Thermal Physics

The states of matter and the particle model, gas pressure and volume, thermal expansion and temperature scales, specific heat capacity, melting, boiling, evaporation and latent heat, and the three ways thermal energy is transferred: conduction, convection and radiation.

2.1.1 States of matter

Property	Solid	Liquid	Gas
shape	fixed shape	takes the shape of its container	takes the shape of its container
volume	fixed	fixed	fills any container (no fixed volume)
can it be squashed (compressed)?	no, hardly at all	no, hardly at all	yes, easily
can it flow?	no	yes	yes

Changes of state

Change	Name
solid to liquid	melting
liquid to solid	freezing (solidification)
liquid to gas	boiling or evaporation
gas to liquid	condensation

2.1.2 Particle model

All matter is made of tiny particles (atoms, molecules, ions and electrons). The properties of each state come from how the particles are arranged, how they move, and how strongly they attract each other.

Note Academy

	Solid	Liquid	Gas
arrangement	closely packed, in a regular pattern	closely packed, in no regular pattern	far apart, in no pattern
movement	vibrate about fixed positions	move around and slide past each other	move quickly in random directions
forces between particles	strong	fairly strong	very weak

Temperature and particle motion. The hotter a substance, the faster its particles move, so the more kinetic energy they have. There is a lowest possible temperature, **absolute zero**, $-273\ ^\circ\mathrm{C}$ (or $0\ \mathrm{K}$), where the particles have the least possible kinetic energy.

Gas pressure. A gas exerts a pressure because its particles collide with the walls of the container. Each collision gives the wall a tiny force, and many collisions every second give a steady force per unit area, which is the pressure.

Change at…	What happens	Explanation in terms of particles
constant volume, heat the gas	the pressure increases	the particles move faster, so they hit the walls harder and more often
constant pressure, heat the gas	the volume increases	the particles hit the walls harder, so the gas expands until the collisions per unit area are back to the original rate
constant temperature, reduce the volume	the pressure increases	the particles hit the walls more often because they have less distance to travel between collisions

For a fixed mass of gas at constant temperature, $p_1V_1 = p_2V_2$. That is, pressure × volume stays the same.

A graph of p against V at constant temperature is a curve that falls as V increases. A graph of p against $\frac{1}{V}$ is a straight line through the origin.

TRY IT

A gas has a volume of $600\ \mathrm{cm}^3$ at a pressure of $100\ \mathrm{kPa}$. It is compressed to $200\ \mathrm{cm}^3$ at the same temperature. Find the new pressure.

$p_2 = \frac{p_1V_1}{V_2} = \frac{100\times600}{200} = 300\ \mathrm{kPa}$

Note Academy

2.2.1 Thermal expansion of solids, liquids and gases

Solids, liquids and gases **expand** when they are heated, and contract when they are cooled.

In terms of particles. When a substance is heated, its particles vibrate or move faster and push each other further apart. The particles themselves do not get bigger. For the same temperature rise, **gases expand the most**, then liquids, then solids expand the least.

Everyday applications and consequences

- Gaps are left in railway lines and bridges so they do not buckle in hot weather.
- Overhead power cables sag more in hot weather.
- A thermostat uses a **bimetallic strip**: two metals joined together that expand by different amounts, so the strip bends when heated and switches a circuit off.

The liquid-in-glass thermometer

The liquid (mercury or coloured alcohol) expands when it is heated and rises up a narrow tube. Two fixed points define the scale: $0\ ^\circ\text{C}$ (melting ice) and $100\ ^\circ\text{C}$ (boiling water at standard atmospheric pressure). A thermometer is more **sensitive** if it has a larger bulb and a narrower tube, because a small expansion then makes the liquid move a long way.

The kelvin scale

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

TRY IT

Convert $25\ ^\circ\text{C}$ into kelvin and $300\ \text{K}$ into degrees Celsius.

$25 + 273 = 298\ \text{K}$ $\quad$ $300 - 273 = 27\ ^\circ\text{C}$

A change of $1\ \text{K}$ is the same size as a change of $1\ ^\circ\text{C}$.

2.2.2 Specific heat capacity

An increase in the temperature of an object increases its **internal energy**. In terms of particles, the average kinetic energy of all the particles increases.

