Course Companion

AP Physics 2

Every topic handout in one volume

全部专题讲义合集

exercises.lol

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Thermodynamics

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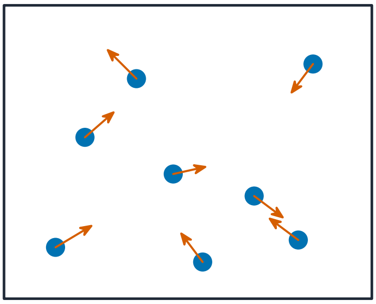
Kinetic Theory of Temperature and Pressure

Thermodynamics 热力学 studies heat and energy in large collections of particles. The **kinetic theory** 分子运动论 explains gas behavior from the random motion of its molecules:

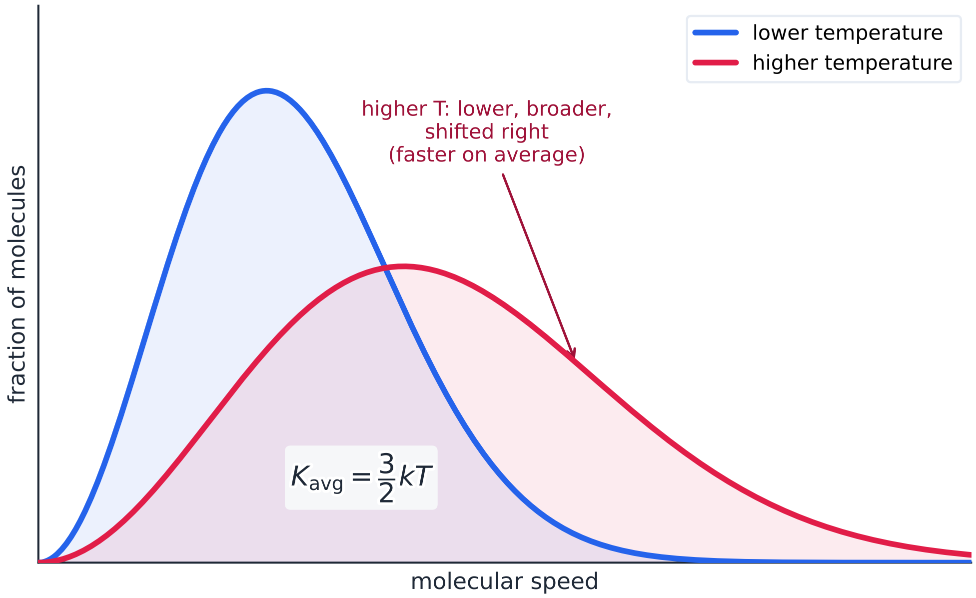


1. many identical molecules, in continuous **random motion**
2. their own volume is **tiny** next to the container
3. straight lines between hits - intermolecular forces **ignored**
4. collisions are **elastic**: no kinetic energy is lost

poor at very high pressure (volume matters) or very low temperature (forces matter)

The key assumptions of the kinetic theory of an ideal gas

- **Temperature** 温度 is a measure of the **average kinetic energy** of the molecules: $K_{\text{avg}} = \frac{3}{2}k_B T$ (with T in kelvin). Hotter means faster-moving molecules.
- **Pressure** 压强 comes from molecules colliding with the container walls – more frequent or harder collisions give more pressure.



The Maxwell-Boltzmann speed distribution shifts right and flattens at higher temperature

Worked example. Find the average kinetic energy of a gas molecule at 300 K, using $k_B = 1.38 \times 10^{-23}$ J/K:

$$K_{\text{avg}} = \tfrac{3}{2}k_B T = 1.5 \times 1.38 \times 10^{-23} \times 300 = 6.2 \times 10^{-21} \text{ J}.$$

It depends only on temperature, not on the type of gas – at the same T, light and heavy molecules share the same average kinetic energy (so the light ones move faster).

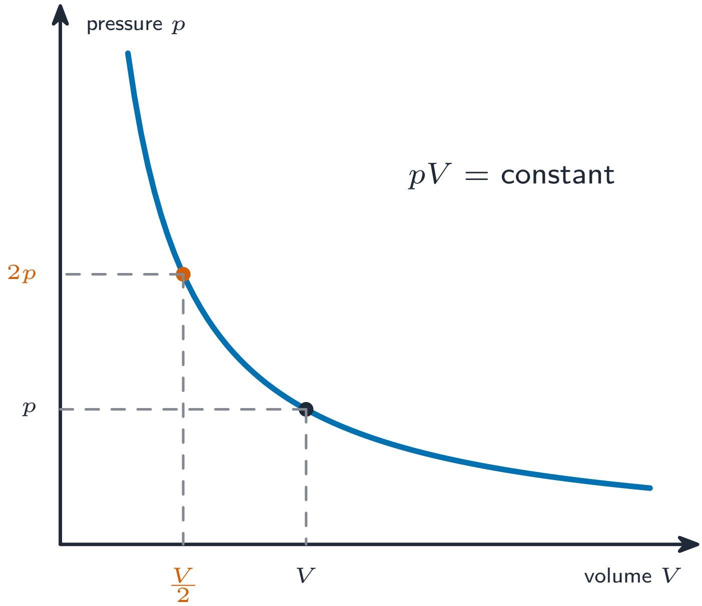
The Ideal Gas Law

An iceberg: heat, density and phase changes connect thermodynamics to fluids and buoyancy

An **ideal gas** 理想气体 obeys

$$PV = nRT \qquad (\text{or } PV = Nk_BT),$$

linking pressure P, volume V, amount (n moles or N molecules), and absolute temperature T. Use it to predict how a gas responds when you change one quantity and hold others fixed (e.g. heating at constant volume raises pressure).



Boyle's law: at constant temperature, pressure times volume is constant

Worked example. A sealed rigid container of gas is at 1.0×10^5 Pa and 300 K. It is heated to 450 K. Because the volume and amount are fixed, P/T is constant:

$$P_2 = P_1 \frac{T_2}{T_1} = 1.0 \times 10^5 \times \frac{450}{300} = 1.5 \times 10^5 \text{ Pa}.$$

Always convert temperatures to **kelvin** before using a gas law – using Celsius here would give nonsense.

Heating the gas inside a balloon lowers its density, so the balloon rises — the ideal gas law in action

Thermal Energy Transfer and Equilibrium

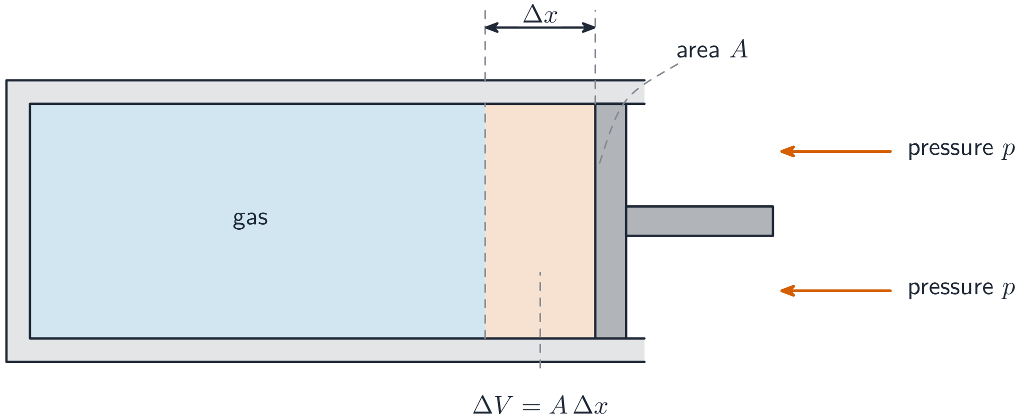
Heat 热量 Q is energy transferred because of a temperature difference; it flows from hot to cold. Two objects in contact reach **thermal equilibrium** 热平衡 when they share the same temperature, and net heat flow stops. The three transfer methods are **conduction** 传导, **convection** 对流, and **radiation** 辐射.

The First Law of Thermodynamics

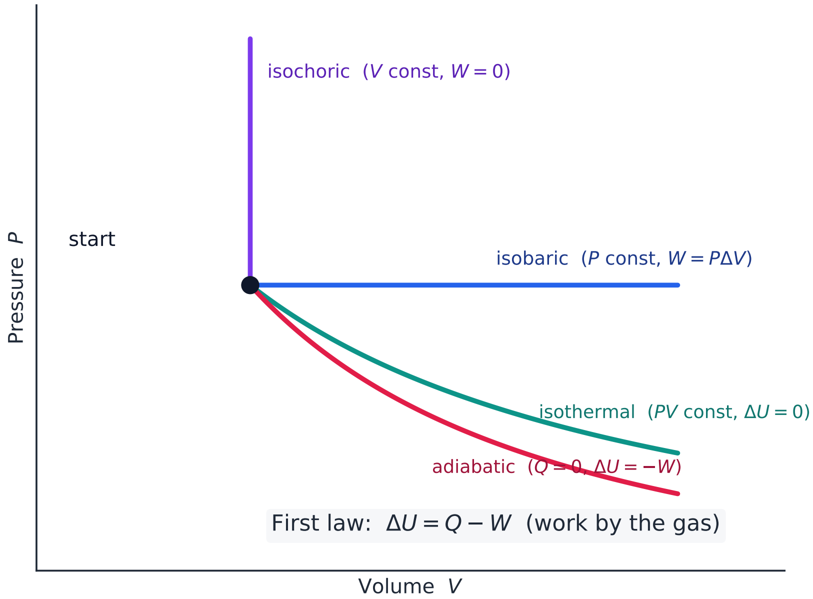
The **first law** 热力学第一定律 is conservation of energy for a gas:

$$\Delta U = Q + W,$$

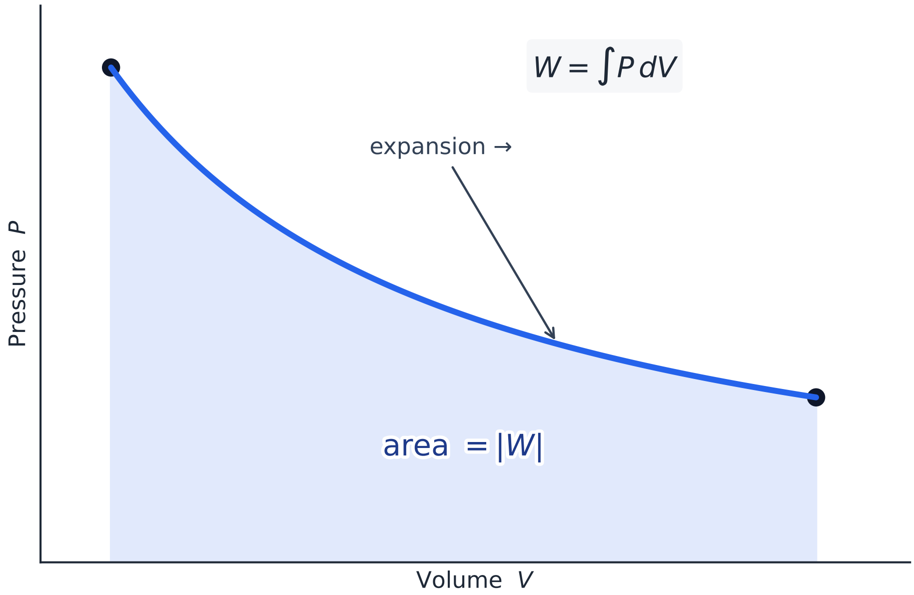
where ΔU is the change in **internal energy** 内能 (tied to temperature), Q is heat added **to** the gas, and W is work done **on** the gas. On a pressure–volume diagram, the work done **by** the gas is the area under the process curve. Watch signs: compressing a gas does positive work on it.



A gas pushing a piston out by a small distance does work equal to p times the volume change



The four thermodynamic processes drawn from a common starting state on a PV diagram



The work done during a volume change equals the area under the P-V curve

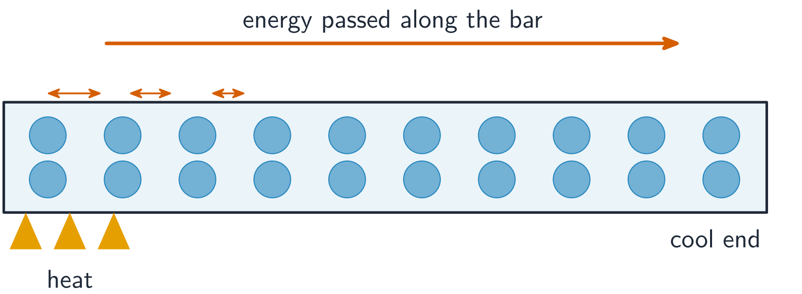
Worked example. A gas absorbs 500 J of heat and, as it expands, does 200 J of work **on its surroundings**. Find the change in its internal energy. Work done *on* the gas is $W = -200$ J (it does work, so it loses that energy):

$$\Delta U = Q + W = 500 + (-200) = 300 \text{ J}.$$

The internal energy rises by 300 J, so the gas ends up hotter. Getting the sign of W right is the whole game in first-law problems.

