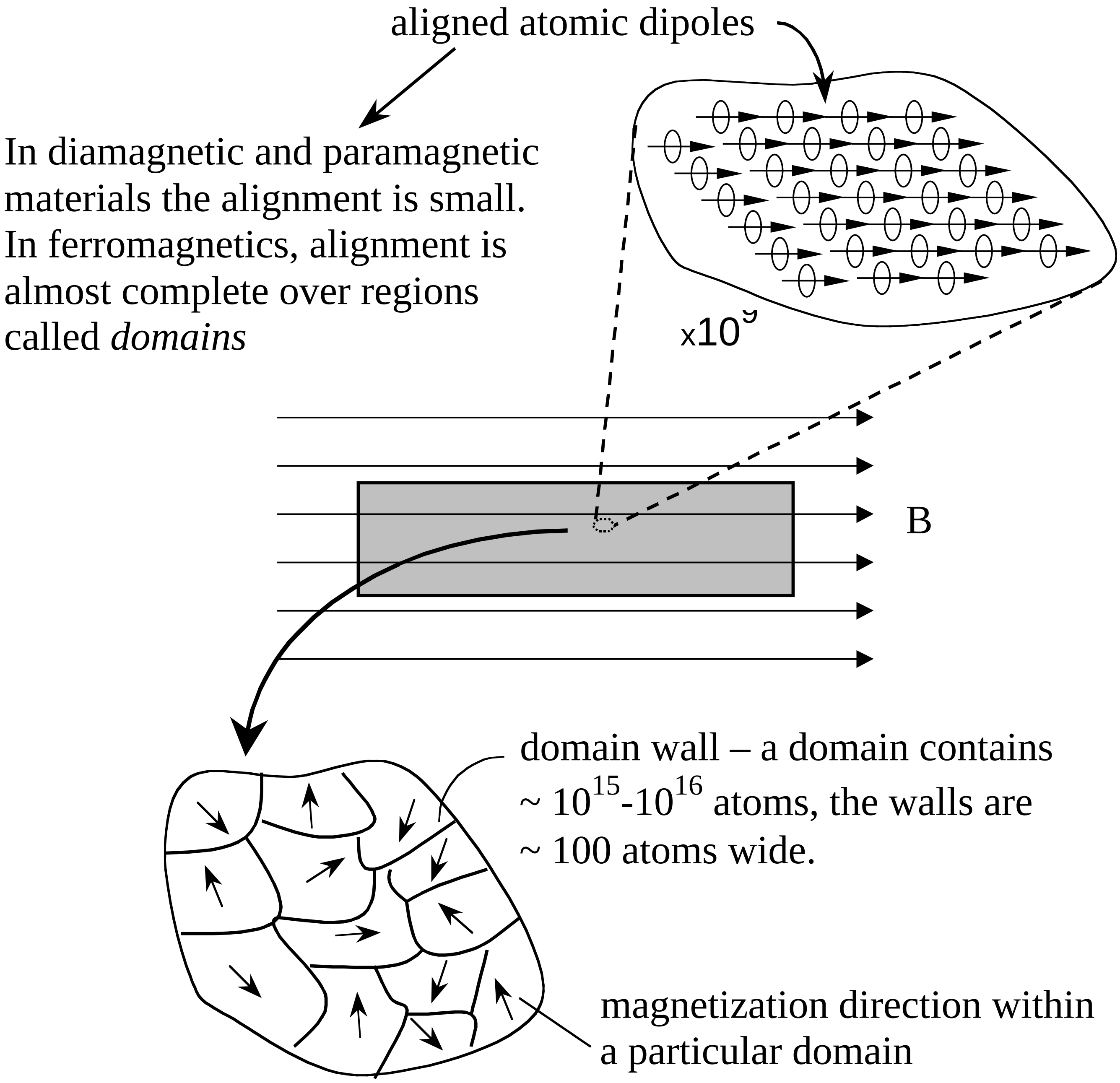
7. FERROMAGNETIC MATERIALS

7.1 What are ferromagnets?

Earlier, in Section 6.2, we considered the following visualization of atomic dipoles in a material in a uniform applied **B** field:



7.2 Domain structure

In ferromagnetic materials, small regions with a particular overall spin orientation are termed **domains.**

