Course Companion

IGCSE Physics

Every topic handout in one volume

全部专题讲义合集

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Contents 目录

1. Motion, forces and energy 2

2. Thermal physics 26

3. Waves 39

4. Electricity and magnetism 55

5. Nuclear physics 82

6. Space physics 96

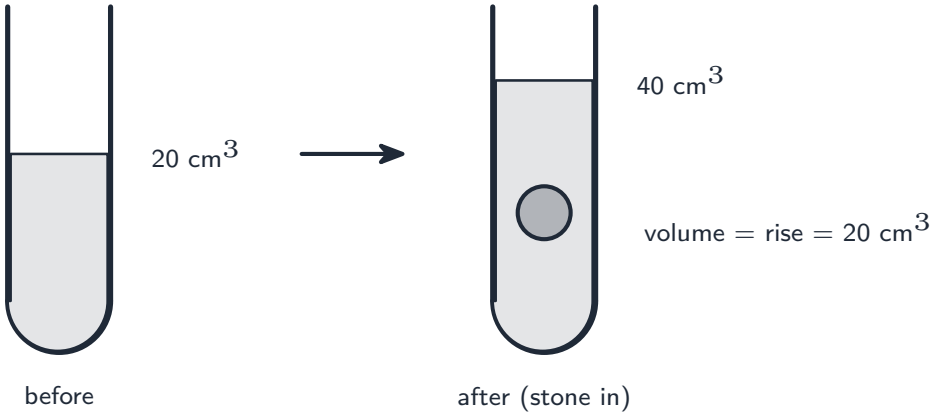
Motion, forces and energy

IGCSE Physics

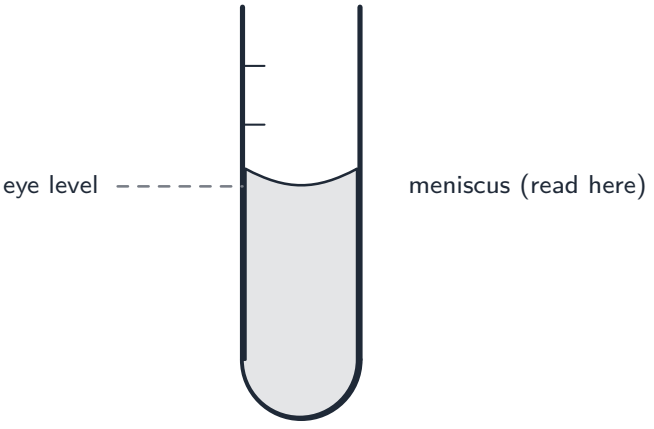
Measurement 测量

■ Length and volume

Use a **ruler** 直尺 to measure length. Read the scale with your eye straight in front of the mark to avoid a reading error.



The water an irregular solid pushes up gives its volume



Read a measuring cylinder at the bottom of the meniscus, with your eye level

Use a **measuring cylinder** 量筒 to measure the volume of a liquid. Read the scale at the bottom of the curved surface (the **meniscus** 弯月面), with your eye level with

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it.

■ Measuring time

Use a **stopwatch** 秒表 or a **digital timer** 数字计时器 to measure a time interval. A clock is fine for long times (minutes or hours). Starting and stopping by hand introduces **reaction time** 反应时间 error; its size depends on the operator and method. To make this error matter less, time a long interval, or time many repeats and divide (see below).

■ Measuring small amounts

A single small length or a short time is hard to measure well. The trick is to **measure many and divide** 测多个再相除:

- To find the average thickness of one sheet, measure a stack of 100 sheets and divide by 100. Count sheets, not printed page numbers.
- To find the time for one swing of a **pendulum** 摆, measure the time for 20 swings and divide by 20. The time for one complete oscillation is called the **period** 周期.

This reduces the effect of a fixed reading or timing **uncertainty** 不确定度 on the average value. It does not remove systematic errors or a miscount.

Worked measurement comparison. A stack of 100 sheets without covers is 10.0 mm thick. Count the sheets, align the stack, avoid gaps or uneven compression, and read at eye level. The thickness is an average, not a precise measurement of every sheet.

$$\text{mean thickness} = \frac{\text{stack thickness}}{N} = \frac{10.0\ \text{mm}}{100} = 0.100\ \text{mm}$$

Three timings of 20 complete pendulum oscillations are 31.8 s, 32.2 s and 32.0 s. Start and finish at a marked position with the pendulum moving in the same direction; count complete cycles.

$$\text{mean time} = \frac{t_1 + t_2 + t_3}{3} = \frac{31.8\ \text{s} + 32.2\ \text{s} + 32.0\ \text{s}}{3} = 32.0\ \text{s}$$

$$T = \frac{\text{mean time}}{N} = \frac{32.0\ \text{s}}{20} = 1.60\ \text{s}$$

Timing multiples reduces the effect of a similar start/stop error per oscillation; repeated trials help check consistency. Neither corrects a wrong cycle count.

■ Practical skills: readings, results and graphs

The practical paper rewards the same few habits in every experiment:

- **Read at eye level.** Looking at a scale from above or below gives a **parallax** 视差 error. Put your eye level with the pointer, the liquid surface or the mark.

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- **Check for a zero error.** A **zero error** 零点误差 is a reading the instrument gives when it should read zero, such as a newton meter showing 0.2 N with nothing on it. Subtract it from every reading, or reset the instrument to zero first.
- **Record to the instrument's precision.** A ruler marked in millimetres gives readings such as 23 mm, or 2.3 cm. Give every value in a column to the same number of decimal places, and put the unit in the column heading, for example *extension / mm*.
- **Repeat and spot anomalies.** An **anomalous result** 异常值 does not fit the pattern of the others. Repeat that reading, and leave it out when you calculate a mean.
- **Draw a line of best fit.** A **line of best fit** 最佳拟合线 is one smooth straight line (or curve) with the points spread evenly on both sides; never join the points dot to dot. To find its gradient, use a triangle that covers more than half of the line.

Worked example. A student hangs loads on a spring and measures its extension with a millimetre ruler.

load / N	**0**	**1.0**	**2.0**	**3.0**	**4.0**	**5.0**
extension / mm	0	8	16	29	32	40

(a) *Identify the anomalous result.* The extension goes up by 8 mm for each extra 1.0 N, except at 3.0 N: 29 mm instead of the expected 24 mm.

(b) *Find the gradient of the line of best fit.* The line through the other points passes through (0, 0) and (5.0 N, 40 mm), so the gradient is $\frac{40\text{ mm}}{5.0\text{ N}} = 8.0\text{ mm/N}$.

(c) *Suggest one precaution.* Fix a pointer to the bottom of the spring and read the ruler with the eye level with the pointer, to avoid parallax error. Check that the spring returns to its original length after the loads are removed: if it does not, it has gone past its limit of proportionality.

■ Scalars and vectors

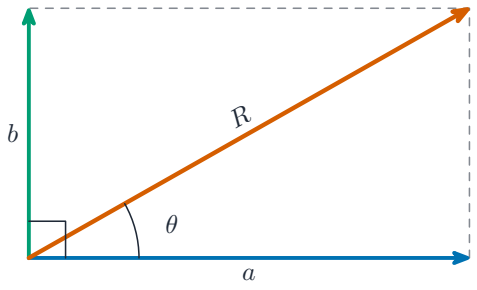
A **scalar quantity** 标量 has size (**magnitude** 大小) only. A **vector quantity** 矢量 has size **and** direction.

- Scalars: distance, speed, time, mass 质量, energy 能量, temperature 温度.
- Vectors: force 力, weight 重力, velocity 速度, acceleration 加速度, momentum 动量, **electric field strength** 电场强度, **gravitational field strength** 重力场强度.

To add two vectors at right angles (90°), draw them as two sides of a rectangle. The **resultant** 合矢量 is the diagonal. Find its size with Pythagoras and its direction with trigonometry.

$$R = \sqrt{a^2 + b^2}$$

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$R = \sqrt{a^2 + b^2}$

Two vectors at right angles add to a resultant R, the diagonal of the rectangle

Motion 运动

■ Speed and velocity

Speed 速率 is the distance travelled per unit time.

$$v = \frac{s}{t}$$

Velocity is speed in a stated direction. So velocity is a vector but speed is a scalar.

$$\text{average speed} = \frac{\text{total distance}}{\text{total time}}$$

> **Worked example.** A cyclist rides 3.6 km to school. The ride takes 10 minutes, plus 2 minutes waiting at traffic lights. Find the average speed in m/s.

Change to SI units first: 3.6 km = 3600 m and 12 min = $12 \times 60 = 720$ s. The waiting time counts, because it is part of the total time.

$$\text{average speed} = \frac{3600 \text{ m}}{720 \text{ s}} = 5.0 \text{ m/s}$$

■ Acceleration

Acceleration is the change in velocity per unit time.

$$a = \frac{\Delta v}{\Delta t}$$

Here Δv means "the change in velocity". A **deceleration** 减速 reduces speed: the acceleration is opposite to the velocity. Its sign depends on the chosen positive direction.

> **Worked example.** A car speeds up from 8 m/s to 20 m/s in 4.0 s. Find its acceleration.

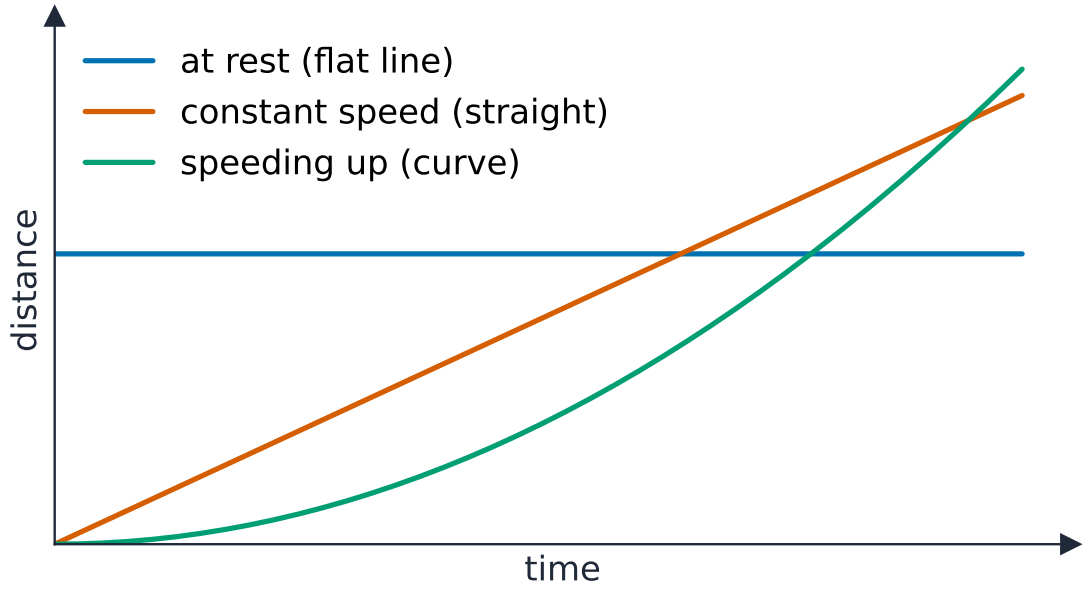
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$$a = \frac{\Delta v}{\Delta t} = \frac{20 - 8}{4.0} = 3.0 \text{ m/s}^2$$

Motion graphs

A **distance–time graph** 距离-时间图 shows how far an object has gone:

- A flat (horizontal) line means the object is **at rest** 静止.
- A straight slope means constant speed. The **gradient** 斜率 (steepness) is the speed.
- A curve that gets steeper means the object is speeding up.

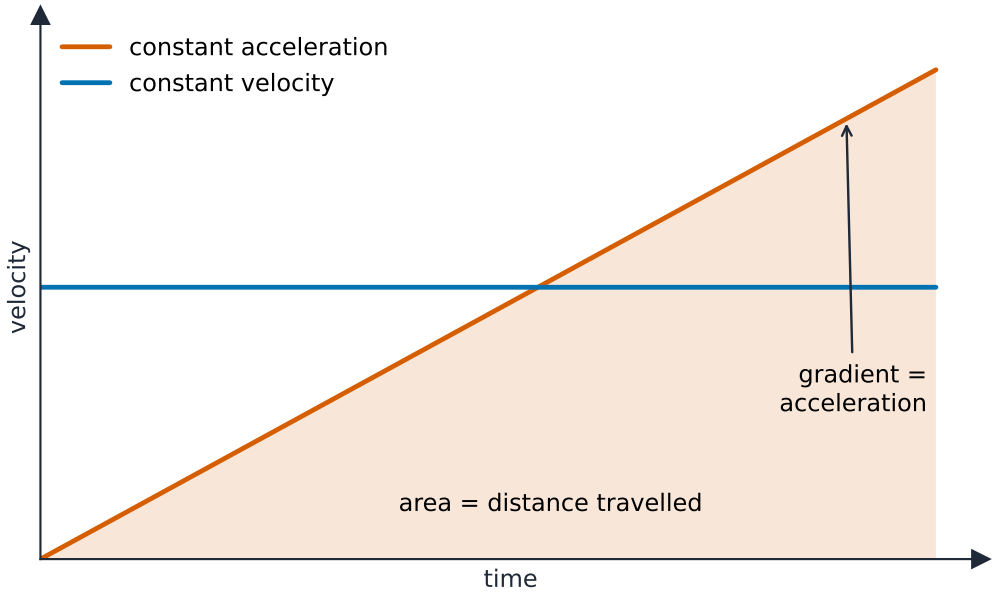


The shape of a distance–time line: flat is at rest, a straight slope is constant speed, a rising curve is speeding up

A **speed–time graph** 速度-时间图 shows how fast an object is going:

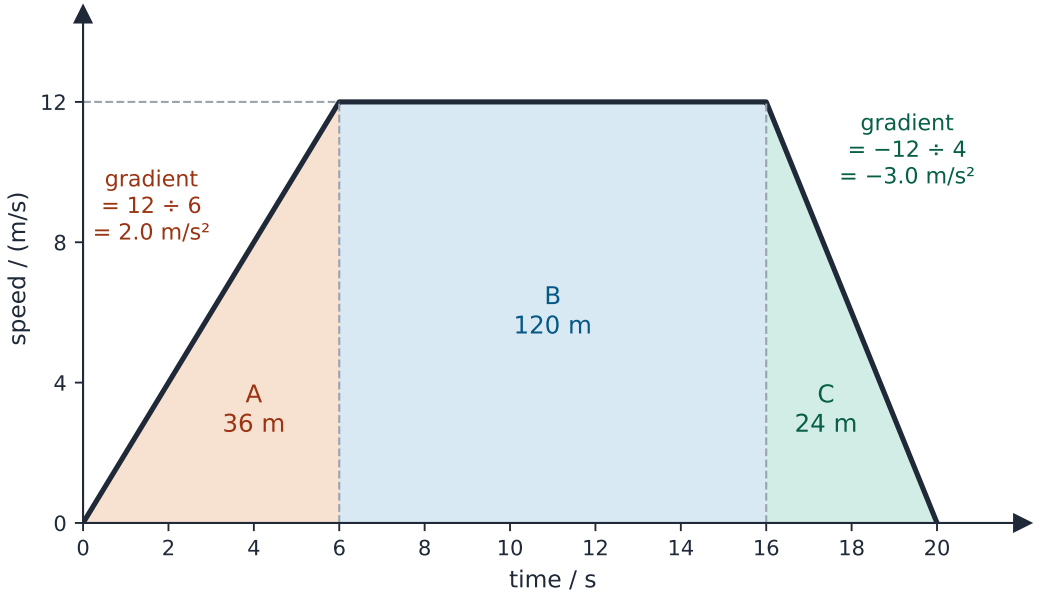
- A flat line means constant speed.
- A straight slope means constant acceleration. The gradient is the acceleration.
- The **area under the line** 线下面积 is the distance travelled.

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On a velocity–time graph the gradient is the acceleration and the area under the line is the distance travelled

Worked example (reading a graph). The graph shows a bus moving between two stops. Find (a) the acceleration in the first 6 s, (b) the acceleration in the last 4 s, (c) the distance between the stops and (d) the average speed.



Split the area into a triangle, a rectangle and a triangle, and add the three parts

(a) Gradient of the first part: $a = \dfrac{12 - 0}{6 - 0} = 2.0\ \text{m/s}^2$.

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(b) Gradient of the last part: $a = \dfrac{0-12}{20-16} = -3.0\ \text{m/s}^2$. The minus sign shows the bus is slowing down: a deceleration of 3.0 m/s^2.

(c) Distance = total area under the line:

$$\text{A} = \tfrac{1}{2} \times 6 \times 12 = 36\ \text{m} \qquad \text{B} = 10 \times 12 = 120\ \text{m} \qquad \text{C} = \tfrac{1}{2} \times 4 \times 12 = 24\ \text{m}$$

$$\text{distance} = 36 + 120 + 24 = 180\ \text{m}$$

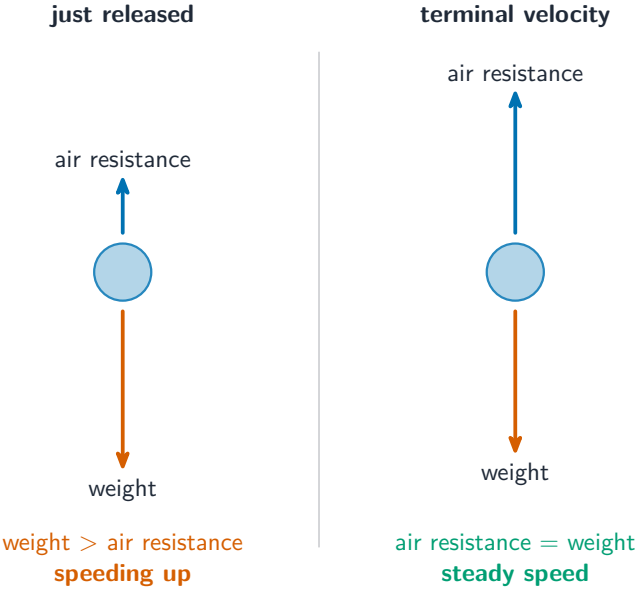
(d) Average speed $= \dfrac{180\ \text{m}}{20\ \text{s}} = 9.0\ \text{m/s}$. This is less than the top speed of 12 m/s, because the bus is slower while it speeds up and slows down.

Read the time for each part from the time axis: part B lasts $16 - 6 = 10$ s, not 16 s.

■ Falling objects

Near the Earth the gravitational field is **uniform** 均匀 (the same strength everywhere), so objects in free fall have the same acceleration when air resistance is negligible. This is the **acceleration of free fall** 自由落体加速度, $g \approx 9.8\ \text{m/s}^2$.

When an object falls through air, **air resistance** 空气阻力 (a drag force) acts upward. As it speeds up, air resistance grows. When air resistance equals the weight, the resultant force is zero and the object stops speeding up. It then falls at a steady **terminal velocity** 收尾速度.



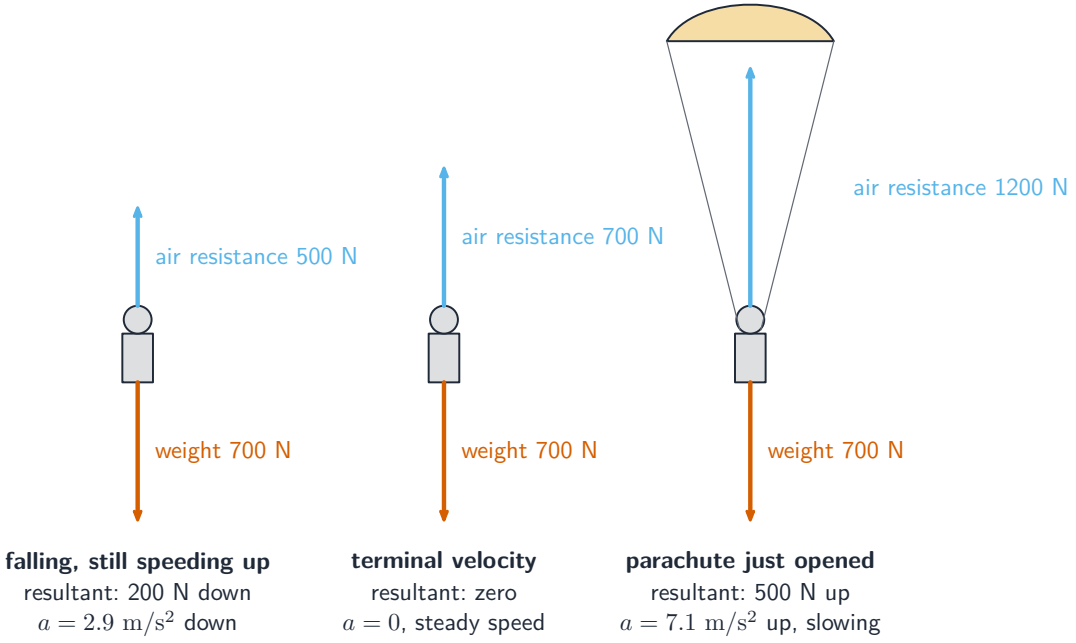
At first the weight is bigger than the air resistance, so the object speeds up; at terminal velocity the two are equal and the speed is steady

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Worked example. A skydiver of mass 70 kg falls through the air ($g = 10$ N/kg, so the weight is 700 N).

- When the air resistance is 500 N: resultant force $= 700 - 500 = 200$ N downwards, so $a = \dfrac{F}{m} = \dfrac{200}{70} = 2.9$ m/s^2 downwards. The skydiver is still speeding up, but less quickly than at the start.
- At terminal velocity the air resistance is 700 N, equal to the weight. Resultant force $= 0$, so $a = 0$.
- The parachute opens and the air resistance jumps to 1200 N. Resultant force $= 1200 - 700 = 500$ N **upwards**, so $a = \dfrac{500}{70} = 7.1$ m/s^2 upwards. The skydiver is still moving down but slows down, until the air resistance falls back to 700 N at a new, lower terminal velocity.

An upward resultant force does not make the skydiver go up. It makes the downward speed get smaller.



Arrows drawn to scale: the weight stays 700 N while the air resistance changes, so the resultant force changes

Mass and weight

Mass is the amount of **matter** 物质 in an object. It is measured in kilograms (kg) and does not change when you move the object.

Weight is the force of gravity on a mass. It is measured in newtons (N). Weight can

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change: it is smaller on the Moon because the Moon's gravity is weaker.

Gravitational field strength is the force per unit mass:

$$g = \frac{W}{m}$$

This g has the same value as the acceleration of free fall (≈ 9.8 N/kg).

> **Worked example.** An astronaut has a mass of 60 kg. Find the weight on the Earth ($g = 9.8$ N/kg) and on the Moon ($g = 1.6$ N/kg).

$$W_{\text{Earth}} = mg = 60 \times 9.8 = 590 \text{ N} \qquad W_{\text{Moon}} = 60 \times 1.6 = 96 \text{ N}$$

The mass is 60 kg in both places. Only the weight changes. You can compare masses with a **balance** 天平.



A laboratory balance measures mass; weight is the gravitational force on that mass

Density 密度

Density is the mass per unit volume.

$$\rho = \frac{m}{V}$$

The symbol ρ is the Greek letter "rho". The unit is kg/m^3 or g/cm^3.

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To find density: measure the mass with a balance, find the volume, then divide.

- **Regular solid** 规则固体 (like a box): measure the sides and calculate the volume.
- **Irregular solid** 不规则固体 (a strange shape): lower it into water in a measuring cylinder. The rise in water level is its volume. This is the **displacement method** 排水法.
- **Liquid**: put an empty measuring cylinder on the balance and read its mass. Pour in the liquid, read the volume on the cylinder, and read the mass again. The mass of the liquid is the difference between the two mass readings.

An object **floats** 漂浮 if its density is less than the density of the liquid. It sinks if its density is greater. In the same way, one liquid floats on top of another (if the two do not mix) when its density is lower: oil floats on water.

> **Worked example.** A stone of mass 54 g is lowered into a measuring cylinder. The water level rises from 20 cm^3 to 40 cm^3. Find the density of the stone.

The volume of the stone is the rise in water level, $40 - 20 = 20$ cm^3, so

$$\rho = \frac{m}{V} = \frac{54}{20} = 2.7 \text{ g/cm}^3$$



An iceberg floats with most of its volume hidden: ice is slightly less dense than water

Forces

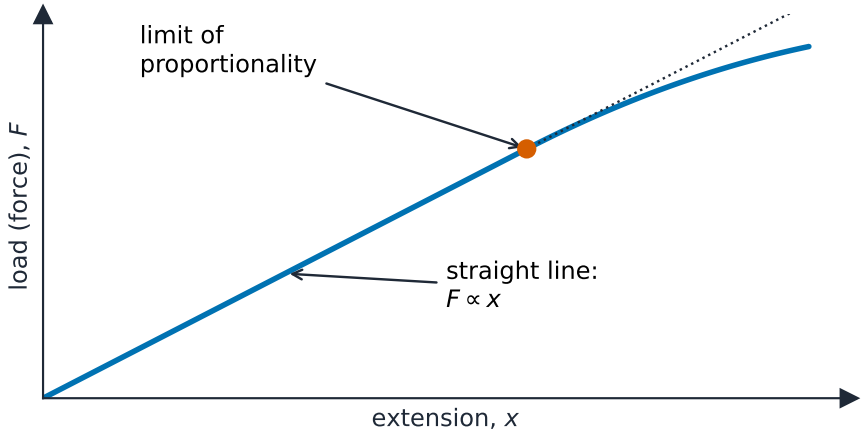
A force is a push or a pull. A force can change the **shape** 形状, the speed, or the direction of an object.

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■ Stretching (Hooke's law)

When you hang a load on a spring, it stretches. The stretch is called the **extension** 伸长量.

On a **load–extension graph** 载荷-伸长图 the line is straight at first: extension is proportional to load. The point where the line stops being straight is the **limit of proportionality** 比例极限.



$F = kx$ (straight section)
$k =$ gradient

Load is proportional to extension until the limit of proportionality, then the line curves

The experiment. Hang the spring from a clamp and stand a ruler beside it. Read the position of the bottom of the spring with no load: this is the original length. Add loads one at a time (for example 1 N each) and record the new length each time. The extension is the new length minus the original length. Plot load on the y-axis against extension on the x-axis.

Within the linear range, the **spring constant** 弹簧常数 is force divided by extension:

$$k = \frac{F}{x}$$

A large k means a stiff spring.

> **Worked example.** A spring is 12.0 cm long with no load. With a 6.0 N load it is 15.0 cm long. Find (a) the spring constant and (b) the length with a 4.0 N load (the limit of proportionality is not reached).

(a) Extension $x = 15.0 - 12.0 = 3.0$ cm $= 0.030$ m, so

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$$k = \frac{F}{x} = \frac{6.0}{0.030} = 200 \text{ N/m}$$

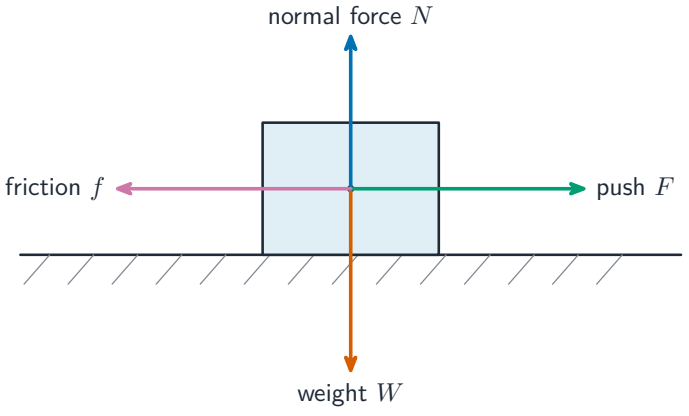
(b) Extension $= \dfrac{F}{k} = \dfrac{4.0}{200} = 0.020$ m $= 2.0$ cm, so the length is $12.0 + 2.0 = 14.0$ cm. Use the extension in $k = F/x$, never the whole length: $6.0 \div 0.150$ gives a wrong answer.

■ Resultant force and Newton's laws

Add forces on a straight line to get the **resultant force** 合力 (forces one way are positive, the other way negative).

- If the resultant force is zero, the object stays at rest **or** keeps moving in a straight line at constant speed. (Newton's first law.)
- If the resultant force is not zero, the object accelerates in the direction of the force:

$$F = ma$$



A free-body diagram shows every force on the box as a labelled arrow

> **Worked example.** A 1200 kg car has a 3000 N driving force and 600 N of friction. Find its acceleration.

