

Particle model

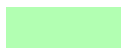
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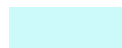
Revision notes for one topic, free to download.

These are the summary notes only. The full edition of this booklet also carries the worked examples, the required practicals and the formula sheets, with every topic in one place.

Colour Codes



Definitions



Diagrams



Notes and warnings



Sub-topic headings

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Define Density

- the mass of a material per unit volume, in kilograms per cubic metre (kg/m^3).

Define Physical change

- no new substance is made, mass is conserved, and the material recovers its original properties if reversed.

Define Internal energy

- the total energy stored by the particles: kinetic energy of movement plus potential energy of position.

Define Specific latent heat (L)

- energy to change the state of 1 kg with no temperature change, in J/ kg: of **fusion** for melting/freezing, of **vaporisation** for boiling/condensing.

Define Kelvin scale

- the absolute scale starting at absolute zero; a change of 1 K equals a change of 1 °C.

Define Kinetic theory

- the model that matter is made of tiny particles in constant motion, whose arrangement, movement and energy explain the three states of matter.

Define Melting / freezing

- solid to liquid and back, at the melting point. **Boiling / condensing** — liquid to gas throughout the liquid at the boiling point, and back. **Evaporating** — liquid to gas from the surface only, below the boiling point. **Sublimating** — solid straight to gas.

Define Temperature

- a measure of the average kinetic energy of the particles.

Define Specific heat capacity (c)

- energy to raise the temperature of 1 kg of a substance by 1 °C, in J/ kg °C.

Define Absolute zero

- −273 °C (0 K), where particles have as little movement, and so as little kinetic energy, as possible.

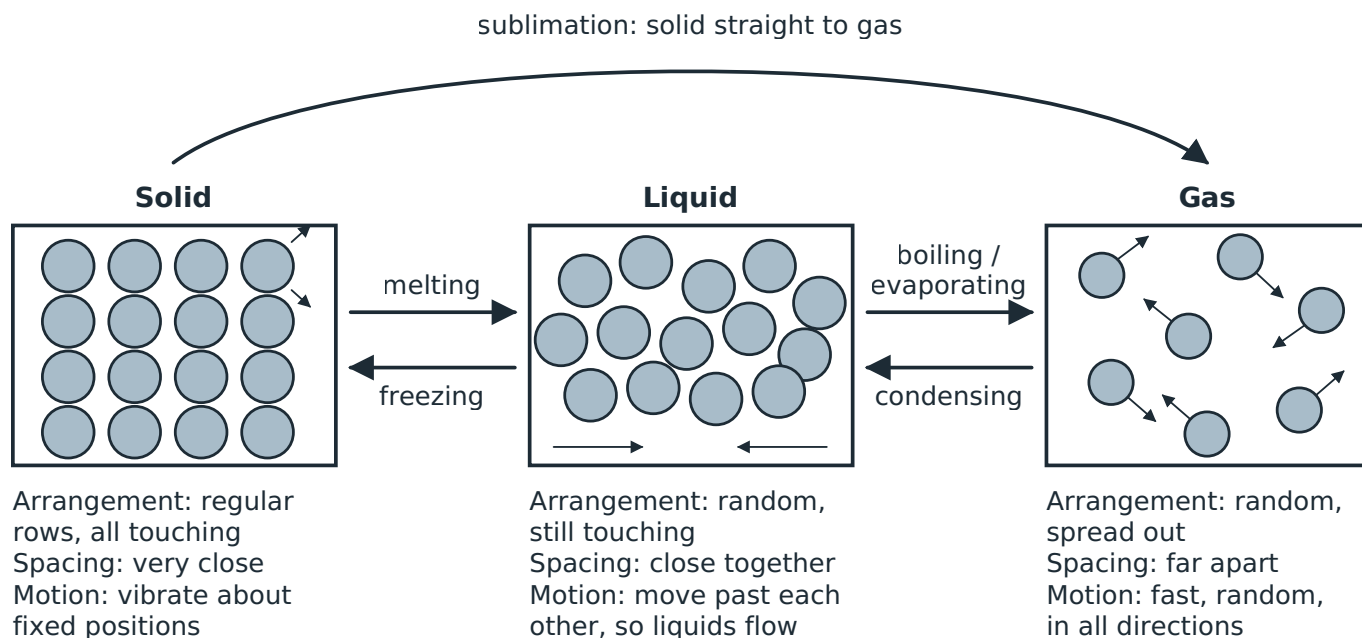
14.1 The kinetic theory model of solids, liquids and gases

A **simple kinetic theory model** explains the three **states of matter** by the **movement** and **arrangement** of particles. The particles themselves never change — only their arrangement, movement and energy.

