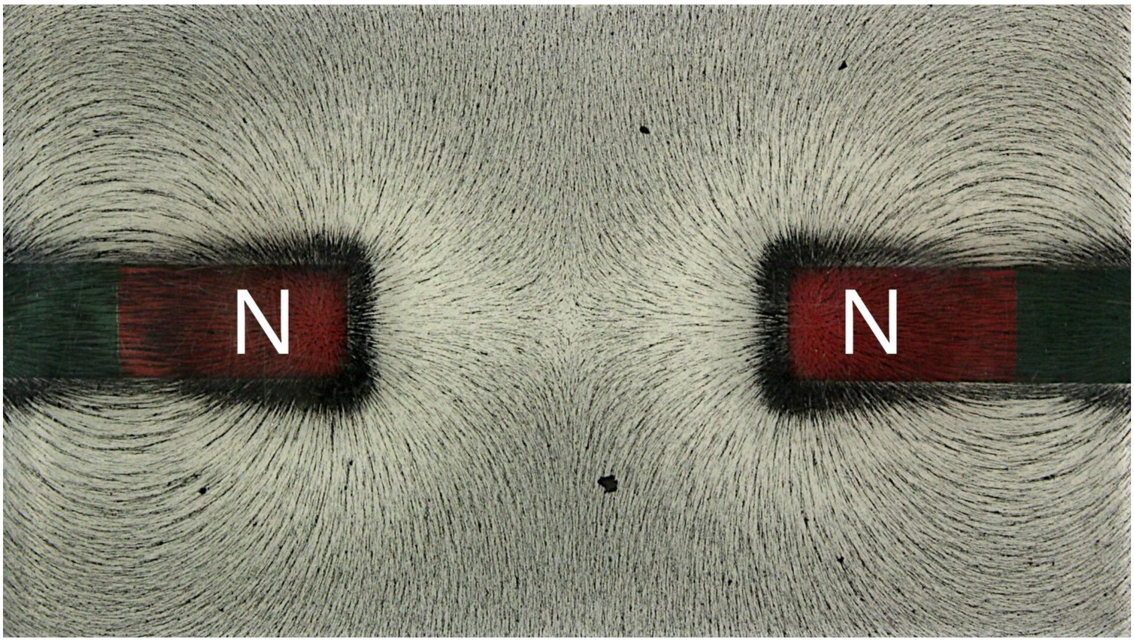
Magnetic fields

A-Level Physics

The magnetic field



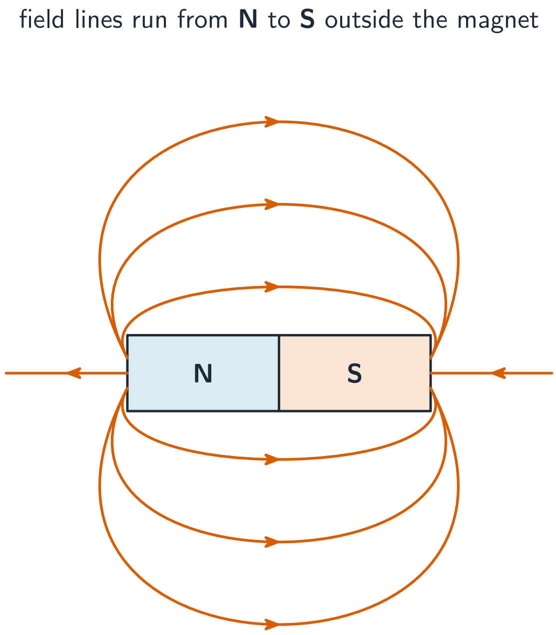
Iron filings trace the field lines around bar magnets.

