Cambridge (CIE) IGCSE Physics

Your notes

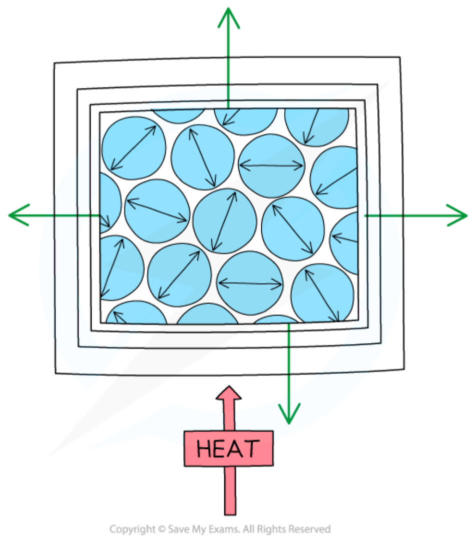
Thermal Properties & Temperature

Contents

Thermal expansion

- When a material is heated at constant pressure:
  - Its temperature increases
  - Its overall volume increases (it **expands**)
  - Its density decreases
- This expansion happens because:
  - The molecules start to move around (or vibrate) faster as they gain kinetic energy
  - This causes them to collide with each other more often and push each other apart

Thermal expansion diagram



When a solid is heated, the molecules vibrate more, pushing each other apart

Thermal expansion in terms of particles

Extended tier only

- Thermal expansion occurs in solids, liquids and gases
- When temperature is increased (at constant pressure):
  - Solids will tend to expand the least
  - Gases expand the most
  - Liquids fall in between the two

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- This behaviour is influenced by the distances and strength of the forces between particles in each state

Table comparing thermal expansion of solids, liquids and gases

State	Magnitude of Expansion	Explanation
Solid	Expands slightly	The low energy molecules cannot overcome the intermolecular forces of attraction holding them together
Liquid	Expands more than solids	The molecules have enough energy to partially overcome the intermolecular forces of attraction holding them together
Gas	Expand significantly	The high energy molecules have enough energy to completely overcome the intermolecular forces of attraction holding them together

Uses & consequences of thermal expansion

- The thermal expansion of materials can have some **useful applications** as well as some **undesirable consequences**

Applications of thermal expansion

- Useful applications of thermal expansion include:
  - Liquid-in-glass thermometers
  - Temperature-activated switches

Liquid-in-glass thermometer

- A liquid-in-glass thermometer relies on the expansion of liquids to measure temperature
- It consists of a thin glass capillary tube containing a liquid that expands with temperature
  - At one end of the tube is a glass bulb, containing a large volume of the liquid which expands into the narrow tube when heated
  - A scale along the side of the tube allows the temperature to be measured based on the length of liquid within the tube

Liquid-in-glass thermometer

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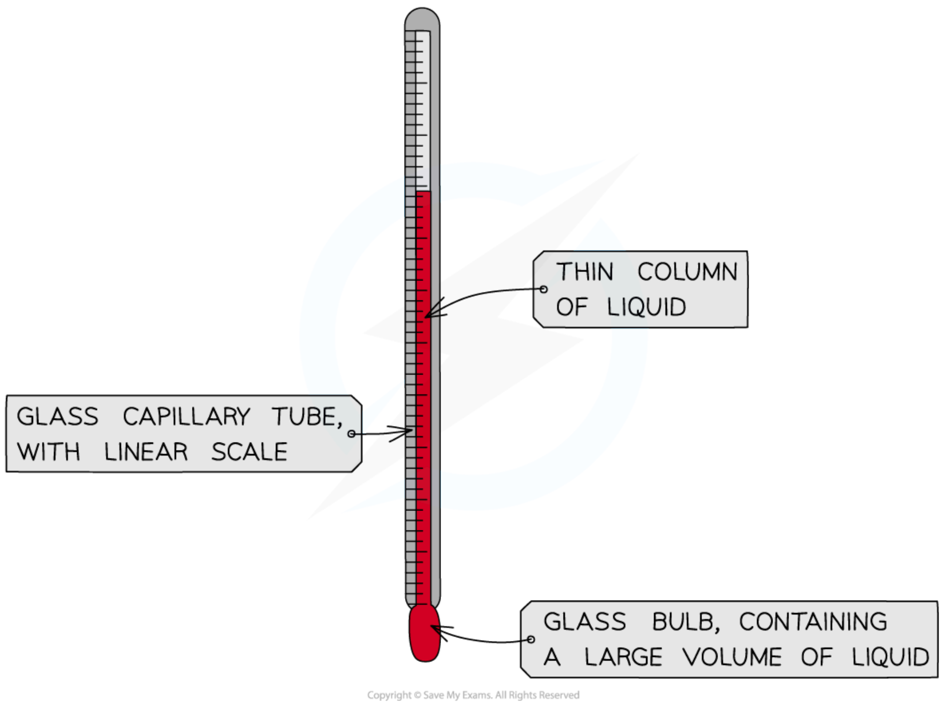
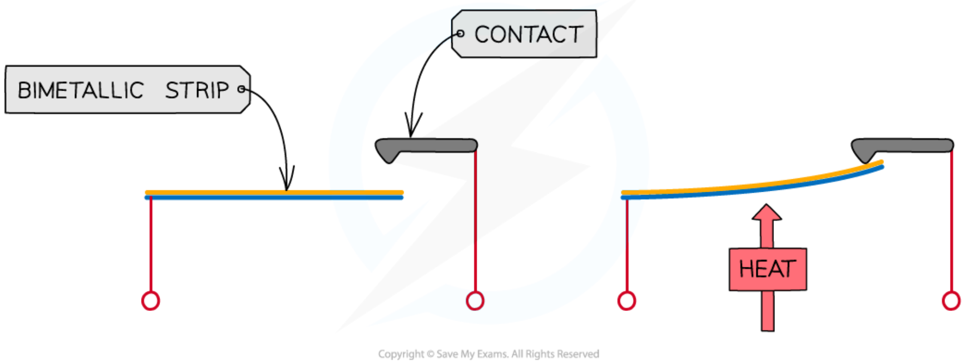


