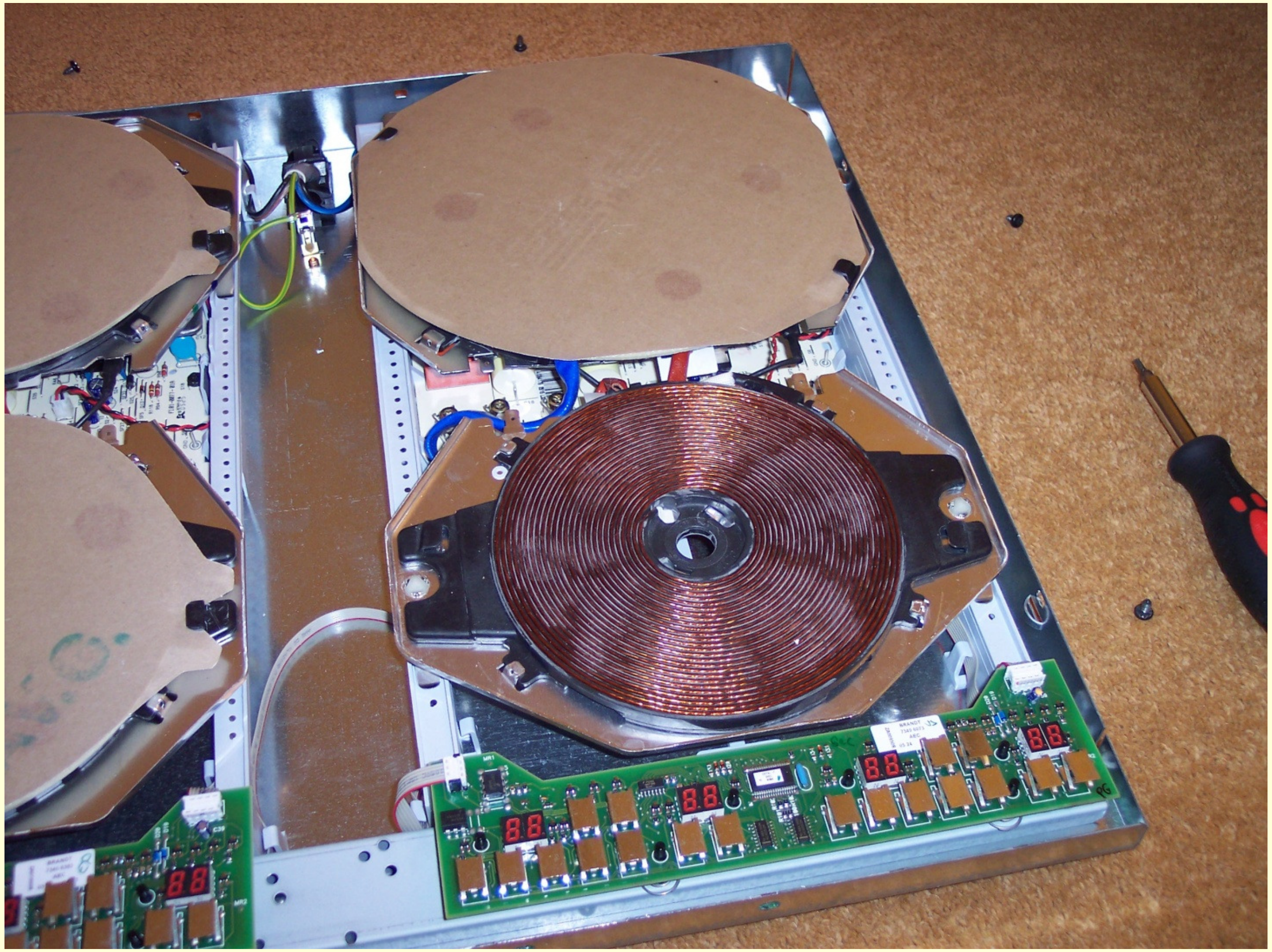
$$E = \int_{B_1}^{B_2} H \, dB$$

- Over a complete cycle the energy lost per unit volume is equal to the area of the hysteresis loop.
- Power dissipated is therefore:
  - (Area of loop) x (frequency) x (core volume).

