

B.1 Thermal energy transfers

Ahmed Gomaa · IB DP Physics SL + HL (no extra HL content) · simple, step by step · original worked examples

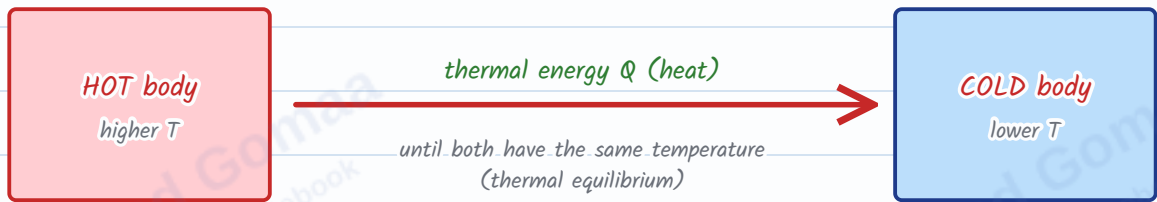
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Pen colours: blue = objects and particles, red = laws, energy flows and key steps, green = answers and results, pencil = construction lines. Boxes: **Why?** = the reasoning, **Mistake** = what students get wrong, yellow note = exam tip.

The big picture

In one line: everything is made of moving particles; temperature tells us how fast they move on average, and thermal energy always flows from hot to cold.



conduction: by contact

convection: a fluid moves

radiation: EM waves

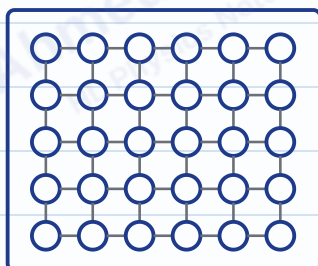
Thermal energy flows from the hotter body to the colder body until both reach the same temperature.

This topic has three parts. **First**, a particle model of matter: what temperature and internal energy mean for the molecules. **Second**, what thermal energy does to a body: it warms it up ($Q = mc\Delta T$) or changes its phase ($Q = mL$). **Third**, how thermal energy travels: conduction, convection and radiation. Radiation leads to stars: their power, their colour and how bright they look from Earth.

Data used in these notes: $k_B = 1.38 \times 10^{-23} \text{ J K}^{-1}$ · $\sigma = 5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$ · Wien constant $2.9 \times 10^{-3} \text{ m K}$ · $c(\text{water}) = 4200 \text{ J kg}^{-1} \text{ K}^{-1}$ · $c(\text{ice}) = 2100 \text{ J kg}^{-1} \text{ K}^{-1}$ · $L_f(\text{ice}) = 334 \text{ kJ kg}^{-1}$ · $L_v(\text{water}) = 2.26 \text{ MJ kg}^{-1}$.

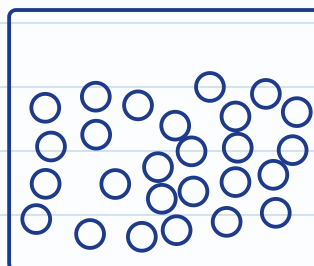
Solids, liquids and gases

forces between particles: strong → weaker → almost zero



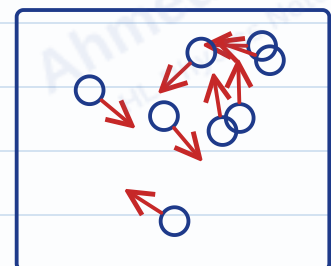
SOLID

fixed places, vibrate



LIQUID

close, slide past each other



GAS

far apart, fast, random

The same particles in three phases. What changes is how far apart they are, how strongly they pull on each other and how they move.