	Solid	Liquid	Gas
Arrangement	Regular, closely packed lattice; touching	Close together, irregular, disordered	Far apart, random, mostly empty space
Movement	Vibrate about fixed positions	Slide past one another	Rapid, random, straight lines between collisions
Forces between particles	Strongest	Weaker than a solid	Almost none, except in collisions
Energy of particles	Least	More than a solid	Most
Shape and volume	Fixed shape and volume	Container's shape, fixed volume	Fills container; compressible

The **hotter** a substance, the **faster** its particles move and the more kinetic energy they store on average. Only a gas has enough space between particles to be **compressed** easily.

The kinetic theory model of solids, liquids and gases



A change of state is a physical change, not a chemical change — no new substance is made.
Mass is conserved: they are the same particles, just arranged and spaced differently.
Reverse the change and the material recovers its original properties.
The spacing changes, so the states have very different densities — a gas is least dense.

WATCH OUT

Particles do not melt, expand or get hotter themselves. When ice melts the water molecules are unchanged — they just gain enough energy to break out of the lattice. The **spacing** changes, never the particle size.

14.2–14.3 Density

Density is the mass packed into each cubic metre. It is a property of the **material**, not the object: a steel nail and a steel girder have the same density.

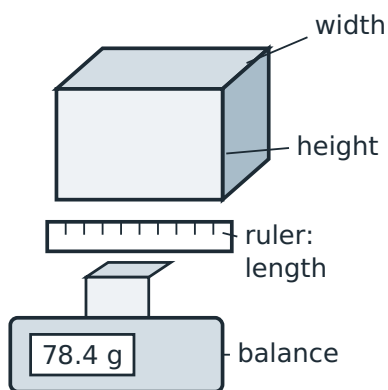
- Volume of a **regular** solid: cuboid = length $\times$ width $\times$ height; cylinder = $\pi r^2 \times$ height. Volume of an **irregular** solid: by **displacement** of water.

Measuring the density of a solid and of a liquid

Core Practical 14.3 — density = mass ÷ volume, $\rho = m / V$

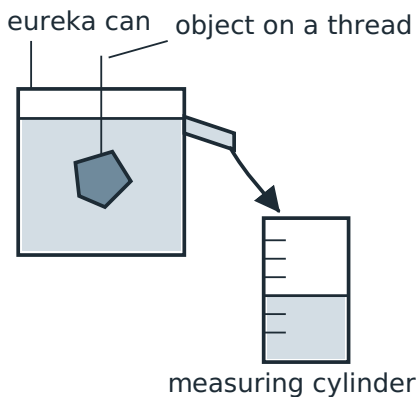
ρ in kg/m^3 (or g/cm^3) · m in kg (or g) · V in m^3 (or cm^3) · $1 \text{ g/cm}^3 = 1000 \text{ kg/m}^3$

A Regular solid



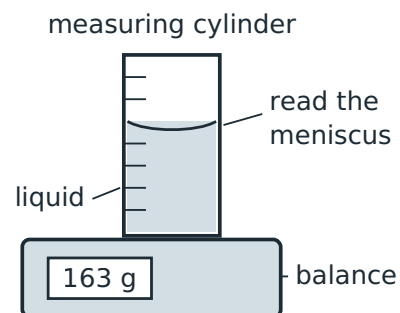
- find the mass on a balance
- measure the length, width and height with a ruler or callipers
- volume = $l \times w \times h$
- density = mass ÷ volume

