Course Companion

AQA · GCSE · Physics

Every topic handout in one volume

全部专题讲义合集

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1 · Energy

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Energy: stores, transfers and resources

Why it matters. In 1845 James Prescott Joule, the son of a brewer from Salford near Manchester, built a small copper tank of water with a paddle wheel inside. Falling weights turned the paddles, and the churned water warmed by only a fraction of a degree, which Joule measured with a thermometer he could read to about one two-hundredth of a degree. In June 1849 he reported to the Royal Society in London that the work done by a weight of 772 pounds falling one foot would warm one pound of water by one degree Fahrenheit. Mechanical work and heating were two ways of moving the same thing. That thing is **energy** 能量, and the rule Joule helped to establish, that energy is never created or destroyed, is the most useful idea in physics.

In this unit you will:

- describe how energy is stored and transferred when a system changes;
- calculate kinetic, elastic potential and gravitational potential energy, and energy changes from heating;
- calculate power and efficiency, and explain how to reduce wasted energy;
- compare the energy resources used for transport, electricity and heating.

AQA GCSE Physics (8463), topic 4.1 Energy, examined on Paper 1. It includes required practical 1 (specific heat capacity) and, for GCSE Physics only, required practical 2 (thermal insulators). Content marked (HT) is Higher tier only. The exam gives you a **Physics Equations Sheet** 物理公式表 with some equations; the others in this unit you must learn.

Energy stores and systems

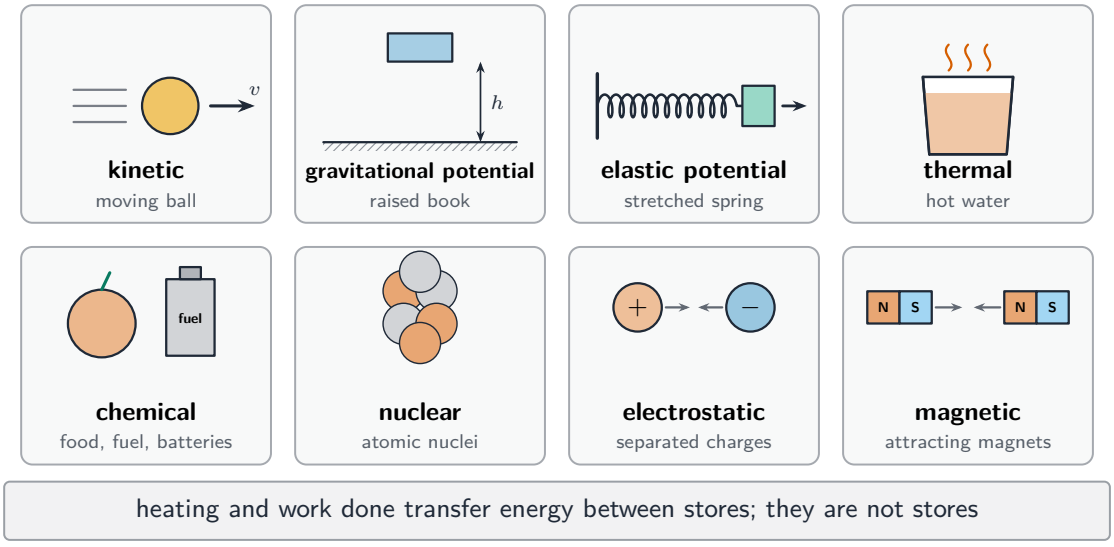
A **system** 系统 is an object, or a group of objects, that you choose to study. When a system changes, energy moves from one of its **energy stores** 能量储存 to another.

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At the top of the hill the cars have a full gravitational potential store; it empties into the kinetic store as they speed down.

Store	**Energy is stored when...**	**Example**
kinetic	an object moves	a rolling ball
gravitational potential	an object is raised in a gravitational field	water behind a dam
elastic potential	an object is stretched or squashed	a drawn bow
thermal (internal)	an object is hot	warm soup
chemical	substances can react	food, petrol, a battery
nuclear	atomic nuclei can change	uranium fuel
electrostatic	charges attract or repel	a charged cloud
magnetic	magnets attract or repel	two fridge magnets

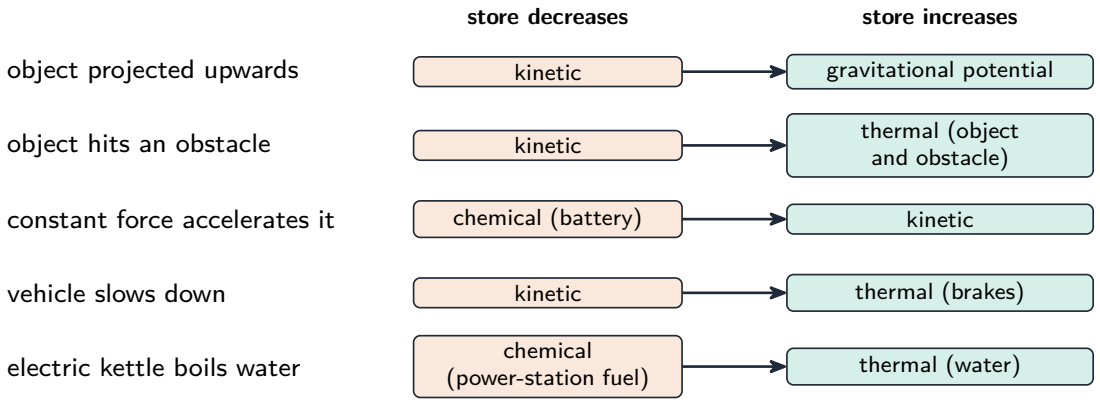


The eight energy stores, with an example of each.

Transfers. Energy moves between stores in four ways: mechanically (a force does work), electrically (a current flows), by **heating** 加热 (because of a temperature difference) and by radiation (light, infrared or sound waves). So you can calculate changes caused by heating, by **work done by forces** 力做的功 and by **work done when a current flows** 电流做的功 (topic 4.2). "Electrical" is a way of transferring energy, not a store.

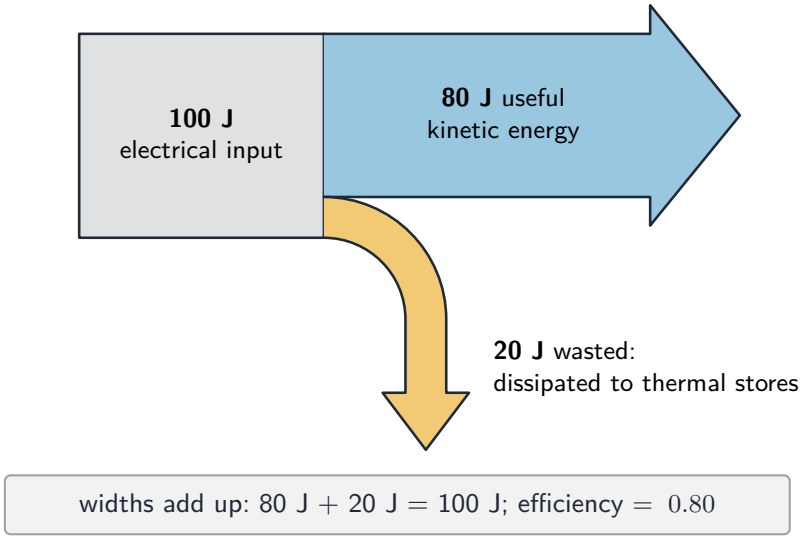
Describing a change. Always say which store empties and which store fills.

- A ball thrown upwards: its kinetic store empties and the gravitational potential store fills. At the top, it stops for an instant.
- A car hitting a wall: the kinetic store empties; the thermal stores of the car and wall fill, and some energy is carried away by sound.
- A battery-powered toy car speeding up: the chemical store of the battery empties; the kinetic store of the car fills.
- A car braking: the kinetic store empties; the thermal store of the brakes fills.
- An electric kettle boiling water: energy is transferred electrically from the mains to the thermal store of the water.



In each change, one store empties and another fills.

Sankey diagrams. A **Sankey diagram** 桑基图 shows energy transfers with arrows whose widths are drawn to scale. The input arrow splits into a useful output and wasted outputs. The output widths always add up to the input width, because energy is conserved.



The width of each arrow, not its length, shows the energy.

Worked example 1. A motor is supplied with 100 J and transfers 80 J to the kinetic store of a fan. The rest heats the motor and the air. Find the wasted energy and the widths of the Sankey arrows. Wasted energy $= 100 - 80 = 20$ J. The arrows are in the ratio $100 : 80 : 20 = 5 : 4 : 1$, so if the input is 5 cm wide, the useful arrow is 4 cm and the wasted arrow 1 cm. Only the widths show the energy, not the lengths.

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Calculating energy changes

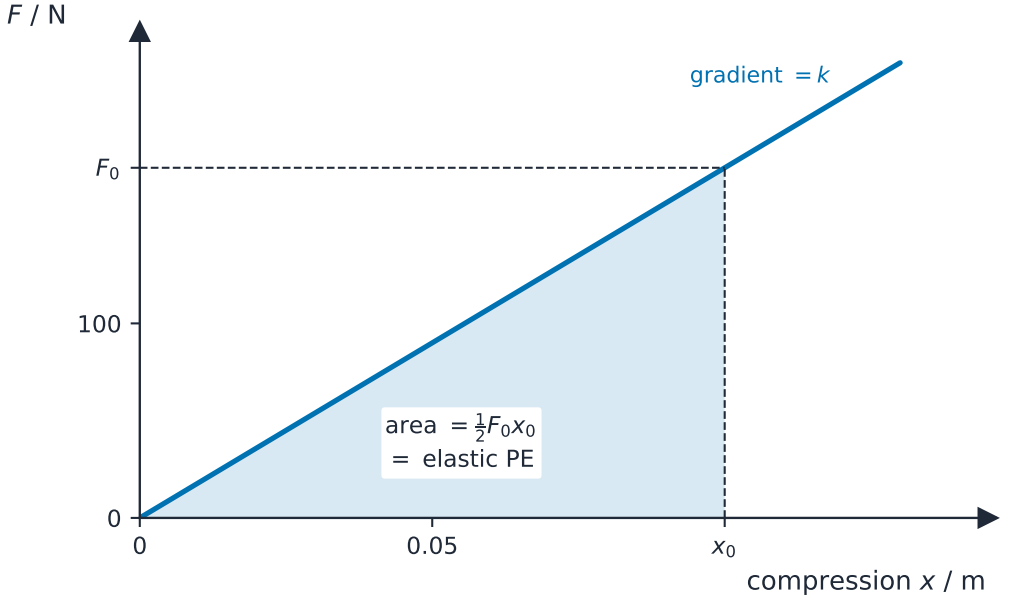
Use mass in kg, speed in m/s, height and extension in m, and the value of g given in the question.

$$E_k = \tfrac{1}{2}mv^2 \qquad E_p = mgh \qquad E_e = \tfrac{1}{2}ke^2$$

- E_k is **kinetic energy** 动能 in J; m is mass in kg; v is speed in m/s.
- E_p is **gravitational potential energy** 重力势能 in J; h is the change in height in m; g is the **gravitational field strength** 重力场强度 in N/kg (9.8 N/kg on Earth).
- E_e is **elastic potential energy** 弹性势能 in J; k is the **spring constant** 劲度系数 in N/m; e is the **extension** 伸长量 in m.

You must learn the first two; the equation for E_e is on the equations sheet.

Extension is the increase in length: stretched length minus original length. The equation for E_e works only while the spring has not gone past its **limit of proportionality** 比例极限. Because e is squared, doubling the extension makes the stored energy four times as big.



The energy stored in a spring is the area under its force–compression graph: $\frac{1}{2}F_0x_0$, which equals $\frac{1}{2}kx_0^2$

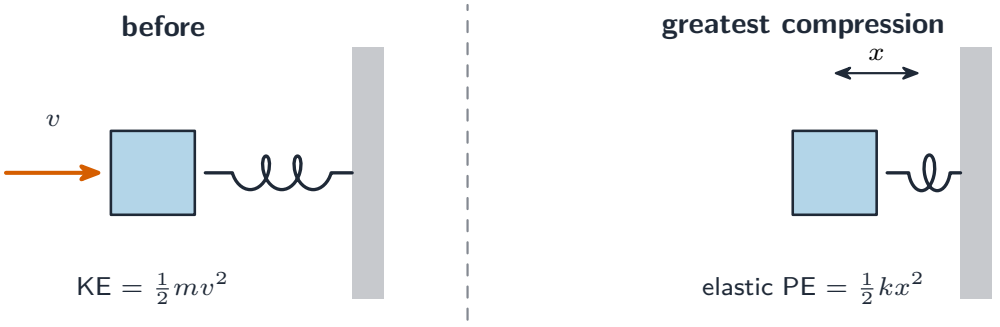
Worked example 2. A spring is 10 cm long. It is stretched to 22 cm, and $k = 50$ N/m. Find the energy stored. Extension $e = 22 - 10 = 12$ cm $= 0.12$ m. Then $E_e = \frac{1}{2} \times 50 \times 0.12^2 = 0.36$ J. If the extension were doubled to 0.24 m, the energy would be $4 \times 0.36 = 1.44$ J.

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Worked example 3. The spring in example 2 launches a 0.020 kg toy plane horizontally. Assume all the elastic potential energy becomes kinetic energy. Find the launch speed.

$$v = \sqrt{\frac{2E_k}{m}} = \sqrt{\frac{2 \times 0.36}{0.020}} = \sqrt{36} = 6.0 \text{ m/s}$$

In a real launch, some energy is transferred to thermal stores, so the speed is a little less.



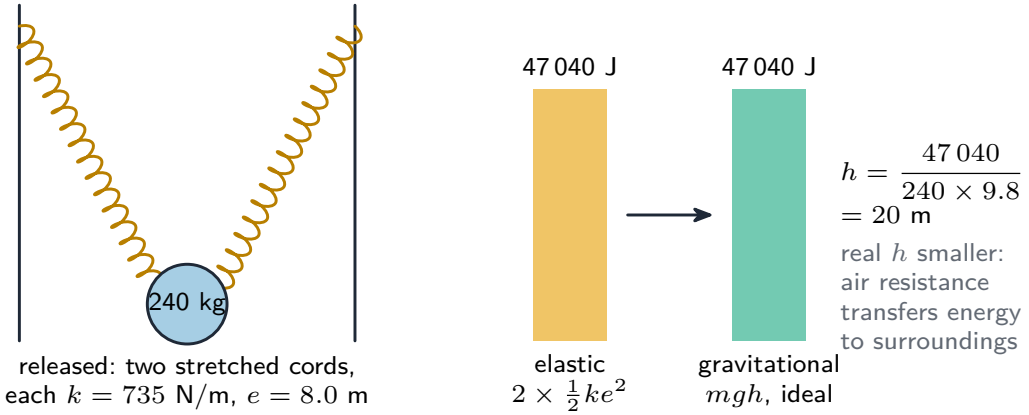
Kinetic energy and elastic potential energy exchange through a spring.

Worked example 4. A 240 kg pod is fired upwards by two stretched cords. Each cord acts like a spring with $k = 735$ N/m and extension 8.0 m. Taking $g = 9.8$ N/kg, find the greatest height the pod could reach.

- Energy in one cord: $E_e = \frac{1}{2} \times 735 \times 8.0^2 = 23\,520$ J.
- Two cords: $2 \times 23\,520 = 47\,040$ J.
- If all of this becomes gravitational potential energy: $h = \dfrac{E_p}{mg} = \dfrac{47\,040}{240 \times 9.8} = 20$ m.

The real height is lower because air resistance acts on the pod, so some energy is transferred to the thermal store of the surroundings instead of the gravitational potential store.

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If no energy is dissipated, all the elastic potential energy becomes gravitational potential energy.

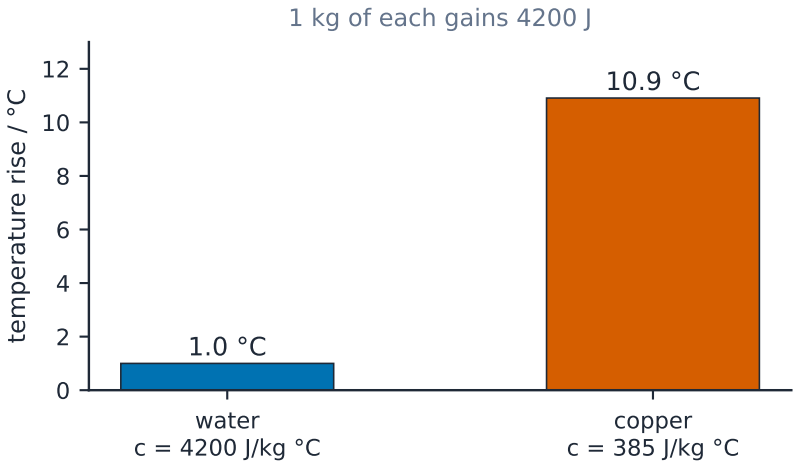
Specific heat capacity

When a substance is heated, the energy in its thermal store increases and its temperature rises:

$$\Delta E = m\,c\,\Delta\theta$$

ΔE is the change in thermal energy in J, m the mass in kg and $\Delta\theta$ the temperature change in °C. The **specific heat capacity** 比热容 c is the energy needed to raise the temperature of 1 kg of a substance by 1 °C, in J/kg °C. This equation is on the equations sheet.

Water has a high specific heat capacity, about 4200 J/kg °C; copper's is about 385 J/kg °C. So if 1 kg of each gains 4200 J, the water warms by 1.0 °C but the copper by $4200 \div 385 = 10.9$ °C.



Same mass, same energy: the material with the lower c heats up more.

Worked example 5. A 2.0 kg metal block gains 26 kJ of thermal energy, and its temperature rises from 22 °C to 50 °C. Find c. Convert the energy: 26 kJ = 26 000 J. The temperature change is $50 - 22 = 28$ °C.

$$c = \frac{\Delta E}{m\,\Delta\theta} = \frac{26\,000}{2.0 \times 28} = 464 \text{ J/kg °C} \approx 460 \text{ J/kg °C}$$

Worked example 6. A small volume of air, mass 2.60×10^{-8} kg, gains 0.0130 J. Its specific heat capacity is 1.01 kJ/kg °C. Find its temperature rise. Convert: $c = 1010$ J/kg °C. Then

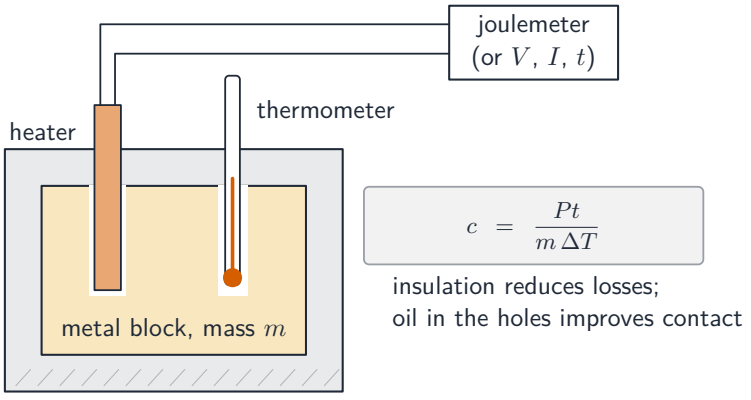
$$\Delta\theta = \frac{\Delta E}{mc} = \frac{0.0130}{2.60 \times 10^{-8} \times 1010} = 495 \text{ °C}$$

This is the rise, not the final temperature.

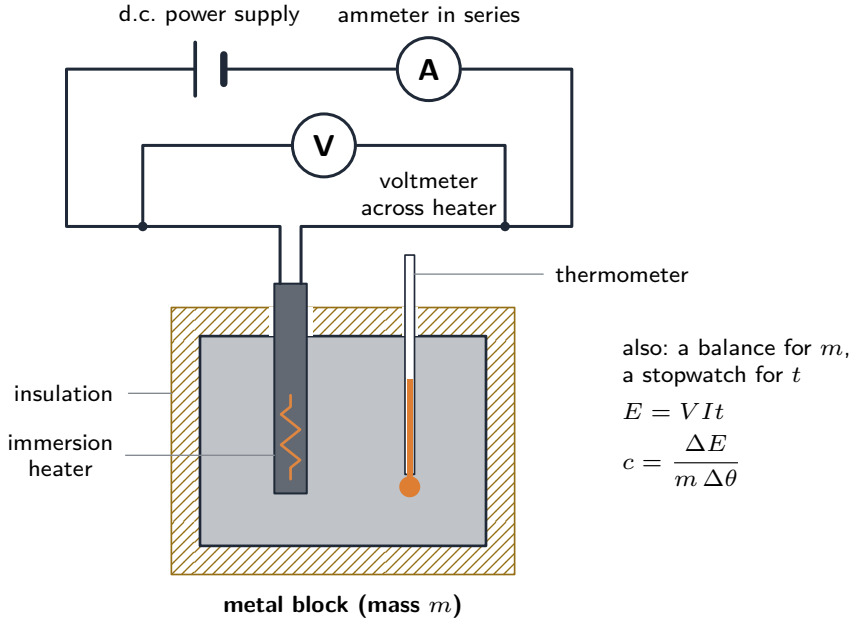
Required practical 1: specific heat capacity.

1. Measure the mass of a metal block on a balance, and wrap it in insulation.
2. Put an electric heater in one hole and a thermometer in the other, with a drop of water for good thermal contact.
3. Connect the heater to a joulemeter, or to a power supply with an ammeter in series and a voltmeter across the heater, so that power $P = VI$.
4. Record the starting temperature, switch on, and record the temperature and energy supplied (or the time, so $E = Pt$) every minute for 10 minutes.
5. Plot temperature against energy supplied, and use the straight part of the graph. Calculate $c = \dfrac{\Delta E}{m\,\Delta\theta}$.

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Energy in from the joulemeter, temperature rise from the thermometer: $c = Pt/(m\,\Delta T)$



Required practical 1: ammeter in series with the heater, voltmeter across it; insulation reduces energy transfer to the surroundings.

The insulation reduces energy transferred to the surroundings. Some energy always escapes, so the block gains less energy than was supplied. Its temperature rise is then smaller than it should be, and the calculated value of c is too high.

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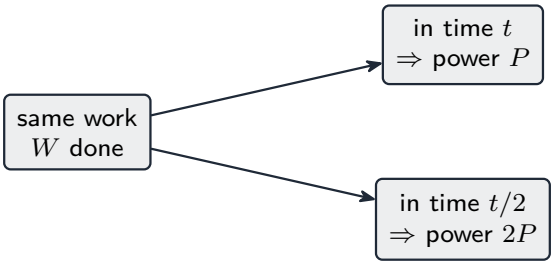
Worked example 7. A 1.0 kg block is supplied with 6000 J and should warm by 12 °C, so $c = \frac{6000}{1.0\times12} = 500$ J/kg °C. Because energy escapes, a student records only a 10 °C rise, giving $c = \frac{6000}{1.0\times10} = 600$ J/kg °C. A smaller temperature rise gives a value of c that is too high.

Power

Power 功率 is the rate at which energy is transferred, or the rate at which work is done. A more **powerful** 功率强的 motor lifts the same load through the same height in less time.

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

P is power in watts, E energy transferred in J, W the **work done** 做的功 in J and t the time in s. A transfer of 1 J per second is a power of 1 **watt** 瓦特 (W). Learn both equations.



$P = \frac{W}{t}$ — less time, more power

The same work done in less time means more power.

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A waterfall: water falling further each second transfers energy at a greater rate

Prefixes: 1 kW = 1000 W, 1 MW = 10^6 W, 1 GW = 10^9 W.

Worked example 8. Motors A and B each lift a 20 kg load through 2.0 m ($g = 10$ N/kg). A takes 2.0 s and B takes 4.0 s. Both gain $E_p = 20 \times 10 \times 2.0 = 400$ J. So $P_A = \frac{400}{2.0} = 200$ W and $P_B = \frac{400}{4.0} = 100$ W. A does the same work in half the time, so its power is twice as big.

Worked example 9. A 60.0 kg athlete runs up stairs with a vertical height of 175 cm in 1.40 s ($g = 9.8$ N/kg). Convert the height: 1.75 m. $E_p = 60.0 \times 9.8 \times 1.75 = 1029$ J, so the useful power is $P = \frac{1029}{1.40} = 735$ W. The athlete's body transfers more energy than this, because some heats the body.

Worked example 10. A power station has an output power of 500 MW. Find the energy it transfers in one hour. $E = Pt = 5.00 \times 10^8 \times 3600 = 1.8 \times 10^{12}$ J.

Conservation and dissipation of energy

Energy can be transferred usefully, stored or **dissipated** 耗散, but it cannot be created or destroyed. Dissipated energy is often called wasted energy; it is stored in less useful ways, usually in the thermal store of the surroundings.

In a **closed system** 封闭系统, no energy enters or leaves, so the total energy stays the same.

Worked example 11. A ball is held above the floor with 20 J of gravitational potential energy. Ignore air resistance.

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Stage	Gravitational potential / J	Kinetic / J	Thermal / J
held still	20	0	0
part way down	5	15	0
after it stops bouncing	0	0	20

The total is 20 J at every stage. In the end the energy is in the thermal stores of the ball, the floor and the air.

Explaining a smaller answer. If a real height, speed or temperature is less than you calculated, say three things: what caused it (air resistance, friction or heating of the surroundings); that some energy was transferred to thermal stores; so less energy reached the useful store.

Reducing unwanted transfers.

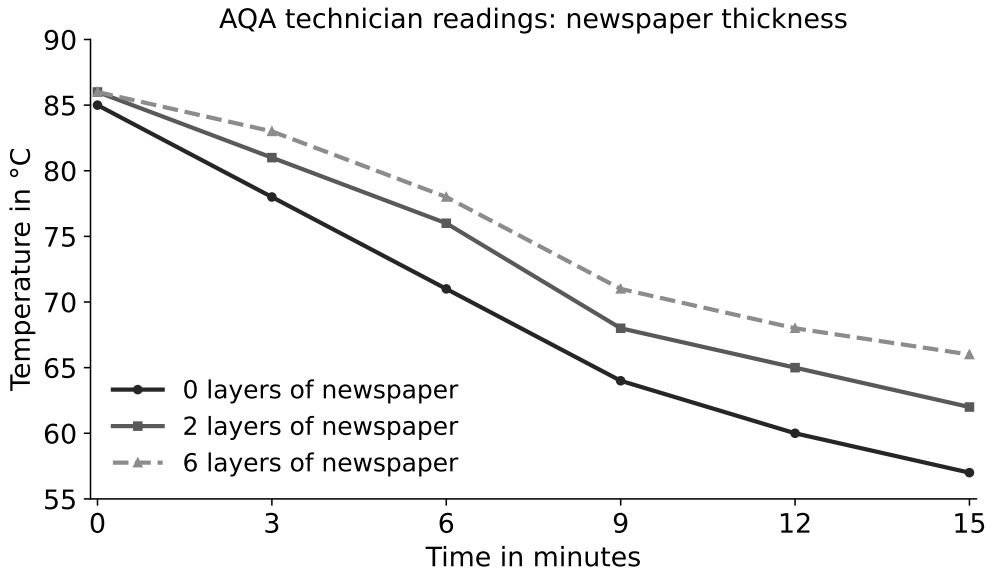
- **Lubrication** 润滑 with oil or grease reduces friction between moving parts, so less energy is dissipated by heating.
- **Thermal insulation** 热绝缘 reduces energy transfer by heating. A material with a lower **thermal conductivity** 热导率 transfers energy more slowly. For a house, the rate of cooling is lower if the walls are thicker and if they are made of a material with a lower thermal conductivity.

Required practical 2 (physics only): thermal insulators.

1. Pour the same volume of hot water into a beaker, put on a lid, and wrap the beaker in one layer of a material such as newspaper, bubble wrap or cotton wool.
2. Record the temperature every minute for 15 minutes.
3. Repeat with other materials of the same thickness, keeping the volume of water, starting temperature, beaker and lid the same.
4. Then repeat with different numbers of layers of one material.