	<i>Solid</i>	<i>Liquid</i>	<i>Gas</i>
Arrangement	regular, close together	irregular, close together	far apart (about 10 times the spacing in a solid)
Motion	vibrate about fixed positions	move around and slide past each other	move fast and randomly in straight lines between collisions
Forces between particles	strong	weaker, but keep the particles close	almost zero (only during collisions)
Shape and volume	fixed shape and volume	takes the shape of the container; fixed volume	fills the whole container; easy to compress

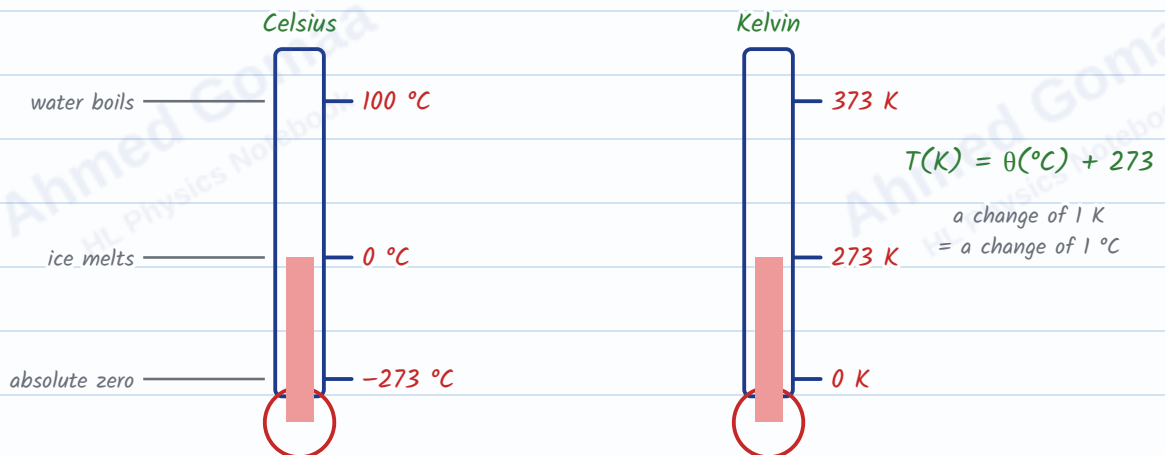
Density: $\rho = m / V$ · unit kg m^{-3}

Solids and liquids have similar densities (iron: $7.9 \times 10^3 \text{ kg m}^{-3}$ solid, $7.0 \times 10^3 \text{ kg m}^{-3}$ liquid). A gas is about 1000 times less dense (air $\approx 1.2 \text{ kg m}^{-3}$), because its particles are about 10 times further apart (10^3 in volume).

✗ Mistake

“A big block of copper has a bigger density than a small one.” Density is mass **per unit volume**; it depends on the material (and its temperature), not on the size of the block.

Temperature: Celsius and kelvin



The Celsius and Kelvin scales use the same size of degree; only the zero is different.

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

A **change** of temperature is the **same number** on both scales: ΔT in K = $\Delta \theta$ in °C.

Learn it word for word.

Temperature (in kelvin) is a measure of the **average kinetic energy** of the particles: $\bar{E}_k = (3/2) k_B T$, where k_B is the Boltzmann constant and T is in kelvin.

So **absolute zero** ($0\text{ K} = -273^{\circ}\text{C}$) is the temperature at which the particles have their lowest possible kinetic energy. Nothing can be colder. Doubling the kelvin temperature doubles the average kinetic energy; doubling the Celsius temperature does not.

Worked example 1

The temperature of a cup of tea falls from 318 K to 295 K. (a) Give both temperatures in °C. (b) State the temperature drop in °C.

1. (a) $318 - 273 = 45\text{ °C}$; $295 - 273 = 22\text{ °C}$.
2. (b) Drop = $318 - 295 = 23\text{ K}$, and a change in kelvin equals the change in °C: 23 °C . (Check: $45 - 22 = 23$.)

