Cambridge AS & A Level · Physics 9702 · Notes

Temperature A2

Read online at **pastopic.com/cambridge/physics-9702/notes/temperature**

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Read first: **Work, energy and power**

What you need to know

By the end of this topic you should be able to:

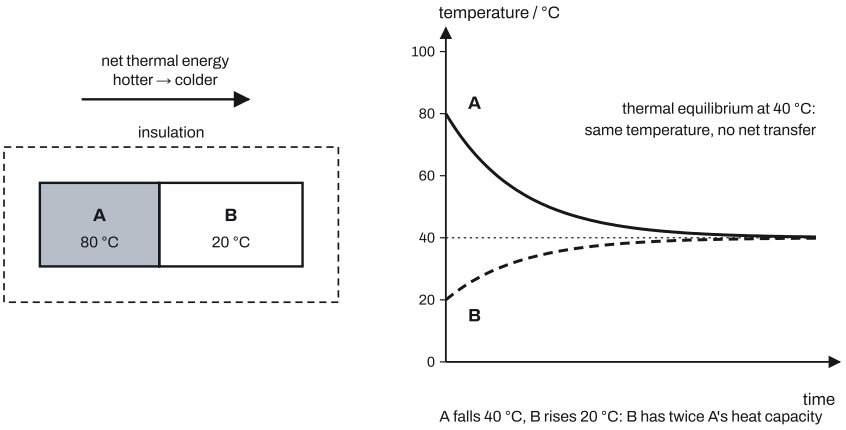
1. **Explain which way thermal energy flows**: from a region at a higher temperature to a region at a lower temperature.
2. **Explain thermal equilibrium**: regions at the same temperature are in thermal equilibrium, with no net transfer of thermal energy between them.
3. **Explain how a thermometer works**: any physical property that changes with temperature can be used to measure it. Give examples: the density of a liquid, the volume of a gas kept at constant pressure, the resistance of a metal, and the e.m.f. of a thermocouple.
4. **Explain why the thermodynamic (kelvin) scale is special**: it does not depend on a property of any particular substance.
5. **Convert between kelvin and degrees Celsius**, recalling $T/\mathrm{K} = \theta/^{\circ}\mathrm{C} + 273.15$.
6. **Explain absolute zero**: the lowest possible temperature, zero kelvin on the thermodynamic scale.
7. **Define and use specific heat capacity.**
8. **Define and use specific latent heat**, and tell the specific latent heat of fusion (melting) from the specific latent heat of vaporisation (boiling).

Paper 4 questions on this topic often go on to the first law of thermodynamics or to $pV = nRT$; those parts belong to the Thermodynamics and Ideal gases topics.

Understand it

Temperature and the direction of energy flow

Temperature tells you which way thermal energy will go. Put two objects in thermal contact and thermal energy flows **from the hotter one to the colder one**, never the other way on its own. The hotter object cools, the colder one warms, and the flow slows as the temperatures get closer.



When the two temperatures are **equal**, the objects are in **thermal equilibrium**. Energy still moves both ways at the molecular level, but the two flows are equal, so the **net** transfer of thermal energy is **zero** and nothing changes any more. This is why a thermometer works: you wait until it is in thermal equilibrium with the object, and then it is at the object's temperature.

- "Same temperature" and "constant temperature" are different ideas. Two objects can each be at a constant temperature without being at the same one.
- Once in thermal equilibrium, they stay at the same temperature (if insulated from everything else).

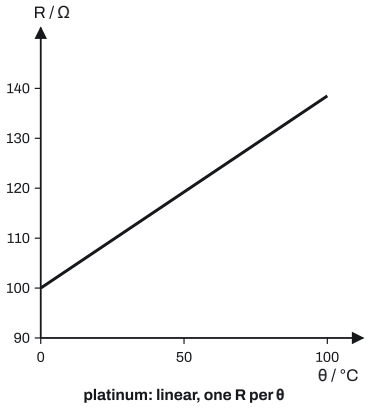
Measuring temperature: thermometric properties

A thermometer uses a **physical property that changes with temperature**. Examples:

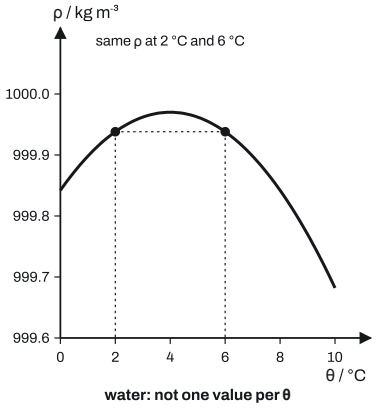
Thermometer	Property that changes
Liquid-in-glass (mercury or alcohol)	Density (so volume) of a liquid
Gas thermometer	Volume of a gas at constant pressure, or pressure of a gas at constant volume
Resistance thermometer (platinum wire)	Resistance of a metal
Thermistor	Resistance of a semiconductor
Thermocouple	E.m.f. between two junctions of different metals