Specific Heat and Thermal Conductivity

- **Specific heat** 比热容 c is the heat needed to raise one kilogram by one degree: $Q = mc\,\Delta T$. A high specific heat (like water's) means a substance resists temperature change.
- **Thermal conductivity** 热导率 measures how fast heat conducts through a material; the rate of conduction rises with area and temperature difference and falls with thickness.



Conduction: vibrating particles pass energy along a metal bar

Worked example. How much heat raises the temperature of 2.0 kg of water from 20 °C to 80 °C? Water's specific heat is $c = 4200$ J/(kg °C):

$$Q = mc\,\Delta T = 2.0 \times 4200 \times (80 - 20) = 5.0 \times 10^5 \text{ J}.$$

Water's large specific heat is why it is used as a coolant and why coastal climates are mild.

Entropy and the Second Law of Thermodynamics

Entropy 熵 measures the disorder, or the number of ways to arrange, a system. The **second law** 热力学第二定律: the total entropy of an isolated system never decreases – energy naturally spreads out. This sets the **direction** of processes: heat flows hot→cold on its own, never the reverse, and no engine can convert heat entirely into work.

Exam tips

- Always convert temperatures to **kelvin** ($T_K = T_C + 273$) before using any gas law.
- In the first law $\Delta U = Q + W$, get the **sign of** W right: work done **on** the gas is positive; when the gas expands and does work on its surroundings, W is negative.
- **Temperature** measures the average kinetic energy of particles, so at the same T lighter molecules move faster.
- On a **PV diagram** the work done by the gas is the **area** under the process curve.
- Use $Q = mc\,\Delta T$ for temperature change; the **second law** fixes the direction — heat flows hot→cold and total entropy never decreases.

Electric Force, Field, and Potential

AP Physics 2

Electric Charge and Electric Force

Electric charge 电荷 is a **fundamental property** of matter, and it comes in two kinds, positive and negative; like charges repel and opposite charges attract. Charge is **conserved** and **quantized** (a multiple of the elementary charge e). The force between two point charges is **Coulomb's law** 库仑定律:

$$F = \frac{kq_1q_2}{r^2},$$

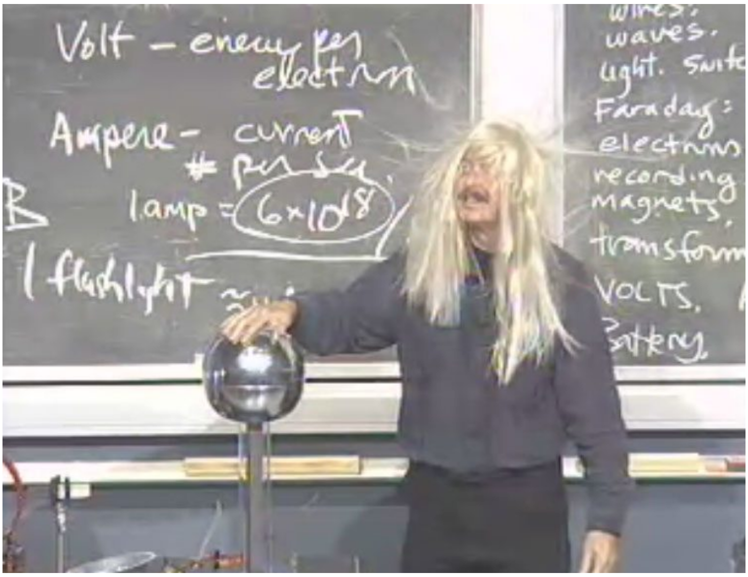
directed along the line joining them – an inverse-square law like gravity, but it can push or pull.

The constant k hides a property of the medium: the **permittivity** 介电常数. Free space has a fixed permittivity of free space ε_0 (with $k = 1/4\pi\varepsilon_0$), while the permittivity of **matter** differs from ε_0, depending on the material's composition and arrangement - which is why a material between two charges changes the force. Note also that although the electric force is vastly **stronger** than gravity, **gravity dominates at large scales**, because large objects are usually electrically **neutral** (equal + and −), leaving only gravity to act.

Worked example. Two point charges, $+3.0\ \mu$C and $-2.0\ \mu$C, sit 0.10 m apart ($k = 9.0 \times 10^9$). The force between them is

$$F = \frac{kq_1q_2}{r^2} = \frac{9.0 \times 10^9 \times (3.0 \times 10^{-6})(2.0 \times 10^{-6})}{(0.10)^2} = 5.4\ \text{N},$$

attractive, because the charges have opposite signs. (Use the magnitudes for the size and decide the direction from the signs.)



Like charges repel: each hair carries the same charge from the Van de Graaff generator, so they push apart

The Process of Charging

Objects charge by moving electrons. A **conductor** 导体 lets charge move freely; an **insulator** 绝缘体 holds it in place. Three methods:

- **Friction**: rubbing transfers electrons.
- **Conduction** 接触起电: touching shares charge.
- **Induction** 感应起电: a nearby charge rearranges charge in a neutral object, which can then be grounded to leave it charged.

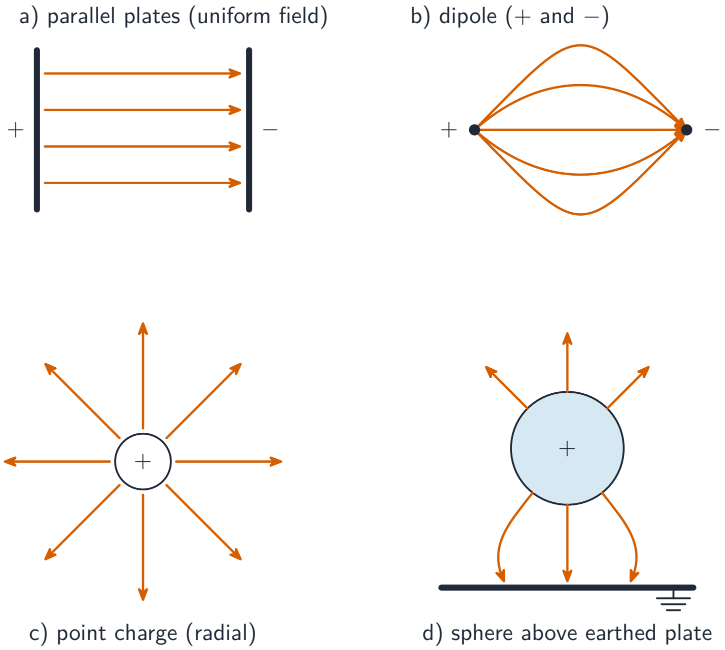
Electric Fields

Lightning: charge builds up until the electric field between cloud and ground is strong enough to tear electrons off air molecules, and a huge current flows

An **electric field** 电场 $\vec{E}$ is the force per unit charge that a small positive test charge would feel:

$$\vec{E} = \frac{\vec{F}}{q}, \qquad E = \frac{kQ}{r^2} \text{ for a point charge.}$$

Field lines point away from positive charges and toward negative ones; where they are denser, the field is stronger. A charge in a field feels $\vec{F} = q\vec{E}$.



Electric field-line patterns for parallel plates, a dipole, and a point charge

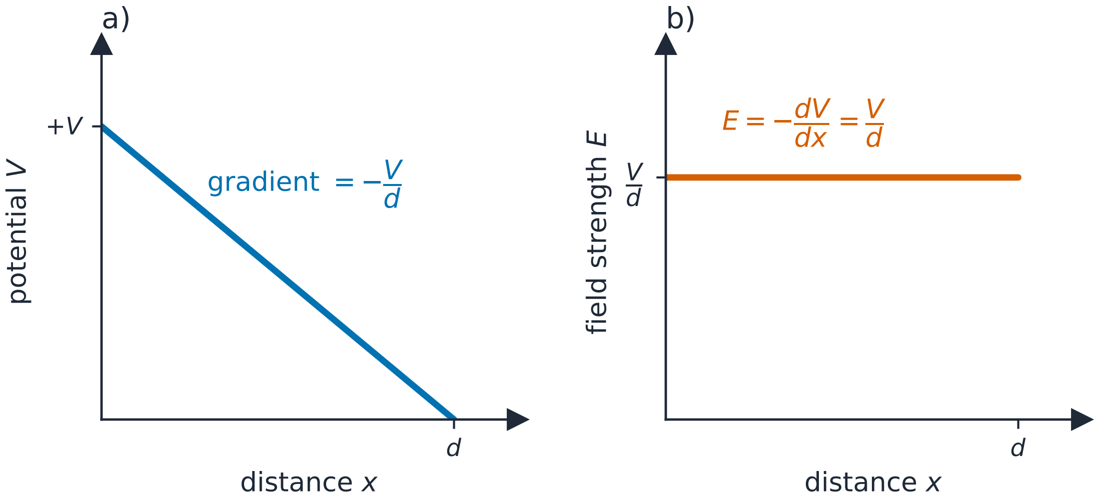
Worked example. Find the electric field 0.20 m from a +5.0 μC point charge: $E = \dfrac{kQ}{r^2} = \dfrac{9.0 \times 10^9 \times 5.0 \times 10^{-6}}{(0.20)^2} = 1.1 \times 10^6$ N/C, pointing away from the charge. A +2 nC charge placed there would feel $F = qE = 2 \times 10^{-9} \times 1.1 \times 10^6 = 2.2 \times 10^{-3}$ N.

Electric Potential Energy

Two charges have **electric potential energy** 电势能 stored in their arrangement:

$$U = \frac{kq_1q_2}{r}.$$

Like charges pushed together store positive energy; opposite charges have negative energy (bound). Moving a charge changes U, and the electric force does work equal to $-\Delta U$.



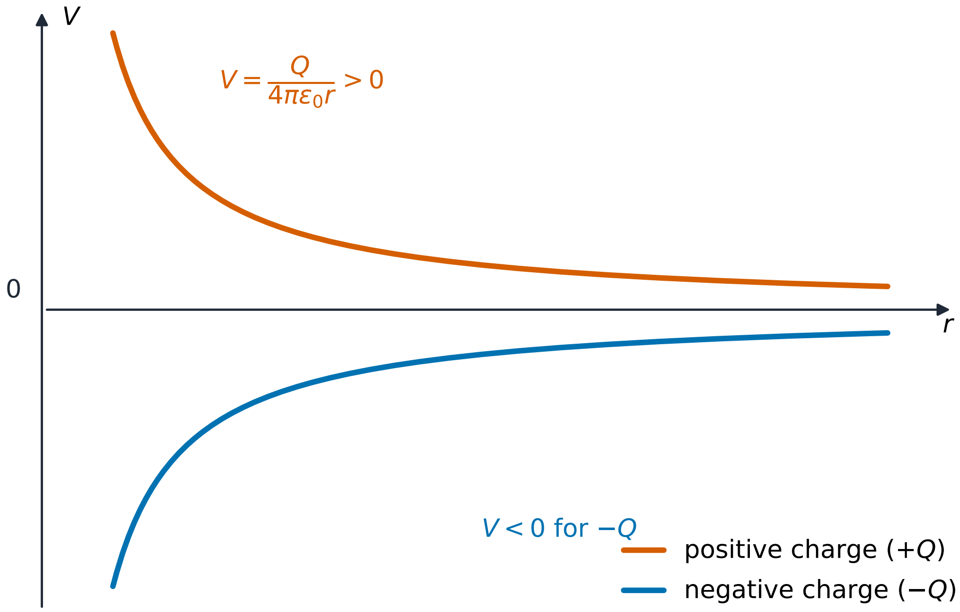
In a uniform field the potential falls steadily with distance, so E relates to V

Electric Potential

Electric potential 电势 V is the potential energy per unit charge – a scalar field, measured in volts:

$$V = \frac{U}{q} = \frac{kQ}{r}.$$

The **potential difference** (voltage) 电压 between two points is the work per unit charge to move between them: $\Delta V = \dfrac{\Delta U}{q}$, and $U = qV$. Positive charges move from high to low potential on their own. Because potential is a **scalar**, adding the potentials from several charges is much easier than adding field vectors.



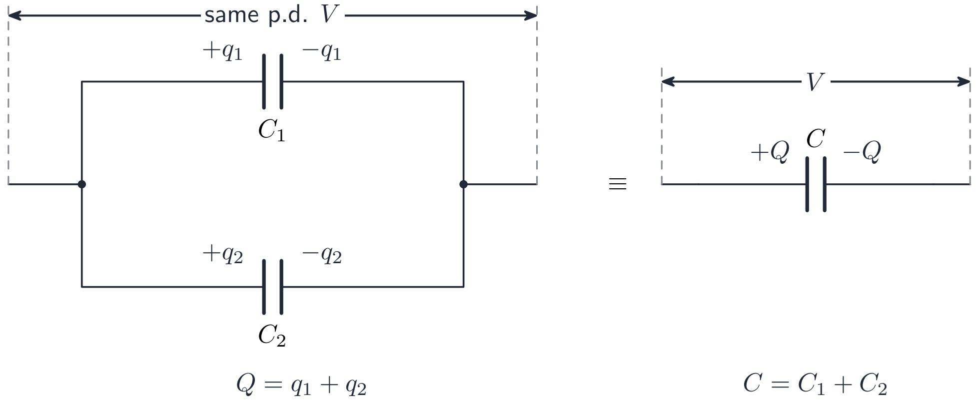
The potential near a point charge varies as 1/r

Capacitors

A **capacitor** 电容器 stores charge and energy on two conductors separated by a gap. Its **capacitance** 电容 relates charge to voltage:

$$C = \frac{Q}{V},$$

and the stored energy is $U = \frac{1}{2}CV^2$. Capacitance depends on the plates' geometry and the material between them, not on the charge placed on it.