A **magnetic field** 磁场 is a region where a moving charge (or a **current** 电流) feels a **force** 力. It is made by:

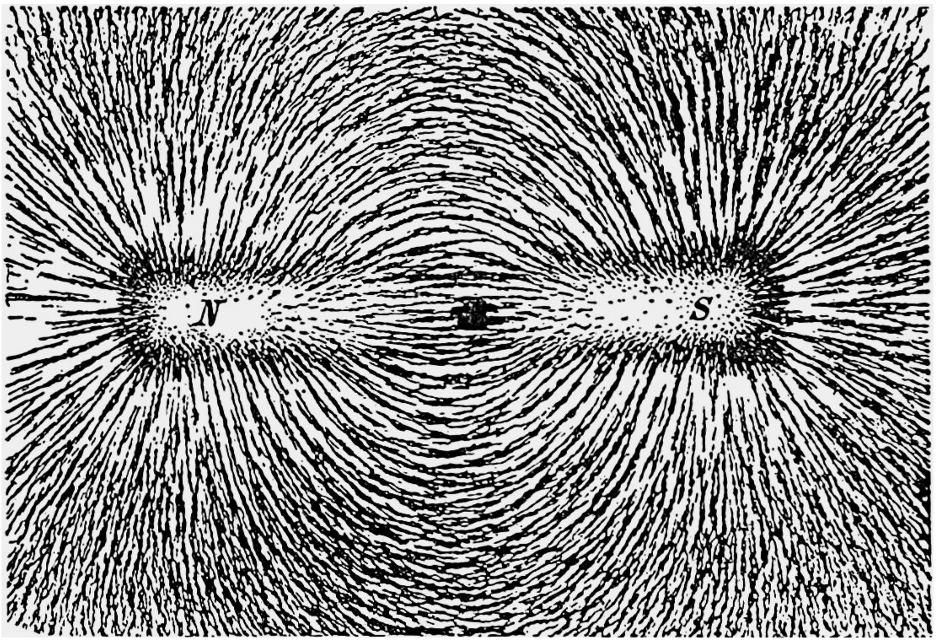
- **moving charges** (usually a current in a wire), or
- **permanent magnets** 永磁体 (where it comes from tiny atomic currents).

Field lines

- **field lines** 场线 point from **N** to **S** outside a magnet, and S to N inside (so they form closed loops).
- lines never cross; closer lines mean a stronger field.



The field of a bar magnet: lines run from N to S, strongest near the poles



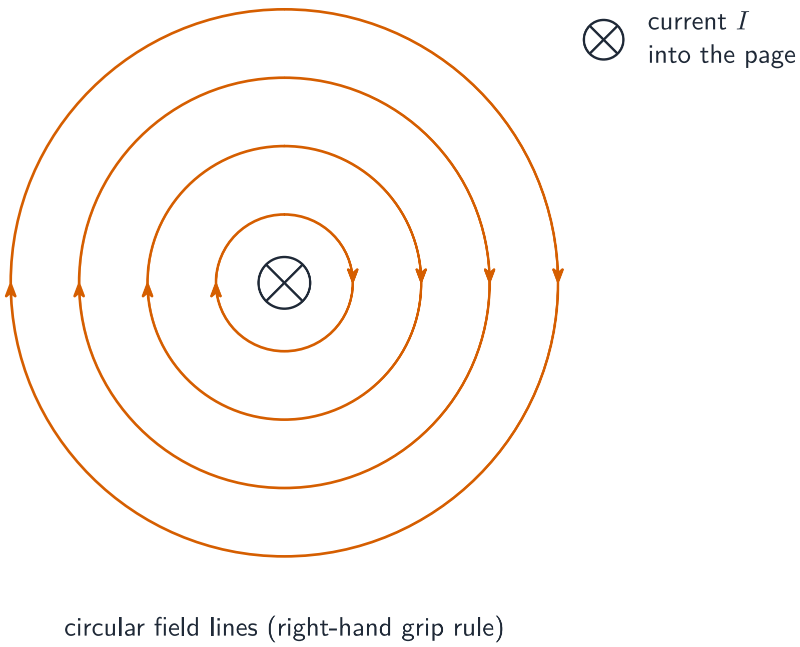
Iron filings around a bar magnet line up along the field, showing its real shape

Image: Newton Henry Black, Public domain (commons.wikimedia.org)