As the bulb is heated, the liquid expands and moves along the capillary tube

Temperature-activated switches

- Temperature-activated switches utilise a **bimetallic** (made from two types of metal) strip
- It consists of two metals that expand at different rates and bends by a predictable amount at a given temperature



The bimetallic strip will bend upwards when heated, closing the circuit

Consequences of thermal expansion

- The expansion of solid materials can cause them to buckle if they get too hot

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- This could include:
  - Metal railway tracks
  - Road surfaces
  - Bridges
- Objects that are prone to buckling in this way have gaps built in to creates space for the expansion to happen without causing damage

Examiner Tips and Tricks

Remember that it is **the material that expands, not the molecules**. This trips up many students, losing marks.

As heat is added;

1. The increase in temperature...
2. Leads to an increase in kinetic energy, so that...
3. Molecules and atoms move more quickly...
4. And move apart
   - This separation of the the molecules makes the substance bigger!

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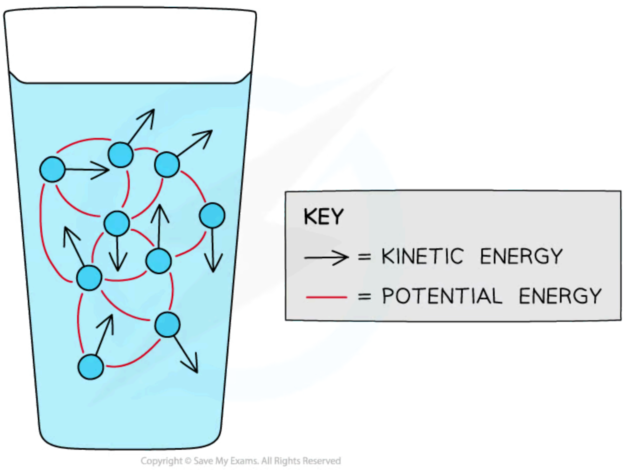
Internal energy

- A rise in the temperature of an object increases its **internal energy**
  - This can be thought of as due to an increase in the average speed of the particles
  - Increasing speed increases kinetic energy

- Internal energy is defined as:

The total energy stored inside a system by the particles that make up the system due to their motion and positions

- **Motion** of the particles affects their **kinetic energy**
- **Positions** of the particles relative to each other affects their **potential energy**
  - Together, these two make up the **internal energy** of the system