First find the resultant force: $3000 - 600 = 2400$ N. Then

$$a = \frac{F}{m} = \frac{2400}{1200} = 2.0 \text{ m/s}^2$$

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Motion in a circle

A resultant force at right angles to the motion does not change the speed. It changes the direction, so the object moves in a circle at a steady speed. This is **circular motion** 圆周运动. The force always points towards the centre of the circle: the pull of the string on a whirling ball, or the gravity of the Sun on a planet.

For an object moving in a circle:

- a bigger force is needed to keep the same mass moving at a higher speed in a circle of the same **radius** 半径;
- a bigger force makes the same mass at the same speed move in a smaller circle (a smaller radius);
- a bigger mass needs a bigger force to keep the same speed and the same radius.

Friction

Friction 摩擦力 is the force between two surfaces that touch. It opposes relative sliding or the tendency to slide, and can cause heating. Drag opposes an object's motion relative to the surrounding fluid.

Moments – the turning effect

The **moment** 力矩 of a force is its turning effect about a **pivot** 支点.

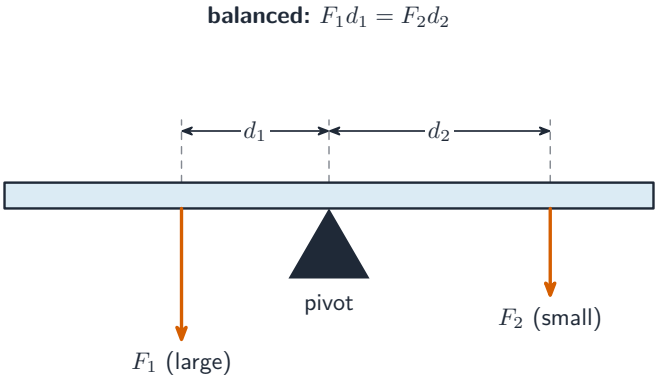
$$\text{moment} = \text{force} \times \text{perpendicular distance from the pivot}$$

The unit is the newton metre (N m).

Principle of moments 力矩原理: when an object is balanced (in **equilibrium** 平衡),

$$\text{total clockwise moment} = \text{total anticlockwise moment}$$

An object is in equilibrium when there is no resultant force **and** no resultant moment.



The beam balances when the clockwise moment equals the anticlockwise moment

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Worked example. A 30 N weight sits 0.20 m to the left of a pivot. How far to the right must a 20 N weight sit to balance the beam?

Balanced, so anticlockwise moment = clockwise moment:

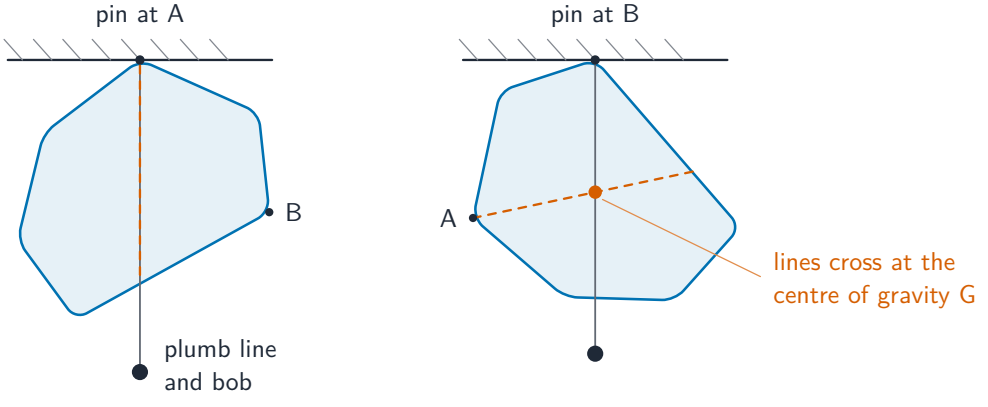
$$30 \times 0.20 = 20 \times d \quad \Rightarrow \quad d = \frac{6.0}{20} = 0.30 \text{ m}$$

Checking the principle by experiment. Balance a metre rule at its centre on a pivot. Hang a known weight on each side and move them until the rule balances again. Measure each distance from the pivot. Force × distance on the left equals force × distance on the right, within the small errors of measurement, so there is no resultant moment on a balanced object.

■ Centre of gravity

The **centre of gravity** 重心 is the single point where all the weight of an object seems to act.

For a flat shape (**lamina** 薄片), hang it from a pin and let it settle; draw a vertical line down from the pin using a plumb line. Repeat from another point. The centre of gravity is where the lines cross.



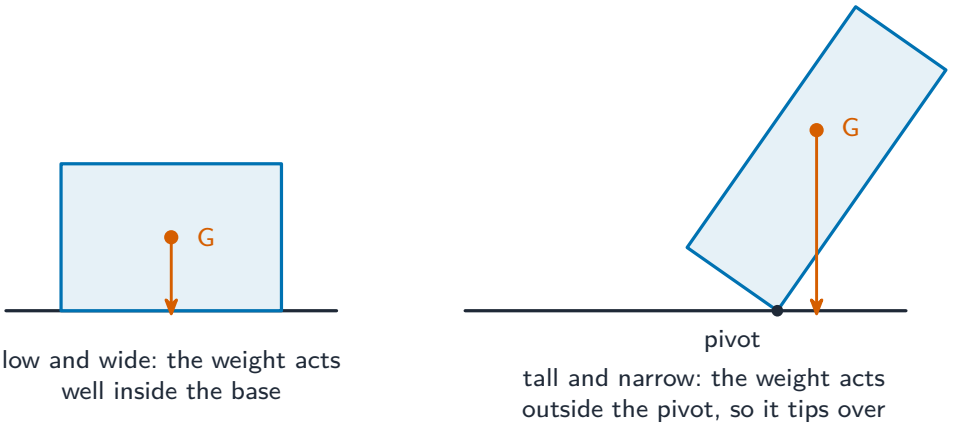
(1) hang from A; draw along the plumb line

(2) hang from B: the new plumb line crosses it at G

Hang the lamina from two points: the plumb lines cross at the centre of gravity

The **stability** 稳定性 of an object depends on where its centre of gravity is. An object is more **stable** 稳定 when its centre of gravity is low and its base is wide. It tips over when a vertical line down from the centre of gravity passes outside the base.

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A low centre of gravity and a wide base keep the weight acting inside the base

Momentum

Momentum is mass times velocity. It is a vector.

$$p = mv$$

Impulse 冲量 is the force times the time it acts, and it equals the change in momentum:

$$\text{impulse} = F\,\Delta t = \Delta(mv)$$

So the resultant force is the change in momentum per unit time:

$$F = \frac{\Delta p}{\Delta t}$$

> **Worked example.** A 0.40 kg ball hits a wall at 10 m/s and bounces straight back at 8.0 m/s. It touches the wall for 0.050 s. Find the impulse and the average force on the ball.

Take towards the wall as positive, so the velocity after is -8.0 m/s.

$$\Delta p = m(v - u) = 0.40 \times (-8.0 - 10) = -7.2 \text{ kg m/s}$$

The impulse is 7.2 N s away from the wall, and

$$F = \frac{\Delta p}{\Delta t} = \frac{7.2}{0.050} = 140 \text{ N}$$

away from the wall. If you forget the change of direction you get $0.40 \times (10 - 8.0) = 0.80$ N s, which is far too small.

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Conservation of momentum 动量守恒: when objects collide and no outside force acts, the total momentum before equals the total momentum after.

$$m_1u_1 + m_2u_2 = m_1v_1 + m_2v_2$$

(Here u is a velocity before and v is a velocity after.)

> **Worked example.** A 2.0 kg trolley moving at 3.0 m/s hits a stationary 1.0 kg trolley and they stick together. Find their common velocity afterwards.

Total momentum is conserved, so

$$(2.0 \times 3.0) + (1.0 \times 0) = (2.0 + 1.0)\,v \quad \Rightarrow \quad v = \frac{6.0}{3.0} = 2.0 \text{ m/s}$$

Energy, work and power

Energy stores

Energy can be **stored** 储存 in different ways: kinetic 动能, gravitational potential 重力势能, chemical 化学能, elastic (strain) 弹性势能, nuclear 核能, electrostatic 静电能, and internal (thermal) 内能.

Energy is **transferred** 转移 between stores by forces (mechanical work), by electric currents, by heating, and by waves (such as light and sound).



Wind turbines transfer energy from the kinetic store of the moving air to electricity

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■ Kinetic and potential energy

Kinetic energy is the energy of a moving object:

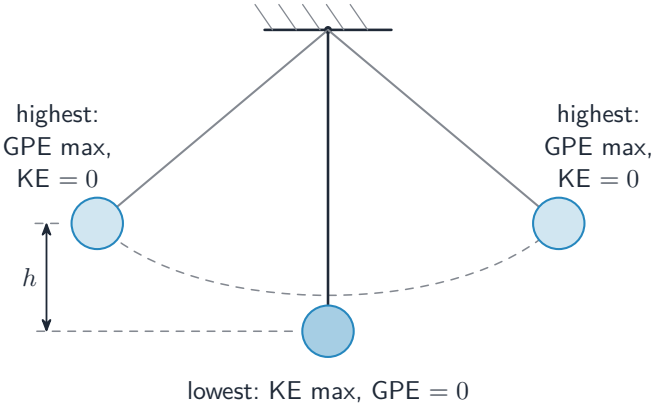
$$E_k = \frac{1}{2}mv^2$$

The change in **gravitational potential energy** when an object goes up or down by a height Δh:

$$\Delta E_p = mg\,\Delta h$$

■ Conservation of energy

The **principle of conservation of energy** 能量守恒定律 says energy is never made or destroyed; it only moves between stores. A falling object turns gravitational potential energy into kinetic energy. A **Sankey diagram** 桑基图 shows how the input energy splits into useful energy and **wasted** 浪费 energy.



Energy moves between gravitational potential energy (at the highest points) and kinetic energy (at the lowest point)

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On a roller-coaster, gravitational potential energy stored at the top of the hill becomes kinetic energy as the cars speed down

> **Worked example.** A 0.50 kg ball is dropped from a height of 1.8 m. Ignoring air resistance, find its speed just before it lands. (Take $g = 10\ \text{m/s}^2$.)

All the gravitational potential energy becomes kinetic energy, so $\frac{1}{2}mv^2 = mg\,\Delta h$. The mass cancels, leaving $v^2 = 2g\,\Delta h$:

$$v = \sqrt{2 \times 10 \times 1.8} = \sqrt{36} = 6.0\ \text{m/s}$$

Because the mass cancels, every object dropped from this height would land at the same speed.

■ Work

Work done 做功 equals the energy transferred. For a constant force, use the displacement in the direction of that force:

$$W = Fd = \Delta E$$

The unit of work and energy is the **joule** 焦耳 (J).

The distance d must be in the direction of the force. When you lift something, use the vertical height, not the length of a slope or a staircase.

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■ Power

Power 功率 is the work done (or energy transferred) per unit time.

$$P = \frac{W}{t} = \frac{\Delta E}{t}$$

The unit is the **watt** 瓦特 (W). 1 W = 1 J/s.

> **Worked example.** A student of weight 500 N runs up a staircase. The stairs rise 3.0 m vertically and are 5.0 m long along the slope. The climb takes 6.0 s. Find the work done against gravity and the power.

The force (the weight) acts vertically, so use the vertical height 3.0 m:

$$W = Fd = 500 \times 3.0 = 1500 \text{ J} \qquad P = \frac{W}{t} = \frac{1500}{6.0} = 250 \text{ W}$$

A student who walks up the same stairs in 15 s does the same work, 1500 J, but with a smaller power, 100 W.

■ Efficiency

Efficiency 效率 tells you how much of the input energy becomes useful energy.

$$\text{efficiency} = \frac{\text{useful energy output}}{\text{total energy input}} \times 100\%$$

Real devices usually transfer some input energy to less useful stores, so their useful efficiency is below 100%. An ideal model can use 100% efficiency; wasted energy is transferred, not destroyed. The same idea works with power:

$$\text{efficiency} = \frac{\text{useful power output}}{\text{total power input}} \times 100\%$$

> **Worked example.** A motor is supplied with 200 J of electrical energy and lifts a load, giving it 150 J of gravitational potential energy. Find its efficiency.

$$\eta = \frac{E_{\text{useful}}}{E_{\text{in}}} \times 100\% = \frac{150 \text{ J}}{200 \text{ J}} \times 100\% = 75\%$$

Comparing energy and power. Suppose the same motor transfers this energy in 5.0 s. Use the same interval for both average powers.

$$P_{\text{in}} = \frac{E_{\text{in}}}{t} = \frac{200 \text{ J}}{5.0 \text{ s}} = 40 \text{ W}$$

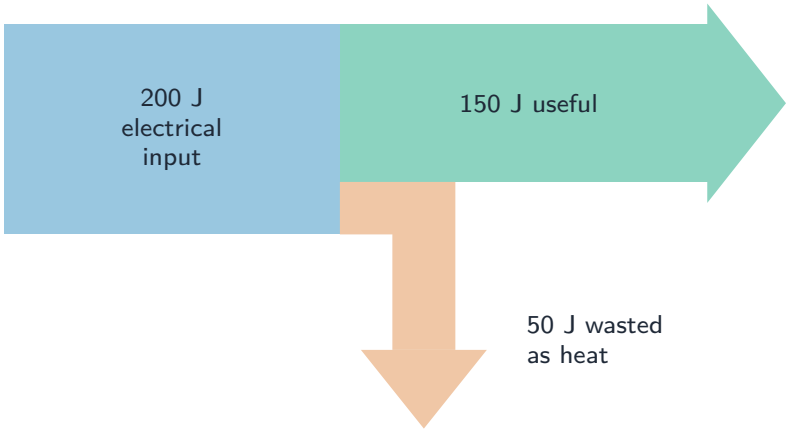
$$P_{\text{useful}} = \frac{E_{\text{useful}}}{t} = \frac{150 \text{ J}}{5.0 \text{ s}} = 30 \text{ W}$$

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$$\eta = \frac{P_{\text{useful}}}{P_{\text{in}}} \times 100\% = \frac{30\ \text{W}}{40\ \text{W}} \times 100\% = 75\%$$

$$E_{\text{wasted}} = E_{\text{in}} - E_{\text{useful}} = 200\ \text{J} - 150\ \text{J} = 50\ \text{J}$$

The power and energy ratios agree because the same time interval applies. Wasted energy is transferred to less useful stores, not destroyed.



A Sankey diagram for this motor: the band widths are proportional to the energy, so the 200 J input splits into 150 J useful and 50 J wasted as heat

Energy resources

We generate electricity from many **energy resources**. Most spin a **turbine** that drives a **generator** – often by boiling water to make steam (**fossil fuels**, **nuclear fuel**, **geothermal**, **biofuels**), or directly by moving water or air (**hydroelectric**, **waves**, **tides**, **wind**). **Solar cells** make electricity from sunlight directly; **solar panels** heat water.

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Resource	Renewable?	Notes
fossil fuels (coal, oil, gas)	no	reliable, high output, but CO_2 and pollution
nuclear fuel	no	no CO_2 from reactor operation; waste
biofuels	yes	replanting absorbs CO_2; production emits CO_2
hydroelectric	yes	water supply matters; dams flood land
wind	yes	no fuel burned; output varies
solar	yes	no fuel burned; needs daylight
geothermal / tidal	yes	site-limited; tidal output is not continuous

The nuclear reactor does not emit carbon dioxide while operating, but fuel supply and construction can cause emissions. Biofuel crops can absorb carbon dioxide as they regrow; emissions from growing, processing and transporting the fuel also matter, so replanting alone does not guarantee zero net emissions.

When you compare resources, use these five ideas: **renewability** 可再生性 (will it run out?), **availability** 可用性 (is it always there? the wind can drop and the Sun sets), **reliability** 可靠性 (does it give a steady output?), **scale** 规模 (how much energy can it supply?) and **environmental impact** 环境影响 (pollution, carbon dioxide, land flooded by a dam).

Most of these trace back to the **Sun** (fossil fuels are ancient stored sunlight; wind and waves come from solar heating) – the exceptions are **geothermal**, **nuclear**, and **tidal** energy. The Sun itself is powered by **nuclear fusion** 核聚变, joining hydrogen nuclei into helium. The syllabus includes research into using energy released by fusion to generate electrical power on a large scale.

Worked energy routes. A school wants electric lighting and hot water. Solar cells supply electrical energy directly; solar water-heating panels transfer energy from solar radiation to the internal energy of water. Neither needs a steam turbine for its stated function. In a fuel-fired power station, a boiler heats water, steam turns a turbine and the turbine drives a generator. Wind or moving water can turn turbines directly. Identify the energy route before naming the components.

Exam transfer. In 0625/22 May/June 2025 Q9, wind is the only one of wind, geothermal and nuclear fuel that gets its energy from the Sun (official answer D). Solar heating helps drive movement of air. Geothermal energy comes from inside the Earth; nuclear fuel supplies energy through nuclear changes. Renewability is a separate test.

Worked resource comparison. A remote clinic needs electricity day and night.

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Solar cells without a battery, backup or grid connection cannot meet its night demand. A hydroelectric scheme may supply at night if suitable flow or stored water is available, but seasonal flow and scheme capacity must be checked. Compare each supply with the clinic's power requirement and assess site, land and habitat effects, especially if a dam is needed. Renewable alone does not mean continuous, adequate or environmentally harmless. Use availability, reliability, scale and environmental impact to explain the choice.

Pressure 压强

Pressure is the perpendicular force per unit surface area.

$$p = \frac{F}{A}$$

The unit is the **pascal** 帕斯卡 (Pa). 1 Pa = 1 $\mathrm{N/m^2}$.

A small area gives a large pressure (a sharp knife cuts well). A large area gives a small pressure (snowshoes stop you sinking).

> **Worked example.** A 600 N student stands on both feet. Each shoe touches the floor over 200 $\mathrm{cm^2}$. Find the pressure on the floor.

The total area is 400 $\mathrm{cm^2}$. Change it to $\mathrm{m^2}$: 1 $\mathrm{m^2}$ = 100 × 100 = 10 000 $\mathrm{cm^2}$, so 400 $\mathrm{cm^2}$ = 0.040 $\mathrm{m^2}$.

$$p = \frac{F}{A} = \frac{600}{0.040} = 15\,000 \text{ Pa}$$

Standing on one foot halves the area, so the pressure doubles to 30 000 Pa.

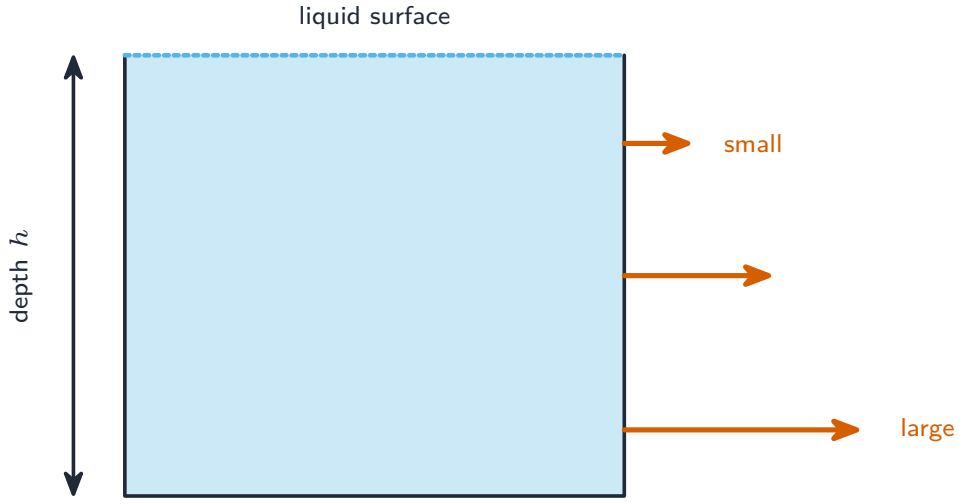
■ Pressure in a liquid

In a liquid, pressure increases with **depth** 深度 and with the liquid's density:

$$\Delta p = \rho g \, \Delta h$$

This is why a dam is built thicker at the bottom, where the water pressure is greatest. Pressure in a liquid acts in all directions.

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The deeper the liquid, the greater the pressure, so the outward push on the wall grows with depth



A real dam is built much thicker at the bottom, because the water pushes hardest where it is deepest

Worked example. Find the extra pressure at a depth of 2.0 m in water (density 1000 kg/m^3, $g = 10$ N/kg).

$$\Delta p = \rho g \, \Delta h = 1000 \times 10 \times 2.0 = 20\,000 \text{ Pa}$$

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Exam tips

- On a **distance–time** graph the gradient is the speed; on a **speed–time** graph the gradient is the acceleration and the *area* under the line is the distance travelled. Never read one graph as if it were the other.
- **Mass** (kg) is the amount of matter and is the same everywhere; **weight** (N) is the force of gravity, $W = mg$. On the Moon your mass is unchanged but your weight is smaller.
- **Speed** is a scalar; **velocity** is a vector. Something moving at steady speed around a curve is still accelerating, because its direction keeps changing.
- In **Hooke's law**, load is proportional to extension only up to the **limit of proportionality**. Use the *extension* (stretched length − original length), never the whole length.
- Total **momentum** is conserved in a collision when the resultant external force is negligible. Give each velocity a + or − sign for its direction *before* you add them.
- Check that units are consistent. $p = F/A$ defines pressure; $\Delta p = \rho g\,\Delta h$ gives the change in pressure between depths in a liquid.

■ Common mistakes

- Joining the points on a graph dot to dot. Draw one line of best fit, and leave out an anomalous point.
- Averaging two speeds to get the average speed. Use total distance ÷ total time, and include the time spent stopped.
- Saying "no forces act" at terminal velocity. The weight and the air resistance both act; they are equal and opposite, so the *resultant* force is zero.
- Writing a weight in kilograms. Weight is a force, measured in newtons; mass is in kilograms.
- Using the whole length of a spring in $k = F/x$. Use the extension (new length − original length), in metres.
- Forgetting the minus sign when an object bounces back. The change in velocity from +10 to −8 m/s is −18 m/s, not −2 m/s.
- Dividing by an area in cm^2 in $p = F/A$. Change to m^2 first: $1\ \text{cm}^2 = 0.0001\ \text{m}^2$.
- Using the slope length to find the work done in lifting. Use the vertical height, because the weight acts vertically.

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Thermal physics

IGCSE Physics

States of matter 物态

Matter exists in three states: **solid** 固体, **liquid** 液体 and **gas** 气体.

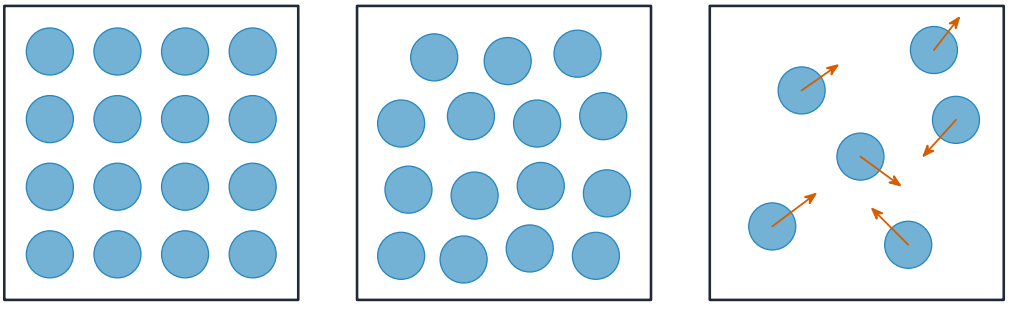
State	Shape	Volume	Particles
Solid	fixed	fixed	close together, in a regular pattern, vibrating
Liquid	takes the shape of the container	fixed	close together, no pattern, can move past each other
Gas	fills the container	changes	far apart, fast, random motion

The changes of state are: melting (solid → liquid), boiling/evaporating (liquid → gas), **condensation** 凝结 (gas → liquid) and **solidification** 凝固 (liquid → solid). In condensation the gas particles slow down and come close together to form a liquid. In solidification the liquid particles lose energy and settle into fixed positions.

The kinetic particle model 分子动理论

All matter is made of tiny **particles** 粒子 that are always moving. This is the kinetic particle model.

- In a solid the particles only **vibrate** 振动 about fixed positions.
- In a liquid they are still close but can slide past each other.
- In a gas they are far apart and move quickly in random directions.



The same particles in three states: fixed and ordered in a solid, close but disordered in a liquid, far apart and fast in a gas

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Temperature and particle energy

When you heat a substance, its particles move faster, so they have more **kinetic energy** 动能. **Temperature** 温度 is a measure of the average kinetic energy of the particles.

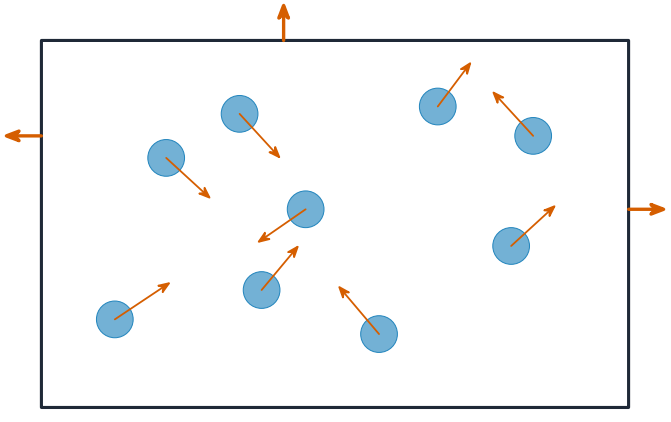
The lowest possible temperature is **absolute zero** 绝对零度, $-273\,°C$. At this point the particles have the least possible energy.



A digital thermometer: its probe comes to the same temperature as the object it touches, and the screen shows that temperature

Gas pressure

Gas particles hit the walls of their container. Each hit is a tiny push. The **pressure** 压强 of the gas is the total force of these hits per unit area.



gas particles hit the walls — each hit is a tiny force.
Pressure = force per unit area

The gas pressure is the total force of countless particle hits on each unit area of the wall

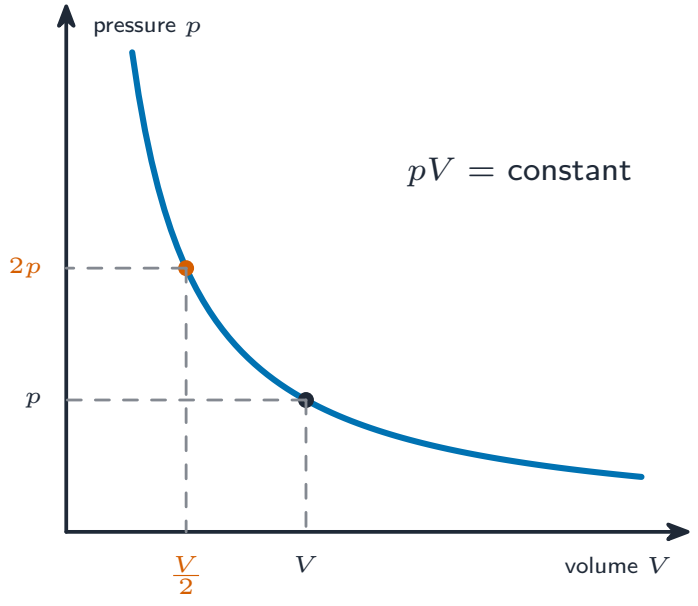
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- Heating a gas (at constant volume) makes particles move faster and hit harder and more often, so the pressure rises.
- Squeezing a gas into a smaller volume (at constant temperature) means more hits per second on each unit of area, so the pressure rises.

For a fixed mass of gas at constant temperature:

$$pV = \text{constant}$$

So if the volume halves, the pressure doubles.



At constant temperature the pressure–volume graph is a curve: halve the volume and the pressure doubles, so pV stays constant

Worked example. A gas has a volume of 200 cm^3 at a pressure of 100 kPa. It is squeezed to 50 cm^3 at constant temperature. Find the new pressure.