B Irregular solid



- find the mass on a balance
- fill the can up to the spout, then lower the object in gently
- the water pushed out is collected in a measuring cylinder: it equals the volume of the object

C Liquid



- find the mass of the empty measuring cylinder
- pour in the liquid, find the new mass
- mass of liquid = new mass – empty mass
- read the volume in cm^3 at the bottom of the meniscus, at eye level

14.4 Explaining density differences between the states of matter

- **Solids** are usually **most dense**: particles packed closely in a lattice, so a lot of mass occupies a small volume.
- **Liquids** are slightly less dense than the same solid — particles a little further apart and irregular; **gases** are **far less dense** (often about a thousand times) because the same particles spread through a much larger volume.
- The **mass of each particle never changes** — only the spacing, and so the volume.
- Water is the exception: ice is **less dense** than liquid water because its molecules form an open lattice, so ice floats.

14.5 Changes of state and conservation of mass

When a substance **melts, freezes, evaporates, boils, condenses** or **sublimates**:

- **Mass is conserved** — no particles are created or destroyed, so mass before = mass after. Melt 20 g of ice and you get 20 g of water.
- These are **physical changes**: no new substance is made, and the **material recovers its original properties if the change is reversed** — water frozen then melted is identical to what you started with. Many chemical changes cannot be reversed and give new substances with new properties.
- Density **does** change, because the volume changes while the mass stays the same.

WATCH OUT

"The water boiled away, so mass was lost." The mass is still there, spread through the room as vapour — in a sealed container the balance reading would not change.

14.6 Heating a system, internal energy and temperature

The **internal energy** of a system is the total energy stored by its particles: **kinetic energy** of movement plus **potential energy** of position. Heating **increases the internal energy**, and this does one of two things:

1. **Raises the temperature** — the particles move faster, so their average **kinetic energy** increases.
2. **Produces a change of state** — the energy weakens or breaks bonds between particles, raising their **potential energy**, so the temperature does **not** change while the state changes.

Cooling reduces the internal energy: particles slow and the temperature falls, or the state changes back.

ANALOGY

Internal energy — the crowded hall. Part of a crowd's "liveliness" is how fast people move (kinetic energy — what a thermometer reads as temperature); part is how far they have broken away from the friends gripping them (potential energy — what changes when melting or boiling). Heating speeds people up **or** frees them, not both at once.

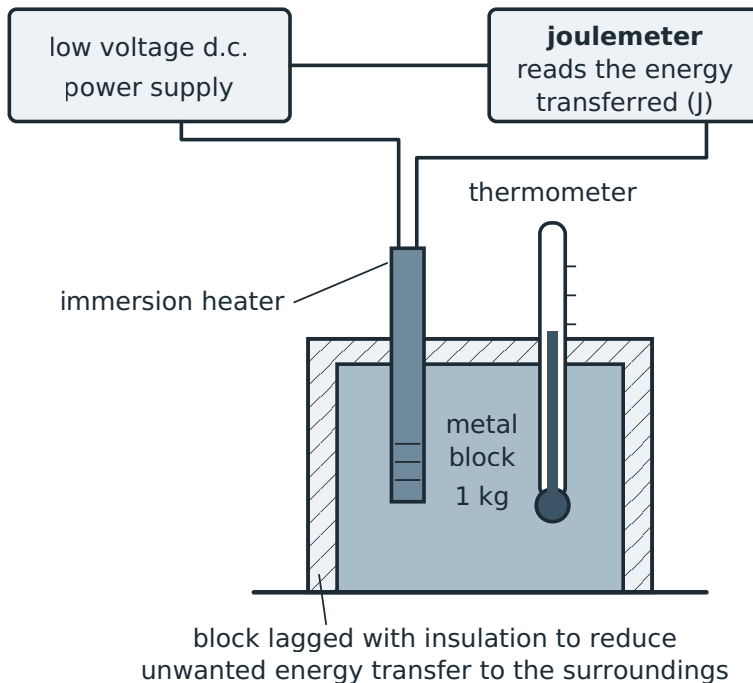
14.7 Specific heat capacity and specific latent heat

- **Specific heat capacity, c** — energy to raise the temperature of **1 kg** by **1 °C** with no change of state (J/kg °C).
- **Specific latent heat, L** — energy to **change the state** of **1 kg** with **no temperature change** (J/kg): of **fusion** for melting/freezing, of **vaporisation** for boiling/condensing.