This strong (large) spin alignment leads to huge permeabilities:

Material	**Relative Permeability μ_r**
Nickel	250
Cobalt	600
Iron (pure)	4,000
Mumetal†	100,000

compare to paramagnetic metal:

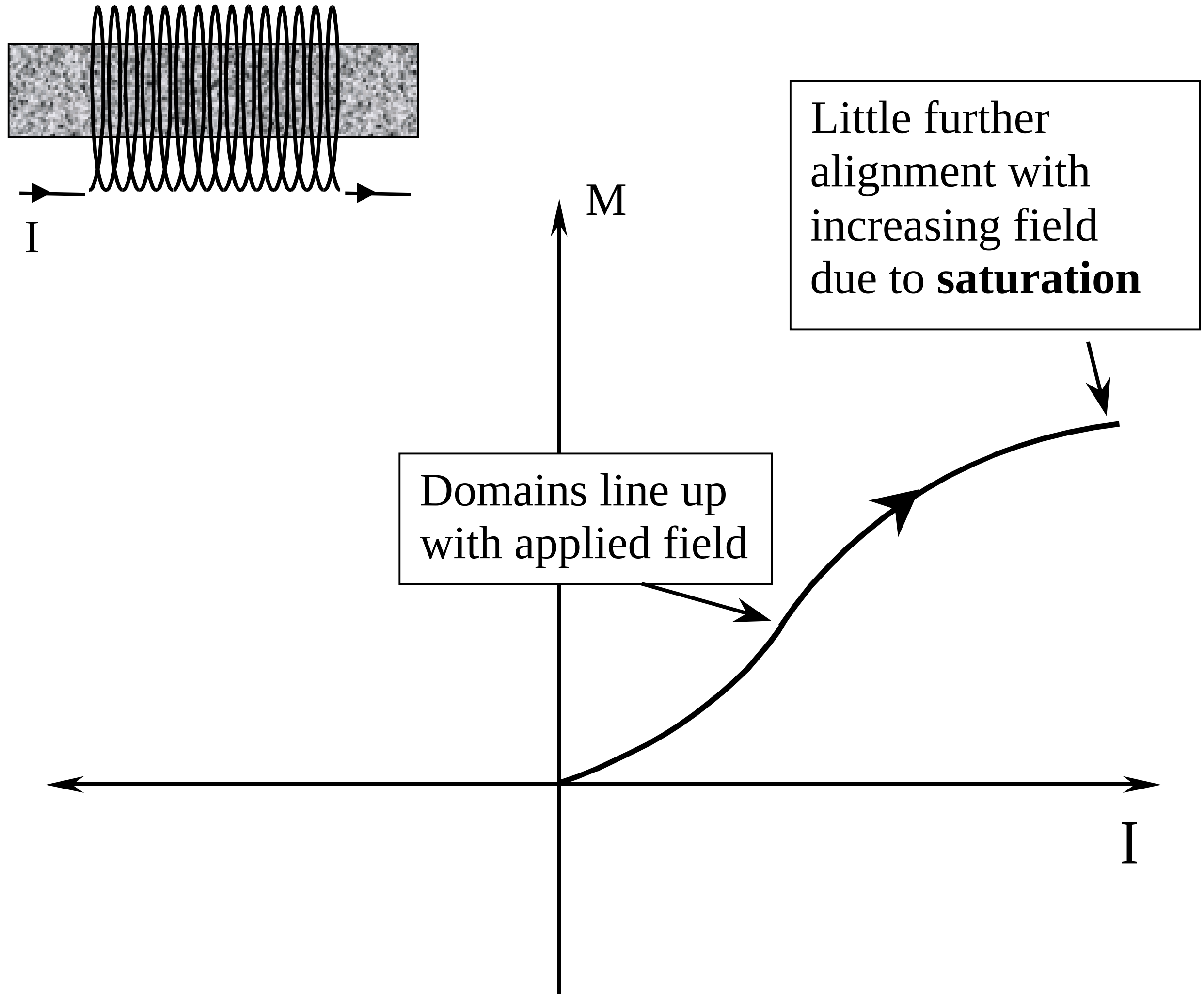
Aluminium	≈ 1	$(\mu_r = \mu/\mu_0 = 1 + \chi_m)$

† mumetal (aka μ-metal) is an alloy of iron (~25%) and nickel (~75%) + small % of other elements. It is sold under various commercial names for transformer cores, magnetic shielding, memory storage devices etc. e.g. 'Nilomag': 83% Ni, 16% Fe + Cu, Mo

7.3 Hysteresis

Ferromagnetic materials exhibit a history-dependent behaviour called hysteresis (from the Greek *to lag behind*).