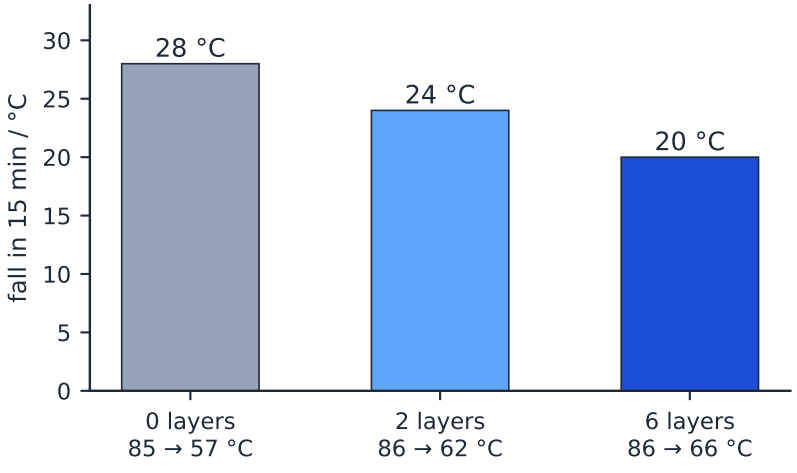
The best insulator gives the smallest fall in temperature over the same time.

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Cooling curves for zero, two and six layers of newspaper (AQA GCSE Physics Required Practical Handbook, sample results).

Worked example 12. In AQA's sample results, water with no newspaper cooled from 85 °C to 57 °C in 15 minutes, with two layers from 86 °C to 62 °C, and with six layers from 86 °C to 66 °C. The falls are $85 - 57 = 28$ °C, $86 - 62 = 24$ °C and $86 - 66 = 20$ °C. More layers gave less cooling. The run with no newspaper started 1 °C cooler, so a fair test should use the same starting temperature every time.



Temperature falls in 15 minutes: more layers, less cooling.

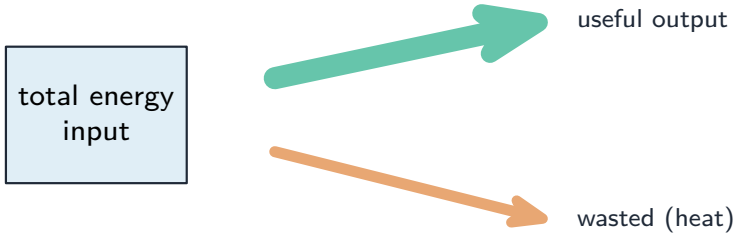
Worked example 13. One beaker, wrapped in 20 mm of cotton wool, cooled from 90 °C to 75 °C in 10 minutes; another, wrapped in 2 mm of foil, cooled from 80 °C to 70 °C. Can we say which material is the better insulator? No. Both the material and the thickness changed, and so did the starting temperature. Use the same thickness and starting temperature, change only the material, and repeat.

Efficiency

Efficiency 效率 tells you what fraction of the input energy is transferred usefully:

$$\text{efficiency} = \frac{\text{useful output energy transfer}}{\text{total input energy transfer}} \qquad \text{efficiency} = \frac{\text{useful power output}}{\text{total power input}}$$

You must learn both. Efficiency can be a decimal or a percentage, and it can never be more than 1 (100%). It has no unit.



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

Only part of the input energy becomes useful output; the rest is dissipated, usually by heating.

Worked example 14. A lamp takes in 4.0 W and has an efficiency of 0.85. Useful light output $= 0.85 \times 4.0 = 3.4$ W. The other $4.0 - 3.4 = 0.6$ W heats the surroundings.

Worked example 15. Two lifting machines each take in 2000 W. Machine A gives a useful output of 1700 W and machine B 1500 W. Efficiency of A $= \frac{1700}{2000} = 0.85 = 85\%$; efficiency of B $= \frac{1500}{2000} = 0.75 = 75\%$.

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Worked example 16. Two ways of storing energy are compared. Method A heats 100 kg of water, storing 33 600 kJ, but 40% is wasted. Method B pumps 100 kg of water up a mountain, storing 490 kJ, and 25% is wasted. A transfers $0.60 \times 33\,600 = 20\,160$ kJ usefully; B transfers $0.75 \times 490 = 367.5$ kJ. B is more efficient, but A gives far more useful energy for each 100 kg, and B needs high mountains.

(HT) Increasing efficiency. Reduce wasted transfers: lubricate moving parts, insulate hot objects, and streamline moving vehicles. For the same input, more energy then reaches the useful store.

National and global energy resources

The main energy resources are **fossil fuels** 化石燃料 (coal, oil and gas), **nuclear fuel** 核燃料, bio-fuel, wind, hydroelectricity, geothermal, the tides, the Sun and water waves. We use them for transport, electricity generation and heating.

A **renewable** 可再生的 resource is one that is being, or can be, replaced as it is used. Fossil fuels and nuclear fuel are **non-renewable** 不可再生的: they will run out.



Wind turbines transfer energy from the kinetic store of moving air electrically to the grid.

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Resource	Reliable?	Main environmental effects
coal, oil, gas	yes, while fuel lasts	carbon dioxide (global warming); sulfur dioxide (acid rain)
nuclear	yes	no carbon dioxide when generating; radioactive waste
bio-fuel	yes	carbon dioxide when burned, partly taken in again as crops grow; needs land
wind	no, depends on wind	noise and changed landscapes
solar	no, none at night	needs large areas and materials
hydroelectric	yes	dams flood valleys and destroy habitats
geothermal	yes, in few places	few; needs suitable sites
tides	yes, at predictable times	affects habitats in estuaries
waves	no, depends on the weather	affects coastal habitats

Renewable resources do not burn fuel, but building them still uses materials and energy, and some are not available all the time. Decisions about energy also depend on cost, politics and what people want, not only on science.

Worked example 17. A nuclear power station generated electricity for 92% of a 365-day year. How many days was that? $0.92 \times 365 = 335.8$, so about 336 days.

Worked example 18. A country's electricity came from fossil fuels and renewables. In year A it used 80 TWh from fossil fuels and 20 TWh from renewables; in year B, 90 TWh and 60 TWh. The fossil share fell from $\frac{80}{100} = 80\%$ to $\frac{90}{150} = 60\%$, but the energy from fossil fuels rose by 10 TWh, so emissions from fossil fuels did not fall.

Worked example 19. A clinic needs electricity all night. Solar panels give none at night, so they would need batteries or a backup supply. A gas generator works at night, but releases carbon dioxide. A good answer compares reliability, cost and environmental effects.

Sources for this lesson

- AQA, *GCSE Physics (8463) specification*, section 4.1 Energy, and the *Required practical handbook* (sample results for practical 2).

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- J. P. Joule, "On the mechanical equivalent of heat", *Philosophical Transactions of the Royal Society*, 140 (1850), read 21 June 1849.
- AQA, *GCSE Physics* Paper 1 Higher, June 2024, questions 1, 2, 6 and 8 (adapted).

Common errors

- Calling "electrical" a store. It is a way of transferring energy.
- Using the stretched length instead of the extension in $E_e = \frac{1}{2}ke^2$.
- Forgetting to square the speed or the extension.
- Using the final temperature instead of the temperature change in $\Delta E = mc\Delta\theta$.
- Leaving time in minutes, mass in grams or energy in kJ.
- Saying energy is "lost" or "used up" without saying where it goes.
- Giving an efficiency greater than 1 or 100%.
- Saying renewable resources are always available.

Key terms

- **Energy store**: a way energy is held, such as kinetic, thermal or chemical.
- **System**: the object or group of objects being studied.
- **Specific heat capacity**: the energy needed to raise 1 kg of a substance by 1 °C.
- **Power**: the rate of energy transfer, in watts.
- **Dissipated energy**: energy stored in less useful ways, usually thermal.
- **Efficiency**: useful output divided by total input.
- **Renewable resource**: an energy resource that is replaced as it is used.

Check yourself

1. Name the store that empties and the store that fills when a car brakes.
2. A 0.50 kg cart moves at 4.0 m/s. Calculate its kinetic energy.
3. A 2.0 kg book is lifted 1.5 m ($g = 9.8$ N/kg). Calculate the gain in gravitational potential energy.
4. How much energy warms 0.50 kg of water by 20 °C? ($c = 4200$ J/kg °C)
5. A motor takes in 5.0 J in 2.0 s and gives the cart 4.0 J. Calculate the input power and the efficiency.
6. Why does the measured specific heat capacity come out too high in required practical 1?
7. Give one advantage and one disadvantage of wind power.

Answers: 1. The kinetic store empties; the thermal store of the brakes fills. 2. $\frac{1}{2} \times 0.50 \times 4.0^2 = 4.0$ J. 3. $2.0 \times 9.8 \times 1.5 = 29.4$ J. 4. $0.50 \times 4200 \times 20 = 42\,000$ J. 5. $\frac{5.0}{2.0} = 2.5$ W; $\frac{4.0}{5.0} = 0.80$ (80%). 6. Some energy heats the surroundings, so the temperature rise is smaller than it would be, and $c = \frac{\Delta E}{m\Delta\theta}$ is too big. 7. Advantage:

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renewable, no carbon dioxide while generating; disadvantage: unreliable when the wind drops (or noise, changed landscape).

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2 · Electricity

AQA · GCSE · Physics

Electricity: circuits, mains and the National Grid

Why it matters. In 1827 Georg Simon Ohm, a mathematics teacher at a school in Cologne, published a short book in Berlin with the results of his experiments on wires. He had connected wires of different lengths and thicknesses to a steady source and measured the current through each with a sensitive magnetic needle. He found a simple rule: for a given wire, the current is proportional to the **potential difference** 电势差 that drives it. Many German scientists dismissed the work, and Ohm struggled to find a university post. In 1841 the Royal Society in London awarded him its Copley Medal, its highest honour, and today the unit of resistance carries his name. Every circuit calculation in this unit starts from his rule.

In this unit you will:

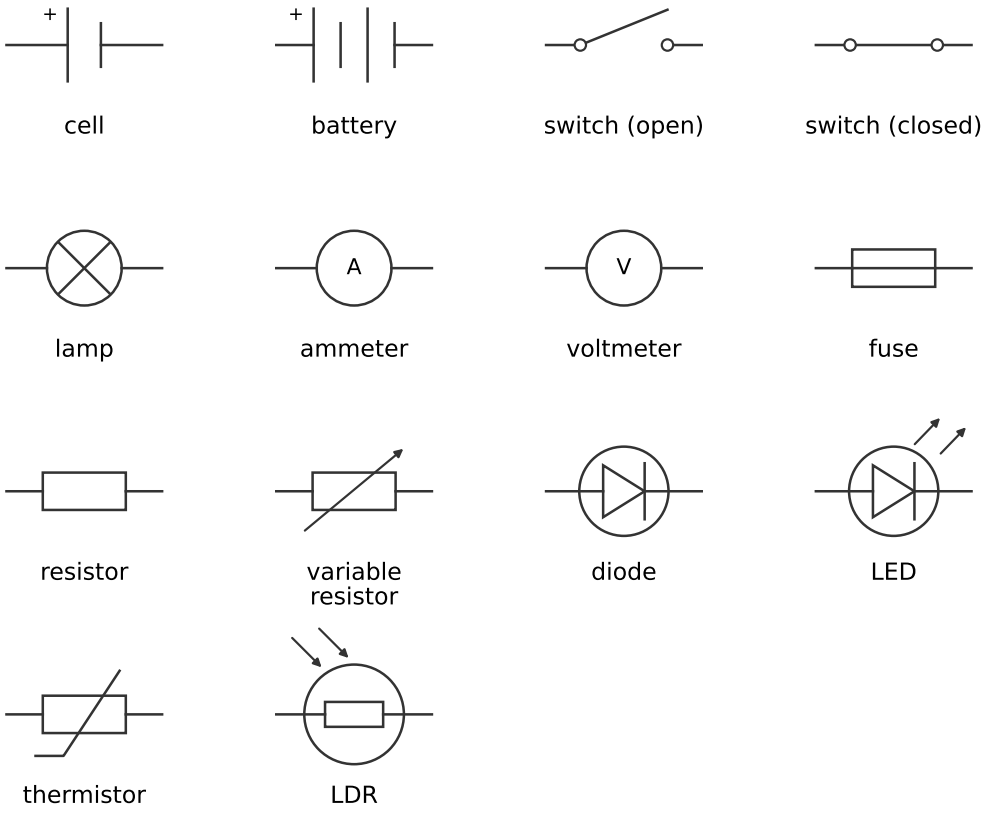
- draw circuit diagrams and calculate charge, current, resistance and potential difference;
- investigate how resistance depends on length and how current depends on potential difference;
- apply the rules for series and parallel circuits;
- explain mains electricity, electrical safety, power and the National Grid;
- (physics only) explain static electricity and electric fields.

AQA GCSE Physics (8463), topic 4.2 Electricity, examined on Paper 1. It includes required practicals 3 (resistance) and 4 (I–V characteristics). Static electricity is in GCSE Physics only. All six equations in this unit must be learned; the **Physics Equations Sheet** 物理公式表 does not list them.

Circuit symbols, charge and current

Circuit diagrams use standard **circuit symbols** 电路符号. Learn the symbols for a cell, battery, open and closed switch, lamp, fuse, resistor, variable resistor, ammeter, voltmeter, diode, LED, thermistor and LDR. An ammeter is always connected **in series** 串联 with a component, and a voltmeter **in parallel** 并联 across it.

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Circuit symbols: light arrows point into an LDR and out of an LED.

For charge to flow, there must be a closed circuit with a source of potential difference, such as a cell. **Electric current** 电流 is the rate of flow of electrical **charge** 电荷:

$$Q = It$$

Q is charge in coulombs (C), I is current in amperes (A) and t is time in seconds (s). One ampere is one coulomb per second. In a single closed loop, the current is the same at every point: a lamp transfers energy, but it does not use up charge.

> **Worked example 1.** 4.0 C passes a point in 2.0 s. The current is $I = \frac{Q}{t} = \frac{4.0}{2.0} = 2.0$ A. If the same charge took 4.0 s, the current would be $\frac{4.0}{4.0} = 1.0$ A.

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Worked example 2. A charger supplies 0.90 A for 25 minutes. Convert the time: $25 \times 60 = 1500$ s. Charge $Q = 0.90 \times 1500 = 1350$ C.

Worked example 3. A fuse wire melts when 2.0 C flows through it in 400 ms. Convert: 400 ms = 0.400 s. Current $I = \frac{2.0}{0.400} = 5.0$ A. Using 400 s by mistake would give an answer 1000 times too small.

Current, resistance and potential difference

The current through a component depends on the potential difference across it and on its **resistance** 电阻:

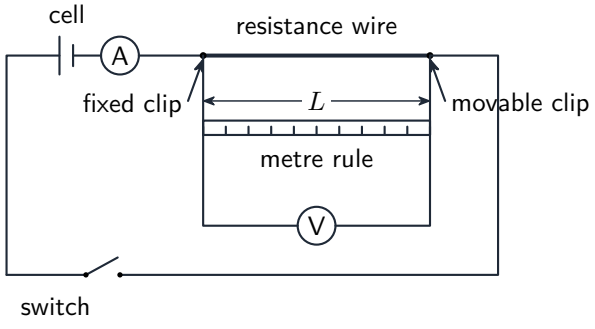
$$V = IR$$

V is potential difference in volts (V), I is current in amperes and R is resistance in ohms (Ω). For the same potential difference, a bigger resistance gives a smaller current.

Worked example 4. A potential difference of 0.45 V drives a current of 0.0075 A through a coin. Its resistance is $R = \frac{V}{I} = \frac{0.45}{0.0075} = 60\ \Omega$.

Required practical 3: resistance. Part 1 investigates how the length of a wire affects its resistance.

1. Tape a resistance wire along a metre rule. Connect one crocodile clip at 0 cm and the other at the length being tested.
2. Connect a cell, switch and ammeter in series with the wire, and a voltmeter across the two clips.
3. Record the current and potential difference for lengths from 10 cm to 100 cm, and calculate $R = \frac{V}{I}$ for each.
4. Switch off between readings so that the wire does not heat up, because heating increases its resistance.

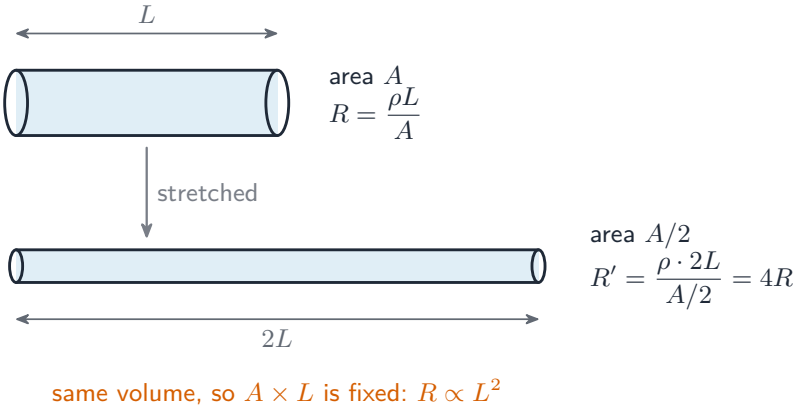


Required practical 3: the ammeter is in series with the wire, and the voltmeter is across the length between the clips.

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Length / cm	Potential difference / V	Current / A	Resistance / Ω
20	0.60	0.30	2.0
40	0.80	0.20	4.0
60	0.90	0.15	6.0

A graph of resistance against length is a straight line through the origin: resistance is directly proportional to length. If the line does not pass through the origin, check whether the length was measured from the actual contact point of the clip.



Stretched to twice the length, the wire has half the area and four times the resistance.

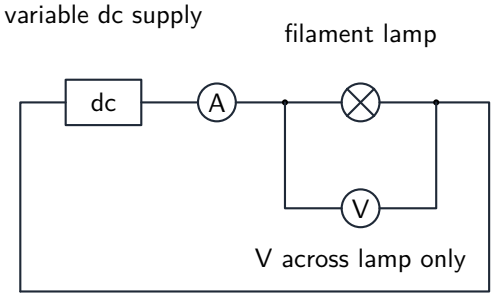
Part 2 compares resistors in series and in parallel. Connect two identical resistors in series, then in parallel, and measure the total current and total potential difference each time. Two 10 Ω resistors give 20 Ω in series but only 5 Ω in parallel.

Resistors and I–V characteristics

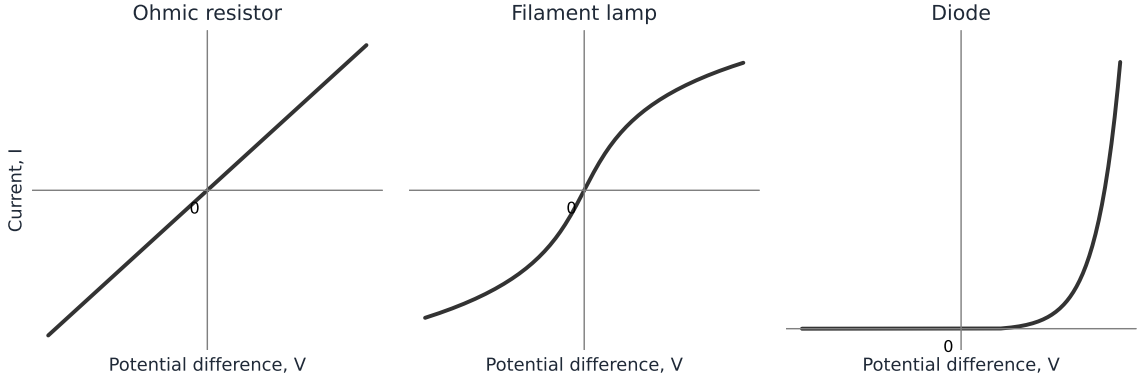
Required practical 4: I–V characteristics.

1. Connect the component in series with an ammeter and a variable resistor (or use a variable power supply), with a voltmeter across the component.
2. Change the potential difference in steps, recording the current each time.
3. Reverse the connections to the supply to get negative values.
4. Plot current (vertical axis) against potential difference (horizontal axis).

For a diode, include a protective resistor in series so the current cannot become too large, and use a milliammeter.



Required practical 4: the ammeter is in series with the lamp, and the voltmeter is across it.



I–V characteristics of a resistor at constant temperature, a filament lamp and a diode.

- An **ohmic conductor** 欧姆导体, such as a fixed resistor at constant temperature, has a constant resistance. The current is directly proportional to the potential difference: a straight line through the origin.
- In a **filament lamp** 白炽灯, the filament gets hotter as the current increases. The ions in the metal vibrate more, so the resistance increases and the graph curves.
- A **diode** 二极管 lets current flow in one direction only. In the reverse direction its resistance is very high, so almost no current flows.

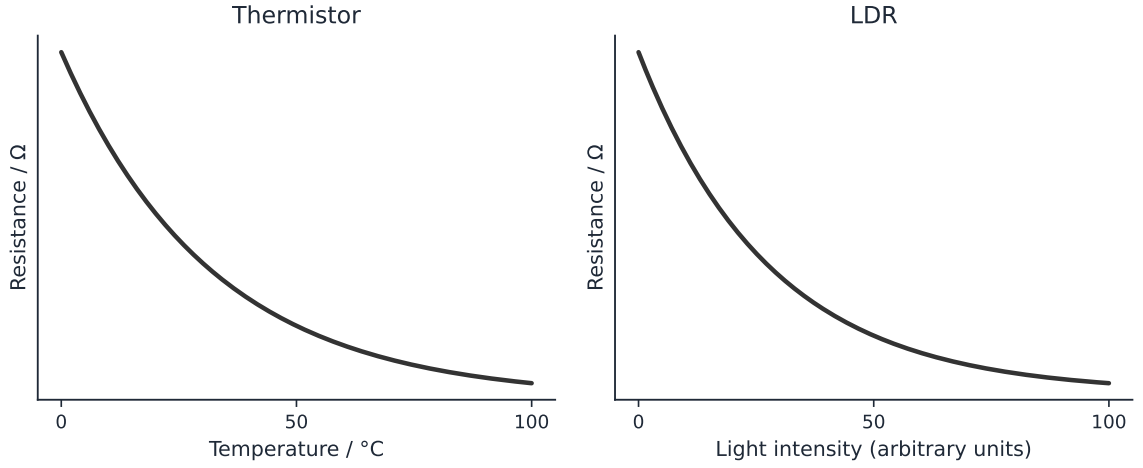
To find resistance at a point on an I–V graph, read off V and I and use $R = \frac{V}{I}$. Do not use the gradient of a curve.

> **Worked example 5.** On a filament lamp's graph, the current is 0.16 A at 3.0 V and 0.21 A at 6.0 V. At 3.0 V, $R = \frac{3.0}{0.16} = 18.75\ \Omega \approx 19\ \Omega$. At 6.0 V, $R = \frac{6.0}{0.21} = 29\ \Omega$. The resistance is higher at the higher potential difference because the filament is hotter.

Sensors.

- The resistance of a **thermistor** 热敏电阻 decreases as its temperature increases. It is used in thermostats.

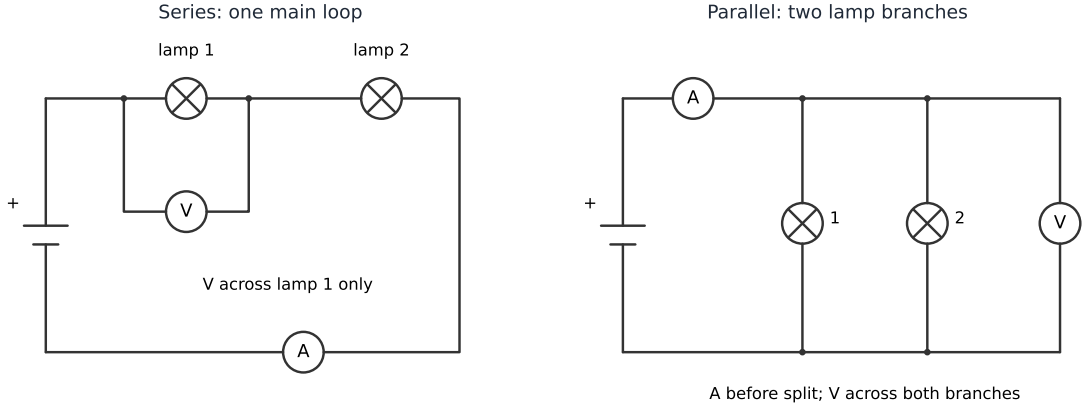
- The resistance of an **LDR** 光敏电阻 (light-dependent resistor) decreases as light intensity increases. It is used in lights that switch on automatically at night.



Resistance against temperature for a thermistor, and against light intensity for an LDR.

Series and parallel circuits

In a series circuit, the components are connected one after another in a single loop. In a parallel circuit, each component is on its own branch.

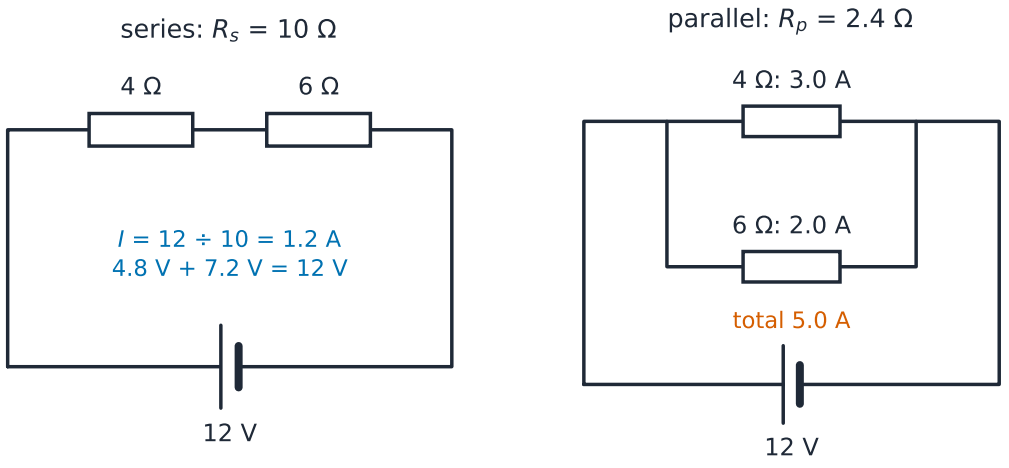


The same two lamps in series and in parallel, with the meters in place.

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	Series	Parallel
current	the same through each component	the total is the sum of the branch currents
potential difference	shared between the components	the same across each branch
total resistance	$R_{total} = R_1 + R_2$	less than the smallest resistance

Adding a resistor in series increases the total resistance, because the charge has to pass through both. Adding a resistor in parallel decreases the total resistance, because it gives the charge an extra path, so more current flows for the same potential difference. You do not need to calculate the total resistance of resistors in parallel.



In series the potential difference is shared; in parallel the current is shared.

Worked example 6. A 6.0 V battery is connected to a 12 Ω lamp in series with a 6.0 Ω resistor.

- Total resistance: $12 + 6.0 = 18\ \Omega$.
- Current: $I = \frac{6.0}{18} = 0.33$ A.
- Potential difference across the lamp: $\frac{6.0}{18} \times 12 = 4.0$ V; across the resistor: $\frac{6.0}{18} \times 6.0 = 2.0$ V.

The two add up to 6.0 V. The bigger resistance takes the bigger share.

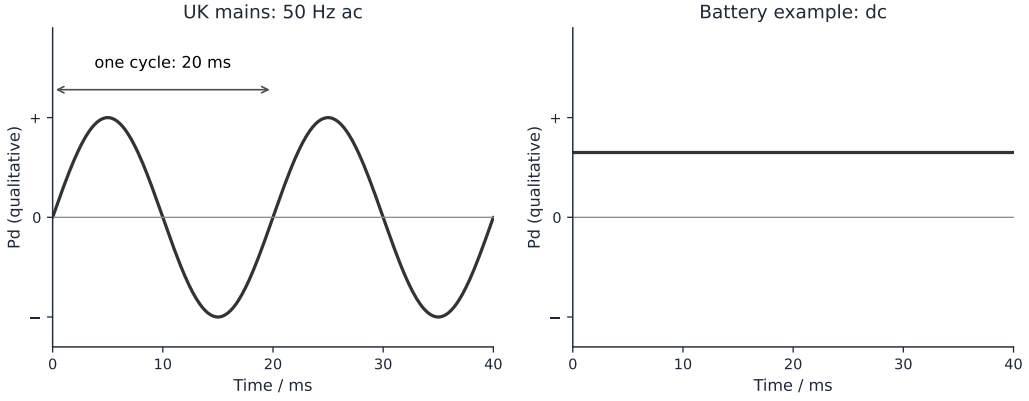
Worked example 7. Two 8.0 Ω resistors are connected to a 12 V supply. In series, $R_{total} = 16\ \Omega$ and $I = \frac{12}{16} = 0.75$ A, so each resistor has $0.75 \times 8.0 = 6.0$ V. In parallel, each resistor has the full 12 V, so each branch carries $\frac{12}{8.0} = 1.5$ A, and the total current is 3.0 A.