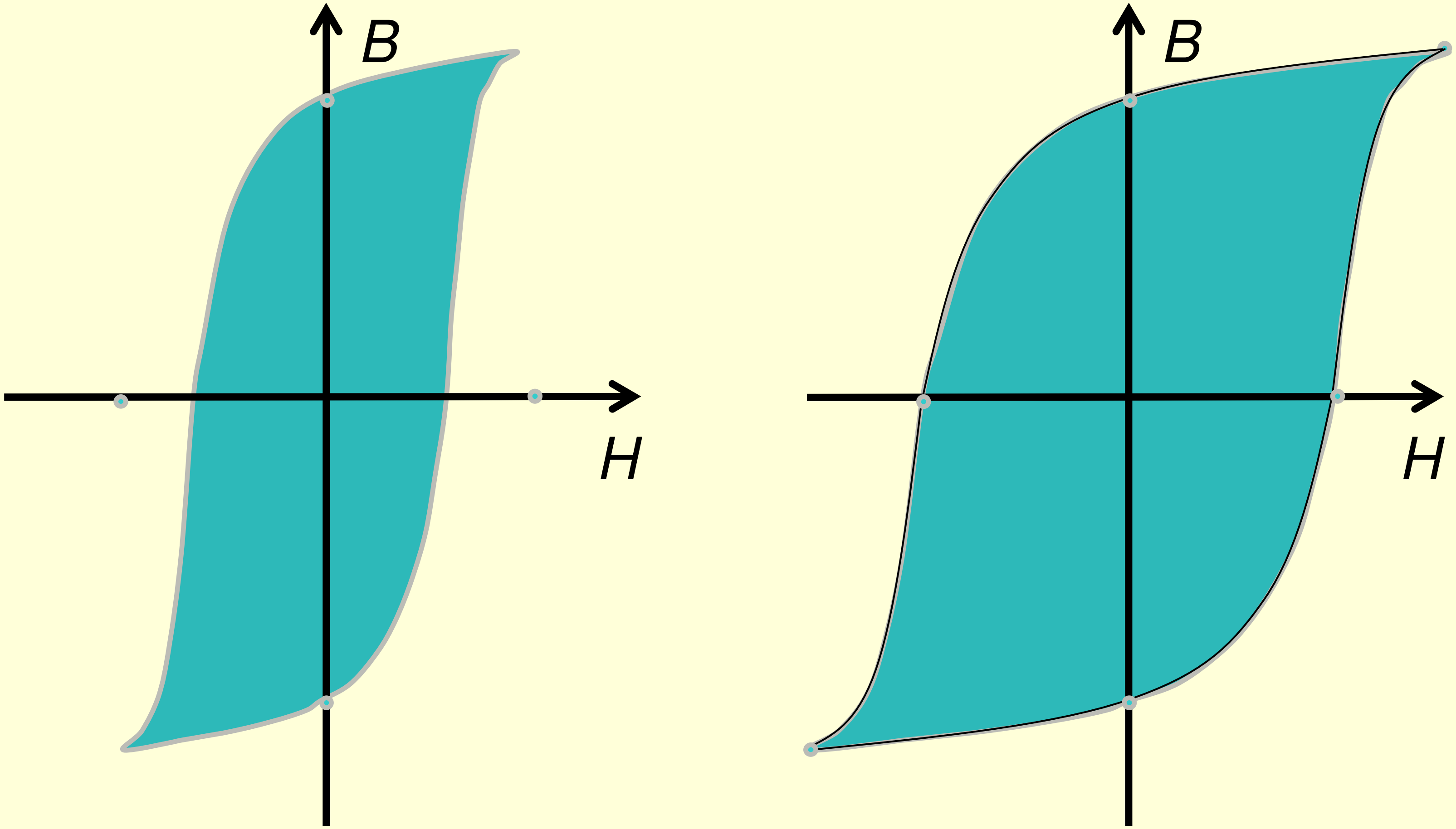


Energy recovered during relaxation of the applied field

Application of inductive heating



“Hard” and “soft” magnetic materials



Magnetisation

- A simple way of mathematically understanding the impact of the internal source of magnetic flux is to divide the it into that coming from the external source, and that from the "atomic magnets".
- *M* is a vector quantity called the ***magnetisation***.

M is related to the remnent magnetisation in a rather obvious way

$$\boxed{B = M + \mu_0 H}$$

“Hard” and “soft” magnetic materials

Soft Magnetic materials

