

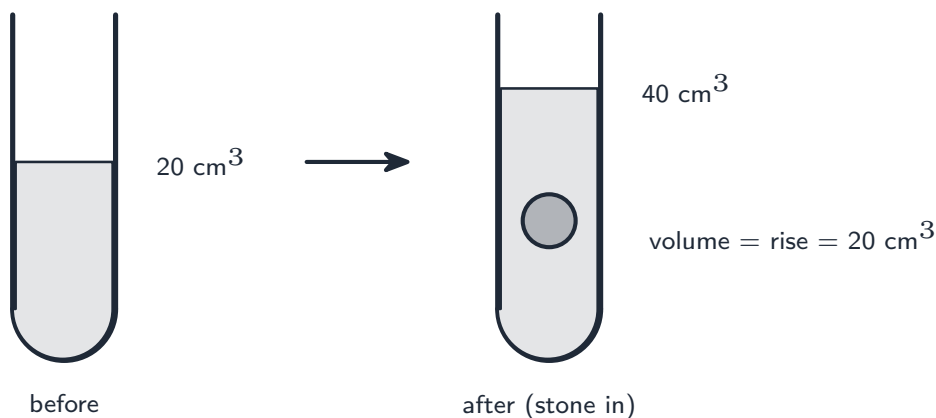
Motion, forces and energy

IGCSE Physics

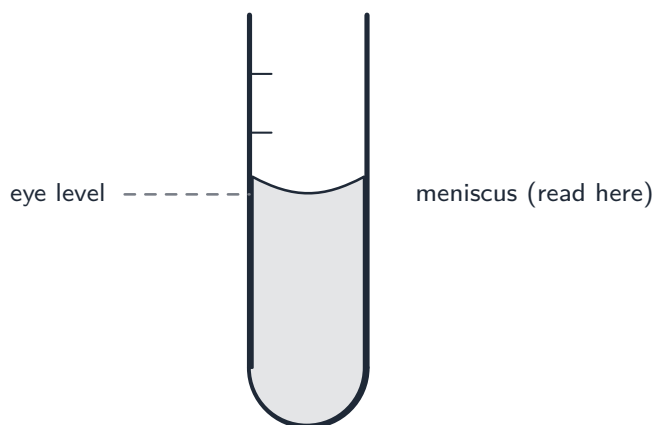
Measurement

■ Length and volume

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



The water an irregular solid pushes up gives its volume



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

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

it.

■ Measuring time

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

■ Measuring small amounts

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

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

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

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

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

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

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

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

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

■ Scalars and vectors

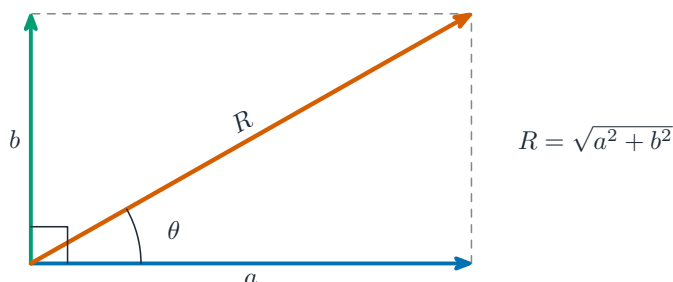
A **scalar quantity** has size (**magnitude**) only. A **vector quantity** has size **and** direction.

- Scalars: distance, speed, time, mass, energy, temperature.

- Vectors: force, weight, velocity, acceleration, momentum, **electric field strength**, **gravitational field strength**.

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

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



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

Motion

■ Speed and velocity

Speed is the distance travelled per unit time.

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

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

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

■ Acceleration

Acceleration is the change in velocity per unit time.

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

Here Δv means "the change in velocity". A **deceleration** (slowing down) is a negative acceleration.