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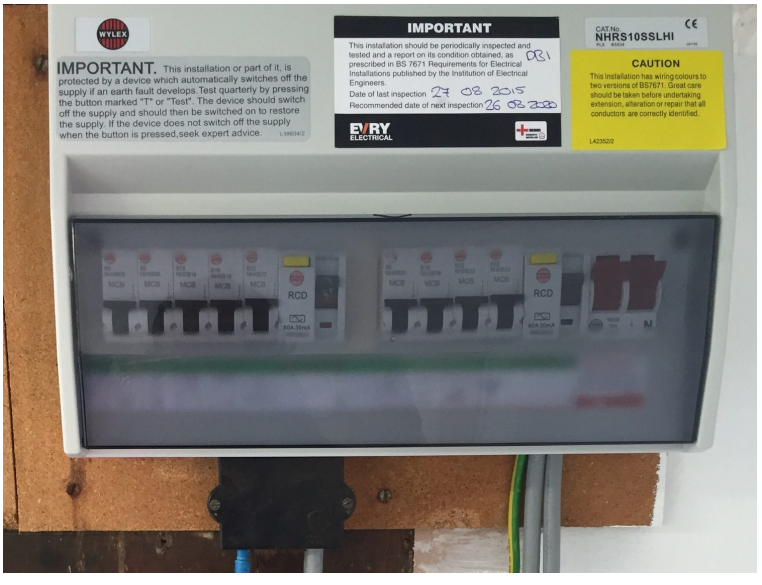
Worked example 8. A thermistor has a resistance of 80 Ω at 20 °C. It is in series with a 400 Ω resistor and a 12 V supply. Total resistance = 480 Ω, so $I = \frac{12}{480} = 0.025$ A. The potential difference across the thermistor is $0.025 \times 80 = 2.0$ V, and across the resistor 10 V. If the temperature rises, the thermistor's resistance falls, so it takes a smaller share of the 12 V.

Mains electricity and safety

Mains electricity in the UK is an **alternating** 交流 current (ac) supply: the potential difference keeps reversing direction. It has a frequency of 50 Hz and a potential difference of about 230 V. A battery gives a **direct** 直流 potential difference (dc), which always acts in the same direction.



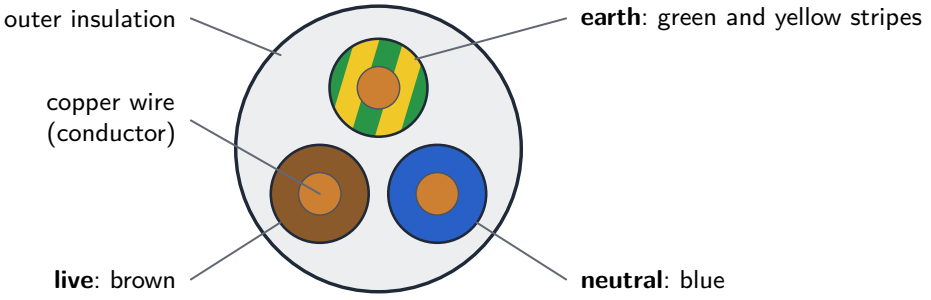
Alternating and direct potential difference; one 50 Hz cycle lasts 20 ms.



A home consumer unit: circuit breakers cut off the supply if the current becomes too large.

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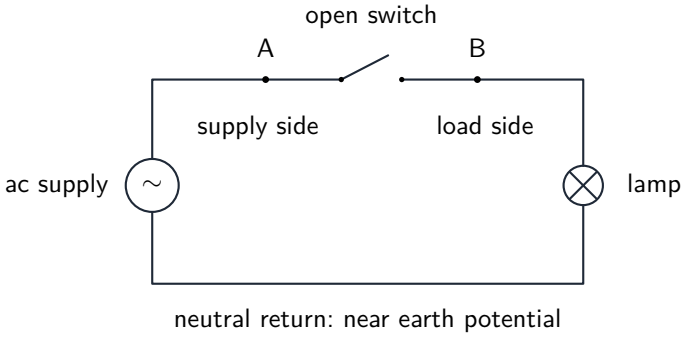
Most appliances are connected to the mains with a three-core cable.



Brown is live, blue is neutral, and green and yellow stripes is earth.

Wire	Colour	Job
live	brown	carries the alternating potential difference from the supply, about 230 V
neutral	blue	completes the circuit; at or close to 0 V
earth	green and yellow stripes	a safety wire that stops the appliance case becoming live; 0 V, carries current only if there is a fault

Why the live wire is dangerous. The live wire is at about 230 V, and your body is at 0 V. If you touch it, there is a large potential difference across your body, so a current flows through you to earth, giving an electric shock that can kill. This can happen even when a switch is off.



An open switch in the live wire: point A, on the supply side, is still at about 230 V.

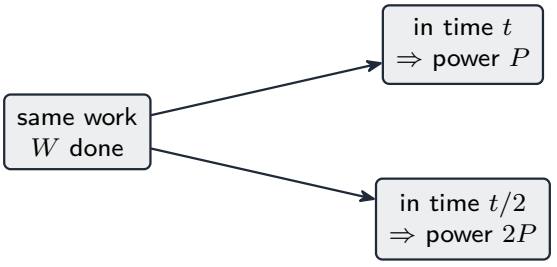
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Worked example 9. A lamp is switched off with a switch in the live wire. Explain why point A, between the supply and the switch, is still dangerous. Point A is still connected to the live wire, so it is at about 230 V. Anyone touching it and earth at the same time has a potential difference of 230 V across them, so a current would flow through their body.

Earth wire and fuse. If a fault connects the live wire to a metal case, a large current flows through the low-resistance earth wire. This current melts the fuse in the live wire, which disconnects the supply, so the case does not stay live.

Power and energy in appliances

Appliances transfer energy from batteries or the mains: a motor transfers energy to a kinetic store, and a heater to a thermal store. The power of an appliance is the energy it transfers each second.



$$P = \frac{W}{t} \text{ — less time, more power}$$

The same work done in less time means more power...

$$P = VI \qquad P = I^2R \qquad E = Pt \qquad E = QV$$

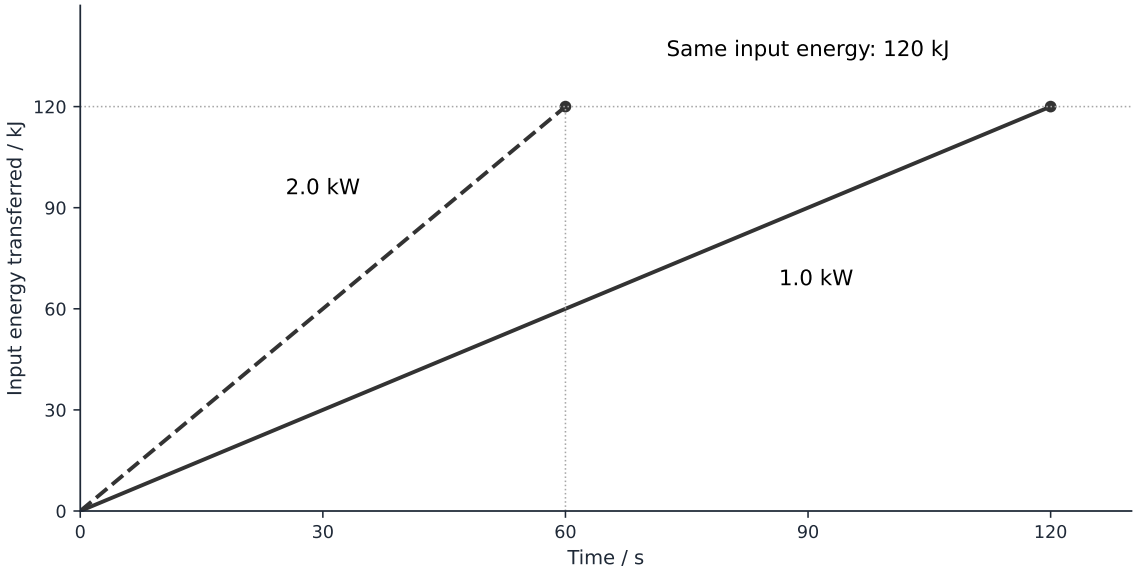
P is power in watts, E is energy in joules and Q is charge in coulombs. Use time in seconds.

Worked example 10. A lamp carries 0.21 A at 6.0 V for 30 minutes. Find the energy transferred. Convert: $30 \times 60 = 1800$ s. Power $P = 6.0 \times 0.21 = 1.26$ W, so $E = 1.26 \times 1800 = 2268$ J ≈ 2300 J. Another way: $Q = 0.21 \times 1800 = 378$ C, and $E = QV = 378 \times 6.0 = 2268$ J.

Worked example 11. A pump motor has a power of 4.86 W and a resistance of 6.0 Ω. Find the charge that flows in 30 minutes. From $P = I^2R$, $I^2 = \frac{4.86}{6.0} = 0.81$, so $I = \sqrt{0.81} = 0.90$ A. Then $Q = It = 0.90 \times 1800 = 1620$ C.

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Worked example 12. A 1.0 kW kettle and a 2.0 kW kettle each transfer 120 kJ. The 1.0 kW kettle takes $t = \frac{E}{P} = \frac{120\,000}{1000} = 120$ s; the 2.0 kW kettle takes 60 s. The more powerful kettle transfers the same energy in half the time.



Energy against time: the 2.0 kW line is twice as steep, so it reaches 120 kJ in half the time.

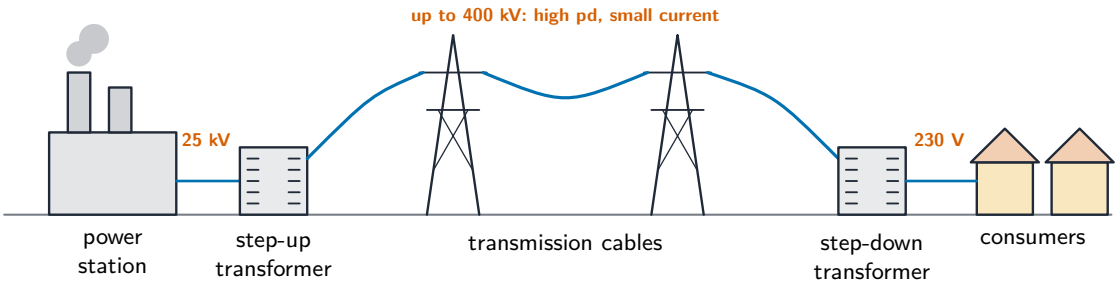
The National Grid

The **National Grid** 国家电网 is a system of cables and transformers that links power stations to consumers.



Pylons carry the cables at a very high potential difference, which keeps the current and the wasted power low.

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same power, higher pd: smaller current, so less energy wasted heating the cables

A higher potential difference gives a smaller current for the same power, so less energy is wasted in the cables.

- A **step-up transformer** 升压变压器 increases the potential difference from the power station to a very high value for transmission.
- For the same power, a higher potential difference means a smaller current ($P = VI$).
- A smaller current heats the cables less ($P = I^2R$), so less energy is wasted and the grid is more efficient.
- A **step-down transformer** 降压变压器 then decreases the potential difference to about 230 V, a safer value for homes.

Worked example 13. 500 kW is sent through cables of total resistance 2.0 Ω. At 10 kV, the current is $\frac{500\,000}{10\,000} = 50$ A and the power wasted in the cables is $50^2 \times 2.0 = 5000$ W. At 20 kV, the current is 25 A and the power wasted is $25^2 \times 2.0 = 1250$ W. Doubling the potential difference halves the current and divides the wasted power by four.

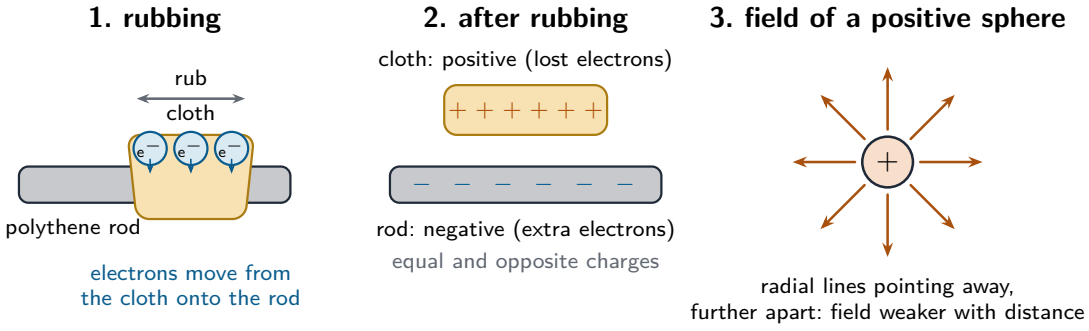
Worked example 14. A transformer has an efficiency of 0.992 and an input of 34.2 GJ. Useful output $= 0.992 \times 34.2 = 33.9$ GJ.

Static electricity (physics only)

When two insulating materials are rubbed together, electrons are transferred from one to the other. The material that gains electrons becomes negatively charged; the material that loses electrons is left with an equal positive charge. Only electrons move; positive charges do not.

Charged objects exert a non-contact force on each other: like charges repel and unlike charges attract.

A charged object has an **electric field** 电场 around it, a region in which another charged object feels a force. The field is strongest close to the object. Draw the field of an isolated charged sphere as straight lines pointing radially away from a positive sphere, or towards a negative one.



Rubbing moves electrons onto the rod; the field lines of a positive sphere point radially outwards.

Sparks. As charge builds up on an object, the potential difference between it and the earth increases, and the electric field gets stronger. If the field is strong enough, electrons flow through the air to an earthed conductor, producing a spark.

Worked example 15. A polythene rod is rubbed with a cloth and becomes negatively charged. Explain why. Electrons move from the cloth to the rod. Electrons are negative, so the rod gains a negative charge, and the cloth is left with an equal positive charge.

Worked example 16. A spark transfers 0.60 J of energy with a charge of 2.0 μC. Find the potential difference. Convert: 2.0 $\mu\text{C} = 2.0 \times 10^{-6}$ C. $V = \frac{E}{Q} = \frac{0.60}{2.0 \times 10^{-6}} = 3.0 \times 10^{5}$ V.

Sources for this lesson

- AQA, *GCSE Physics (8463) specification*, section 4.2 Electricity, and the *Required practical handbook* (practicals 3 and 4).
- G. S. Ohm, *Die galvanische Kette, mathematisch bearbeitet* (Berlin, 1827); Royal Society, Copley Medal award, 1841.
- AQA, *GCSE Physics* Paper 1 Higher, June 2022 to June 2025 (fuse, lamp, thermistor, pump, grid and spark questions, adapted).

Common errors

- Saying a lamp uses up current. The current is the same all round a series loop; energy is transferred.
- Putting an ammeter in parallel or a voltmeter in series.
- Adding parallel resistances as if they were in series. The total is less than the smallest resistance.
- Leaving current in mA or time in minutes.

- Using the gradient of a curved I–V graph as the resistance. Use $R = \frac{V}{I}$ at the point.
- Getting sensor trends backwards: thermistor resistance falls as temperature rises; LDR resistance falls as light increases.
- Saying the earth wire carries current all the time.
- Saying positive charges move when objects are rubbed. Only electrons move.

Key terms

- **Current**: the rate of flow of charge, in amperes.
- **Potential difference**: what drives charge round a circuit, in volts.
- **Resistance**: opposition to current, in ohms.
- **Ohmic conductor**: a conductor whose current is directly proportional to the potential difference at constant temperature.
- **Alternating current**: current that keeps reversing direction.
- **National Grid**: the network of cables and transformers that links power stations to consumers.
- **Electric field**: a region where a charged object feels a force.

Check yourself

1. 30 C flows through a lamp in 1 minute. Calculate the current.
2. A 12 V supply drives 0.40 A through a resistor. Calculate its resistance.
3. Sketch the I–V graph of a filament lamp and explain its shape.
4. Two resistors of 4.0 Ω and 6.0 Ω are in series with a 10 V battery. Calculate the current.
5. State the frequency and potential difference of the UK mains supply.
6. A 2.0 kW heater is used for 15 minutes. Calculate the energy transferred.
7. Explain why the National Grid uses a very high potential difference.

Answers: 1. $\frac{30}{60} = 0.50$ A. 2. $\frac{12}{0.40} = 30$ Ω. 3. An S-shaped curve through the origin that flattens at higher potential differences, because the filament gets hotter and its resistance increases. 4. $\frac{10}{10} = 1.0$ A. 5. 50 Hz, about 230 V. 6. $2000 \times 900 = 1\,800\,000$ J (1.8 MJ). 7. For the same power, a higher potential difference gives a smaller current, so less energy is wasted heating the cables.

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3 · Particle model of matter

AQA · GCSE · Physics

Particle model of matter: density, heating and gases

Why it matters. In the winter of 1761 to 1762, Joseph Black, a professor of medicine in Glasgow, watched snow and ice melting outside. If melting needed only a tiny amount of heat, he reasoned, a warm spring day would melt all the snow at once and cause huge floods. Instead, snow melts slowly. Black put ice at 0 °C next to the same mass of water just above 0 °C in a warm room. The water warmed steadily, but the ice stayed at 0 °C for hours while it melted, even though it was taking in heat all the time. On 23 April 1762 he described this hidden, or "latent", heat to a society of professors at the University of Glasgow. One of the people who later learned from Black was James Watt, who used the idea to make steam engines far more efficient.

In this unit you will:

- calculate density, and measure it for regular and irregular objects and for liquids;
- explain changes of state and internal energy with the particle model;
- calculate the energy needed to change temperature and to change state, and read heating graphs;
- explain gas pressure, and (physics only) use $pV =$ constant and explain why doing work on a gas warms it.

AQA GCSE Physics (8463), topic 4.3 Particle model of matter, examined on Paper 1. It includes required practical 5 (density). Pressure in gases is in GCSE Physics only, and doing work on a gas is also Higher tier only. You must learn $\rho = \frac{m}{V}$; the equations for specific heat capacity, specific latent heat and $pV =$ constant are on the equations sheet.

Density of materials

Density 密度 is the mass of each cubic metre of a material:

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

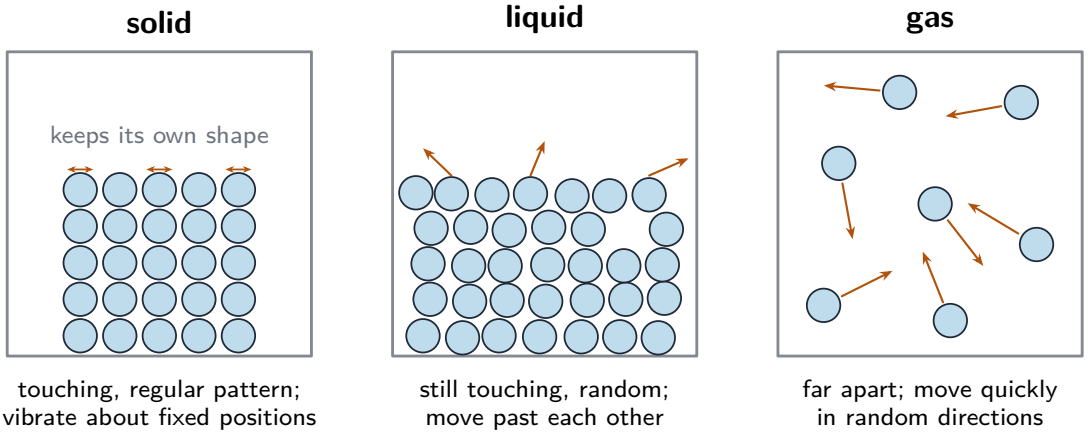
ρ is density in kg/m^3, m is mass in kg and V is volume in m^3. Densities are often given in g/cm^3; to convert, 1 g/cm^3 = 1000 kg/m^3.

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An iceberg floats with most of its volume under water, because ice is slightly less dense than water.

The particle model. All matter is made of tiny particles.



Particles in a solid, a liquid and a gas.

State	Arrangement	Movement
solid	close together, in a regular pattern	vibrate about fixed positions
liquid	close together, no regular pattern	move around each other
gas	far apart, no pattern	move quickly in random directions

Solids and liquids are much denser than gases because their particles are packed closely; a gas is mostly empty space. Ice is unusual: water expands when it freezes, so ice is

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slightly less dense than water and floats.

Worked example 1. A gold ring has a mass of 9.46 g and a volume of 0.44 cm^3. Find its density in kg/m^3. Convert first: $m = 9.46 \times 10^{-3}$ kg and $V = 0.44 \times 10^{-6} = 4.4 \times 10^{-7}$ m^3.

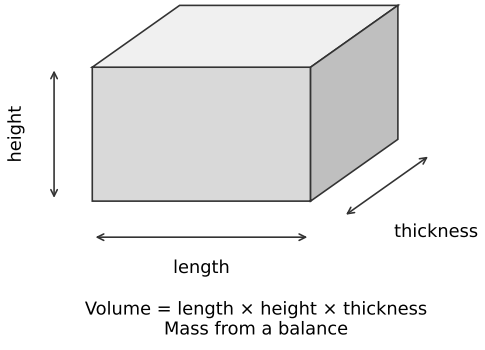
$$\rho = \frac{9.46 \times 10^{-3}}{4.4 \times 10^{-7}} = 21\,500 \text{ kg/m}^3$$

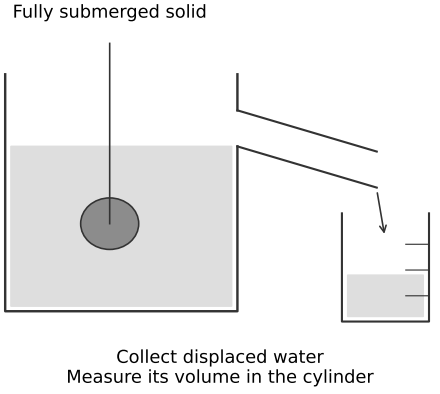
Worked example 2. 824 000 kg of seawater passes through a tidal turbine each second. Seawater has a density of 1030 kg/m^3. The volume passing each second is $V = \frac{m}{\rho} = \frac{824\,000}{1030} = 800$ m^3.

Required practical 5: density.

- Regular solid: measure its length, width and height with a ruler (or vernier callipers for small objects), multiply to find the volume, and measure its mass on a balance.
- Irregular solid: fill a displacement (eureka) can until water runs out of the spout, and wait for it to stop. Lower the object in on a thin thread. Collect the water that overflows in a measuring cylinder; its volume equals the object's volume.
- Liquid: measure the mass of an empty measuring cylinder, pour in a known volume of liquid, and measure the mass again. The difference is the mass of the liquid.

Read the measuring cylinder at eye level, at the bottom of the meniscus, and repeat each measurement to calculate a mean.





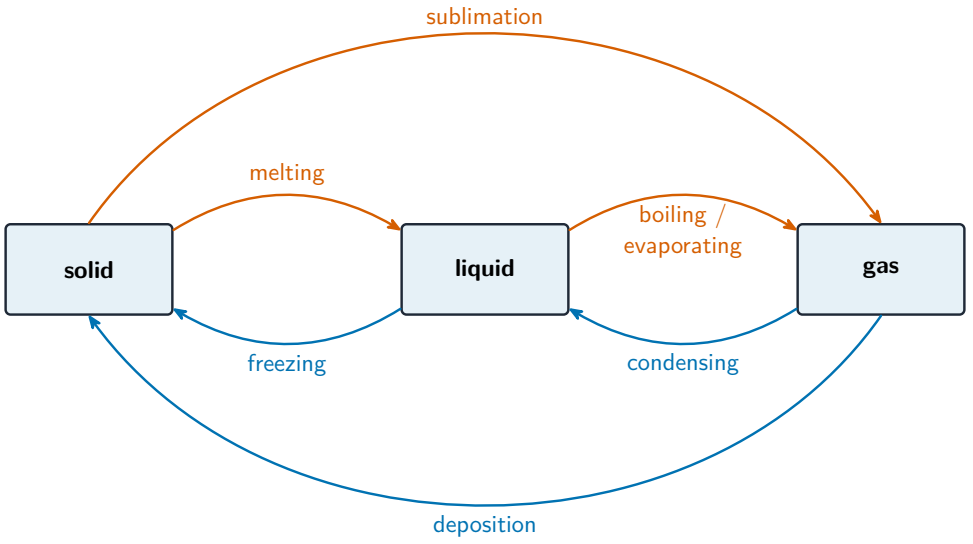
Required practical 5: measure a regular block with a ruler; find the volume of an irregular object by displacement.

Worked example 3. An empty measuring cylinder has a mass of 42 g. With 60 cm^3 of liquid in it, the mass is 90 g. Mass of liquid $= 90 - 42 = 48$ g, so the density is $\frac{48}{60} = 0.80$ g/cm^3, or 800 kg/m^3.

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Changes of state and internal energy

A substance can melt, freeze, boil, evaporate, condense or go straight from solid to gas, which is called sublimation; a solid that does this **sublimates** 升华.



Changes shown in orange take in energy; changes shown in blue release it.

- Mass is conserved: when a substance changes state, the number of particles stays the same.
- Changes of state are **physical changes** 物理变化: if you reverse the change, the material gets back its original properties. No new substance is made.

Internal energy 内能 is the total kinetic and potential energy of all the particles in a system. Heating a system increases its internal energy. This either raises its temperature, because the particles move faster and gain kinetic energy, or changes its state, because the particles move apart and gain potential energy. While a pure substance melts or boils, its temperature stays the same.

Specific heat capacity and temperature changes

When the temperature of a substance changes, the energy transferred is:

$$\Delta E = m\,c\,\Delta\theta$$

The **specific heat capacity** 比热容 c is the energy needed to raise the temperature of 1 kg of the substance by 1 °C, in J/kg °C. Required practical 1, which measures it, is in topic 1.

Worked example 4. 0.030 kg of olive oil ($c = 1800$ J/kg °C) is heated from 21 °C to 96 °C. The temperature change is $96 - 21 = 75$ °C, so $\Delta E = 0.030 \times 1800 \times 75 = 4050$ J.

Worked example 5. A 0.20 kg heating pad with $c = 900$ J/kg °C warms from 22 °C to 46 °C. $\Delta E = 0.20 \times 900 \times 24 = 4320$ J.

Specific latent heat and heating graphs

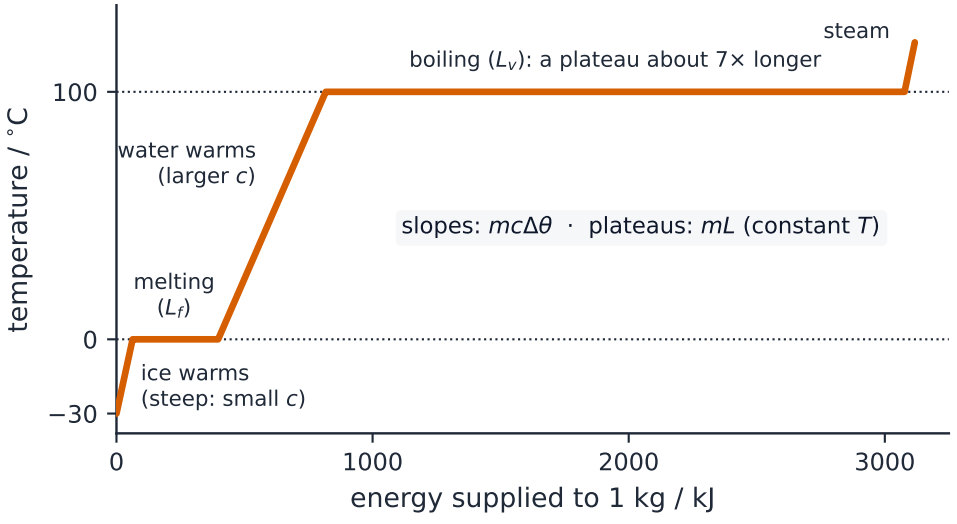
When a substance changes state, energy is transferred but the temperature does not change. This energy is called **latent heat** 潜热:

$$E = mL$$

E is the energy in J, m is the mass that changes state in kg and L is the **specific latent heat** 比潜热 in J/kg: the energy needed to change the state of 1 kg of a substance with no change in temperature.

- The specific latent heat of **fusion** 熔化 is for changing from solid to liquid.
- The specific latent heat of **vaporisation** 汽化 is for changing from liquid to vapour.

For water, the latent heat of vaporisation (about 2 260 000 J/kg) is almost seven times the latent heat of fusion (about 334 000 J/kg), because the particles must be separated completely.