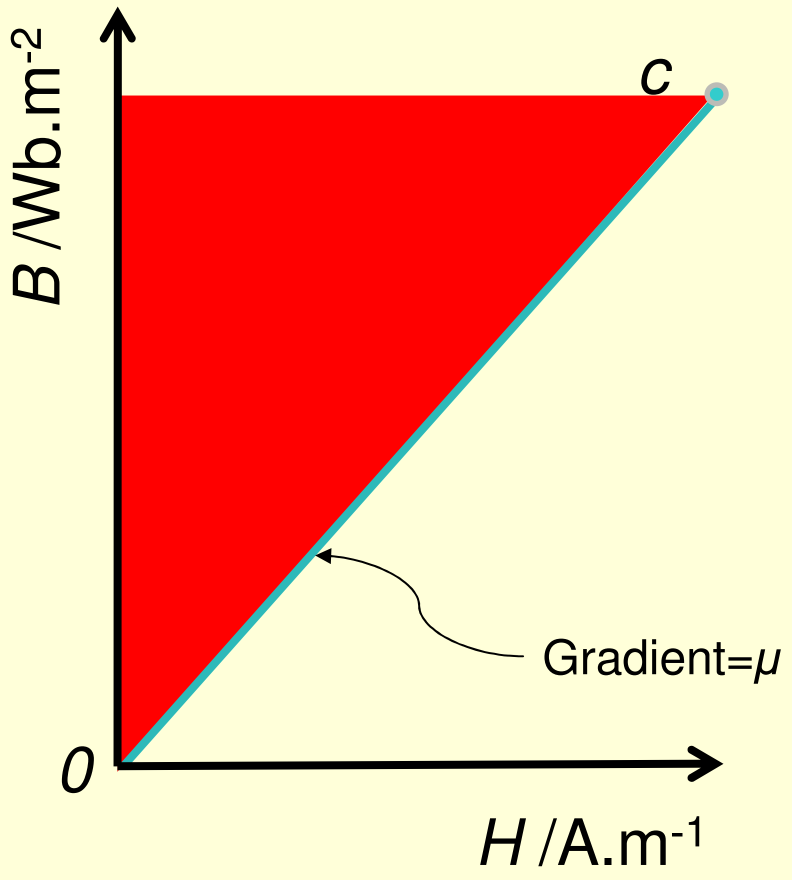
- Small coercive force
- Low hysteretic loss
- Does not hold a substantial permanent magnetism
- Suitable for ferrous cores such as in a.c. magnetic fields.

Hard Magnetic materials

- Large coercive force
- High hysteretic loss
- Do hold a substantial permanent magnetism
- Suitable for permanent magnets, and a.c. inductive heating

Linear soft magnets

- In an ***ideal*** magnet, $B=\mu H$, with a constant permeability.
- The energy stored in the magnetising of the core is ***completely recovered*** when the field is removed.
  - – There is no loss here!