Note Academy

$$\text{specific heat capacity} = \frac{\text{change in energy}}{\text{mass} \times \text{change in temperature}}$$, **that is** $c = \frac{\Delta E}{m\,\Delta\theta}$. **The unit is** $\text{J/(kg }^\circ\text{C)}$.

The specific heat capacity is the energy needed to raise the temperature of $1\ \text{kg}$ of a substance by $1\ ^\circ\text{C}$. Water has a high value, $4200\ \text{J/(kg }^\circ\text{C)}$, which is why it takes a long time to heat up and is good for storing heat.

TRY IT

How much energy is needed to raise the temperature of $2.0\ \text{kg}$ of water by $30\ ^\circ\text{C}$? ($c = 4200\ \text{J/(kg }^\circ\text{C)}$)

$\Delta E = mc\,\Delta\theta = 2.0 \times 4200 \times 30 = 252\,000\ \text{J}$

TRY IT

A $0.50\ \text{kg}$ block of metal needs $9000\ \text{J}$ to warm up by $20\ ^\circ\text{C}$. Find its specific heat capacity.

$c = \frac{9000}{0.50 \times 20} = 900\ \text{J/(kg }^\circ\text{C)}$

Experiment to measure the specific heat capacity of a solid.

1. Find the mass of a metal block with a balance.
2. Put an electric heater and a thermometer into holes in the block (add a drop of oil for good thermal contact) and wrap the block in insulation to reduce heat losses.
3. Record the starting temperature. Switch on the heater for a measured time. Record the final temperature.
4. Calculate the energy supplied: $E = VIt$ (or from a joulemeter). Then use $c = \frac{\Delta E}{m\,\Delta\theta}$.

For a liquid, do the same with the heater and thermometer in the liquid in an insulated container, using the mass of the liquid. Stir the liquid so the temperature is the same throughout. The value is too high if heat is lost to the surroundings, so insulate well.

2.2.3 Melting, boiling and evaporation

At standard atmospheric pressure, water **melts** at $0\ ^\circ\text{C}$ and **boils** at $100\ ^\circ\text{C}$.

During melting or boiling, the substance takes in energy but its **temperature does not change**. On a graph of temperature against time for a heated substance, these are the flat parts. The same is true in reverse when a substance solidifies or condenses: energy is given out while the temperature stays constant.

Note Academy

Latent heat is the energy needed to change the state of a substance without changing its temperature.

- When a solid melts, the energy is used to break the bonds between the particles so they can move past each other.
- When a liquid boils, the energy is used to separate the particles completely, against the forces between them.
- The kinetic energy of the particles does not change, so the temperature stays the same.

Boiling and evaporation

Boiling	Evaporation
happens only at one temperature (the boiling point)	happens at any temperature
happens throughout the liquid, with bubbles of vapour	happens only at the surface
fast	slow

Evaporation in terms of particles. The particles in a liquid move at different speeds. The more energetic particles near the surface can escape from the liquid if they are moving fast enough to overcome the attraction of the others.

Evaporation is faster when:

- the **temperature** is higher,
- the **surface area** is larger,
- there is **air movement** (wind) over the surface, which carries away the escaped particles.

Evaporation causes cooling. The particles that escape are the ones with the most kinetic energy, so the average kinetic energy of those left behind falls. The liquid gets cooler. This is why sweating cools the body.

2.3.1 Conduction

Conduction is the transfer of thermal energy through a material without the material itself moving.

- In **all solids**, the particles vibrate. The hot end vibrates more, and this passes along the lattice from particle to particle.
- In **metals**, there are also **free (delocalised) electrons** that move through the metal. They gain energy at the hot end and carry it quickly by colliding with atoms. This is why metals are good conductors.

Gases and liquids are poor conductors because their particles are further apart. Materials that conduct badly, such as wood, plastic, wool and air, are **insulators**.

Note Academy

Experiment to compare conductors. Fix equal rods of different materials to a heated tank (or heat their ends equally). Stick a drawing pin on each rod with wax. The pin falls first from the best conductor, because heat travels along it fastest.

2.3.2 Convection

Convection is the transfer of thermal energy by the movement of a liquid or gas. It cannot happen in solids or in a vacuum.