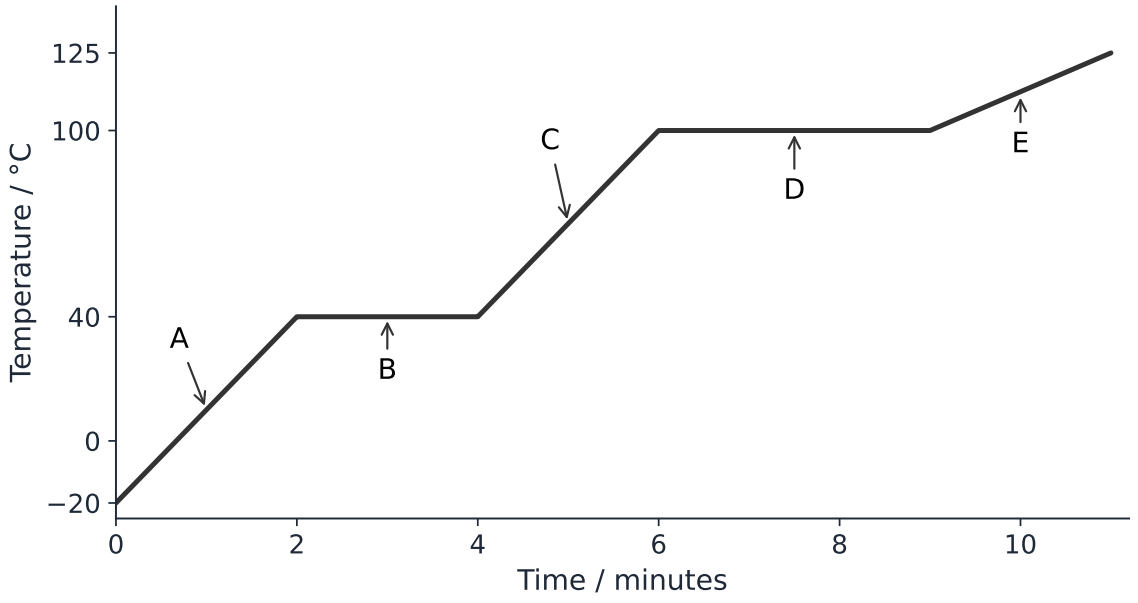
Heating curve for 1 kg of water: on the sloping parts the temperature rises; on the flat parts the state changes.

Reading a heating graph. When a substance is heated at a steady rate:

- on the sloping parts, its temperature rises and the particles gain kinetic energy ($\Delta E = mc\Delta\theta$);

- on the flat parts, it is changing state and the particles gain potential energy ($E = mL$).

A cooling graph has flat parts too, where the substance condenses or freezes and releases latent heat.



A heating graph: the substance warms in sections A, C and E, melts in B and boils in D.

Specific heat capacity is about changing temperature; specific latent heat is about changing state at a constant temperature.

Worked example 6. A 30 W heater boils off 6.6 g of water that is already at 100 °C in 11 minutes. Energy supplied $E = Pt = 30 \times 660 = 19\,800$ J, and $m = 6.6 \times 10^{-3}$ kg, so

$$L = \frac{E}{m} = \frac{19\,800}{6.6 \times 10^{-3}} = 3.0 \times 10^{6} \text{ J/kg}$$

This is higher than the true value because some energy from the heater warmed the surroundings instead of boiling the water.

Worked example 7. 9950 J boils 50 g of liquid nitrogen at its boiling point. $L = \frac{9950}{0.050} = 199\,000$ J/kg. During boiling, the internal energy increases because the potential energy of the particles increases; their kinetic energy, and so the temperature, stay the same.

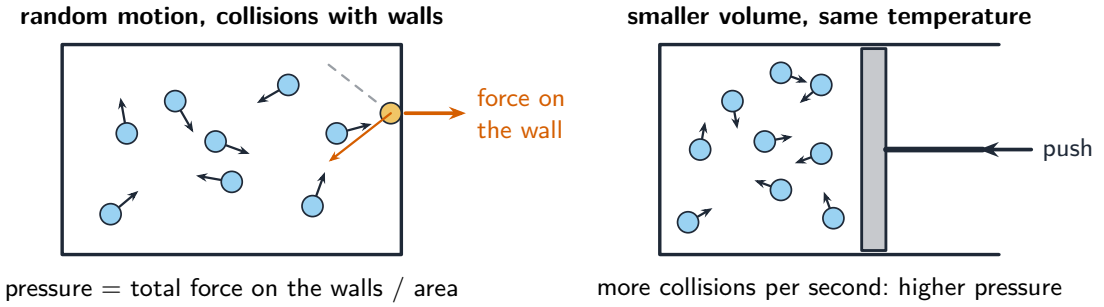
Worked example 8. A beaker of boiling water has a mass of 0.080 kg at the start and 0.071 kg at the end, while a heater transfers 25 200 J. The mass boiled off is 0.009 kg, so $L = \frac{25\,200}{0.009} = 2.8 \times 10^{6}$ J/kg.

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Particle motion in gases

The particles of a gas are in constant random motion. The temperature of a gas is related to the average kinetic energy of its particles: the hotter the gas, the faster they move.

Pressure 压强 in a gas is caused by its particles colliding with the walls of the container. Each collision exerts a force at right angles to the wall, and pressure is the total force on each square metre.



Particles hitting the walls exert forces at right angles to them; compressing the gas makes the collisions more frequent.

If a gas is heated in a container of fixed volume, its pressure increases. The particles move faster on average, so they hit the walls more often and with more force.

> **Worked example 9.** Nitrogen gas is heated in a sealed container. Explain why its pressure rises. The volume is fixed. The particles gain kinetic energy and move faster, so they collide with the walls more often and each collision exerts a bigger force. The force on each square metre of wall increases.

Pressure in gases (physics only)

For a fixed mass of gas at a constant temperature:

$$pV = \text{constant} \qquad \text{or} \qquad p_1V_1 = p_2V_2$$

p is pressure in pascals (Pa) and V is volume in m^3.

If the volume increases, the particles travel further between collisions with the walls, so they hit each square metre of wall less often, and the pressure decreases. If the volume decreases, the pressure increases.

> **Worked example 10.** A syringe contains 50 cm^3 of air at 100 kPa. The air is compressed slowly to 20 cm^3 at constant temperature.

$$p_2 = \frac{p_1V_1}{V_2} = \frac{100 \times 50}{20} = 250 \text{ kPa}$$

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The volume units cancel, so you can leave them in cm^3 as long as both are the same.

(HT) Doing work on a gas. Work is the transfer of energy by a force. When you push the handle of a bicycle pump quickly, you do work on the air inside. This increases the internal energy of the air: the particles gain kinetic energy, so the temperature of the air rises, and the pump feels warm.

Sources for this lesson

- AQA, *GCSE Physics (8463) specification*, section 4.3 Particle model of matter, and the *Required practical handbook* (practical 5).
- J. Black, *Lectures on the Elements of Chemistry*, ed. J. Robison (Edinburgh, 1803), the account of latent heat first given in Glasgow in April 1762.
- AQA, *GCSE Physics* Paper 1 Higher, June 2022, June 2024 and June 2025 (ring, turbine, boiling water and nitrogen questions, adapted).

Common errors

- Forgetting to convert g/cm^3 to kg/m^3, or cm^3 to m^3.
- Saying the temperature rises while a substance melts or boils.
- Using $\Delta E = mc\Delta\theta$ for a change of state; use $E = mL$.
- Mixing up fusion (melting) and vaporisation (boiling).
- Saying gas particles get bigger when heated; they move faster.
- Explaining gas pressure by particles hitting each other; it comes from collisions with the walls.
- Using $pV =$ constant when the temperature changes.

Key terms

- **Density**: mass per unit volume.
- **Internal energy**: the total kinetic and potential energy of the particles in a system.
- **Specific heat capacity**: the energy to raise 1 kg of a substance by 1 °C.
- **Specific latent heat**: the energy to change the state of 1 kg of a substance with no temperature change.
- **Gas pressure**: the force per unit area caused by particles hitting the walls of a container.

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Check yourself

1. A 2.0 kg block has a volume of 0.00025 m^3. Calculate its density.
2. Describe how to find the volume of a small stone.
3. What happens to the particles of a substance on the flat part of a heating graph?
4. How much energy melts 0.50 kg of ice at 0 °C? ($L = 334\,000$ J/kg)
5. Explain why the pressure of a gas rises when it is heated in a sealed can.
6. (Physics only) A gas at 200 kPa has a volume of 3.0 m^3. It expands at constant temperature to 4.0 m^3. Find its new pressure.

Answers: 1. $\frac{2.0}{0.00025} = 8000$ kg/m^3. 2. Lower it into a full eureka can and measure the volume of water that overflows in a measuring cylinder. 3. They gain potential energy as they move apart; their kinetic energy and the temperature stay the same. 4. $0.50 \times 334\,000 = 167\,000$ J. 5. The particles move faster, so they hit the walls more often and harder, increasing the force per unit area. 6. $\frac{200 \times 3.0}{4.0} = 150$ kPa.

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4 · Atomic structure

AQA · GCSE · Physics

Atomic structure: the nucleus and radioactivity

Why it matters. In 1909, in a darkened laboratory at the University of Manchester, Hans Geiger and a 20-year-old student, Ernest Marsden, fired alpha particles at a sheet of gold foil thinner than a page of this book. Most went straight through, as everyone expected. But about one in every 8000 bounced back towards the source. Their professor, Ernest Rutherford, later said it was "as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you." In May 1911 Rutherford published his explanation: almost all the mass of an atom is packed into a tiny, positively charged centre, the nucleus. That idea led to nuclear medicine, nuclear power and the radiation safety rules you will learn here.

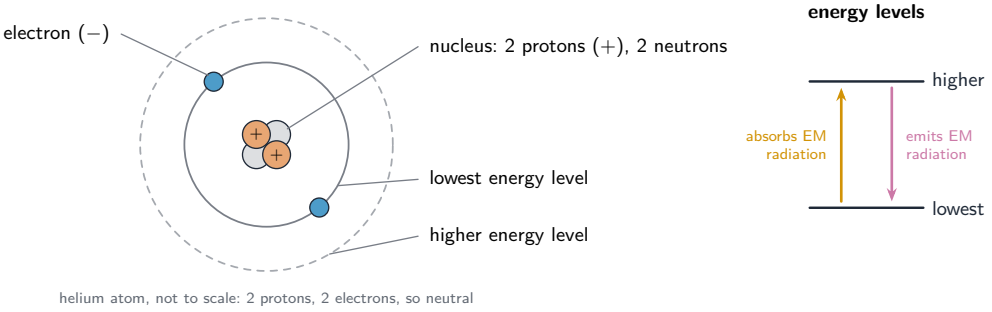
In this unit you will:

- describe the structure of atoms and isotopes, and how the model of the atom developed;
- compare alpha, beta and gamma radiation, and write balanced nuclear equations;
- use half-life, and explain the hazards of contamination and irradiation;
- (physics only) explain background radiation, medical uses of radiation, fission and fusion.

AQA GCSE Physics (8463), topic 4.4 Atomic structure, examined on Paper 1. Background radiation, the uses of radiation, and fission and fusion are in GCSE Physics only. Content marked (HT) is Higher tier only.

The structure of an atom and isotopes

An atom has a radius of about 1×10^{-10} m.



helium atom, not to scale: 2 protons, 2 electrons, so neutral

atom radius about 1×10^{-10} m; the nucleus is less than $1/10\,000$ of that

An atom: a small positive nucleus of protons and neutrons, with electrons in energy levels.

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- The **nucleus** is positively charged and contains protons and neutrons. It contains almost all the mass of the atom, but its radius is less than $\frac{1}{10\,000}$ of the radius of the atom.
- **Electrons** are negatively charged and are arranged at different distances from the nucleus, in energy levels. If an electron absorbs electromagnetic radiation, it moves to a higher energy level, further from the nucleus; if it emits radiation, it moves to a lower level.

Particle	Relative mass	Relative charge
proton	1	+1
neutron	1	0
electron	very small	−1

An atom has the same number of electrons as protons, so it has no overall charge. If an atom loses one or more outer electrons, it becomes a positive ion.

Notation. In ${}^{A}_{Z}\mathrm{X}$, the atomic number Z is the number of protons, and the mass number A is the number of protons plus neutrons. The number of neutrons is $A - Z$.

Isotopes 同位素 are atoms of the same element (same number of protons) with different numbers of neutrons.

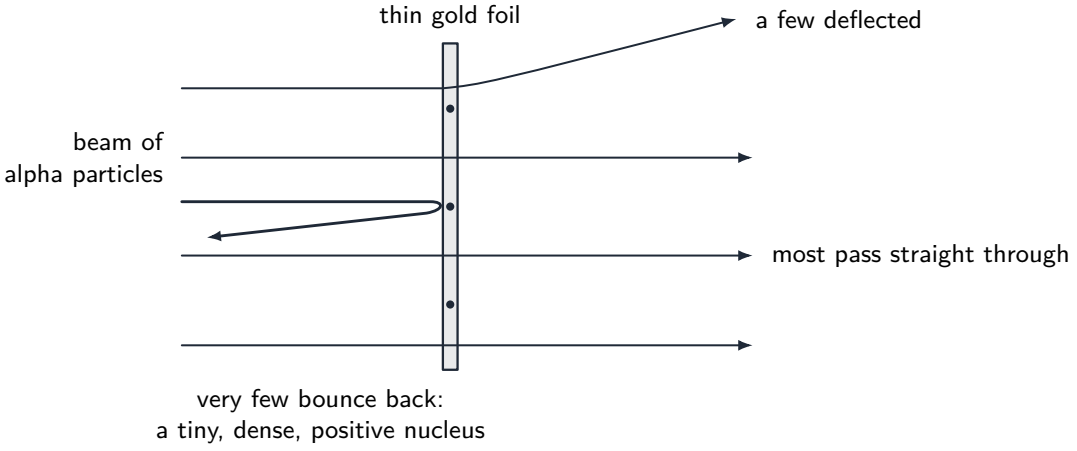
> **Worked example 1.** Carbon-14 is ${}^{14}_{6}\mathrm{C}$. It has 6 protons, 6 electrons and $14-6=8$ neutrons. Carbon-12 has 6 neutrons; the two are isotopes of carbon.

The development of the model of the atom

Scientific models change when new experimental evidence does not fit them.

1. Before the electron was discovered, atoms were thought to be tiny spheres that could not be divided.
2. J. J. Thomson discovered the electron in 1897, which led to the plum pudding model: a ball of positive charge with negative electrons scattered through it.
3. The alpha scattering experiment (Geiger and Marsden, explained by Rutherford) showed that the mass and positive charge are concentrated in a tiny nucleus. The nuclear model replaced the plum pudding model.
4. Niels Bohr suggested that electrons orbit the nucleus at fixed distances. His calculations agreed with experimental results.
5. Later experiments showed that the positive charge of the nucleus is made of whole-number amounts of smaller particles, called protons.
6. In 1932, about 20 years after the nucleus was proposed, James Chadwick showed that the nucleus also contains neutrons.

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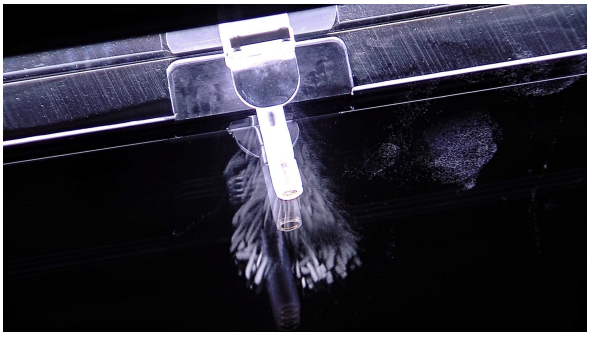
Alpha scattering: most particles pass through; a few rebound from a tiny dense nucleus.

Worked example 2. Explain how the alpha scattering experiment showed that the plum pudding model was wrong. In the plum pudding model, the positive charge is spread out, so all the alpha particles should pass through with only small deflections. Most did pass straight through, so the atom is mostly empty space. A few were deflected through large angles or bounced back, which can only happen if the positive charge and mass are concentrated in a tiny nucleus.

Radioactive decay and nuclear radiation

Some atomic nuclei are unstable. They give out radiation to become more stable. This is **radioactive decay** 放射性衰变, and it is a random process.

- The **activity** 放射性活度 of a source is the rate at which its nuclei decay, measured in **becquerel** 贝克勒尔 (Bq). 1 Bq is one decay per second.
- **Count-rate** 计数率 is the number of decays recorded each second by a detector, such as a Geiger–Müller tube.

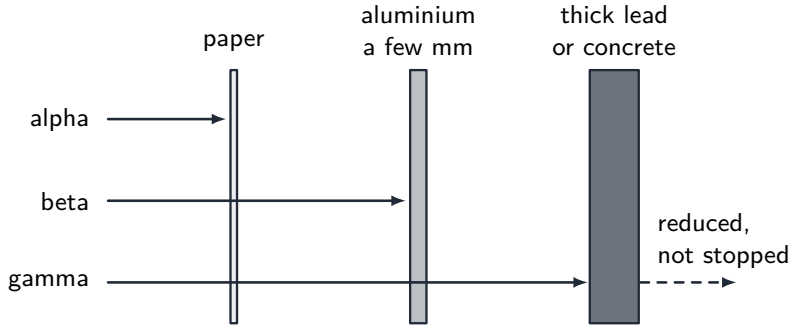


Alpha-particle tracks in a cloud chamber, fanning out from an americium-241 source..

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Radiation	What it is	Ionising power	Range in air	Stopped by
alpha (α)	two protons and two neutrons (a helium nucleus)	strong	a few cm	paper or skin
beta (β)	a high-speed electron from the nucleus	medium	about 1 m	a few mm of aluminium
gamma (γ)	electromagnetic radiation	weak	very far	reduced by thick lead or concrete

A nucleus can also emit a neutron.



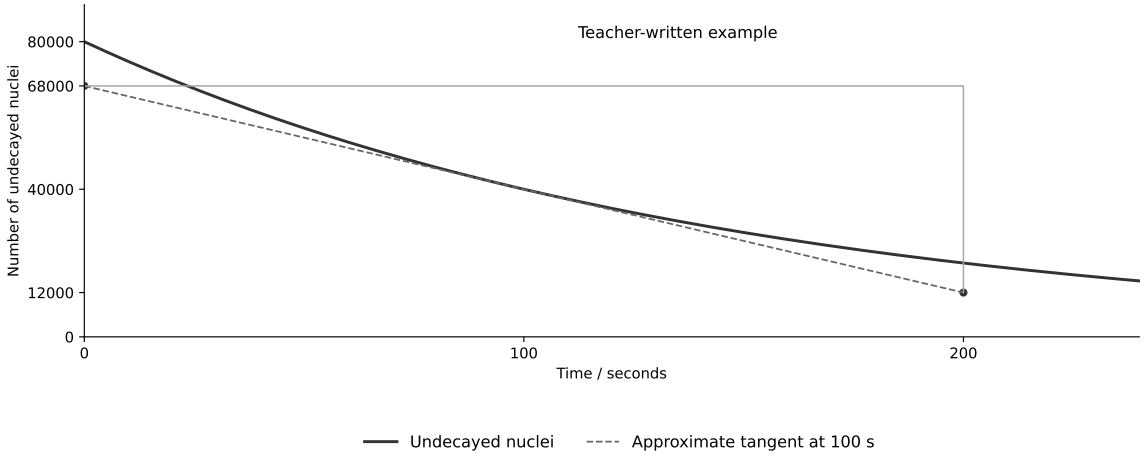
Penetration: alpha stopped by paper, beta by aluminium, gamma reduced by thick lead.

Choosing a source. Match the properties to the use.

- Smoke alarms use alpha: it ionises the air strongly and is stopped by smoke.
- Paper thickness gauges use beta: some passes through paper, and the amount depends on the thickness.
- Medical tracers use gamma: it passes out of the body to a detector.

Activity from a graph. On a graph of the number of undecayed nuclei against time, the activity at a time is the gradient of a tangent drawn at that time.

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Number of undecayed nuclei against time, with a tangent drawn at 100 s to find the activity.

Worked example 3. A tangent drawn at 100 s passes through (0 s, 68 000) and (200 s, 12 000). Activity $= \frac{68\,000 - 12\,000}{200} = 280$ Bq.

Nuclear equations

In a nuclear equation, the mass numbers on each side must add up to the same total, and so must the atomic numbers.

- **Alpha decay**: the mass number decreases by 4 and the atomic number by 2. An alpha particle is written ${}^{4}_{2}\mathrm{He}$.

$$ {}^{238}_{92}\mathrm{U} \rightarrow {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He} $$

- **Beta decay**: a neutron changes into a proton and an electron. The mass number stays the same and the atomic number increases by 1. A beta particle is written ${}^{0}_{-1}\mathrm{e}$.

$$ {}^{14}_{6}\mathrm{C} \rightarrow {}^{14}_{7}\mathrm{N} + {}^{0}_{-1}\mathrm{e} $$

- **Gamma emission** does not change the mass number or the atomic number; the nucleus loses energy.

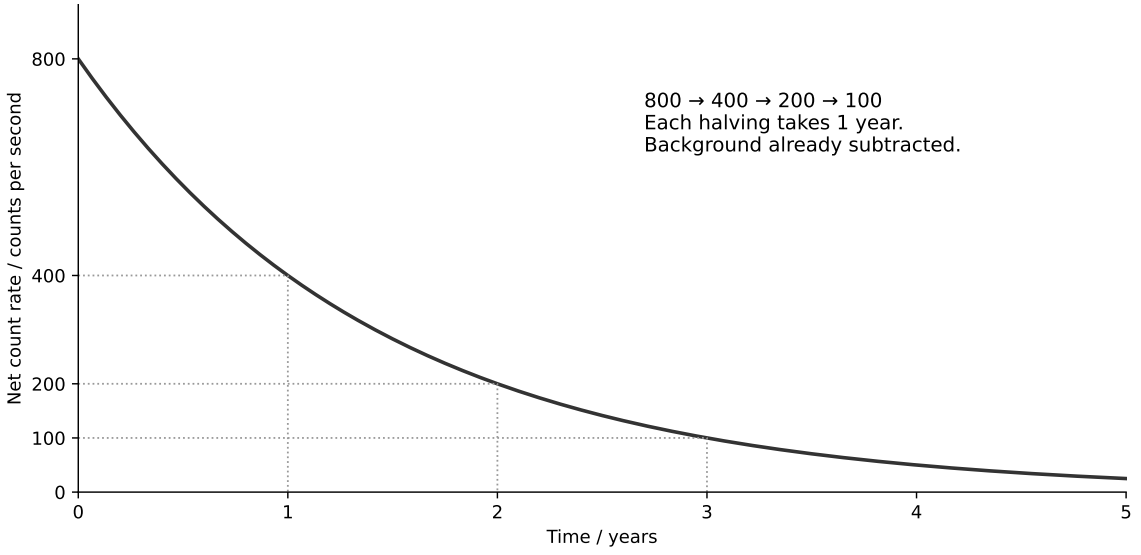
Worked example 4. Polonium-210 (${}^{210}_{84}\mathrm{Po}$) decays by alpha emission. The new mass number is $210 - 4 = 206$ and the new atomic number is $84 - 2 = 82$, so the product is ${}^{206}_{82}\mathrm{Pb}$ (lead). Check: $206 + 4 = 210$ and $82 + 2 = 84$.

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Half-lives and the random nature of decay

Radioactive decay is random: you cannot predict when a particular nucleus will decay. But with very many nuclei, the overall pattern is predictable.

The **half-life** 半衰期 of a radioactive isotope is the time it takes for the number of nuclei in a sample to halve, or the time it takes for the count rate (or activity) from a sample to fall to half its starting level.



A decay curve: count rate halves every half-life (1 year in this example).

To find a half-life from a graph, read the time for the count rate to fall from any value to half that value. Repeat for another pair of values and take the mean.

> **Worked example 5.** The activity of a sample falls from 800 Bq to 200 Bq in 12 years. $800 \to 400 \to 200$ is two half-lives, so the half-life is $\frac{12}{2} = 6$ years.

> **Worked example 6.** Polonium-210 has a half-life of 138 days. How long does it take for 256 000 atoms to decay to 16 000? $256\,000 \to 128\,000 \to 64\,000 \to 32\,000 \to 16\,000$ is four half-lives, so the time is $4 \times 138 = 552$ days.

(HT) Net decline. After n half-lives, the fraction remaining is $\frac{1}{2^n}$. **Worked example 7.** A sample has a count rate of 600 counts per second. After three half-lives, $\frac{1}{8}$ remains, which is 75 counts per second. The net decline is $600 - 75 = 525$, and the ratio of the net decline to the initial count rate is $\frac{525}{600} = \frac{7}{8}$.

Radioactive contamination

- **Contamination** 污染 is the unwanted presence of radioactive atoms on or inside other materials. The atoms keep decaying, so the danger continues until they are removed or have decayed.

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- **Irradiation** 辐照 is exposing an object to nuclear radiation. The irradiated object does not become radioactive, and the exposure stops when the source is removed.

Alpha outside the body is stopped by the skin, but alpha emitters inside the body are the most dangerous, because alpha ionises strongly and damages nearby cells.

To protect people, keep sources in lead-lined boxes, handle them with tongs at arm's length, keep the time of exposure short, and wear dosimeter badges. It is important for findings about the effects of radiation to be published and checked by other scientists (peer review).

Background radiation (physics only)

Background radiation 本底辐射 is around us all the time. It comes from:

- natural sources, such as rocks (radon gas) and cosmic rays from space;
- man-made sources, such as fallout from nuclear weapons testing and nuclear accidents.



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

The dose you receive depends on your job and where you live; for example, it is higher for airline crews and in areas with granite rocks. Radiation dose is measured in sieverts (Sv); 1000 mSv = 1 Sv.

Always measure the background count rate first and subtract it from every reading.

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Uses of nuclear radiation (physics only)

Half-life and hazard. For the same number of nuclei, an isotope with a short half-life has a high activity at first but soon becomes safe. An isotope with a long half-life stays radioactive for a long time, so its waste must be stored safely for many years.

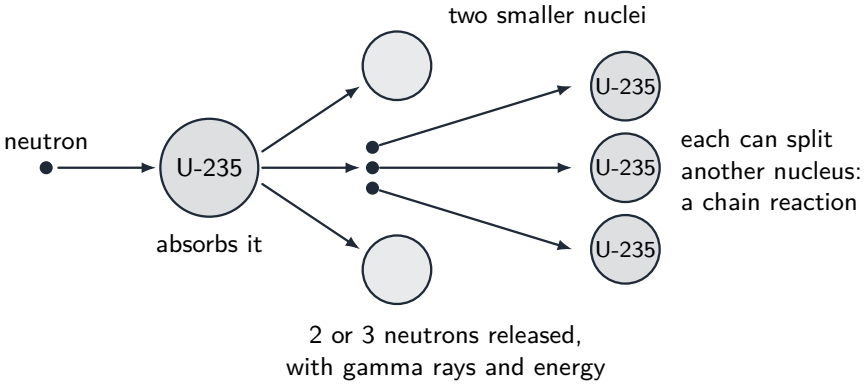
Medical uses.

- Exploring the body: a tracer that emits gamma radiation, such as technetium-99m, is injected or swallowed. The gamma rays pass out of the body to a camera. The half-life must be long enough for the scan (technetium-99m has a half-life of 6 hours) but short enough that the patient's dose stays low.
- Destroying unwanted tissue: beams of gamma rays from outside the body, or radioactive implants placed inside a tumour, kill cancer cells (radiotherapy).

Doctors weigh the risk from the radiation against the benefit of finding or treating the disease.

Nuclear fission and fusion (physics only)

Fission 核裂变 is the splitting of a large, unstable nucleus, such as uranium-235 or plutonium-239.



Fission: a neutron splits a U-235 nucleus into two fragments, releasing neutrons and gamma rays.

- The nucleus usually has to absorb a neutron first; spontaneous fission is rare.
- It splits into two smaller nuclei of roughly equal size, and gives out two or three neutrons and gamma rays. Energy is released, and all the products have kinetic energy.
- The released neutrons can cause more fissions: a chain reaction. In a nuclear reactor, control rods absorb some neutrons to keep the reaction steady; in a nuclear weapon, the chain reaction is uncontrolled.

Fusion 核聚变 is the joining of two light nuclei, such as isotopes of hydrogen, to form

a heavier nucleus. Some of the mass is converted into energy. Fusion powers the Sun; it needs very high temperatures and pressures because the positive nuclei repel each other.

Sources for this lesson

- AQA, *GCSE Physics (8463) specification*, section 4.4 Atomic structure.
- H. Geiger and E. Marsden, "On a diffuse reflection of the α-particles", *Proceedings of the Royal Society A*, 82 (1909); E. Rutherford, "The scattering of α and β particles by matter and the structure of the atom", *Philosophical Magazine*, 21 (May 1911).
- AQA, *GCSE Physics* Paper 1 Higher, June 2024 and June 2025 (activity and polonium questions, adapted).