Capacitors in parallel share the same p.d., and their charges add

Worked example. A 100 μF capacitor is charged to 12 V. It holds $Q = CV = 100 \times 10^{-6} \times 12 = 1.2 \times 10^{-3}$ C of charge and stores $U = \frac{1}{2}CV^2 = \frac{1}{2} \times 100 \times 10^{-6} \times 12^2 = 7.2 \times 10^{-3}$ J of energy.

Conservation of Electric Energy

Energy is conserved for charges just as for masses. A charge released in a field converts electric potential energy into kinetic energy:

$$q\,\Delta V = \frac{1}{2}mv^2 \quad \text{(gaining speed as it "falls" through a potential difference).}$$

Worked example. An electron ($q = 1.6 \times 10^{-19}$ C, $m = 9.1 \times 10^{-31}$ kg) is accelerated from rest through a potential difference of 100 V. Its final speed is

$$v = \sqrt{\frac{2q\,\Delta V}{m}} = \sqrt{\frac{2 \times 1.6 \times 10^{-19} \times 100}{9.1 \times 10^{-31}}} = 5.9 \times 10^6 \text{ m/s}.$$

This is exactly how the electron gun in an old television or an electron microscope works.

Exam tips

- **Coulomb's law** and the point-charge field are **inverse-square** — doubling the separation makes the force (or field) four times smaller.
- Use magnitudes for the size of a force and decide direction from the **signs**; the field points the way a **positive** test charge would move.
- **Potential (V) is a scalar** so potentials from several charges simply add; the **field (E) is a vector** and must be added by direction.

- For a charge accelerated through a voltage use energy conservation $qV = \frac{1}{2}mv^2$.
- Capacitor relations: $C = Q/V$ (capacitance is fixed by geometry) and energy $U = \frac{1}{2}CV^2$.

Electric Circuits

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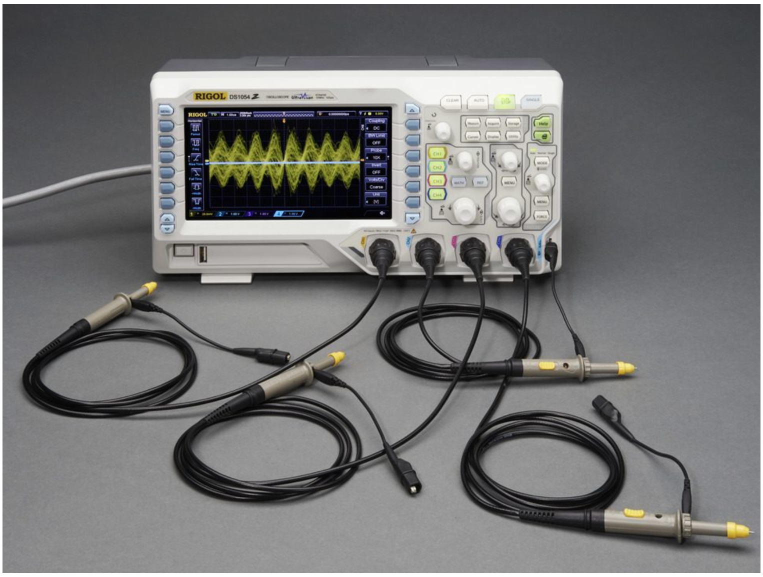
Electric Current

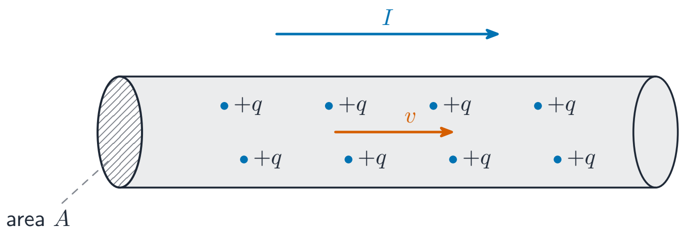


An oscilloscope: circuit behaviour over time is measured as voltage against time

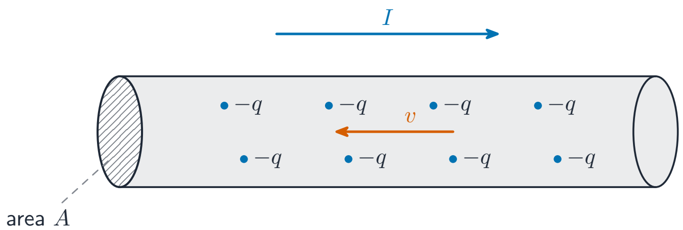
Electric current 电流 is the rate at which charge flows past a point, measured in **amperes** 安培 (A):

$$I = \frac{\Delta q}{\Delta t}.$$

By convention, current points the way **positive** charge would move (opposite to the electrons in a wire). A steady current needs a complete loop and an energy source (a battery's **electromotive force**, or emf).



(a) positive carriers drift with I

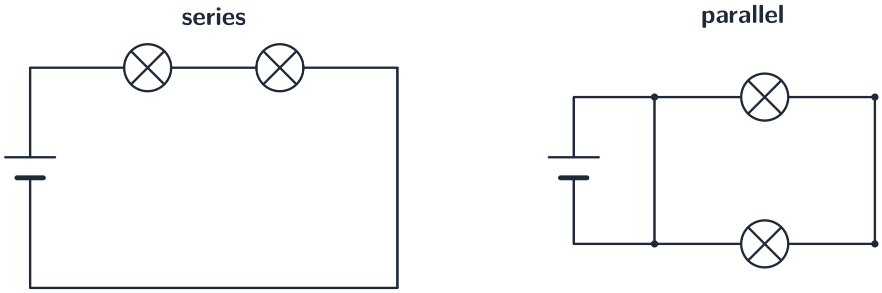


(b) electrons drift against I

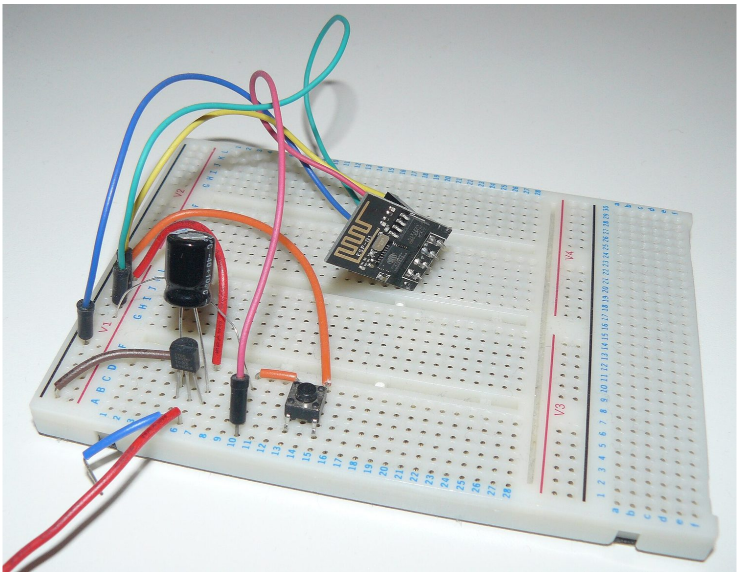
Charge carriers drift slowly through a conductor to make a current

Simple Circuits

A **circuit** is a closed loop of conductors, a source (battery), and components. In a **series** 串联 path the same current flows through each element; in a **parallel** 并联 path the same voltage is across each branch. A **circuit diagram** uses standard symbols; reading it correctly is the first step of any circuit problem.



Components can be joined in series or in parallel



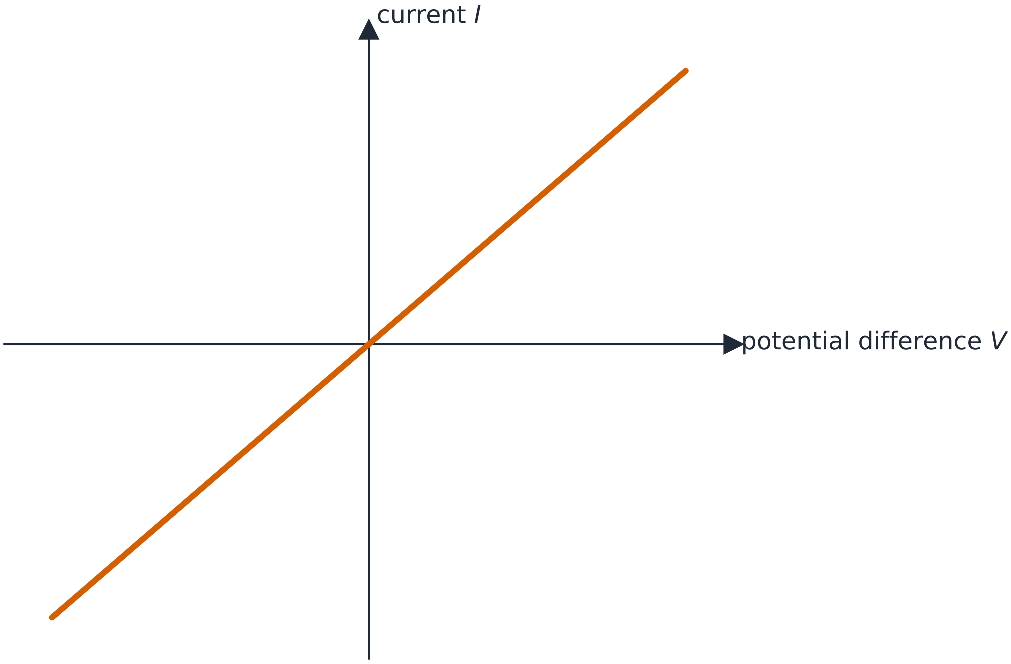
A real circuit: components pushed into a breadboard and joined by wires so current has a complete path

Resistance, Resistivity, and Ohm's Law

Resistance 电阻 R opposes current, measured in ohms. **Ohm's law 欧姆定律** links the three key quantities:

$$V = IR.$$

A component's resistance depends on the material's **resistivity 电阻率** ρ, its length, and its cross-sectional area: $R = \dfrac{\rho L}{A}$ – longer and thinner means more resistance.



The I-V line of an ohmic conductor is straight through the origin

Worked example. A 2.0 A current flows through a 6.0 Ω resistor. The voltage across it is $V = IR = 2.0 \times 6.0 = 12$ V.

Electric Power

Electric power 电功率 is the rate a component converts electrical energy (to heat, light, motion):

$$P = IV = I^2R = \frac{V^2}{R}.$$

Pick the form that uses the quantities you know. A resistor's power all becomes heat.

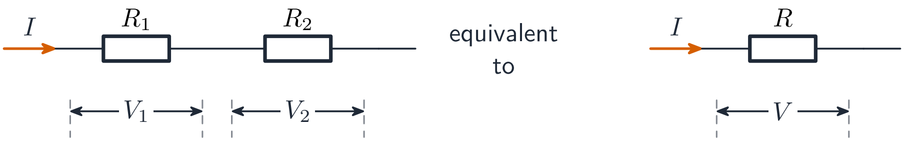
Worked example. The 6.0 Ω resistor above, carrying 2.0 A, dissipates $P = I^2R = 2.0^2 \times 6.0 = 24$ W – equivalently $P = IV = 2.0 \times 12 = 24$ W.

A **light bulb** 灯泡 is just a resistor that glows, and its **brightness** 亮度 rises with the **power** it dissipates. So to rank bulbs, compare their power. In a series string every bulb carries the same current, so by $P = I^2R$ the bulb with the **largest** resistance is brightest; wired in parallel every bulb gets the full battery voltage, so by $P = V^2/R$ the bulb with the **smallest** resistance is brightest.

High-voltage power lines: electrical power is transmitted as high voltage so current (and I^2R loss) stays low

Compound DC Circuits

Combine resistors to find an **equivalent resistance** 等效电阻:



Resistors in series add to a single equivalent resistance

- **Series:** $R_{\text{eq}} = R_1 + R_2 + \cdots$ (resistances add).
- **Parallel:** $\dfrac{1}{R_{\text{eq}}} = \dfrac{1}{R_1} + \dfrac{1}{R_2} + \cdots$ (the total is **less** than the smallest).

Reduce the network step by step to find the total current from the battery, then work back to each element.

Worked example. A 12 V battery drives a 4.0 Ω and a 12 Ω resistor in **parallel**. First combine them: $\frac{1}{R_{\text{eq}}} = \frac{1}{4} + \frac{1}{12} = \frac{4}{12} \Rightarrow R_{\text{eq}} = 3.0\ \Omega$. The total current from the battery is $I = \frac{V}{R_{\text{eq}}} = \frac{12}{3.0} = 4.0$ A, which splits so that the smaller resistor carries the larger share (3.0 A through the 4 Ω, 1.0 A through the 12 Ω).

Measuring Current and Voltage

Two meters read a circuit. An **ammeter** 电流表 measures the current at a point, so it must be wired **in series** – the current you want to measure has to flow *through* it. A **voltmeter** 电压表 measures the potential difference between two points, so it is wired **in parallel**, bridging across the component whose voltage you want.