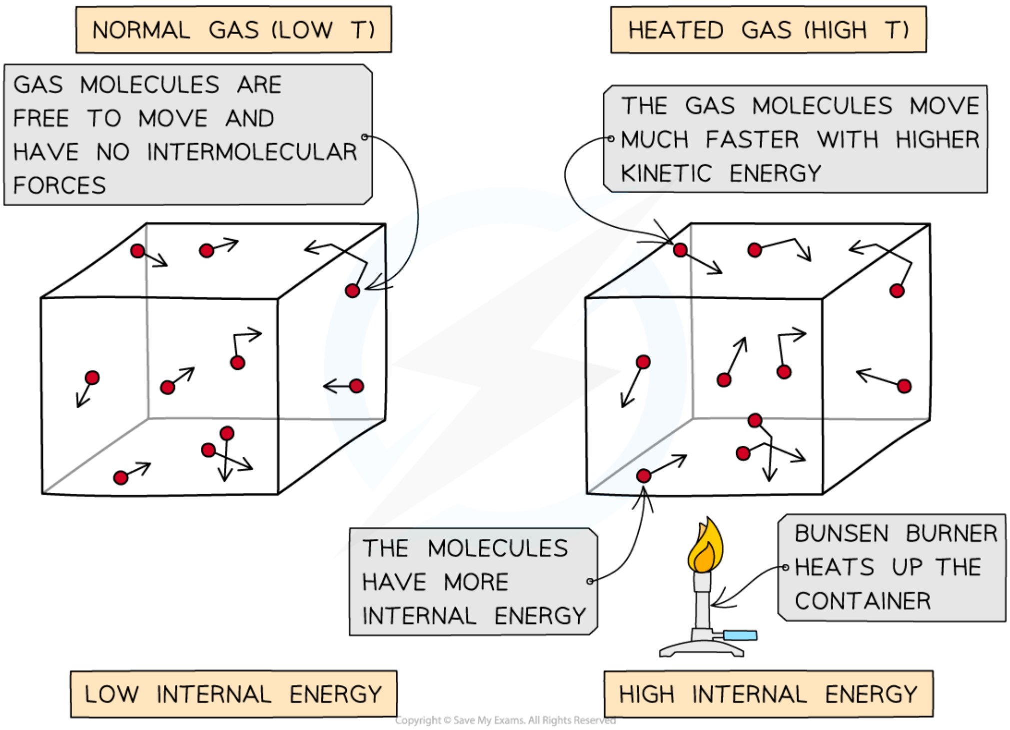
Substances have internal energy due to the motion of the particles and their positions relative to each other

Average kinetic energy

Extended tier only

- Heating a system changes a substance's internal energy by increasing the kinetic energy of its particles
  - The **temperature** of the material, therefore, is related to the **average kinetic energy** of the molecules

- An **increase** in **temperature** leads to an **increase** of the **average kinetic energy** of the particles in the substance
  - This also means that **internal energy increases,** as internal energy is the sum of all kinetic and potential energies



As the container heats up, the gas molecules move faster. Faster motion causes higher kinetic energy and therefore higher internal energy

Worked Example

What property of an object is a measure of the energy in the kinetic stores of its particles?

Answer:

- As temperature increases, so does the average kinetic energy of the particles
- This means **temperature** is a **measure** of the energy in the kinetic stores of the particles

Specific heat capacity

Extended tier only

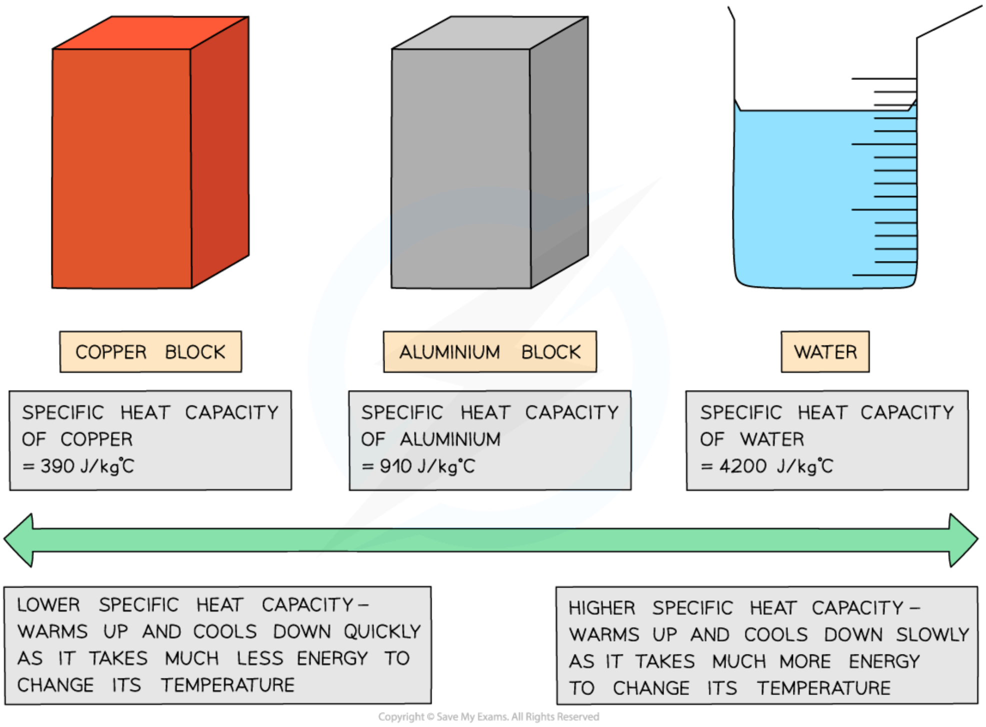
What is specific heat capacity?