Common errors

- Swapping mass number and atomic number.
- Changing the mass number in beta decay; it stays the same.
- Saying the whole sample has gone after two half-lives; a quarter remains.
- Forgetting to subtract the background count.
- Saying an irradiated object becomes radioactive.
- Calling gamma the most dangerous radiation in every case; alpha inside the body is the most harmful.
- Mixing up fission (splitting large nuclei) and fusion (joining light nuclei).

Key terms

- **Isotopes**: atoms of the same element with different numbers of neutrons.
- **Activity**: the rate at which nuclei in a source decay, in becquerel.
- **Half-life**: the time for the number of nuclei, or the count rate, to halve.
- **Contamination**: unwanted radioactive atoms on or inside a material.
- **Irradiation**: exposure to nuclear radiation, without becoming radioactive.
- **Fission**: the splitting of a large nucleus.
- **Fusion**: the joining of two light nuclei.

Check yourself

1. How many protons, neutrons and electrons are in an atom of $^{23}_{11}\mathrm{Na}$?
2. Which radiation is stopped by paper, and which is the most penetrating?
3. Radium-226 ($^{226}_{88}\mathrm{Ra}$) decays by alpha emission. Write the equation.
4. A count rate falls from 640 to 80 counts per second in 15 minutes. Find the half-life.

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5. Why is contamination by an alpha source more dangerous than irradiation by it?
6. (Physics only) Describe what happens in nuclear fission.

Answers: 1. 11 protons, $23 - 11 = 12$ neutrons, 11 electrons. 2. Alpha is stopped by paper; gamma is the most penetrating. 3. ${}^{226}_{88}\mathrm{Ra} \rightarrow {}^{222}_{86}\mathrm{Rn} + {}^{4}_{2}\mathrm{He}$. 4. $640 \rightarrow 320 \rightarrow 160 \rightarrow 80$ is three half-lives, so 5 minutes. 5. Outside the body, alpha is stopped by the skin; inside the body, the alpha source keeps decaying and its strong ionisation damages nearby cells. 6. A large nucleus absorbs a neutron and splits into two smaller nuclei, releasing two or three neutrons, gamma rays and energy; the neutrons can cause a chain reaction.

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5 · Forces

AQA · GCSE · Physics

Forces: interactions, motion and momentum

Why it matters. On 2 August 1971, at the end of the third moonwalk of Apollo 15, the commander David Scott stood in front of the television camera holding a geologist's hammer in one hand and a falcon feather in the other. "In my left hand I have a feather, in my right hand a hammer," he said, and let go of both at the same moment. With no air on the Moon to slow the feather, the two fell side by side and hit the dusty ground together. "How about that! Mr Galileo was correct in his findings," Scott said. On Earth the feather drifts down slowly because air resistance is large compared with its tiny weight. The difference between the two worlds is a story about forces, and forces explain how everything from cars to skydivers moves.

In this unit you will:

- describe forces as vectors, calculate weight and resultant forces, and calculate work done;
- investigate the extension of a spring and the effect of force and mass on acceleration;
- describe motion with equations and graphs, and apply Newton's three laws;
- explain stopping distances and (HT) momentum;
- (physics only) use moments, levers and gears, and pressure in fluids.

AQA GCSE Physics (8463), topic 4.5 Forces, examined on Paper 2. It includes required practicals 6 (force and extension) and 7 (force, mass and acceleration). Moments and pressure in fluids are in GCSE Physics only. Content marked (HT) is Higher tier only; momentum is Higher tier, and its calculations are in GCSE Physics only.

Scalars, vectors and resultant forces

A **scalar** 标量 quantity has size (magnitude) only, such as distance, speed, mass, time and energy. A **vector** 矢量 quantity has both magnitude and direction, such as displacement, velocity, force, acceleration and momentum. A vector is drawn as an arrow: its length shows the magnitude and it points in the direction.

A force is a push or a pull caused by an interaction between objects.

- **Contact** 接触 forces need the objects to touch: friction, air resistance, tension and the normal contact force.
- **Non-contact** 非接触 forces act at a distance: gravitational, magnetic and electrostatic forces.

Weight 重力 is the force acting on an object because of gravity. It acts at the object's **centre of mass** 质心 and is measured with a newtonmeter.

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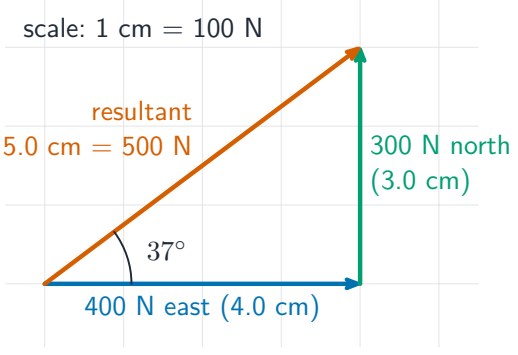
$$W = mg$$

W is weight in newtons (N), m is mass in kg and g is gravitational field strength in N/kg (9.8 N/kg on Earth). Weight is directly proportional to mass.

> **Worked example 1.** A 65 kg astronaut stands on Mars, where $g = 3.7$ N/kg. Her weight is $65 \times 3.7 = 240$ N (2 s.f.). Her mass is still 65 kg.

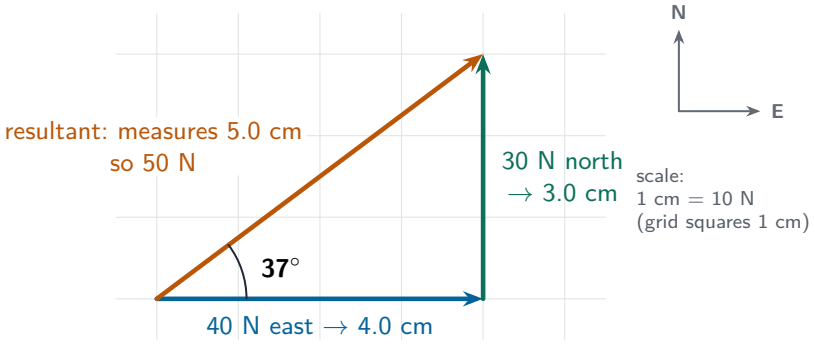
A **resultant force** 合力 is the single force that has the same effect as all the forces acting on an object. For forces along one line, add those in the same direction and subtract those in opposite directions. For example, a 50 N push forwards with 20 N of friction gives a resultant of 30 N forwards.

(HT) Free-body diagrams and scale drawings. Free-body diagrams 自由体图 show only the forces acting on one object, as arrows. To add two forces at an angle, draw them to scale, head to tail. The resultant is the arrow from the start of the first to the end of the second. A single force can also be split into two components at right angles.



Forces drawn head to tail to scale: the resultant runs from the start of the first arrow to the end of the last.

> **Worked example 2 (HT).** A 40 N force acts east and a 30 N force acts north. Using 1 cm for 10 N, draw 4.0 cm east, then 3.0 cm north from the end of the first arrow. The resultant measures 5.0 cm, so it is 50 N, at an angle of 37° north of east (measured with a protractor).



answer: 50 N at 37° north of east

Scale drawing with 1 cm for 10 N: 40 N east and 30 N north give a resultant of 50 N.

Work done and energy transfer

When a force moves an object, the force does work and energy is transferred:

$$W = Fs$$

W is work done in joules (J), F is force in N, and s is the distance moved along the line of the force, in m. One joule is the work done when a force of one newton moves an object one metre, so 1 J = 1 N m. Work done against friction transfers energy to thermal stores and makes the object warmer.

> **Worked example 3.** A child pushes a baby walker 2.8 m with a horizontal force of 25 N. Work done = $25 \times 2.8 = 70$ J.

Forces and elasticity

To stretch, bend or squash an object that is not moving, you need more than one force; one force alone would just move it. **Elastic** 弹性 deformation means the object returns to its original shape when the forces are removed. **Inelastic** 非弹性 deformation means it does not.

For a spring, up to its limit of proportionality:

$$F = ke$$

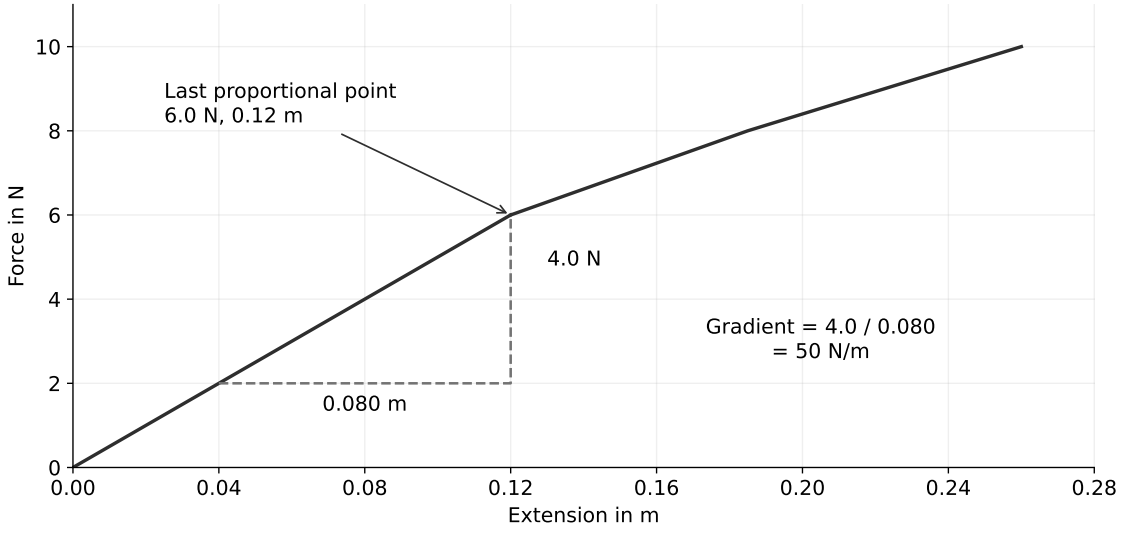
F is force in N, k is the spring constant in N/m and e is the extension in m. A stiff spring has a large spring constant. The work done to stretch a spring is stored as elastic potential energy, $E_e = \frac{1}{2}ke^2$ (topic 1).

Required practical 6: force and extension.

1. Hang a spring from a clamp stand next to a vertical metre rule, and note the position of the bottom of the spring.

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2. Add 1 N weights one at a time, and record the new position each time, reading the ruler at eye level.
3. Calculate the extension (new length minus original length) for each force.
4. Plot force against extension. The gradient of the straight part is the spring constant. Beyond the limit of proportionality, the graph curves.



Required practical 6: force against extension is a straight line, then curves beyond the limit of proportionality.

Worked example 4. A force of 4.0 N stretches a spring by 0.064 m. $k = \frac{F}{e} = \frac{4.0}{0.064} = 62.5$ N/m.

Use a graph of extension, not of total length. If you plot total length, the line does not pass through the origin, because the spring has a length even when no force acts.

Moments, levers and gears (physics only)

A force can make an object turn about a pivot. The turning effect is called the **moment** 力矩:

$$M = Fd$$

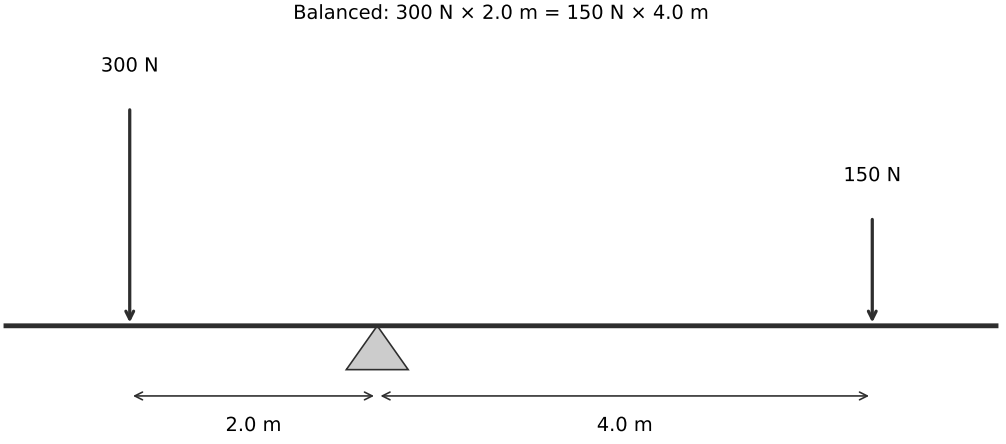
M is the moment in newton-metres (N m), F is the force in N, and d is the perpendicular distance from the pivot to the line of action of the force, in m.

If an object is balanced, the total clockwise moment about a pivot equals the total anticlockwise moment.

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The moment of a tower crane's counterweight about the mast balances the moment of the load.



A balanced beam: 300 N at 2.0 m balances 150 N at 4.0 m.

Worked example 5. A 300 N load sits 2.0 m to the left of a pivot. What force 4.0 m to the right of the pivot balances it? Anticlockwise moment $= 300 \times 2.0 = 600$ N m, so the force is $\frac{600}{4.0} = 150$ N.

Levers and gears. A lever lets a small force produce a large moment, because the force acts a long way from the pivot. Gears are wheels with teeth that turn each other. When a small gear drives a larger gear, the larger gear turns more slowly but with a bigger moment. Two gears that touch turn in opposite directions.

Worked example 6. A 2.0 N force acts at a perpendicular distance of 7.5 cm from a pivot. Convert: 0.075 m. $M = 2.0 \times 0.075 = 0.15$ N m.

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Pressure in fluids (physics only)

A fluid is a liquid or a gas. A fluid exerts a force at right angles to any surface in contact with it.

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

p is pressure in pascals (Pa), F is the force normal to the surface in N, and A is the area in m^2.

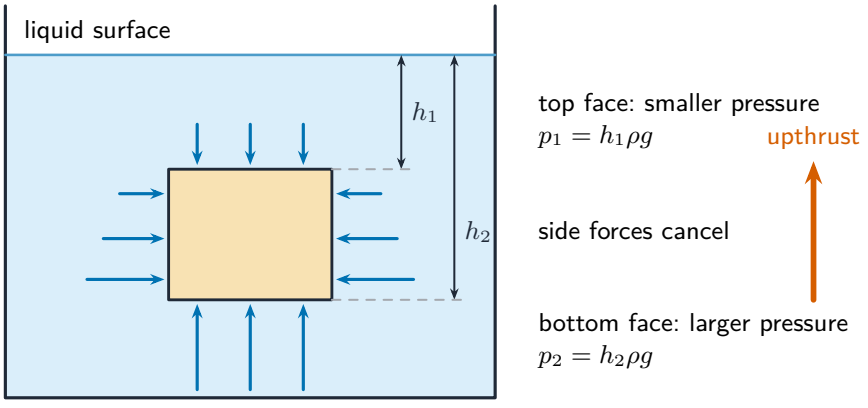
(HT) Pressure in a liquid. Pressure increases with depth, because there is more liquid above pushing down, and with the density of the liquid:

$$p = h\rho g$$

h is the height of the column of liquid in m, ρ is its density in kg/m^3 and g is gravitational field strength in N/kg.

> **Worked example 7 (HT).** Find the pressure caused by 2.0 m of water (density 1000 kg/m^3). $p = 2.0 \times 1000 \times 9.8 = 19\,600$ Pa.

Upthrust. An object in a liquid has more pressure on its bottom surface (which is deeper) than on its top. This gives a resultant upward force called **upthrust** 浮力. An object floats if the upthrust equals its weight before it is completely under water; if its weight is greater than the upthrust, it sinks.



pressure rises with depth: a bigger push up than down gives upthrust

The pressure on the bottom of the object is greater than on the top, which gives an upward resultant force: upthrust.

Atmospheric pressure. The atmosphere is a thin layer of air around the Earth. Air molecules colliding with a surface cause atmospheric pressure. The higher you go, the less air there is above you, so the atmospheric pressure decreases with height.

Describing motion along a line

- **Distance** 路程 is how far an object moves; it is a scalar.
- **Displacement** 位移 is the distance in a straight line from the start to the end, with a direction; it is a vector.
- **Speed** 速率 is a scalar. Typical speeds: walking 1.5 m/s, running 3 m/s, cycling 6 m/s, sound in air 330 m/s.
- **Velocity** 速度 is speed in a given direction; it is a vector. An object moving in a circle at constant speed has a changing velocity, because its direction changes.

For constant speed, distance travelled = speed × time, or $s = vt$.

Acceleration 加速度 is the rate of change of velocity:

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

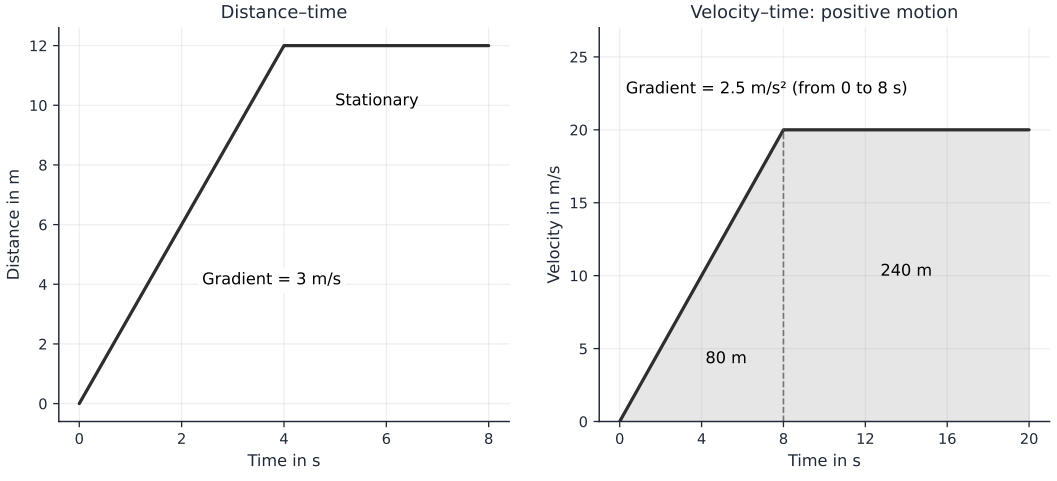
a is acceleration in m/s^2, Δv is the change in velocity in m/s, and t is time in s. A negative acceleration is a deceleration. For uniform acceleration, you can also use

$$v^2 - u^2 = 2as$$

where u is the initial velocity, v the final velocity and s the distance. An object falling freely near the Earth accelerates at about 9.8 m/s^2.

Graphs of motion.

- On a distance–time graph, the gradient is the speed. (HT) For an accelerating object, draw a tangent and find its gradient to get the speed at that moment.
- On a velocity–time graph, the gradient is the acceleration, and (HT) the area under the graph is the distance travelled.



The gradient of a distance–time graph is speed; the gradient of a velocity–time graph is acceleration and the area under it is distance.

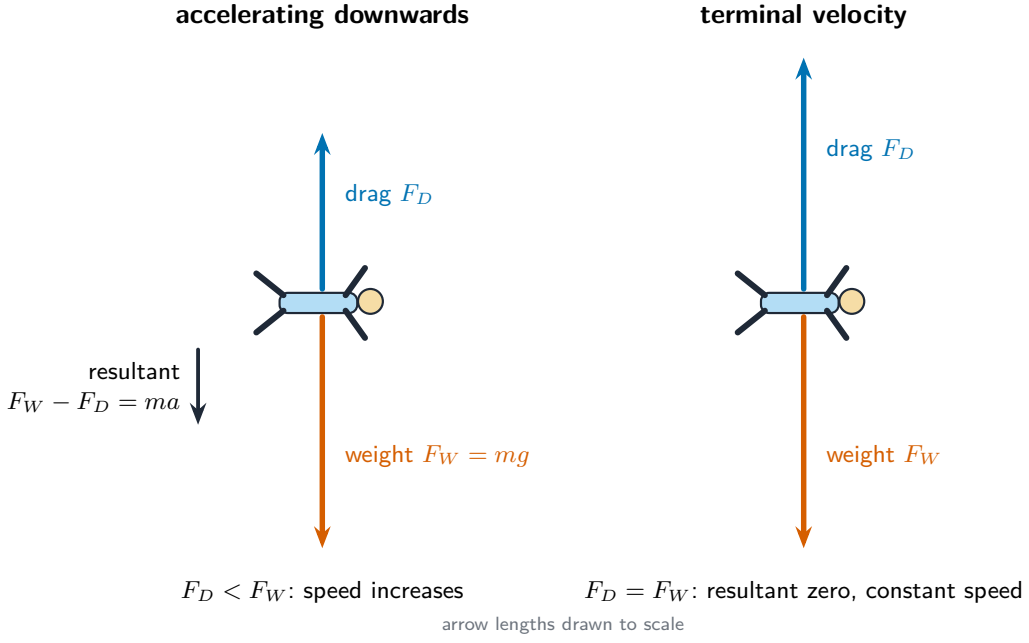
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Worked example 8. A velocity–time graph rises in a straight line from 0 to 20 m/s in 8 s, then stays at 20 m/s for 12 s. Acceleration $= \frac{20}{8} = 2.5$ m/s^2. (HT) Distance $= \frac{1}{2} \times 8 \times 20 + 20 \times 12 = 80 + 240 = 320$ m.

Worked example 9 (HT). A tangent to a distance–time curve passes through (2 s, 3 m) and (6 s, 15 m). The speed at that moment is $\frac{15-3}{6-2} = 3.0$ m/s.

Worked example 10. A rocket accelerates from rest at 0.64 m/s^2 for 2.5 minutes. Convert: 150 s. Its final velocity is $0 + 0.64 \times 150 = 96$ m/s.

Terminal velocity. When a skydiver jumps, the weight is bigger than the air resistance, so the skydiver accelerates downwards. As the speed increases, the air resistance, also called **drag** 空气阻力, increases. Eventually the drag equals the weight, the resultant force is zero, and the skydiver falls at a steady speed: the **terminal velocity** 终端速度. When the parachute opens, the drag suddenly becomes larger than the weight, so the skydiver slows down until a new, lower terminal velocity is reached. (Interpreting these graphs is physics only.)



Forces on a skydiver: drag is smaller than weight while accelerating, and equal to it at terminal velocity.

Newton's laws

Newton's first law. If the resultant force on an object is zero, a stationary object stays still, and a moving object keeps moving at the same speed in the same direction. A car moving at a steady speed has a driving force equal to the resistive forces. (HT) The tendency of an object to stay at rest or keep moving steadily is called **inertia** 惯性.

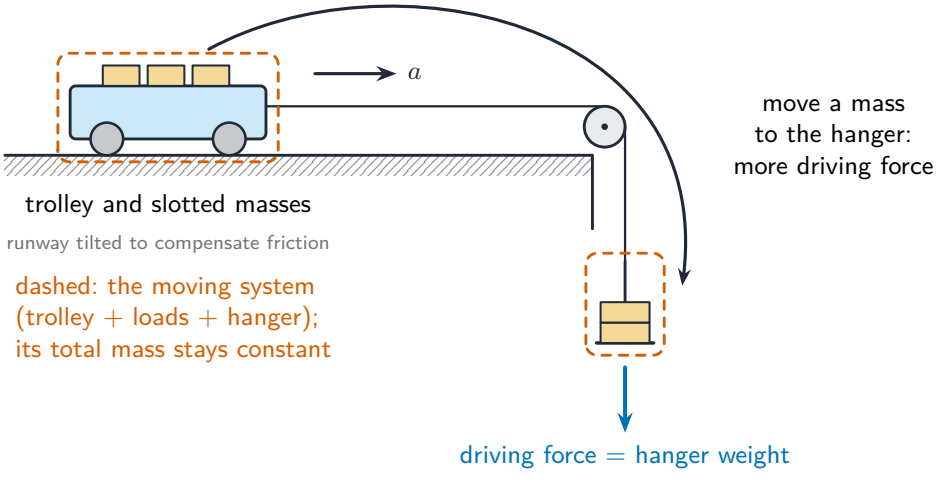
Newton's second law. The acceleration of an object is proportional to the resultant force on it, and inversely proportional to its mass:

$$F = ma$$

(HT) Inertial mass measures how hard it is to change the velocity of an object; it is the ratio of force to acceleration.

Required practical 7: force, mass and acceleration.

1. Attach a trolley by a string over a pulley to a hanging mass holder. The weight of the hanging masses provides the force.
2. Release the trolley and measure its acceleration with light gates (or with a ruler, a stopwatch and $v^2 - u^2 = 2as$).
3. To vary the force, move masses from the trolley to the holder one at a time, so the total mass that moves stays the same.
4. To vary the mass, add masses to the trolley while keeping the hanging mass the same.
5. Plot acceleration against force, and acceleration against $\frac{1}{\text{mass}}$.



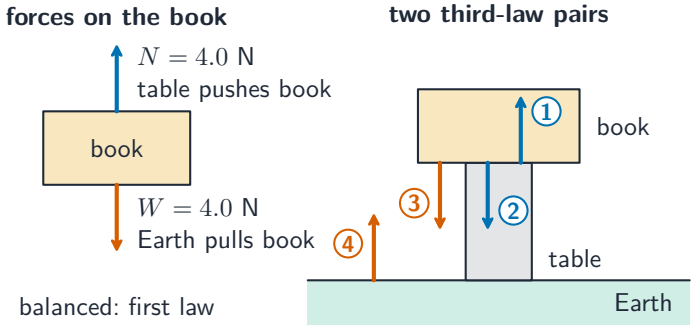
Required practical 7: the moving mass is the trolley, the hanger and all the masses they carry.

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Worked example 11. Three measurements of acceleration were 1.36, 1.39 and 1.33 m/s^2. The mean is 1.36 m/s^2. The range is $1.39 - 1.33 = 0.06$ m/s^2, so the uncertainty is half the range, ± 0.03 m/s^2.

Newton's third law. When two objects interact, they exert equal and opposite forces on each other. The two forces are the same type and act on different objects.

Worked example 12. A book with a weight of 4.0 N rests on a table. The forces on the book are its weight (4.0 N down) and the normal contact force from the table (4.0 N up). They balance, so the book stays still (first law). They are not a third-law pair, because they act on the same object and are different types of force. The third-law partner of the table pushing up on the book is the book pushing down on the table; the partner of the Earth pulling the book down is the book pulling the Earth up.



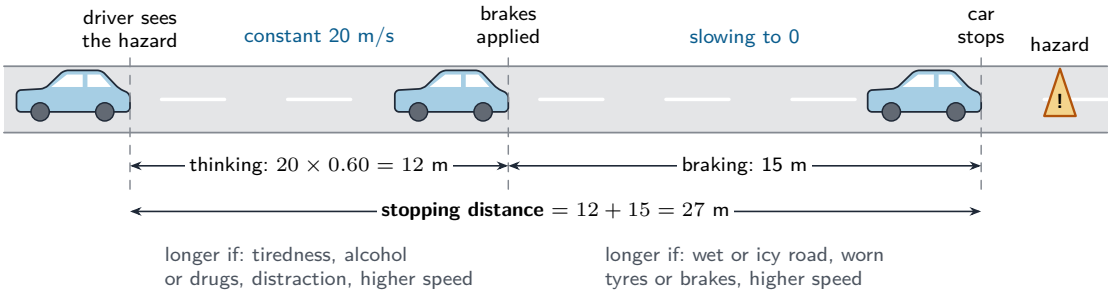
The weight and the normal force on the book balance, but they are not a pair: each third-law pair acts on two different objects

Stopping distances

The stopping distance of a vehicle is the thinking distance plus the braking distance.

- **Thinking distance** is how far the vehicle travels during the driver's reaction time: thinking distance = speed × reaction time. Reaction times are usually 0.2 to 0.9 s. They are longer if the driver is tired, has taken drugs or alcohol, or is distracted.
- **Braking distance** is how far the vehicle travels after the brakes are applied. It is longer at higher speeds, on wet or icy roads, and with worn brakes or tyres.

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Thinking distance plus braking distance gives the stopping distance.

Worked example 13. A car travels at 20 m/s and the driver's reaction time is 0.60 s. Thinking distance $= 20 \times 0.60 = 12$ m. If the braking distance is 15 m, the stopping distance is $12 + 15 = 27$ m.

Measuring reaction time. One person holds a ruler; the other waits with a thumb and finger at the zero mark. When the ruler is dropped, the second person catches it. The distance the ruler falls gives the reaction time from $s = \frac{1}{2}gt^2$. **Worked example 14.** The ruler falls 0.20 m: $t = \sqrt{\frac{2 \times 0.20}{9.8}} = 0.20$ s.