A property is good for a thermometer if:

- it changes by a **measurable amount** for a small change in temperature (sensitive);
- it has **one value for each temperature** over the range (so a reading means only one temperature);
- ideally it changes **linearly** with temperature, so the scale is easy to calibrate between two fixed points.



platinum: linear, one R per θ



water: not one value per θ

The thermometers compared:

- **Platinum resistance thermometer**: resistance rises almost linearly with temperature, works over a wide range, and is accurate. But the wire sits inside a protective tube, so it has a **large heat capacity**: it needs a lot of energy and a long time to reach the object's temperature. It is **no good for a rapidly changing temperature**.
- **Thermistor** (negative temperature coefficient): its resistance **falls** as temperature rises, and **not linearly**. It is very sensitive over a narrow range.
- **Thermocouple**: two wires of different metals joined at a junction; the e.m.f. depends on the temperature difference between the junctions. The junction is **tiny**, so it has a small heat capacity: it responds **quickly** (use it for rapidly changing temperatures), measures the temperature at a **point** or of a small object, and works over a very wide range. Its e.m.f. is not linear with temperature.
- **Liquid-in-glass**: cheap and simple, but a limited range and slow response.
- **Constant-volume gas thermometer**: a bulb of gas whose pressure is measured (see below). Accurate over a wide range, and it gives the thermodynamic temperature directly, so it is used to **calibrate** other thermometers. But it is **large** and awkward to use, it takes a **long time** to reach thermal equilibrium, and it takes a lot of energy from the thing it measures. It cannot follow rapidly changing temperatures or measure small objects. It suits measuring a large body that stays at a constant temperature.

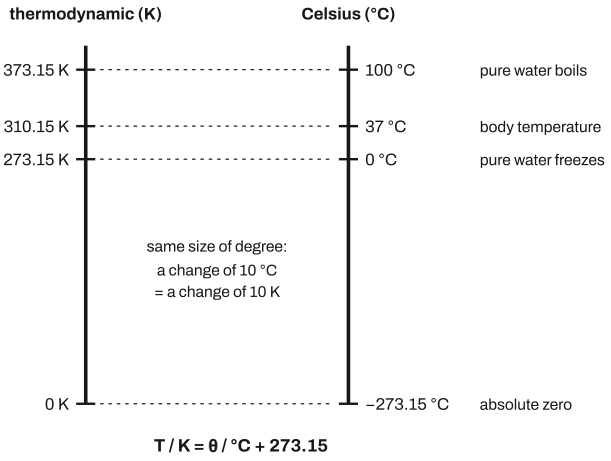
A thermometer disturbs what it measures. To reach thermal equilibrium, the thermometer takes energy from (or gives energy to) the object, which changes the object's temperature. A thermometer with a **smaller heat capacity** (less liquid, a smaller bulb or junction) disturbs it less and gives a more accurate reading.

The thermodynamic scale and absolute zero

Thermometers that use different properties agree at their calibration points (for example the melting and boiling points of pure water) but can **disagree in between**, because each property varies with temperature in its own way. A mercury thermometer and a resistance thermometer both read $0\,^{\circ}\text{C}$ and $100\,^{\circ}\text{C}$ at the fixed points, yet may differ slightly at $50\,^{\circ}\text{C}$. A Celsius reading from a liquid-in-glass thermometer depends on how that liquid expands, so it is not a measurement of thermodynamic temperature.

The **thermodynamic temperature scale** is defined so that it does **not depend on the property of any particular substance**. An **ideal gas** behaves exactly the same whatever the gas, with pV proportional to the thermodynamic temperature, so a gas thermometer with a gas that behaves nearly ideally gives thermodynamic temperatures.

Absolute zero is the **lowest possible temperature**: 0 K. On the Celsius scale it is $-273.15\,^{\circ}$C. At absolute zero a substance has its minimum internal energy; nothing can be colder.



$$T/\mathrm{K} = \theta/^{\circ}\mathrm{C} + 273.15$$

- $25\,^{\circ}$C $= 298.15$ K (often written 298 K). 77 K $= -196.15\,^{\circ}$C.
- The degrees are the **same size**, so a **temperature change** is the same number in both: a rise of $15\,^{\circ}$C is a rise of 15 K. **Never add 273 to a temperature change.**
- The symbol T means thermodynamic temperature (in K); θ means Celsius temperature. Kelvin is written **K**, not °K.