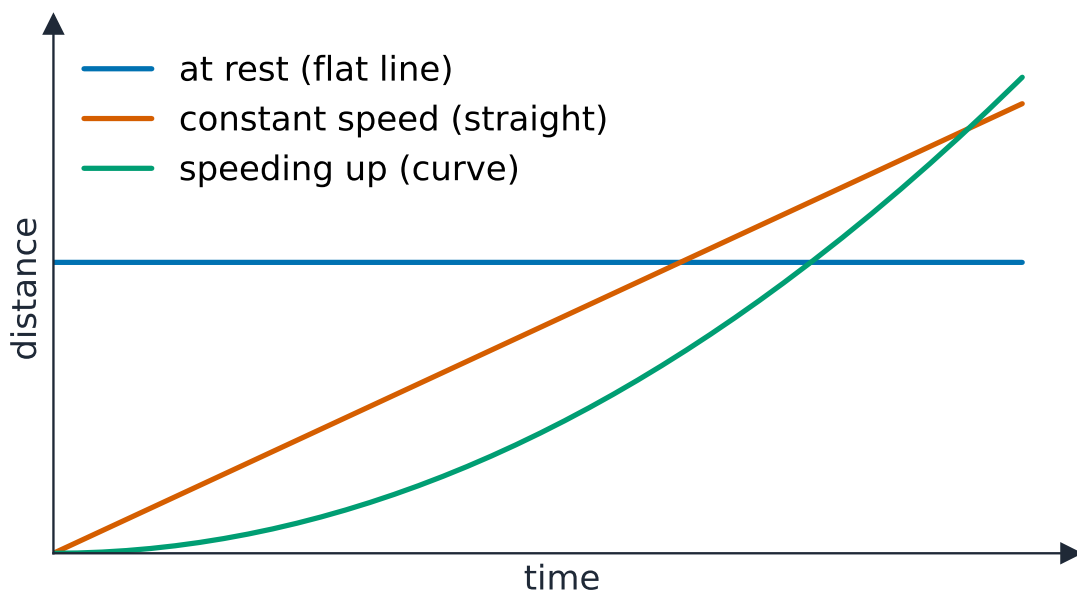
Worked example. A car speeds up from 8 m/s to 20 m/s in 4.0 s. Find its acceleration.

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

■ Motion graphs

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

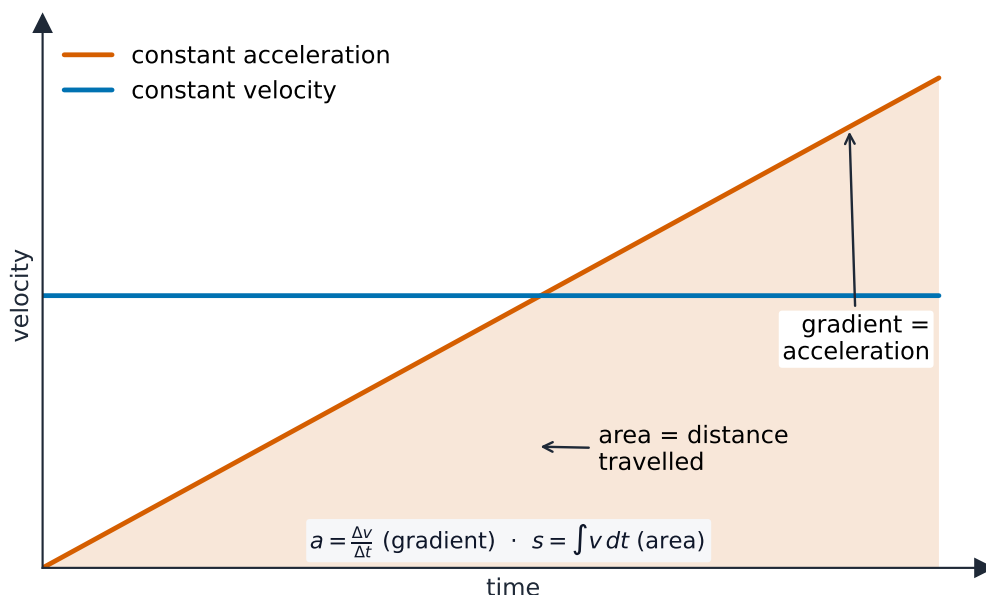
- A flat (horizontal) line means the object is **at rest**.
- A straight slope means constant speed. The **gradient** (steepness) is the speed.
- A curve that gets steeper means the object is speeding up.