Worked example 2

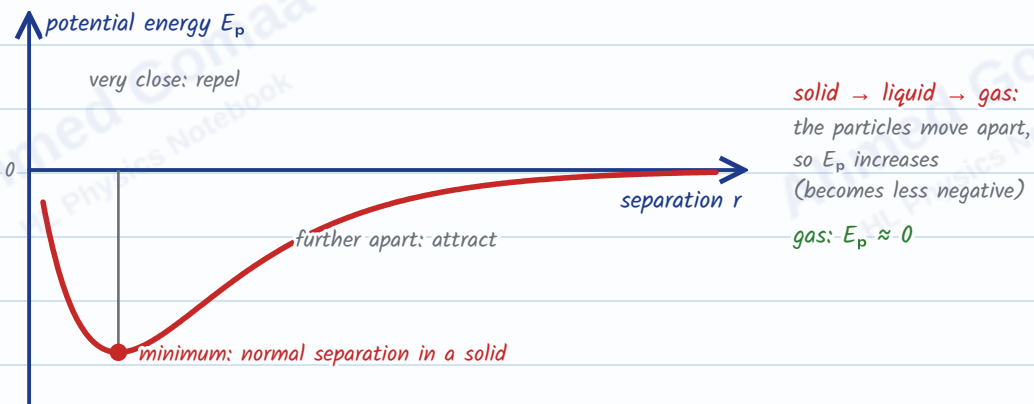
Find the average kinetic energy of the molecules of a gas at 27 °C. What is it at 327 °C? Helium and neon are at the same temperature: compare their average kinetic energies.

1. Kelvin first: $T = 27 + 273 = 300\text{ K}$.
2. $\bar{E}_k = (3/2) k_B T = 1.5 \times 1.38 \times 10^{-23} \times 300 = 6.21 \times 10^{-21}\text{ J}$.
3. $327\text{ °C} = 600\text{ K}$: the kelvin temperature doubles, so $\bar{E}_k$ doubles: $1.24 \times 10^{-20}\text{ J}$.
4. Same temperature → **same average kinetic energy**, even though a neon atom is heavier. The lighter helium atoms therefore move faster on average.

× Mistake

Using °C in $\bar{E}_k = (3/2)k_B T$, or saying “twice the temperature in °C means twice the kinetic energy”. Always change to kelvin first.

Internal energy



The potential energy of two molecules against their separation. Moving them apart (melting, boiling) increases the potential energy.

Particles have two kinds of energy. They **move randomly**, so they have random kinetic energy. They **pull on each other** (like tiny springs between them), so they have intermolecular potential energy. In a solid this potential energy is negative; it rises towards zero as the particles move apart. For an ideal gas it is zero.

Learn it word for word.

Internal energy of a system: the **total intermolecular potential energy** arising from the forces between the molecules **plus** the **total random kinetic energy** of the molecules arising from their random motion.

Exam tip

Always say **whose** energy it is: the energy of the **molecules** (or atoms, or particles). Then write **total** (not average), **random** kinetic energy and **intermolecular** potential energy. "Kinetic energy plus potential energy", with no molecules, atoms or particles, scores 0.

Does a gas on a fast plane have more internal energy?

No. Internal energy uses the **random** motion of the molecules relative to each other. The plane moves all the molecules together; that ordered motion is not part of the internal energy. Same gas, same temperature → same internal energy.

Word	What it is	Unit
Temperature	measures the average kinetic energy of one particle	K or °C
Internal energy	total random KE + total intermolecular PE of all the particles	J
Thermal energy (heat)	energy transferred because of a temperature difference	J

× Mistake

"A hot body has more internal energy than a cold body." Not always: a bath of warm water has far more internal energy than a hot spark, because it has many more particles. Temperature is about the **average** per particle; internal energy is the **total**.

Thermal energy and thermal equilibrium

Put a hot body in contact with a cold one. Energy is transferred from the hot body to the cold body, never the other way, until they reach the same temperature. Then there is no more net transfer: the bodies are in **thermal equilibrium**.

Learn it word for word.

Thermal energy (heat) is the energy transferred from one body to another because of a **temperature difference**. The temperature difference decides the **direction** of the net transfer: from higher to lower temperature.

The energy given out by the hot body equals the energy taken in by the cold body (if none is lost to the surroundings). This is the idea behind every "mixing" calculation: **energy lost = energy gained**.

✗ Mistake

"Heat is stored in a hot body." A body has internal energy; heat is energy **on the move** between bodies. The word "capacity" in specific heat capacity does not mean the body holds heat like a bottle holds water.

Specific heat capacity

Learn it word for word.