For a meter to read the true value it must barely disturb the circuit:

- an **ideal ammeter** has **zero resistance**, so putting it in series does not reduce the current it reads;
- an **ideal voltmeter** has **infinite resistance**, so almost no current is diverted through it.

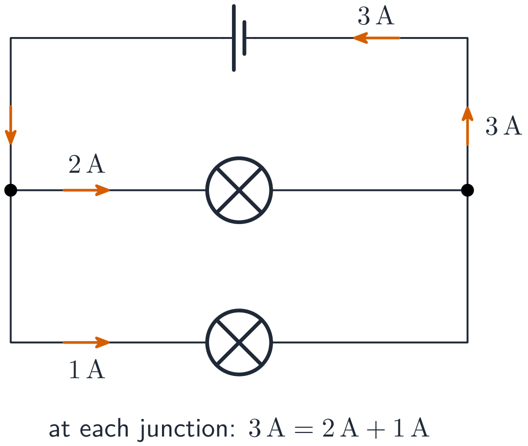
A real, **nonideal** 非理想 meter is imperfect: a real ammeter has a small resistance (it slightly lowers the current), and a real voltmeter lets a little current leak through (it slightly lowers the voltage it reads). So connecting any meter changes, a little, the very quantity it is measuring.

Kirchhoff's Loop Rule

Kirchhoff's loop rule 基尔霍夫电压定律 (energy conservation): around any closed loop, the voltage gains and drops sum to **zero**. Add the battery's emf and subtract each IR drop as you go around. This gives one equation per independent loop.

Kirchhoff's Junction Rule

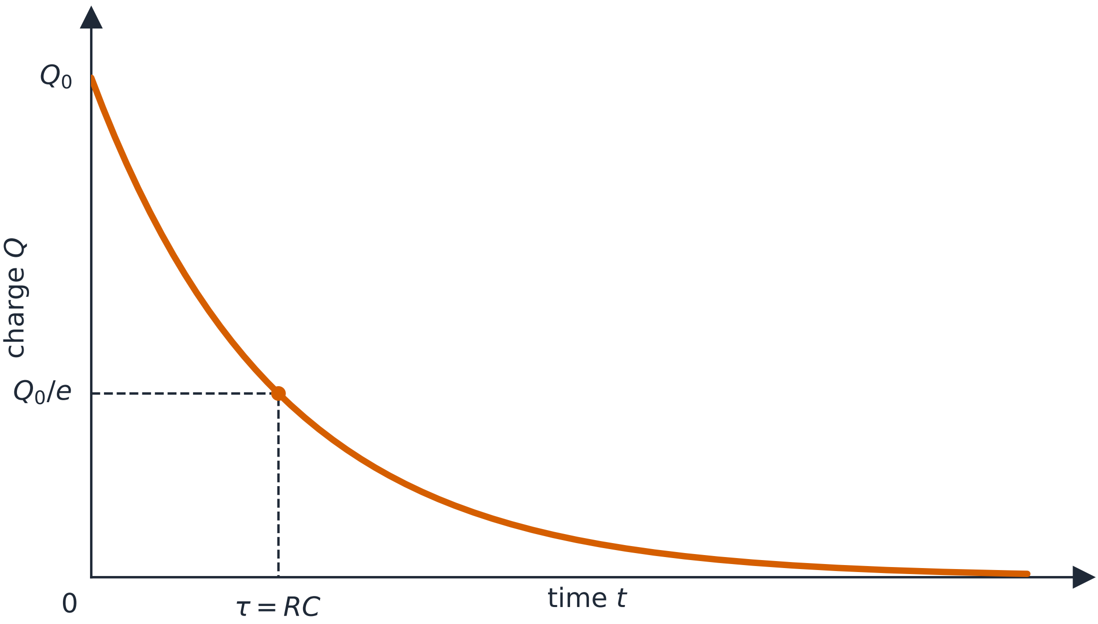
Kirchhoff's junction rule 基尔霍夫电流定律 (charge conservation): the total current **into** any junction equals the total current **out**. Together with the loop rule, it lets you solve any multi-loop circuit for its unknown currents.



Current divides at a junction: what flows in equals what flows out

RC Circuits

An **RC circuit** RC 电路 contains a resistor and a capacitor. When charging, the capacitor's voltage rises and the current falls, both **exponentially**, over a characteristic time $\tau = RC$. Key limits: at the first instant the uncharged capacitor acts like a plain wire (maximum current); after a long time it is fully charged and blocks current (acts like a break).



The charge on a capacitor decays exponentially as it discharges

Worked example. For $R = 10$ kΩ and $C = 100$ μF, the time constant is $\tau = RC = (10 \times 10^3)(100 \times 10^{-6}) = 1.0$ s. After one time constant the capacitor reaches about 63% of the supply voltage; after about 5τ it is essentially fully charged.

Exam tips

- In **series** the current is the same throughout; in **parallel** the voltage is the same across each branch — never mix these up.
- Combine resistors: series **add**; parallel $1/R_{\text{eq}} = \sum 1/R_i$ (the total is **less** than the smallest).
- Apply **Kirchhoff's rules**: junction (current in = current out, charge conserved) and loop (voltages sum to zero, energy conserved).
- Pick the power form that fits your knowns: $P = IV = I^2R = V^2/R$.
- An **ammeter** goes in **series** (ideal: zero resistance); a **voltmeter** goes in **parallel**

(ideal: infinite resistance). A real meter slightly disturbs the circuit it measures.

- A bulb is brighter when it dissipates more **power** – in series the biggest resistance (I^2R) glows brightest; in parallel the smallest (V^2/R) does.
- In an **RC circuit** the capacitor acts like a plain wire the instant it starts charging and like a break once fully charged.

Magnetism and Electromagnetism

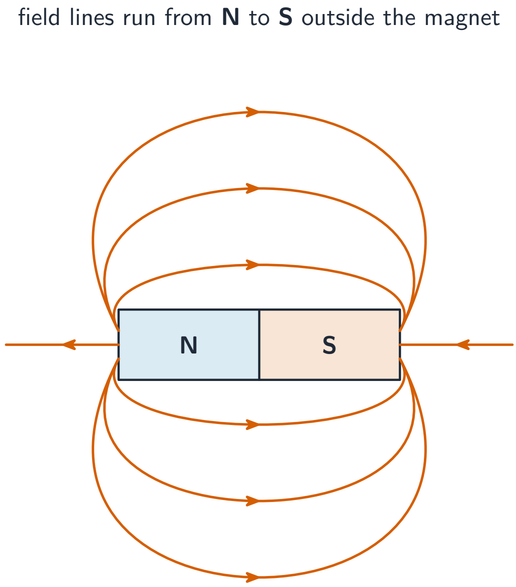
AP Physics 2

Magnetic Fields

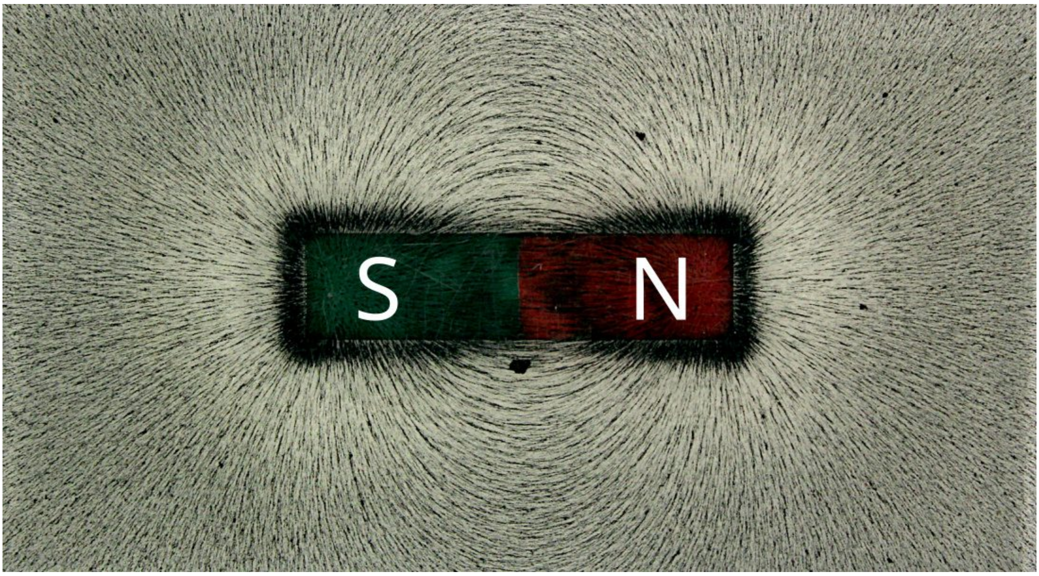
An aurora: charged particles from the Sun are steered by Earth's magnetic field toward the poles, where they hit the air and make it glow

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



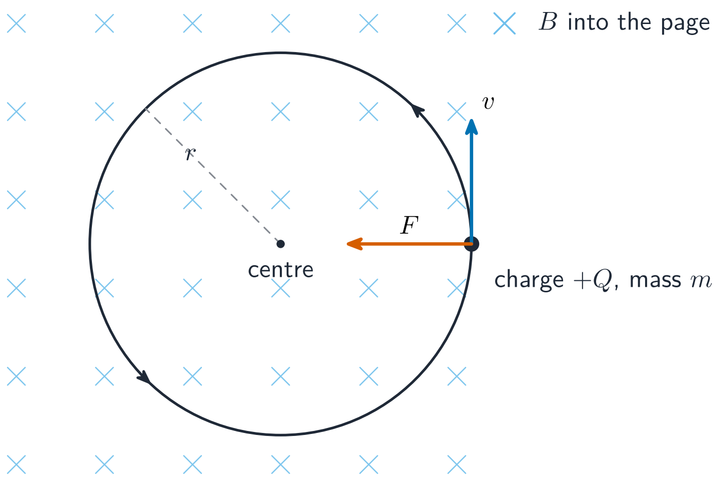
Iron filings line up along the magnetic field, making the invisible field lines of a bar magnet visible

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

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

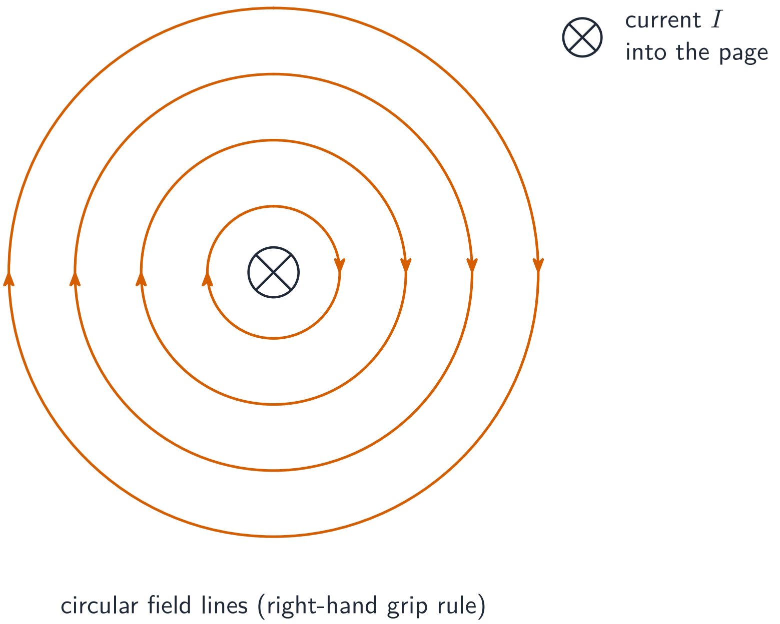
Setting $qvB = \dfrac{mv^2}{r}$ and cancelling gives that neat $r = mv/(qB)$ – the principle behind mass spectrometers.