Since pV stays constant, $p_1V_1 = p_2V_2$:

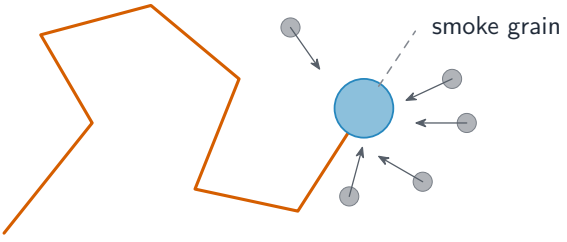
$$100 \times 200 = p_2 \times 50 \quad \Rightarrow \quad p_2 = \frac{20\,000}{50} = 400 \text{ kPa}$$

Check the answer with a ratio: the volume became $\frac{1}{4}$ as big, so the pressure became 4 times as big. You can keep cm^3 and kPa here, because the same units are on both sides of the equation.

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■ Brownian motion

If you look at smoke in air under a microscope, you see tiny specks moving in a jerky, random way. This is **Brownian motion** 布朗运动. The specks are pushed by fast, invisible air particles hitting them. It is strong evidence for the kinetic particle model.



fast, invisible air particles hit the smoke grain from random directions, so it moves in a jerky, random path

Random hits from fast air particles push a smoke grain along a jerky, random path

■ The kelvin scale

Scientists often use the **kelvin** 开尔文 (K) temperature scale, which starts at absolute zero. To convert:

$$T \text{ (in K)} = \theta \text{ (in } ^\circ\text{C)} + 273$$

So $0\,^\circ\text{C} = 273$ K.

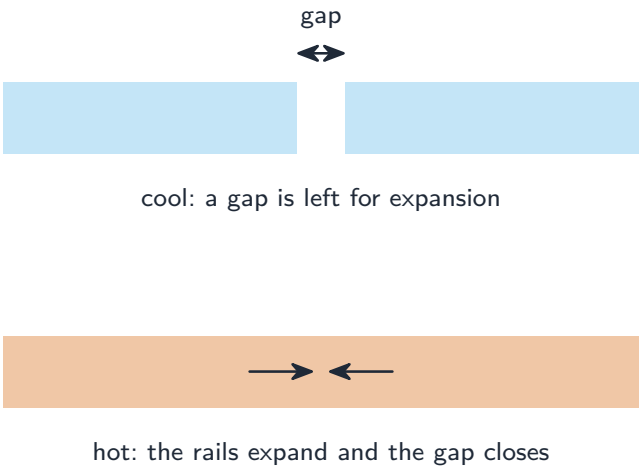
Worked example. Convert $25\,^\circ\text{C}$ to kelvin, and 200 K to degrees Celsius.

$$25 + 273 = 298 \text{ K}, \qquad 200 - 273 = -73\,^\circ\text{C}$$

Thermal expansion 热膨胀

When matter is heated, its particles move more and take up more space, so the material expands. Gases expand the most, then liquids, then solids. This order comes from the forces between the particles: in a solid the particles are held tightly in a **lattice** 晶格 (a fixed pattern), so they can only vibrate a little more; in a liquid they are held less strongly; in a gas the forces are very weak, so the particles spread out much more.

Everyday examples: gaps are left between railway lines; bridges sit on rollers; a tight metal lid loosens when heated.



A small gap is left between rails when cool, so when they expand in the heat the gap closes instead of buckling the track

Internal energy and specific heat capacity

The **internal energy** 内能 of an object is the total microscopic random kinetic and potential energy of its particles, excluding the motion and position of the object as a whole. Heating an object raises its internal energy and usually its temperature.

The **specific heat capacity** 比热容 is the energy needed to raise the temperature of 1 kg of a material by 1 °C.

$$c = \frac{\Delta E}{m\,\Delta\theta}$$

A material with a high specific heat capacity (like water) needs a lot of energy to warm up and cools down slowly.

> **Worked example.** How much energy is needed to heat 2.0 kg of water from 20 °C to 70 °C? The specific heat capacity of water is 4200 J/(kg °C).

Rearranging $c = \frac{\Delta E}{m\,\Delta\theta}$ gives $\Delta E = mc\,\Delta\theta$, with $\Delta\theta = 70 - 20 = 50$ °C:

$$\Delta E = 2.0 \times 4200 \times 50 = 420\,000 \text{ J} = 420 \text{ kJ}$$

Measuring specific heat capacity. For a solid, use a metal block with two holes: one for an electric **heater** 加热器 and one for a **thermometer** 温度计. Measure the mass m of the block. Switch on the heater for a measured time t and record the current I and the voltage V, so the energy supplied is $E = IVt$ (or read the energy from a joulemeter). Record the temperature rise $\Delta\theta$. Then $c = \dfrac{E}{m\,\Delta\theta}$. For a liquid,

heat a measured mass of the liquid in a container and stir it, so the temperature is the same all through. Wrap the block or the container in **insulating material** 隔热材料, so less energy escapes to the air.

> **Worked example (from experimental data).** A 1.0 kg aluminium block is heated by a 12 V heater with a current of 4.0 A for 5.0 minutes. Its temperature rises from 20 °C to 35 °C. Find the specific heat capacity of aluminium.

Time in seconds: $t = 5.0 \times 60 = 300$ s. Energy supplied:

$$E = IVt = 4.0 \times 12 \times 300 = 14\,400 \text{ J}$$

Temperature rise: $\Delta\theta = 35 - 20 = 15\,^{\circ}\text{C}$.

$$c = \frac{\Delta E}{m\,\Delta\theta} = \frac{14\,400}{1.0 \times 15} = 960 \text{ J/(kg °C)}$$

The book value for aluminium is about 900 J/(kg °C). The measured value is too **high**, because some of the energy from the heater escaped to the air and did not warm the block. The calculation assumes all 14 400 J went into the block, so it gives a value that is too big. Better insulation brings the result closer.

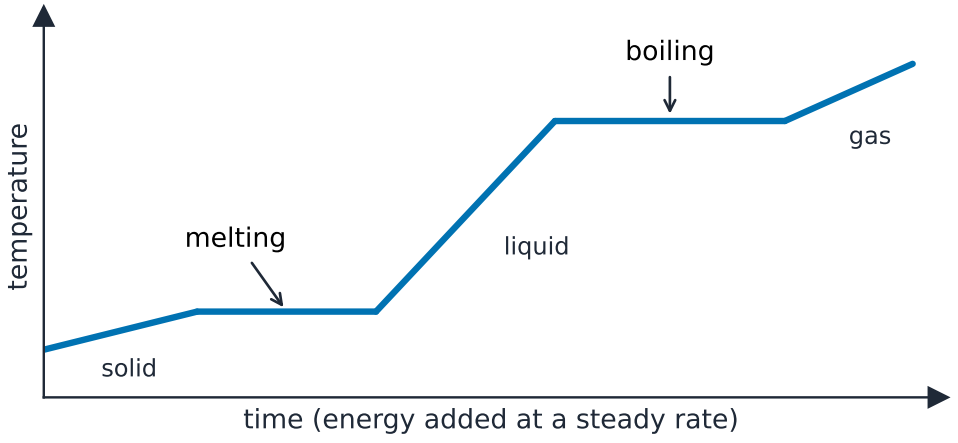


Boiling water: internal energy rises with temperature; specific heat capacity is energy per kg per °C

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Melting, boiling and evaporation

Melting 熔化 and **boiling** 沸腾 need energy, but the temperature stays the same while the state changes. This energy breaks the forces between particles. For water at normal air pressure, melting is at 0 °C and boiling at 100 °C.



plateau: energy changes the state, so the temperature stays constant

While the substance melts and while it boils the temperature stays flat, even though energy is still being added

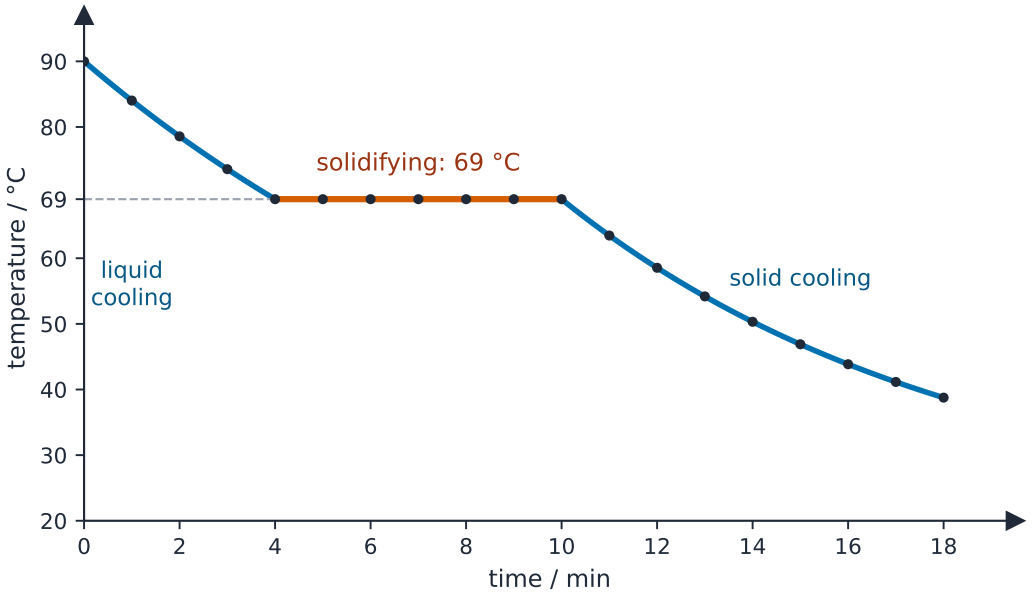
Evaporation 蒸发 is when a liquid changes to a gas at its surface, below the boiling point. The fastest particles escape from the surface. Because the fastest (most energetic) particles leave, the average energy of those left behind falls, so the liquid **cools down** 冷却. An object touching an evaporating liquid also cools, because the liquid takes energy from it: this is why sweat cools your skin.

Evaporation is faster when the temperature is higher, the surface area is larger, and there is more air movement over the surface.

	Evaporation	**Boiling**
Where	only at the surface	throughout the liquid (bubbles form inside)
Temperature	any temperature	only at the boiling point
Effect on the liquid	cools it	temperature stays at the boiling point

Worked example (reading a cooling curve). Hot liquid wax in a boiling tube is left to cool in a room at 20 °C. A student reads its temperature every minute and plots the graph.

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Cooling curve of liquid wax: the flat part is where the wax changes from liquid to solid

(a) *What is the melting point of the wax?* The flat part is at 69 °C. A substance melts and solidifies at the same temperature, so the melting point is 69 °C.

(b) *What is happening between 4 and 10 minutes?* The wax is **solidifying**: the tube holds both liquid and solid wax.

(c) *Why does the temperature stay constant while energy is still being lost to the room?* As the wax solidifies, its particles move closer together and are held in fixed positions by the forces between them. This releases energy, and that energy replaces the energy lost to the room, so the temperature does not fall.

(d) *Why does the solid cool more slowly at the end?* The wax is now closer to room temperature, so it transfers energy to the room more slowly.

Transfer of thermal energy 热能传递

Thermal energy moves from hotter places to colder places in three ways.

■ Conduction

Conduction 热传导 is the transfer of thermal energy through a material without the material moving. The particles in a solid sit in a lattice. Heated particles vibrate more and pass the energy to their neighbours. In metals, free electrons (**delocalised electrons** 自由电子) carry energy quickly, so metals are good **thermal conductors** 热导体.

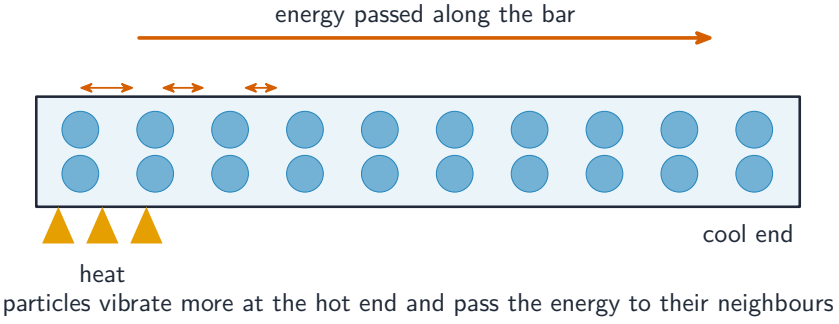
Materials that conduct badly (like air, wood and plastic) are **thermal insulators** 热绝缘体.

Testing conductors. Fix a drawing pin with a little wax to one end of rods of copper,

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iron, glass and wood, and heat the other ends equally. The pin drops first from the copper rod, then from the iron rod, and last (or never) from the glass and the wood: metals are the best conductors. A metal rod held in a flame soon feels hot; a wooden rod does not.

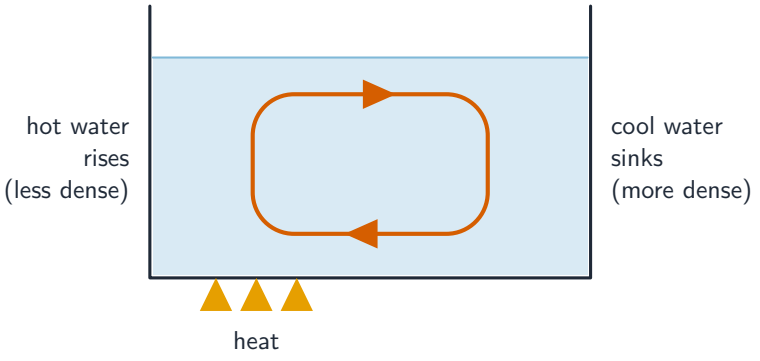
Gases and most liquids are bad conductors because their particles are far apart and only pass on energy when they happen to collide. There is no lattice and there are no free electrons.



In conduction the vibrating particles pass energy to their neighbours, so energy flows from the hot end to the cool end

■ Convection

Convection 对流 happens in liquids and gases. When a fluid is heated it expands, becomes less dense, and rises. Cooler, denser fluid sinks to take its place. This circle of moving fluid is a **convection current**.



Heated fluid rises and cooler fluid sinks, setting up a convection current

Showing convection. Drop a crystal of purple **potassium permanganate** 高锰酸钾 into a beaker of water and heat the beaker gently under the crystal. A coloured stream rises above the heat, spreads across the top and sinks at the sides. In air, a lit candle under one chimney of a smoke box pulls smoke down the other chimney and up above the flame.

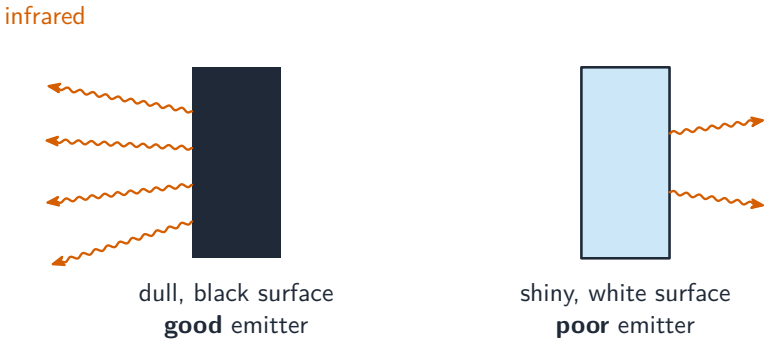
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Convection cannot happen in a solid because the particles cannot move from place to place.

■ Radiation

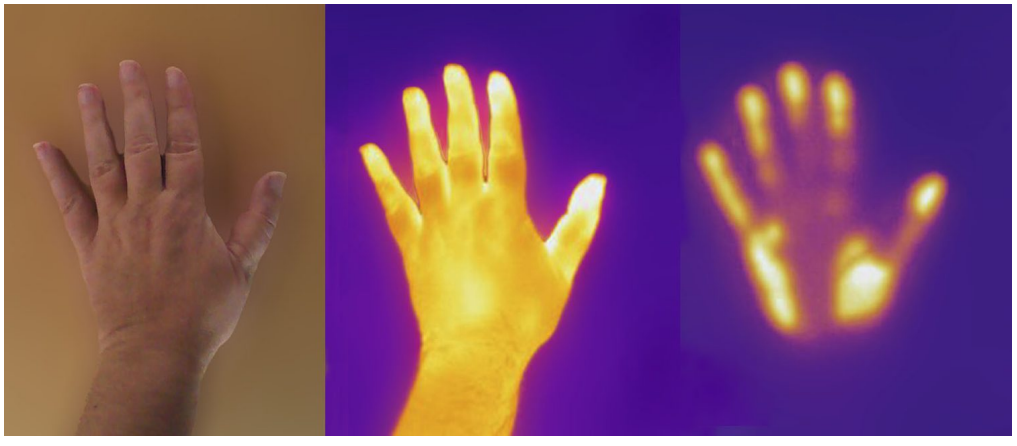
Thermal radiation 热辐射 is energy carried by **infrared** 红外线 waves. All objects emit it, and it needs no material to travel through – it can cross empty space (this is how energy reaches us from the Sun).

A surface that is **dull** 暗淡 and black is a good **emitter** 发射体 and a good **absorber** 吸收体 of infrared. A surface that is shiny and white is a poor emitter and a good **reflector** 反射体.



A dull black surface emits (and absorbs) infrared much better than a shiny, white one

Comparing surfaces. Fill two cans, one dull black and one shiny silver, with hot water at the same temperature, and put a thermometer in each. The black can cools faster, so it is the better emitter. Then put the same two cans, full of cold water, at equal distances from a heater. The black can warms faster, so it is the better absorber. A **Leslie cube** 莱斯利立方体 (a metal box with one side of each finish) shows the same thing.



A thermal (infrared) camera turns the infrared given off by a warm hand into a picture; brighter means hotter

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An object stays at a constant temperature when it emits energy at the same rate as it absorbs energy. The rate of emission is greater when the surface is hotter and larger. If an object absorbs energy faster than it emits it, its temperature rises; if it emits faster than it absorbs, its temperature falls.

The Earth's temperature. The Earth absorbs radiation from the Sun and emits infrared radiation back into space. Its average temperature stays constant only when the two rates are equal. Anything that changes this balance changes the temperature. Gases in the **atmosphere** 大气 such as carbon dioxide absorb some of the emitted infrared and send part of it back down, so more of these gases warms the Earth. Clouds and ice reflect incoming sunlight, so less ice means more energy is absorbed, and the Earth warms further.

■ Investigating insulation

Practical questions often ask you to plan or analyse an investigation into how well materials reduce energy transfer.

Method. Pour the same volume of hot water (say 200 cm^3) at the same starting temperature into identical beakers. Wrap one beaker in cotton wool, one in bubble wrap and one in aluminium foil, and leave one bare as a **control**. Put a lid on each and a thermometer through each lid. Record each temperature every 2 minutes for 20 minutes.

- **Independent variable** 自变量 (what you change): the insulating material.
- **Dependent variable** 因变量 (what you measure): the temperature after a fixed time, or the fall in temperature.
- **Control variables** 控制变量 (kept the same): the volume and starting temperature of the water, the type of beaker, the thickness of the wrapping, the lid, and the room temperature.

Worked example. A student's results after 20 minutes:

Beaker	Start / °C	After 20 min / °C	Fall / °C
no insulation	80	52	28
aluminium foil	80	58	22
bubble wrap	80	64	16
cotton wool	80	66	14

(a) Which material is the best insulator? **Cotton wool**: its water fell by only 14 °C, the smallest fall. (b) Explain why. Cotton wool and bubble wrap trap **air**, which is a poor conductor, and the trapped air cannot move, so convection is reduced too. The shiny foil helps only a little: it reflects some infrared back, but it is a thin metal, a good conductor, and traps no air. (c) Suggest one improvement. Repeat each test and find a mean, so one odd result does not decide the answer; or use a thinner thermometer, or stir before each reading so the reading is the temperature of all the water. (d) Why does every beaker cool more slowly as time goes on? The water gets closer to room

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temperature, and the rate of energy transfer depends on the temperature **difference**. Read the thermometer with your eye level with the liquid surface, to avoid a **parallax** 视差 error.

Everyday examples

- A kitchen pan has a metal base that conducts energy quickly to the food, and a plastic or wooden handle that is an insulator, so you can hold it.
- A **radiator** 散热器 heats a room by convection: the air next to it warms, rises, and cooler air flows in to take its place, so the whole room warms.
- Sitting near a fire you feel its radiation on your face at once; the air between you and the fire is a poor conductor.
- A **vacuum flask** 保温瓶 keeps a drink hot by reducing all three transfers: the vacuum between its double walls stops conduction and convection across the gap, and its shiny silver surfaces reduce radiation. A little energy still escapes through the stopper and the neck.

Exam tips

- In the **kinetic particle model**, heating a gas makes its particles move faster and hit the walls harder and more often, so the pressure rises. The particles themselves do not get bigger.
- **Evaporation** happens only at the surface and at any temperature; **boiling** happens throughout the liquid at one fixed temperature. Evaporation cools the liquid left behind, because the fastest particles escape.
- During **melting** and **boiling** the temperature stays constant even though energy is still being supplied – that energy breaks the forces between particles.
- For **specific heat capacity** use $\Delta E = mc\,\Delta\theta$, where $\Delta\theta$ is the *change* in temperature, not the final temperature.
- In an investigation, name the **independent**, **dependent** and **control** variables, and keep everything except the one you change the same.
- Dull black surfaces are the best **emitters and absorbers** of infrared; shiny, light surfaces are the best reflectors. **Convection** needs a fluid to flow, so it cannot happen in a solid.

Common mistakes

- Using the final temperature in $\Delta E = mc\,\Delta\theta$. Use the temperature *change*.
- Leaving the heating time in minutes in $E = IVt$. Change it to seconds.
- Saying the particles expand when a substance is heated. The particles stay the same size; they move faster and further apart.
- Saying "no energy is supplied" on a flat part of a heating curve. Energy is still supplied; it changes the state instead of raising the temperature.

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- Adding 273 to a temperature that is already in kelvin, or forgetting to add it when converting from °C.
- Saying convection happens because "heat rises". The heated fluid expands, becomes less dense and rises; cooler, denser fluid sinks.

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Waves

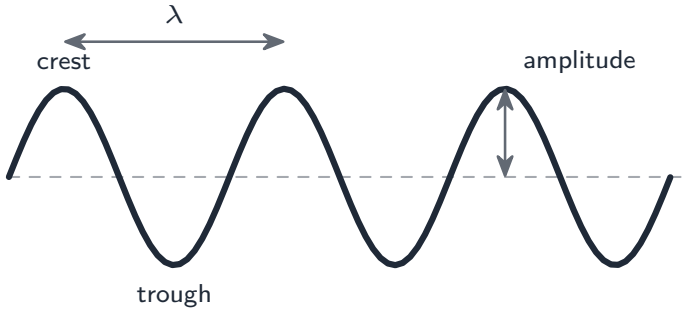
IGCSE Physics

General properties of waves

A **wave** 波 carries **energy** 能量 from place to place **without** carrying matter. For example, a water wave makes a floating cork bob up and down, but the cork does not travel along with the wave. You can make a wave on a rope by shaking one end up and down, or on a long spring by pushing one end back and forth. In a **ripple tank** 波纹水槽 (a shallow tray of water with a light above it) you can watch water waves on a screen below.

Describing a wave

- **wavefront** 波前: a line joining points on a wave that move together (for example, the top of one ripple)
- **wavelength** 波长 (λ): the distance between two neighbouring wavefronts (one full wave)
- **frequency** 频率 (f): the number of waves passing a point each second, measured in hertz (Hz)
- **crest** 波峰 (also called the **peak** 峰, the top) and **trough** 波谷 (bottom)
- **amplitude** 振幅: the largest distance a point moves from its rest position
- **wave speed** 波速 (v): how fast a wavefront travels

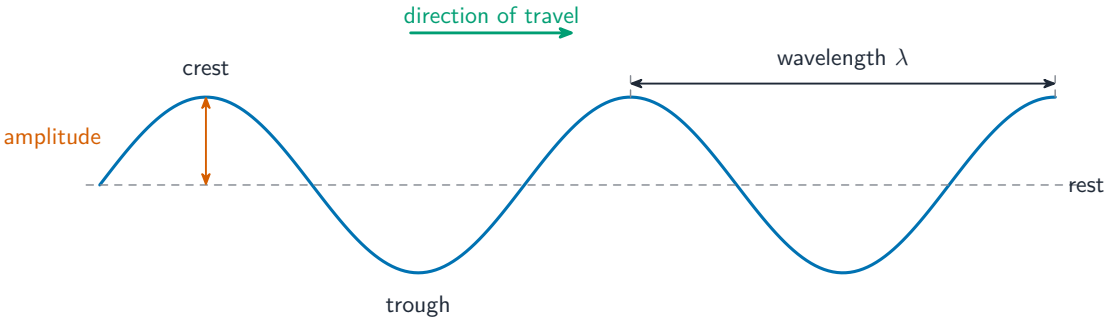


The parts of a wave: wavelength, amplitude, crest and trough

These are linked by the **wave equation**:

$$v = f\lambda$$

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The wavelength is the distance between two crests; the amplitude is the height from the rest position to a crest

Worked example. A sound wave travels at 340 m/s and has a frequency of 170 Hz. Find its wavelength.

Rearranging $v = f\lambda$ gives $\lambda = \dfrac{v}{f}$:

$$\lambda = \frac{340}{170} = 2.0 \text{ m}$$

Worked example (ripple tank). In a ripple tank, 12 wavefronts pass a point in 4.0 s. On the screen, the distance from the 1st wavefront to the 6th wavefront is 10 cm. Find the frequency, the wavelength and the wave speed.

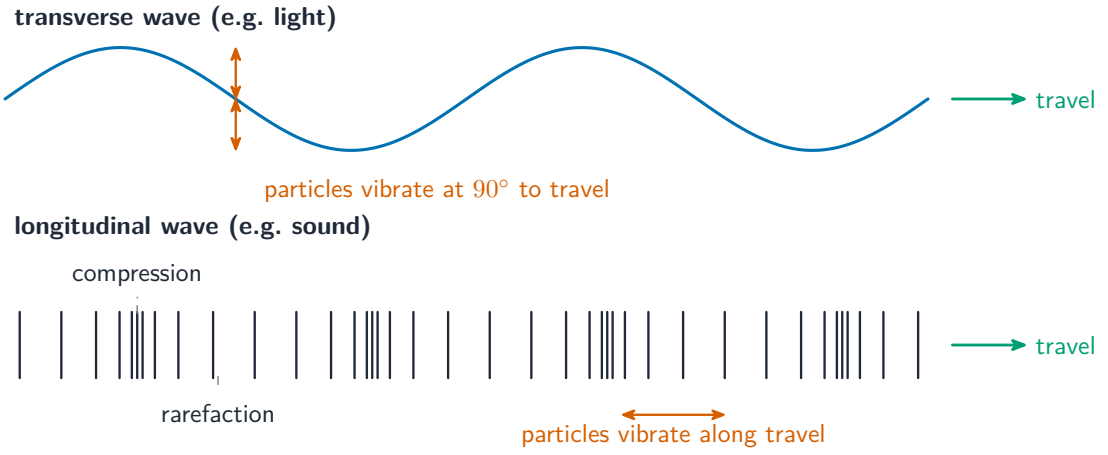
$$f = \frac{12}{4.0} = 3.0 \text{ Hz}$$

From the 1st to the 6th wavefront there are 5 gaps, not 6, so

$$\lambda = \frac{10 \text{ cm}}{5} = 2.0 \text{ cm} = 0.020 \text{ m} \qquad v = f\lambda = 3.0 \times 0.020 = 0.060 \text{ m/s}$$

■ Two types of wave

- In a **transverse wave** 横波 the oscillations are at right angles (90°) to the direction the wave travels (its **propagation** 传播). Light, water waves and seismic S-waves (the sideways shaking in an earthquake) are transverse.
- In a **longitudinal wave** 纵波 the particles vibrate along the same direction as the wave travels. Sound and seismic P-waves are longitudinal.