Specific heat capacity c : the energy required to raise the temperature of 1 kg of a substance by 1 K.

$Q = m c \Delta T$ · Q in J, m in kg, ΔT in K (or °C), c in $\text{J kg}^{-1} \text{K}^{-1}$
Water: 4200 · ice: 2100 · aluminium: 900 · iron: 440 · copper: 385 ·
lead: 130 $\text{J kg}^{-1} \text{K}^{-1}$

A large c means the substance needs a lot of energy to warm up, and it gives out a lot of energy as it cools. Water has a very large c ; this is why the sea warms and cools slowly, and why water is used to carry energy in radiators.

Worked example 3

(a) 6600 J of thermal energy is given to a 0.40 kg block of aluminium. Find its temperature rise. (b) 6600 J is removed from 0.40 kg of water at 60 °C. Find its final temperature.

1. (a) $\Delta T = Q/(mc) = 6600/(0.40 \times 900) = 18 \text{ K}$. (We do not need the starting temperature.)
2. (b) $\Delta T = 6600/(0.40 \times 4200) = 3.9 \text{ K}$, so the water ends at $60 - 3.9 \approx 56 \text{ °C}$.
3. Same energy, same mass, but water changes temperature about 4.7 times less: its c is 4.7 times bigger.

Worked example 4

A 0.30 kg copper block at 250 °C is dropped into 0.80 kg of water at 18 °C. Find the final temperature. Ignore the container and any losses.

1. Let the final temperature be θ . Copper cools from 250 to θ ; water warms from 18 to θ .
2. Energy lost by copper = energy gained by water: $0.30 \times 385 \times (250 - \theta) = 0.80 \times 4200 \times (\theta - 18)$.
3. $28\,875 - 115.5\theta = 3360\theta - 60\,480 \rightarrow 3475.5\theta = 89\,355 \rightarrow \theta = 25.7 \text{ °C} \approx 26 \text{ °C}$.
4. Check: the final temperature is between 18 °C and 250 °C, and much closer to the water's temperature, because the water has much more mass $\times c$.

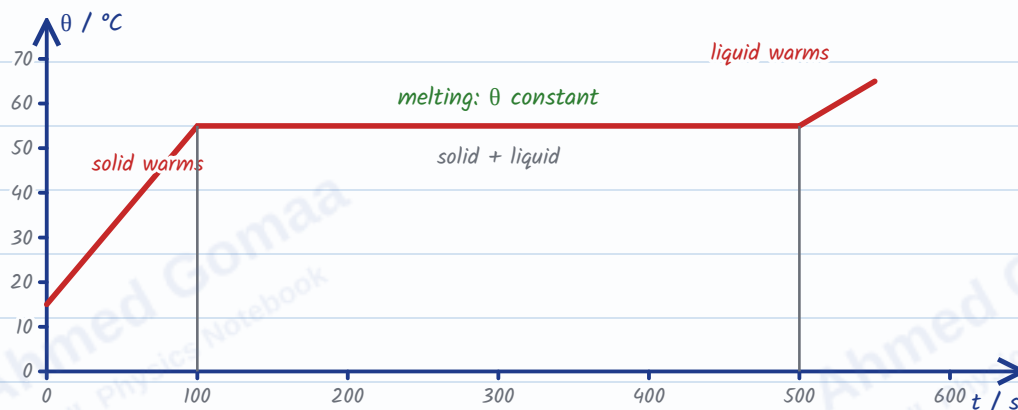
Method for every mixing problem

1. Write "energy lost = energy gained". 2. For each body write $mc\Delta T$ with ΔT as (higher – lower), so every term is positive. 3. Solve for the unknown. 4. Check the answer lies between the starting temperatures.

Measuring c : two methods

1. The electrical method

A heater of known power P warms the sample for a time t , so the energy supplied is $Q = Pt$ (or IVt). Measure the temperature rise, then $c = Pt/(m\Delta T)$. Stir, insulate the container, and include the energy taken by the container if it is not negligible.



Worked example 5: the heating curve of a 150 g sample heated by a heater of constant power.