Magnetism and Current-Carrying Wires

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

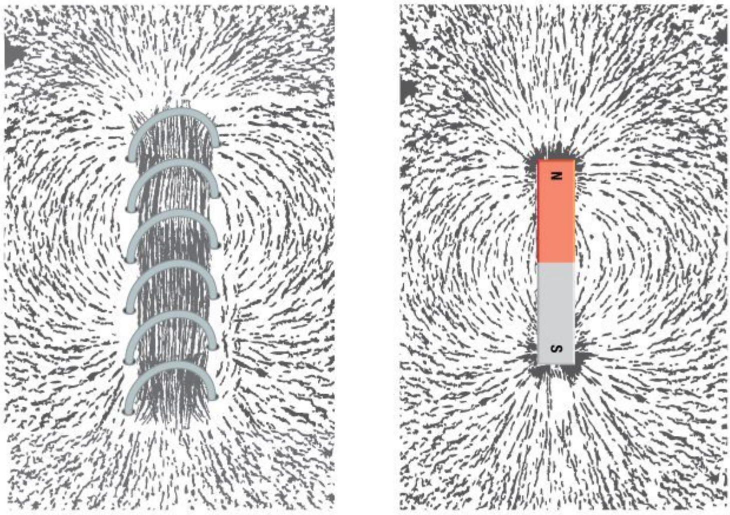
$$F = BIL\sin\theta.$$

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) (b)

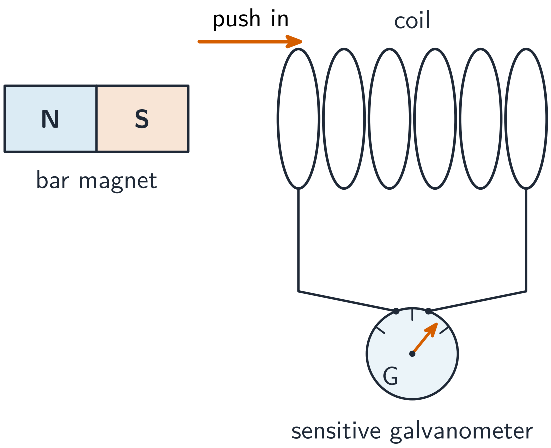
A current-carrying coil (solenoid) makes a magnetic field shaped just like a bar magnet's

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

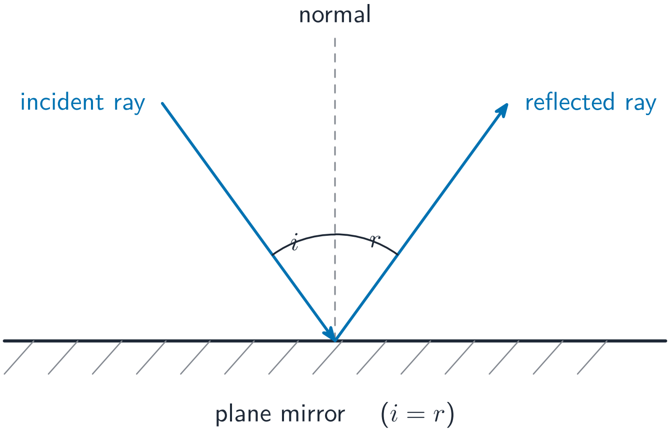
- The magnetic force $F = qvB \sin\theta$ is **perpendicular** to the velocity, so it changes direction (a circle) but not speed; a stationary charge or one moving **along** the field feels no force.
- Use $F = BIL$ for the force on a current-carrying wire (the motor effect).
- A current **creates** 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).

Geometric Optics

AP Physics 2

Reflection

Geometric optics 几何光学 treats light as straight-line rays. The **law of reflection** 反射定律: when light bounces off a surface, the **angle of incidence** 入射角 equals the **angle of reflection** 反射角, both measured from the **normal** (the line perpendicular to the surface). Smooth surfaces reflect a clear image; rough surfaces scatter the rays.



The law of reflection: the angle of incidence equals the angle of reflection

Images Formed by Mirrors

A curved mirror focuses parallel rays at its **focal point**, a distance f from the mirror. The **mirror equation** relates object and image distances:

$$\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}, \qquad m = -\frac{d_i}{d_o}.$$

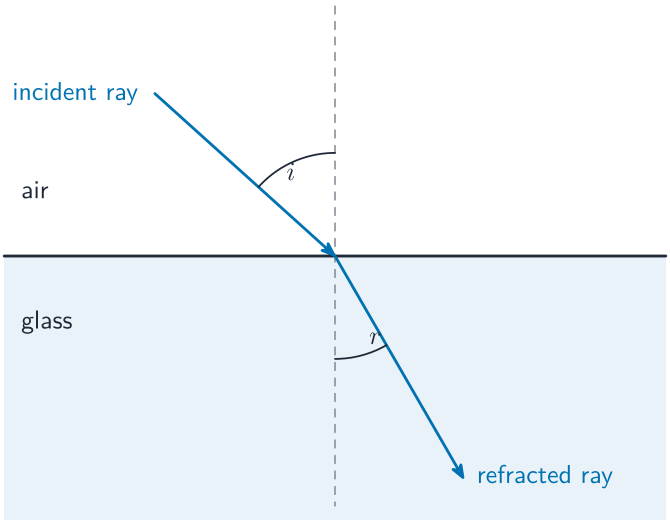
A **concave mirror** 凹面镜 (converging) can form a **real image** 实像 (rays actually meet, projectable, inverted); a **convex mirror** 凸面镜 always forms a **virtual image** 虚像 (rays only appear to meet, upright, reduced). The **magnification** m gives the image's size and orientation. Sign convention matters: a **negative** image distance means a virtual image behind the mirror or lens.

Refraction

Light bends when it passes between materials because its speed changes – **refraction** 折射. Each material has an **index of refraction** 折射率 $n = \dfrac{c}{v}$ (how much it slows light). **Snell's law** 斯涅尔定律:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2.$$

Light entering a denser medium (larger n) bends **toward** the normal. Beyond a critical angle, light going to a less-dense medium reflects entirely – **total internal reflection** 全反射, used in fibre optics.



Light refracts, bending towards the normal as it enters glass

Worked example. A ray in air ($n_1 = 1.00$) strikes water ($n_2 = 1.33$) at 40° to the normal. By Snell's law,

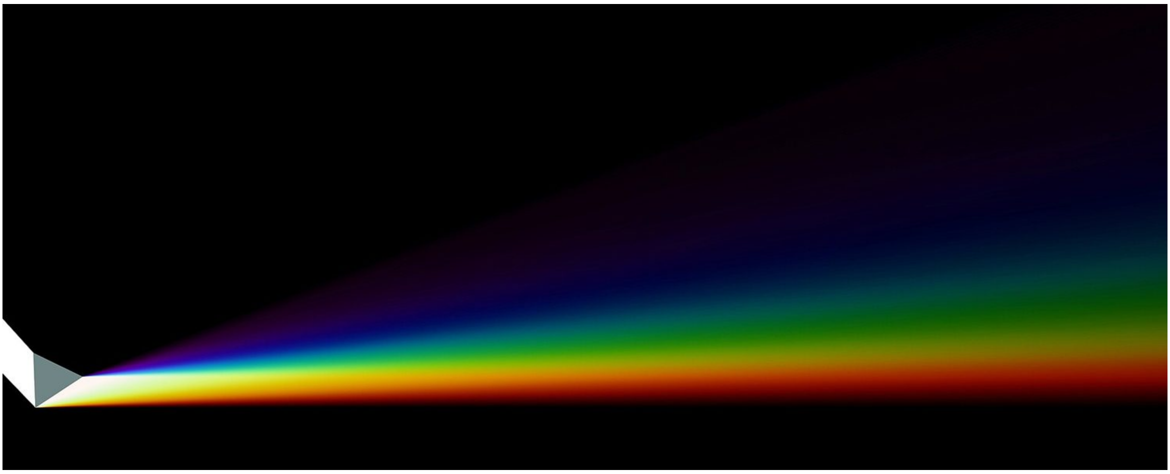
$$\sin\theta_2 = \frac{n_1}{n_2}\sin\theta_1 = \frac{1.00}{1.33}\sin 40^\circ = 0.483 \;\Rightarrow\; \theta_2 = 29^\circ.$$

The ray bends toward the normal, as expected going into the denser medium.

Worked example (critical angle). For light trying to leave glass ($n = 1.50$) for air, total internal reflection begins at the critical angle θ_c where the refracted ray grazes the surface:

$$\sin\theta_c = \frac{1}{n} = \frac{1}{1.50} = 0.667 \;\Rightarrow\; \theta_c = 42^\circ.$$

Any ray hitting the inside surface more steeply than 42° is trapped – the reason optical fibres carry light for kilometres.



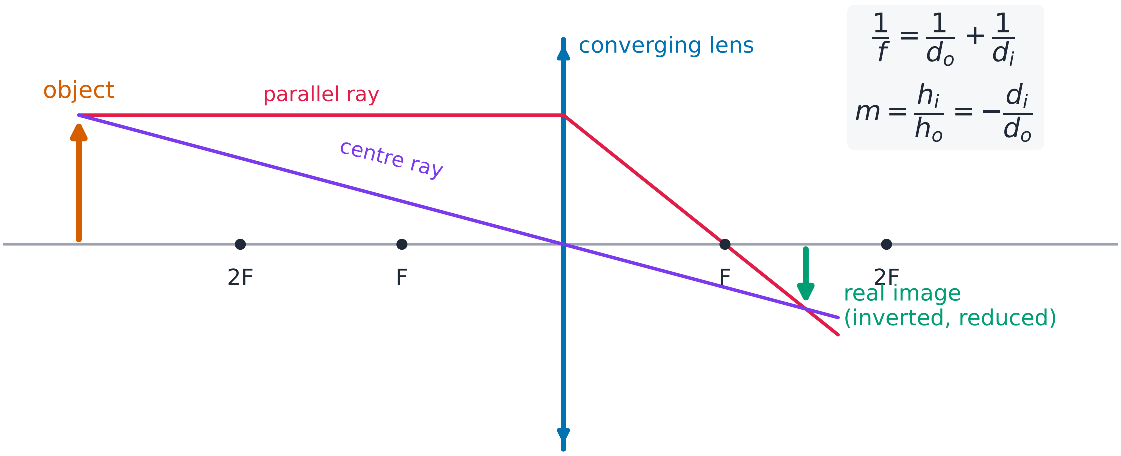
Refraction bends each colour by a different amount, so a prism spreads white light into a rainbow

Images Formed by Lenses

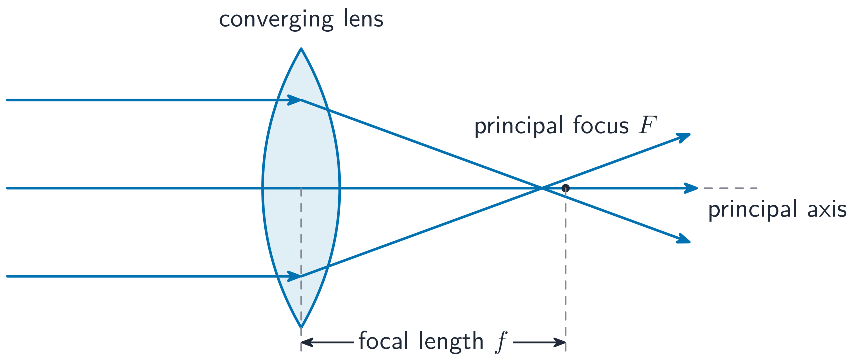
A **lens** bends light through refraction. The **thin-lens equation** has the same form as the mirror equation:

$$\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}, \qquad m = -\frac{d_i}{d_o}.$$

A **converging** 会聚 (convex) lens can form a real, inverted image or, for a close object, a virtual, upright, enlarged image (a magnifying glass). A **diverging** 发散 (concave) lens always forms a virtual, upright, reduced image. Ray diagrams locate the image quickly using two easy rays: one parallel to the axis that bends to pass through the far focus, and one straight through the centre of the lens (undeviated).



Two rays locate the image: parallel-then-focus, and straight through the centre



A converging lens brings parallel rays to its principal focus

Worked example. An object sits 30 cm from a converging lens of focal length $f = 10$ cm. Find the image. From the thin-lens equation,

$$\frac{1}{d_i} = \frac{1}{f} - \frac{1}{d_o} = \frac{1}{10} - \frac{1}{30} = \frac{2}{30} \Rightarrow d_i = 15 \text{ cm},$$

and the magnification is $m = -d_i/d_o = -15/30 = -0.5$. The image is real (positive d_i), inverted (negative m), and half the object's size – just what a camera lens does.

A convex lens forms a real, inverted image of a distant scene, exactly as the ray diagram predicts

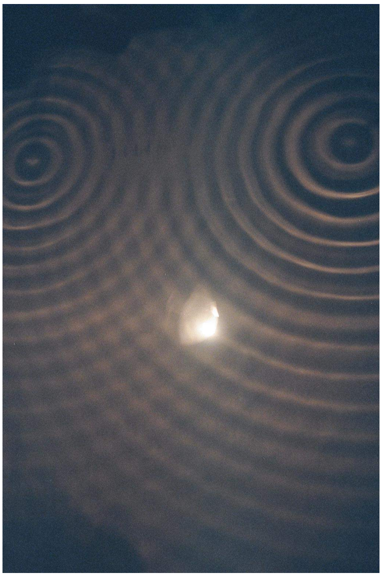
Exam tips

- Measure all angles from the **normal**, not the surface.
- Light entering a **denser** medium (larger n) bends **toward** the normal; use Snell's law $n_1 \sin\theta_1 = n_2 \sin\theta_2$.
- Total internal reflection happens only going into a **less** dense medium, beyond the critical angle ($\sin\theta_c = 1/n$).
- For mirrors and lenses use $\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}$ and $m = -d_i/d_o$: a **positive** d_i is a real image, negative is virtual.
- $n = c/v$, so a bigger index means a slower speed of light in the material.