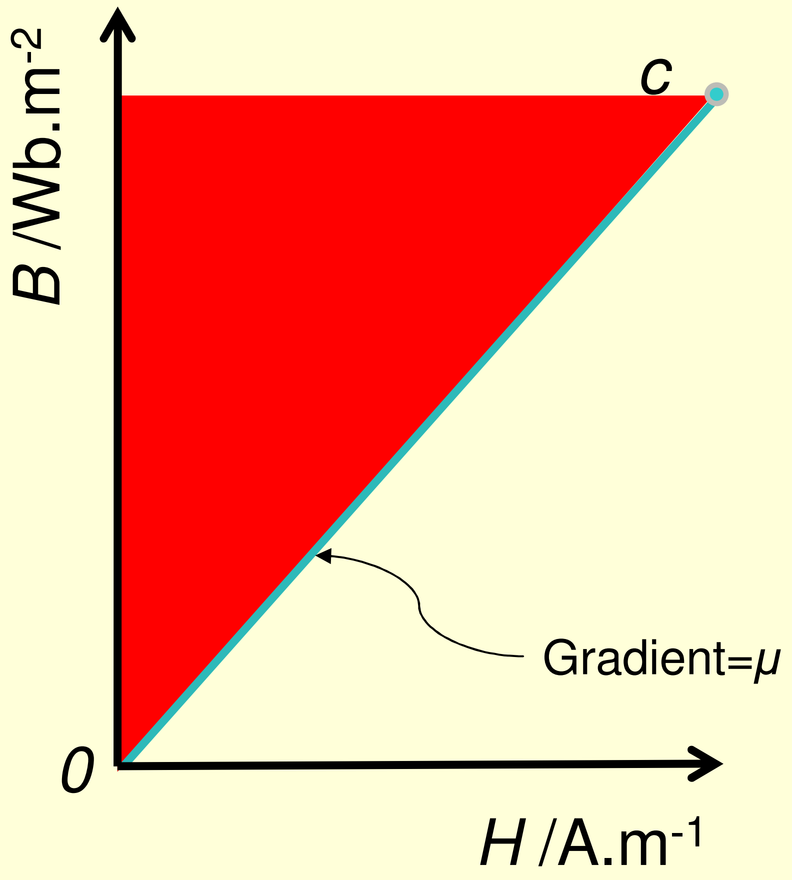
Linear soft magnets

- Stored energy density in this system, while at an applied *H* is

$$\int_0^B H\,dB = \int_0^B \frac{B}{\mu}dB$$

$$= \frac{B^2}{2\mu} = \frac{\mu H^2}{2}$$

(J.m^{-3})