Worked example 5

A 150 g sample of a solid at 15 °C is heated by a heater of constant power. Its specific heat capacity as a solid is 2000 J kg⁻¹ K⁻¹. The graph shows how its temperature changes with time. Use the graph to find (a) the power of the heater, (b) the melting point, (c) the specific latent heat of fusion, (d) the specific heat capacity of the liquid.

1. Read the graph first: three parts. 0 → 100 s: the solid warms from 15 °C to 55 °C. 100 → 500 s: flat, the solid melts. 500 → 550 s: the liquid warms from 55 °C to 65 °C.
2. Key idea: the heater gives the same energy every second, so on every part of the graph the energy supplied is $Q = P \times (\text{time of that part})$.
3. (a) Power (use the part where we know everything: the solid warming). $Q = mc\Delta T = 0.150 \times 2000 \times (55 - 15) = 12\,000 \text{ J}$ in 100 s, so $P = Q/t = 12\,000/100 = 120 \text{ W}$.
4. (b) Melting point = the temperature of the flat part = 55 °C.
5. (c) Latent heat. Time on the flat part: 500 - 100 = 400 s. Energy: $Q = Pt = 120 \times 400 = 48\,000 \text{ J}$. Then $Q = mL_f$ gives $L_f = 48\,000/0.150 = 3.2 \times 10^5 \text{ J kg}^{-1}$.
6. (d) c of the liquid. Time: 550 - 500 = 50 s, so $Q = 120 \times 50 = 6000 \text{ J}$. Temperature rise: 65 - 55 = 10 K. $c = Q/(m\Delta T) = 6000/(0.150 \times 10) = 4.0 \times 10^3 \text{ J kg}^{-1} \text{ K}^{-1}$.

Reading a heating curve

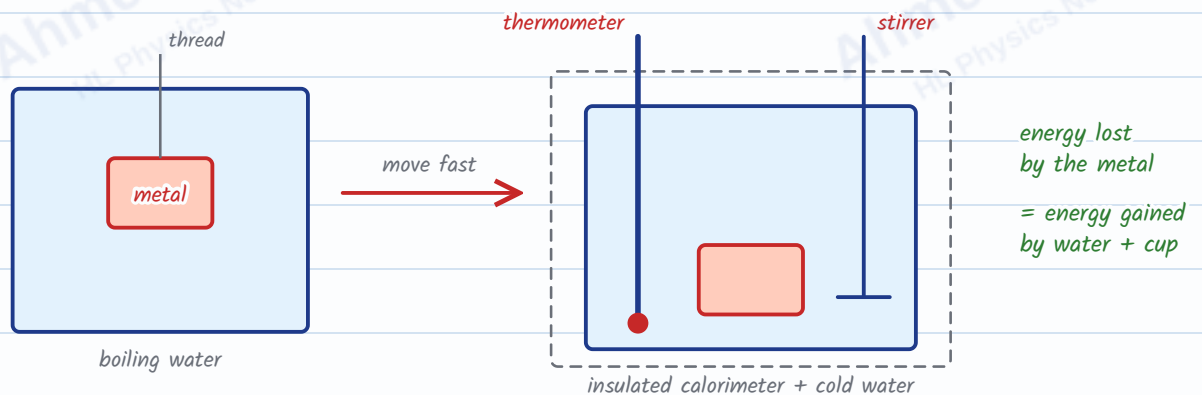
Flat part → phase change: use $Q = mL$ with $Q = P \times (\text{length of the flat part})$. **Sloping part** → one phase warming: use $Q = mc\Delta T$ with $Q = P \times \text{time}$. The **gradient** of a sloping part is $\Delta T / \Delta t = P / (mc)$: the steeper the line, the smaller c . Here the liquid line (10 K in 50 s) is less steep than the solid line (40 K in 100 s), so the liquid has the larger c .

Worked example 6

A 20 W heater runs for 4.0 minutes in 0.30 kg of a liquid held in a 0.10 kg copper cup ($c = 385 \text{ J kg}^{-1} \text{ K}^{-1}$). The temperature of both rises by 6.0 K. Find the specific heat capacity of the liquid. Is the true value larger or smaller than your answer?