Using a constant-volume gas thermometer. At constant volume, the pressure of an ideal gas is proportional to its thermodynamic temperature, $p \propto T$. The gas pressure pushes a liquid column up; the height difference Δh between two liquid levels gives the pressure through $\Delta p = \rho g \Delta h$, which needs the **density of the liquid**. If Δh is proportional to p, then $\Delta h \propto T$:

$$\frac{T}{T_0} = \frac{\Delta h}{\Delta h_0}$$

For example: with the reference level at 3.00 cm on a scale, the other level is at 12.40 cm at $0\,^{\circ}$C and at 15.10 cm at the unknown temperature. Then $\Delta h_0 = 9.40$ cm and $\Delta h = 12.10$ cm, so $T = 273.15 \times \frac{12.10}{9.40} = 351.6$ K, which is $78.5\,^{\circ}$C. Always work in **kelvin** for the proportion: θ in °C is **not** proportional to Δh.

Specific heat capacity

Supplying thermal energy Q to an object raises its temperature (when it does not change state). How much it rises depends on the **mass** and on the **material**.

The **specific heat capacity** c of a material is the **thermal energy per unit mass needed to raise its temperature by one degree** (per unit change in temperature):

$$Q = mc\,\Delta\theta \qquad \text{so} \qquad c = \frac{Q}{m\,\Delta\theta}$$

Units: J kg^{-1} K^{-1} (the same as J kg^{-1} °C^{-1}, since the degrees are the same size). Sometimes J g^{-1} K^{-1}: water's 4.18 J g^{-1} K^{-1} is 4180 J kg^{-1} K^{-1}.

- Warming 0.50 kg of water by 20 K needs $0.50 \times 4180 \times 20 = 41\,800$ J.
- A large c means a lot of energy for each degree: the temperature changes **slowly**.
- **Heat capacity** of a whole object is mc (J K^{-1}). In the diagram of blocks A and B, A drops 40 K while B rises 20 K for the same energy, so B's heat capacity is twice A's.
- **Heated by an electric heater** of power P for time t: $Q = Pt$ (or VIt), so $Pt = mc\,\Delta\theta$.
- **Energy losses** to the surroundings mean less energy reaches the object than the heater supplies, so a value of c calculated from Pt comes out **too large**. Insulation, or starting below room temperature and finishing the same amount above it, reduces the error.

Energy balance (mixing, thermal contact). When hot and cold objects reach thermal equilibrium inside insulation, energy is conserved:

$$\text{thermal energy lost by the hotter parts} = \text{thermal energy gained by the colder parts}$$

Each side is a sum of $mc\,\Delta\theta$ terms, one for every object that changes temperature (including a container, if its heat capacity is not negligible), plus mL for anything that changes state. Every $\Delta\theta$ is a positive **change** (higher minus lower).

Specific latent heat

While a substance **changes state** (melting, freezing, boiling, condensing), energy goes in or out but the **temperature stays constant**. The energy changes the arrangement and separation of the molecules, not their average kinetic energy.

The **specific latent heat** L is the **thermal energy per unit mass needed to change the state of a substance without a change of temperature**:

$$Q = mL$$

Units: J kg^{-1}.

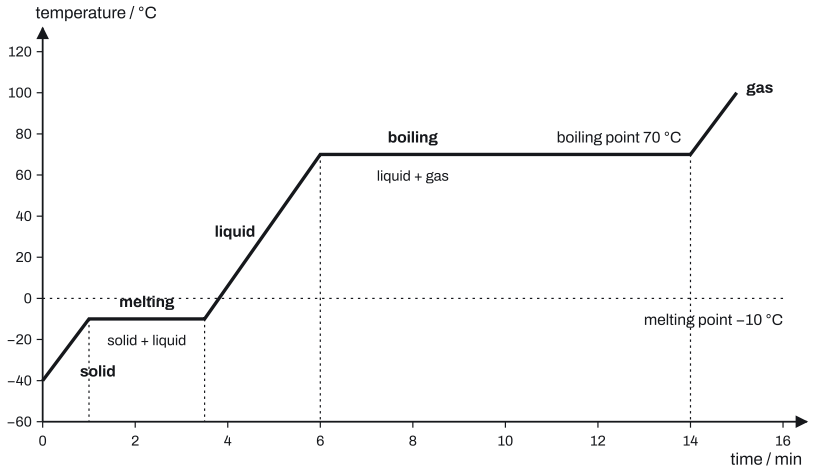
- **Specific latent heat of fusion** L_f: solid $\leftrightarrow$ liquid at the melting point. For ice, about 3.34×10^5 J kg^{-1}, so melting 0.20 kg of ice at $0\,^\circ$C needs $0.20 \times 3.34 \times 10^5 = 66\,800$ J.
- **Specific latent heat of vaporisation** L_v: liquid $\leftrightarrow$ gas at the boiling point. For water, about 2.26×10^6 J kg^{-1}.
- The same energy per kilogram comes **out** when the substance freezes or condenses.

Why L_v is much larger than L_f. In a solid and a liquid the molecules are about the same distance apart; in a gas they are very much further apart. So:

- **boiling** gives a much **larger increase in the separation** of the molecules than melting, so a much larger increase in their potential energy;

- the volume increases hugely on boiling, so the substance also does much more **work pushing back the atmosphere**;
- the temperature is constant in both cases, so the kinetic energy of the molecules does not change: all the extra energy goes into these two.

