L13 Ferromagnetism

Lecture outline:

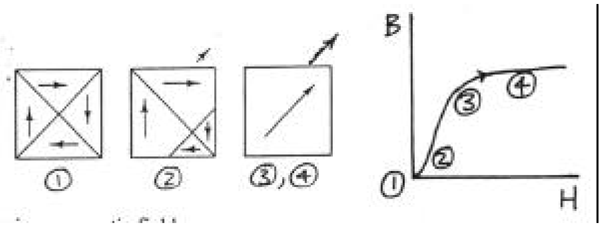
- The mechanism of ferromagnetism
- Domains.
- Antiferromagnetism.
- Ampere s law in a magnetic material.
- Electromagnets
- Magnetic recording

L13.1 Ferromagnetism

The Mechanism of Ferromagnetism

Iron crystals are made of domains, in which the magnetic dipoles are aligned.

4 domains:



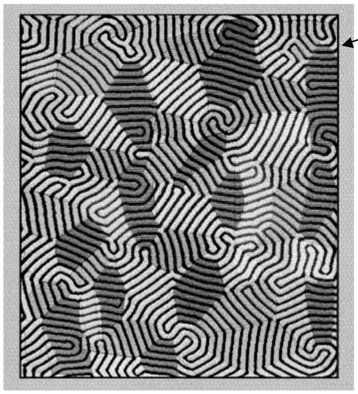
(1) Dipoles cancel, not magnetized

(2) Domains grow

(3) Some domains disappear,

(4) All dipoles aligned, saturation

L13.2 Ferromagnetism



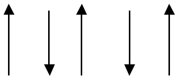
Magnetic domains as seen in a polarizing microscope

There is a critical temperature, the Curie temperature, above which the thermal motion randomizes the domains and destroys the magnetization.

	T_c
Fe	1043 K
Co	1388 K
Ni	627 K

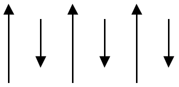
L13.3 Ferromagnetism

<u>Anti-ferromagnetism</u>: interaction between neighbouring dipoles has opposite sign: adjacent moments tend to align antiparallel (paramagnetic), eg Cr, Mn.



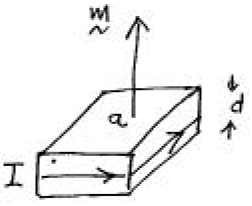
<u>Ferrimagnetism:</u>

If there are 2 unequal kinds of moments, there is a net magnetization even under complete antiparallel ordering:



Such materials are <u>ferrites</u>, eg lodestone, $FeOFe_2O_3$.

L13.4 Ferromagnetism



Consider a little loop: dipole moment **m**

Magnetization $\mathbf{M} = \mathbf{m}/volume = \dfrac{\mathbf{m}}{ad}$

$m = Mad = Ia$ so $I = Md$

and $\dfrac{I}{d} =$ "surface current density" (Am^{-1}) $= M = J_{surface}$

(compare result relating polarization to surface charge density)

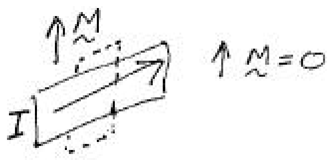
L13.5 Ferromagnetism

<u>Ampere's law:</u>

$$\oint \mathbf{B} \cdot d\mathbf{s} = \mu_0 \oint (\mathbf{H} + \mathbf{M}) \cdot d\mathbf{s} = \mu_0 i = \mu_0 (i_{free} + i_{surface})$$

Here $i_{surface} = i_{bound}$ (due to internal dipoles)

i_{free} = current applied from outside



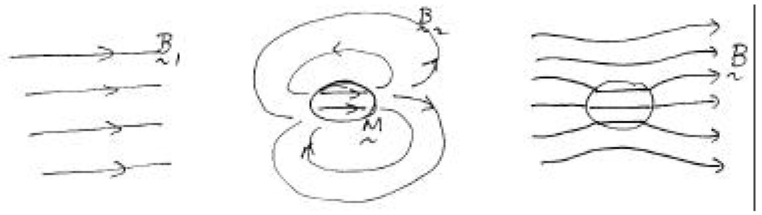
But $\mu_0 \oint \mathbf{M} \cdot d\mathbf{s} = \mu_0 I = \mu_0 i_{surface}$

so $\oint \mathbf{H} \cdot d\mathbf{s} = i_{free}$

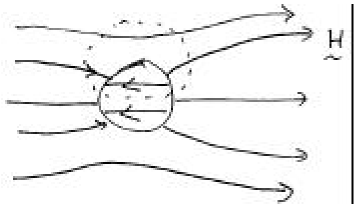
This is Ampere's law in a magnetic material.

L13.6 Ferromagnetism

Put a magnetized sphere in a magnetic field:



M in sphere is uniform. **B** is continuous (can’t start or stop).