1. Energy supplied: $Q = Pt = 20 \times 240 = 4800 \text{ J}$.
2. Energy taken by the cup: $0.10 \times 385 \times 6.0 = 231 \text{ J}$. The rest goes to the liquid: $4800 - 231 = 4569 \text{ J}$.
3. $c = 4569 / (0.30 \times 6.0) = 2.5 \times 10^3 \text{ J kg}^{-1} \text{ K}^{-1}$.
4. Some energy escapes to the room, so less than 4569 J really went into the liquid: the true c is **smaller** than calculated.

2. The method of mixtures



The method of mixtures. The metal must be moved quickly so it loses little energy on the way.

Heat a metal sample in boiling water (so its temperature is known), move it quickly into an insulated calorimeter of cold water, stir, and record the highest temperature reached. Then use energy lost = energy gained.

Worked example 7

A 0.50 kg metal block at 95 °C is put into a 0.12 kg aluminium calorimeter holding 0.60 kg of water at 18 °C. The final temperature is 24 °C. Find c for the metal, and say how energy losses affect the answer.

1. Energy gained by the cup and the water (both warm by 6 K): $0.12 \times 900 \times 6 + 0.60 \times 4200 \times 6 = 648 + 15\,120 = 15\,768 \text{ J}$.
2. Energy lost by the metal (cools by $95 - 24 = 71 \text{ K}$): $0.50 \times c \times 71 = 35.5c$.
3. $35.5c = 15\,768 \rightarrow c = 444 \text{ J kg}^{-1} \text{ K}^{-1}$.
4. The block cools a little in the air on the way, so it really entered the water below 95 °C. Its true temperature drop is smaller, so the true c is **larger** than calculated.

Changes of phase

Change	From → to	Energy
melting	solid → liquid	taken in
freezing (solidifying)	liquid → solid	given out
boiling (vaporisation)	liquid → gas, throughout the liquid, at the boiling point	taken in
condensing	gas → liquid	given out
evaporation	liquid → gas, only at the surface, at any temperature	taken in (the liquid cools)

Learn it word for word.

A **phase change** happens at **constant temperature**. The energy supplied changes the **intermolecular potential energy** (the particles move further apart, bonds are broken), **not** the average random kinetic energy. So the temperature stays the same, but the internal energy **increases**.

Why does freezing give energy out?

When a liquid freezes, bonds between the molecules **form**. Forming bonds releases energy: the intermolecular potential energy decreases and this energy is transferred to the surroundings. The average kinetic energy does not change, so the temperature stays at the freezing point.

Why does evaporation cool a liquid?

Only the **fastest** molecules near the surface have enough energy to escape. They take a lot of kinetic energy with them, so the **average kinetic energy** of the molecules left behind falls, and so does the temperature. Evaporation is faster at a higher temperature, with a larger surface area, and when air blows the escaped molecules away.

Specific latent heat

Learn it word for word.

Specific latent heat L : the energy required to change the phase of **1 kg** of a substance at **constant temperature**. L_f (fusion) is for melting or freezing; L_v (vaporisation) is for boiling or condensing.

$$Q = m L \quad \cdot L \text{ in } \text{J kg}^{-1} \cdot \text{water: } L_f = 334 \text{ kJ kg}^{-1}, L_v = 2260 \text{ kJ kg}^{-1}$$

L_v is about 7 times larger than L_f . In melting the molecules move only a little further apart; in boiling they are pulled completely apart, so much more work is done against the forces between them.

Worked example 8

To measure L_f of ice: 20 g of ice at 0 °C is dropped into a 200 g aluminium cup holding 250 g of water at 26 °C. The lowest temperature reached is 19 °C. Find L_f .