Heating curves



0.050 kg heated at 90 W: sloping = warming (c), flat = changing state (L)

Heat a substance at a **constant power** P, insulated, and plot temperature against time:

- **Sloping sections**: one state warms. $P\,\Delta t = mc\,\Delta\theta$, so the **gradient** is $\frac{\Delta\theta}{\Delta t} = \frac{P}{mc}$. A **less steep** section means a **larger** specific heat capacity.
- **Flat sections**: a change of state at the melting point or boiling point. $P\,\Delta t = mL$, where Δt is the **length of the flat section**. A longer flat section means a larger L.
- In the diagram, melting takes 2.5 min and boiling 8.0 min at the same power, so $\frac{L_\text{v}}{L_\text{f}} = \frac{8.0}{2.5} = 3.2$.
- The melting point is the temperature of the **first** flat section; the boiling point is the **second** (not the end of the line).
- Doubling the specific heat capacity (same mass and power) **halves** the gradient of a sloping section.

Key facts and formulas

"Given" means it is on the data sheet in the exam. "Learn it" means you must remember it. None of this topic's formulas are on the data sheet.

Formula	Status
$T/\text{K} = \theta/^\circ\text{C} + 273.15$; absolute zero $= 0$ K $= -273.15\,^\circ$C	Learn it
A temperature change is the same number in K and °C: $\Delta T = \Delta\theta$	Learn it
Specific heat capacity $Q = mc\,\Delta\theta$	Learn it
Specific latent heat $Q = mL$	Learn it

Formula	Status
Energy from a heater $Q = Pt = VIt$	Learn it
Energy balance: energy lost by hotter parts = energy gained by colder parts	Learn it
Heating curve: gradient $\frac{\Delta\theta}{\Delta t} = \frac{P}{mc}$; flat section $P\,\Delta t = mL$	Learn it
Constant-volume gas thermometer: $\frac{T}{T_0} = \frac{p}{p_0} = \frac{\Delta h}{\Delta h_0}$ (T in kelvin)	Learn it

How to do it

In the Paper 4 questions we have tagged for this topic (18 different questions, 2021–2025; 8 more appear on two papers), the types came up this often. 7 of the 18 questions mix two or more types, so the counts add up to more than 18. Many also have parts on ideal gases or the first law of thermodynamics.

Question type	Questions
Specific heat capacity: define and calculate	9
Specific latent heat: define, calculate, compare L_f and L_v	5
Thermal equilibrium	5
Thermometers and temperature scales	5
Heating and cooling graphs	3

1. Specific heat capacity: define and calculate (9 questions)

1. **Write** $Q = mc\,\Delta\theta$ for each object whose temperature changes.
2. **Find** Q from the energy source ($Q = Pt$) or from an energy balance (lost = gained).
3. **Solve**, with $\Delta\theta$ as a temperature **change** and consistent units (g with J g^{-1} K^{-1}, kg with J kg^{-1} K^{-1}).

Variations you will meet:

- **"Define specific heat capacity"**: thermal energy **per unit mass per unit change in temperature** (needed to raise the temperature). Both "per" phrases earn marks.
- **Electrical heating**: $Pt = mc\,\Delta\theta$ or $VIt = mc\,\Delta\theta$. Convert minutes to seconds.
- **A container that also warms**: energy supplied = $m_1c_1\Delta\theta + m_2c_2\Delta\theta$ (same $\Delta\theta$ if in thermal equilibrium all the time). Subtract the container's share before finding the liquid's c.
- **Two objects in contact reaching the same temperature**: energy lost by one = energy gained by the other, $m_1c_1(\theta_1 - \theta) = m_2c_2(\theta - \theta_2)$; solve for the unknown c or final θ.
- **Energy supplied to one of two objects in contact, both end at the same temperature**: both rise by the same ΔT, so $Q = (m_1c_1 + m_2c_2)\Delta T$.

- **A thermometer placed in a liquid**: the thermometer warms up and the liquid cools until they are at the same temperature; write the balance for both. The reading is a little **below** the liquid's original temperature. To make it more **accurate**, use a thermometer with a smaller heat capacity (less liquid, smaller bulb).
- **Energy converted to heating a target** (for example electrons hitting a metal, with a percentage turned into other forms): thermal energy = the useful fraction of VIt, then $\Delta T = \frac{Q}{mc}$.
- **A ratio of masses given**: write the balance with m and $1.3m$ (or whatever the ratio is) and cancel m.
- **Parts using the first law of thermodynamics** ($\Delta U = q + W$, $W = -p\Delta V$ for expansion): find the thermal energy q supplied first, then $c = \frac{q}{m\,\Delta\theta}$. A substance that expands needs more thermal energy for the same temperature rise, because some energy goes into doing work. (The first law itself is in the Thermodynamics topic.)