Braking. When the brakes are applied, friction between the brakes and the wheels does work, transferring energy from the kinetic store of the car to the thermal store of the brakes, which get hot. A faster car needs a bigger braking force to stop in the same distance. Large decelerations can make the brakes overheat or the driver lose control.

Worked example 15 (HT). A 1400 kg car slows from 18 m/s to rest over a braking distance of 24 m.

$$a = \frac{v^2 - u^2}{2s} = \frac{0 - 18^2}{2 \times 24} = -6.75 \text{ m/s}^2$$

The braking force is $F = ma = 1400 \times 6.75 = 9450$ N, opposite to the motion.

Momentum (HT)

Momentum 动量 is mass multiplied by velocity:

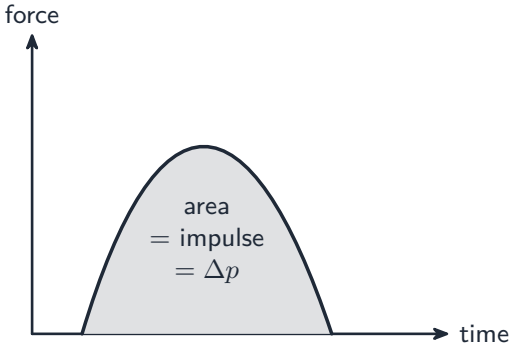
$$p = mv$$

p is momentum in kg m/s, m is mass in kg and v is velocity in m/s. Momentum is a vector. In a closed system, the total momentum before an event, such as a collision or an explosion, equals the total momentum after it. This is conservation of momentum.

Worked example 16. A 2.0 kg trolley moving right at 3.0 m/s collides with and sticks to a stationary 1.0 kg trolley. Momentum before $= 2.0 \times 3.0 + 0 = 6.0$ kg m/s. After, the 3.0 kg pair moves at $\frac{6.0}{3.0} = 2.0$ m/s to the right.

(Physics only) Changes in momentum. When a force acts on an object, its momentum changes. The force equals the rate of change of momentum:

$$F = \frac{m\Delta v}{\Delta t}$$



The area under a force–time graph equals the change in momentum.

Worked example 17. A 1000 kg car moving at 20 m/s hits a barrier and stops in 0.25 s. Change in momentum $= 1000 \times 20 = 20\,000$ kg m/s, so the mean force is $\frac{20\,000}{0.25} = 80\,000$ N. With a crumple zone that makes the stop last 0.50 s, the force halves to 40 000 N.

Worked example 18. A 0.16 kg ball hits a wall at 12 m/s and bounces back at 8.0 m/s. Take the first direction as positive. Change in momentum $= 0.16 \times (-8.0 - 12) = -3.2$ kg m/s. If the contact lasts 0.020 s, the mean force on the ball is $\frac{3.2}{0.020} = 160$ N, away from the wall.

Safety features. Air bags, seat belts, crumple zones, cycle helmets, gymnasium crash mats and cushioned playground surfaces all increase the time it takes for a person's momentum to change. The rate of change of momentum is smaller, so the force on the person is smaller and injuries are less serious.

Sources for this lesson

- AQA, *GCSE Physics (8463) specification*, section 4.5 Forces, and the *Required practical handbook* (practicals 6 and 7).
- NASA, *Apollo 15 Lunar Surface Journal*, "The hammer and the feather", 2 August 1971.

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- AQA, *GCSE Physics* Paper 2 Higher, June 2024 and June 2025 (spring, rocket, braking, air bag and acceleration questions, adapted).

Common errors

- Giving weight in kilograms; weight is a force, in newtons.
- Using the length of the spring instead of the extension in $F = ke$.
- Using a distance that is not perpendicular to the force when calculating a moment.
- Saying zero resultant force means the object is not moving; it may be moving at a constant velocity.
- Putting both forces of a third-law pair on the same object.
- Reading the wrong part of a graph: gradient of distance–time is speed, gradient of velocity–time is acceleration, area under velocity–time is distance.
- Mixing up the factors: tiredness, drugs and distraction affect thinking distance; road and vehicle conditions affect braking distance.
- Ignoring direction in momentum calculations.

Key terms

- **Vector**: a quantity with magnitude and direction.
- **Resultant force**: the single force that has the same effect as all the forces acting.
- **Weight**: the force on an object due to gravity.
- **Moment**: the turning effect of a force.
- **Terminal velocity**: the steady speed reached when the drag equals the weight.
- **Inertia**: the tendency of an object to keep its state of motion.
- **Stopping distance**: thinking distance plus braking distance.
- **Momentum**: mass multiplied by velocity.

Check yourself

1. Name two contact forces and two non-contact forces.
2. A 5.0 kg bag is lifted 1.2 m. Calculate its weight ($g = 9.8$ N/kg) and the work done.
3. A spring has $k = 40$ N/m. What force stretches it by 0.15 m?
4. A car accelerates from 10 m/s to 30 m/s in 8.0 s. Calculate its acceleration.
5. A 1200 kg car accelerates at 2.5 m/s^2. Calculate the resultant force.
6. Explain why a skydiver reaches terminal velocity.
7. Give two factors that increase the braking distance of a car.
8. (HT) A 60 kg skater moving at 4.0 m/s grabs a stationary 40 kg skater. Find their speed together.

Answers: 1. Contact: friction, air resistance (or tension, normal contact force);

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non-contact: gravitational, magnetic (or electrostatic). 2. $W = 5.0 \times 9.8 = 49$ N; work done $= 49 \times 1.2 = 58.8$ J. 3. $40 \times 0.15 = 6.0$ N. 4. $\frac{30-10}{8.0} = 2.5$ m/s^2. 5. $1200 \times 2.5 = 3000$ N. 6. As speed increases, drag increases until it equals the weight; the resultant force is then zero, so the speed stays constant. 7. Higher speed, wet or icy road (or worn tyres, worn brakes). 8. $\frac{60 \times 4.0}{100} = 2.4$ m/s.

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6 · Waves

AQA · GCSE · Physics

Waves: sound, light and the electromagnetic spectrum

Why it matters. In 1887, in a lecture room in Karlsruhe, Germany, Heinrich Hertz made sparks jump across a small gap in an electric circuit. A few metres away, a loop of wire with its own tiny gap began to spark as well, although nothing connected the two. Hertz had made and detected radio waves, invisible waves that travel at the speed of light, just as James Clerk Maxwell had predicted twenty years earlier. Hertz thought his discovery had no practical use. On 12 December 1901, Guglielmo Marconi sat in a hut on Signal Hill in Newfoundland, Canada, holding an earphone connected to a wire held up by a kite. He heard three faint clicks, the letter S in Morse code, sent by radio from Cornwall in England, more than 3000 km across the Atlantic. Radio, television, mobile phones, Wi-Fi and satellite navigation all grew from those sparks.

In this unit you will:

- describe transverse and longitudinal waves, and use the wave equation;
- measure the speed of waves in water and in a solid;
- describe the electromagnetic spectrum, its uses and its dangers, and investigate infrared radiation;
- (physics only) explain reflection, sound, ultrasound and seismic waves, lenses, colour and black body radiation.

AQA GCSE Physics (8463), topic 4.6 Waves, examined on Paper 2. It includes required practicals 8 (waves), 9 (reflection and refraction, physics only) and 10 (infrared radiation). Reflection, sound, waves for detection, lenses, colour and black body radiation are in GCSE Physics only. Content marked (HT) is Higher tier only. You must learn $v = f\lambda$; $T = \frac{1}{f}$ and the magnification equation are on the equations sheet.

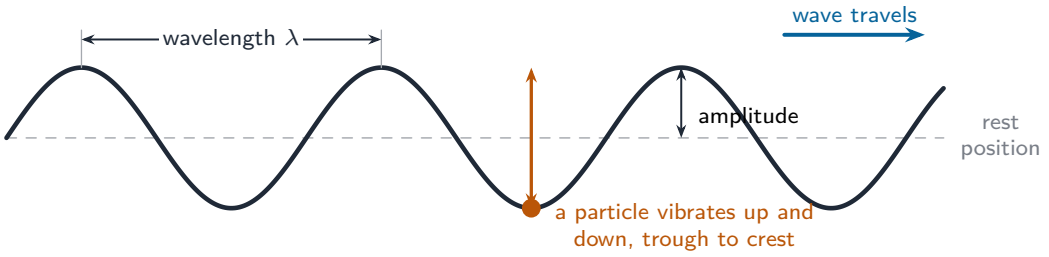
Transverse and longitudinal waves

Waves transfer energy from one place to another without transferring matter.

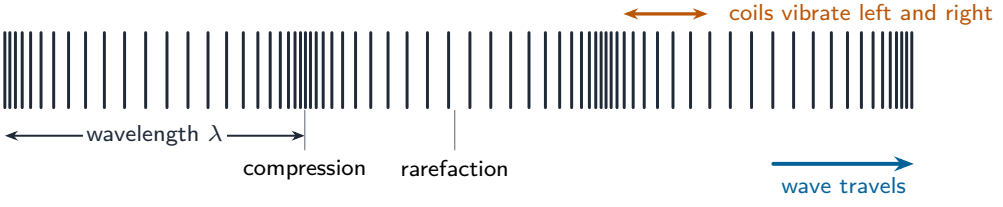
- In a **transverse** 横波 wave, the oscillations are at right angles to the direction the wave travels. Examples: ripples on water, waves on a string, and all electromagnetic waves.
- In a **longitudinal** 纵波 wave, the oscillations are in the same direction as the wave travels. Sound waves in air are longitudinal. They have **compressions** 密部, where the particles are close together, and **rarefactions** 疏部, where they are spread out.

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transverse: vibration perpendicular to the direction of travel



longitudinal: vibration parallel to the direction of travel



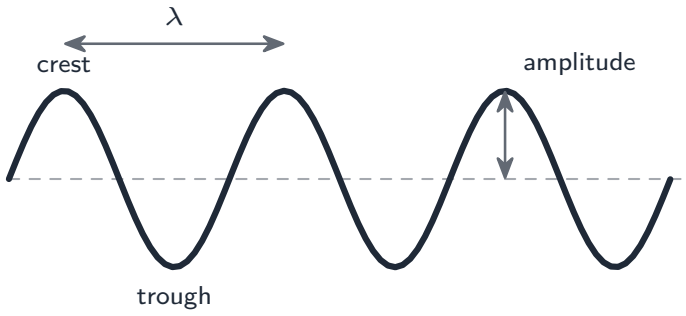
A transverse wave on a rope and a longitudinal wave on a slinky, with compressions and rarefactions.

It is the wave that travels, not the water or air. A ball floating on a pond bobs up and down as ripples pass, but it does not move across the pond with them.

Properties of waves and the wave equation

- The **amplitude** 振幅 is the maximum displacement of a point on the wave from its undisturbed position.
- The **wavelength** 波长 is the distance from a point on one wave to the equivalent point on the next wave, such as crest to crest.
- The **frequency** 频率 is the number of waves passing a point each second, in hertz (Hz).
- The **period** 周期 is the time for one complete wave to pass a point.

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

$$T = \frac{1}{f} \qquad v = f\lambda$$

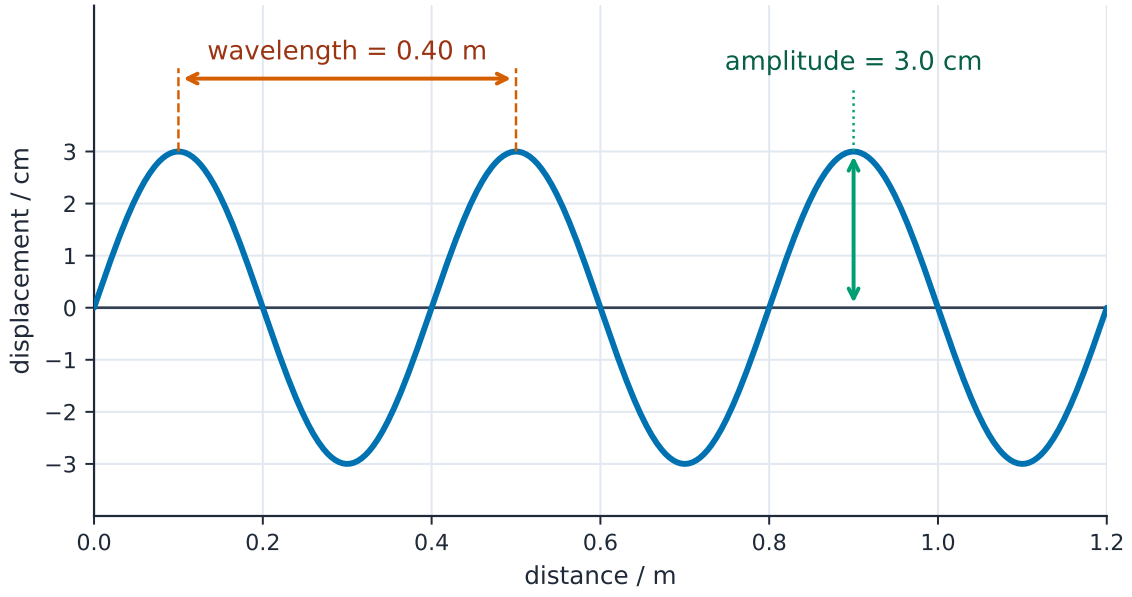
T is the period in s, f is frequency in Hz, v is wave speed in m/s and λ is wavelength in m. The wave speed is the speed at which energy is transferred through the medium.

Worked example 1. A water wave has a frequency of 2.0 Hz and a wavelength of 0.35 m. Its speed is $v = 2.0 \times 0.35 = 0.70$ m/s, and its period is $T = \frac{1}{2.0} = 0.50$ s.

Worked example 2. A sound wave of frequency 4.0 kHz travels at 330 m/s. Convert: 4000 Hz. $\lambda = \frac{v}{f} = \frac{330}{4000} = 0.083$ m (2 s.f.).

Worked example 3. The graph shows a water wave at one instant, and 5 waves pass a point every 2.0 s.

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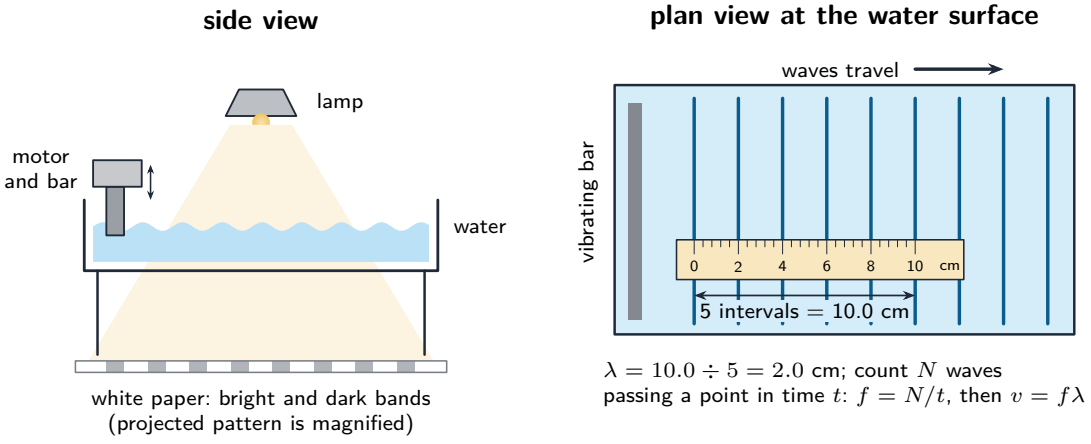


Wavelength is measured crest to crest; amplitude is measured from the rest position to a crest.

- Three complete waves fit in 1.20 m, so $\lambda = \frac{1.20}{3} = 0.40$ m.
- The amplitude, from the rest position to a crest, is 3.0 cm. The height from crest to trough, 6.0 cm, is twice the amplitude.
- $f = \frac{5}{2.0} = 2.5$ Hz, so $v = 2.5 \times 0.40 = 1.0$ m/s.

Required practical 8: measuring wave speeds.

- Waves on water: set up a ripple tank with a motor-driven bar, and a lamp above that makes a pattern of the waves on paper below. Measure the length of several waves together and divide by the number of waves to find the wavelength. Count the waves passing a point in 10 s to find the frequency, then use $v = f\lambda$.
- Waves on a string: stretch a string over a pulley with a hanging mass, and make it vibrate with a vibration generator. Change the frequency until you see a clear wave that does not move along the string. Each loop is half a wavelength. Read the frequency from the signal generator and use $v = f\lambda$.



Required practical 8: a ripple tank, and the wave pattern measured with a ruler across 5 wavelengths.

> **Worked example 4.** In a ripple tank, 5 complete waves measure 10.0 cm, so $\lambda = 2.0$ cm $= 0.020$ m. If the frequency is 12 Hz, $v = 12 \times 0.020 = 0.24$ m/s.

> **Worked example 5.** A 1.2 m string vibrating at 50 Hz shows 3 loops. Each loop is half a wavelength, so $\lambda = \frac{2 \times 1.2}{3} = 0.80$ m, and $v = 50 \times 0.80 = 40$ m/s.

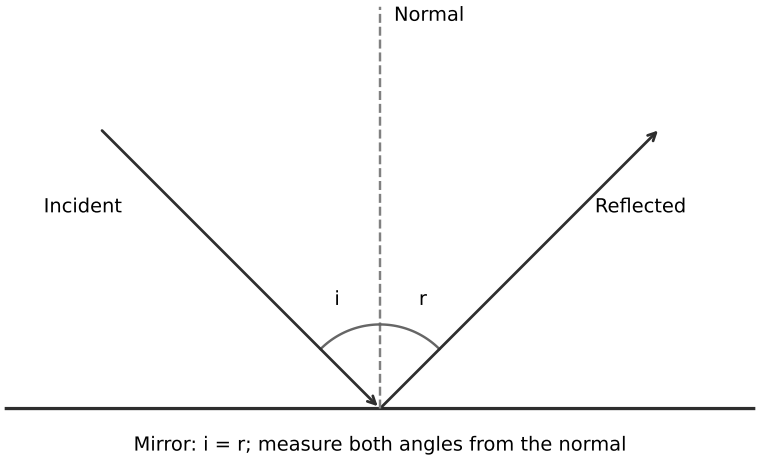
Speed of sound in air. Stand 100 m from a large wall, make a sharp sound and time the echo. **Worked example 6.** The echo arrives after 0.60 s. The sound travels to the wall and back, 200 m, so $v = \frac{200}{0.60} = 330$ m/s (2 s.f.).

Reflection (physics only)

When a wave reaches the boundary between two materials, it can be reflected, absorbed or transmitted.

- **Specular reflection** 镜面反射 happens at a smooth surface, such as a mirror: all the light is reflected in one direction.
- **Diffuse reflection** 漫反射 happens at a rough surface, such as paper: the light is scattered in many directions.

To draw a ray diagram for reflection, draw the normal at right angles to the surface where the ray hits it. The angle of incidence equals the angle of reflection; both are measured from the normal.



Reflection ray diagram with the normal, angle of incidence and angle of reflection.

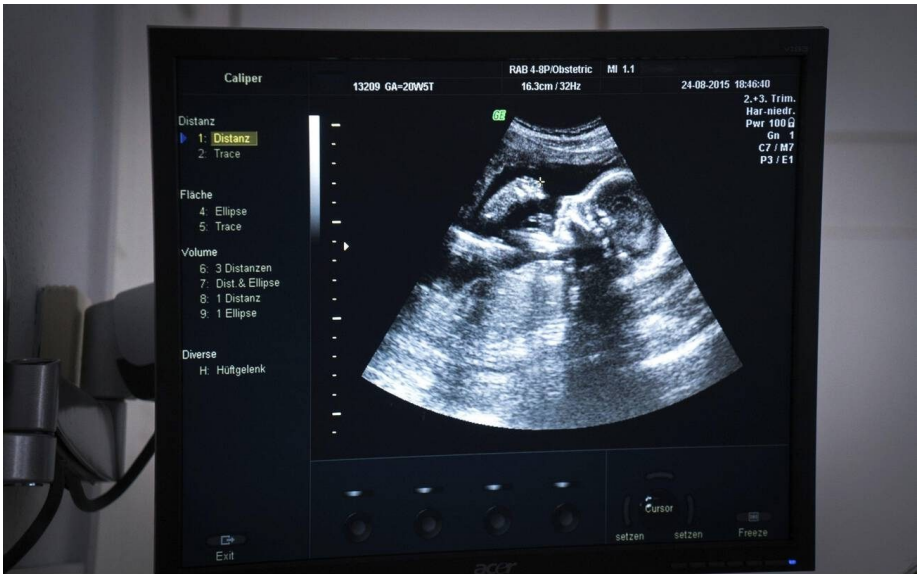
Required practical 9 (physics only): reflection and refraction. Shine a narrow ray of light from a ray box at a plane mirror. Mark the incident and reflected rays with crosses, draw them with a ruler, draw the normal and measure the angles with a protractor. Then shine the ray into a glass block, and trace the ray as it enters and leaves, to measure the angles of incidence and refraction. Repeat with blocks of other materials. Do this in a darkened room, and take care because the ray box gets hot.

Sound and detection (physics only, HT)

Sound waves can travel through solids, liquids and gases. When sound reaches your ear, it makes the eardrum vibrate. The vibrations pass through small bones to the inner ear, which sends signals to the brain. This works only for a limited range of frequencies: humans can hear from about 20 Hz to 20 kHz. When sound passes from air into another medium, its speed and wavelength change, but its frequency stays the same.

Ultrasound is sound with a frequency above 20 kHz, too high for humans to hear. When ultrasound reaches a boundary between two materials, some of it is reflected. The time taken for the echo to return gives the distance to the boundary. Ultrasound is used for scanning unborn babies, because it is not ionising and so is safer than X-rays, and to find cracks inside metal objects.

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An ultrasound scan of an unborn baby: each bright point is an echo from a boundary between tissues.

> **Worked example 7.** Ultrasound travels at 1500 m/s in body tissue. An echo returns after 0.000 040 s. The pulse travels to the boundary and back, so the depth is $\frac{1500 \times 0.000\,040}{2} = 0.030$ m, or 3.0 cm.

Echo sounding. Ships send sound pulses down to the seabed and time the echoes.
Worked example 8. Sound travels at 1500 m/s in sea water, and an echo returns after 0.40 s. Depth $= \frac{1500 \times 0.40}{2} = 300$ m.

Seismic waves. Earthquakes produce P-waves, which are longitudinal and can travel through solids and liquids, and S-waves, which are transverse and cannot travel through liquids. Detectors around the world find that S-waves do not reach the side of the Earth opposite an earthquake. This shows that the Earth has a liquid outer core. Studying seismic waves gave the first evidence for the Earth's layered structure, which nobody can see directly.

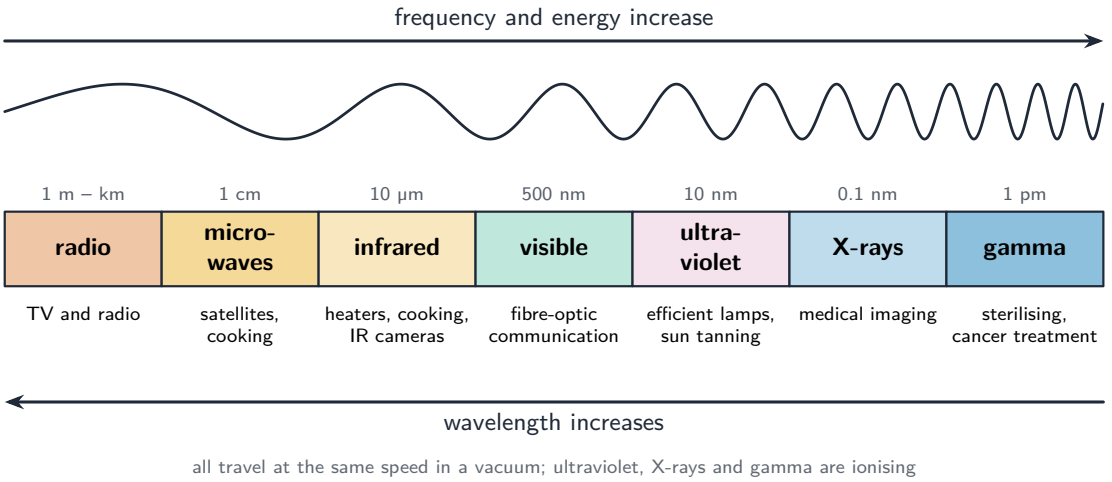
Electromagnetic waves

Electromagnetic (EM) waves are transverse waves that transfer energy from a source to an absorber. They form a continuous spectrum, and they all travel at the same speed in a vacuum or in air: 3×10^8 m/s. In order of decreasing wavelength and increasing frequency:

radio → microwaves → infrared → visible light → ultraviolet → X-rays → gamma rays

Our eyes detect only visible light, a very small part of the spectrum.

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The electromagnetic spectrum: frequency increases and wavelength decreases from radio waves to gamma rays.

Worked example 9. A radio station broadcasts at 100 MHz. Its wavelength is $\lambda = \frac{3\times10^8}{100\times10^6} = 3.0$ m.

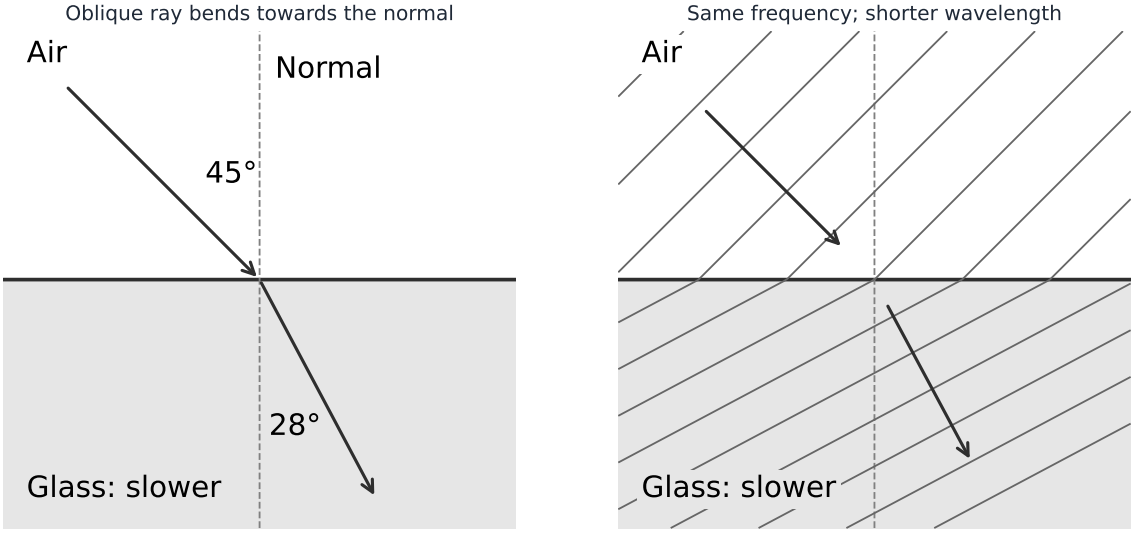
EM wave	Uses	Why it is suitable
radio waves	television and radio	they travel long distances and can be reflected by the atmosphere
microwaves	satellite communications, cooking	they pass through the atmosphere; water in food absorbs them
infrared	electric heaters, cooking, infrared cameras	all warm objects emit it, and absorbing it warms things
visible light	fibre optic communications	it reflects along inside glass fibres
ultraviolet	energy-efficient lamps, sun tanning	it makes some substances glow (fluoresce)
X-rays and gamma rays	medical imaging and treatment	they pass through soft tissue; X-rays are absorbed by bone

Dangers. Ultraviolet waves can make skin age early and increase the risk of skin cancer. X-rays and gamma rays are ionising radiation: they can cause mutations in genes and lead to cancer. The risk of harm is measured as radiation dose, in sieverts (1000 mSv = 1 Sv).

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(HT) How EM waves are made and absorbed. Oscillations in electrical circuits produce radio waves. When radio waves are absorbed by a wire, they can create an alternating current with the same frequency as the radio wave. Changes in atoms can produce or absorb EM waves over a wide range of frequencies, and changes in the nucleus of an atom produce gamma rays.

(HT) Refraction. Different substances may absorb, transmit, refract or reflect EM waves in different ways, depending on the wavelength. Refraction happens because the wave changes speed when it enters a new material. A ray entering glass at an angle slows down and bends towards the normal. On a wavefront diagram, the wavefronts are closer together in the material where the wave is slower. A ray that hits the boundary along the normal does not change direction.



Refraction as a ray bending towards the normal, and as wavefronts bunching in the slower medium.