1. Energy lost by the cup and water (cool by 7 K): $(0.20 \times 900 + 0.25 \times 4200) \times 7 = 1230 \times 7 = 8610 \text{ J}$.
2. Energy gained by the ice: melting, $0.020 \times L_f$, then the melted water warms from 0 to 19 °C: $0.020 \times 4200 \times 19 = 1596 \text{ J}$.
3. $0.020L_f + 1596 = 8610 \rightarrow L_f = 7014/0.020 = 3.5 \times 10^5 \text{ J kg}^{-1}$.
4. Tips: the ice must be at 0 °C (take it from a mixture of ice and water) and dried before it goes in; find its mass by weighing the cup again at the end.

energy taken in by the ice (① + ② + ③) = energy given out by the water
 $m \cdot L(f)$

② ice melts at 0 °C

$m \cdot c(\text{ice}) \cdot \Delta T$
① ice warms

$m \cdot c(\text{water}) \cdot \theta$
③ melted ice warms



Worked example 9 on one temperature line: the ice takes in energy in three stages; the water gives out energy as it cools.

Worked example 9

(a) An ice cube of mass 30 g at $-12\text{ }^{\circ}\text{C}$ is dropped into 250 g of water at $25\text{ }^{\circ}\text{C}$. Find the final temperature. (b) The same is done with 120 g of ice at $-12\text{ }^{\circ}\text{C}$. Find the final temperature and the mass of ice that melts. Ignore the container. $c_{\text{ice}} = 2100$, $c_{\text{water}} = 4200\text{ J kg}^{-1}\text{ K}^{-1}$, $L_f = 334\text{ kJ kg}^{-1}$.

1. Masses in kg. Ice: 0.030 kg. Water: 0.250 kg. Call the final temperature θ .

2. Energy taken in by the ice, stage by stage.

① ice warms from $-12\text{ }^{\circ}\text{C}$ to $0\text{ }^{\circ}\text{C}$: $0.030 \times 2100 \times 12 = 756\text{ J}$

② ice melts at $0\text{ }^{\circ}\text{C}$: $0.030 \times 334\text{ }000 = 10\text{ }020\text{ J}$

③ the melted ice (now water) warms from $0\text{ }^{\circ}\text{C}$ to θ : $0.030 \times 4200 \times \theta = 126\theta$

3. Check that all the ice melts. To get to ②, the ice needs $756 + 10\text{ }020 = 10\text{ }776\text{ J}$. Cooling the water all the way to $0\text{ }^{\circ}\text{C}$ would give $0.250 \times 4200 \times 25 = 26\text{ }250\text{ J}$. $26\text{ }250 > 10\text{ }776$, so yes: all the ice melts and θ is above $0\text{ }^{\circ}\text{C}$.

4. Energy given out by the water as it cools from $25\text{ }^{\circ}\text{C}$ to θ : $0.250 \times 4200 \times (25 - \theta) = 26\text{ }250 - 1050\theta$.

5. Energy lost = energy gained. $26\text{ }250 - 1050\theta = 756 + 10\text{ }020 + 126\theta$.

6. Solve. Numbers on one side, θ on the other: $26\text{ }250 - 10\text{ }776 = 1050\theta + 126\theta \rightarrow 15\text{ }474 = 1176\theta \rightarrow \theta = 13\text{ }^{\circ}\text{C}$. Check: between $0\text{ }^{\circ}\text{C}$ and $25\text{ }^{\circ}\text{C}$ ✓.

7. (b) Do the check again with 120 g: warming the ice needs $0.120 \times 2100 \times 12 = 3024\text{ J}$, and melting all of it needs $0.120 \times 334\text{ }000 = 40\text{ }080\text{ J}$; $43\text{ }104\text{ J}$ in total. The water can give only $26\text{ }250\text{ J}$ (by cooling to $0\text{ }^{\circ}\text{C}$). Not all the ice melts.

8. So the final temperature is $0\text{ }^{\circ}\text{C}$ (ice and water together). Energy left for melting after warming the ice: $26\text{ }250 - 3024 = 23\text{ }226$

1. Mass melted = $23\,226/334\,000 = 0.070\text{ kg} = 70\text{ g}$ (50 g of ice is left).

Stage	Equation	Energy in (a)
① ice warms to $0\text{ }^{\circ}\text{C}$	$m_{\text{ice}} c_{\text{ice}} (0 - \theta_{\text{ice}})$	756 J
② ice melts	$m_{\text{ice}} L_f$	10 020 J
③ melted ice warms to θ	$m_{\text{ice}} c_{\text{water}} (\theta - 0)$	126 θ
water cools to θ	$m_{\text{water}} c_{\text{water}} (\theta_{\text{water}} - \theta)$	26 250 - 1050 θ

Always do the check first

If the water cannot give enough energy to melt all the ice, the answer is $0\text{ }^{\circ}\text{C}$ and some ice is left. Using the full equation anyway gives a negative θ , which is impossible for melted ice.