2. Specific latent heat: define, calculate, compare (5 questions)

1. **Identify every stage**: melting or boiling (mL), then warming or cooling ($mc\,\Delta\theta$) of each part.
2. **Write the energy balance** (lost = gained) or $Pt = mL$ for a heater.
3. **Solve** for L, a mass or the final temperature.

Variations you will meet:

- **"Define specific latent heat"**: thermal energy **per unit mass** to **change the state** of a substance **at constant temperature**. For "of vaporisation", say liquid to gas; for "of fusion", solid to liquid.
- **Ice added to water**: the ice gains $m_{\text{ice}}L_{\text{f}}$ to melt, **then** $m_{\text{ice}}c\,(\theta - 0)$ to warm from $0\,^{\circ}$C to the final θ; the water loses $m_{\text{water}}c\,(\theta_{\text{start}} - \theta)$. Don't forget the melted ice warming up.
- **Expressions in symbols**: write each term with the letters given, set energy lost = energy gained, then rearrange (collect the θ terms on one side, factorise).
- **Does all the ice melt?** Compare the energy to melt all of it with the energy the water gives out cooling to $0\,^{\circ}$C. If there is not enough, the final temperature is $0\,^{\circ}$C with some ice left.
- **From a heating curve**: $Pt = mL$ with t the length of the flat section in seconds; give L in the unit asked (J kg^{-1} or kJ kg^{-1}).
- **Why is L_{v} greater than L_{f}?** Much greater increase in the separation of the molecules (so in their potential energy), and much more work done against the atmosphere because the volume increases so much; the temperature is constant, so the kinetic energy of the molecules does not change.
- **With the first law**: for boiling at atmospheric pressure, the thermal energy supplied mL_{v} equals the increase in internal energy plus the work done by the vapour pushing back the atmosphere, $p\Delta V$. Melting has a tiny volume change, so almost no work.

3. Thermal equilibrium (5 questions)

1. **State both ideas**: the objects are at the **same temperature**, and there is **no net transfer of thermal energy** between them.
2. **Use it**: objects in thermal equilibrium have the same temperature, so a temperature found for one is the temperature of the other.

Variations you will meet:

- **"State what is meant by thermal equilibrium"**: same temperature (B1) and no **net** transfer of **thermal** energy (B1). Both key words matter.
- **"Why are two objects at the same temperature in thermal equilibrium?"**: because there is no net flow of thermal energy between them.
- **Two gases in thermal equilibrium**: their temperatures are equal, so use the temperature of one (for example from $pV = nRT$) for the other.
- **Waiting for equilibrium**: a thermometer (or bulb) must reach thermal equilibrium with the object before it is read; the time this takes depends on its heat capacity.
- **Final state of a mixing experiment**: everything ends at the same temperature, which is the θ in every energy term.

4. Thermometers and temperature scales (5 questions)

1. **Name the property** and say how it varies (linear? one value per temperature?).
2. **Judge the thermometer**: range, response time (heat capacity), size, linearity, whether it gives thermodynamic temperature.
3. **Convert** Celsius to kelvin with $+273.15$ (or $+273$ in a calculation) when a formula needs T.

Variations you will meet:

- **Absolute zero**: 0 K on the thermodynamic scale; $-273.15\,^{\circ}$C on the Celsius scale (the exact value is expected). Give the unit.
- **State properties used to measure temperature** (other than the density of a liquid): the volume of a gas at constant pressure, the resistance of a metal, the e.m.f. of a thermocouple. Say **what** changes ("resistance of a metal wire"), not just "resistance".
- **Why a liquid-in-glass (or any real-substance) thermometer does not give thermodynamic temperature**: its reading depends on the properties of that liquid, and its zero ($0\,^{\circ}$C) is not absolute zero.
- **Which substance gives thermodynamic temperature?** An ideal gas ($pV \propto T$).
- **Is this property suitable?** From a graph: suitable if it varies **linearly** (or at least has **one value for each temperature**) over the range; unsuitable if the graph has a flat part, a maximum or minimum (two temperatures with the same value), or is very non-linear. Don't call a straight line that does not pass through the origin "proportional".
- **Platinum resistance thermometer**: resistivity (resistance) changes with temperature, linearly, one value per temperature. Not suited to rapidly changing temperatures because of its large heat capacity (it takes time to reach the object's temperature).
- **Thermometer for rapidly changing temperatures, or a small object**: a **thermocouple** (small junction, small heat capacity).
- **Thermistor compared with a platinum wire**: its resistance **decreases** as temperature rises, and **non-linearly**.
- **Constant-volume gas thermometer**:

- pressure from Δh uses the **density of the liquid** (and g);
- $T \propto \Delta h$, so $T = T_0 \times \frac{\Delta h}{\Delta h_0}$ with $T_0 = 273$ K at $0\,^\circ$C; subtract 273 to get θ; Δh is the difference between the two scale readings;
- disadvantages: large, slow to reach thermal equilibrium, takes a lot of energy from what it measures (so it changes that temperature), can't follow changing temperatures or measure small objects, awkward to read;
- good for: a large body at a steady temperature, or calibrating other thermometers.