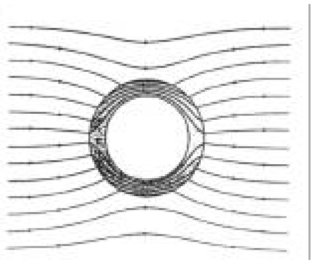


But **H** may not be continuous:

On the path, $\oint \mathbf{H} \cdot d\mathbf{s} = 0$

so **H** may reverse in the material.

L13.7 Ferromagnetism



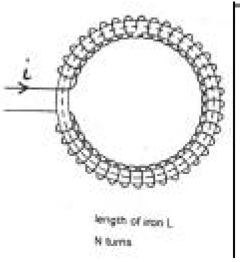
Magnetic shielding: put a hole in a ferromagnet. The field gets trapped in the magnet, with zero field inside hole. (compare electrical shielding).

L13.8 Ferromagnetism

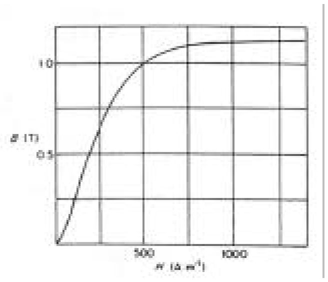
Use Ampere's law in an iron toroid:

$$\oint \mathbf{H} \cdot d\mathbf{s} = i_{free} = Ni = HL$$

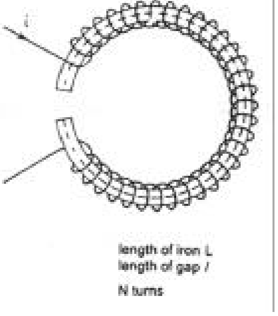
so $H = \frac{Ni}{L}$ and $B = \mu \frac{Ni}{L}$ inside.



Example: Ni =1000, L = 1 m,
so H = 1000 Am^{-1}.
From the chart, B = 1.15 T,
so $\mu = B/H = 1.15 \times 10^{-3}$,
and $\mu_r = \mu/\mu_0 = 1.15 \times 10^{-3}/(4\pi \times 10^{-7})$
$=900$.



L13 Ferromagnetism



<u>Electromagnet</u> with a gap. For a small gap, **B** is continuous, so **B** is nearly the same in the iron and the gap.

Now H in the iron is $H_1 = \frac{B}{\mu} = \frac{B}{\mu_r \mu_0}$

and H in the gap is $H_2 = \frac{B}{\mu_0}$

so $$\oint \mathbf{H} \cdot d\mathbf{s} = H_1 L + H_2 l = \frac{BL}{\mu_r \mu_0} + \frac{Bl}{\mu_0} = Ni$$

$\therefore B = \frac{\mu_0 Ni}{L/\mu_r + l} \simeq \frac{\mu_0 Ni}{l}$ because μ_r is very big.

Example: L = 1m, l = 1cm, Ni = 1000, then $B = 4\pi \times 10^{-7} \times 1000/0.01$
$=0.13$T

L13.10 Ferromagnetism

For a permanent magnet, i =0, so

$$H_1L + H_2l = 0 \quad \text{so} \quad H_{iron} = -\frac{H_{gap}l}{L} = -\frac{Bl}{\mu_0 L}$$

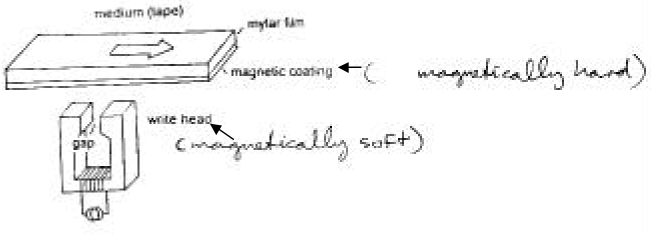
(note the minus sign)

Example: L = 1m, l = 1cm, B = 0.1T,

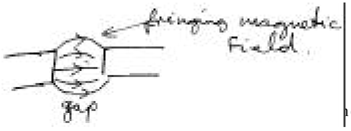
$$H_{gap} = \frac{B}{\mu_0} = \frac{0.1}{4\pi \times 10^{-7}} \simeq 80000Am^{-1} \quad \text{and} \quad H_{iron} = -800Am^{-1}$$

L13.11 Ferromagnetism

Magnetic recording:



There are 3 heads: erase, write and read. The tape with magnetic coating moves over the heads. At the gap in the electromagnet, there is a fringing magnetic field that extends over the tape.



In writing, the time variation in the field is translated to a space varying magnetization in the moving tape.

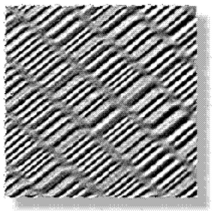
L13.12 Ferromagnetism

Audio tape uses needle-like particles of Fe_2O_3 or CrO_2 (~ 1µm), on a substrate of mylar (a polyester).

The spatial frequency translates to an audio frequency (analogue).
Video tape is similar.

In reading, the changing field in the tape induces a signal in the coil.

Computer disks store information digitally, as bits. Domains are magnetized in up or down direction. ⟶



Field of view 30µm.