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

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

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

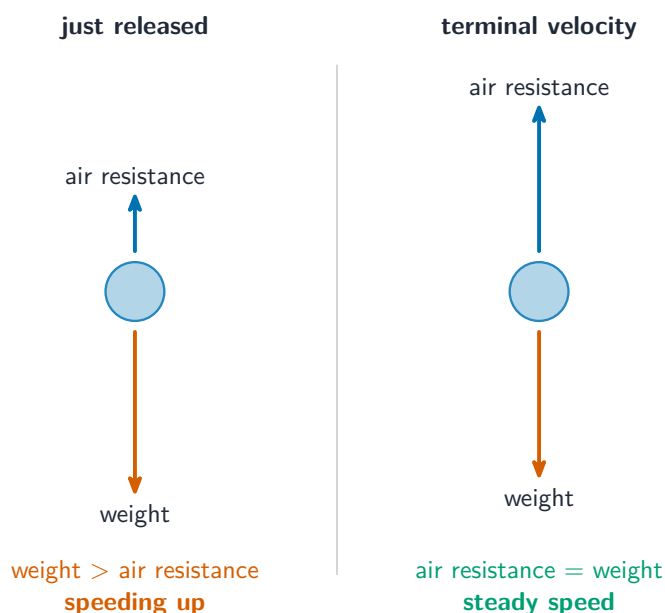


On a velocity–time graph the gradient is the acceleration and the area under the line is the distance travelled

■ Falling objects

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

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



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

Mass and weight

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

Weight is the force of gravity on a mass. It is measured in newtons (N). Weight can change: it is smaller on the Moon because the Moon's gravity is weaker.

Gravitational field strength is the force per unit mass:

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

This g has the same value as the acceleration of free fall ($\approx 9.8 \text{ N/kg}$). You can compare masses with a **balance**.



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

Density

Density is the mass per unit volume.

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

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

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

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

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

Worked example. A stone of mass 54 g is lowered into a measuring cylinder. The water level rises from 20 cm³ to 40 cm³. Find the density of the stone.

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

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



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

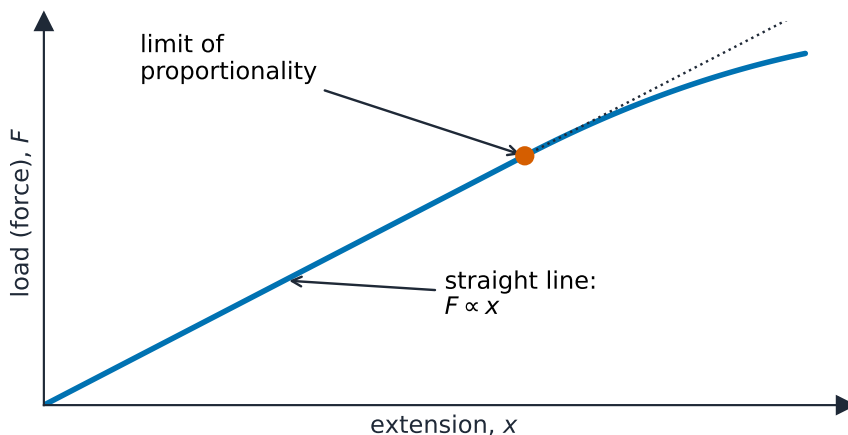
Forces

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

■ Stretching (Hooke's law)

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

On a **load–extension graph** – the line is straight at first: extension is proportional to load. The point where the line stops being straight is the **limit of proportionality**.



$$F = kx \text{ (straight section)}$$

$$k = \text{gradient}$$

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

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

The **spring constant** is the force per unit extension:

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

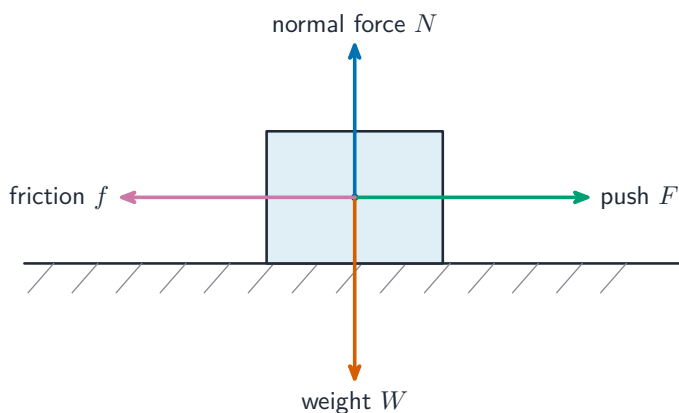
A large k means a stiff spring.

■ Resultant force and Newton's laws

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

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

$$F = ma$$



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

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

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

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

■ Motion in a circle

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

For an object moving in a circle:

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

■ Friction

Friction is the force between two surfaces that touch. It tries to stop motion and makes things heat up. Drag (friction in a liquid or gas, like air resistance) also slows objects down.

■ Moments – the turning effect

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

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

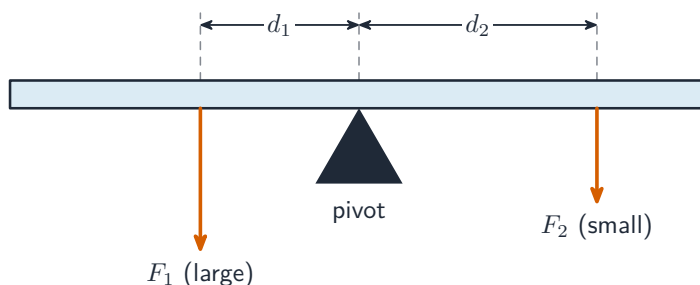
The unit is the newton metre (N m).

Principle of moments : when an object is balanced (in **equilibrium**),

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

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

$$\text{balanced: } F_1 d_1 = F_2 d_2$$



The beam balances when the clockwise moment equals the anticlockwise moment

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

Balanced, so anticlockwise moment = clockwise moment:

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

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

■ Centre of gravity

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

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

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

Momentum

Momentum is mass times velocity. It is a vector.

$$p = mv$$

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

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

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

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

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

$$m_1 u_1 + m_2 u_2 = m_1 v_1 + m_2 v_2$$

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

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

Total momentum is conserved, so

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

Energy, work and power

■ Energy stores

Energy can be **stored** in different ways: kinetic, gravitational potential, chemical, elastic (strain), nuclear, electrostatic, and internal (thermal).

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



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

■ Kinetic and potential energy

Kinetic energy is the energy of a moving object:

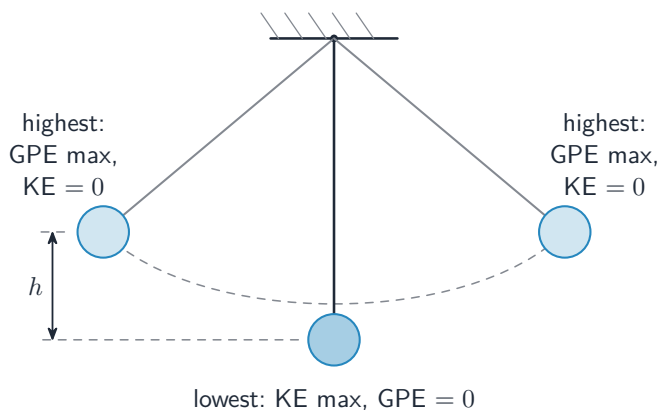
$$E_k = \frac{1}{2}mv^2$$

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

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

■ Conservation of energy

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



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



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

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

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

mass cancels, leaving $v^2 = 2g \Delta h$:

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

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

■ Work

Work done equals the energy transferred. When a force moves an object:

$$W = Fd = \Delta E$$

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

■ Power

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

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

The unit is the **watt** (W). $1 \text{ W} = 1 \text{ J/s}$.