5. Heating and cooling graphs (3 questions)

1. **Read the key values**: the starting temperatures, the flat sections (melting and boiling points) and the final temperature.
2. **Measure times** along the flat or sloping section you need, and convert to seconds.
3. **Use $Pt = mL$ or $Pt = mc\,\Delta\theta$**, or compare gradients.

Variations you will meet:

- **Melting point from the graph**: the temperature of the **first** flat section (not the end of the graph, not the boiling point).
- **L from a flat section**: $L = \frac{Pt}{m}$ with t the length of that flat section.
- **Comparing sloping sections**: less steep means larger specific heat capacity (same mass and power).
- **Two blocks in contact, conclusions from their temperature–time graphs**: they end at the same temperature (thermal equilibrium); read each initial and final temperature and each change; the block with the **smaller** temperature change has the **larger** heat capacity; if the energy lost by one equals the energy gained by the other, no energy was lost to the surroundings.
- **Sketch a new heating curve** (for example a liquid with twice the specific heat capacity, same mass and power): same starting temperature, sloping part with **half** the gradient, then flat at the **new** boiling point if it is reached in the time shown.

Worked examples

The bold codes show where marks are earned, as in Cambridge mark schemes. The number is how many marks.

- **M1** method mark: for a correct method, even if the numbers slip.
- **A1** accuracy mark: for a correct answer; it needs the M mark before it.
- **B1** mark for a correct result on its own, with no method needed.

Example 1

A metal block of mass 2.40 kg is insulated and heated by an electric heater of power 48 W for 5.0 min. Its temperature rises from $19.5\,^{\circ}$C to $26.0\,^{\circ}$C.

(a) Define specific heat capacity. **[2]**

(b) Calculate the specific heat capacity of the metal. **[3]**

(c) The accepted value for this metal is 900 J kg^{-1} K^{-1}. Suggest why the value in (b) is larger. **[1]**

Solution

(a) The thermal energy per unit mass **B1** needed to raise the temperature by one degree (per unit change in temperature). **B1**

(b) Energy supplied $Q = Pt = 48 \times 5.0 \times 60 = 14\,400$ J **C1** $\Delta\theta = 26.0 - 19.5 = 6.5$ K **C1** $c = \dfrac{14\,400}{2.40 \times 6.5} = 923$ J kg^{-1} K^{-1} **A1**

(c) Some of the energy from the heater is lost to the surroundings, so less than $14\,400$ J goes into the block, and dividing the full $14\,400$ J by $m\,\Delta\theta$ gives too large a value. **B1**

Example 2

A sample of mass 0.050 kg of a substance is heated by a 90 W heater. It is insulated from its surroundings. The graph in the Heating curves section shows how its temperature varies with time.

(a) State the melting point of the substance. **[1]**

(b) Calculate the specific latent heat of vaporisation of the substance, in kJ kg^{-1}. **[3]**

(c) Calculate the specific heat capacity of the substance as a liquid. **[2]**

(d) Explain, in terms of molecules, why the flat section at the boiling point is longer than the flat section at the melting point. **[2]**

Solution

(a) $-10\,^{\circ}$C (the first flat section) **B1**

(b) Boiling lasts from 6.0 min to 14.0 min: $t = 8.0 \times 60 = 480$ s **C1** $Pt = mL$: $90 \times 480 = 0.050 \times L_{\text{v}}$ **C1** $L_{\text{v}} = 864\,000$ J kg^{-1} $= 864$ kJ kg^{-1} **A1**

(c) The liquid warms from $-10\,^{\circ}$C to $70\,^{\circ}$C ($\Delta\theta = 80$ K) in 2.5 min $= 150$ s: $90 \times 150 = 0.050 \times c \times 80$ **C1** $c = 3380$ J kg^{-1} K^{-1} (3375) **A1**

(d) On boiling, the separation of the molecules increases far more than on melting, so their potential energy increases far more (and more work is done against the atmosphere as the volume grows). **M1** So more energy is needed per kilogram, and at the same power this takes longer. **A1**

Example 3

A copper block of mass 0.250 kg is heated to $98.0\,^\circ$C and then placed in 0.180 kg of water at $20.0\,^\circ$C. The water is in an aluminium cup of mass 0.060 kg, also at $20.0\,^\circ$C, which is insulated. When the block, water and cup reach thermal equilibrium, their temperature is $28.5\,^\circ$C.

Specific heat capacity of water $= 4180$ J kg^{-1} K^{-1}; of aluminium $= 900$ J kg^{-1} K^{-1}.