Required practical 10: infrared radiation. Fill a Leslie cube, a metal cube with differently coloured faces (matt black, shiny black, matt white, shiny silver), with hot water. Point an infrared detector at each face from the same distance, and record the readings. The matt black face emits the most infrared and the shiny silver face the least. To compare absorption, put identical cans with different surfaces the same distance from a heater and measure how much the temperature of the water inside each rises in the same time. Matt black surfaces are the best absorbers as well as the best emitters.

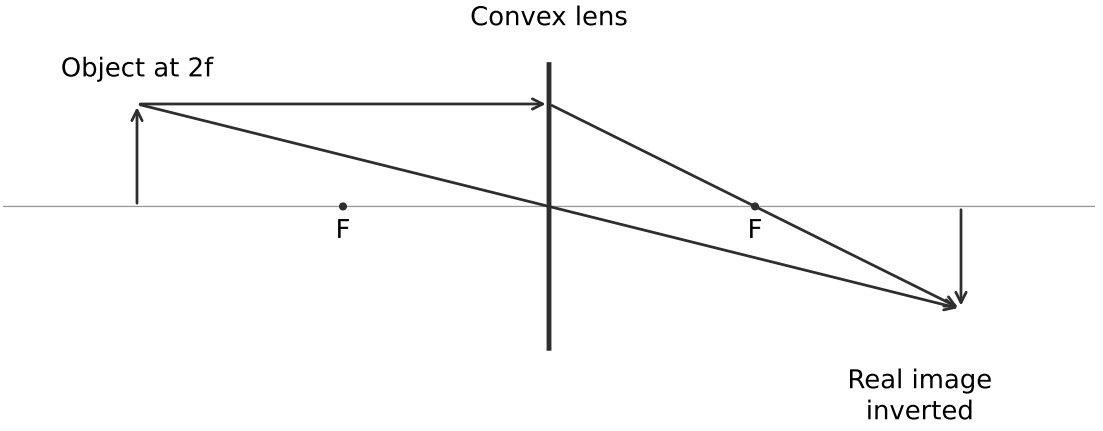
Lenses (physics only)

A lens forms an image by refracting light.

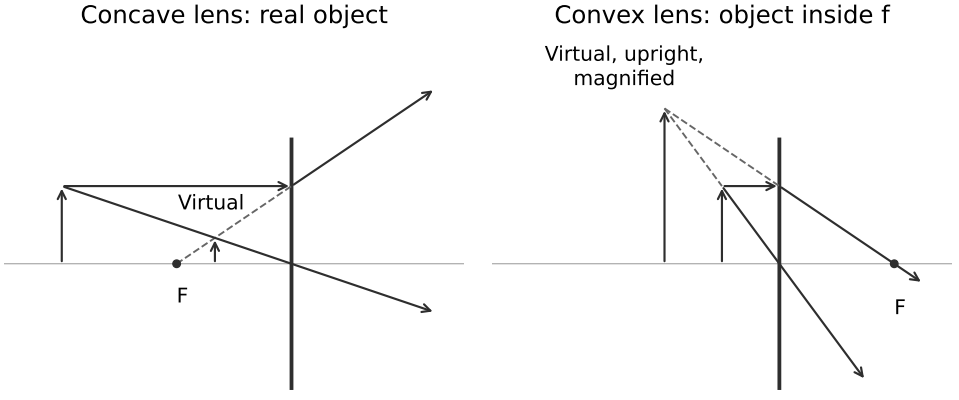
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- A **convex** 凸透镜 lens makes parallel rays of light converge (come together) at the principal focus. The distance from the lens to the principal focus is the focal length. A convex lens can form a real or a virtual image.
- A **concave** 凹透镜 lens makes parallel rays spread out, as if they came from a principal focus behind the lens. A concave lens always forms a virtual, upright, smaller image.

Drawing a ray diagram. Use two rays from the top of the object. A ray parallel to the principal axis refracts through the principal focus (convex lens) or appears to come from it (concave lens). A ray through the centre of the lens goes straight on. The image is where the rays meet. A virtual image is where the rays only appear to come from, so draw the extensions as dashed lines.



A convex lens ray diagram forming a real inverted image.



Virtual images: concave lens with a real object, and convex lens with an object inside its focal length.

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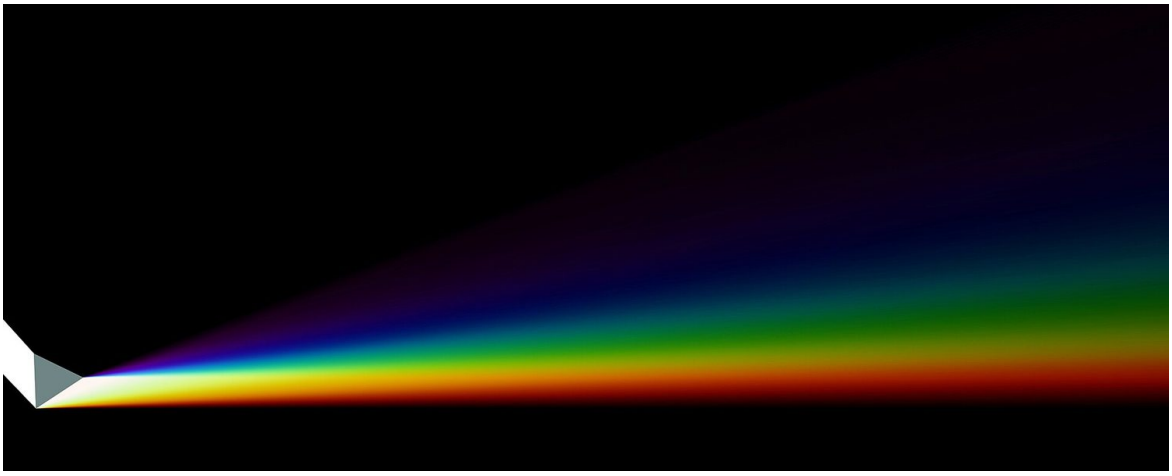
$$\text{magnification} = \frac{\text{image height}}{\text{object height}}$$

Magnification is a ratio, so it has no unit. Use the same unit for both heights.

Worked example 10. An object 5.0 mm tall forms an image 20 mm tall. Magnification $= \frac{20}{5.0} = 4.0$.

Visible light and colour (physics only)

Each colour in the visible spectrum has its own narrow band of wavelengths and frequencies. Red light has the longest wavelength, and violet the shortest.



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

- An opaque object reflects some wavelengths and absorbs the rest. A red apple looks red because it reflects red light and absorbs the other colours. A white object reflects all wavelengths equally; a black object absorbs them all.
- Colour filters absorb some wavelengths and transmit others. A red filter transmits only red light.
- Transparent and translucent objects transmit light.

Worked example 11. A red book is seen through a green filter. Explain why it looks black. The book reflects only red light. The green filter absorbs red light, so no light from the book reaches the eye.

Black body radiation (physics only)

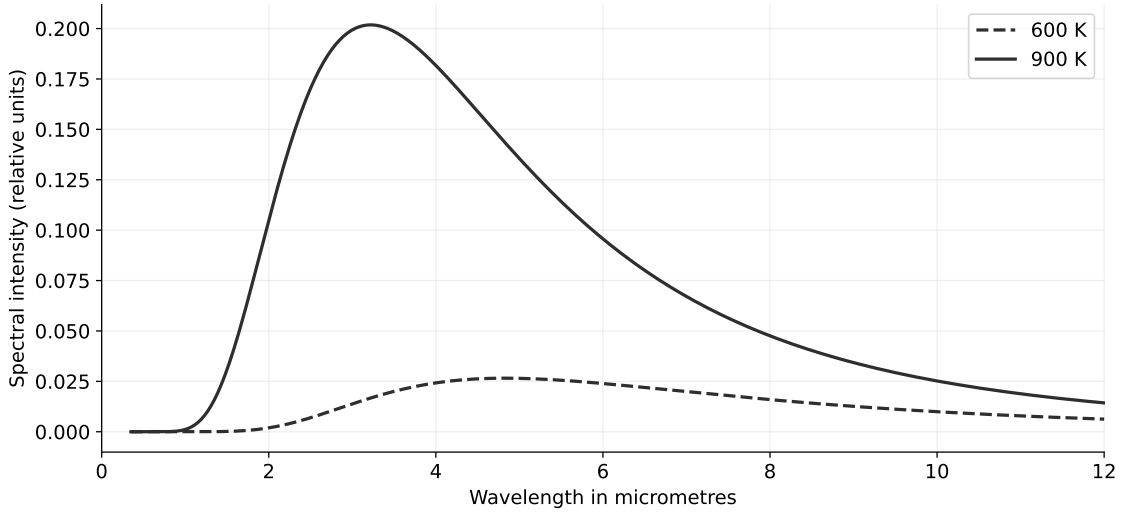
All bodies, whatever their temperature, emit and absorb infrared radiation. The hotter a body is, the more infrared radiation it emits in a given time.

A perfect black body absorbs all the radiation that hits it; it does not reflect or transmit any. Because a good absorber is also a good emitter, a perfect black body is

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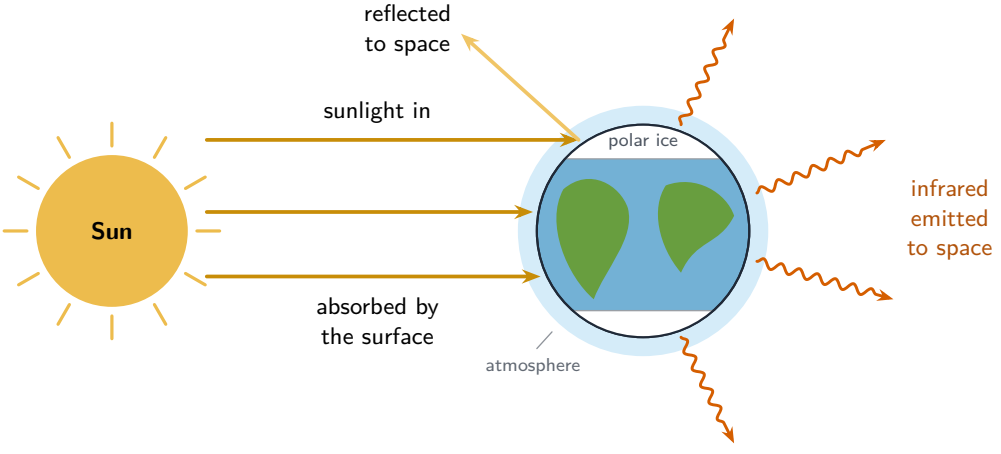
the best possible emitter.

The intensity and wavelength distribution of the radiation a body emits depend on its temperature. As the temperature increases, the body emits more radiation at every wavelength, and the peak moves to a shorter wavelength. That is why a piece of metal glows red, then orange, then white as it gets hotter.



A hotter body emits more radiation at every wavelength, and its peak is at a shorter wavelength.

(HT) Temperature and radiation. A body at constant temperature absorbs radiation at the same rate as it emits it. If it absorbs radiation faster than it emits it, its temperature rises. The temperature of the Earth depends on many factors, including how fast light and infrared radiation are absorbed and emitted by its surface and atmosphere, and how much is reflected back into space, for example by ice.



The Earth's radiation balance: absorbed, reflected and emitted radiation.

Sources for this lesson

- AQA, *GCSE Physics (8463) specification*, section 4.6 Waves, and the *Required practical handbook* (practicals 8, 9 and 10).
- H. Hertz, *Electric Waves* (London, 1893), English translation of his papers of 1887 to 1890; Marconi Society, account of the first transatlantic radio signal, 12 December 1901.
- AQA, *GCSE Physics* Paper 2 Higher, June 2023 to June 2025 (wave graph, ripple tank and lens questions, adapted).

Common errors

- Saying the material travels with the wave; waves transfer energy, and particles only oscillate.
- Measuring amplitude from crest to trough; it is from the rest position to a crest.
- Forgetting to convert kHz to Hz or MHz to Hz.
- Saying refraction changes the frequency; the speed and wavelength change.
- Measuring angles from the surface instead of from the normal.
- Saying higher-frequency EM waves travel faster; all travel at the same speed in a vacuum.
- Giving magnification a unit.
- Saying a red filter turns light red; it absorbs the other colours.

Key terms

- **Transverse wave**: oscillations at right angles to the direction of travel.
- **Longitudinal wave**: oscillations along the direction of travel.
- **Wavelength**: the distance from one point on a wave to the same point on the next.
- **Frequency**: the number of waves passing a point each second.
- **Electromagnetic spectrum**: the family of transverse waves from radio to gamma rays.
- **Refraction**: the change of direction of a wave as its speed changes at a boundary.
- **Perfect black body**: an object that absorbs all the radiation that hits it.

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Check yourself

1. Give one example each of a transverse and a longitudinal wave.
2. A wave has a frequency of 25 Hz and a wavelength of 0.12 m. Calculate its speed and its period.
3. List the electromagnetic spectrum from longest to shortest wavelength.
4. Why are X-rays dangerous?
5. Describe how to measure the wavelength of water waves in a ripple tank.
6. (Physics only) Why is ultrasound used for scanning unborn babies instead of X-rays?
7. (Physics only) An image is 36 mm tall and the object is 12 mm tall. Calculate the magnification.

Answers: 1. Transverse: water ripples or light; longitudinal: sound. 2. $v = 25 \times 0.12 = 3.0$ m/s; $T = \frac{1}{25} = 0.04$ s. 3. Radio, microwaves, infrared, visible, ultraviolet, X-rays, gamma rays. 4. They are ionising, so they can damage genes and cause cancer. 5. Measure the length of several waves in the pattern with a ruler and divide by the number of waves. 6. Ultrasound is not ionising, so it does not damage cells. 7. $\frac{36}{12} = 3.0$.

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7 · Magnetism and electromagnetism

AQA · GCSE · Physics

Magnetism and electromagnetism: motors, generators and transformers

Why it matters. In April 1820, during a lecture at the University of Copenhagen, Hans Christian Ørsted noticed that a compass needle swung away from north whenever he switched on a current in a nearby wire. Electricity could make magnetism. Eleven years later in London, on 29 August 1831, Michael Faraday wound two coils of wire on opposite sides of an iron ring. When he connected a battery to one coil, a needle connected to the other coil flicked for a moment, then returned to zero; when he disconnected the battery, it flicked the other way. A changing magnetic field could make electricity. Ørsted's discovery leads to every electric motor, and Faraday's to every generator in every power station, and to the transformers of the National Grid.

In this unit you will:

- describe magnets, magnetic fields and the field around a current;
- explain electromagnets and (HT) the motor effect, using Fleming's left-hand rule and $F = BIl$;
- explain how electric motors and (physics only) loudspeakers work;
- (physics only, HT) explain the generator effect, alternators, dynamos, microphones and transformers.

AQA GCSE Physics (8463), topic 4.7 Magnetism and electromagnetism, examined on Paper 2. Content marked (HT) is Higher tier only. Loudspeakers, the generator effect and transformers are in GCSE Physics only and are Higher tier. $F = BIl$ and the transformer equations are on the equations sheet.

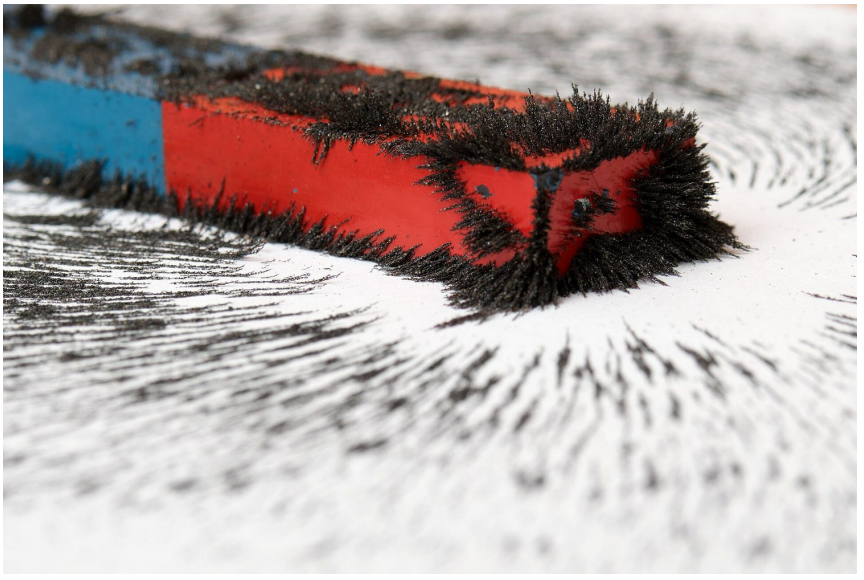
Magnets and magnetic fields

The **poles** 磁极 of a magnet are the places where the magnetic forces are strongest. When two magnets are brought close together, like poles repel and unlike poles attract. This is a non-contact force.

- A **permanent magnet** 永磁体 produces its own magnetic field.
- An **induced magnet** 感磁体 is a material that becomes a magnet when it is placed in a magnetic field. Induced magnetism always causes attraction. When the induced magnet is taken out of the field, it loses most or all of its magnetism quickly.

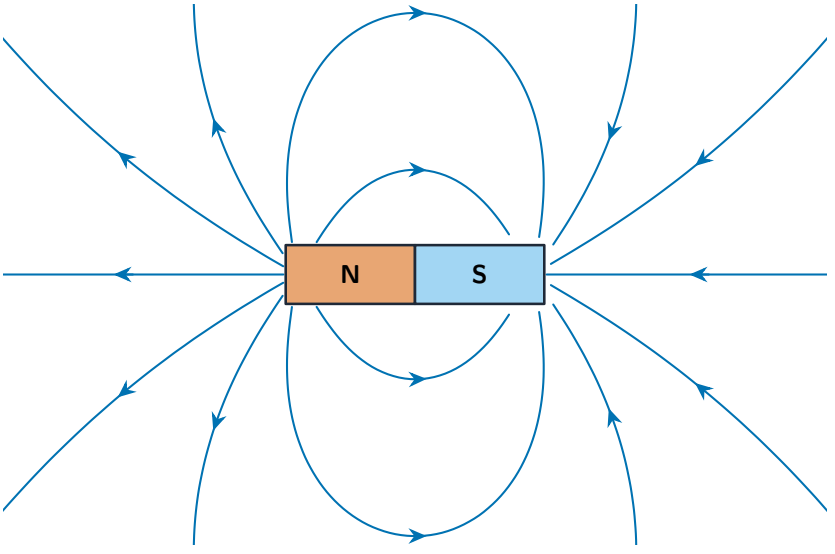
The **magnetic field** 磁场 is the region around a magnet where a force acts on another magnet or on a magnetic material: iron, steel, cobalt or nickel. The force between a magnet and a magnetic material is always attraction.

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Iron filings line up along the field lines of a bar magnet.

The direction of a magnetic field at any point is the direction of the force on the north pole of a magnet placed there. Field lines go from the north pole to the south pole of a magnet. The field is strongest at the poles, where the lines are closest together.



Field lines run from north to south outside a bar magnet.

Plotting a field. Place a magnet on paper and put a small plotting compass near its north pole. Mark the position of the end of the needle that points away from the magnet, then move the compass so that its other end is on the mark. Repeat until you reach the south pole, and join the marks to make a field line. Repeat from other starting points.

The Earth's magnetic field. A compass needle is a small bar magnet. It points

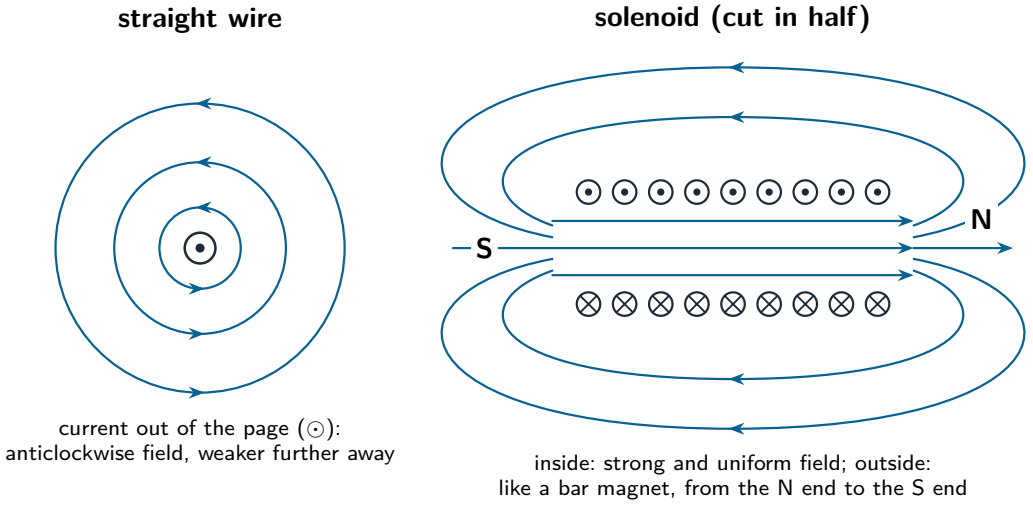
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north because the Earth has a magnetic field, produced by its core.

Electromagnetism

When a current flows through a wire, it produces a magnetic field around the wire. The field lines are circles around the wire. The field is stronger with a bigger current, and weaker further from the wire. Reversing the current reverses the direction of the field.

A **solenoid** 螺线管 is a wire wound into a long coil. The fields of the loops add together, so the field inside a solenoid is strong and uniform. Outside, the field has the same shape as the field of a bar magnet.



Circular field lines around a straight wire, and the strong uniform field inside a solenoid.

Putting an iron core inside the solenoid makes the field much stronger. A solenoid with an iron core is an **electromagnet** 电磁铁. Unlike a permanent magnet, an electromagnet can be switched on and off, and its strength can be changed by changing the current. Electromagnets are used in scrapyard cranes, electric bells and relays.

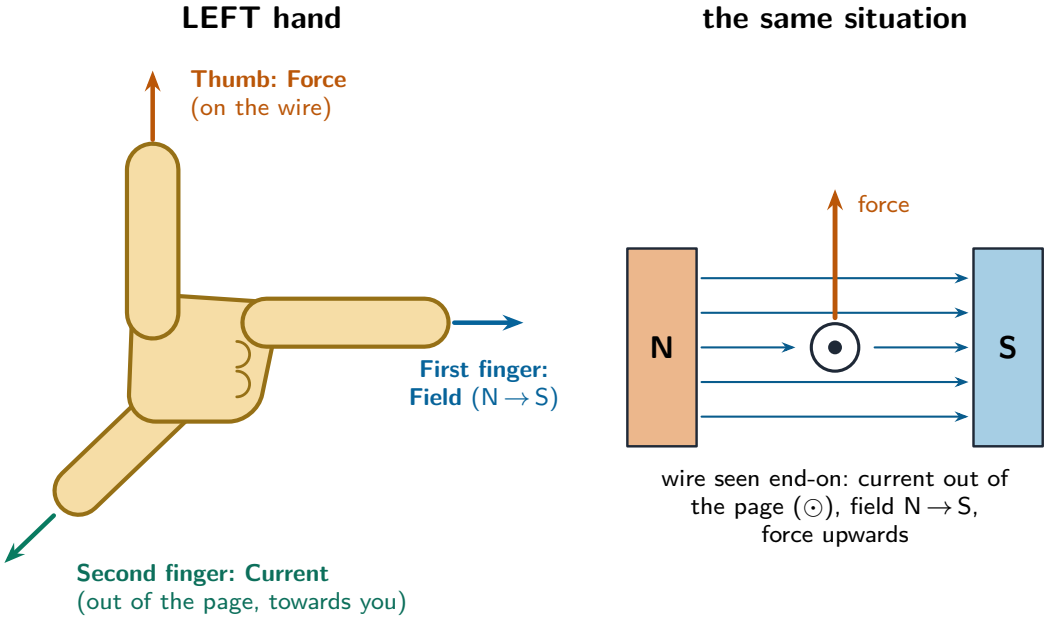
> **Worked example 1.** Give three ways to make an electromagnet stronger. Increase the current, add more turns of wire to the coil, and use an iron core.

> **Worked example 2 (physics only).** Explain how a relay lets a small current switch on a large one. A small current flows through the coil of an electromagnet. It becomes magnetised and attracts an iron armature, which pushes two contacts together and completes a second circuit carrying the large current. When the small current stops, a spring pulls the armature back and the large circuit is broken.

The motor effect (HT)

When a wire carrying a current is placed in a magnetic field, the magnet and the wire exert a force on each other. This is the motor effect.

Fleming's left-hand rule. Hold the thumb, first finger and second finger of your left hand at right angles to each other. The first finger points along the field (from north to south), the second finger points along the current, and the thumb shows the direction of the force (the motion).



Fleming's left-hand rule: force, field and current at right angles.

For a wire at right angles to the field:

$$F = BIl$$

F is force in N, B is **magnetic flux density** 磁感应强度 in tesla (T), I is current in A, and l is the length of wire in the field, in m. If the wire is parallel to the field, there is no force.

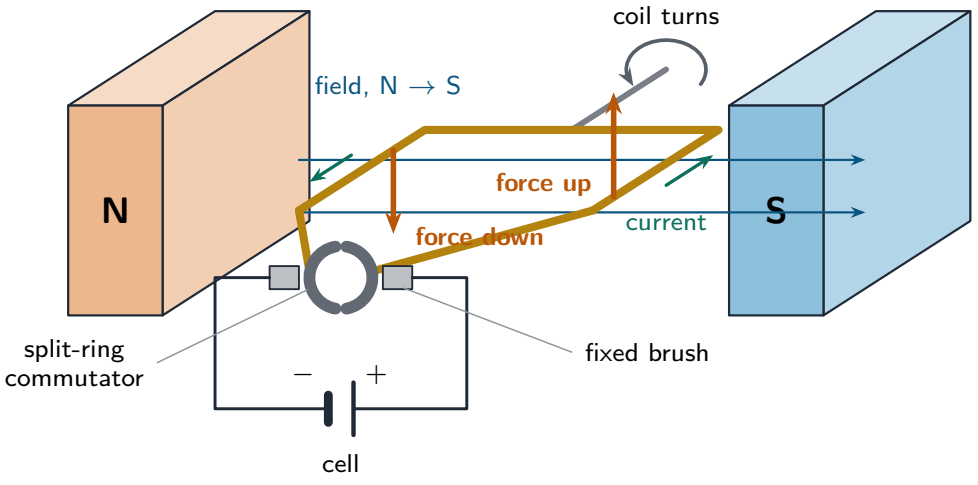
> **Worked example 3.** A wire carries a current of 3.0 A at right angles to a magnetic field of 0.20 T. 5.0 cm of the wire is in the field. Convert: $l = 0.050$ m. $F = 0.20 \times 3.0 \times 0.050 = 0.030$ N.

> **Worked example 4.** A wire 0.15 m long carrying 4.0 A feels a force of 0.12 N. The flux density is $B = \frac{F}{Il} = \frac{0.12}{4.0 \times 0.15} = 0.20$ T.

Electric motors. A coil of wire carrying a current in a magnetic field rotates. The

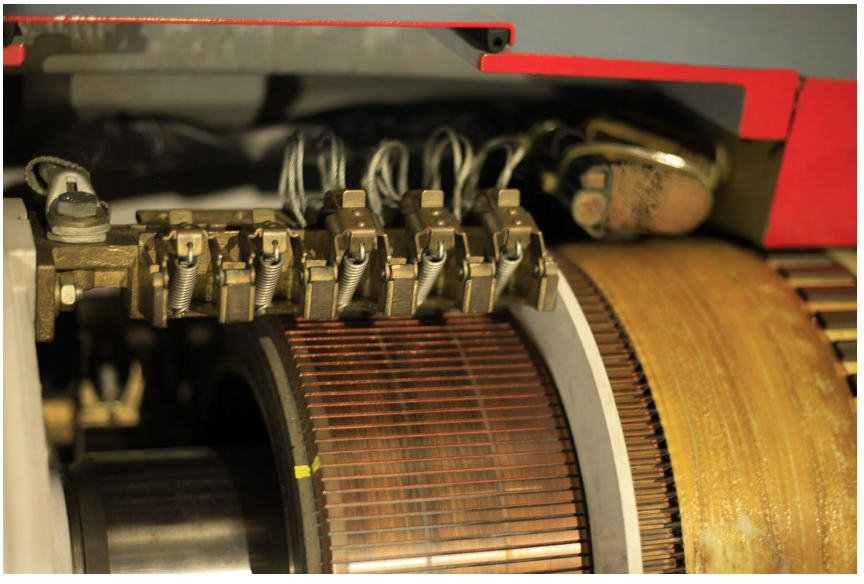
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current flows in opposite directions in the two sides of the coil, so one side is pushed up and the other is pushed down.