- When heated, a substance's temperature can increase

- The amount by which the temperature increases depends on:
  - The **mass** of the substance heated
  - The **type** of material
  - The amount of **thermal energy** transferred in to the system
- The **specific heat capacity**, c, of a substance is defined as:

The energy required per unit mass per unit temperature increase

- In other words, this is the amount of energy required to raise the temperature of 1 kg of a substance by 1 °C
- Different substances have different specific heat capacities
  - If a substance has a **low** specific heat capacity, it heats up and cools down quickly (i.e. it takes less energy to change its temperature)
  - If a substance has a **high** specific heat capacity, it heats up and cools down slowly (i.e. it takes more energy to change its temperature)



Low vs high specific heat capacity

Calculating specific heat capacity

- The amount of energy needed to raise the temperature of a given mass by a given amount can be calculated using the equation:

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

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- Where:
    - ΔE = change in thermal energy, in joules (J)
    - m = mass, in kilograms (kg)
    - c = specific heat capacity, in joules per kilogram per degree Celsius (J/kg °C)
    - $\Delta\theta$ = change in temperature, in degrees Celsius (°C)

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Worked Example

What unit is used to measure energy when calculating specific heat capacity?

A. kilograms

B. joules

C. joules per kilogram per degree Celsius

D. kelvin

Answer: B

- The question asks what unit is used to measure **energy** when calculating specific heat capacity
- The units of energy are **joules**
    - A common mistake is for students to see 'specific heat capacity' and state the units of that, not energy
    - Reading the question thoroughly and underlining key information avoids these mistakes

Worked Example

Water of mass 0.48 kg is increased in temperature by 0.7 °C. The specific heat capacity of water is 4200 J / kg °C.

Calculate the amount of thermal energy transferred to the water.

Answer:

Step 1: Write down the known quantities

- Mass, m = 0.48 kg
- Change in temperature, ΔT = 0.7 °C
- Specific heat capacity, c = 4200 J/kg °C

Step 2: Write down the relevant equation

$$\Delta E = mc\Delta\theta$$

Step 3: Calculate the thermal energy transferred by substituting in the values

$$\Delta E = (0.48) \times (4200) \times (0.7) = 1411.2$$

Step 4: Round the answer to 2 significant figures and include the units

$$\Delta E = 1400 \text{ J}$$

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Examiner Tips and Tricks

While you must remember the equation for specific heat capacity, you will always be given the specific heat capacity of a substance so you do not need to memorise any values.

However, it's useful to have the general idea that, the **larger the number**, the **less the substance will increase in temperature** for a given amount of heat.

You can see this for yourself in your own kitchen at home. Metal pans, which have a relatively low specific heat capacity get very hot, very quickly when put on the hob. Add water to the pan, which has a relatively high specific heat capacity and the water will take much longer to heat up.

Notice the **units** of specific heat capacity:

joules *per* kilogram *per* degree Celsius : J / kg °C

'per' means 'divided by'. We say 'per' in front of every value that is being divided by, hence 'per kilogram per degree Celsius'

Investigating specific heat capacity

Extended tier only

Aim of the experiment

- The aim of the experiment is to determine the specific heat capacity of a substance, by linking the decrease of one energy store (or work done) to the increase in temperature and subsequent increase in thermal energy stored

Variables

- **Independent variable** = Time, t
- **Dependent variable** = Temperature, θ
- Control variables:
  - Material of the block
  - Current supplied, I
  - Potential difference supplied, V

Equipment

Equipment list

Equipment	Purpose
Thermometer	To measure the temperature change of the solid / the water
Solid block of aluminium	To investigate temperature changes
Beaker of water (400 ml)	To investigate temperature changes
Immersion heater	To heat the solid / the water
Voltmeter	To measure the voltage across the immersion heater
Ammeter	To measure the current through the immersion heater
Power supply	To supply power to the immersion heater
Digital balance	To measure the mass of the solid / the water