We magnetize an iron rod by placing it in a solenoid and turning up the current:

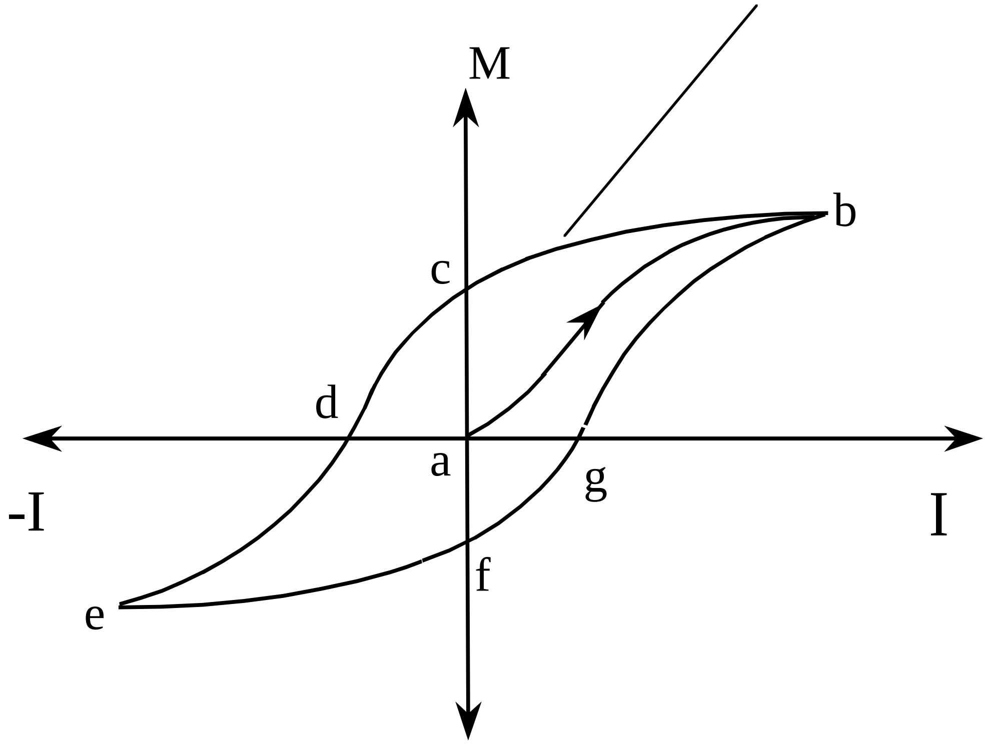


As the current in the coil is increased, initially large numbers of domains align with the externally applied field: there is a torque on the dipoles of unaligned domains.

Once most domains are aligned there can be little further increase in **M** – this is called **saturation**.

If the current is now wound back to zero, the magnetization does not follow the original curve – it lags behind: this is **hysteresis**. Follow the magnetization – demagnetization path shown below:

The loop b-c-e-f-b traced out is called a **hysteresis loop**



a-b : initial magnetization, saturation at b

b-c : demagnetization but $M \neq 0$ again when $I = 0$ again

c-d : current direction reversed, $M \neq 0$ at d, some –ve I

d-e : saturation with all dipoles in reverse direction

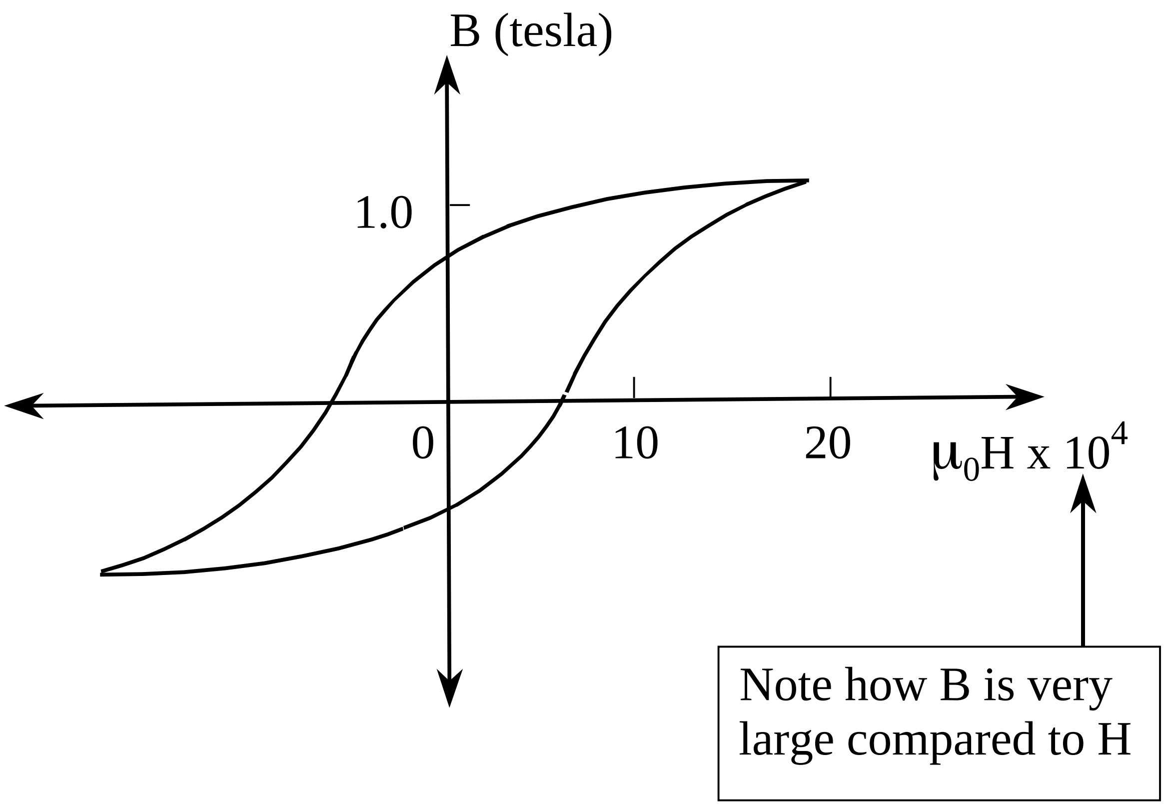
At <u>c and f</u> the rod has a **permanent magnetization** even with $I = 0$

By convention, we plot the hysteresis curve **B** against **H** (not I vs. M as shown above).

H = nI

and

$\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M})$. Since $\mathbf{M} >>> \mathbf{H}$ we have $\mathbf{B} \,\alpha\, \mathbf{M}$



