Magnetism and Electromagnetism

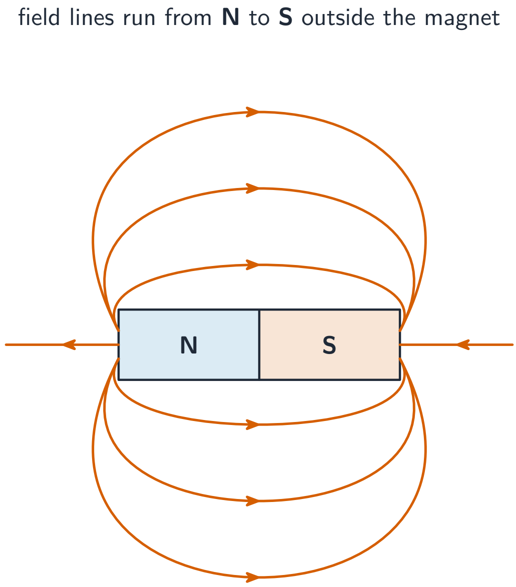
AP Physics 2

Magnetic Fields

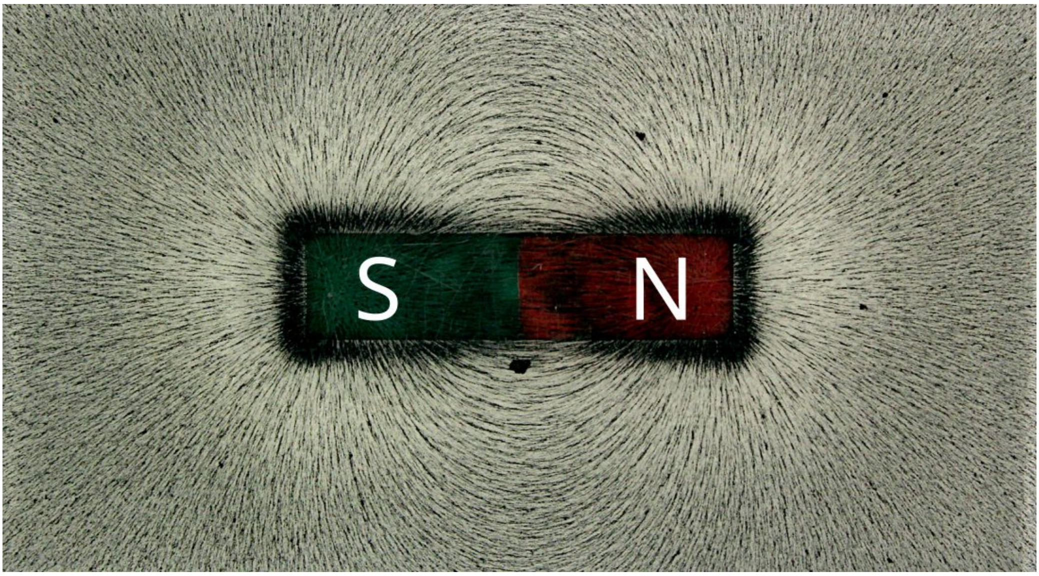
An aurora: charged particles from the Sun are steered by Earth's magnetic field toward the poles, where they hit the air and make it glow

Different materials respond very differently to a magnetic field, and the course names three. **Ferromagnetic** 铁磁性 materials (iron, nickel, cobalt) have dipoles that align strongly and *stay* aligned, so they can be permanent magnets. **Paramagnetic** 顺磁性 materials (aluminium, titanium) align only weakly and do not stay aligned. **Diamagnetic** 抗磁性 materials - in fact **all** materials have some diamagnetism - align weakly *opposite* the field. This behaviour comes from a material property, the **permeability** 磁导率: free space has a fixed permeability of free space μ_0, while the permeability of matter differs from it and is not even constant for a given material.

A **magnetic field** 磁场 $\vec{B}$ surrounds magnets and moving charges. Field lines run from a magnet's north pole to its south pole outside the magnet, and denser lines mean a stronger field. Magnetic poles always come in **pairs** – cutting a magnet in half makes two smaller magnets, never an isolated pole.