Stopwatch	To time the heating of the solid / the water

- **Resolution** of measuring equipment:
  - Thermometer = 0.1 °C
  - Voltmeter = 0.1 V
  - Ammeter = 0.1 A
  - Stopwatch = 0.01 s
  - Digital balance = 0.1 g

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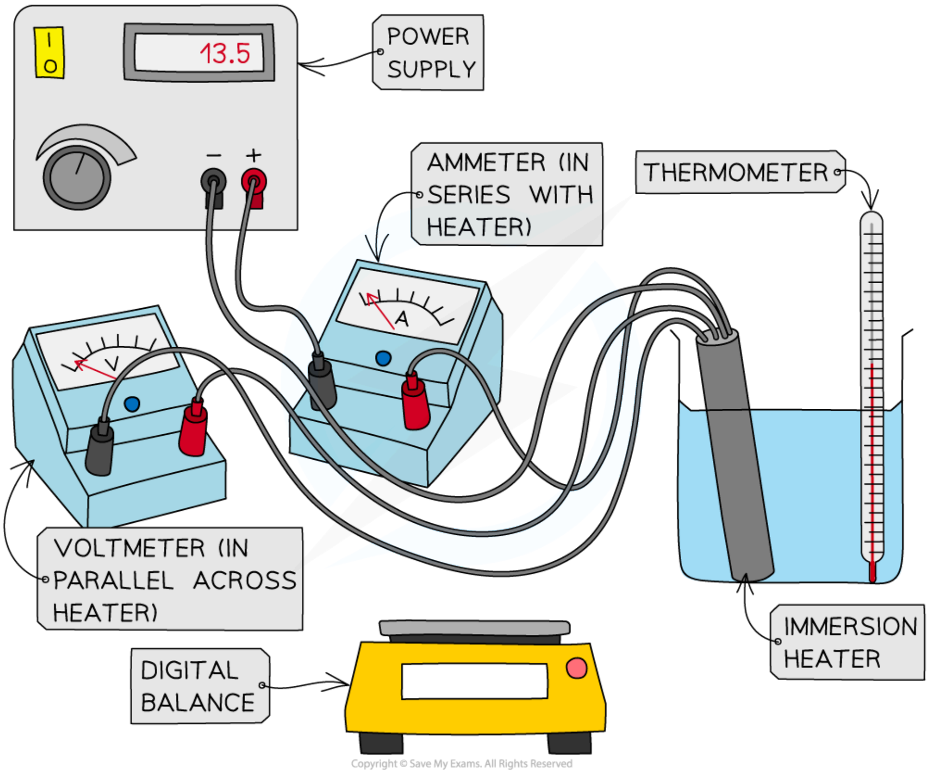
Method

The experiment set up for the specific heat capacity practical



Apparatus for heating water and measuring energy supplied

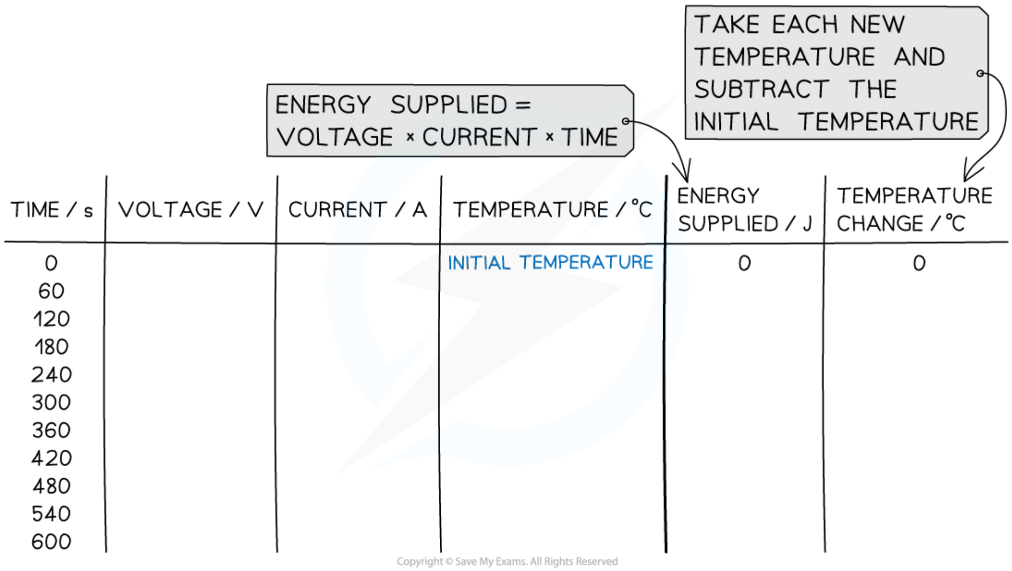
1. Place the beaker on the digital balance and press 'zero'
2. Add approximately 250 ml of water and record the mass of the water using the digital balance
3. Place the immersion heater and thermometer in the water
4. Connect up the circuit as shown in the diagram, with the ammeter in series with the power supply and immersion heater, and the voltmeter in parallel with the immersion