Waves, Sound, and Physical Optics

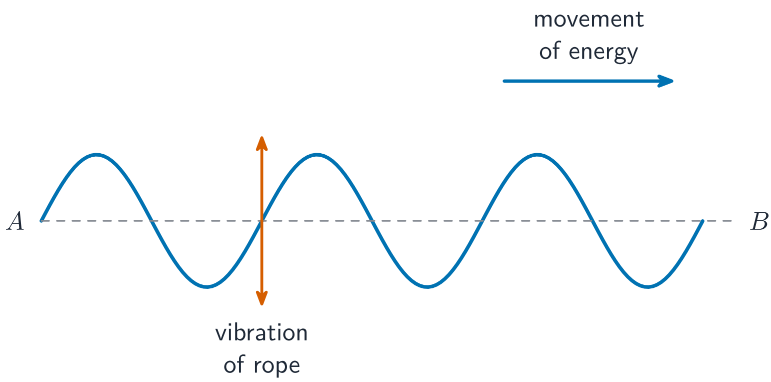
AP Physics 2

Properties of Wave Pulses and Waves



Ripple-tank interference: wave paths add constructively and destructively

A **wave** 波 carries **energy** through a medium (or space) without carrying the matter along. A single disturbance is a **pulse**; a repeating one is a wave. Two types:



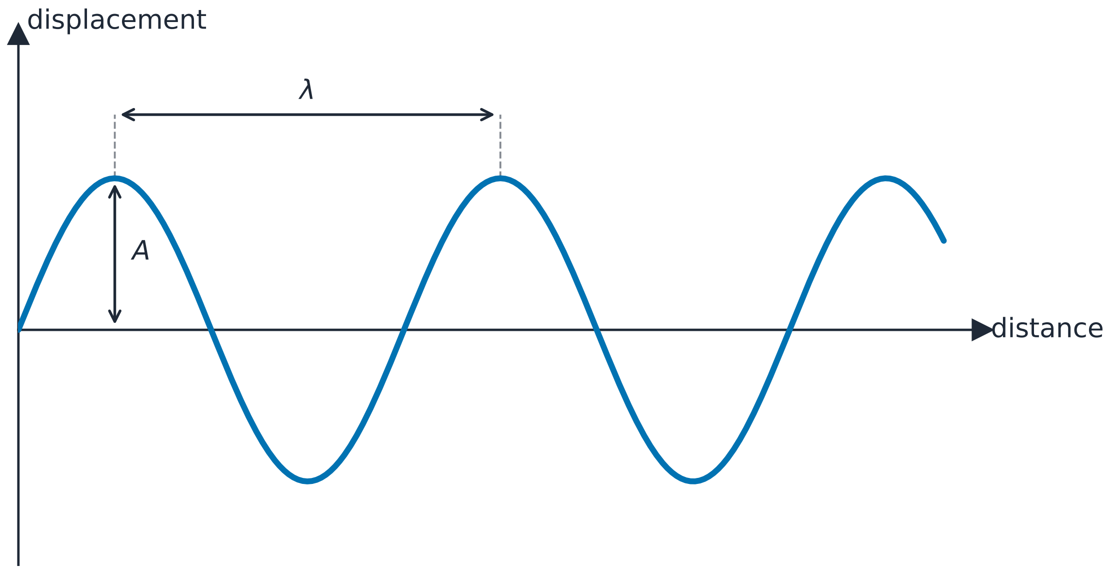
A transverse wave: the medium moves at right angles to the wave's travel

- **Transverse** 横波: the medium moves perpendicular to the wave's travel (a wave on a rope, light).

- **Longitudinal 纵波**: the medium moves along the direction of travel (sound).

Periodic Waves

A repeating wave is described by:



A displacement-distance graph shows the amplitude and wavelength

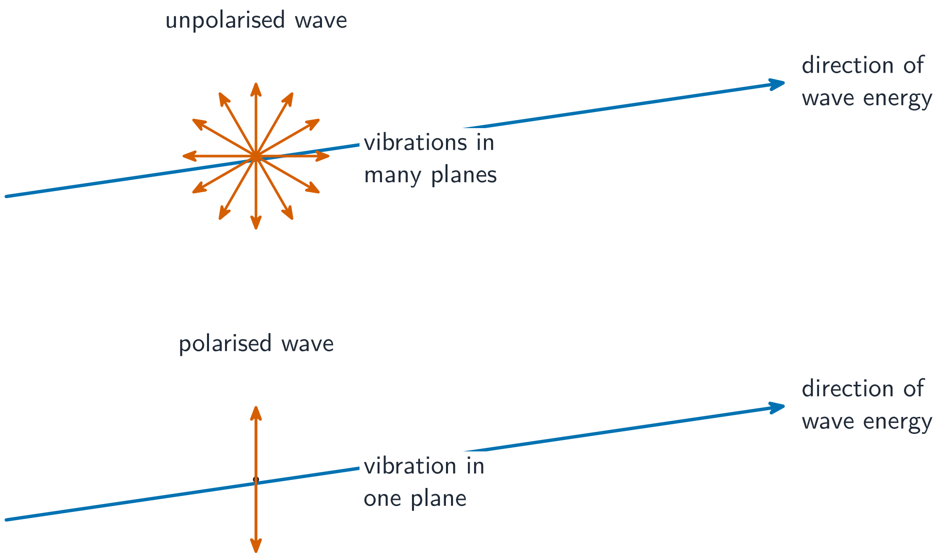
- **wavelength 波长** λ (distance between repeats),
- **frequency 频率** f (cycles per second) and **period** $T = 1/f$,
- **amplitude 振幅** A (maximum displacement – related to energy),
- **wave speed 波速** $v = f\lambda$, set by the **medium**, not the source.

Worked example. A musical note has frequency 340 Hz and the speed of sound is 340 m/s. Its wavelength is $\lambda = v/f = 340/340 = 1.0$ m. If the same note travels into water (where sound moves at ≈ 1500 m/s) the **frequency stays** 340 **Hz** but the wavelength stretches to $1500/340 \approx 4.4$ m – the source sets the frequency, the medium sets the speed and hence the wavelength.

Boundary Behavior and Polarization

At a boundary a wave partly **reflects** and partly **transmits**. Reflecting off a denser medium **inverts** the wave; off a less-dense medium it does not. **Polarization 偏振** applies to transverse waves only: a polarizer passes just one direction of oscillation, which is why polarized sunglasses cut glare.

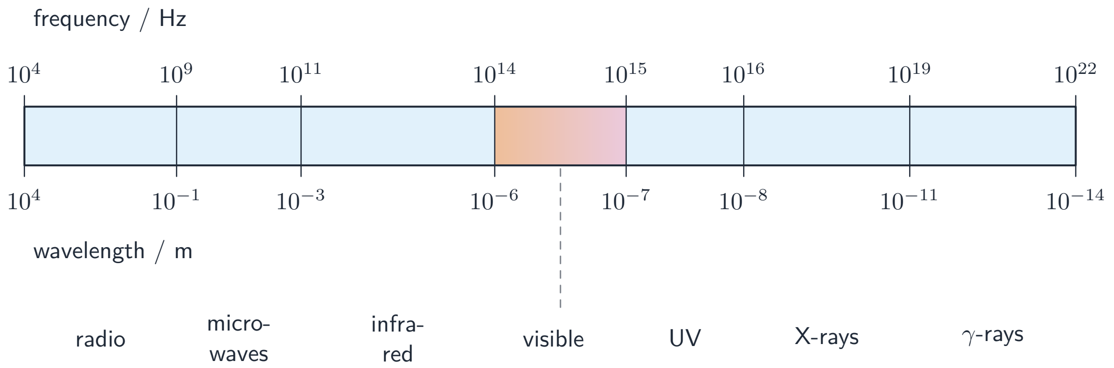
The effect of a polarizer is measured through **intensity** 强度 - the average power a wave delivers **per unit area** over one period, in W m^{-2}. Because a polarizer removes the components of the oscillation that are not aligned with it, it **reduces the wave's intensity**: unpolarized light passing a single ideal polarizer drops to **half** its intensity, and a second polarizer at an angle cuts it further. Intensity also falls with distance from a source, since the same power spreads over a larger area.



Unpolarised waves vibrate in many planes; a polarised wave vibrates in one

Electromagnetic Waves

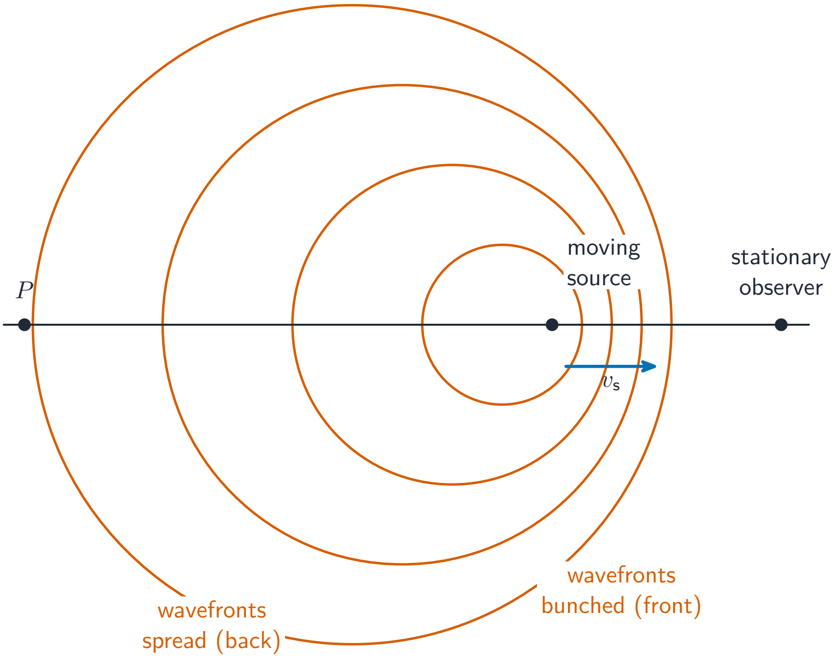
Electromagnetic waves 电磁波 are oscillating electric and magnetic fields that travel through vacuum at the speed of light c, needing no medium. They span the spectrum from radio to gamma rays; higher frequency means shorter wavelength and higher photon energy.



The electromagnetic spectrum, from radio waves to gamma rays

The Doppler Effect

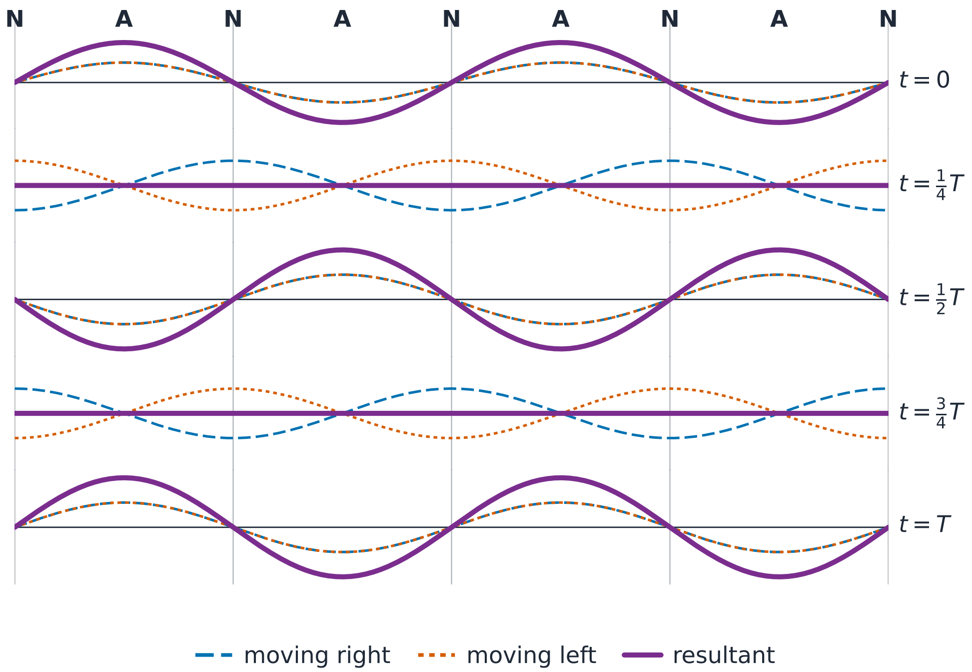
The **Doppler effect** 多普勒效应 is the change in observed frequency when a wave source and observer move relative to each other. Approaching ⇒ higher frequency (shorter wavelength); receding ⇒ lower frequency. It explains a passing siren's drop in pitch and the redshift of receding galaxies.



A moving source squashes the wavefronts ahead of it, raising the observed frequency

Wave Interference and Standing Waves

When waves overlap they **superpose** (add). **Constructive interference** 相长干涉 (crests aligned) gives a bigger wave; **destructive interference** 相消干涉 (crest on trough) cancels. Two waves travelling opposite ways in a bounded medium form a **standing wave** 驻波 with fixed **nodes** 波节 (no motion) and **antinodes** 波腹 (maximum motion) – the basis of resonance on strings and in pipes.



A standing wave forms where two waves travelling in opposite directions overlap

Worked example. A guitar string 0.65 m long is fixed at both ends. Its **fundamental** (first harmonic) fits half a wavelength between the ends, so $\lambda = 2L = 1.30$ m. If waves travel along the string at 260 m/s, the note's frequency is $f = v/\lambda = 260/1.30 = 200$ Hz. Shortening the string (a fret) raises the pitch.