	Specific heat capacity, c	Specific latent heat, L
The energy changes the...	temperature	state
Temperature during it	rises or falls	stays constant
Store that increases	kinetic energy	potential energy (bonds broken)
Equation	$\Delta Q = m \times c \times \Delta\theta$	$Q = m \times L$
Units of the constant	J/kg °C	J/kg
Value for water	4200 J/kg °C	fusion 334 000; vaporisation 2 260 000 J/kg

- A **high** specific heat capacity means a substance needs a lot of energy to warm up and releases a lot as it cools — hence water in central heating and as a coolant.

Apparatus for measuring a specific heat capacity



No joulemeter? Put an ammeter in series and a voltmeter across the heater, then $E = V \times I \times t$

Variables

Independent variable

the energy transferred to the block, read from the joulemeter (J)

Dependent variable

the temperature of the block ($^{\circ}\text{C}$), read from the thermometer

Control variables

the mass and material of the block, the power of the heater, the insulation, the starting temperature and the room temperature

Equation used

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

ΔE = change in thermal energy, J

m = mass, kg

c = specific heat capacity, $\text{J/kg } ^{\circ}\text{C}$

$\Delta \theta$ = temperature change, $^{\circ}\text{C}$

Rearranged: $c = \Delta E \div (m \times \Delta \theta)$

- Latent heat of **vaporisation** is much larger than of **fusion**: boiling separates the particles completely; melting only lets them slide past each other.

14.8 The specific heat capacity equation

14.9 The specific latent heat equation

ANALOGY

Latent heat — why the temperature stalls. Melting is a crowd leaving a stadium through a turnstile: while people queue to break free, extra effort makes nobody move faster. A thermometer measures speed, not freedom, so it reads a flat line throughout the change of state even though energy keeps pouring in.

14.10 Reducing unwanted energy transfer by thermal insulation

- Use materials of **low thermal conductivity**, in **thicker** layers — both slow conduction.
- **Trap air** in small pockets (loft insulation, cavity wall foam, double glazing, foam cups): air conducts poorly, and trapping it stops **convection currents** carrying energy away.
- Use **shiny, silvered surfaces** (vacuum flask, survival blanket) to cut **infrared radiation**; fit draught excluders and close curtains so moving air cannot carry energy away.

The object then cools more slowly — its temperature falls less in a given time.