Field lines run from N to S outside a bar magnet, closer where the field is stronger



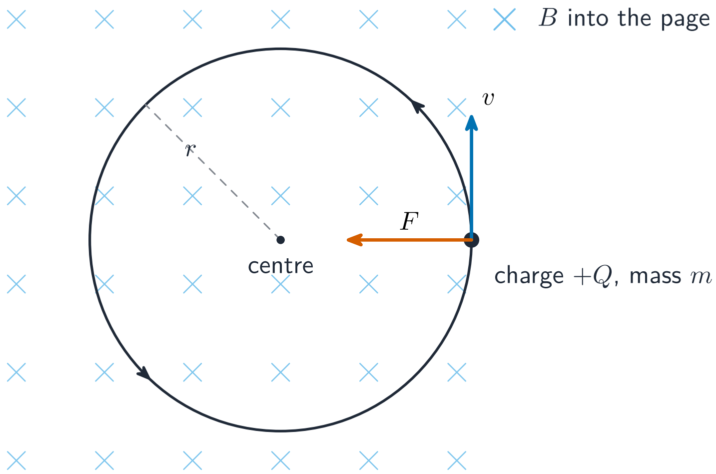
Iron filings line up along the magnetic field, making the invisible field lines of a bar magnet visible

Magnetism and Moving Charges

A charge moving through a magnetic field feels a **magnetic force 磁力**:

$$F = qvB\sin\theta,$$

where θ is the angle between the velocity and the field. The force is **perpendicular** to both $\vec{v}$ and $\vec{B}$ (use the right-hand rule), so it changes direction but not speed – a charge moving perpendicular to a uniform field travels in a **circle**. A stationary charge, or one moving parallel to the field, feels no magnetic force.



$$BQv = \frac{mv^2}{r} \Rightarrow r = \frac{mv}{BQ}$$

A charged particle moving across a magnetic field follows a circular path

Worked example. A proton ($q = 1.6 \times 10^{-19}$ C, $m = 1.67 \times 10^{-27}$ kg) enters a 0.50 T field at 2.0×10^5 m/s, at right angles to the field. The magnetic force is

$$F = qvB = 1.6 \times 10^{-19} \times 2.0 \times 10^5 \times 0.50 = 1.6 \times 10^{-14}\ \text{N}.$$

This force is the centripetal force, so it bends the proton into a circle of radius

$$r = \frac{mv}{qB} = \frac{1.67 \times 10^{-27} \times 2.0 \times 10^5}{1.6 \times 10^{-19} \times 0.50} = 4.2 \times 10^{-3}\ \text{m}.$$

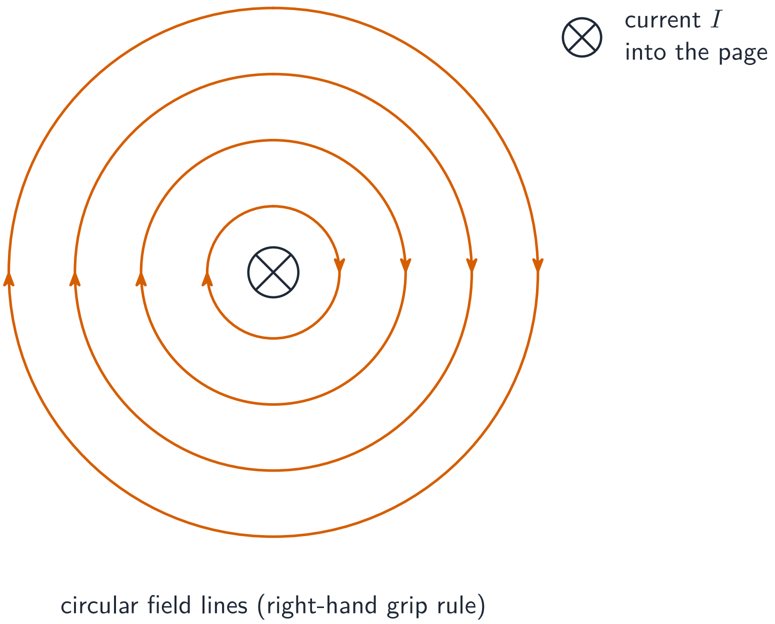
Setting $qvB = \dfrac{mv^2}{r}$ and cancelling gives that neat $r = mv/(qB)$ – the principle behind mass spectrometers.