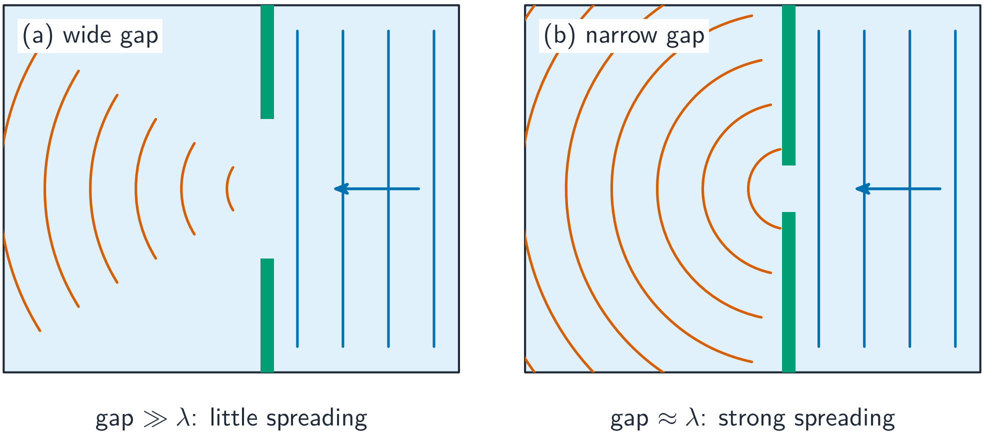
When two waves of **slightly different** frequency overlap, they drift in and out of step, so the combined sound swells loud and soft in a slow throb called **beats** 拍. The **beat frequency** 拍频 is simply the difference of the two frequencies:

$$f_{\text{beat}} = |f_1 - f_2|.$$

Two tuning forks of 256 Hz and 260 Hz sounded together give $|260 - 256| = 4$ beats each second; a musician tunes an instrument by slowing these beats towards zero against a reference note.

Diffraction

Diffraction 衍射 is the bending and spreading of waves around edges or through openings. The spreading is significant when the opening is comparable to the wavelength – so sound (long wavelength) bends around doorways easily, while light (tiny wavelength) needs a very narrow slit.



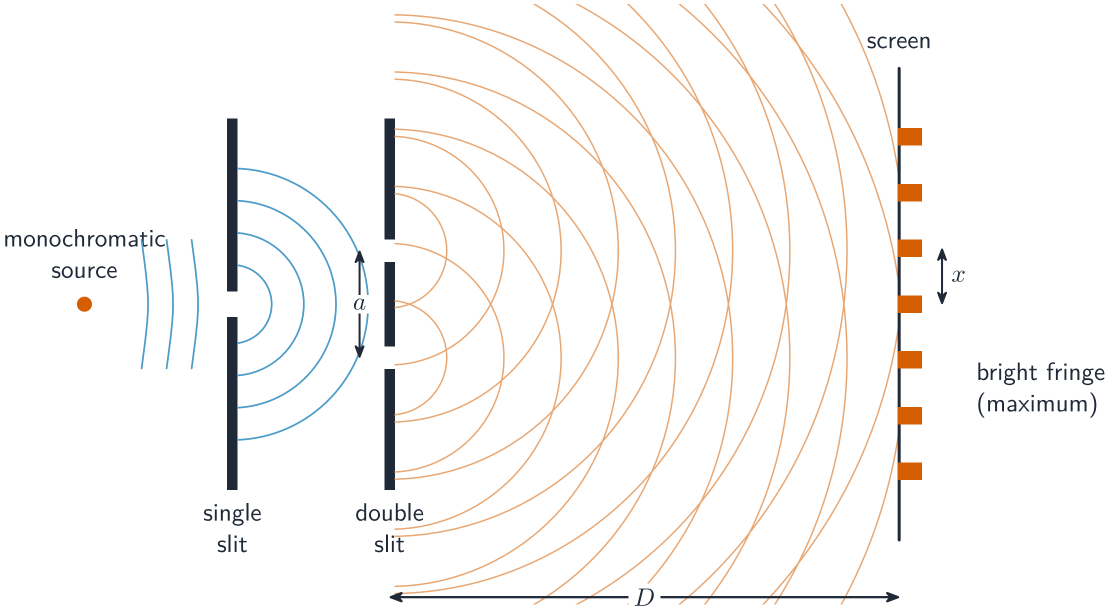
Waves spread out (diffract) as they pass through a gap

Double-Slit Interference and Diffraction Gratings

Coherent 相干 light through two closely spaced slits produces a pattern of bright and dark fringes. Bright fringes occur where the path difference is a whole number of wavelengths:

$$d\sin\theta = m\lambda.$$

A **diffraction grating** 衍射光栅 has many slits, giving sharp, widely spaced bright lines – useful for separating light into its wavelengths.

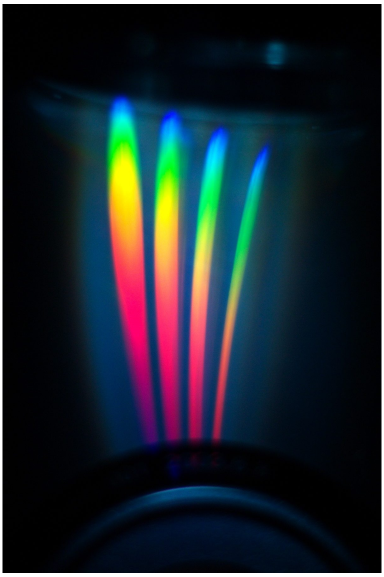


Young's double slits give an interference pattern of bright and dark fringes

Worked example. Light of wavelength 600 nm passes through two slits 0.20 mm apart. The first bright fringe ($m = 1$) sits at

$$\sin\theta = \frac{m\lambda}{d} = \frac{1 \times 600 \times 10^{-9}}{0.20 \times 10^{-3}} = 3.0 \times 10^{-3} \;\Rightarrow\; \theta = 0.17°.$$

The tiny angle is why the slits must be very close together and the screen far away to see the fringes clearly.



The fine tracks on a CD act as a diffraction grating, splitting white light into a spectrum

Thin-Film Interference

Light reflecting off the top and bottom of a **thin film** 薄膜 (soap bubble, oil slick) interferes with itself. Depending on the film's thickness and a possible half-wavelength phase flip on reflection off a denser medium, particular wavelengths interfere constructively – producing the shifting colours you see.

The same physics is put to work in an **antireflection coating** 增透膜 on camera lenses, glasses, and solar cells: a thin transparent layer whose two reflected waves interfere **destructively**, so almost no light reflects and more is transmitted. The simplest coating is one **quarter of a wavelength** thick (measured in the coating), and its refractive index sits **between** that of air and the glass beneath, so the reflected light cancels itself out.

Exam tips

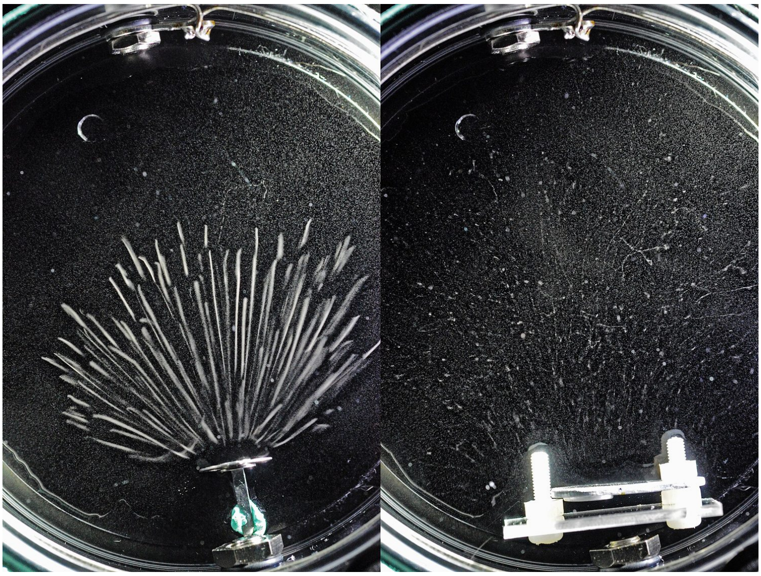
- Use $v = f\lambda$; the **source sets the frequency**, and when a wave enters a new medium the frequency stays fixed while the speed and wavelength change.
- Distinguish **transverse** (vibration perpendicular, can be polarised) from **longitudinal** (vibration along the travel, e.g. sound).
- **Constructive** interference needs a path difference of a whole number of wavelengths; **destructive** needs a half-odd number.
- On a string fixed at both ends the fundamental fits **half a wavelength** ($\lambda = 2L$).

- **Diffraction** is significant only when the gap is comparable to the wavelength — sound bends round doorways, light needs a very narrow slit.
- **Beats**: two waves of *slightly different* frequency throb at $f_{\text{beat}} = |f_1 - f_2|$ (e.g. two tuning forks; tuning to zero beats).
- An **antireflection coating** is a quarter-wavelength-thick layer (index between air and glass) whose two reflections cancel, cutting the reflected light.

Modern Physics

AP Physics 2

Quantum Theory and Wave-Particle Duality

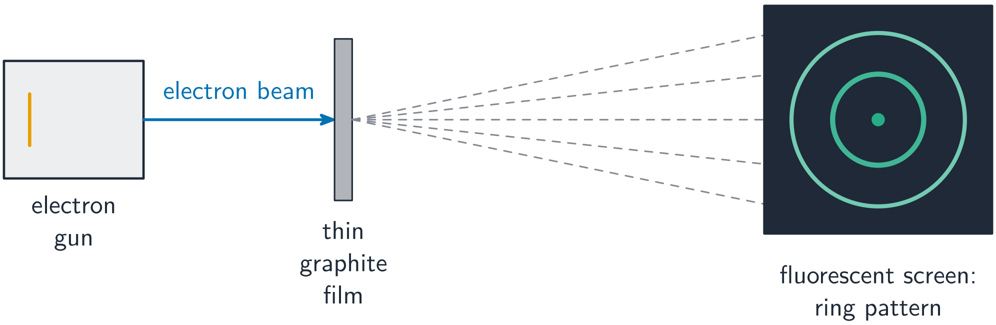


A cloud chamber: modern physics tracks charged particles from radioactive decays

At tiny scales, energy comes in discrete packets called **quanta** 量子. Light is carried by **photons** 光子, each with energy set by its frequency:

$$E = hf,$$

where h is Planck's constant. **Wave–particle duality** 波粒二象性: light and matter each show both wave behavior (interference, diffraction) and particle behavior (photons, electrons as localized hits). A particle also has a **matter wavelength** $\lambda = \frac{h}{p}$, and particles genuinely produce interference - a variation of Young's **double-slit experiment** 双缝实验 done with electrons builds up the same fringe pattern as light.



Electrons form a diffraction pattern, showing that particles have a wave nature

Worked example. Find the energy of a photon of orange light with frequency 5.0×10^{14} Hz ($h = 6.63 \times 10^{-34}$ J s): $E = hf = 6.63 \times 10^{-34} \times 5.0 \times 10^{14} = 3.3 \times 10^{-19}$ J, which is about 2.1 eV (dividing by 1.6×10^{-19}). Visible-light photons carry a few electronvolts – just right to trigger the chemistry of vision and photosynthesis.

The Bohr Model of Atomic Structure

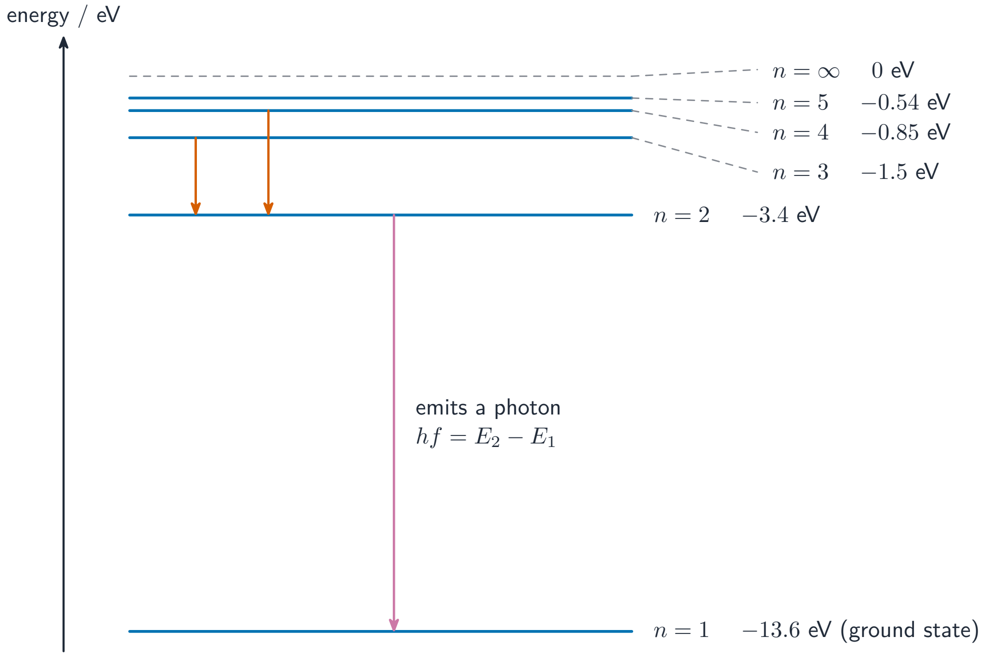
The **Bohr model** 玻尔模型 pictures electrons orbiting the nucleus only in certain allowed **energy levels** 能级. An electron can jump between levels only by absorbing or emitting a photon whose energy exactly matches the gap:

$$E_{\text{photon}} = |E_{\text{final}} - E_{\text{initial}}|.$$

Because the levels are discrete, only specific photon energies are allowed.