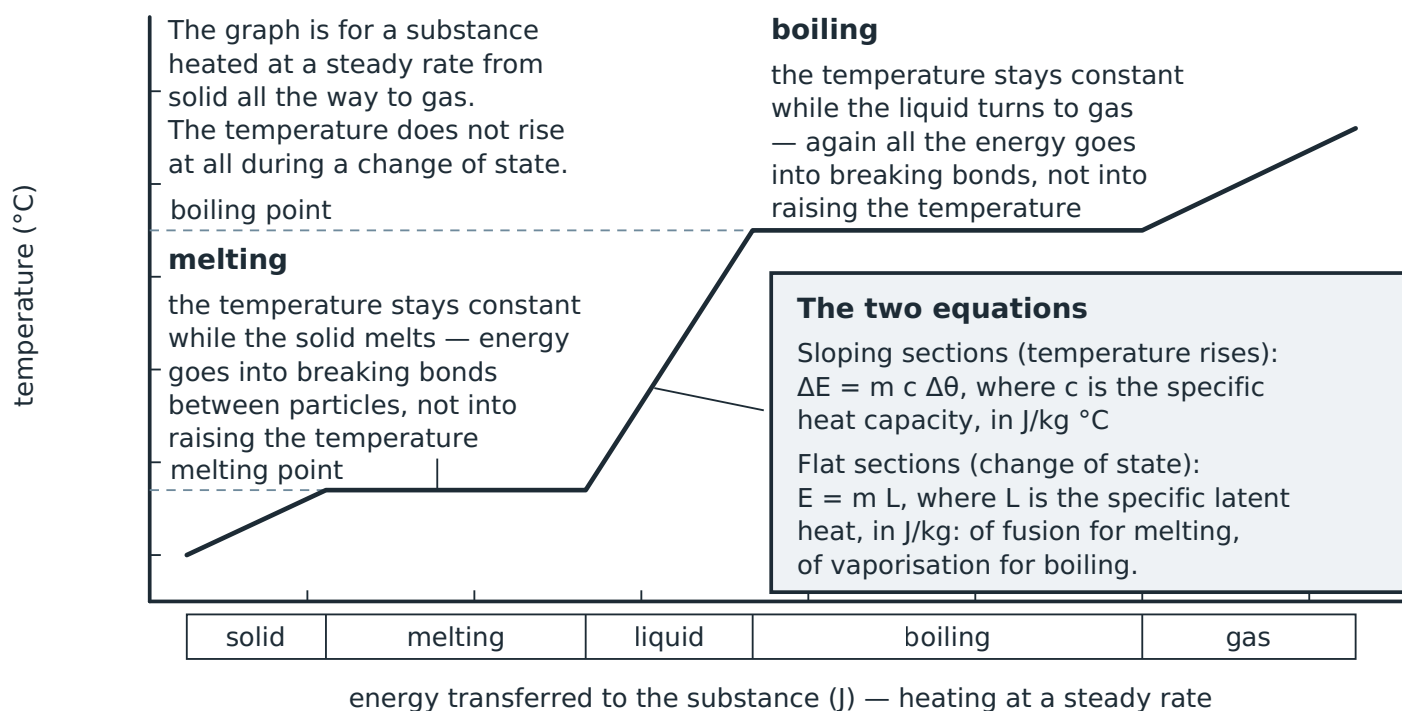
14.11 Core Practical: the properties of water

Interpreting heating and cooling graphs

On a **temperature–time** graph for steady heating:

- **Sloping sections** — one state, temperature rising. A **shallower slope means a higher specific heat capacity** (same mass and power).
- **Flat sections (plateaus)** — a **change of state**: the first at the melting point, the second at the boiling point, with two states present at once.
- The **longer** the plateau, the **larger the specific latent heat**; for water the boiling plateau is far longer than the melting one.
- A **cooling** graph is the mirror image: plateaus at the condensing and freezing points, where energy is **released** at constant temperature.

A heating curve, with plateaus at the melting and boiling points



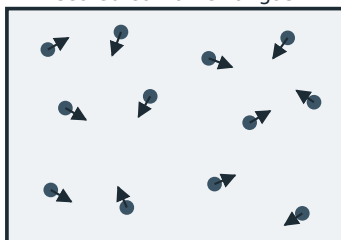
14.12 The pressure of a gas explained by particle motion

- Gas particles move **rapidly in random directions** and **collide with the walls**; each collision exerts a small force as the particle's momentum changes.
- Pressure** is the total force of those collisions per unit area of wall. More frequent or harder collisions mean **greater pressure**.

Gas pressure explained by the particle model

Gas pressure and the particle model

sealed container of gas



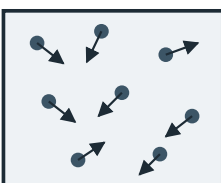
The particles of a gas move quickly, in all directions. They collide with the walls of the container, and each collision exerts a small force on the wall. Gas pressure is the total force per unit area of wall. The pressure produces a net force at right angles (90°) to any surface it acts on.

Heating a gas at constant volume



cool gas

heat



hot gas

Heating makes the particles move faster. They hit the walls harder and more often. The volume is fixed, so the pressure of a fixed mass of gas increases.

Changing the volume

Physics only



piston

At constant temperature, a large volume means the particles travel further and hit the walls less often → lower pressure.