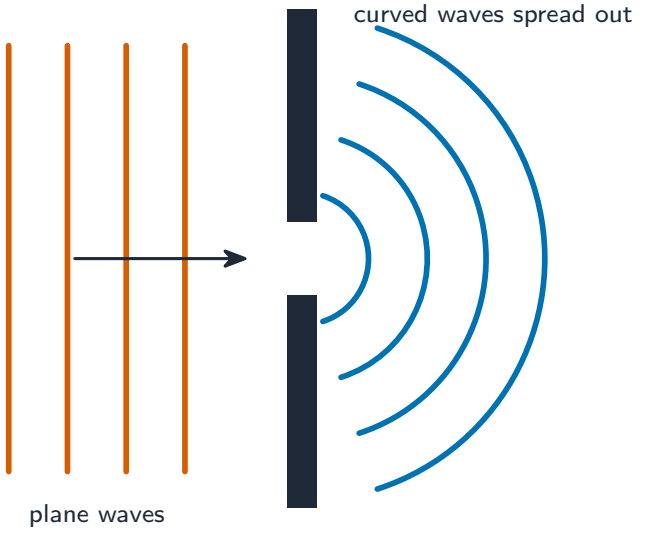


In a transverse wave the particles vibrate across the travel direction; in a longitudinal wave they vibrate along it, making compressions and rarefactions

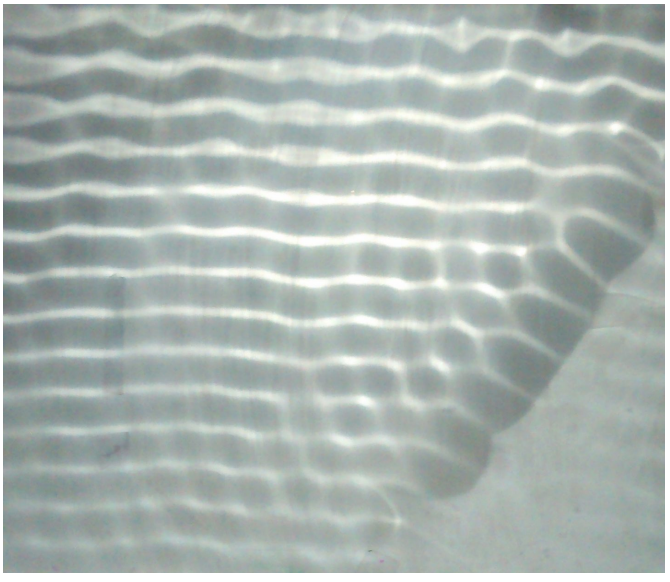
Wave behaviour

All waves can show three behaviours, which you can see in a ripple tank:

- **reflection** 反射: the wave bounces off a surface.
- **refraction** 折射: the wave changes speed (and usually direction) when it enters a different material or depth.
- **diffraction** 衍射: the wave spreads out after passing through a gap or around an edge. The spreading is greatest when the gap is about the same size as the wavelength.



Plane waves passing through a narrow gap spread out into curved waves – diffraction is strongest when the gap is about one wavelength wide



Plane waves in a ripple tank reflect off a straight barrier: the reflected wavefronts leave at the same angle they arrived

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Light 光

■ Reflection

When light hits a mirror, it reflects. We measure angles from the **normal** 法线 (a line at 90° to the surface).

The **law of reflection**: the **angle of incidence** 入射角 equals the **angle of reflection** 反射角.

The incident ray, reflected ray and normal lie in one plane.

> **Worked example.** A ray makes 30° with the mirror surface. Draw the normal at the point of incidence. The normal makes 90° with the surface, so the angle of incidence is the remaining angle:

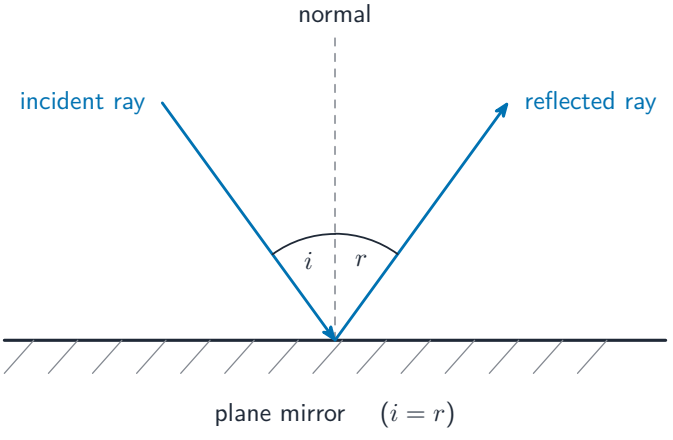
$$i = 90° - \theta = 90° - 30° = 60°$$

Apply the law of reflection:

$$r = i = 60°$$

Draw the reflected ray away from the mirror on the opposite side of the normal. It makes 60° with the normal and 30° with the mirror surface. Do not use the surface angle as the angle of incidence.

A **plane mirror** 平面镜 forms an image that is the same size as the object, the same distance behind the mirror, and **virtual** (it cannot be caught on a screen).

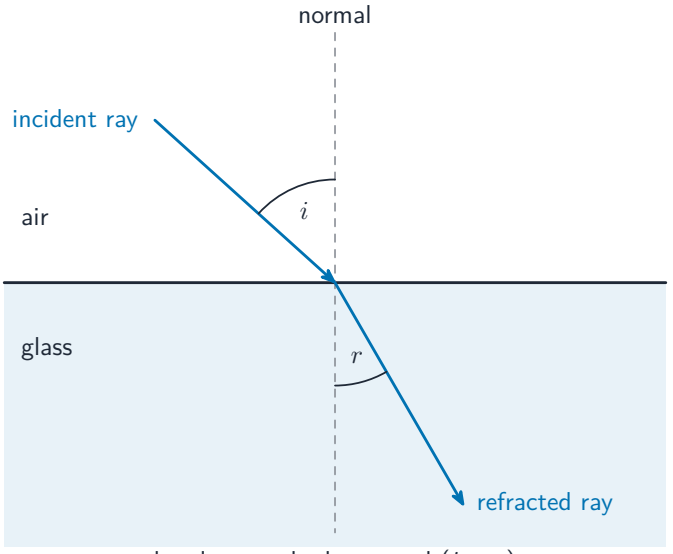


At a plane mirror the angle of incidence i equals the angle of reflection r, both measured from the normal

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Refraction

When light passes from one material into another, it changes speed and bends. The angle in the second material is the **angle of refraction** 折射角.



bends towards the normal ($i > r$)

Going from air into glass the light slows down and bends towards the normal, so $i > r$

Seeing refraction. Shine a narrow ray from a **ray box** 光线盒 into a rectangular glass block standing on paper. Mark the ray going in and the ray coming out, remove the block, and join the marks to draw the ray inside the glass. Draw the normal where the ray enters and measure the angle of incidence and the angle of refraction with a protractor. Repeat with a semicircular block or a prism: the ray always bends towards the normal on entering the glass and away from the normal on leaving.

The **refractive index** 折射率 n compares the speed of light in the two materials:

$$n = \frac{\sin i}{\sin r}$$

Worked example. A ray of light passes from air into glass. The angle of incidence is 60° and the angle of refraction is 35°. Find the refractive index of the glass. (Take $\sin i = 0.87$ and $\sin r = 0.57$.)

$$n = \frac{\sin i}{\sin r} = \frac{0.87}{0.57} = 1.5$$

The refractive index is also the speed of light in air divided by its speed in the glass. Light travels at 3.0×10^8 m/s in air, so in this glass it travels at $\dfrac{3.0 \times 10^8}{1.5} = 2.0 \times 10^8$ m/s.

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Investigating refraction in the lab. A common exam question asks you to plan or improve this experiment.

1. Place a rectangular glass block on a sheet of white paper and draw round it. Remove the block and draw a **normal** at a point on one long side.
2. Draw an incident ray at a measured angle of incidence i, for example $20°$, meeting the normal at that point. Put the block back.
3. Shine a narrow ray from the ray box along your line (or stick two pins on it), and mark the ray that leaves the far side with two crosses (or two pins), far apart.
4. Remove the block, join the marks to the point where the ray left the block, and draw the ray **inside** the block. Measure the angle of refraction r from the normal.
5. Repeat for $i = 30°, 40°, 50°, 60°$, then plot $\sin i$ (up) against $\sin r$ (across). The graph is a straight line through the origin, and its **gradient** is the refractive index.

Precautions that improve accuracy: use a **narrow** ray and a sharp pencil; place the marks (or pins) **far apart**, so a small error in placing them gives only a small error in the line; with pins, look at their **bases** when you line them up; and measure each angle from the **normal**, not from the surface of the block.

Worked example. A student obtains these results. Find the refractive index.

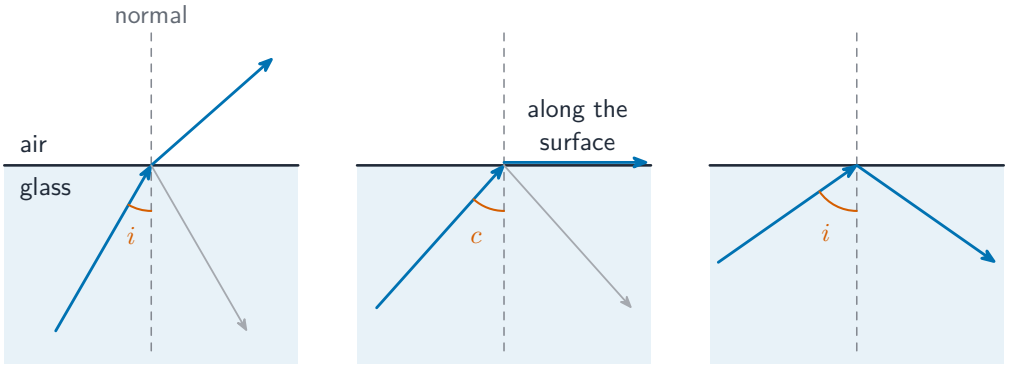
i	$20°$	$30°$	$40°$	$50°$	$60°$
r	$13°$	$19.5°$	$25°$	$31°$	$35°$
$\sin i$	0.34	0.50	0.64	0.77	0.87
$\sin r$	0.22	0.33	0.42	0.51	0.57

Each value of $\sin i \div \sin r$ is close to 1.5 (for example $0.77 \div 0.51 = 1.5$), so $n = 1.5$. On the graph, the gradient of the best-fit line gives the same value; using a line through all the points is better than using one pair of readings, because it averages out small errors in each angle.

When light tries to leave glass or water and the angle is too large, it cannot get out and instead reflects completely. This is **total internal reflection** 全反射. It happens when the angle inside is bigger than the **critical angle** 临界角 c:

$$n = \frac{1}{\sin c}$$

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(a) $i < c$: light refracts out

(b) $i = c$, the critical angle: $\sin c = 1/n$

(c) $i > c$: total internal reflection

Below the critical angle the light refracts out; above it the light is totally internally reflected

Worked example. Glass has a refractive index of 1.5. (a) Find the critical angle. (b) A ray inside the glass meets the glass–air surface at 50° to the normal. What happens? (c) Another ray meets the surface at 30° to the normal. Find the angle at which it leaves.

(a) $\sin c = \dfrac{1}{n} = \dfrac{1}{1.5} = 0.667$, so $c = 42°$.

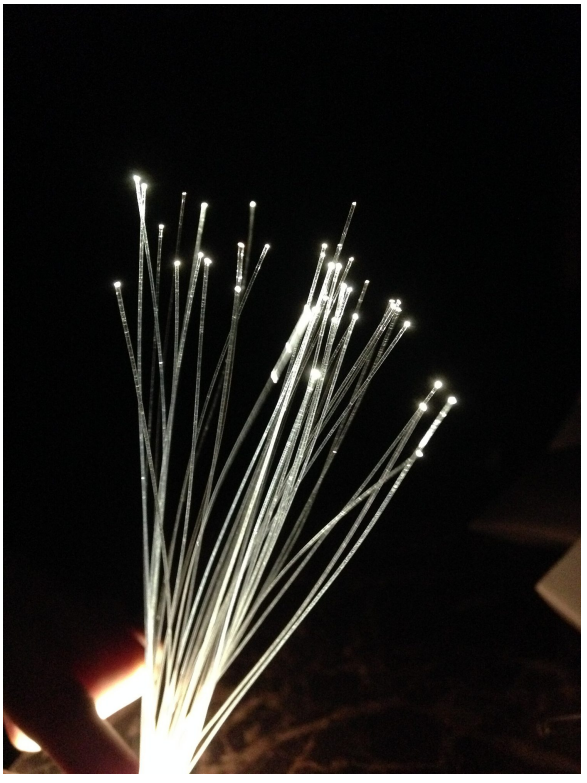
(b) 50° is bigger than 42°, so the ray is totally internally reflected. It reflects back into the glass at 50° to the normal.

(c) 30° is smaller than 42°, so the ray refracts out into the air. The angle in the air is the larger angle, so use $n = \dfrac{\sin(\text{angle in air})}{\sin(\text{angle in glass})}$:

$$\sin(\text{angle in air}) = 1.5 \times \sin 30° = 1.5 \times 0.50 = 0.75 \quad \Rightarrow \quad \text{angle in air} = 49°$$

The ray bends away from the normal ($49° > 30°$), as it should when light leaves glass. This effect is used in **optical fibres** 光纤, thin glass threads that carry light signals for telephones and the internet.

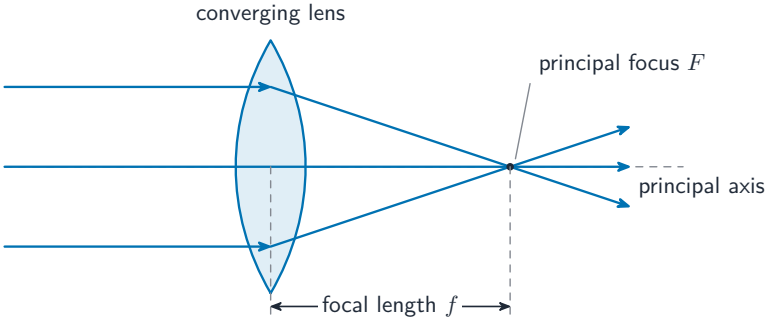
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Total internal reflection keeps light bouncing along each fibre until it shines out at the tip

Lenses

A **converging lens** 凸透镜 (fat in the middle) brings rays parallel to its principal axis to a point called the **principal focus** 焦点. The **principal axis** 主光轴 is the straight line through the centre of the lens at right angles to it; the principal focus lies on this axis. The distance from the centre of the lens to the principal focus is the **focal length** 焦距. A **diverging lens** 凹透镜 (thin in the middle) spreads parallel rays out, as if they came from a focus on the incoming side.



A converging lens bends parallel rays to meet at the principal focus; the focal length f is the lens-to-focus distance

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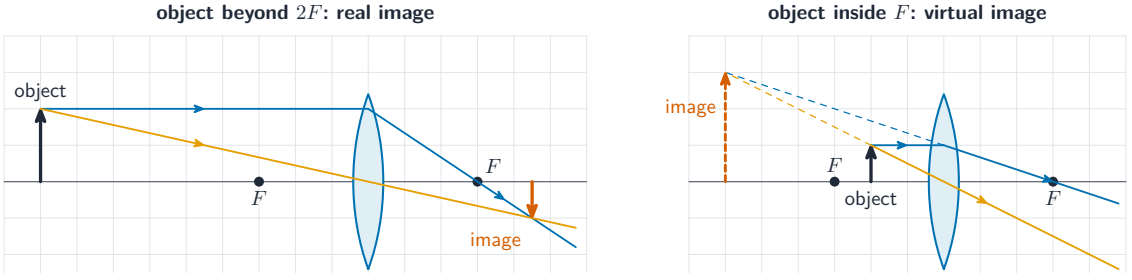
A converging lens can form a **real image** 实像 (rays really meet; can be shown on a screen) or, when the object is very close, a **virtual image** 虚像 (rays only seem to come from it). Used close to the eye, a converging lens is a **magnifying glass** 放大镜.

Describe an image with three pairs of words: **enlarged** 放大的 or **diminished** 缩小的 (or the same size), **upright** 正立 or **inverted** 倒立 (upside down), and real or virtual. An object far beyond the focus gives a diminished, inverted, real image (as in a camera). An object between the focus and the lens gives an enlarged, upright, virtual image (a magnifying glass).

Drawing a ray diagram. Draw the lens as a vertical line on the principal axis and mark a principal focus F on each side. From the top of the object draw two rays:

1. a ray **parallel to the principal axis**, which leaves the lens through the principal focus on the far side;
2. a ray **through the centre of the lens**, which goes straight on without bending.

The top of the image is where these two rays meet. If the rays spread apart after the lens, extend them backwards with dashed lines: they meet at a virtual image on the same side as the object.



Each grid square is 1 cm. Blue: the ray parallel to the axis; orange: the ray through the centre; dashed: rays extended backwards

Worked example (ray diagrams). A converging lens has a focal length of 3.0 cm.

(a) An object 2.0 cm tall stands 9.0 cm from the lens (left diagram). The two rays meet 4.5 cm behind the lens, 1.0 cm below the axis. The image is **real** (the rays really meet, so it can be caught on a screen), **inverted** and **diminished** (1.0 cm tall compared with 2.0 cm).

(b) An object 1.0 cm tall stands 2.0 cm from the lens, inside the focal length (right diagram). After the lens the rays spread apart and never meet. Extended backwards, they meet 6.0 cm from the lens on the same side as the object, 3.0 cm above the axis. The image is **virtual**, **upright** and **enlarged** (three times as tall). This is how a magnifying glass works.

Draw the diagram to scale on squared paper, then read the image distance and height from the grid. A sharp pencil and a ruler matter: a small error in the angle of a ray

moves the image a long way.

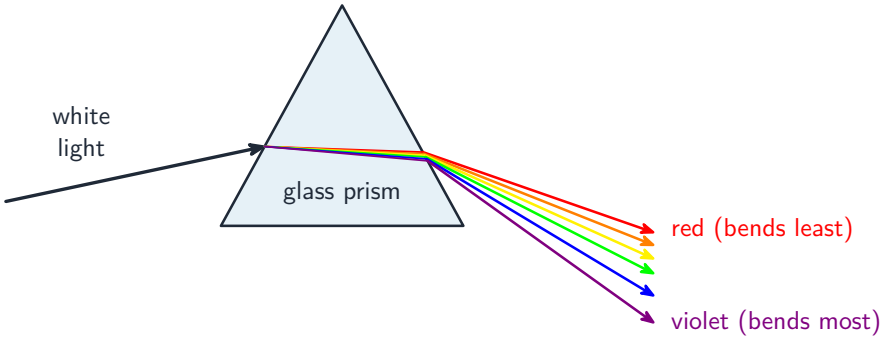
Correcting sight. A person with **short-sightedness** 近视 sees near things clearly but distant things are blurred: the eye focuses the light in front of the **retina** 视网膜 (the back of the eye). A diverging lens in front of the eye spreads the rays out first, so they focus on the retina. A person with **long-sightedness** 远视 sees distant things clearly but near things are blurred: the eye focuses the light behind the retina. A converging lens brings the rays together a little before they enter the eye.



Held away from the eye, a converging lens forms a real image – here the houses behind it appear upside down

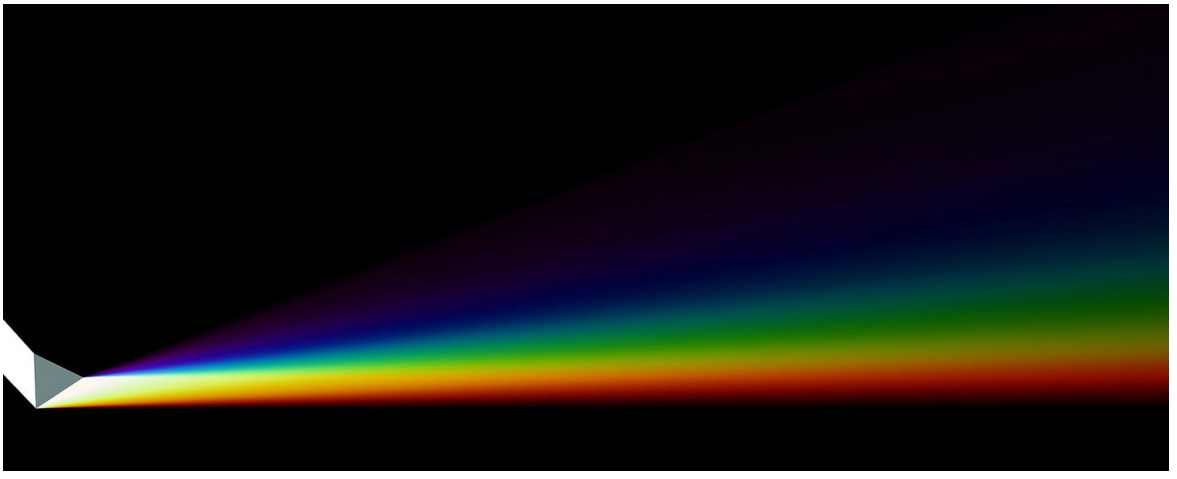
■ Dispersion

A glass **prism** 棱镜 splits white light into the colours of the **spectrum** 光谱. This splitting is called **dispersion** 色散.



A prism refracts violet light most and red light least, so white light spreads into a spectrum

The order of colours is red, orange, yellow, green, blue, indigo, violet. Red light has the longest wavelength and the lowest frequency; violet is the opposite. Light of a single frequency (one pure colour) is **monochromatic** 单色.



White light entering a real glass prism spreads into the full spectrum of colours

The electromagnetic spectrum 电磁波谱

The **electromagnetic spectrum** is a family of waves that all travel at the same high speed in a **vacuum** 真空, 3.0×10^8 m/s. In order from longest wavelength (lowest frequency) to shortest:

Region	A typical use	Danger from too much
radio waves 无线电波	radio and TV signals, astronomy, RFID tags	–
microwaves 微波	mobile phones, satellite TV, cooking	heating of body cells
infrared 红外线	remote controls, thermal imaging, grills, optical fibres	skin burns
visible light	seeing, photography	–
ultraviolet 紫外线	sterilising water, checking bank notes	skin cancer, eye damage
X-rays X射线	medical and security scans	damage to cells
gamma rays 伽马射线	sterilising equipment, treating cancer	mutation of cells

As you go from radio waves to gamma rays, the frequency rises, the wavelength falls, and the energy (and danger) rises. The speed of electromagnetic waves in air is almost

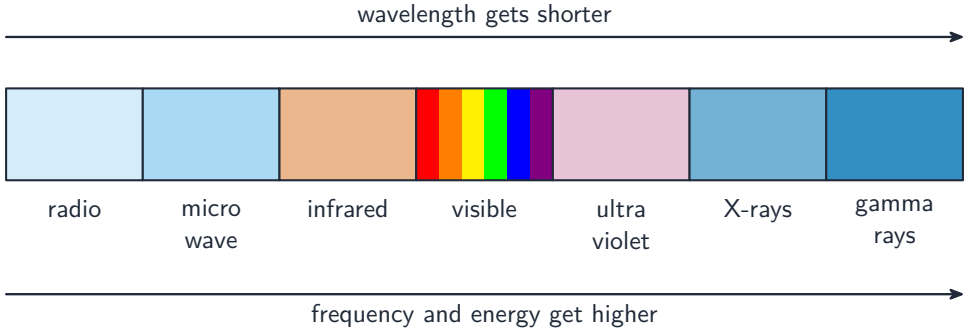
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the same as in a vacuum.

> **Worked example.** A radio station broadcasts at 100 MHz (1.0×10^8 Hz). Find the wavelength of its radio waves.

$$\lambda = \frac{v}{f} = \frac{3.0 \times 10^8}{1.0 \times 10^8} = 3.0 \text{ m}$$

Satellites. Communication with **artificial satellites** 人造卫星 mainly uses microwaves, because they pass through the atmosphere. Some satellite phones use satellites in **low orbit** 低轨道, close to the Earth. Other satellite phones, and direct broadcast satellite television, use satellites in **geostationary orbit** 地球静止轨道, which stay above the same point on the Earth.



From radio waves to gamma rays the wavelength falls while the frequency and energy rise

■ Digital and analogue signals

Radio waves and microwaves carry information as signals, and a signal is either **analogue** 模拟 or **digital** 数字. An **analogue signal** varies **continuously** and can take any value; a **digital signal** is a stream of just two values, on or off (`1` or `0`). Sound can be sent as either kind of signal: a microphone gives an analogue signal, which can be turned into a digital one.

Digital communication can support a **higher rate** of data transmission and a **greater range** due to accurate signal regeneration. These are separate benefits; the actual rate depends on the equipment and channel.

> **Worked example.** A simplified receiver reads levels below 0.5 as `0` and above 0.5 as `1`. It receives 0.12, 0.86, 0.73 and 0.19. The recovered message is `0110`. A repeater sends fresh signals at clean levels 0, 1, 1 and 0, removing the small changes in level. Repeating this along a link supports increased range while the two levels can still be distinguished.

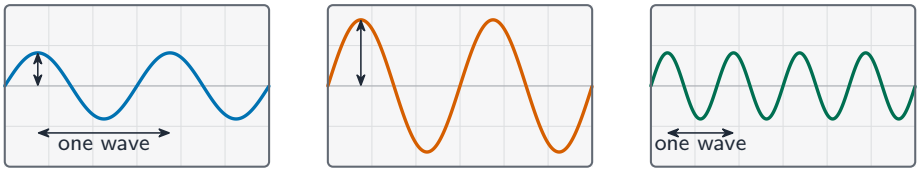
Regeneration is not guaranteed to repair every damaged message. If the third level becomes 0.41, this receiver reads `0` instead of the original `1`. Excessive noise can cause

a wrong digit. For an analogue signal, a received value such as 0.73 could be the true value or a different value changed by noise. There are no two fixed levels to restore; simply amplifying the signal also amplifies its noise.

Sound 声音

Sound is made by a vibrating object. It is a **longitudinal wave**: the air is squeezed into a **compression** 压缩 (particles close together) and stretched into a **rarefaction** 稀疏 (particles far apart).

- Sound needs a **medium** 介质 (a material) to travel through, so it cannot travel through a vacuum.
- Humans can hear frequencies from about 20 Hz to 20 000 Hz.
- Sound travels much slower than light (about 340 m/s in air), and faster in liquids and solids than in gases.
- A **larger amplitude** makes a louder sound (greater **loudness** 响度); a **higher frequency** makes a higher **pitch** 音调. So a dolphin's rapid clicks are high-pitched, and a hard drum-hit (big vibration) is loud.



(a) a quiet, low note

(b) louder: larger amplitude, same frequency (same pitch)

(c) higher pitch: higher frequency, same amplitude (same loudness)

Louder means a larger amplitude; a higher pitch means a higher frequency

A reflected sound is an **echo** 回声.

Measuring the speed of sound. Two students stand a known distance apart, for example 500 m, measured with a tape or a trundle wheel. One bangs two blocks of wood together. The other starts a stopwatch when they see the blocks hit and stops it when they hear the bang. Light arrives almost at once, so the time measured is the time the sound takes, and speed = distance ÷ time. Repeat and take an average to reduce the reaction-time error. The echo method needs one person: clap at a known distance from a large wall and time the reflected sound, remembering that the sound travels there and back.

> **Worked example.** A student stands 85 m from a large wall and claps once. The echo returns 0.50 s later. Find the speed of sound.

The sound travels to the wall and back, a distance of $2 \times 85 = 170$ m, in 0.50 s:

$$v = \frac{s}{t} = \frac{170}{0.50} = 340 \text{ m/s}$$

Ultrasound 超声波 is sound above 20 000 Hz – too high for humans to hear. Its uses rely on reflection: **sonar** measures water depth, **medical scanning** images a baby or soft tissue, and **non-destructive testing** finds cracks inside metal without cutting it open. Like an echo, an ultrasound pulse travels **there and back**, so halve the total distance to reach the object.

> **Worked example.** A sonar pulse returns from the seabed 0.10 s after it is sent; sound travels at 1500 m/s in water. The pulse covers $s = v \times t = 1500 \times 0.10 = 150$ m there and back, so the sea is $150/2 = 75$ m deep.



A microphone converts sound vibrations in air into an electrical signal

Exam tips

- Learn $v = f\lambda$ and be ready to rearrange it. Measure all angles of incidence, reflection and refraction from the **normal** (the line at 90° to the surface), never from the surface itself.
- **Transverse** waves vibrate across the direction of travel (light, water); **longitudinal** waves vibrate along it (sound). Sound needs a **medium**, so it cannot cross a vacuum; light can.
- **Total internal reflection** happens only when light travels from a material with a higher refractive index to one with a lower refractive index (for example glass → air) *and* the angle inside is bigger than the **critical angle**.

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- Know the **electromagnetic spectrum** in order – radio, microwave, infrared, visible, ultraviolet, X-ray, gamma. All travel at the same speed in a vacuum; frequency and energy rise from radio to gamma.
- Going into an optically denser material (higher refractive index, air → glass) light slows down and bends *towards* the normal; leaving it (glass → air) light speeds up and bends *away*.