Emission and Absorption Spectra

- An **emission spectrum** 发射光谱 is the set of bright lines given off when electrons drop to lower levels – each line a specific wavelength.
- An **absorption spectrum** 吸收光谱 is the set of dark lines where those same wavelengths are absorbed from a continuous source.



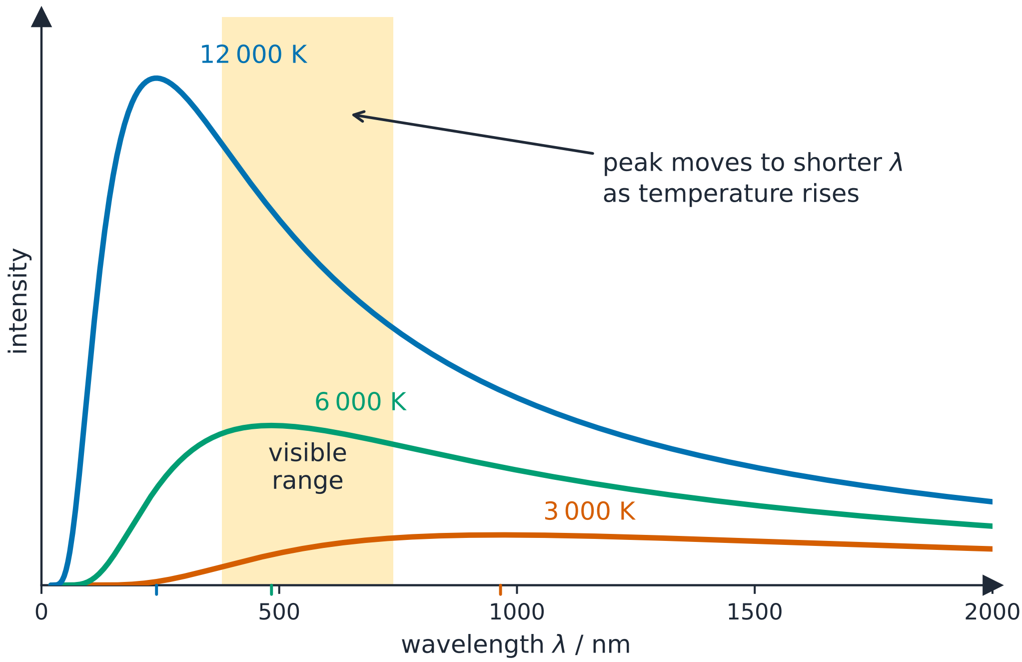
The discrete energy levels of hydrogen produce a line spectrum

The line pattern is a **fingerprint** of the element, since every element has its own energy levels.

Hydrogen's emission spectrum: each bright line is light from an electron dropping between fixed energy levels

Blackbody Radiation

A **blackbody** 黑体 emits a continuous spectrum that depends only on its temperature. Hotter objects glow brighter and peak at **shorter** wavelengths (red-hot to white-hot to blue-hot). Explaining this spectrum required quantized energy – a founding problem of quantum theory.



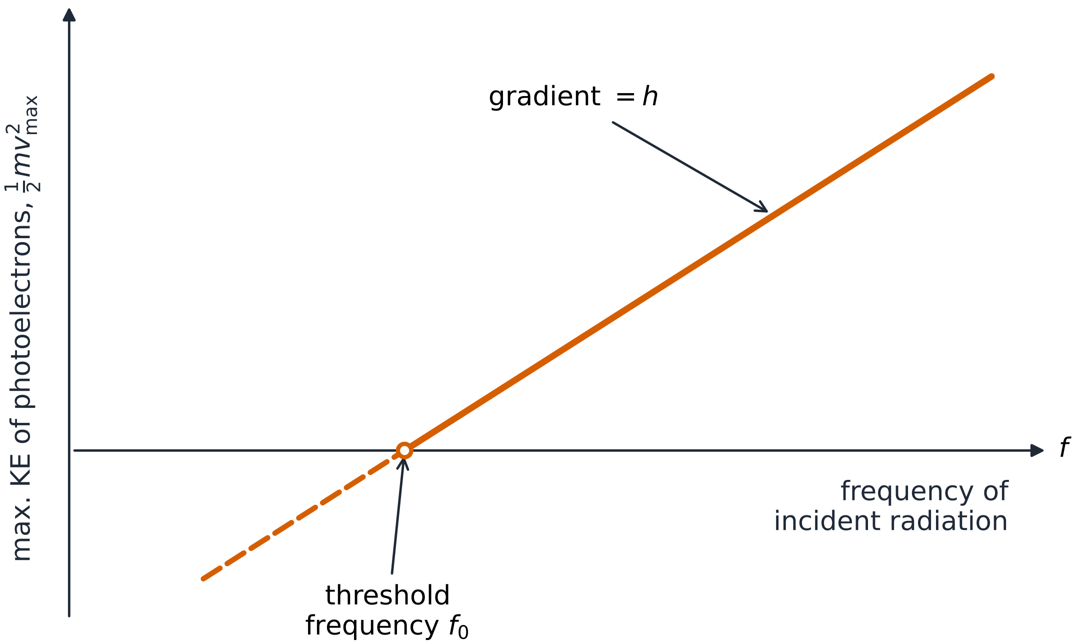
A hotter black body radiates more, and its peak shifts to shorter wavelengths

The Photoelectric Effect

Shining light on a metal can eject electrons – the **photoelectric effect** 光电效应. Key facts (which only the photon picture explains): electrons come out only if the photon's frequency exceeds a threshold, no matter how bright a dimmer, lower-frequency light is. Energy conservation gives

$$K_{\max} = hf - \phi,$$

where ϕ is the metal's **work function** 逸出功 (the energy to free an electron).



The maximum kinetic energy of photoelectrons rises linearly with frequency

Worked example. Light of frequency 8.0×10^{14} Hz falls on a metal with work function $\phi = 3.0 \times 10^{-19}$ J. The most energetic electrons come off with

$$K_{\max} = hf - \phi = (6.63 \times 10^{-34} \times 8.0 \times 10^{14}) - 3.0 \times 10^{-19} = 5.3 \times 10^{-19} - 3.0 \times 10^{-19} = 2.3 \times 10^{-19} \text{ J}.$$

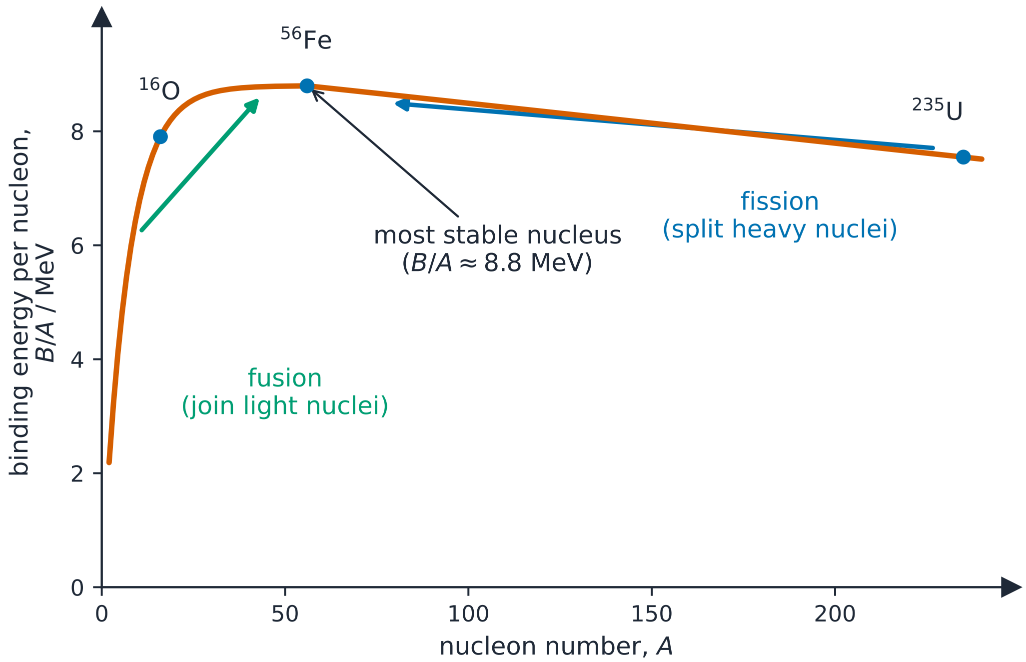
Below the threshold frequency ϕ/h, $K_{\max}$ would be negative – meaning no electrons escape at all, however bright the light.

Compton Scattering

In **Compton scattering** 康普顿散射, a photon collides with an electron like two particles, transferring some energy and momentum. The scattered photon comes out with **less energy** (longer wavelength). This is direct evidence that photons carry momentum and behave as particles.

Fission, Fusion, and Nuclear Decay

The **nucleus** 原子核 stores enormous energy. **Fission** 裂变 splits a heavy nucleus into lighter ones, releasing energy (nuclear reactors, bombs). **Fusion** 聚变 joins light nuclei into a heavier one (the Sun's power). Both release energy because the products have slightly **less mass**, converted by $E = mc^2$.



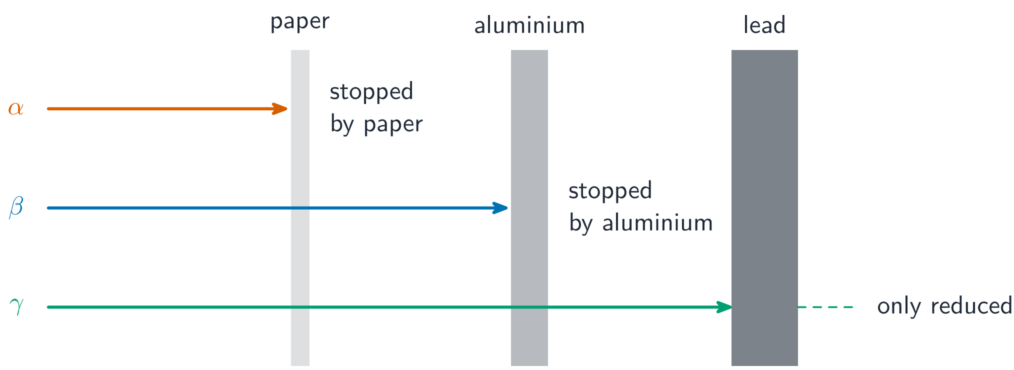
Binding energy per nucleon peaks near iron, so both fusion and fission can release energy

Worked example. Even a tiny mass converts to a huge energy. If a nuclear reaction loses 1.0×10^{-3} kg of mass, it releases $E = mc^2 = 1.0 \times 10^{-3} \times (3.0 \times 10^8)^2 = 9.0 \times 10^{13}$ J – roughly the energy of 20 000 tonnes of TNT.

A nuclear power station: fission of heavy nuclei releases the energy that drives the plant

Types of Radioactive Decay

Unstable nuclei undergo **radioactive decay** 放射性衰变, emitting:



The penetrating power of alpha, beta, and gamma radiation

- **Alpha decay** 阿尔法衰变 (α): a helium nucleus – mass number drops by 4.
- **Beta decay** 贝塔衰变 (β) comes in two kinds. In **beta-minus** (β^-) a neutron becomes a proton, emitting an electron and an **antineutrino** 反中微子: $n \to p + e^- + \bar{\nu}$. In **beta-plus** ($\beta^+$) a proton becomes a neutron, emitting a **positron** 正电子 and a **neutrino** 中微子: $p \to n + e^+ + \nu$.
- **Gamma decay** 伽马衰变 (γ): a high-energy photon – the nucleus sheds excess energy.

The neutrino and antineutrino (symbols ν, $\bar{\nu}$) are tiny, chargeless, almost-massless particles that carry off energy and keep beta decay balanced. Decay is random, but a sample halves every **half-life 半衰期**: after each half-life, half of the remaining nuclei have decayed. Every decay equation conserves three quantities: **nucleon number** (mass number), **charge**, and **lepton number 轻子数** – an electron or neutrino counts as $+1$ lepton, a positron or antineutrino as -1, and the totals must match on both sides.

Worked example. A radioactive sample has a half-life of 8.0 days. What fraction is left after 24 days? That is $24/8.0 = 3$ half-lives, so the fraction remaining is $\left(\frac{1}{2}\right)^3 = \frac{1}{8}$ – about 12.5%. In an alpha decay of uranium-238 ($^{238}_{92}\mathrm{U}$), the daughter has mass number $238 - 4 = 234$ and atomic number $92 - 2 = 90$: thorium-234.

Exam tips

- Photon energy is $E = hf$; below the **threshold frequency** no electrons are emitted **however bright** the light (the photoelectric effect).
- Use $K_{\max} = hf - \phi$ for the fastest photoelectrons (ϕ = work function).
- Electrons jump between **discrete energy levels** by absorbing/emitting a photon whose energy equals the level gap — the source of line spectra.
- In fission and fusion the small **mass lost** becomes energy via $E = mc^2$.
- Balance decay equations by conserving **mass number, charge, and lepton number** (write the antineutrino in β^-, the neutrino in β^+), and halve the sample every **half-life** ($(\frac{1}{2})^n$ after n half-lives).