(a) State what is meant by the block and the water being in thermal equilibrium. **[2]**

(b) Determine the specific heat capacity of copper. **[4]**

Solution

(a) They are at the same temperature **B1** and there is no net transfer of thermal energy between them. **B1**

(b) Energy gained by the water $= 0.180 \times 4180 \times 8.5 = 6395$ J **C1** Energy gained by the cup $= 0.060 \times 900 \times 8.5 = 459$ J **C1** Energy lost by the copper $= 0.250 \times c \times (98.0 - 28.5) = 17.375c$, and energy lost $=$ energy gained: $17.375c = 6854$ **C1** $c = 394$ J kg^{-1} K^{-1} **A1**

Example 4

Ice cubes of total mass 0.040 kg at $0\,^\circ$C are added to 0.250 kg of a drink at $24.0\,^\circ$C in an insulated flask of negligible heat capacity. The drink has the specific heat capacity of water, 4180 J kg^{-1} K^{-1}. The specific latent heat of fusion of ice is 3.34×10^5 J kg^{-1}.

(a) Show that all the ice melts. **[2]**

(b) Determine the final temperature of the drink. **[3]**

(c) Without calculation, state and explain whether the final temperature would be higher or lower if the ice had come from a freezer at $-18\,^\circ$C. **[2]**

Solution

(a) Energy to melt all the ice $= 0.040 \times 3.34 \times 10^5 = 13\,360$ J **C1** Energy the drink could give out cooling to $0\,^\circ$C $= 0.250 \times 4180 \times 24.0 = 25\,080$ J, which is more than $13\,360$ J, so all the ice melts. **A1**

(b) Energy lost by the drink $=$ energy to melt the ice $+$ energy to warm the melted ice from $0\,^\circ$C to θ: $0.250 \times 4180 \times (24.0 - \theta) = 13\,360 + 0.040 \times 4180 \times \theta$ **C1** $25\,080 - 1045\theta = 13\,360 + 167.2\theta$ **C1** $\theta = \dfrac{11\,720}{1212.2} = 9.7\,^\circ$C **A1**

(c) Lower. **B1** The ice must first gain energy to warm from $-18\,^\circ$C to $0\,^\circ$C, so the drink gives out more energy and cools further. **B1**

Common mistakes

- **Leaving "net" out of thermal equilibrium.** The June 2023 report says many answers missed that energy still moves both ways but the **net** transfer is zero, and some did not say the energy is **thermal** energy. The March 2025 report adds that "constant temperature" was often confused with "equal temperatures".
- **Definitions that are not "per unit".** The November 2021 and November 2022 reports describe definitions of specific heat capacity missing "per unit change in temperature", or defining an energy instead of an energy per unit mass per degree. The June 2022 report says specific latent heat definitions often missed "per unit mass", the change of state, or "at constant temperature".
- **Using temperatures instead of temperature changes.** The November 2022 report describes candidates who put a temperature where $\Delta\theta$ was needed, and others who made the working longer by converting everything to kelvin. The June 2023 report describes candidates converting a temperature **change** of $55\,^{\circ}\text{C}$ to kelvin by adding 273: a change is the same number in both units.
- **Forgetting the container.** The June 2023 report says many ignored the energy taken by the beaker, and some wrongly set the beaker's energy equal to the liquid's. Every object that warms needs its own $mc\,\Delta\theta$ term.
- **Missing an energy transfer.** The March 2025 report says only the strongest candidates analysed all the energy transfers correctly after writing $Q = mc\,\Delta T$. List every object and every stage before writing the balance.
- **Wrong section of a heating curve.** The March 2021 report describes candidates giving the end of the line or the boiling point for the melting point, using the wrong time interval for L, forgetting $\times 60$ for minutes, and not converting J to kJ.
- **Explaining $L_{\text{v}} > L_{\text{f}}$ with "bonds breaking".** The March 2021 report says many answered in terms of forces or bonds when the question asked about the **spacing** of molecules, or described the spacings without comparing the **increase** in spacing at the two changes of state.
- **Gradient versus property.** The March 2021 report says weaker answers about a less steep section just mentioned the slope, or talked about latent heat; the point is a **larger specific heat capacity**.
- **Thermometric properties that are too vague.** The November 2022 report says many wrote "resistance" without saying resistance of **what**, and many answered about the liquid-in-glass thermometer instead of naming other properties.
- **Precision instead of accuracy.** The November 2022 report says almost all candidates suggested a more **precise** thermometer when the point was that the thermometer's own heat capacity made the reading **inaccurate**.
- **"Proportional" for a straight line not through the origin.** The June 2023 report says some described the variation of mercury's density with temperature as proportional; say **linear**.
- **Absolute zero.** The June 2023 report notes that the exact conversion, $-273.15\,^{\circ}\text{C}$, is expected. The November 2021 and November 2022 reports say candidates often forgot that T in a gas equation is the **thermodynamic** temperature.
- **Thermal energy versus internal energy.** The June 2022, November 2022 and March 2025 reports all describe confusion between the thermal energy **supplied** (which c and L are defined from) and the change in internal energy.