A dc motor: the two sides of the coil are pushed in opposite directions, and the split-ring commutator keeps it turning.

A split-ring commutator reverses the direction of the current in the coil every half turn. This keeps the forces turning the coil in the same direction. Carbon brushes press against the commutator to carry the current into the coil.



Carbon brushes press on the copper commutator of a real dc motor to carry current to the spinning coil.

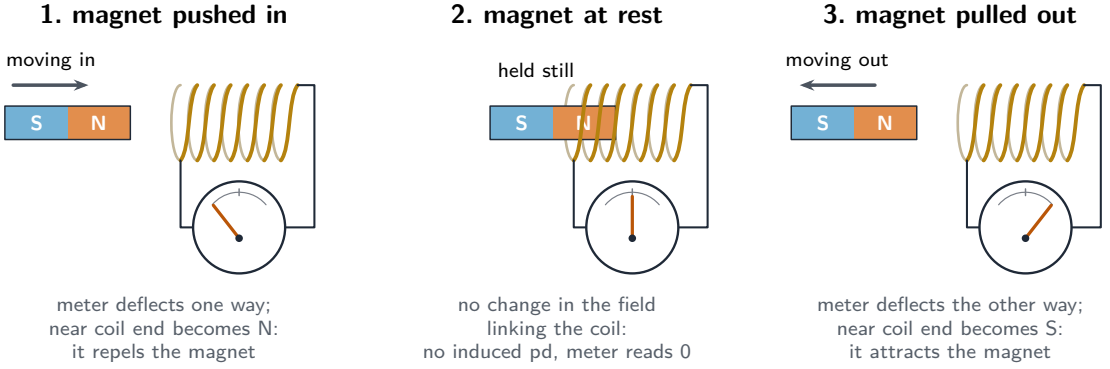
The motor turns faster with a bigger current, a stronger magnetic field or more turns on the coil.

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Loudspeakers (physics only). An alternating current flows through a coil attached to a paper cone, inside the field of a permanent magnet. The force on the coil keeps changing direction, so the coil and cone vibrate. The cone makes the air vibrate, producing sound waves with the same frequency as the current.

The generator effect (physics only, HT)

If a wire moves through a magnetic field, cutting the field lines, or if the magnetic field through a coil changes, a potential difference is induced across the ends of the wire. If the wire is part of a complete circuit, a current flows. This is the generator effect.



Moving a magnet into or out of a coil induces a potential difference; a still magnet induces none.

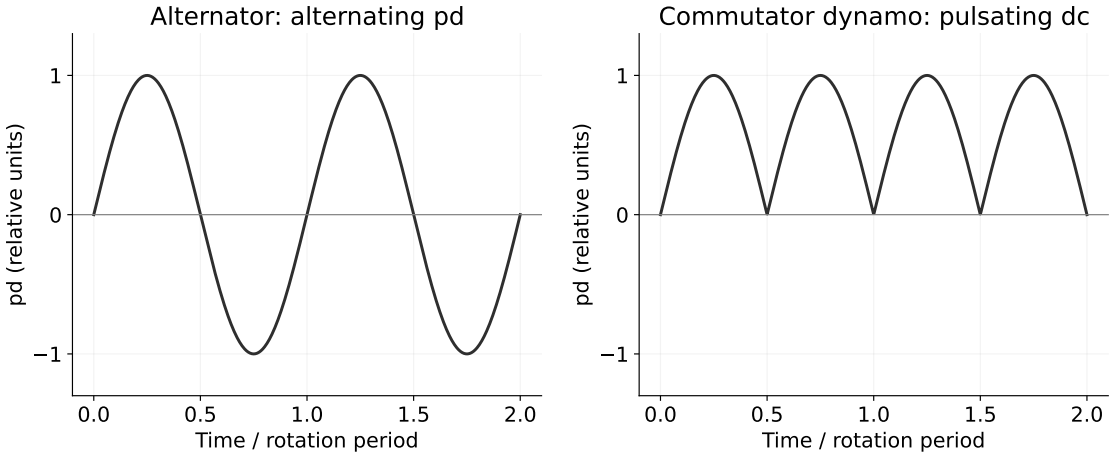
The induced current produces its own magnetic field, and this field opposes the change that caused it. For example, pushing the north pole of a magnet into a coil makes that end of the coil a north pole, which repels the magnet.

The induced potential difference is bigger if:

- the magnet or wire moves faster;
- the magnetic field is stronger;
- the coil has more turns.

Reversing the movement, or the poles of the magnet, reverses the potential difference. If the magnet stops moving, no potential difference is induced.

Alternators and dynamos. In an alternator, a coil rotates in a magnetic field, and the ends of the coil connect to slip rings. The induced potential difference reverses every half turn, so an alternator produces alternating current. A dynamo has a split-ring commutator instead, which swaps the connections every half turn, so the output is direct current that rises and falls but never reverses.



An alternator gives an alternating pd that changes direction; a dynamo gives a pd that rises and falls but never reverses.

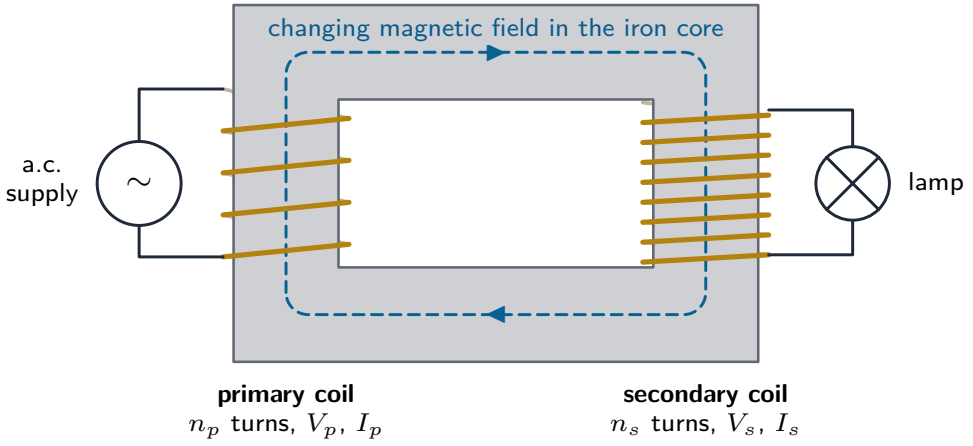
Worked example 5. The coil of an alternator is made to spin twice as fast. Describe two changes to the graph of potential difference against time. The peaks are higher, because the coil cuts the field lines faster. The peaks are closer together, because the frequency doubles.

Microphones. A microphone works like a loudspeaker in reverse. Sound waves make a diaphragm vibrate, which moves a coil in the field of a magnet. This induces a potential difference that changes in the same pattern as the sound wave, which can be amplified or recorded.

Transformers (physics only, HT)

A **transformer** 变压器 has two coils of wire, the primary coil and the secondary coil, wound on an iron core. Iron is used because it is easily magnetised.

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$$\frac{V_p}{V_s} = \frac{n_p}{n_s} \qquad V_s I_s = V_p I_p \quad \text{(100 \% efficient)}$$

more secondary turns than primary turns here: a step-up transformer

A transformer: the changing field in the iron core links the primary and secondary coils.

An alternating current in the primary coil produces a changing magnetic field in the iron core. This changing field passes through the secondary coil and induces an alternating potential difference across it. A transformer does not work with direct current, because a steady current produces a field that does not change.

$$\frac{V_p}{V_s} = \frac{n_p}{n_s} \qquad V_s I_s = V_p I_p$$

V_p and V_s are the potential differences across the primary and secondary coils, and n_p and n_s are the numbers of turns. A step-up transformer has more turns on the secondary coil, so $V_s > V_p$; a step-down transformer has fewer turns on the secondary. The second equation applies to a transformer that is 100% efficient: the power output equals the power input.

Worked example 6. A transformer has 345 turns on the primary coil and 6000 on the secondary, and the input is 230 V.

$$V_s = V_p \times \frac{n_s}{n_p} = 230 \times \frac{6000}{345} = 4000 \text{ V}$$

It is a step-up transformer. If it supplies 50 mA at 4000 V and is 100% efficient, the output power is $4000 \times 0.050 = 200$ W, so the current in the primary is $I_p = \frac{200}{230} = 0.87$ A.

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Worked example 7. A phone charger steps 230 V down to 11.5 V. Its primary has 2000 turns. $n_s = n_p \times \frac{V_s}{V_p} = 2000 \times \frac{11.5}{230} = 100$ turns.

In the National Grid (topic 2), step-up transformers increase the potential difference so that the current in the cables is smaller and less energy is wasted heating them; step-down transformers reduce it again for homes.

Sources for this lesson

- AQA, *GCSE Physics (8463) specification*, section 4.7 Magnetism and electromagnetism.
- H. C. Ørsted, *Experimenta circa effectum conflictus electrici in acum magneticam* (Copenhagen, July 1820); M. Faraday, laboratory diary, 29 August 1831, Royal Institution, London.
- AQA, *GCSE Physics* Paper 2 Higher (motor, generator and transformer questions, adapted).

Common errors

- Drawing field lines from south to north outside a magnet.
- Saying an induced magnet can repel; induced magnetism always attracts.
- Using the right hand for the motor effect; use Fleming's left-hand rule.
- Leaving the length in cm in $F = BIl$, or using the whole wire instead of the part in the field.
- Saying a pd is induced when a magnet sits still inside a coil; the field must change.
- Saying a transformer works with direct current.
- Saying a step-up transformer increases the power; the current goes down as the pd goes up.

Key terms

- **Magnetic field**: the region where a magnet or magnetic material feels a force.
- **Induced magnet**: a material that becomes magnetic only when placed in a magnetic field.
- **Electromagnet**: a solenoid with an iron core.
- **Motor effect**: the force on a current-carrying wire in a magnetic field.
- **Generator effect**: the induction of a potential difference by a changing magnetic field.
- **Transformer**: two coils on an iron core, used to change an alternating potential difference.

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Check yourself

1. Name the four magnetic elements and alloys you need to know.
2. Describe the magnetic field inside a solenoid.
3. Give two advantages of an electromagnet over a permanent magnet.
4. (HT) A 0.30 m wire carries 2.0 A at right angles to a 0.50 T field. Calculate the force.
5. (HT) What does the commutator in a dc motor do?
6. (Physics only, HT) State three ways to increase the potential difference induced by a moving magnet.
7. (Physics only, HT) A transformer has 100 primary turns and 500 secondary turns. The input is 12 V. Find the output pd.

Answers: 1. Iron, steel, cobalt and nickel. 2. Strong and uniform, with straight parallel lines. 3. It can be switched on and off, and its strength can be changed. 4. $0.50 \times 2.0 \times 0.30 = 0.30$ N. 5. It reverses the current in the coil every half turn, so the coil keeps turning the same way. 6. Move the magnet faster, use a stronger magnet, use a coil with more turns. 7. $12 \times \frac{500}{100} = 60$ V.

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8 · Space physics (physics only)

AQA · GCSE · Physics

Space physics: stars, orbits and the expanding universe

Why it matters. Between 1912 and 1917, Vesto Slipher at the Lowell Observatory in Arizona photographed the spectra of faint, fuzzy patches of light called spiral nebulae. In most of them, the dark lines in the spectrum were shifted towards the red end, which meant that the nebulae were moving away from us, some at hundreds of kilometres per second. In 1929, Edwin Hubble, using the 100-inch telescope on Mount Wilson in California, measured the distances to many of these objects and showed that they are whole galaxies far outside our own. He also found a simple pattern: the further away a galaxy is, the faster it is moving away. The universe is expanding. Run the expansion backwards, and everything began in one tiny, extremely hot and dense region. That is the Big Bang theory.

In this unit you will:

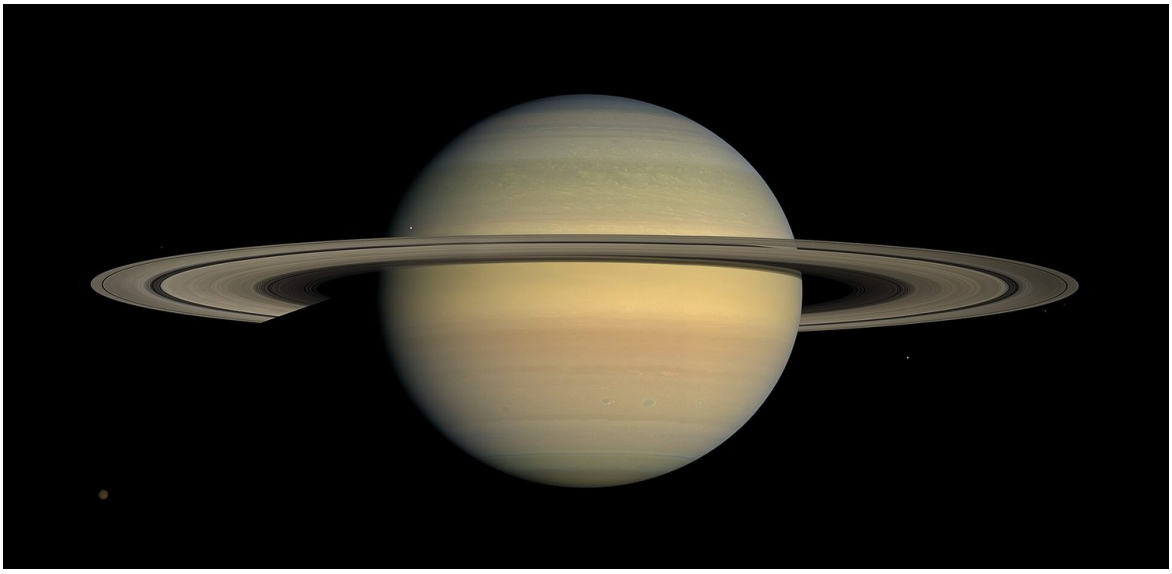
- describe the solar system and how the Sun formed;
- describe the life cycles of stars, and explain where the chemical elements come from;
- explain how gravity keeps planets and satellites in orbit;
- explain how red-shift provides evidence for the Big Bang.

AQA GCSE Physics (8463), topic 4.8 Space physics, examined on Paper 2. This whole topic is in GCSE Physics only. Content marked (HT) is Higher tier only.

The solar system

Our solar system has one star, the Sun, with eight planets and the dwarf planets that orbit it, and the natural satellites, called moons, that orbit the planets. The solar system is a very small part of the Milky Way galaxy, which contains hundreds of billions of stars.

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Saturn and its rings, photographed by the Cassini spacecraft.

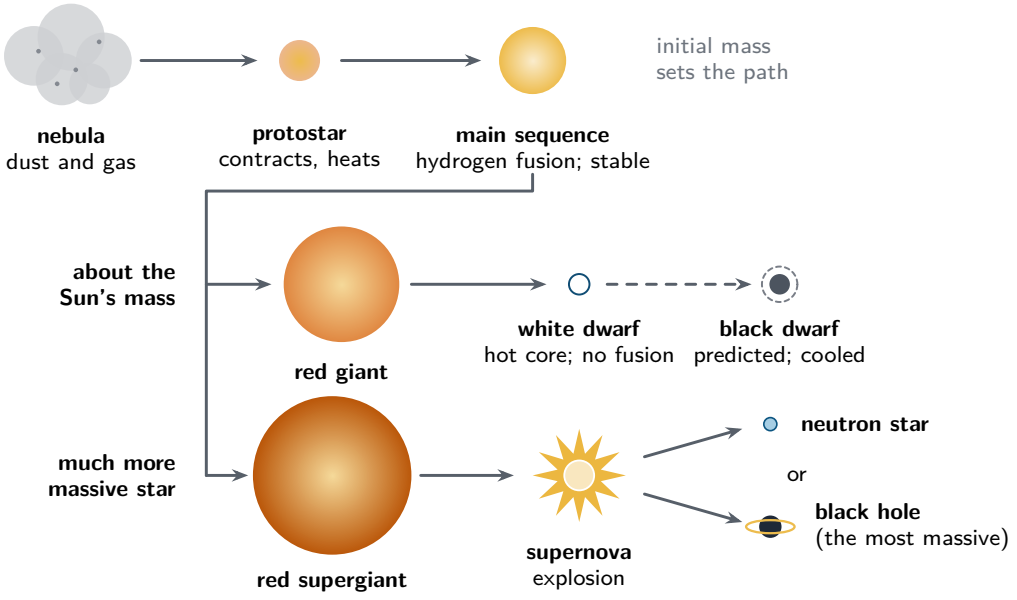
How the Sun formed. The Sun formed from a **nebula** 星云, a cloud of dust and gas. Gravity pulled the dust and gas together. As the cloud collapsed, it got hotter, forming a protostar. When the centre was hot and dense enough, hydrogen nuclei began to join together by nuclear fusion, releasing energy, and a star was born.

Main sequence. During the main sequence stage, a star is stable. The outward pressure caused by the energy released in fusion balances the inward pull of gravity. Our Sun has been a main sequence star for about 4.6 billion years.

The life cycle of a star

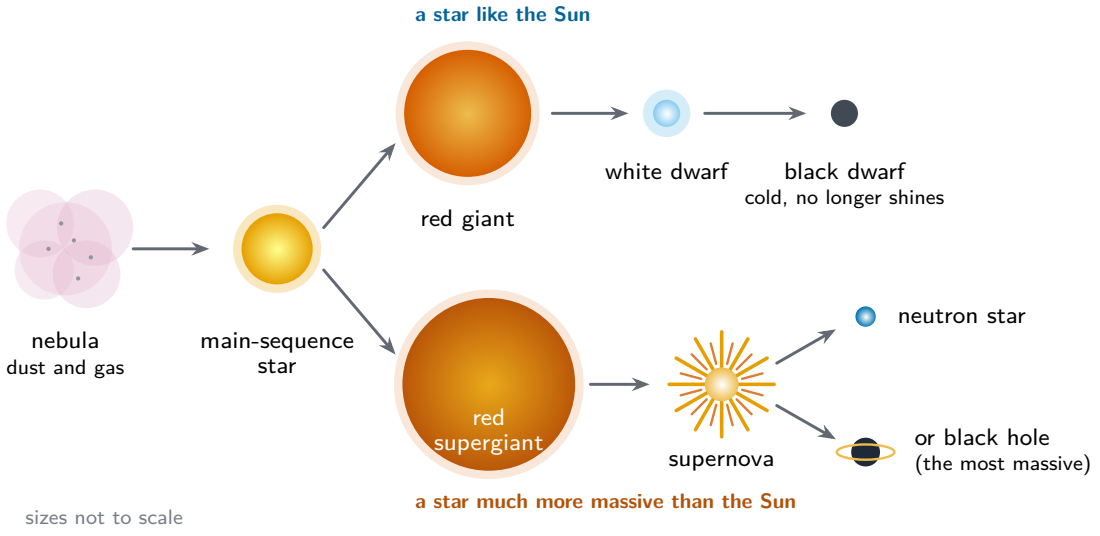
What happens to a star depends on its mass.

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The life cycles of a star like the Sun and of a much more massive star.

- **A star about the size of the Sun**: nebula → protostar → main sequence star → red giant → white dwarf → black dwarf. When the hydrogen in its core runs low, the star swells into a red giant and fuses helium into heavier elements. Its outer layers drift away, leaving a hot, small core: a white dwarf. Fusion has stopped, so the white dwarf slowly cools and fades; after a very long time, it would become a cold black dwarf.
- **A star much more massive than the Sun**: nebula → protostar → main sequence star → red supergiant → **supernova** 超新星 → neutron star or black hole. The red supergiant fuses heavier and heavier elements until its core is iron, then collapses and explodes as a supernova. The core that remains becomes a very dense neutron star or, for the most massive stars, a black hole, from which not even light can escape.



A star like the Sun ends as a white dwarf, then a black dwarf; a massive star ends in a supernova, leaving a neutron star or a black hole.

Where the elements come from. Fusion in stars makes all the naturally occurring elements up to iron: first hydrogen fuses into helium, and in massive stars later stages make carbon, oxygen and so on up to iron. Elements heavier than iron, such as gold and uranium, are made in a supernova. The explosion spreads all these elements through the universe, where they become part of new stars, planets and living things.

Worked example 1. Betelgeuse has a mass of 2.2×10^{31} kg, and the Sun has a mass of 2.0×10^{30} kg. How many times more massive is Betelgeuse? $\frac{2.2\times10^{31}}{2.0\times10^{30}} = 11$. Betelgeuse is much more massive than the Sun, so it will end as a supernova, leaving a neutron star or a black hole. The Sun will become a white dwarf.

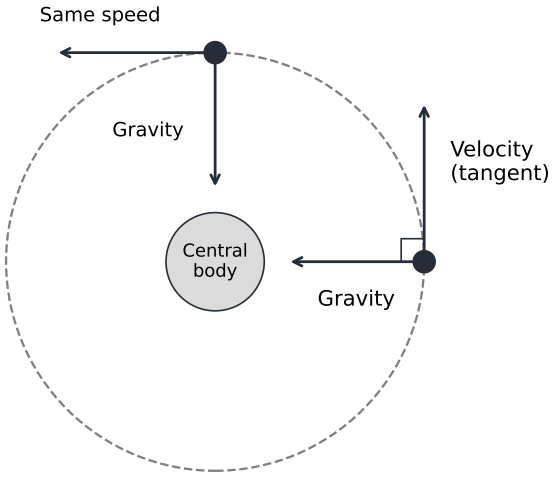
Worked example 2. The star Arcturus is 3.6×10^{14} km from the Earth. How long does its light take to reach us? Convert: 3.6×10^{17} m. Light travels at 3.0×10^{8} m/s, so

$$t = \frac{s}{v} = \frac{3.6 \times 10^{17}}{3.0 \times 10^{8}} = 1.2 \times 10^{9} \text{ s}$$

That is about 38 years: we see Arcturus as it was 38 years ago.

Orbital motion and satellites

Gravity keeps planets in orbit around the Sun, and keeps moons and artificial satellites in orbit around planets. Moons are natural satellites; artificial satellites are made by people, for communications, weather forecasting and navigation.



HT: velocity direction changes; speed stays constant

A circular orbit with gravity as the centripetal force and velocity at a tangent.

(HT) Changing velocity at constant speed. An object moving in a circle at a constant speed has a changing velocity, because velocity is a vector and the direction keeps changing. The force of gravity acts towards the centre of the circle, at right angles to the motion. It changes the direction of the object but not its speed, so the object accelerates towards the centre without speeding up.

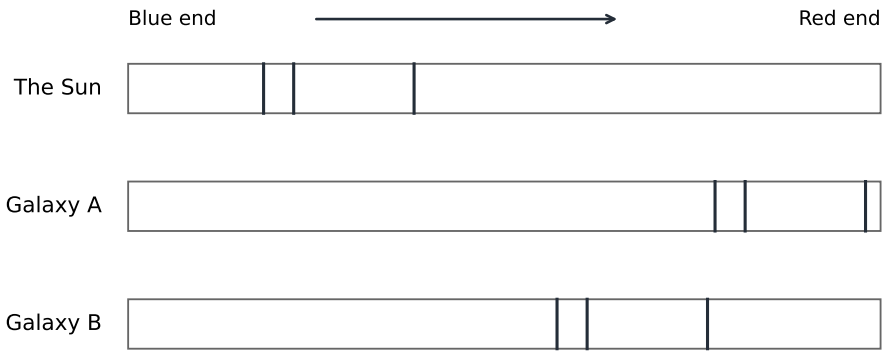
(HT) Speed and radius. For a stable orbit, the radius must change if the speed changes. An object in a smaller orbit, closer to the Earth, feels a stronger pull of gravity, so it must move faster to stay in orbit. The International Space Station, about 400 km up, travels at about 7.7 km/s and goes round the Earth every 92 minutes; the Moon, about 384 000 km away, travels at about 1 km/s and takes 27 days.

> **Worked example 3 (HT).** Explain why a satellite moving at a constant speed is accelerating. Its direction of motion keeps changing, so its velocity changes. A change in velocity is an acceleration. The acceleration is caused by the gravitational force, which acts towards the centre of the Earth.

Red-shift and the Big Bang

When a light source moves away from us, the light we receive has a longer wavelength: it is shifted towards the red end of the spectrum. This is **red-shift** 红移. Astronomers measure it by comparing dark lines in a galaxy's spectrum with the same lines measured in a laboratory.

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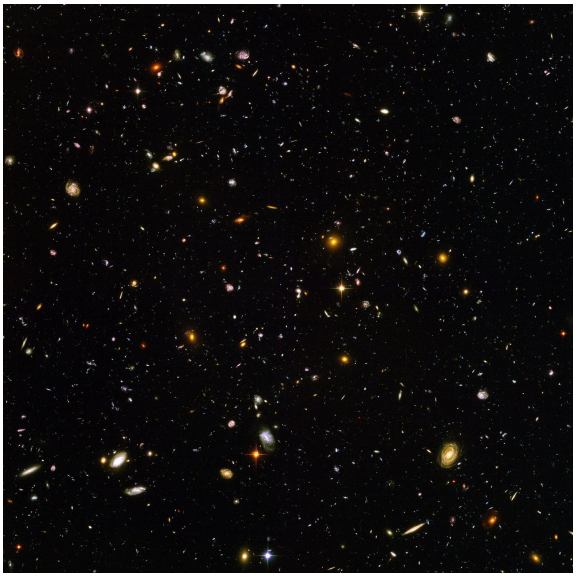


Schematic redrawing of AQA June2024 8463/2H Q03.4

The galaxy's spectral lines are shifted to longer wavelengths (AQA GCSE Physics Paper 2H, June 2024, question 3, redrawn).

- Light from most distant galaxies is red-shifted, so they are moving away from us.
- The further away a galaxy is, the bigger its red-shift, so the faster it is moving away.

These observations show that the universe is expanding. If the universe is expanding now, it must have been smaller in the past. The Big Bang theory says that the universe began from a very small region that was extremely hot and dense, and has been expanding ever since.



The Hubble Ultra Deep Field: almost every point of light is a whole galaxy, and most are moving away from us.

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Worked example 4. Describe how red-shift supports the Big Bang theory. Light from distant galaxies is red-shifted, so they are moving away from us. More distant galaxies have a bigger red-shift, so they are moving away faster. This means the universe is expanding, so in the past it was smaller, hotter and denser, which is what the Big Bang theory predicts.

Still unexplained. Since 1998, observations of supernovae in very distant galaxies have shown that the expansion of the universe is speeding up. Scientists do not yet understand why. They suggest that most of the universe consists of dark matter and dark energy, which have not been directly detected. This shows how science works: new observations can change our theories, and there is still much that we do not know about the universe.

Sources for this lesson

- AQA, *GCSE Physics (8463) specification*, section 4.8 Space physics.
- E. Hubble, "A relation between distance and radial velocity among extra-galactic nebulae", *Proceedings of the National Academy of Sciences*, 15 (1929); V. M. Slipher, "Nebulae", *Proceedings of the American Philosophical Society*, 56 (1917).
- AQA, *GCSE Physics* Paper 2 Higher, June 2024, question 3 (Betelgeuse, Arcturus and spectral lines, adapted).

Common errors

- Saying stars burn fuel; they release energy by nuclear fusion.
- Giving the Sun a supernova; it will become a white dwarf.
- Saying elements heavier than iron are made in main sequence stars; they are made in supernovae.
- Saying red-shift means a galaxy looks red; it means its spectral lines have longer wavelengths.
- Saying a satellite moving at constant speed has no acceleration.
- Saying a smaller orbit is slower; a smaller orbit needs a higher speed.

Key terms

- **Nebula**: a cloud of dust and gas from which stars form.
- **Main sequence**: the stable stage of a star's life, when fusion balances gravity.
- **Supernova**: the explosion of a very massive star.
- **Satellite**: an object that orbits a larger object; it can be natural or artificial.
- **Red-shift**: the increase in wavelength of light from a source moving away.
- **Big Bang theory**: the theory that the universe began from a very small, extremely hot and dense region and has been expanding since.

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Check yourself

1. What is the Milky Way?
2. Explain why a main sequence star stays the same size.
3. Give the life cycle of a star much more massive than the Sun.
4. Where are elements heavier than iron made?
5. (HT) A satellite moves into a larger stable orbit. What happens to its speed?
6. What does it mean that light from a galaxy is red-shifted?
7. Name one thing scientists cannot yet explain about the universe.

Answers: 1. The galaxy that contains our solar system. 2. The outward pressure from the energy released by fusion balances the inward pull of gravity. 3. Nebula, protostar, main sequence star, red supergiant, supernova, neutron star or black hole. 4. In supernovae. 5. It decreases. 6. Its wavelength has increased because the galaxy is moving away from us. 7. Dark matter or dark energy (or why the expansion is speeding up).

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