■ Common mistakes

- Counting wavefronts instead of gaps. From the 1st to the 6th wavefront is 5 wavelengths.
- Measuring angles from the surface. Angles of incidence, reflection and refraction are measured from the normal.
- Saying total internal reflection happens when light goes from air into glass. It only happens inside the denser material (glass or water), at an angle bigger than the critical angle.
- Drawing the ray through the centre of a lens with a bend in it. That ray goes straight on.
- Calling an image "virtual" because it is small or upside down. Real means the rays really meet (a screen can show it); virtual means they only seem to come from it.
- Forgetting to halve the distance in an echo or sonar question. The sound travels there and back.
- Leaving MHz or kHz in $v = f\lambda$. Change to Hz first: 1 MHz = 1 000 000 Hz.

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Electricity and magnetism

IGCSE Physics

Magnetism

A **magnet** 磁体 can attract some metals. Every magnet has two ends, called **poles** 磁极: a **north pole** 北极 (N pole) and a **south pole** 南极 (S pole).



Like poles repel; unlike poles attract

The rule for two poles is like the rule for charges:

- Poles that are the same (N and N, or S and S) **repel** 排斥 (push apart): this is **repulsion** 排斥力.
- Poles that are different (N and S) **attract** 吸引 (pull together): this is **attraction** 吸引力.

A magnet attracts a **magnetic material** 磁性材料, such as iron, steel, cobalt and nickel. Materials such as copper, plastic and wood are classed as non-magnetic here: they are not strongly attracted by a stationary bar magnet.

Induced magnetism

Put a piece of iron near or touching a magnet, and the iron becomes a magnet itself. This is **induced magnetism** 感应磁性. The end of the iron nearest the magnet gains the opposite pole, so the two then attract.

Temporary and permanent magnets

- **Soft iron** 软铁 is easy to **magnetise** 磁化 but loses its magnetism quickly. It is used for a **temporary magnet** 临时磁体.
- **Steel** 钢 is harder to magnetise but keeps its magnetism. It is used for a **permanent magnet** 永磁体.

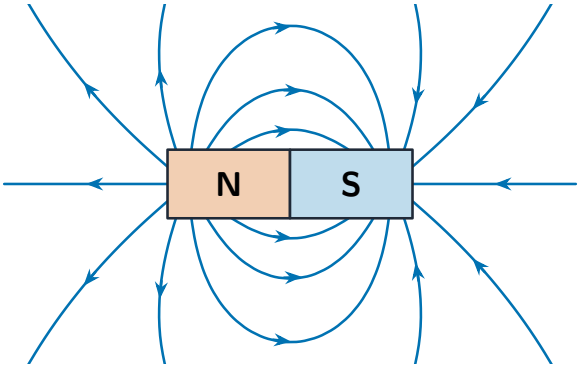
An initially **unmagnetised** 未磁化 soft-iron core is suitable when magnetism should fall quickly after the current stops. Steel is a suitable permanent-magnet material in these examples.

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Magnetic fields

A **magnetic field** 磁场 is a **region** 区域 where a magnetic pole feels a force. We draw it with **magnetic field lines** 磁场线:

- The lines come *out of* the N pole and go *into* the S pole.
- The field direction at a point is the direction of the force on the N pole of a small test magnet placed there.
- Where the lines are close together the field is strong; where they are far apart the field is weak.



field lines leave N and enter S; they never cross,
and they are closest together at the poles, where the field is strongest

The field lines of a bar magnet come out of the N pole and go into the S pole

You can show the pattern by sprinkling **iron filings** 铁屑 on paper over a magnet, or by moving a small plotting **compass** 指南针 around it (the needle points along the field).



Iron filings line up along the field lines, showing the field pattern of a bar magnet

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■ Uses of magnets

- **Permanent magnets**: fridge door catches, compass needles, loudspeakers.
- **Electromagnets** 电磁铁 (their field is controlled by current): cranes that lift scrap iron, electric bells, relays. Changing the current controls an electromagnet's field; soft iron reduces remaining magnetism when the current stops.

Magnetic forces happen because the fields of the two magnets push and pull on each other.

Static electricity

There are two kinds of **electric charge** 电荷: **positive charge** 正电荷 and **negative charge** 负电荷. The rule is like the rule for poles – same charges repel, different charges attract.



Every hair picks up the same charge from the dome, and like charges repel – so the hairs push apart

■ Charging by friction

When you rub two different materials together, **electrons** 电子 (tiny negative particles) move from one to the other. This is **charging by friction** 摩擦起电.

- The material that gains electrons becomes negative.
- The material that loses electrons becomes positive.

In charging solids by friction, electrons transfer; positive nuclei do not move between the solids. If a rod gains electrons from a cloth, it becomes negative and the cloth positive. The direction of transfer depends on the pair of materials.

Detecting a charge. A charged rod picks up small pieces of paper, and it bends a thin stream of water from a tap. Hang one charged rod from a thread and bring

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another charged rod near it: if the two have the same kind of charge, the hanging rod swings away. Repulsion is the only sure test for a charge, because attraction also happens with uncharged objects.

Conductors and insulators

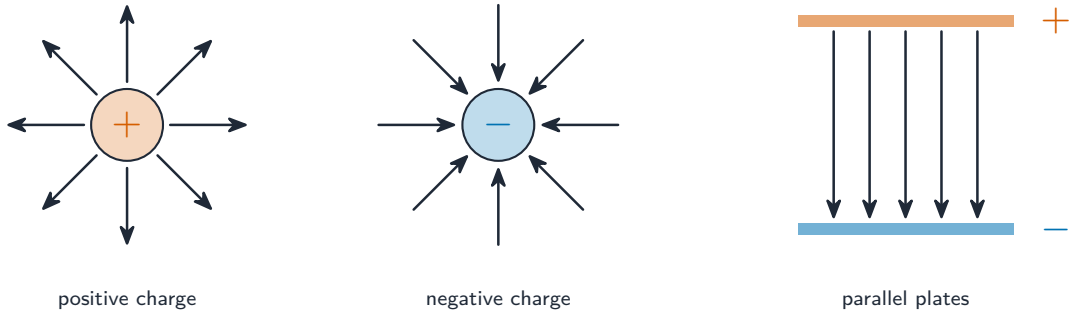
- A **conductor** 导体 (copper and other metals) lets charge flow through it easily, because it has free electrons that can move.
- An **insulator** 绝缘体 (plastic, rubber, glass) does not let charge flow, because its electrons cannot move freely.

In a supervised low-voltage test, place the sample in a working cell-and-lamp circuit. A lit lamp shows enough current passes. If it does not light, first check the connections and the lamp with a known conductor; a fault or a very small current can also prevent lighting.

Electric fields and ions

Charge is measured in **coulombs** 库仑 (C). An **electric field** 电场 is a region where an electric charge feels a force. Its direction at a point is the direction of the force on a positive charge. Simple field patterns (the arrows show the direction):

- around a **point charge** 点电荷: straight lines, pointing away from a positive charge and towards a negative charge;
- around an isolated charged conducting sphere: radial lines, like a point charge outside the sphere;
- between two parallel plates with opposite charges, ignoring edge effects: straight, evenly spaced lines from the positive plate to the negative plate.



Electric field lines point away from a positive charge and towards a negative one; between parallel plates the field is uniform

An atom is normally neutral. If it loses electrons it becomes a positive **ion** 离子; if it gains electrons it becomes a negative ion.

Electric current

An **electric current** 电流 is a flow of electric charge. It is measured in **amperes** 安培 (A) with an **ammeter** 电流表, joined in series in the circuit.

An **analogue** 模拟 ammeter has a needle that moves over a scale; a **digital** 数字 ammeter shows the reading as a number. Both come with different **ranges** 量程. Start with a range high enough to avoid overloading the meter, then use a suitable lower range that still includes the reading: a 0–1 A range for a current of about 0.4 A, or a 0–100 mA range for a few milliamps.

Current is the charge that passes a point each second:

$$I = \frac{Q}{t}$$

Here I is current (A), Q is charge (C) and t is time (s). Rearranged, $Q = It$.

> **Worked example.** A current of 3.0 A flows through a lamp for 20 s. How much charge passes through it?

Known: $I = 3.0$ A and $t = 20$ s. Current is charge per unit time, so rearrange $I = Q/t$:

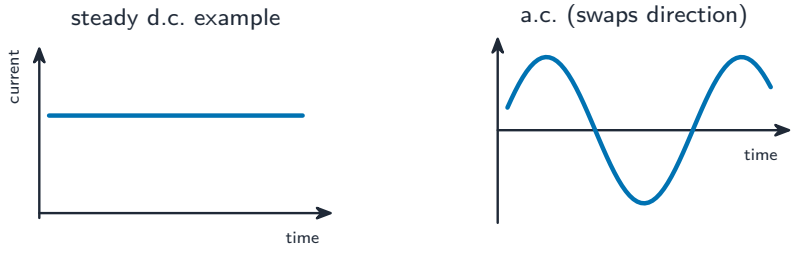
$$Q = It$$

$$Q = (3.0\ \text{A})(20\ \text{s}) = 60\ \text{C}$$

In a metal the current is a flow of **free electrons** 自由电子. There are two "directions" to know:

- **Conventional current** 常规电流 is taken to flow from + to − round the outside of the cell.
- The free electrons really drift the other way, from − to +.

A **direct current** 直流电 (d.c.) flows in one direction; its size need not be constant. A steady battery current is one example. An **alternating current** 交流电 (a.c.) keeps swapping direction many times each second, as from the **mains supply** 市电.



The d.c. example is steady and one-directional; the a.c. example reverses direction

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E.m.f. and potential difference

A cell gives **energy** 能量 to the charges that move through it. Two quantities describe this, and both are measured in **volts** 伏特 (V).

- The **electromotive force** 电动势 (e.m.f.) of a source is the electrical work it does to drive unit charge all the way round a complete **circuit** 电路.
- The **potential difference** 电势差 (p.d.) across a component is the work done by unit charge as it passes *through that component*.

A **voltmeter** 电压表 measures e.m.f. or p.d. It is joined in parallel (across the component). Like ammeters, voltmeters are analogue or digital and have different ranges: pick the range just above the largest voltage you expect.



*The voltmeter across the **cell** measures its terminal p.d.; this equals the e.m.f. for the ideal cell assumed here. The meter across the **lamp** measures that component's p.d.*

Both are work done per unit charge:

$$E = \frac{W}{Q}, \qquad V = \frac{W}{Q}$$

where W is the energy transferred (J) and Q is the charge (C). For a source giving $W = 120$ J to $Q = 60$ C, use work per unit charge:

$$E = \frac{W}{Q}$$

$$E = \frac{120\ \text{J}}{60\ \text{C}} = 2.0\ \text{V}$$

Here E denotes e.m.f. in volts; in the energy section E denotes energy in joules. Read the context and unit.

Resistance

Resistance 电阻 measures how hard it is for current to flow. At the same p.d., a bigger resistance gives a smaller current. It is measured in **ohms** 欧姆 (Ω).

$$R = \frac{V}{I}$$

Measuring resistance. Connect the component in series with a cell, a switch, an ammeter and a **variable resistor** 可变电阻器, and connect a voltmeter across the component. Close the switch, read I and V, then change the variable resistor to get several more pairs of readings. For a resistor held at constant temperature, repeated $R = V/I$ values can be compared and averaged. A V-against-I graph has gradient R; an I-against-V graph has gradient $1/R$. For a heating filament, resistance changes, so averaging across different operating temperatures would hide the change.

> **Worked example.** A 12 V battery drives a current of 0.50 A through a lamp. Find the lamp's resistance.

Use the p.d.-to-current ratio at this operating point:

$$R = \frac{V}{I}$$

$$R = \frac{12\ \text{V}}{0.50\ \text{A}} = 24\ \Omega$$

For wires of the same metal at constant temperature:

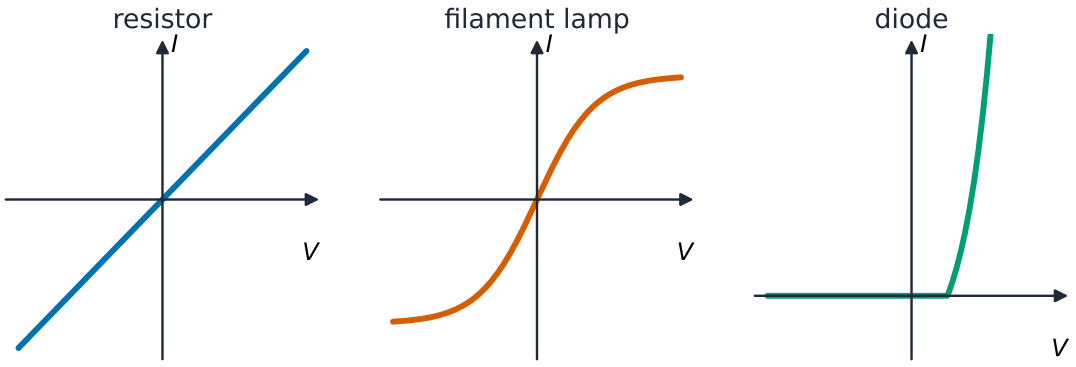
- a longer wire has a bigger resistance – resistance is **directly proportional** 成正比 to length, $R \propto l$;
- a thicker wire has a smaller resistance – resistance is **inversely proportional** 成反比 to **cross-sectional area** 横截面积, $R \propto \dfrac{1}{A}$.

So doubling the length doubles the resistance; doubling the area halves it. (Area depends on the diameter squared, so a small change in diameter changes the resistance a lot.)

Current–voltage graphs show how three components behave:

Component	Shape of the I–V graph	What it tells you
resistor 电阻器 (fixed)	straight line through the origin	resistance is constant, so $I \propto V$
filament lamp 灯丝灯泡	S-shaped, getting flatter as V rises	the wire heats up, so its resistance rises
diode 二极管	current one way only	very high resistance the "wrong" way

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resistor (ohmic): $V = IR$ straight · filament: resistance rises with heat · diode: one-way

A resistor gives a straight line; a filament lamp curves as it heats up; a diode lets current pass only one way

Electrical energy and power

A circuit transfers energy from a source (a cell or the mains) to the components, and then into the surroundings (often as heat, light or sound).

Electrical power 电功率 is the energy transferred each second, measured in **watts** 瓦特 (W):

$$P = IV$$

The **electrical energy** 电能 transferred in a time t, measured in **joules** 焦耳 (J), is:

$$E = IVt$$

> **Worked example.** A 12 V motor draws a current of 2.0 A. Find its power, and the energy it transfers in 30 s.

Power is energy transferred per second. Known: $I = 2.0$ A, $V = 12$ V, $t = 30$ s.

$$P = IV$$

$$P = (2.0\ \text{A})(12\ \text{V}) = 24\ \text{W}$$

$$E = Pt$$

$$E = (24\ \text{W})(30\ \text{s}) = 720\ \text{J}$$

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The kilowatt-hour

Home electricity bills use a bigger energy unit, the **kilowatt-hour** 千瓦时 (kWh). One kilowatt-hour is the energy used by a 1 kW **appliance** 电器 in 1 hour.

$$\text{energy (kWh)} = \text{power (kW)} \times \text{time (h)}$$

$$\text{cost} = \text{energy (kWh)} \times \text{price per kWh}$$

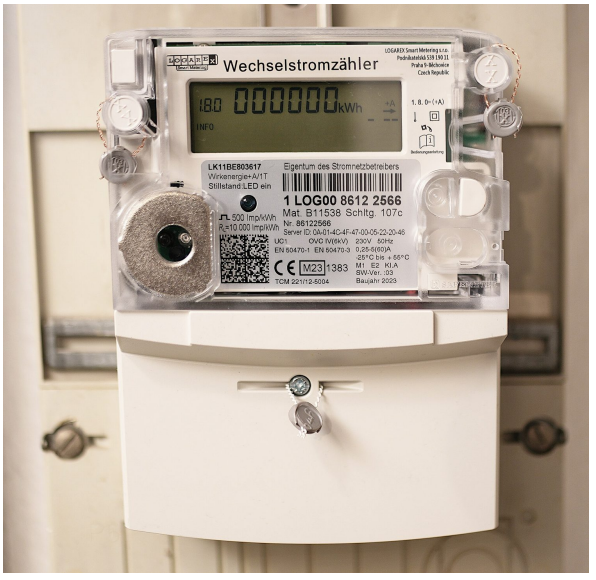
For a 2 kW **heater** 加热器 used for 3 h at a fictional price of 20 cents per kWh:

$$E = Pt$$

$$E = (2\ \text{kW})(3\ \text{h}) = 6\ \text{kWh}$$

$$\text{cost} = E \times \text{price per kWh}$$

$$\text{cost} = (6\ \text{kWh})(20\ \text{cents/kWh}) = 120\ \text{cents}$$



A household electricity meter counts the energy used, in kilowatt-hours (kWh) – billing uses the change in its reading, together with the tariff

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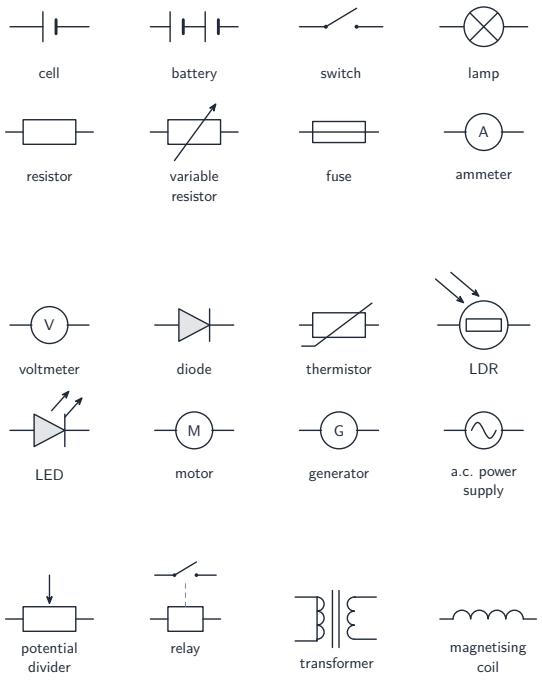
Circuits

■ Circuit components

You should know these components and how they behave:

Component	What it does
cell 电池 / **battery** 电池组	drives current round the circuit (a battery is two or more cells)
power supply 电源	a source of d.c. or a.c.
switch 开关	breaks or completes the circuit
resistor (fixed)	gives a fixed resistance
variable resistor	a resistance you can change, to control the current
fuse 保险丝	melts and breaks the circuit if the current is too big
lamp / **heater**	turns electrical energy into light / into heat
thermistor 热敏电阻	the NTC type studied here falls in resistance when hotter
light-dependent resistor 光敏电阻 (LDR)	its resistance falls as the light gets brighter
diode / **light-emitting diode** 发光二极管 (LED)	lets current one way only; an LED also gives out light
relay 继电器	a switch worked by an electromagnet (small current controls a big one)
motor 电动机	turns electrical energy into movement
bell 电铃	makes a sound
transformer 变压器	changes the size of an a.c. voltage

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The standard symbols used to draw circuit diagrams



Real resistors: the coloured bands give each one's resistance in ohms

■ Series and parallel

In a **series** 串联 circuit the parts form one single loop:

- the current is the same at every point;
- the supply p.d. is shared between the components;
- cells in series add their e.m.f.s (when they point the same way);

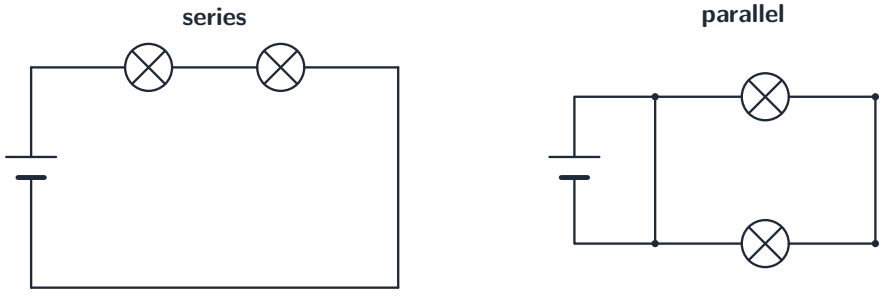
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- resistors in series add up: $R_{\text{total}} = R_1 + R_2 + \ldots$

In a **parallel** 并联 circuit the parts are on separate branches:

- each branch gets the full supply p.d.;
- the current splits, so the current from the source is bigger than the current in any one branch;
- the **total resistance** 总电阻 is less than the smallest single resistance.

Lamps in a home are wired in parallel: each gets the full voltage, and if one fails the others stay on.



In a series circuit the components share one loop; in a parallel circuit each lamp has its own branch

For calculations (with the rules above):

- at a **junction** 节点, the total current flowing in equals the total current flowing out;
- in series, the supply p.d. equals the sum of the p.d.s across the components;
- in parallel, the p.d. across each branch is the same;
- two resistors in parallel combine as

$$\frac{1}{R_{\text{total}}} = \frac{1}{R_1} + \frac{1}{R_2}$$

Worked example. A 6 Ω resistor and a 3 Ω resistor are connected in parallel. Find their combined resistance.

Use the parallel-resistance relation because both resistors have the same p.d.:

$$\frac{1}{R_{\text{total}}} = \frac{1}{R_1} + \frac{1}{R_2}$$

$$\frac{1}{R_{\text{total}}} = \frac{1}{6\ \Omega} + \frac{1}{3\ \Omega} = \frac{1}{2\ \Omega}$$

$$R_{\text{total}} = 2\ \Omega$$

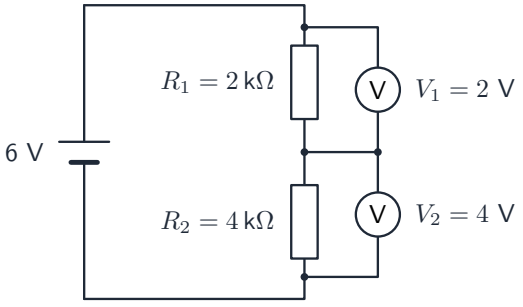
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Notice the combined resistance (2 Ω) is smaller than the smaller of the two resistors.

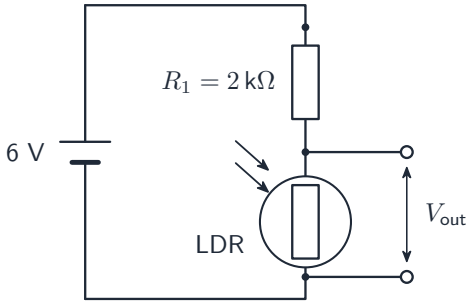
■ Potential dividers

Two resistors in series share the supply voltage. This is a **potential divider** 分压器. For the same current, a bigger resistance has a bigger p.d. across it, so the bigger resistor takes the bigger share:

$$\frac{R_1}{R_2} = \frac{V_1}{V_2}$$



(1) bigger resistor, bigger share of the 6 V



(2) darker: LDR resistance up, so V_{out} goes up

The bigger resistance takes the bigger share; with an LDR the output follows the light level

A *variable potential divider* uses a movable contact to change the output voltage smoothly, for example from 0 V up to the full supply. If you use a thermistor or an LDR as one of the resistors, the output voltage changes with temperature or light – handy for switching a heater or a lamp on and off automatically.

Electrical safety

A home is fed by the mains. The mains is dangerous if it is used wrongly.

■ Hazards

These are **hazards** 危险 (dangers) with mains electricity:

- damaged **insulation** 绝缘层 – bare wires can give a shock or start a fire;
- **overheating** 过热 cables – too much current makes a cable hot, which can start a fire;
- **damp** 潮湿 conditions – water lets current pass into a person, raising the risk of a shock;
- **overloading** 过载 – plugging too many appliances into one **socket** 插座 draws too much current.

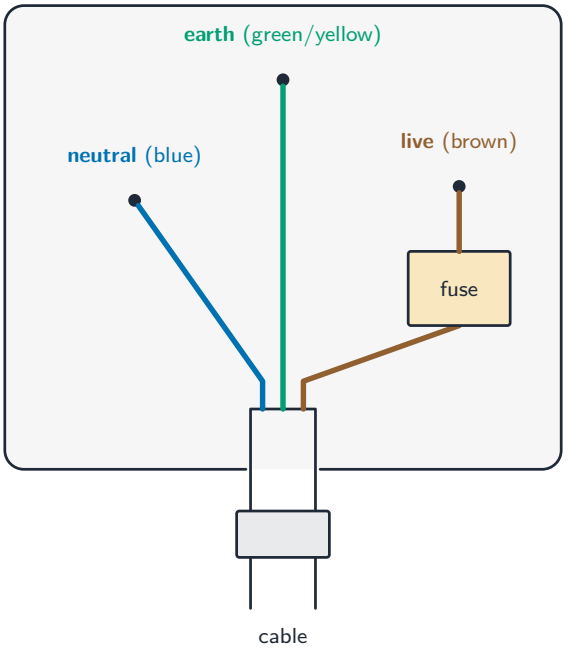
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Live, neutral and earth

A mains cable has three wires:

- the **live wire** 火线 carries the high voltage;
- the **neutral wire** 零线 completes the circuit at about zero voltage;
- the **earth wire** 地线 is a safety wire joined to the ground.

A switch (and a fuse) must be fitted in the *live* wire. Opening that switch disconnects the appliance from the live supply in the circuit model. A switch being off is not proof that real equipment is safe to open or work on.



*In a three-pin plug the **live** (brown) and **neutral** (blue) carry the current, the **earth** (green/yellow) is the safety wire, and the **fuse** always sits in the live wire.*

Fuses, trip switches and earthing

A fuse is a thin wire that melts if the current gets too big, breaking the circuit before the cable overheats. For a simplified exam choice, select a **fuse rating** 额定值 above normal working current and appropriate for the stated cable and appliance limits. For real equipment, use the specified protection.

> **Worked example (choosing a fuse).** Fuses of 3 A, 5 A and 13 A are available. Choose a fuse for (a) a 2300 W kettle and (b) a 60 W lamp, both on a 230 V supply.

(a) $I = \dfrac{P}{V} = \dfrac{2300}{230} = 10$ A. The fuse must be above 10 A, so choose 13 A. A 5 A fuse would melt every time the kettle is switched on.

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(b) $I = \dfrac{60}{230} = 0.26$ A. Choose the 3 A fuse: it is the smallest rating above the working current, so it melts soonest if a fault makes the current rise.

An overcurrent **trip switch** 跳闸开关 (circuit breaker) opens the circuit when excessive current is detected and can be reset after the fault is corrected. Operating time depends on the device and fault; it is not always faster than every fuse.

The metal **casing** 外壳 of an appliance must be made safe in one of two ways:

- **earthed** 接地: the casing is joined to the earth wire. If a live wire touches the casing, a large current flows to earth and blows the fuse.
- **double-insulated** 双重绝缘: double or reinforced insulation separates the user from live parts; a non-conducting outer casing is a common example. A plastic-looking case alone does not establish double insulation. Such an appliance needs no protective earth connection; its fuse still protects circuit cabling.



A home consumer unit contains different protection devices. An MCB responds to overcurrent; an RCD responds to an imbalance between live and neutral currents. The printed ratings describe different properties, not a single trip current.

Electromagnetic effects

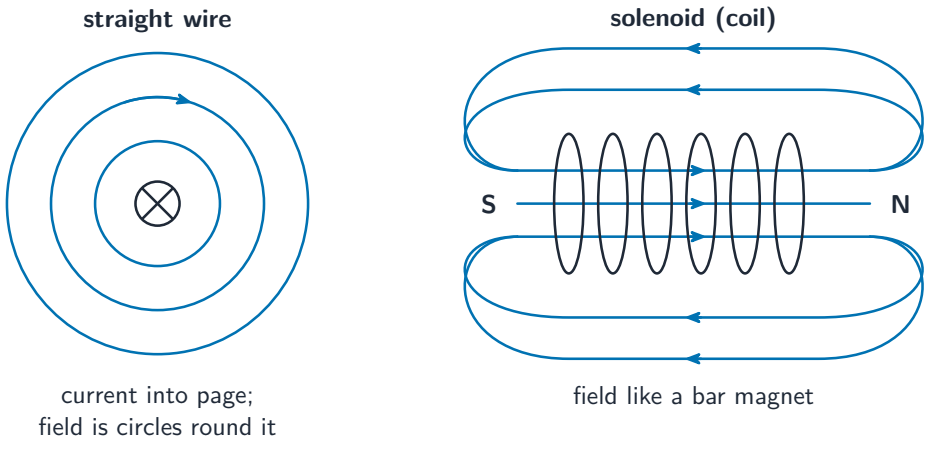
■ The magnetic effect of a current

A current in a wire makes a magnetic field around it.