heater

5. Record the initial temperature of the water at time 0 s
6. Turn on the power supply, set it at approximately 10 V, and start the stopwatch
7. Record the voltage from the voltmeter and the current from the ammeter
8. Continue to record the temperature, voltage and current every 60 seconds for 10 minutes
9. Repeat steps 2–8, replacing the beaker of water for the solid block of aluminium and starting with recording its mass using the digital balance

Results

An example of a results table for the specific heat capacity practical



An example of a suitable results table for the specific heat capacity experiment looks like this. Energy supplies = voltage x current x time.

Analysis of results

- The thermal energy supplied to the block can be calculated using the equation:

$$E = IVt$$

- Where:
  - E = thermal energy, in joules (J)
  - I = current, in amperes (A)
  - V = potential difference, in volts (V)
  - t = time, in seconds (s)
- The change in thermal energy is defined by the equation:

Your notes

$$\Delta E = mc\Delta\theta$$

- Where:
  - ΔE = change in thermal energy, in joules (J)
  - m = mass, in kilograms (kg)
  - c = specific heat capacity, in joules per kilogram per degree Celsius (J/kg °C)
  - $\Delta\theta$ = change in temperature, in degrees Celsius (°C)
- Rearranging for the specific heat capacity, c:

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

- To calculate Δθ:

$$\Delta\theta = \text{final temperature} - \text{initial temperature}$$

- To calculate ΔE:

$$\Delta E = IV\Delta t$$

- Where:
  - I = average current, in amperes (A)
  - V = average potential difference (V)
  - Δt = time spent heating, in seconds (s)
- These values are then substituted into the specific heat capacity equation to calculate the specific heat capacity of the aluminium block

Evaluating the specific heat capacity practical

Systematic Errors:

- Ensure the digital balance is set to zero before taking measurements of mass
- Some water may be lost to the surroundings by evaporation. Calculate an average mass of water (using the mass before the experiment and the mass after) to account for this
- Remember to only take gradients on the straight-line region
  - Before this point the energy supplied is being used to heat the immersion heater itself

Random Errors:

- Stir the water constantly whilst heating it to ensure the temperature measured is the temperature throughout the fluid
- When the current or voltage values appear to be changing between two values next to one another then be consistent in choosing the higher value

Safety considerations for the specific heat capacity practical

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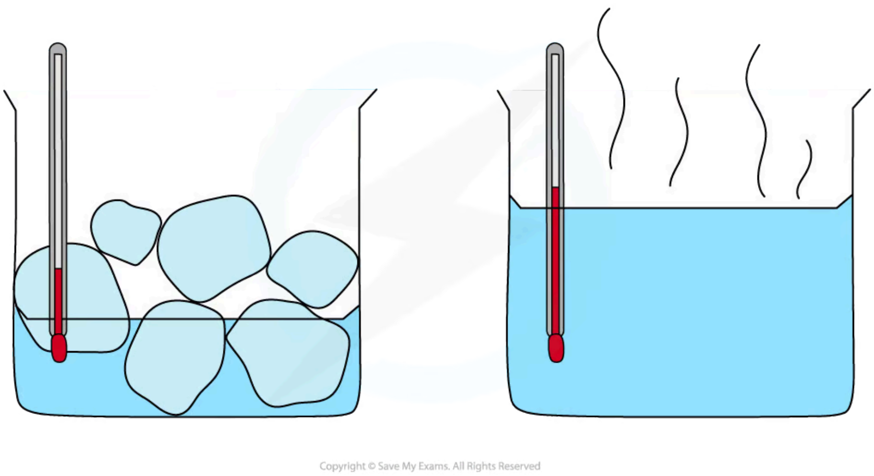
- The immersion heater will get very **hot**
  - Make sure not to touch it, and have a heatproof mat ready to place it on
- Make sure that the immersion heater is connected to a **Direct Current** supply
- The beaker may become **unstable** with an immersion heater and thermometer resting in it
  - If you feel this is the case then use a clamp stand to hold both
- Wear goggles while heating water
- Make sure to stand up during the whole experiment, to react quickly to any spills