1. The fluid is heated. Its particles move apart, so it **expands** and becomes **less dense**.
2. The warm, less dense fluid **rises**.
3. Cooler, denser fluid **sinks** to take its place.
4. This sets up a circulating **convection current**.

Experiment. Drop a crystal of potassium permanganate to the bottom of a beaker of water and heat the water just beside it. The purple streak rises over the heat, travels across the top and sinks on the other side, showing the current. Smoke in a box above a candle shows the same thing in air.

2.3.3 Radiation

Thermal radiation is **infrared radiation**, a type of electromagnetic wave. All objects emit it, and the hotter the object the more it emits. Radiation needs **no medium**: it can travel through a vacuum. This is how the Sun's energy reaches the Earth.

Surface	Emits	Absorbs	Reflects
dull black	best	best	worst
shiny (silver) or white	worst	worst	best

The rate at which an object emits radiation also **increases with its surface temperature and its surface area**.

Experiments

- *Good and bad emitters.* Fill identical cans (one painted dull black, one shiny, others white or rough) with hot water of the same temperature and measure how fast each cools. The dull black can cools fastest.
- *Good and bad absorbers.* Place two metal plates (one dull black, one shiny) the same distance from a heater, each with a ball bearing stuck on the back with wax. The wax on the dull black plate melts first, so the ball falls first.

Note Academy

2.3.4 Consequences of thermal energy transfer

- **A cooking pan.** The base is metal, a good conductor, so heat passes through quickly. The handle is plastic or wood, a good insulator, so it stays cool.
- **Heating a room.** A radiator warms the air next to it. The warm air rises by convection and cooler air flows in to be heated, so the whole room warms. This is why a radiator is placed low down.
- **An infrared thermometer.** It detects the infrared radiation emitted by an object and so measures its temperature without touching it.
- **Thermal insulation.** A **vacuum flask** has a double wall with a vacuum between them (stops conduction and convection), silvered surfaces (reduce radiation) and a stopper (reduces convection and evaporation). In buildings, loft insulation and cavity-wall insulation trap pockets of air, which is a poor conductor, and double glazing does the same.

2.1.3 Gases and the absolute scale of temperature

Gas pressure

A gas is made of particles moving randomly at high speed. **Gas pressure** is caused by the particles **colliding with the walls** of the container: each collision pushes on the wall, and many collisions every second add up to a steady force on each square metre of wall.

- **Heating a gas** at constant volume makes the particles move faster. They hit the walls **harder and more often**, so the pressure rises.
- **Squeezing a gas** into a smaller volume at constant temperature packs the particles closer. They hit the walls **more often**, so the pressure rises.

The absolute scale of temperature

A gas cannot be cooled forever. The lowest possible temperature is **absolute zero**, where the particles have the least possible energy. It is $-273\ ^\circ\text{C}$, or $0\ \text{K}$.

Temperature in kelvin: $T\ (\text{K}) = \theta\ (^\circ\text{C}) + 273$**. A change of** $1\ ^\circ\text{C}$ **is the same size as a change of** $1\ \text{K}$**.**

TRY IT

Convert $25\ ^\circ\text{C}$ to kelvin, and $350\ \text{K}$ to degrees Celsius.

$25 + 273 = 298\ \text{K}$. And $350 - 273 = 77\ ^\circ\text{C}$.

Note Academy

Pressure and volume (Supplement)

NOTE

Supplement only. This topic is in the Extended (Supplement) syllabus, so it is asked in Papers 2, 4 and 6. If you sit the Core papers you do not need it.

For a fixed mass of gas at **constant temperature**, pressure and volume are **inversely proportional**: if the volume halves, the pressure doubles.

$pV = \text{constant}$**, so** $p_1V_1 = p_2V_2$ **(temperature in kelvin does not matter here because it stays the same).**

TRY IT

A gas at $100\ \text{kPa}$ has a volume of $6.0\ \text{m}^3$. It is compressed to $2.0\ \text{m}^3$ at constant temperature. Find the new pressure.

$$p_2 = \frac{p_1V_1}{V_2} = \frac{100 \times 6.0}{2.0} = 300\ \text{kPa}.$$

At **constant volume**, pressure is directly proportional to the **kelvin** temperature, so $\frac{p_1}{T_1} = \frac{p_2}{T_2}$. Always change degrees Celsius into kelvin first.

Note Academy