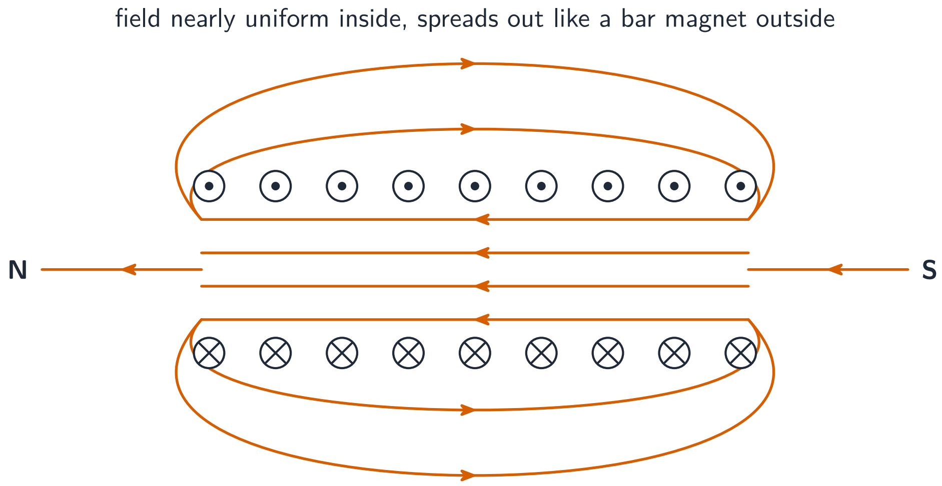
Patterns to know:

- **bar magnet** 条形磁铁—curved lines from N to S outside, strongest near the poles.
- **long straight wire** —circles around the wire; the direction comes from the **right-hand grip rule** 右手定则 (thumb along the current, fingers curl the way the field points).

- **flat circular coil** —the field through the centre is at right angles to the coil; the coil acts like a small bar magnet.
- **long solenoid** 螺线管—the field inside is nearly **uniform** along the axis, like a stretched bar magnet; outside it falls off fast.



Field around a long straight wire



Field of a solenoid

An **iron core** 铁芯 inside a solenoid greatly **increases** the field, because the iron's atomic magnets line up and add to it. This is why **electromagnets** 电磁铁 and **transformers** 变压器 have iron cores.

Force on a current-carrying conductor

A current I in a wire of length L in a magnetic field of flux density B feels a force

$$F = BIL\sin\theta,$$

where θ is the angle between the wire and the field. The force is largest when the wire is at right angles to the field ($F = BIL$) and zero when the wire is along the field.

Worked example. A wire of length 0.20 m carries a current of 3.0 A at right angles to a magnetic field of flux density 0.50 T. Find the force on it.

$$F = BIL = 0.50 \times 3.0 \times 0.20 = 0.30 \text{ N}.$$

Magnetic flux density

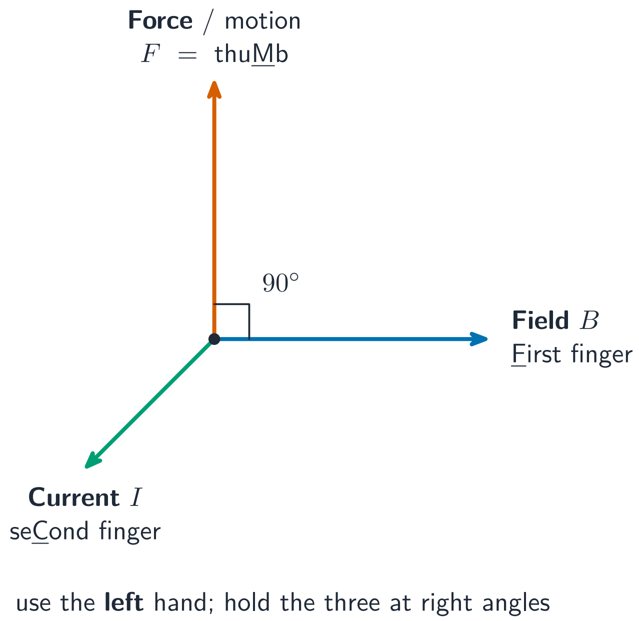
This equation also **defines** the **magnetic flux density** 磁通密度 B:

$$B = \frac{F}{IL} \quad \text{(wire at right angles to the field).}$$

So B is the force per unit current per unit length on a wire at right angles to the field. Unit: **tesla** 特斯拉, $\text{T} = \text{N A}^{-1}\text{ m}^{-1}$.