- Around a straight wire the field lines are circles around the wire; the field is stronger close to the wire. Reverse the current and the field reverses.
- A **solenoid** 螺线管 (a long **coil** 线圈 of wire) makes a field just like a bar magnet, with a N pole at one end and a S pole at the other. The field inside is strong and even.

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You can show both patterns with iron filings or a plotting compass. For a solenoid of fixed length, increasing current or turns, or adding a soft-iron core, strengthens the field. Around a straight wire, the field strengthens with current and weakens with distance.



A current makes circular field lines around a straight wire, and a bar-magnet-like field for a solenoid

The magnetic effect is used in a relay and in a loudspeaker. In a relay, a small current in a coil magnetises a soft-iron core, which pulls a switch closed in a second circuit. The second circuit can carry a large current, so a small switch or a sensor can safely control a motor or a heater (for example, the ignition switch of a car starts its motor through a relay). In a **loudspeaker** 扬声器 a changing current in a coil makes the coil push and pull a paper cone, which moves the air and makes sound.

■ Electromagnetic induction

When a wire moves across a magnetic field, or the field through a coil changes, an e.m.f. is **induced** in the wire. If the wire is part of a complete circuit, this e.m.f. drives a current. This is **electromagnetic induction** 电磁感应.

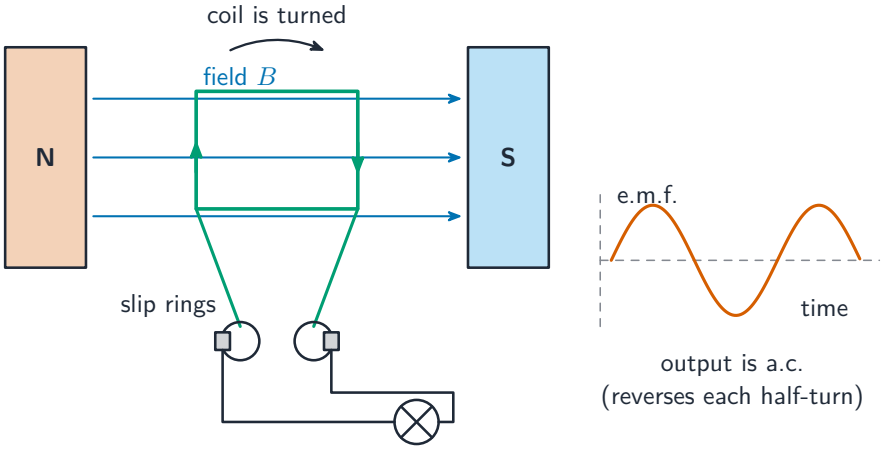
To show it: move a magnet in and out of a coil joined to a sensitive meter, and watch the needle flick. The induced e.m.f. is bigger when you use a stronger magnet, move faster, or use more turns on the coil. The induced e.m.f. always acts to *oppose* the change that causes it. For a wire moving upward across a rightward field in a closed circuit, the right-hand rule gives induced conventional current into the page. Its motor-effect force is downward, opposing the motion. The direction of the induced current is given by **Fleming's right-hand rule** 弗莱明右手定则: hold the thumb, first finger and second finger of the right hand at right angles to one another; the thumb points along the motion of the wire, the first finger along the field (N to S), and the second finger then gives the induced current.

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The a.c. generator

An **a.c. generator** 交流发电机 turns movement into electricity. A coil is spun in a magnetic field (or a magnet is spun near a coil). As it turns, the field through the coil keeps changing, so an alternating e.m.f. is induced.

- **Slip rings** 滑环 and carbon **brushes** 电刷 carry the current out to the circuit while the coil keeps turning.
- For a coil rotating at constant speed, the e.m.f. magnitude is greatest when the coil's plane is parallel to the magnetic field, and zero when its plane is perpendicular to the field. "Flat" and "upright" depend on how a diagram is drawn, so use the field direction as the reference. So the e.m.f.–time graph is a wave: peak, zero, opposite peak, zero, for each turn.



Turning the coil induces an alternating e.m.f.; the slip rings carry the a.c. out to the circuit

Force on a current-carrying conductor

When a current-carrying wire lies in a magnetic field, the field of the wire and the field of the magnet push on each other, so the wire feels a force. This is the **motor effect**.

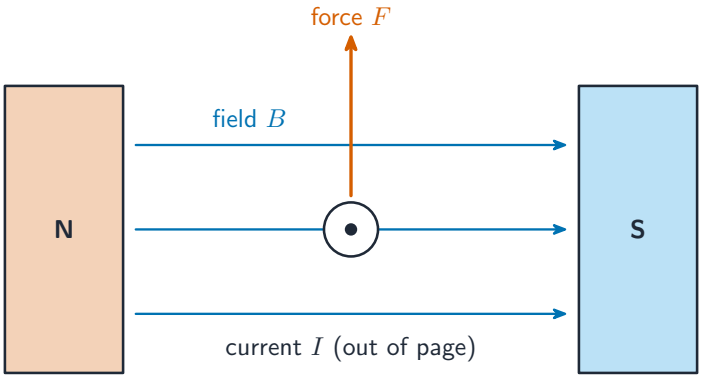
- Reverse the current, *or* reverse the field, and the force reverses.
- Make the current bigger or the field stronger, and the force is bigger.

For a conductor perpendicular to the field, the force is perpendicular to both field and current. A conductor parallel to the field has no motor-effect force. You can find the force direction with **Fleming's left-hand rule** 弗莱明左手定则: thumb = force (motion), first finger = field (N to S), second finger = current.

Showing the force. Lay a stiff copper wire (or a strip of aluminium foil) between the poles of a U-shaped magnet and connect it to a cell through a switch. When the current flows, the wire jumps up or down. Reverse the cell and the wire jumps the other way; turn the magnet over and it reverses again. A bigger current or a stronger

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magnet gives a bigger jump.



F, B and I are all at 90° (Fleming's left-hand rule)

A current-carrying wire in a magnetic field feels a force at right angles to both the field and the current

Worked example (direction of the force). A horizontal wire carries a current from left to right across the page. The N pole of a magnet is above the wire and the S pole is below it, so the field points down the page. Find the direction of the force on the wire.

Point your left hand's first finger down the page (field, N to S) and your second finger to the right (current). Your thumb then points **into the page**: that is the direction of the force. Reverse the current, or swap the poles, and the force points out of the page.

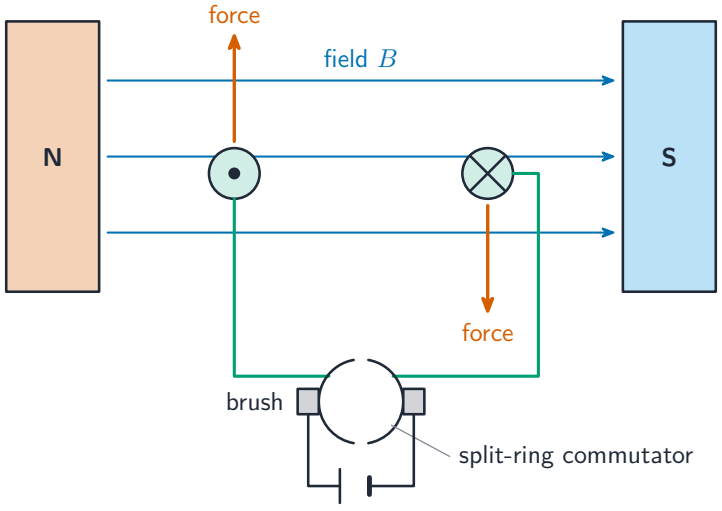
A moving stream of charged particles acts as a current, so motion across a magnetic field can produce a sideways force – it **deflects** 偏转 the beam. (Remember electrons flow opposite to the conventional current.)

■ The d.c. motor

A coil carrying a current in a magnetic field feels a **turning effect** 转动效应, because the forces on its two sides act in opposite directions. This is a **d.c. motor** 直流电动机. The turning effect is bigger with more turns on the coil, a bigger current, or a stronger field.

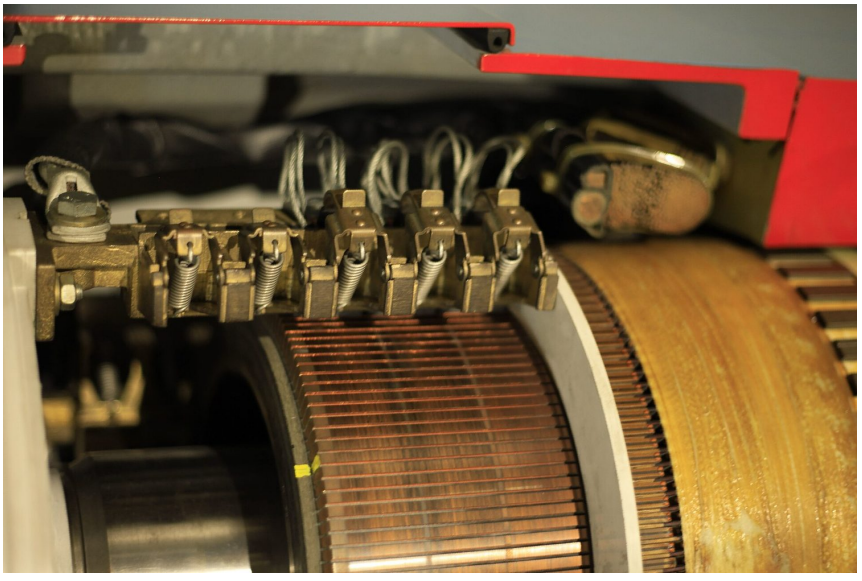
A **split-ring commutator** 换向器 swaps the current direction in the coil every half-turn. This keeps the coil turning the same way instead of stopping after half a turn.

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the two forces form a couple that turns the coil

The forces on the two sides of the coil form a couple; the split-ring commutator keeps it turning one way



In a real d.c. machine, carbon brushes press on the copper commutator bars to feed current to the spinning coil

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The transformer

A **transformer** changes the size of an a.c. voltage. It has two coils wound on a **soft-iron core** 软铁芯:

- the **primary coil** 原线圈 takes in the a.c. voltage;
- the **secondary coil** 副线圈 gives out the changed voltage.

The a.c. in the primary makes a changing magnetic field in the core. The core carries this field to the secondary, where it induces an a.c. e.m.f. The coils are made of insulated copper wire, so the current goes round the turns instead of short-circuiting between them, and the two coils are **not** connected to each other electrically: energy passes between them only through the changing magnetic field. The core is **soft** iron because it is magnetised and demagnetised very easily, so its field can follow the a.c. as it reverses many times a second. The voltages and the numbers of turns are linked by:

$$\frac{V_p}{V_s} = \frac{N_p}{N_s}$$

> **Worked example.** A transformer has 1200 turns on the primary coil and 100 turns on the secondary coil. The primary is connected to a 240 V a.c. supply. Find the secondary voltage.

Use the voltage-to-turns ratio, then rearrange for the secondary voltage:

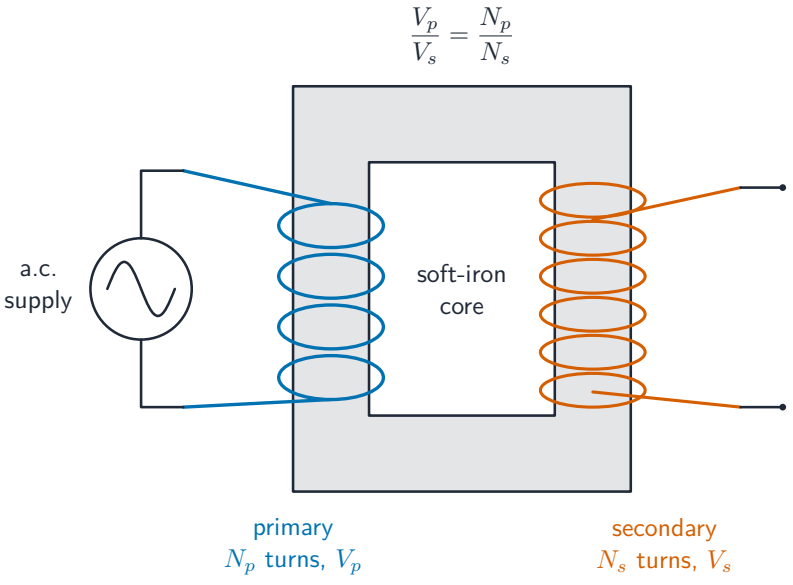
$$\frac{V_p}{V_s} = \frac{N_p}{N_s}$$

$$V_s = V_p \frac{N_s}{N_p}$$

$$V_s = (240\ \text{V})\frac{100}{1200} = 20\ \text{V}$$

Fewer turns on the secondary, so this is a step-down transformer.

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The changing field in the core links the two coils; the voltage ratio equals the turns ratio



A real transformer on a power pole steps the high voltage in the cables down to domestic supply voltage; this is still hazardous

If the secondary has more turns it is a **step-up** 升压 transformer (voltage rises); fewer turns make a **step-down** 降压 transformer (voltage falls). For example, a transformer changing 240 V to 12 V is a step-down type, and the primary has 20 times as many turns as the secondary.

If a transformer is 100% efficient, the power in equals the power out:

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$$I_p V_p = I_s V_s$$

So a step-up transformer raises the voltage but lowers the current.

■ Why we use high voltage to send power

Electricity is sent across the country by **high-voltage transmission** 高压输电. The power lost as heat in the cables is

$$P = I^2 R$$

where R is the resistance of the cables. A step-up transformer raises the voltage and so lowers the current for the same power ($P = IV$). A smaller current means much less power wasted in the cables. A step-down transformer then lowers the voltage for domestic supply; mains voltage remains hazardous.



Pylons hold the cables that carry electricity at very high voltage, which keeps the current – and the wasted power – low

Exam tips

- **Current** is the same everywhere in a **series** circuit; in a **parallel** circuit it splits between the branches. Voltage (p.d.) is shared out in series, but is the same across every parallel branch.
- Adding resistors in **series** increases the total resistance ($R_1 + R_2$); adding them in **parallel** makes the total *less* than the smallest single resistor.
- An **ammeter** goes in *series* and has very low resistance; a **voltmeter** goes in *parallel* across a component and has very high resistance.

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- In a **transformer** $\frac{V_p}{V_s} = \frac{N_p}{N_s}$: more turns on the secondary steps the voltage *up*, fewer steps it *down*. A transformer needs a changing magnetic field; steady d.c. does not give a sustained secondary output
- Power is sent across country at **high voltage** so the current – and the heat wasted in the cables, $P = I^2R$ – is small.
- Fit the **switch and the fuse in the live wire**, and choose a fuse rating just above the appliance's normal working current.

■ Common mistakes

- Choosing a fuse rating below the working current, or far above it. Work out $I = P/V$, then choose the next rating above it.
- Putting the fuse or the switch in the neutral wire. They go in the live wire, so the appliance is disconnected from the high voltage when the fuse melts or the switch is off.
- Mixing up the two hand rules. Left hand for the **motor** effect (force on a current); right hand for the **generator** effect (induced current).
- Pointing the "field" finger from S to N. Magnetic field lines go from the N pole to the S pole.
- Expecting a transformer to work on d.c. A steady current gives a steady field in the core, so no e.m.f. is induced in the secondary.
- Saying a step-up transformer increases the power. It raises the voltage and lowers the current; at best the power stays the same.
- Saying the current is "used up" by a lamp. The current is the same before and after a component in series; energy is transferred, not current.

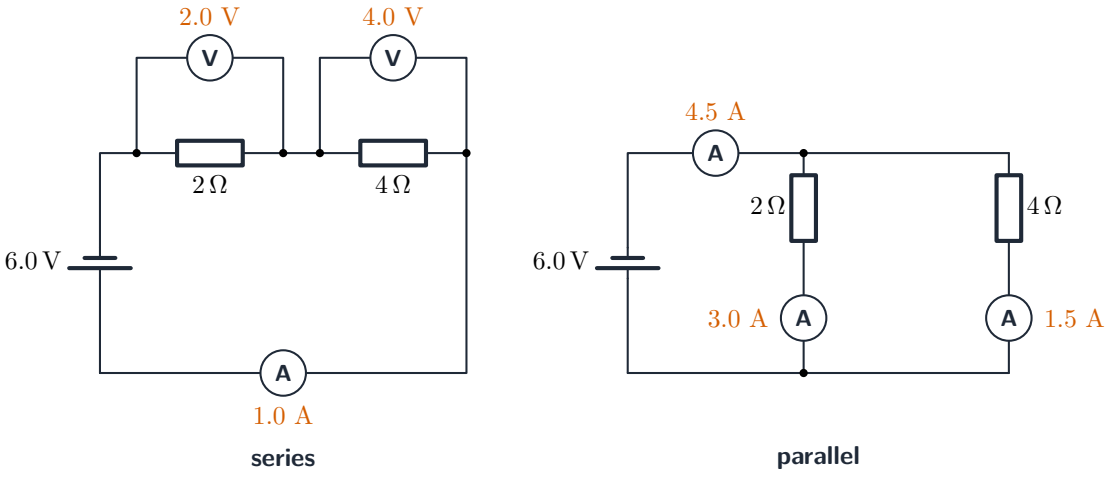
Worked practice and source grounding

These original practice tasks support syllabus 4.1–4.5. They are not reproduced past-paper questions.

■ Compare series and parallel

Connect fixed 2 Ω and 4 Ω resistors to an ideal 6 V source. Find the current and p.d. for each resistor in each arrangement.

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The same two resistors on 6 V: in series one current and shared p.d.s; in parallel the full p.d. on each branch and currents that add

In series, add the resistances; then use Ohm's law to find the common current:

$$R_{\text{total}} = R_1 + R_2$$

$$R_{\text{total}} = (2\ \Omega) + (4\ \Omega) = 6\ \Omega$$

$$I = \frac{V}{R_{\text{total}}}$$

$$I = \frac{6\ \text{V}}{6\ \Omega} = 1\ \text{A}$$

The p.d. across each resistor follows from this same current:

$$V_1 = IR_1$$

$$V_1 = (1\ \text{A})(2\ \Omega) = 2\ \text{V}$$

$$V_2 = IR_2$$

$$V_2 = (1\ \text{A})(4\ \Omega) = 4\ \text{V}$$

In parallel, each branch has the full supply p.d. Use Ohm's law separately for each branch, then conserve charge at the junction:

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$$I_1 = \frac{V}{R_1}$$

$$I_1 = \frac{6\ \text{V}}{2\ \Omega} = 3\ \text{A}$$

$$I_2 = \frac{V}{R_2}$$

$$I_2 = \frac{6\ \text{V}}{4\ \Omega} = 1.5\ \text{A}$$

$$I_{\text{total}} = I_1 + I_2$$

$$I_{\text{total}} = (3\ \text{A}) + (1.5\ \text{A}) = 4.5\ \text{A}$$

Charge is conserved; it is not used up by the resistors.

■ Follow a potential-divider output

An ideal 6 V supply connects to a fixed 2 kΩ resistor and an NTC thermistor in series. Take the unloaded output across the thermistor. Find the output before and after warming reduces its resistance from 4 kΩ to 1 kΩ.

The p.d. ratio equals the resistance ratio. Before warming:

$$\frac{V_{\text{fixed}}}{V_{\text{thermistor}}} = \frac{R_{\text{fixed}}}{R_{\text{thermistor}}}$$

$$\frac{V_{\text{fixed}}}{V_{\text{thermistor}}} = \frac{2\ \text{k}\Omega}{4\ \text{k}\Omega} = \frac{1}{2}$$

$$V_{\text{fixed}} + V_{\text{thermistor}} = V_{\text{supply}}$$

$$\frac{1}{2}V_{\text{thermistor}} + V_{\text{thermistor}} = 6\ \text{V}$$

$$V_{\text{thermistor}} = \frac{6\ \text{V}}{1.5} = 4\ \text{V}$$

After warming, use the new resistance in the same ratio and sum:

$$\frac{V_{\text{fixed}}}{V_{\text{thermistor}}} = \frac{R_{\text{fixed}}}{R_{\text{thermistor}}}$$

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$$\frac{V_{\text{fixed}}}{V_{\text{thermistor}}} = \frac{2\ \text{k}\Omega}{1\ \text{k}\Omega} = 2$$

$$V_{\text{fixed}} + V_{\text{thermistor}} = V_{\text{supply}}$$

$$2V_{\text{thermistor}} + V_{\text{thermistor}} = 6\ \text{V}$$

$$V_{\text{thermistor}} = \frac{6\ \text{V}}{3} = 2\ \text{V}$$

The output across the thermistor falls. The output across the other resistor rises from 2 V to 4 V; the two p.d.s still add to 6 V.

■ Time a generator waveform

A coil turns twice each second and its plane starts perpendicular to the magnetic field. It starts at zero e.m.f., reaches a peak after a quarter-turn, zero after a half-turn, the opposite peak after three quarters, and zero after one turn. One turn takes half a second, so the period is 0.50 s. The sign of the first peak depends on the chosen rotation and terminal reference.

■ Find an ideal transformer's input current

Given $V_p = 240$ V, $V_s = 20$ V and $I_s = 3.0$ A, find I_p. This model assumes 100% efficiency, so input power equals output power:

$$I_p V_p = I_s V_s$$

$$I_p = \frac{I_s V_s}{V_p}$$

$$I_p = \frac{(3.0\ \text{A})(20\ \text{V})}{240\ \text{V}} = 0.25\ \text{A}$$

■ Compare transmission losses

For the same transmitted power, raise the transmission voltage by a factor of ten. Find the change in current and cable heating, assuming the same cable resistance.

Rearrange the power relation and use equal transmitted power:

$$P = IV$$

$$I = \frac{P}{V}$$

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$$I_{\text{new}} = \frac{P}{10V_{\text{old}}} = \frac{I_{\text{old}}}{10}$$

Cable heating depends on the square of the current:

$$P_{\text{loss}} = I^2 R$$

$$P_{\text{loss,new}} = \left(\frac{I_{\text{old}}}{10}\right)^2 R = \frac{I_{\text{old}}^2 R}{100}$$

The heating loss falls to one hundredth. High voltage does not itself make the cable resistance smaller.

■ Grounding and scope

Scope was checked against the local Cambridge IGCSE Physics 0625 syllabus extracts 4.1–4.5. Demand spot-check: June 2025 paper 41 questions 6–8 and their official schemes require magnetic materials and field spacing, graph identification, resistance and energy with minutes converted to seconds, parallel-branch current, generator timing and transmission/turns ratio. This is a spot-check, not a claim that every mapped paper has been re-audited.

Historical paper files and bank entries were read without modification. Safety clarifications: Electrical Safety First: plugs and fuses, HSE: electrical isolation, Association for Science Education: double insulation. Demonstrations use supervised low-voltage classroom equipment; these notes do not instruct students to work on mains appliances.

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Nuclear physics

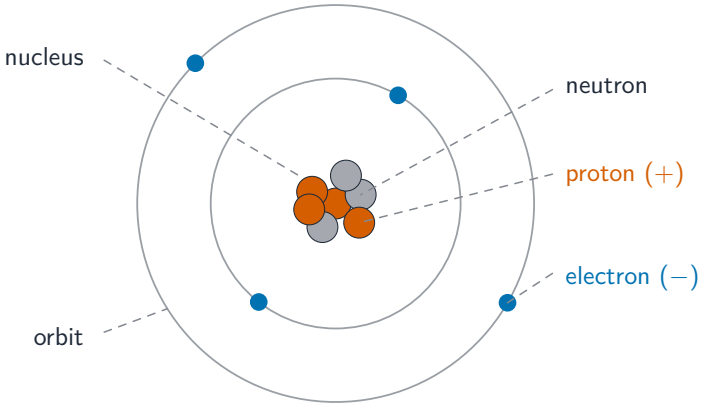
IGCSE Physics

The atom

In a simple model, an **atom** 原子 has a tiny central **nucleus** 原子核 with **electrons** 电子 shown around it in an **orbit** 轨道. These orbit diagrams are a model, not literal planet-like paths.

- The nucleus has a positive **charge** 电荷.
- The electrons have a negative charge.
- The atom as a whole is neutral, because the positive and negative charges are equal.

Almost all the **mass** 质量 is in the nucleus, but the nucleus is very small compared with the whole atom. So an atom is mostly empty space.



The nuclear atom: a tiny dense nucleus of protons and neutrons, with electrons in orbits around it

Ions

An atom is neutral, but it can gain or lose electrons to become an **ion** 离子.

- Lose one or more electrons → a positive ion (now there are more protons than electrons).
- Gain one or more electrons → a negative ion.

Worked comparison. A neutral sodium atom has 11 protons, 12 neutrons and 11 electrons. Losing one electron leaves 10 electrons, so the ion has one more positive charge than negative charge: it is Na^+. A neutral chlorine atom with 17 protons, 18 neutrons and 17 electrons gains one electron. It now has 18 electrons and one extra negative charge: Cl^-. In both cases only the electron count changes. The nucleus, proton number, nucleon number and identity of the element stay the same.

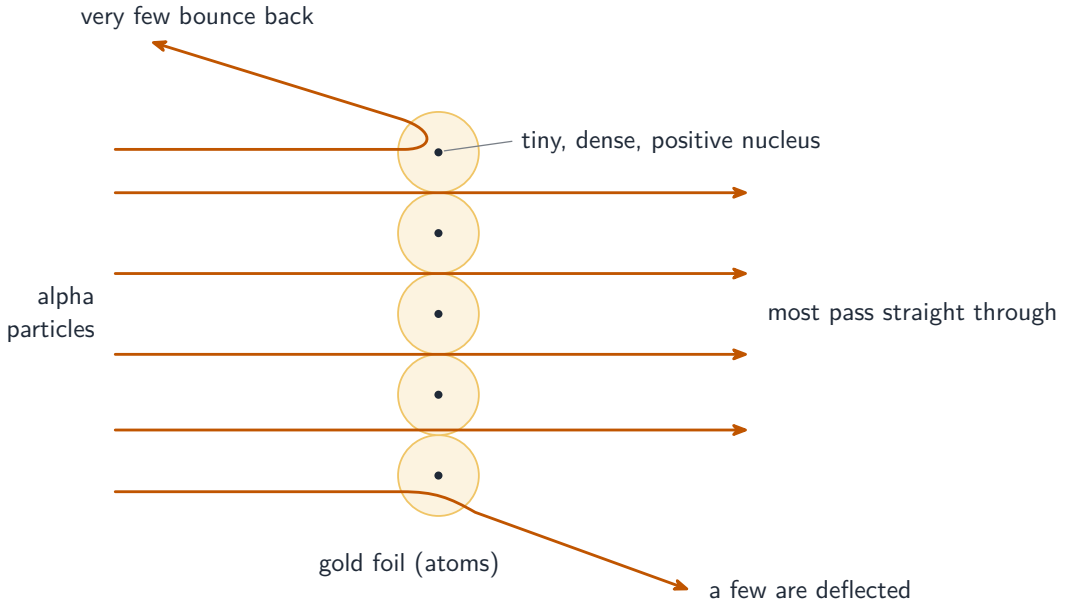
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The alpha-scattering experiment

This experiment gave the evidence for the nuclear model. **Alpha particles** α 粒子 (small, fast, positive) were fired at a very thin **gold foil** 金箔, and the **scattering** 散射 (the way they bounced off) was watched.

The results and what they tell us:

- Almost all the alpha particles went straight through. → The atom is mostly empty space.
- A few were **deflected** 偏转 (bent) through small angles. → The nucleus has a positive charge, which pushes the positive alpha particles away.
- A very few bounced almost straight back. → The nucleus is very small and very heavy, and holds most of the mass of the atom.



Most alpha particles pass straight through; a few are deflected and a very few bounce back off the tiny dense nucleus

Inside the nucleus

The nucleus is made of two kinds of particle, together called **nucleons** 核子:

- **protons** 质子, which have a **relative** 相对 charge of +1;
- **neutrons** 中子, which have a relative charge of 0 (they are neutral).

An electron has a relative charge of −1. A proton and a neutron each have a **relative mass** of about 1; an electron is almost massless in comparison.

Two numbers describe a nucleus:

- the **proton number** 质子数 Z (also called the atomic number) – the number of protons;
- the **nucleon number** 核子数 A (also called the mass number) – the number of protons plus neutrons.

So the number of neutrons is $A - Z$.