How to get the marks

- **Definitions** (key words):
  - Thermal equilibrium: **same temperature** and **no net** transfer of **thermal energy**.
  - Specific heat capacity: thermal energy **per unit mass per unit change in temperature**.
  - Specific latent heat: thermal energy **per unit mass** to **change state** at **constant temperature** (say which change for fusion or vaporisation).
  - Absolute zero: 0 K, or $-273.15\,^{\circ}$C.
- **Calculations (C1 then A1)**: write $Q = mc\,\Delta\theta$ or $Q = mL$ (or $Q = Pt$) first; then the energy balance with every term; then the answer with its unit. A correct $\Delta\theta$ or energy often earns a mark by itself.
- **"Show that"** or **"give an expression"**: use only the letters given, write each energy term separately, then show the algebra step by step to the printed result.
- **Significant figures**: when the question asks for three significant figures, give exactly three (for example 335 J g^{-1}, not 335.3).
- **Units**: "give a unit with your answer" means marks for J kg^{-1} K^{-1} (or J kg^{-1} °C^{-1}) or J kg^{-1}. Keep g or kg consistent with the data.
- **Kelvin**: use T in K in any gas-thermometer proportion or gas equation; the mark scheme usually accepts 273. A difference needs no conversion.
- **"Suggest" questions about thermometers**: give a **specific** reason: large heat capacity → slow response; small junction → fast response; linear → easy calibration; one value per temperature.
- **"Conclusions from a graph"**: each conclusion earns one mark; mix qualitative ones (thermal equilibrium, which block has the larger heat capacity, no loss to the surroundings) with read-off values (initial and final temperatures, changes).
- **Sketches**: start at the same point as the original, make the gradient change match the calculation (half, double), and put flat sections at the right temperature.

Quick check

1. Convert $-195.8\,^{\circ}$C to kelvin, and 300 K to degrees Celsius. What is a temperature rise of $15\,^{\circ}$C in kelvin?
2. A constant-volume gas thermometer has a gas pressure of 88.0 kPa at $0.00\,^{\circ}$C and 115.0 kPa at an unknown temperature. Treating the gas as ideal, find the unknown temperature in °C.
3. A kettle of power 2.4 kW contains 1.2 kg of water at $18\,^{\circ}$C. Ignoring energy losses, how long does it take to reach $100\,^{\circ}$C, and how much longer to boil away 0.10 kg of the water? ($c = 4180$ J kg^{-1} K^{-1}, $L_{\mathrm{v}} = 2.26 \times 10^{6}$ J kg^{-1}.)
4. Explain why a thermocouple, not a platinum resistance thermometer, should be used to measure a rapidly changing temperature.
5. An aluminium block (mass 0.80 kg, $c = 900$ J kg^{-1} K^{-1}) at $90\,^{\circ}$C is placed in contact with an iron block (mass 1.5 kg, $c = 450$ J kg^{-1} K^{-1}) at $20\,^{\circ}$C. They are insulated from the surroundings. Find their temperature at thermal equilibrium.

Answers

1. $-195.8 + 273.15 = 77.35$ K. $300 - 273.15 = 26.85\,^{\circ}$C. A rise of $15\,^{\circ}$C is a rise of 15 K.
2. $T = 273.15 \times \dfrac{115.0}{88.0} = 357.0$ K, so $\theta = 357.0 - 273.15 = 83.8\,^{\circ}$C.
3. $Q = 1.2 \times 4180 \times 82 = 411\,312$ J, so $t = \dfrac{411\,312}{2400} = 171$ s. Boiling: $t = \dfrac{0.10 \times 2.26 \times 10^{6}}{2400} = 94$ s more.
4. The thermocouple's junction is very small, so it has a small heat capacity: it needs little energy and little time to reach the temperature of its surroundings and can follow the changes. The platinum thermometer has a large heat capacity, so it takes a long time to reach thermal equilibrium and lags behind.
5. Energy lost by aluminium = energy gained by iron: $0.80 \times 900 \times (90 - \theta) = 1.5 \times 450 \times (\theta - 20)$, so $720(90 - \theta) = 675(\theta - 20)$, $78\,300 = 1395\theta$, $\theta = 56.1\,^{\circ}$C.

Past questions to try

- **9702/43/M/J/23 Q3**: thermal equilibrium, choosing a liquid for a thermometer from density graphs, a heating curve with a beaker, and a sketch.
- **9702/43/O/N/22 Q2**: thermometric properties, a thermometer placed in warm water, and why a Celsius thermometer is not thermodynamic.
- **9702/42/F/M/21 Q3**: why $L_{\mathrm{v}} > L_{\mathrm{f}}$, and a heating curve with melting point and L_{v}.
- **9702/42/F/M/25 Q3**: thermal equilibrium and energy supplied to two metal blocks in contact.