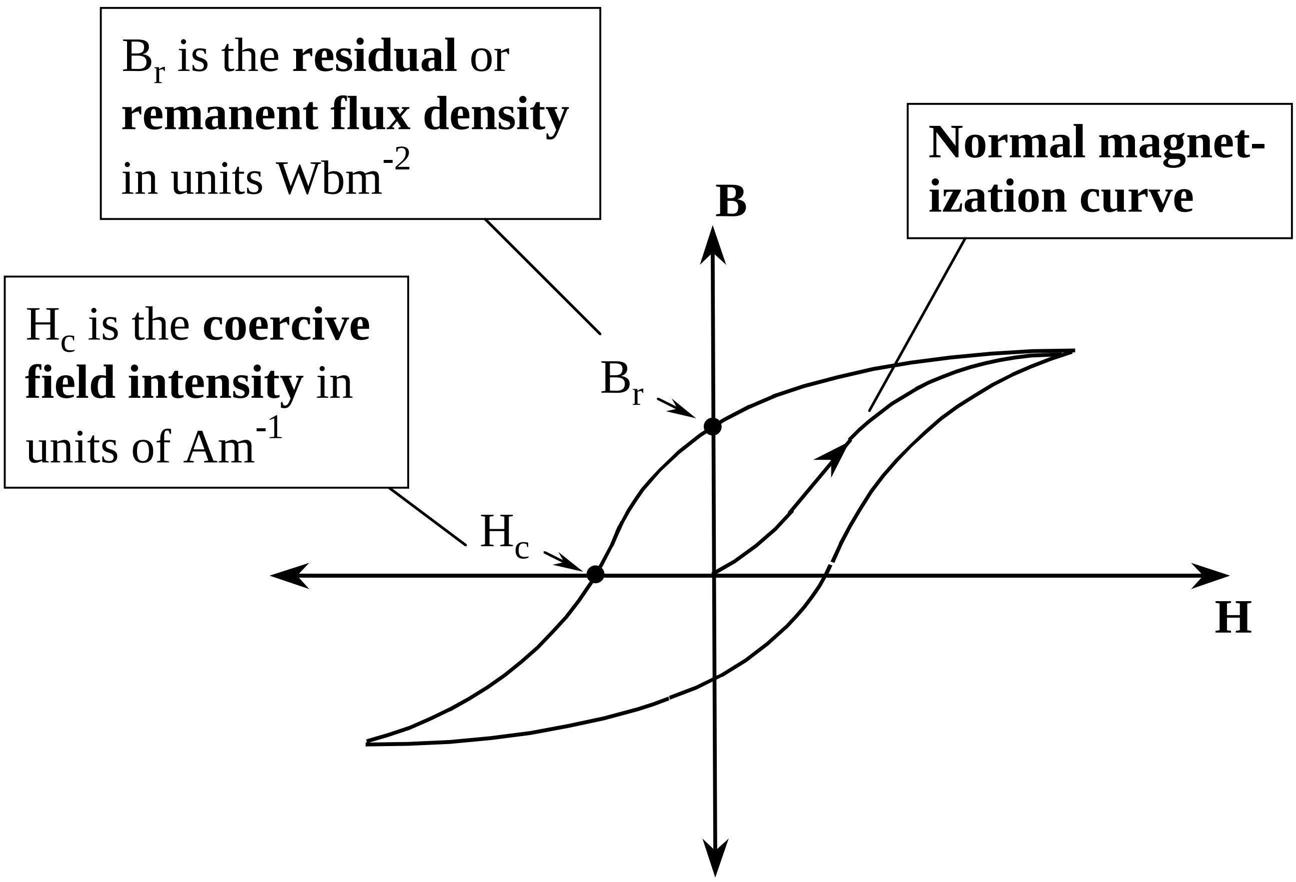
7.4 Why is the magnetization cycle hysteretic?

An applied field shifts and rotates the domains in a ferromagnetic material such that the volume of domains aligned with the applied field grows.

If only small fields are applied, the domain-wall movements and hence the magnetization process is reversible. For higher applied fields, the movement of domains is irreversible – domains do not shift back to their initial position upon decreasing the applied field.

We can see that the magnetization of ferromagnetic materials is a **non-linear** process. Ferromagnetics are thus known as **non-linear media**.

7.5 Ferromagnetics terminology



Note: we know that

$$\mathbf{B} = \mu\mathbf{H}$$

but the **B-H** curve is clearly non-linear (diagram directly above) – the permeability μ is a function of **H**. Permeability μ is also 'history dependent'. Locally (around a particular value of **H**) we can talk about the incremental permeability for small applied alternating fields.

7.6 Curie temperature

The very significant dipole alignment in ferromagnetic materials is a magnetic ordering due to quantum effects. (Remember that the spin we've been talking about is a quantum property of the atom!!)
Spin ordering is disrupted by thermal energy

$$E_{thermal} = k_B T$$

Boltzmann constant   temperature in kelvin

Above a critical temperature called the **Curie temperature**, T_c ferromagnetic ordering is destroyed and the material behaves *paramagnetically*. Above T_c the spontaneous magnetization due to ferromagnetic ordering is lost.

Curie temperatures:

$$\text{Fe: } T_c = 1043\,\text{K} \quad (770^0\text{C})$$

$$\text{Ni: } T_c = 627\,\text{K} \quad (354^0\text{C})$$

$$\text{Co: } T_c = 1388\,\text{K} \quad (1115^0\text{C})$$