■ Efficiency

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

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

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

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

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

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

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

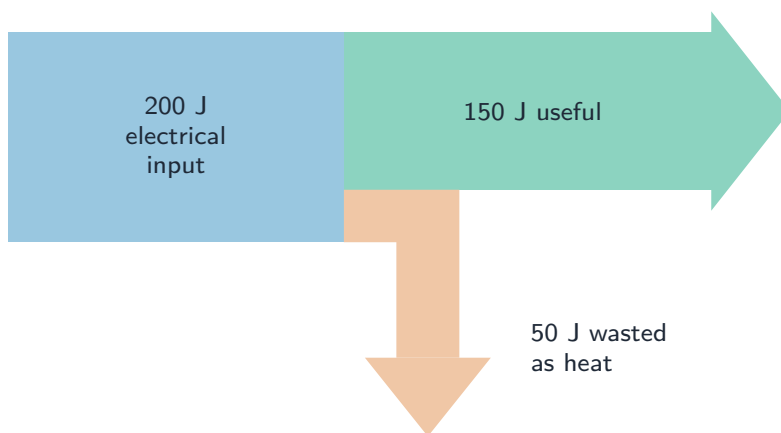
$$P_{\text{in}} = \frac{E_{\text{in}}}{t} = \frac{200 \text{ J}}{5.0 \text{ s}} = 40 \text{ W}$$

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

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

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

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



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

■ Energy resources

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

Resource	Renewable?	Notes
fossil fuels (coal, oil, gas)	no	reliable, high output, but CO ₂ and pollution
nuclear fuel	no	no CO ₂ from reactor operation; waste
biofuels	yes	replanting absorbs CO ₂ ; production emits CO ₂
hydroelectric	yes	water supply matters; dams flood land
wind	yes	no fuel burned; output varies
solar	yes	no fuel burned; needs daylight
geothermal / tidal	yes	site-limited; tidal output is not continuous

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

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

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

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

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

Worked resource comparison. A remote clinic needs electricity day and night. Solar cells without a battery, backup or grid connection cannot meet its night demand.

A hydroelectric scheme may supply at night if suitable flow or stored water is available, but seasonal flow and scheme capacity must be checked. Compare each supply with the clinic's power requirement and assess site, land and habitat effects, especially if a dam is needed. Renewable alone does not mean continuous, adequate or environmentally harmless. Use availability, reliability, scale and environmental impact to explain the choice.

Pressure

Pressure is the force per unit area.

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

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

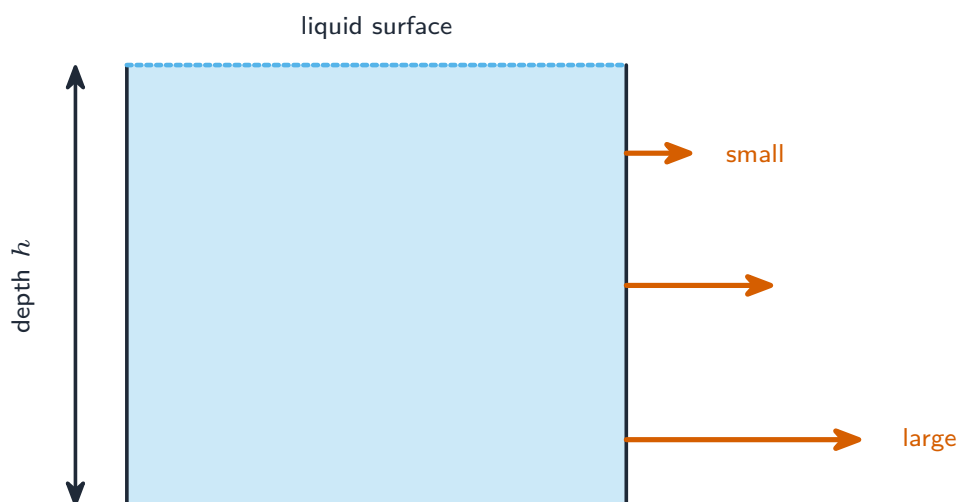
A small area gives a large pressure (a sharp knife cuts well). A large area gives a small pressure (snowshoes stop you sinking).

■ Pressure in a liquid

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

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

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



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



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

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

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

Exam tips

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