Fixed points of water

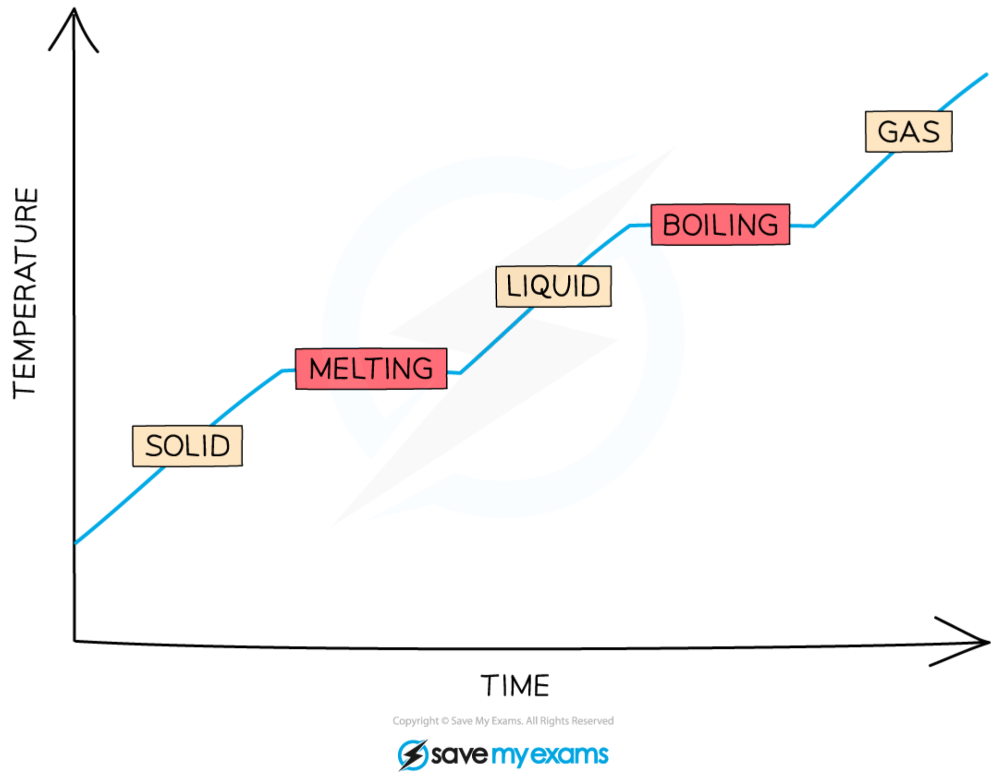
- The melting and boiling points of pure water are known as **fixed points**
  - Ice melts at 0 °C
  - Pure water boils at 100 °C
- These are the accepted values for **pure water** at **atmospheric pressure**



Ice melts at 0 °C and water boils at 100 °C

Melting & boiling

- While a substance is **changing state** (e.g. melting or boiling) the substance **does not change temperature,** even though energy is being transferred to or away from the thermal energy store of the substance
- One major difference between melting and boiling is that boiling occurs at higher energy
  - While melting results in particles being able to flow and move more freely, during boiling enough energy is transferred such that the intermolecular forces can be completely **overcome**



When the substance is changing state, the temperature remains constant as shown by the horizontal regions of this graph

Boiling

- When liquid water is heated by adding thermal energy (say from a gas flame or kettle element), the temperature of the water rises until the water boils
  - At the **boiling** point, even if more thermal energy is added, the temperature of the liquid water does not increase
  - This means that the internal energy is not rising
- The additional thermal energy goes into overcoming the intermolecular forces between the molecules of water
  - As the forces are overcome, the liquid water becomes water vapour (steam)
  - This is **evaporation** or vaporisation; the water is now a **gas**

Melting

- When solid water (ice) is heated by adding thermal energy, the temperature of the ice increases up until the melting point
  - At the **melting** point, even if more thermal energy is added, the ice does not get warmer
  - This means that the internal energy is not rising

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- The additional thermal energy goes into overcoming the intermolecular forces between the molecules of the ice
  - As the forces are overcome, the solid water becomes liquid
  - This is **melting**; the ice is now a **liquid**

Condensation & solidification

- Changes of state depend on whether energy is being transferred **to** or **away from** the system
  - Heating is when energy is transferred **to** the system and the kinetic energy of the molecules increases (red arrows to the right)
  - Cooling is when energy is transferred **away from** the system (or dissipated to the surroundings) and the kinetic energy of the molecules decreases (blue arrows to the left)