> **Worked example.** A neutral boron atom has nucleon number 11 and proton number 5. Its nucleus contains five protons. Subtract the protons from the total number of nucleons to find its neutrons:
>
> $$N = A - Z = 11 - 5 = 6$$

There are six neutrons. Neutrality means it also has five electrons. Do not subtract electrons from the nucleon number: electrons are outside the nucleus and are not nucleons.

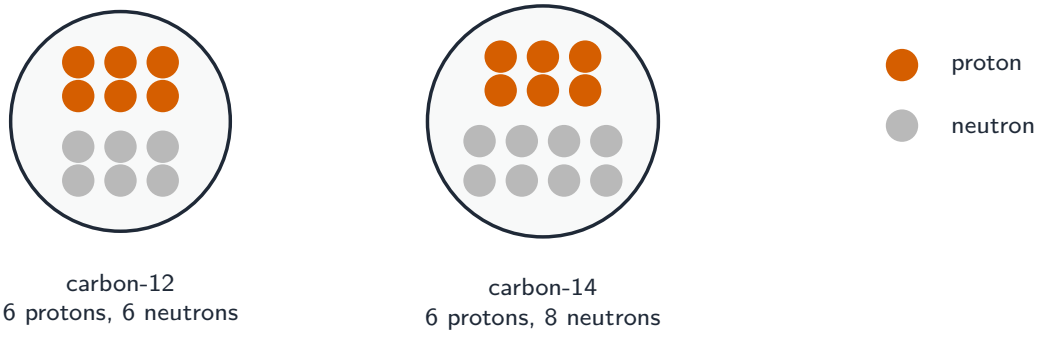
We write a nucleus in **nuclide** 核素 notation:

$$^{A}_{Z}\mathrm{X}$$

where X is the chemical symbol. For example, $^{197}_{79}$Au has 79 protons and $197 - 79 = 118$ neutrons. The relative charge of the whole nucleus is just $+Z$ (here $+79$), and its relative mass is about A.

Isotopes

Isotopes 同位素 are atoms of the same element (the same Z) but with different numbers of neutrons (different A). They behave the same in chemistry but differently in the nucleus. For example, $^{12}_{6}$C and $^{14}_{6}$C are both carbon.



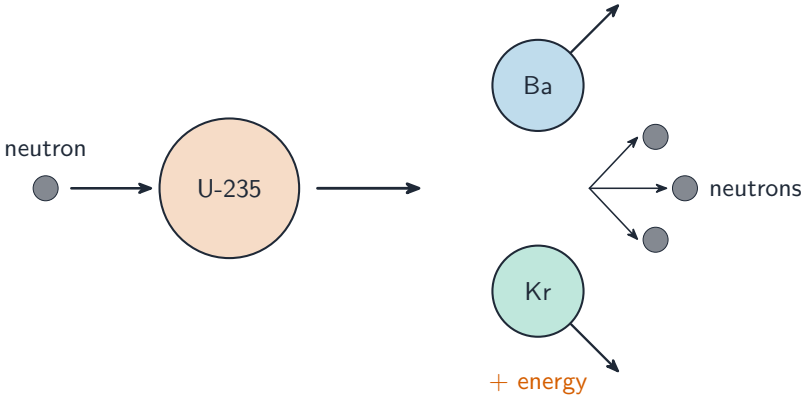
Isotopes of carbon have the same six protons but different numbers of neutrons, so they are the same element with a different mass

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Nuclear fission and fusion

In **nuclear fission** 核裂变, a heavy nucleus absorbs a neutron and then splits into two smaller nuclei, giving out two or three neutrons and a lot of **energy** 能量:

$$^{235}_{92}\mathrm{U} + ^{1}_{0}\mathrm{n} \rightarrow \ ^{141}_{56}\mathrm{Ba} + ^{92}_{36}\mathrm{Kr} + 3\,^{1}_{0}\mathrm{n}$$



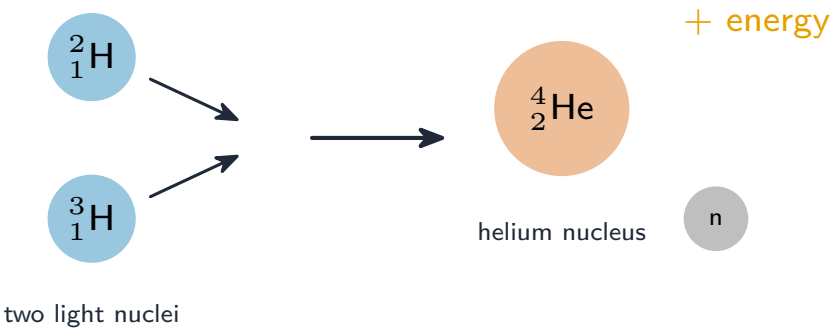
A neutron splits a U-235 nucleus into two smaller nuclei, releasing more neutrons and energy

The top numbers (nucleon numbers) balance on both sides, and so do the bottom numbers (proton numbers). You can use this to find a missing number – for example, how many neutrons are released.

In **nuclear fusion** 核聚变, two light nuclei join to make a heavier one, also giving out energy. This is how the Sun makes its energy, joining **hydrogen** 氢 nuclei to make **helium** 氦. The reaction below – two heavy forms of hydrogen (deuterium and tritium) joining into helium – is the one used in fusion reactors on Earth:

$$^{2}_{1}\mathrm{H} + ^{3}_{1}\mathrm{H} \rightarrow \ ^{4}_{2}\mathrm{He} + ^{1}_{0}\mathrm{n}$$

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In fusion two light nuclei join into a heavier one, releasing a neutron and energy – the deuterium–tritium reaction used in fusion reactors

In both fission and fusion, a small amount of mass is lost and turned into energy.



A nuclear power station uses the energy from fission to make electricity; the towers release waste heat as steam

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Radioactivity

A nucleus that is **unstable** 不稳定 will sooner or later break down and give out **radiation** 辐射. This is **radioactive** 放射性 **decay** 衰变. A nucleus may be unstable because it has too many neutrons, or because it is too heavy.

Decay is **spontaneous** 自发 (it happens on its own, and you cannot speed it up or slow it down) and **random** 随机 (you cannot say which nucleus will decay next, or exactly when).

■ Background radiation

Some radiation is around us all the time. This is **background radiation** 背景辐射. Its main sources are:

- **radon** 氡 gas in the air (usually the biggest source);
- rocks and buildings;
- food and drink;
- **cosmic rays** 宇宙射线 from space.

■ Measuring radiation

Radiation can be measured with a **detector** 探测器 joined to a **counter** 计数器. The **count rate** 计数率 is the number of counts each second (or each minute).

To find the true count rate from a source, first measure the background count rate on its own, then subtract it. The answer is the **corrected** 修正 count rate:

$$\text{corrected count rate} = \text{measured count rate} - \text{background count rate}$$

> **Worked example.** A detector placed next to a source reads 250 counts/min. With the source taken away, the background count rate is 30 counts/min. Find the corrected count rate.

$$250 - 30 = 220 \text{ counts/min}$$

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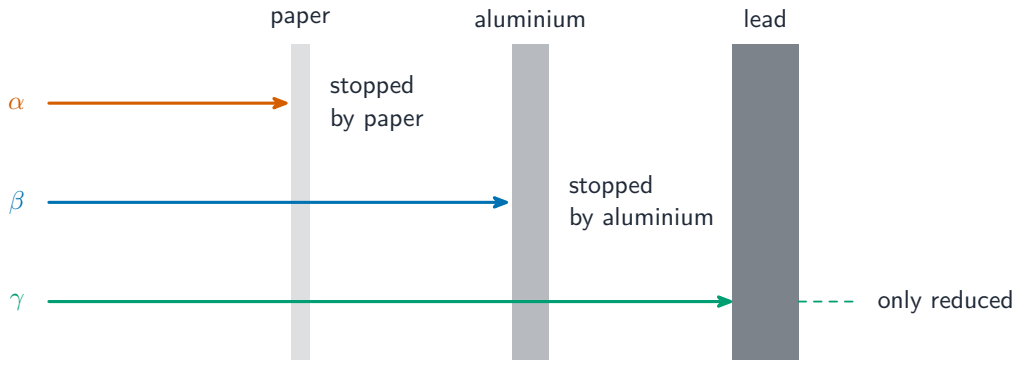
A portable Geiger counter detects ionising radiation and shows the count rate on its screen

The three types of radiation

The radiation can be one of three types. Each type is **ionising** 电离, which means it can knock electrons off atoms in its path.

Type	What it is	Ionising effect	Stopped by
alpha (α)	a helium nucleus: 2 protons + 2 neutrons, charge +2	strongest	a sheet of paper, or a few cm of air
beta (β)	a fast-moving electron, charge −1	medium	a few mm of **aluminium** 铝
gamma (γ)	a high-energy **electromagnetic wave** 电磁波, no charge	weakest	thick **lead** 铅 or concrete (only reduced, never fully stopped)

So an **alpha particle** is the most **ionising** but the least **penetrating** 穿透 (it is easily **absorbed** 吸收). A **beta particle** β 粒子 is in the middle. **Gamma radiation** γ 射线 is the least ionising but the most penetrating.

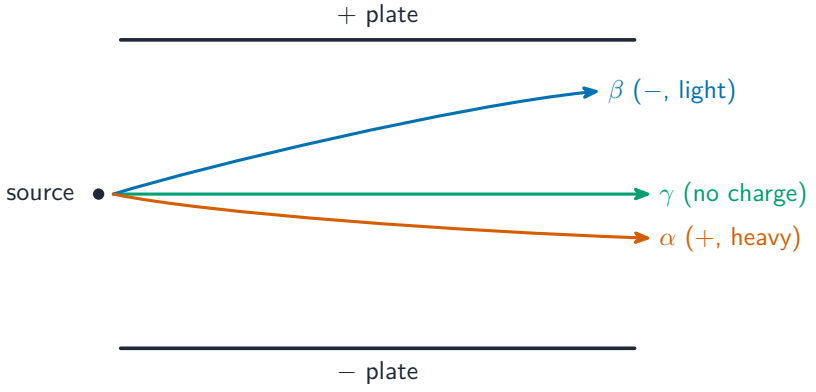


Paper stops alpha, a few millimetres of aluminium stops beta, and thick lead only reduces gamma

We can explain the ionising effects from charge and **kinetic energy** 动能: an alpha particle has a large charge (+2) and is slow and heavy, so it pulls strongly on the electrons it passes and ionises a lot. A beta particle has a smaller charge and moves faster, so it ionises less.

■ Deflection in fields

Because alpha and beta particles are charged, they are deflected by an **electric field** 电场 and by a **magnetic field** 磁场. They bend in *opposite* directions, because their charges have opposite signs, and the lighter beta particle bends more. Gamma rays have no charge, so they are not deflected at all.



Alpha and beta bend in opposite directions; the lighter beta bends more, and uncharged gamma is not deflected

Decay equations

When a nucleus decays, the nucleon and proton numbers must balance on both sides.

Alpha decay – the nucleus loses 2 protons and 2 neutrons, so A falls by 4 and Z falls by 2. It becomes a *different element*:

$$ {}^{A}_{Z}\mathrm{X} \rightarrow {}^{A-4}_{Z-2}\mathrm{Y} + {}^{4}_{2}\,\alpha $$

> **Worked example.** A radium nucleus ${}^{226}_{88}\mathrm{Ra}$ emits an alpha particle. Find the nucleon number and proton number of the new nucleus.

Alpha decay lowers A by 4 and Z by 2:

$$ {}^{226}_{88}\mathrm{Ra} \rightarrow {}^{222}_{86}\mathrm{Rn} + {}^{4}_{2}\,\alpha $$

So the new nucleus (radon) has nucleon number 222 and proton number 86.

$$ {}^{226}_{88}\mathsf{Ra} \rightarrow {}^{222}_{86}\mathsf{Rn} + {}^{4}_{2}\alpha \qquad A\text{: } 226 = 222 + 4; \quad Z\text{: } 88 = 86 + 2 $$

$$ {}^{24}_{11}\mathsf{Na} \rightarrow {}^{24}_{12}\mathsf{Mg} + {}^{0}_{-1}\beta \qquad A\text{: } 24 = 24 + 0; \quad Z\text{: } 11 = 12 + (-1) $$

top numbers balance, bottom numbers balance: a different element each time

Top numbers balance and bottom numbers balance.

Beta decay – inside the nucleus a neutron changes into a proton plus an electron:

$$ \text{neutron} \rightarrow \text{proton} + \text{electron} $$

The fast electron leaves as the beta particle. So A stays the same but Z rises by 1, giving a different element:

$$ {}^{24}_{11}\mathrm{Na} \rightarrow {}^{24}_{12}\mathrm{Mg} + {}^{0}_{-1}\,\beta $$

Gamma emission – the nucleus loses only energy, so A and Z do not change. Alpha and beta decay leave the nucleus more **stable** 稳定; gamma is often given out at the same time to carry away spare energy.

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Half-life

Because decay is random, we cannot follow one nucleus. Instead we describe a large **sample** 样品 using its half-life.

The **half-life** 半衰期 of an isotope is the time taken for half the unstable nuclei in a sample to decay. After each half-life, the count rate (or the number of unstable nuclei left) falls to half.

For example, if a source has a count rate of 800 counts/min and a half-life of 3 hours:

Time / hours	**0**	**3**	**6**	**9**
Count rate / (counts/min)	800	400	200	100

After 6 hours (two half-lives) the count rate has halved twice: $800 \to 400 \to 200$. You can read a half-life off a decay graph by finding the time for the count rate to drop from any value to half of it. If the readings include background radiation, subtract the background count rate from every reading first, then find the half-life from the corrected values.

> **Worked example.** The activity of a source falls from 800 counts/min to 100 counts/min. Its half-life is 5 days. How long did this take?

Count the halvings: $800 \to 400 \to 200 \to 100$ is three half-lives, so the time is $3 \times 5 = 15$ days.

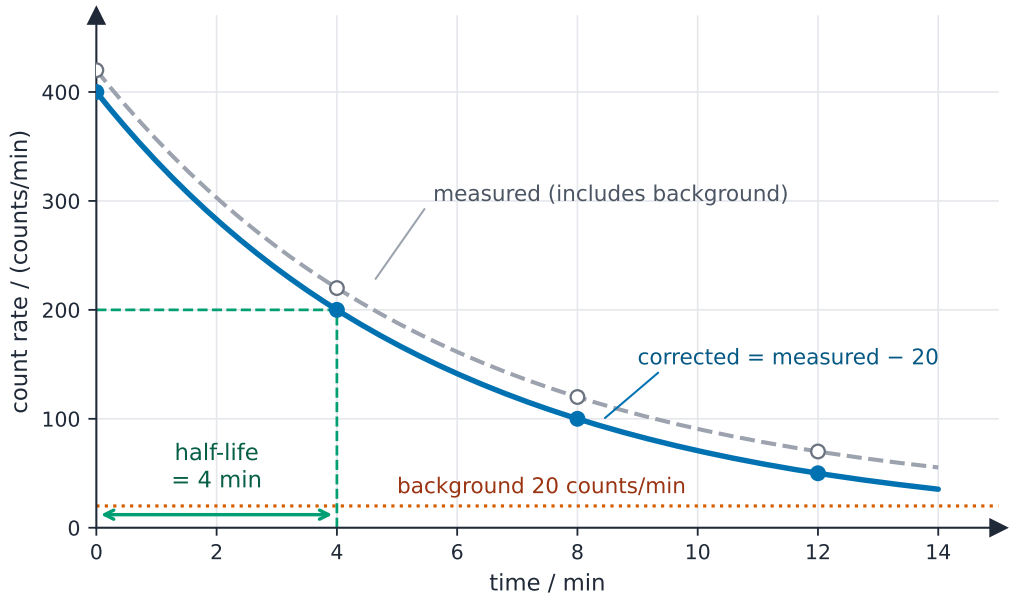
> **Worked example (with background).** A student measures a source every 4 minutes. The background count rate is 20 counts/min.

Time / min	**0**	**4**	**8**	**12**
Measured count rate / (counts/min)	420	220	120	70
Corrected count rate / (counts/min)	400	200	100	50

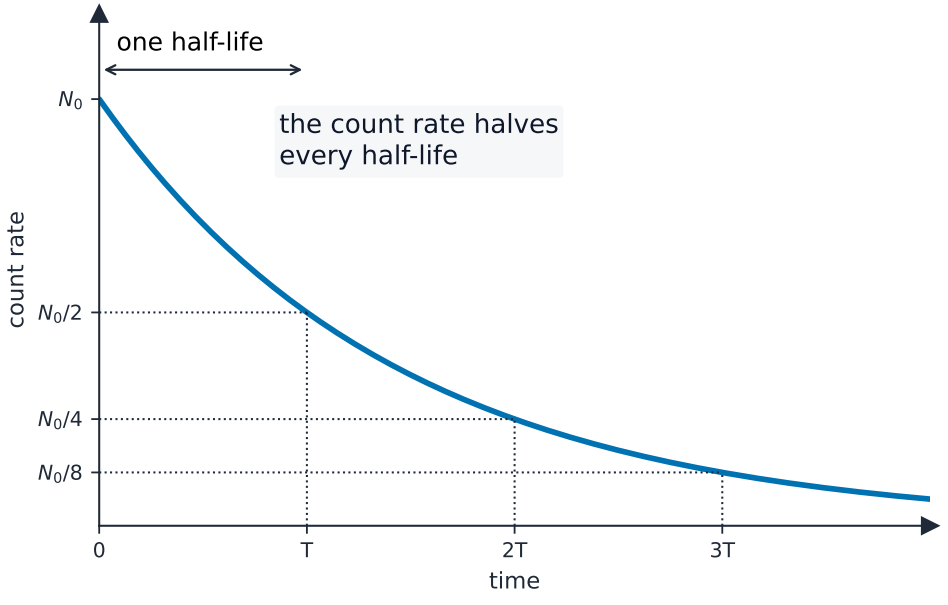
Subtract 20 from every reading first. The corrected count rate halves every 4 minutes ($400 \to 200 \to 100 \to 50$), so the half-life is 4 minutes.

Without the correction, the measured rate would seem to fall from 420 to 220 in 4 minutes. That is not a halving ($420 \div 2 = 210$), so the measured readings do not show the half-life directly.

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Subtract the background first; only the corrected curve halves every 4 minutes



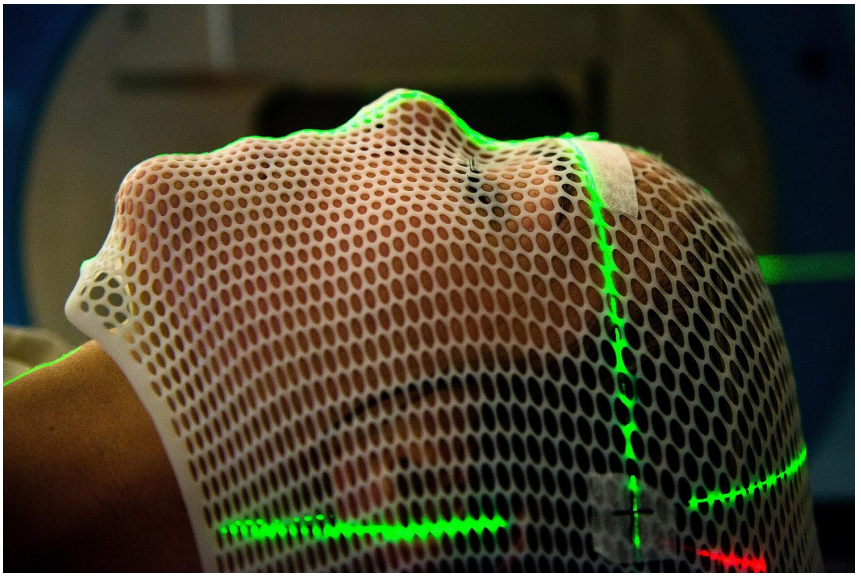
Each half-life T the count rate halves: $N_0 \to N_0/2 \to N_0/4 \to N_0/8$

Uses of radioactivity

The isotope chosen for a job depends on its type of radiation and its half-life:

- **smoke alarms** 烟雾报警器 use an alpha source (alpha is easily blocked, so it is safe outside the alarm, and a long half-life means it lasts for years);

- using radiation on food, or on equipment, kills **bacteria** 细菌 and germs – this needs penetrating gamma rays to **sterilise** 消毒 the sealed item;
- measuring and controlling the thickness of paper or metal sheets uses a beta source (the amount that passes through changes with the thickness);
- a **medical tracer** 医用示踪剂 is a small amount of a gamma-emitting isotope with a short half-life, injected into the body: a detector outside the body follows where it goes, gamma rays escape from the body easily, and the activity soon falls to a safe level;
- gamma rays are used to find and to treat **cancer** 癌症 inside the body, because they can pass out of (or into) the body.



Radiotherapy: a mesh mask holds the patient still while alignment lasers aim gamma rays precisely at a tumour to treat cancer

Worked example: choosing an isotope. Four isotopes are available:

Isotope	Radiation	Half-life
P	alpha	430 years
Q	beta	30 years
R	gamma	6 hours
S	gamma	5 years

- **Smoke alarm: P** (in real alarms, americium-241). Alpha ionises the air in a small gap, so a tiny current flows; smoke absorbs the alpha particles, the current falls, and the alarm sounds. Alpha is stopped by a few centimetres of air or by the plastic case, so it is safe outside, and a long half-life means the alarm works for years without a new source.
- **Paper thickness gauge: Q.** Beta passes partly through paper, so the count

rate changes with thickness; alpha would be stopped completely and gamma would pass through almost unchanged. A long half-life keeps the count rate steady over months, so a change in reading means a change in thickness, not decay.

- **Medical tracer: R.** Gamma escapes from the body to the detector, and a short half-life means the activity in the patient falls to a low level within a day or two. S would stay active in the body for years.
- **Sterilising sealed medical equipment: S.** Penetrating gamma passes through the packaging, and a long half-life means the source need not be replaced often.

How a thickness gauge controls the paper. The source is on one side of the paper and the detector on the other. If the paper becomes **too thick**, more beta is absorbed, so the count rate **falls**; the control system moves the rollers closer together. If the count rate rises, the paper is too thin, and the rollers move apart.

Safety

Ionising radiation harms **living cells** 细胞. It can cause cell death, **mutations** 突变 (changes to the genes) and cancer.

When working with radioactive sources, keep the **dose** 剂量 (the amount of radiation received) low by:

- reducing the **exposure** 照射 time – spend as little time near the source as possible;
- increasing the distance between you and the source;
- using **shielding** 屏蔽, such as lead, between the source and your body.

Radioactive sources should be handled with tongs (not bare hands), kept pointing away from people, and stored in a lead-lined box.

Radioactive waste 放射性废物 from hospitals and power stations must be disposed of safely. Waste with a short half-life can be stored until its activity has fallen to a safe level. Waste with a long half-life stays dangerous for thousands of years, so it is sealed in thick containers (for example, set in glass or concrete) and stored deep underground, away from people and from water that could carry it into the environment.

Exam tips

- The **nucleon number** (top) is protons + neutrons; the **proton number** (bottom) is protons only. Number of neutrons = nucleon number − proton number.
- **Isotopes** have the same proton number but different nucleon numbers – the same element with a different number of neutrons.
- Rank the radiations two ways: **alpha** is the most ionising but least penetrating (stopped by paper); **gamma** is the least ionising but most penetrating (needs thick lead). Beta is in between (stopped by a few mm of aluminium).
- In every **decay equation** the top numbers must balance and the bottom numbers must balance. Alpha decay: $A - 4$, $Z - 2$. Beta decay: A unchanged, $Z + 1$.

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- Always subtract the **background count rate** before using a source's readings. After n half-lives the count rate has halved n times – count the halvings rather than guessing from the total time.

■ Common mistakes

- Saying that after two half-lives all of the sample has decayed. After one half-life, half is left; after two, a quarter is left.
- Finding a half-life from readings that still include background radiation. Subtract the background count rate from every reading first.
- Saying isotopes have different numbers of protons. Isotopes of one element have the same number of protons and different numbers of neutrons.
- Saying a beta particle comes from the electron shells. It is made in the nucleus, when a neutron changes into a proton and an electron.
- Changing A or Z in gamma emission. Gamma carries away only energy, so the nucleus stays the same element.
- Mixing up ionising and penetrating. Alpha is the most ionising and the least penetrating; gamma is the opposite.

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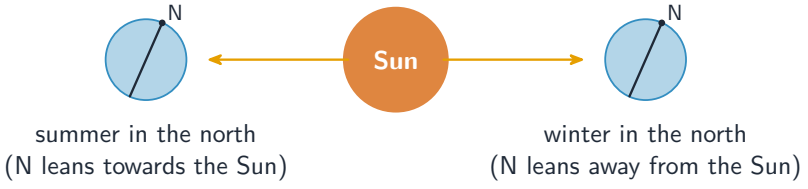
Space physics

IGCSE Physics

The Earth, the Sun and the Moon

The Earth spins (**rotates** 自转) on its **axis** 轴 once in about 24 hours. The axis is **tilted** 倾斜 (not straight up). This spin gives us day and night, and makes the **Sun** 太阳 appear to move across the sky each day.

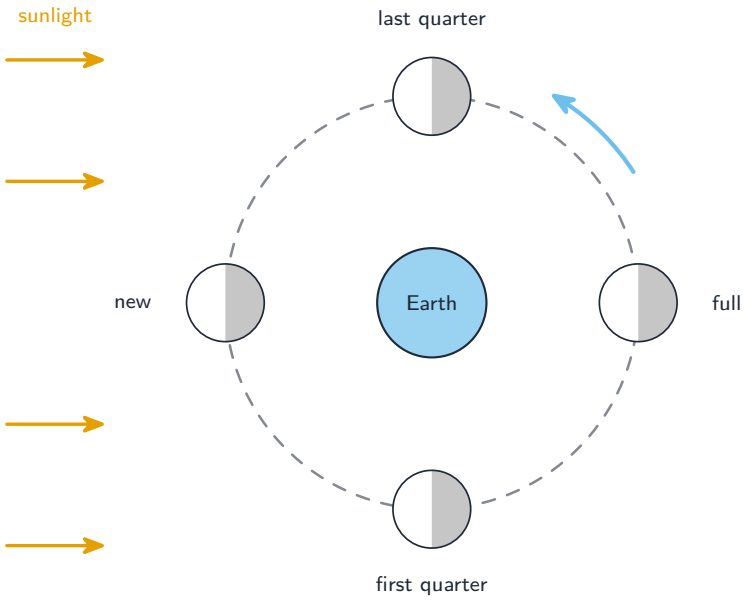
The Earth also moves around the Sun in an **orbit** 轨道, once in about 365 days (one year). Because the axis is tilted, different parts of the Earth lean towards the Sun at different times of the year. This gives the **seasons** 季节: it is summer in the half of the Earth that leans towards the Sun.



The axis keeps the same tilt all year, so each hemisphere leans toward the Sun for one half of the orbit and away for the other

The **Moon** 月球 orbits the Earth once in about one month. As it goes round, we see different amounts of its lit side, which gives the **phases** 月相 of the Moon (new moon, half moon, full moon).

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The Moon's lit half always faces the Sun, so as it orbits we see different amounts of it: a new moon between us and the Sun, a full moon opposite the Sun, and half moons in between

So, from shortest to longest: one day (Earth's spin) < one month (Moon's orbit) < one year (Earth's orbit).



The full Moon, Earth's natural satellite

Orbital speed

For an object going round a circle, the distance for one full orbit is the **circumference** 周长 $2\pi r$, where r is the radius of the orbit. The **orbital speed** 轨道速率 is this distance divided by the **period** 周期 T (the time for one orbit):

$$v = \frac{2\pi r}{T}$$

The same equation works for planets, moons and satellites.

> **Worked example.** A space station orbits the Earth at a radius of $r = 7000$ km and takes $T = 5800$ s for one orbit. Find its orbital speed.