Other types of magnetism

Ordered magnetism

- Ferromagnetism
- Anti-ferromagnetism
- Ferrimagnetism

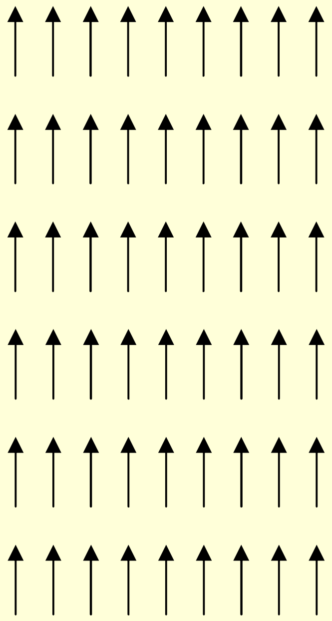
Disordered magnetism

- Paramagnetism

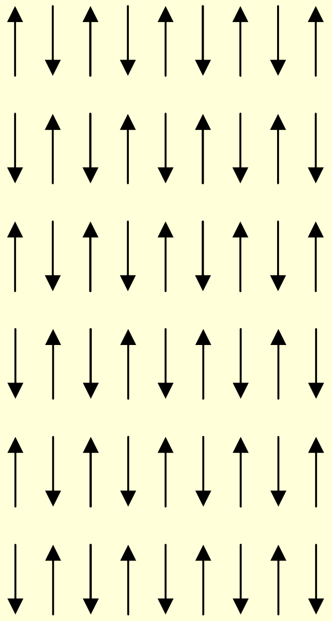
Diamagnetism

Ordered magnetism

Ferromagnet

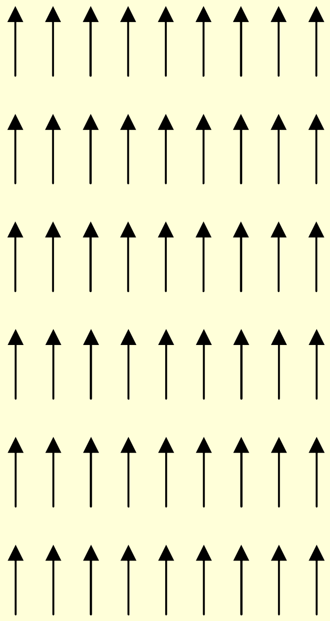


Antiferromagnet

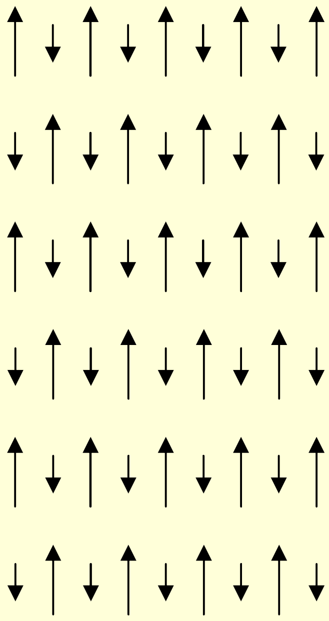


Ordered magnetism

Ferromagnet

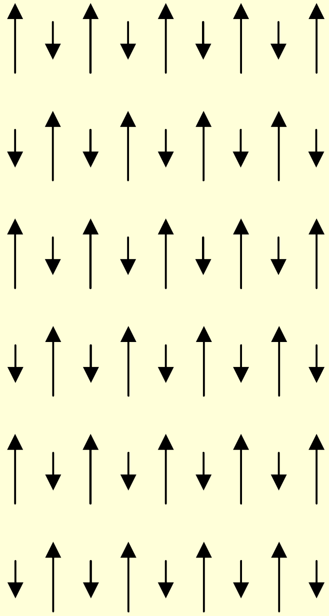


Ferrimagnet



Ordered magnetism

- Ferrimagnets are typically oxides and electrically insulating.
- The relatively low magnetic moment per unit yields lower saturation flux densities than ferromagnets:
  - – 0.2-0.6T *c.f.* ~2T for Fe.