Magnetism and Current-Carrying Wires

Because a current is moving charge, a magnetic field pushes on a **current-carrying wire**:

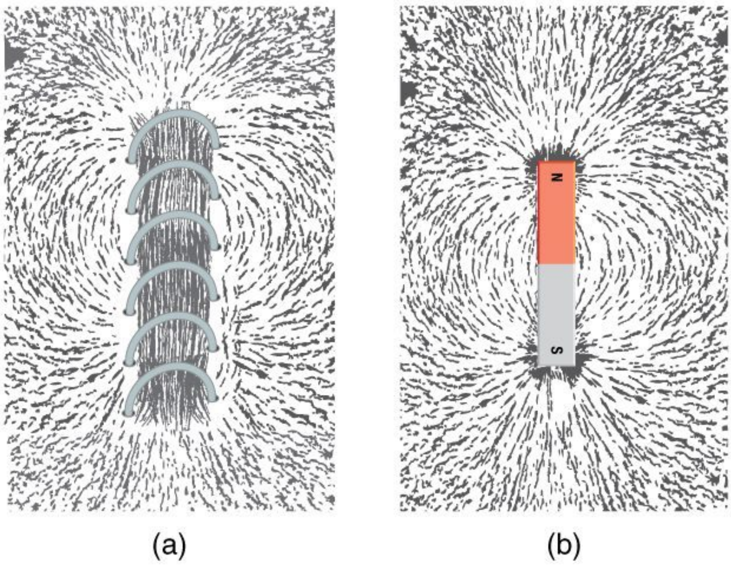
$$F = BIL\sin\theta.$$

A current also **creates** its own magnetic field: circular field lines wrap around a straight wire (right-hand rule), and a coil (solenoid) makes a field like a bar magnet. This is how electromagnets and motors work.



Concentric circular field lines surround a straight current-carrying wire

Worked example. A 0.30 m length of wire carries 4.0 A at right angles to a 0.20 T field. The force on it is $F = BIL = 0.20 \times 4.0 \times 0.30 = 0.24$ N – the push that turns a motor's coil.



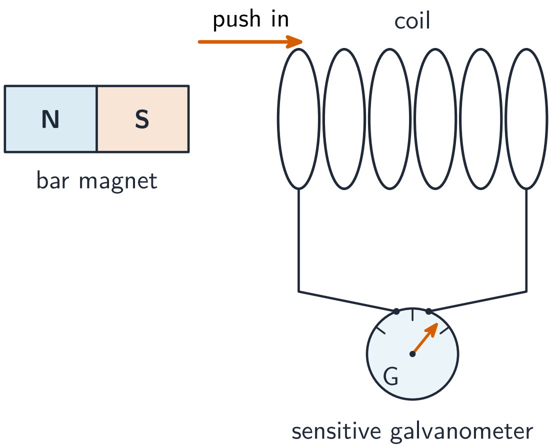
A current-carrying coil (solenoid) makes a magnetic field shaped just like a bar magnet's

Electromagnetic Induction and Faraday's Law

A **changing** magnetic field through a loop drives a current – **electromagnetic induction** 电磁感应. The **magnetic flux** 磁通量 $\Phi = BA\cos\theta$ measures how much field passes through the loop. **Faraday's law** 法拉第定律 gives the induced emf:

$$\varepsilon = -\frac{\Delta\Phi}{\Delta t}.$$

The flux changes if the field, the area, or the loop's orientation changes. **Lenz's law** 楞次定律 (the minus sign) says the induced current flows so as to **oppose** the change that caused it – the basis of generators.



Moving a magnet into a coil induces an e.m.f. that drives a current

Worked example. The magnetic flux through a single loop drops from 0.020 Wb to 0.008 Wb in 0.030 s. The average induced emf is

$$\varepsilon = \left|\frac{\Delta\Phi}{\Delta t}\right| = \frac{0.020 - 0.008}{0.030} = 0.40 \text{ V}.$$

A coil of N turns would give N times this – which is why generators and transformers use many-turn coils.

A substation transformer: changing magnetic flux in coils induces the voltages that power the grid

Exam tips

- The magnetic force $F = qvB\sin\theta$ is **perpendicular** to the velocity, so it changes direction (a circle) but not speed; a stationary charge or one moving **along** the field feels no force.
- Use $F = BIL$ for the force on a current-carrying wire (the motor effect).
- A current **creates** a magnetic field (circles around a wire; a solenoid acts like a bar magnet).
- **Induction** needs a **changing** flux $\Phi = BA$ — a stationary magnet in a coil induces nothing.
- **Faraday**: $\varepsilon = \Delta\Phi/\Delta t$ (times N turns); **Lenz**: the induced current opposes the change (energy conservation).