First convert the radius to metres: $7000 \text{ km} = 7.0 \times 10^6$ m. Then

$$v = \frac{2\pi r}{T} = \frac{2\pi \times 7.0 \times 10^6}{5800} \approx 7600 \text{ m/s}$$



The ISS in orbit: orbital speed is the speed that keeps a satellite in free-fall circular motion

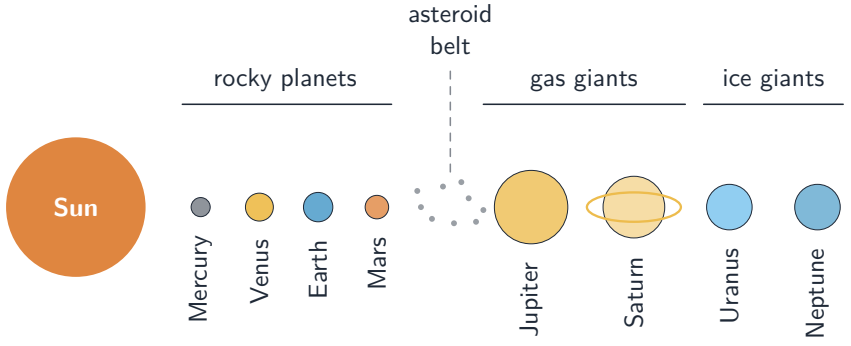
The Solar System

The **Solar System** 太阳系 has one star, the Sun, at its centre. Around it move the eight **planets** 行星. In order from the Sun they are: Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus and Neptune.

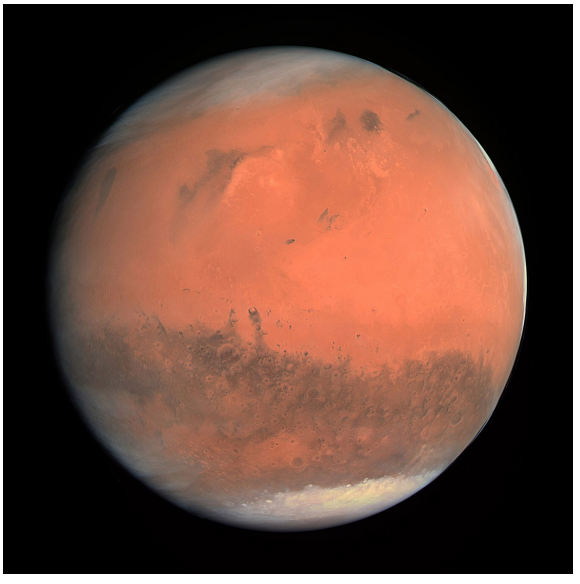
- The four planets nearest the Sun are small and **rocky** 岩石.

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- The four planets furthest from the Sun are large and **gaseous** 气态 in the syllabus comparison: they have deep atmospheres of gas 气体 rather than an Earth-like solid surface.
- The two nearer giants, Jupiter and Saturn, are **gas giants** 气态巨行星. The two outer giants, Uranus and Neptune, are **ice giants** 冰巨行星: their composition differs from that of Jupiter and Saturn. The name does not mean that their interiors are solid frozen ice.

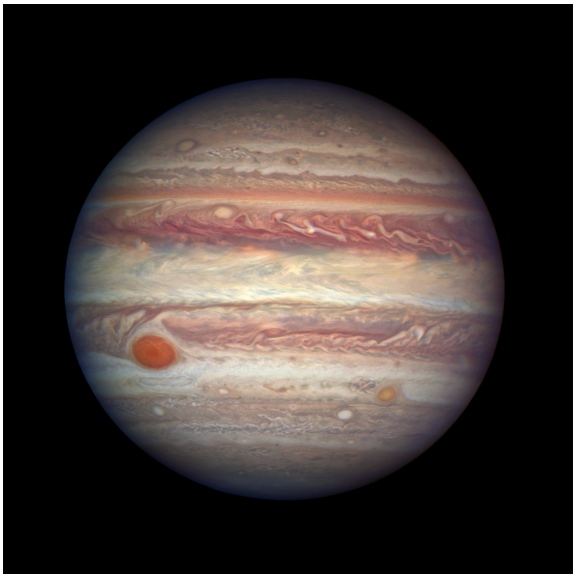


The Sun and its eight planets in order: four small rocky planets, then the asteroid belt, then four large gaseous planets – the gas giants Jupiter and Saturn and the ice giants Uranus and Neptune (not to scale)

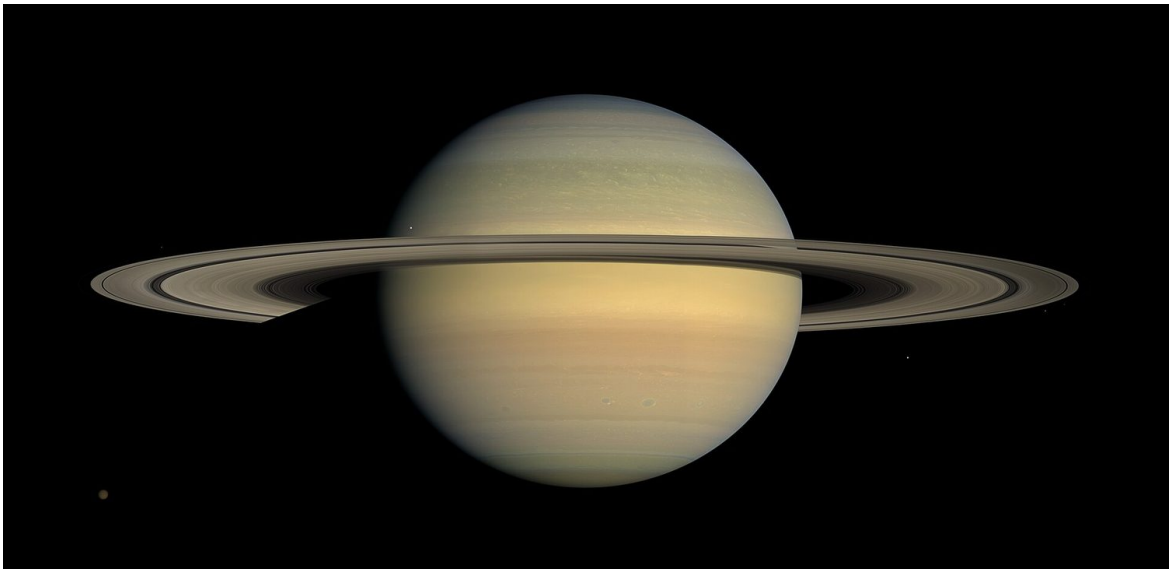


Mars, the red planet, one of the rocky inner planets

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Jupiter, the largest planet, with its swirling bands of gas



Saturn and its rings, photographed by the Cassini spacecraft

The Solar System also contains:

- minor planets, such as **dwarf planets** 矮行星 like Pluto, and **asteroids** 小行星 (most lie in the asteroid belt between Mars and Jupiter);
- moons (natural **satellites** 卫星) that orbit the planets;
- **comets** 彗星 and other small bodies.

Worked classification. The Sun is a star. Mars and Jupiter are planets. Pluto is a dwarf planet, so it is not one of the eight named planets. An asteroid or a comet orbits the Sun; the Moon is Earth's natural satellite and orbits Earth while Earth orbits the Sun.

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Orbits and gravity

The Sun holds most of the mass of the Solar System. Its **gravity** 引力 (gravitational pull) reaches out and keeps the planets in their orbits. This force is the gravitational attraction of the Sun.

The **gravitational field strength** 重力场强度 tells you how strong gravity is:

- at the surface of a planet it depends on both the mass and the radius of the planet;
- around a planet it gets weaker as you move further away.

In the same way, the Sun's gravity gets weaker further out, so the outer planets move more slowly (smaller orbital speed) than the inner ones.

Planetary data

Exam questions often give a table like this one and ask you to read a pattern from it.

Planet	Distance from Sun / million km	Orbital period	Density / g/cm^3	Temperature / °C	Surface g / N/kg
Mercury	58	88 days	5.4	170	3.7
Venus	108	225 days	5.2	460	8.9
Earth	150	365 days	5.5	15	9.8
Mars	228	687 days	3.9	−60	3.7
Jupiter	779	11.9 years	1.3	−110	23
Saturn	1430	29.5 years	0.7	−140	9.0
Uranus	2870	84 years	1.3	−195	8.7
Neptune	4500	165 years	1.6	−200	11

For the giant planets, temperature values refer to atmospheric levels, not a solid surface.

Patterns to notice: the further a planet is from the Sun, the longer its orbital period. The outer planets are colder, but temperature does not fall for every successive planet: Venus is hotter than Mercury. The four inner planets are dense (rock and metal), while the four outer planets have low densities (gas and ice). The gravitational field strength at the surface depends on the planet's mass and size, not on its distance from the Sun.

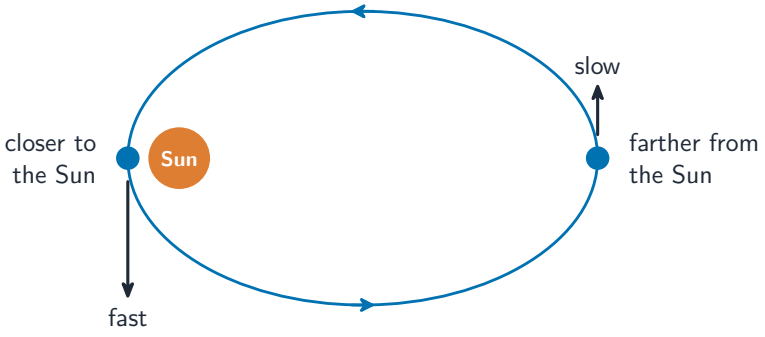
Worked interpretation. Mercury has density 5.4 g/cm^3 and Jupiter has density 1.3 g/cm^3. These values support the inner/outer density comparison. But a claim that every more distant planet is colder fails: Venus is farther from the Sun than

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Mercury (108 versus 58 million km) yet has a higher listed temperature (460°C versus 170°C). Venus's thick atmosphere traps heat. Use the data to support a pattern, then state exceptions; distance alone does not determine temperature.

■ Elliptical orbits

Most orbits are not perfect circles but **ellipses** 椭圆 (a stretched circle), and the Sun is not at the centre of the ellipse. A comet has a very stretched orbit. An object in an elliptical orbit moves **faster** when it is closer to the Sun. We explain this with the **conservation of energy** 能量守恒 – the total **energy** 能量 stays the same, so as the object's **gravitational potential energy** 重力势能 falls (coming closer), its **kinetic energy** 动能 rises (it speeds up).



The Sun sits at one focus of the ellipse; the planet speeds up as it comes closer and slows down as it moves away

■ Light travel time

Distances in space are huge, so we often work out how long light takes to cross them. Light travels at 3.0×10^8 m/s. Using time $= \dfrac{\text{distance}}{\text{speed}}$, light from the Sun (about 1.5×10^{11} m away) takes about 500 s, which is roughly 8 minutes, to reach the Earth.

> **Worked example.** (a) How far is one light-year in metres? (b) The star Sirius is 8.6 light-years away. How far is that in metres? (One year $= 3.2 \times 10^7$ s.)

(a) Distance = speed × time $= 3.0 \times 10^8 \times 3.2 \times 10^7 = 9.6 \times 10^{15}$ m. (With a more exact year, 3.15×10^7 s, it is 9.5×10^{15} m.)

(b) $8.6 \times 9.5 \times 10^{15} = 8.2 \times 10^{16}$ m. The light we see from Sirius tonight left it 8.6 years ago.

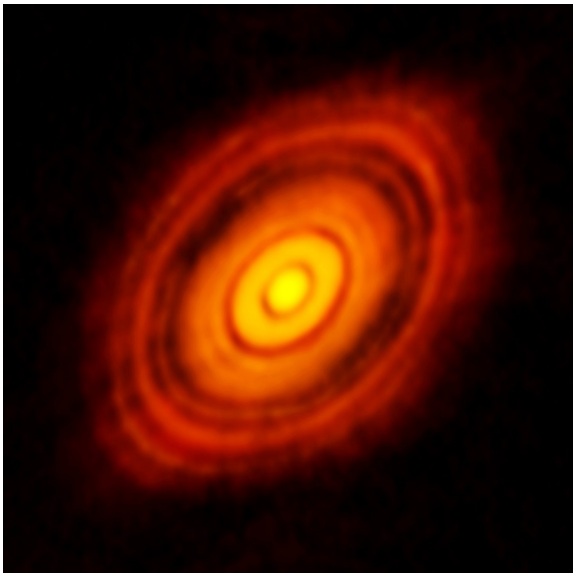
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How the Solar System formed

The planets formed from a giant cloud of **gas** and **dust** 尘埃 in space, which contained many chemical **elements** 元素. This is the **accretion** 吸积 model:

- gravity pulled the cloud together;
- the cloud was spinning, so it flattened into a spinning **accretion disc** 吸积盘;
- most of the matter fell to the centre and became the Sun, while the planets grew from the leftover material in the disc.

Near the hot young Sun, only rock and metal could stay solid, so the inner planets are rocky. Far out, where it was cold, gases could also collect, so the outer planets grew large and gaseous.



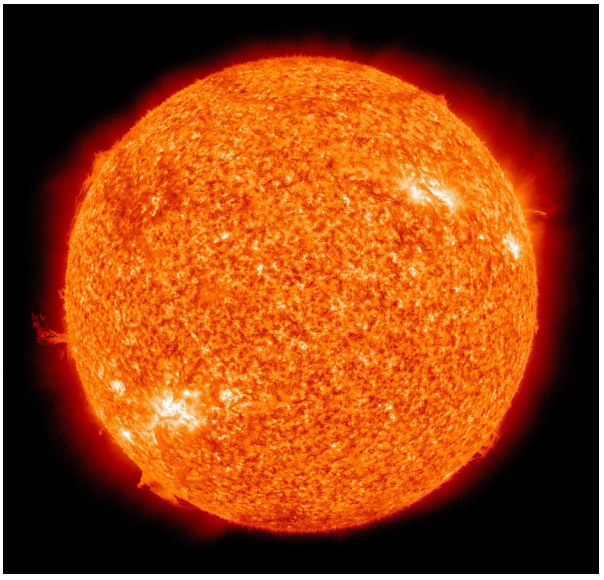
A real accretion disc around the young star HL Tauri: the dark gaps are where new planets are gathering up the dust – our Solar System began the same way

The Sun as a star

The Sun is a **star** 恒星 of medium size, made mostly of **hydrogen** 氢 and **helium** 氦. It radiates most of its **energy** in the infrared, visible light and **ultraviolet** 紫外线 parts of the **electromagnetic spectrum** 电磁波谱.

A star is powered by **nuclear reactions** 核反应 in its core. In a stable star, the reaction is **nuclear fusion** 核聚变: hydrogen nuclei join to make helium, releasing huge amounts of energy.

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The Sun, our nearest star, seen in ultraviolet light

Stars, galaxies and the Universe

A **galaxy** 星系 is a group of many billions of stars held together by gravity. Our Sun is one star in the galaxy called the **Milky Way** 银河系. All the other stars in the Milky Way are very much further from the Earth than the Sun is.

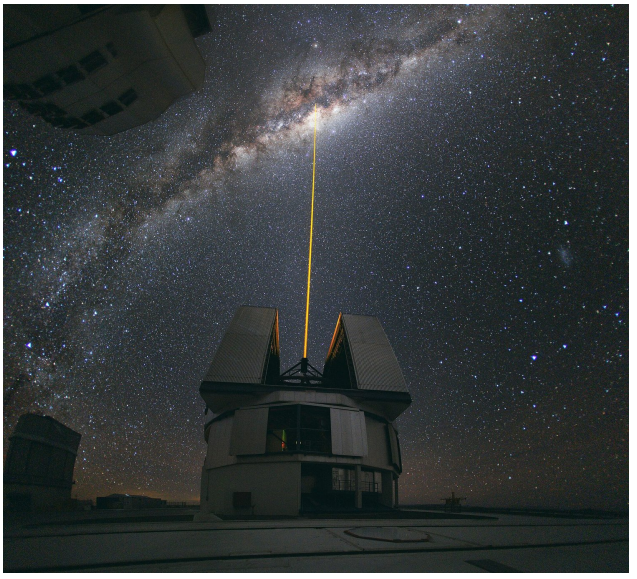


A spiral galaxy: billions of stars held together by gravity

Distances between stars are so big that we measure them in **light-years** 光年. One light-year is the distance light travels in one year (in the vacuum of space), which is about 9.5×10^{15} m.

The Milky Way is about 100 000 light-years across (its **diameter** 直径). It is just one

of many billions of galaxies. All of these galaxies together make up the **Universe** 宇宙.



A giant telescope studies the night sky; the laser helps it make sharp images of distant stars

The life cycle of a star

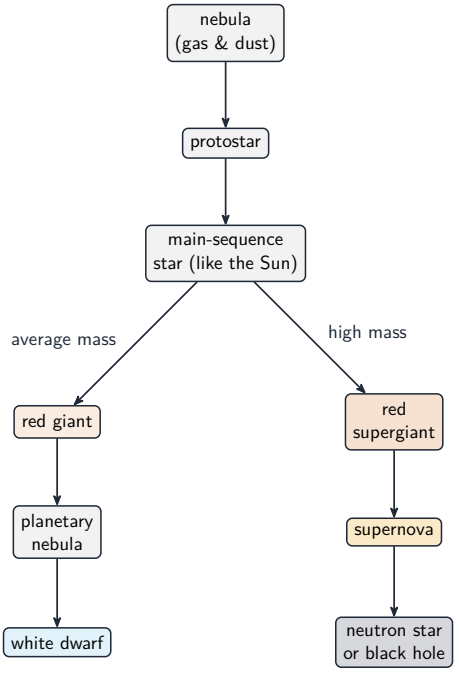
A star is born, lives and dies over a very long time:

1. A star forms from an **interstellar cloud** 星际云 of gas and dust that contains hydrogen.
2. Gravity pulls the cloud inwards, and it heats up. This collapsing, heating cloud is a **protostar** 原恒星.
3. The protostar becomes a **stable** 稳定 star when the inward pull of gravity is balanced by an outward pressure force. Its hot interior provides the pressure needed for this balance.
4. In time, every star runs out of hydrogen **fuel** 燃料 for fusion.

What happens next depends on the mass of the star:

- A medium star (like the Sun) swells into a **red giant** 红巨星. It then throws off its outer layers as a glowing cloud called a planetary **nebula** 星云, leaving a small, hot **white dwarf** 白矮星 at the centre.
- A much heavier star swells into a **red supergiant** 红超巨星 and then explodes as a **supernova** 超新星. This blast spreads out a nebula containing hydrogen and new, heavier elements, and leaves behind a **neutron star** 中子星 or a **black hole** 黑洞.

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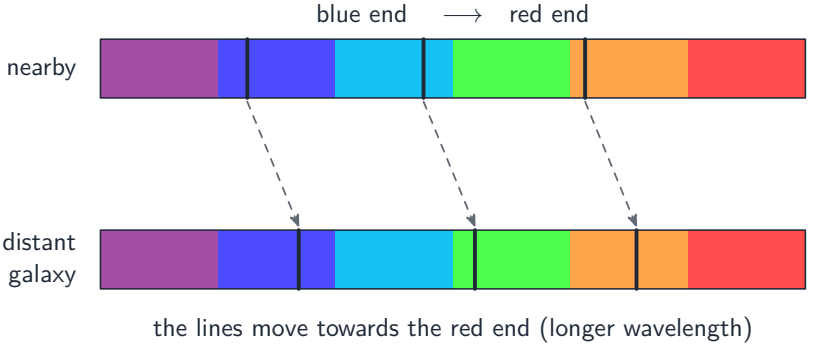


Every star begins in a nebula; how it ends depends on its mass

The nebula from a supernova can later form new stars, with planets orbiting them – so our own Solar System came from earlier stars.

The expanding Universe

When a star or galaxy moves away from us (it is **receding** 退行), the light we receive from it has a longer **wavelength** 波长 than normal – it is shifted towards the red end of the spectrum. This is **redshift** 红移.

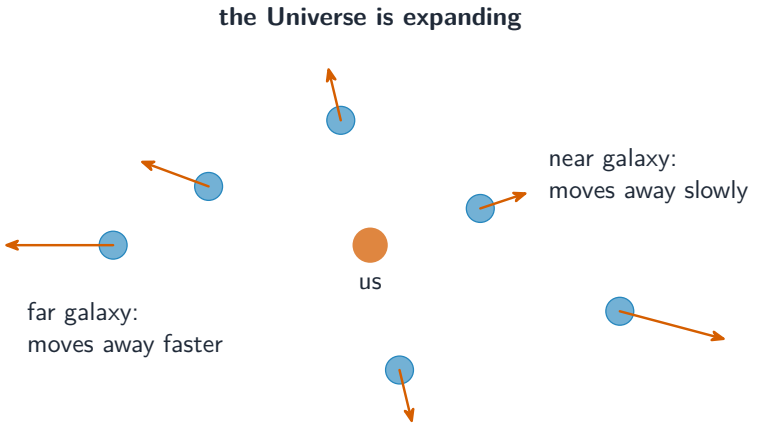


The dark lines in a distant galaxy's spectrum are shifted toward the red end – this is redshift

The light from distant galaxies is redshifted, and the further away a galaxy is, the bigger its redshift. This tells us that the galaxies are moving apart: the Universe is

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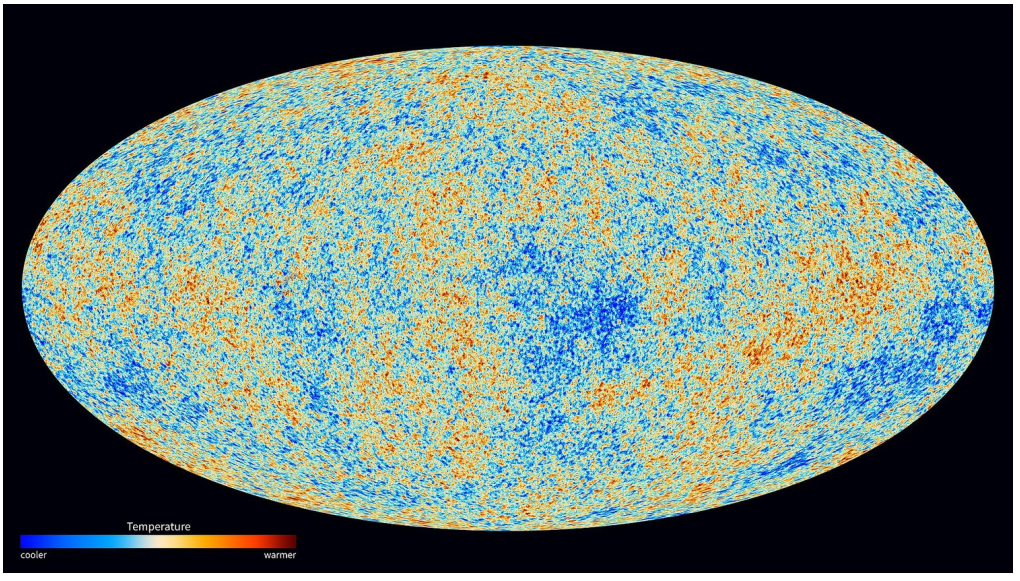
expanding 膨胀. Running the expansion backwards points to an earlier, hotter and denser Universe, as described by the **Big Bang** 大爆炸 theory.



Distant galaxies move away from us, and the farther ones move away faster – the Universe is expanding

More evidence and the age of the Universe

Faint **microwave** 微波 **radiation** 辐射 is found coming from every direction in space. This is the **cosmic microwave background radiation** 宇宙微波背景辐射 (CMBR). It was made as high-energy radiation soon after the Big Bang, and has been stretched out into the microwave part of the spectrum as the Universe expanded.



The whole sky mapped in microwaves: this faint glow reaches us from every direction as the leftover heat of the young Universe – strong evidence for the Big Bang

For a distant galaxy:

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- its speed v of moving away can be found from the redshift of its starlight;
- its distance d can be found from the brightness of a **supernova** seen in it.

The **Hubble constant** 哈勃常数 H_0 links these two:

$$H_0 = \frac{v}{d}$$

Its value today is about 2.2×10^{-18} per second. Turning this around gives an estimate for the age of the Universe:

$$\frac{d}{v} = \frac{1}{H_0}$$

Worked example. The Hubble constant is about $H_0 = 2.2 \times 10^{-18}$ per second. Estimate the age of the Universe.

$$\frac{1}{H_0} = \frac{1}{2.2 \times 10^{-18}} \approx 4.5 \times 10^{17} \text{ s}$$

That is roughly 14 billion years.

This estimate assumes constant recession speeds. A model that allows the expansion to speed up or slow down can give a different age.

Worked example. A galaxy is moving away from us at 2.2×10^7 m/s. Use $H_0 = 2.2 \times 10^{-18}$ per second to find its distance.

$$d = \frac{v}{H_0} = \frac{2.2 \times 10^7}{2.2 \times 10^{-18}} = 1.0 \times 10^{25} \text{ m}$$

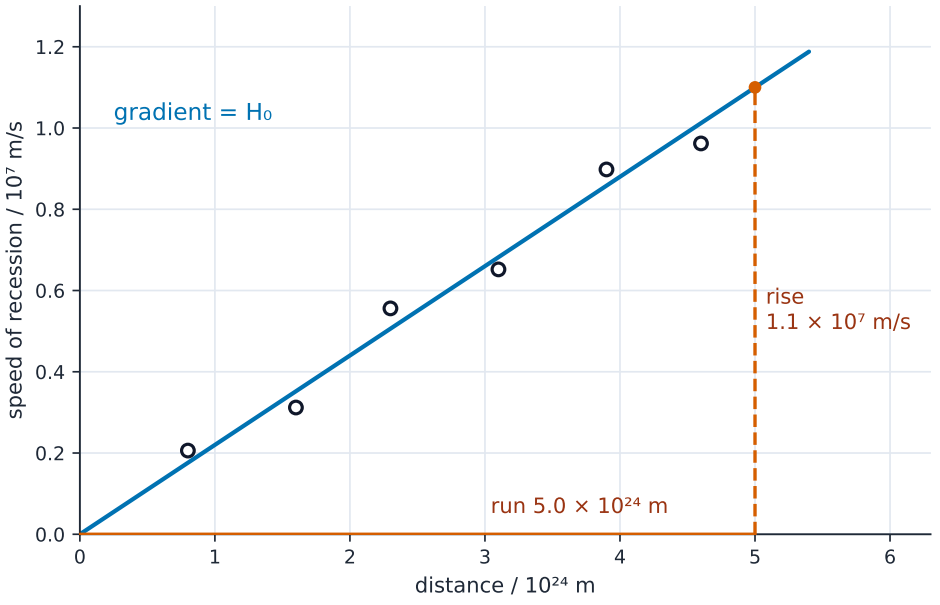
That is about $1.0 \times 10^{25} \div 9.5 \times 10^{15} \approx 1.1 \times 10^9$ light-years: about a billion light-years.

Worked example (Hubble constant from a graph). Astronomers measure the distance and the speed of recession of six galaxies and plot speed against distance. The best-fit line passes through the origin and through $(5.0 \times 10^{24}\text{ m},\ 1.1 \times 10^7\text{ m/s})$.

$$H_0 = \text{gradient} = \frac{v}{d} = \frac{1.1 \times 10^7}{5.0 \times 10^{24}} = 2.2 \times 10^{-18} \text{ per second}$$

Read the scale factors on the axis labels: a reading of 1.1 on an axis labelled "speed / 10^7 m/s" means 1.1×10^7 m/s. Use two points far apart on the line, not two data points, because the points scatter around the line. A straight line through the origin shows that speed is proportional to distance.

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The gradient of the speed–distance line is the Hubble constant

Exam tips

- In $v = \dfrac{2\pi r}{T}$, r is the orbit radius and T is the time for one full orbit in seconds – convert km to m and hours to seconds first.
- Planets closer to the Sun feel stronger gravity, so they orbit faster and take less time. In an elliptical orbit a body speeds up as it nears the Sun (gravitational potential energy turns into kinetic energy).
- A **light-year** is a *distance*, not a time – how far light travels in one year.
- A star is **stable** when the inward pull of gravity is balanced by the outward push from the energy released by **fusion** in its core. What it becomes when its fuel runs out depends on its **mass**.
- **Redshift** – light from distant galaxies shifted to longer (redder) wavelengths, with a bigger shift the further away – is the evidence that the Universe is **expanding**, which supports the Big Bang.

■ Common mistakes

- Treating a light-year as a time. It is the distance light travels in one year.
- Using the diameter, or the height above the surface, as r in $v = 2\pi r/T$. Use the orbit radius, measured from the centre of the planet or star.
- Leaving T in hours or days. Change it to seconds when v is wanted in m/s.
- Saying redshift means the galaxy looks red. It means the lines in its spectrum are shifted to longer wavelengths.

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- Saying the Sun is at the centre of an elliptical orbit. It is at one focus, off-centre, so the distance to the Sun changes around the orbit.

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