Direction —Fleming's left-hand rule

Use the **left hand** (**Fleming's left-hand rule** 弗莱明左手定则): first finger = **F**ield, second finger = **C**urrent, thumb = force (thrust). Hold the three at right angles.



Fleming's left-hand rule: thumb = force, first finger = field, second finger = current

Force on a moving charge

A charge Q moving at **velocity** 速度 v through a field feels

$$F = BQv \sin\theta,$$

with θ the angle between v and B. Same left-hand rule (the second finger is the motion of a **positive** charge —reverse it for a negative charge). The force is largest when v is at right angles to B, and zero when v is along B.

Circular motion in a uniform field

A charge moving at right angles to a **uniform field** 匀强场 feels a force at right angles to both v and B. This force does **no work** (always at right angles to the motion), so the **kinetic energy** 动能 and speed stay constant —the particle moves in a **circle**. Set the magnetic force equal to the **centripetal force** 向心力:

$$BQv = \frac{mv^2}{r}, \qquad r = \frac{mv}{BQ}.$$

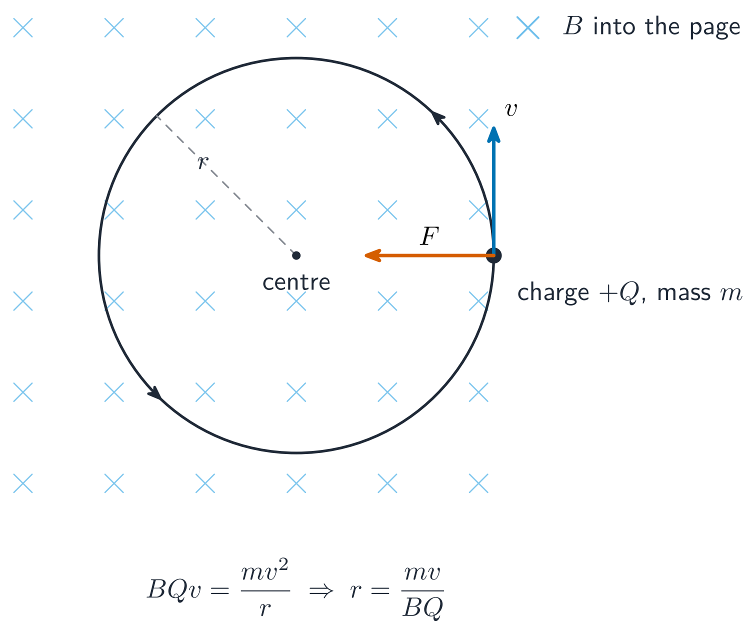
Worked example. A proton (mass 1.7×10^{-27} kg, charge 1.6×10^{-19} C) moves at 2.0×10^6 m s^{-1} at right angles to a 0.50 T field. Find the radius of its circular path.

$$r = \frac{mv}{BQ} = \frac{(1.7 \times 10^{-27})(2.0 \times 10^6)}{(0.50)(1.6 \times 10^{-19})} \approx 0.043 \text{ m}.$$

So the radius depends on the **momentum** 动量 mv. The period is

$$T = \frac{2\pi m}{BQ},$$

which does **not** depend on the speed —a faster particle goes in a bigger circle but takes the same time per turn. If v also has a part along B, that part is unchanged, and the path is a **helix** 螺旋.