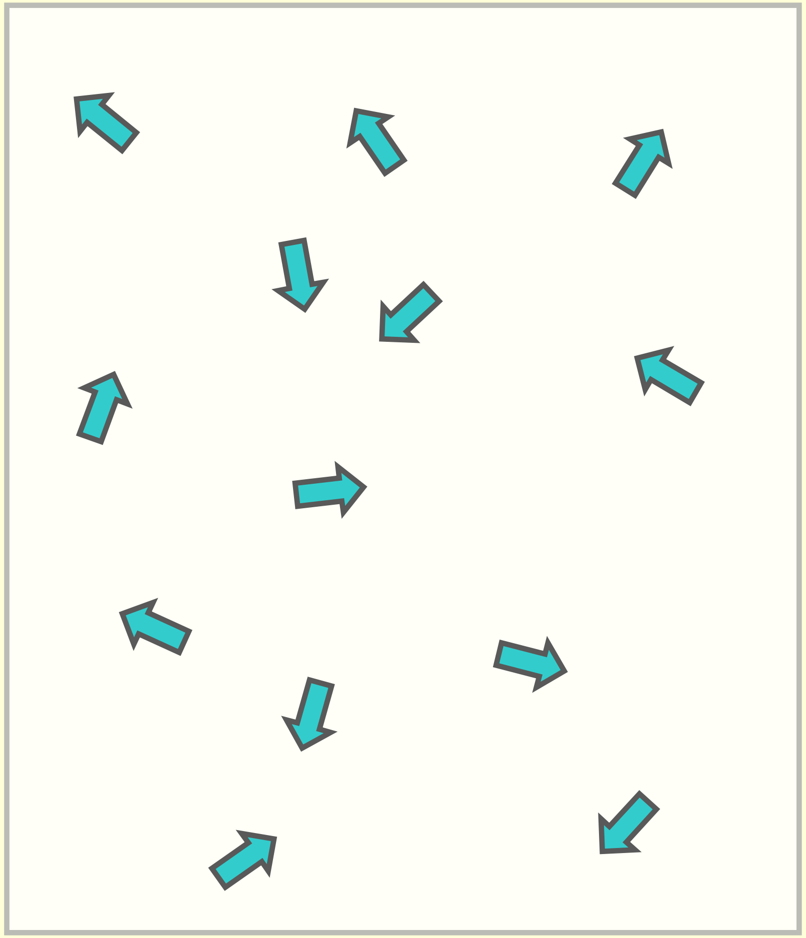


Temperature effects

- As the temperature of the magnetic material is raised, the thermal agitation tends to introduce disorder into this order.
- For a ferromagnet (and ferrimagnet), above a critical point any permanent magnetism is **lost**.
- This is called the **Curie temperature.**
- Hysteresis dissappears above this point.
- Antiferromagnets also show hysteresis, and have critical point above which magnetic order is lost: the Néel temperature.

Substance	T_c **(K)**
Iron	1043
Cobalt	1394
Nickel	631
Gadolinium	317
Fe_2O_3	893

Disordered magnets

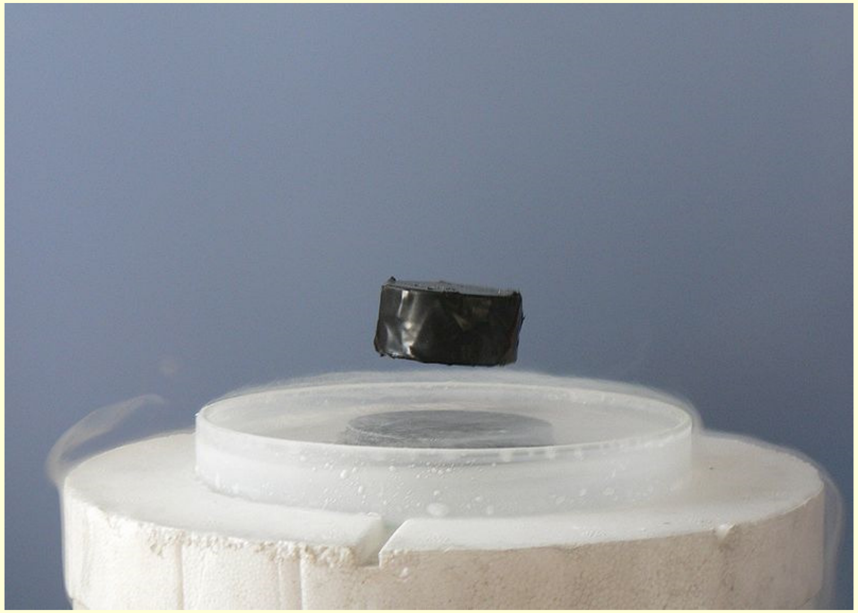


- In paramagnets, individual “atomic magnets” are randomly oriented.
- Most metals exhibit paramagnetism
  - – Al: μ_r~1.00002
- External magnetic fields align these spins (e.g. EPR spectroscopy).

Diamagnets

- Diamagnets are materials which are slightly repelled by magnetic fields
  - e.g. Bi: $\mu_r \sim 0.99983$
- A superconductor acts as a perfect diamagnet!

The Meissner Effect



- Meissner Effect
- The repulsion from the magnetic field leads to a “levitation” effect which is an important characterising aspect of superconducting materials.