Condensation

- When a gas **cools**, energy is transferred away from the system and kinetic energy decreases until the temperature reaches **boiling point**
  - At boiling point, energy transferred away from the system reduces its potential energy
  - The particles no longer have enough energy to overcome the **intermolecular forces** of attraction
  - They only have enough energy to **flow** over one another
- The gas has condensed; it is now a liquid
  - As the energy has been transferred away from the **potential** store of the particles, the energy in the **kinetic** store is unchanged, so **temperature remains constant** through this process

Solidification

- When a liquid **cools**, energy is transferred away from the system and kinetic energy decreases until the temperature reaches **melting point**
  - At melting point, energy transferred away from the system reduces its potential energy
  - The particles no longer have enough energy to overcome the **intermolecular forces** of attraction
  - They are now low enough in energy to be bound to each other and can only vibrate around a fixed point
- The liquid has solidified; it is now a solid
  - As the energy has been transferred away from the **potential** store of the particles, the energy in the **kinetic** store is unchanged, so **temperature remains constant**

Your notes

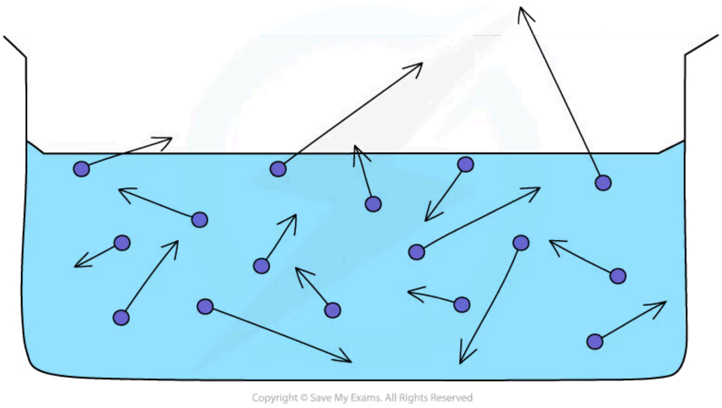
through this process

Your notes

Your notes

Evaporation

- **Evaporation** is a change in state of a liquid to a gas
- It happens:
  - At **any** temperature
  - Only from the **surface** of a liquid
- The molecules in a liquid have a **range** of energies
  - Some have lots of energy, others have very little
  - Their **average energy** relates to the temperature of the liquid
- Evaporation occurs when **more energetic molecules** moving near the surface of the liquid have enough energy to **escape**
  - The average energy of the liquid is **reduced** when the particles with most energy leave
  - Therefore liquids are **cooled down** by evaporation



Evaporation occurs when more energetic molecules near the surface of a liquid escape

Factors affecting evaporation & explaining cooling

Extended tier only

Factors affecting evaporation

- These factors all affect the rate of evaporation

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Temperature of the liquid

- Increased temperature increases the **kinetic energy** of the molecules in the liquid
  - Molecules with more energy are more likely to **overcome the intermolecular forces** holding them in the liquid state and escape the surface
  - Therefore **higher temperature** leads to a **higher rate of evaporation**

Surface area of the liquid

- Molecules only **escape** the intermolecular forces of attraction at the **surface** of the liquid
  - Therefore a **larger surface area** leads to a **higher rate of evaporation**

Air movement

- Air movement carries away the water vapour which has just evaporated
  - This replaces the air above the liquid with drier air, which accept water vapour more easily
  - Therefore **increasing air movement** (e.g. wind or a fan) **increases the rate of evaporation**

Evaporation & cooling

- The process of evaporation can be used to cool things down
- As evaporation occurs, the liquid cools
  - This is because the most energetic particles leave, **reducing** average kinetic energy
- Placing an object next to this liquid **cools** the object
  - This is because the cooler liquid **absorbs thermal energy** from the object
  - This process is used in some refrigerators and air conditioning units

Boiling vs evaporation

Extended tier only

Difference between evaporation and boiling

- Boiling is **also** a change in state from liquid to gas
  - Boiling happens only at the boiling point of the liquid
  - The change of state happens **throughout** the liquid (seen as bubbles at the bottom of a pan of boiling water, for example)

Table showing the difference between evaporation and boiling

	Evaporation	Boiling
Change of state?	Liquid to gas	Liquid to gas
Temperature?	Any temperature between melting and boiling point	Boiling point
Location in liquid?	From the surface	Throughout the whole liquid

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