Circular path of a charged particle in a magnetic field

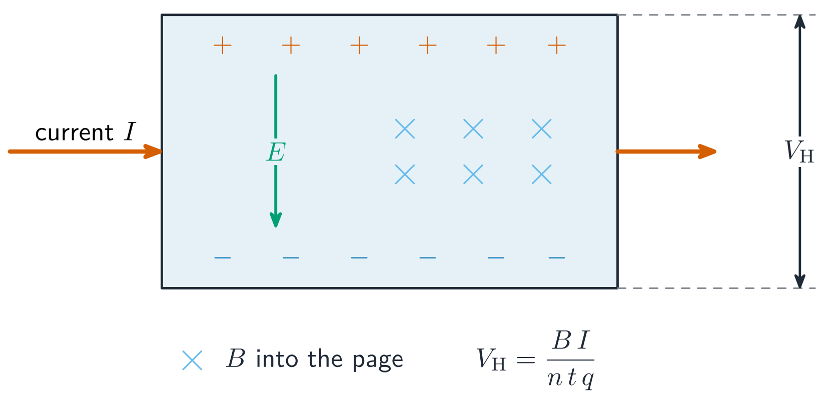
Hall effect

A slab of conductor carrying current I, in a field B at right angles to the current, develops a voltage across its faces —the **Hall voltage** 霍尔电压 V_{H} (the **Hall effect** 霍尔效应).

The moving charges feel a magnetic force BQv_{d} (v_{d} is the **drift velocity** 漂移速度), so they build up on one face, making an **electric field** 电场 E that opposes more build-up. At steady state $eE = Bev_{\mathrm{d}}$, so $E = Bv_{\mathrm{d}}$. With $V_{\mathrm{H}} = Ew$ and $I = nev_{\mathrm{d}}wt$:

$$V_{\mathrm{H}} = \frac{BI}{ntq},$$

where q is the carrier charge. A **Hall probe** 霍尔探头 uses this to measure B: pass a known current through a thin **semiconductor** 半导体 slab and read V_{H} (largest when the slab is at right angles to B).



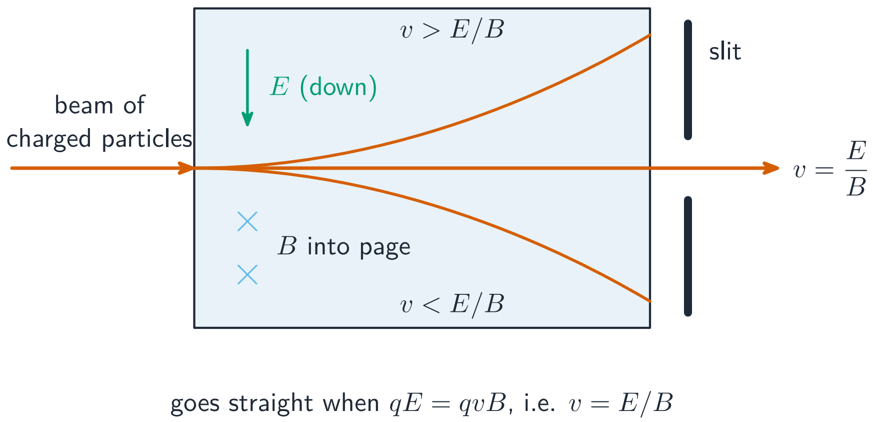
The Hall effect

Velocity selector

A **velocity selector** 速度选择器 uses crossed electric and magnetic fields to let through only one speed. With the electric force qE and magnetic force qvB set to oppose each other, the net force is zero only when

$$qE = qvB \quad \Rightarrow \quad v = \frac{E}{B}.$$

Particles at speed E/B go straight through; faster or slower ones are deflected.



Velocity selector

Force between parallel currents

Two long parallel wires each sit in the other's magnetic field. Using Fleming's left-hand rule: **parallel currents (same direction) attract; antiparallel currents (opposite directions) repel**. This is the basis of the SI definition of the ampere.

Electromagnetic induction

Magnetic flux

The **magnetic flux** 磁通量 Φ through a flat area A at right angles to B is

$$\Phi = BA.$$

If the area's normal is at angle θ to B, use $\Phi = BA\cos\theta$. Unit: **weber** 韦伯, $\mathrm{Wb} = \mathrm{T\ m^2}$. For a **coil** 线圈 of N turns, the **flux linkage** 磁链 is $N\Phi = NBA$.

Faraday's and Lenz's laws

When the flux linkage through a circuit **changes**, an **electromotive force** 电动势 (e.m.f.) is induced —this is **electromagnetic induction** 电磁感应.