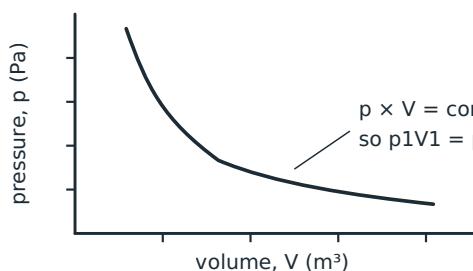


push

A smaller volume means the same particles hit the walls more often → higher pressure.

Pressure-volume graph

Physics only



Absolute zero and the kelvin scale



At absolute zero, $-273\text{ }^{\circ}\text{C}$, the particles have no movement. It is the lowest possible temperature, and it is 0 K on the kelvin scale.

$$\text{temperature in K} = \text{temperature in } ^{\circ}\text{C} + 273$$

ANALOGY

Gas pressure — hail on a roof. One hailstone gives a tiny push; millions a second give a steady, measurable pressure. Throw the hail faster (higher temperature) or shrink the roof (smaller volume) and the pressure rises.

14.13 Temperature and the pressure of a fixed mass of gas at constant volume

For a **fixed mass of gas** at **constant volume** (qualitative only):

- Raising the temperature raises the **average kinetic energy** of the particles, so they move at **higher velocities**.
- Faster particles cross the container more quickly, so hit the walls **more often**, and each collision exerts a **bigger force**. So the **pressure increases**; cooling does the opposite. Hence tyre pressure rising after a long drive, and never heating an aerosol can.

14.14 Absolute zero

- **Absolute zero** is **-273 °C**, the lowest possible temperature: the particles have the **least possible movement** and so minimum kinetic energy, and a gas would exert zero pressure. Nothing can be cooled below it.

14.15 Converting between the kelvin and Celsius scales

PHYSICS ONLY 14.16P–14.18P Compressing and expanding gases

PHYSICS ONLY Gases can be compressed or expanded by **pressure changes** (14.16P): the particles are far apart with much empty space between them, so greater pressure squeezes them into a smaller volume and lower pressure lets the gas expand. Solid and liquid particles already touch, so barely compress.

- **PHYSICS ONLY** Gas pressure produces a **net force at right angles (normal) to any surface** (14.17P):

particles arrive from all directions, so sideways components cancel.

- **PHYSICS ONLY** Changing the **volume** of a fixed mass of gas at **constant temperature** (14.18P):
- **Smaller volume** → shorter distances between walls, so particles **collide with the walls more often each second**; the rate of collisions rises, so the **pressure rises**.
- **Larger volume** → fewer collisions per second, so the **pressure falls**.
- The particles do **not** speed up: at constant temperature the force of each collision is unchanged; only the **frequency** changes.

PHYSICS ONLY 14.19P Pressure and volume calculations for a fixed mass of gas

PHYSICS ONLY HT ONLY 14.20P Doing work on a gas

HIGHER TIER

PHYSICS ONLY HT ONLY Doing work on a gas transfers energy to it and can raise its temperature.

Compressing a gas quickly means the moving piston pushes the particles bouncing off it, so they **rebound faster** than they arrived; their average kinetic energy — and so the **temperature** — rises.

PHYSICS ONLY HT ONLY **Bicycle pump:** pushing the handle exerts a force through a distance, so you **do work on the gas**; the barrel warms because the internal energy of the air has increased (friction at the seal adds a little more).

- **PHYSICS ONLY HT ONLY** The reverse happens too: a gas expanding rapidly does work on its surroundings and **cools**, which is why an aerosol can gets cold in use.

Use of mathematics in this topic

- **Convert units** by ratio ($\text{g} \leftrightarrow \text{kg}$, $\text{cm}^3 \leftrightarrow \text{m}^3$, $\text{g/cm}^3 \leftrightarrow \text{kg/m}^3$), and apply density–mass–volume where **mass is conserved**.
- Apply $\Delta Q = m \times c \times \Delta\theta$ and $Q = m \times L$, rearranged for any quantity, adding the stages of a process: warming ice $\rightarrow$ melting $\rightarrow$ warming the water $\rightarrow$ boiling.
- Read a **temperature–time graph**: gradients, plateaus, power $\times$ time for energy supplied.
- Suggested practicals: temperature–volume and volume–pressure for a gas; latent heat of vaporisation.