Faraday's law 法拉第定律: the induced e.m.f. equals the rate of change of flux linkage:

$$|\varepsilon| = N\frac{d\Phi}{dt}.$$

Worked example. A coil of 200 turns and area 0.010 m^2 sits with its plane at right angles to a 0.50 T field. The field falls steadily to zero in 0.20 s. Find the average induced e.m.f.

The flux linkage changes from $N\Phi = NBA = 200 \times 0.50 \times 0.010 = 1.0$ Wb to zero, so

$$|\varepsilon| = \frac{\Delta(N\Phi)}{\Delta t} = \frac{1.0}{0.20} = 5.0\text{ V}.$$

Lenz's law 楞次定律: the induced e.m.f. acts to **oppose the change** that makes it. This is **conservation of energy** 能量守恒—if it reinforced the change, energy would come from nothing. Combined:

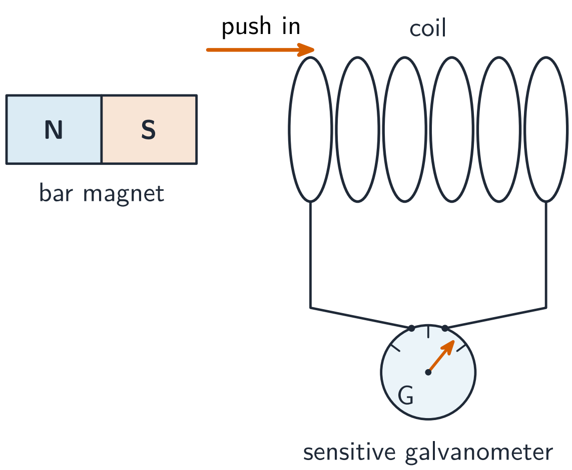
$$\varepsilon = -\frac{d(N\Phi)}{dt}.$$

What changes the flux?

- **changing** B (moving a magnet near a coil),
- **changing area** A (a rod sliding along rails),
- **changing orientation** (a coil turning in a field —the a.c. generator, next topic).

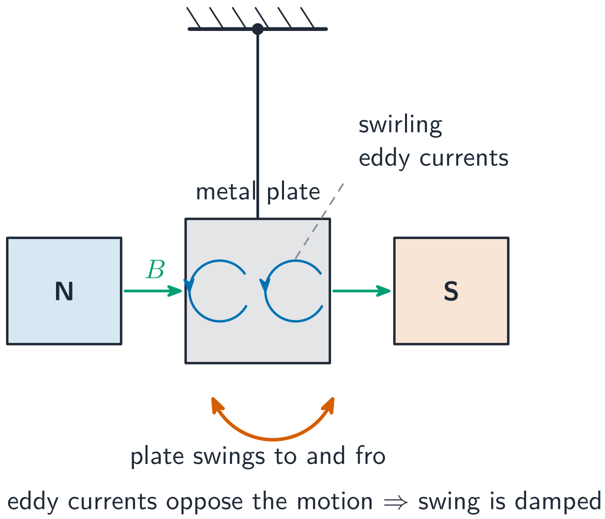
Demonstrations

- moving a bar magnet into a coil deflects a **galvanometer** 检流计; the deflection reverses when the magnet is pulled out (Lenz's law), and is larger for faster motion (Faraday's law).



Demonstrating electromagnetic induction

- a copper disc swinging into a field is quickly slowed —**eddy currents** 涡流 are induced that oppose the motion.



Eddy-current damping

What makes the induced e.m.f. larger

From $\varepsilon = N\,d\Phi/dt$ with $\Phi = BA$: more turns N, a stronger B, a larger area A, or a faster change —each gives a larger induced e.m.f.

Exam tips

- Force on a current $F = BIL\sin\theta$; on a moving charge $F = BQv$; find the direction with **Fleming's left-hand rule**.
- A charge moving perpendicular to B moves in a **circle** ($BQv = mv^2/r$).
- **Electromagnetic induction**: e.m.f. = rate of change of flux linkage (Faraday); its direction opposes the change (Lenz's law).