Worked example 10

Steam at $100\text{ }^{\circ}\text{C}$ is bubbled into 0.50 kg of water at $20\text{ }^{\circ}\text{C}$ until the water reaches $60\text{ }^{\circ}\text{C}$. What mass of steam condenses? Why is a burn from steam worse than one from boiling water?

1. The steam condenses (gives out mL_v), then the condensed water cools from 100 to $60\text{ }^{\circ}\text{C}$ (gives out $m \times 4200 \times 40$).
2. The water gains $0.50 \times 4200 \times 40 = 84\,000\text{ J}$.
3. $m(2.26 \times 10^6 + 4200 \times 40) = 84\,000 \rightarrow m = 84\,000/2\,428\,000 = 0.035\text{ kg} = 35\text{ g}$.
4. Steam on the skin first **condenses**, giving out its large latent heat (35 g gives about 79 kJ) before it even starts to cool. Boiling water only gives out $mc\Delta T$.

✗ Mistake

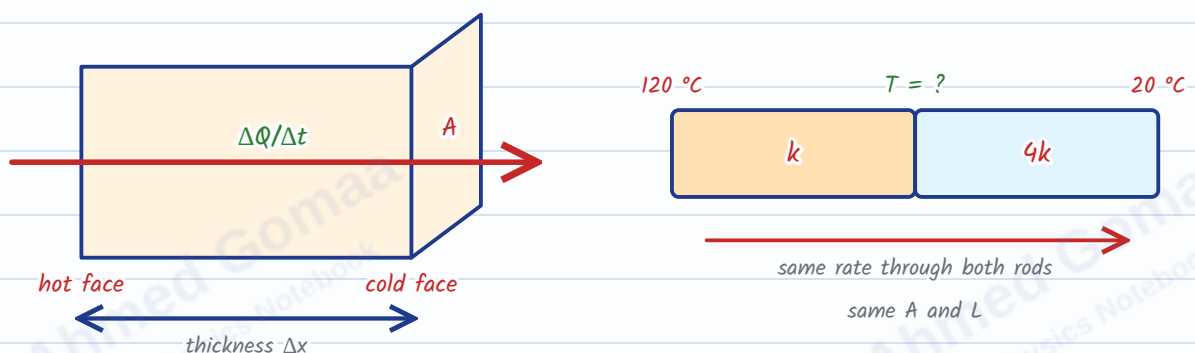
Forgetting a step in a phase problem. Ice at $-12\text{ }^{\circ}\text{C}$ needs three terms (warm the ice, melt it, warm the water), and you must check that all of it melts.

Conduction

Thermal energy moves through a material from the hot end to the cold end, with no movement of the material itself.

Learn it word for word.

Conduction: the particles at the hot end have a **higher average kinetic energy**. They pass kinetic energy to their neighbours in **collisions** (and through vibrating bonds), so energy is transferred from the hot side to the cold side. In metals, **free electrons** move through the metal and carry energy quickly, so metals are good conductors.



Left: the quantities in the conduction equation. Right: two rods in series (Worked example 11b).

$$\Delta Q/\Delta t = k A \Delta T/\Delta x$$

$\Delta Q/\Delta t$: rate of energy transfer (W) · k : thermal conductivity (W m⁻¹ K⁻¹) · A : cross-sectional area · $\Delta T/\Delta x$: temperature gradient (temperature difference ÷ thickness)

Double the area → double the rate · double the thickness → half the rate · copper $k \approx 400$, glass ≈ 0.8 , air ≈ 0.025 W m⁻¹ K⁻¹

Worked example 11

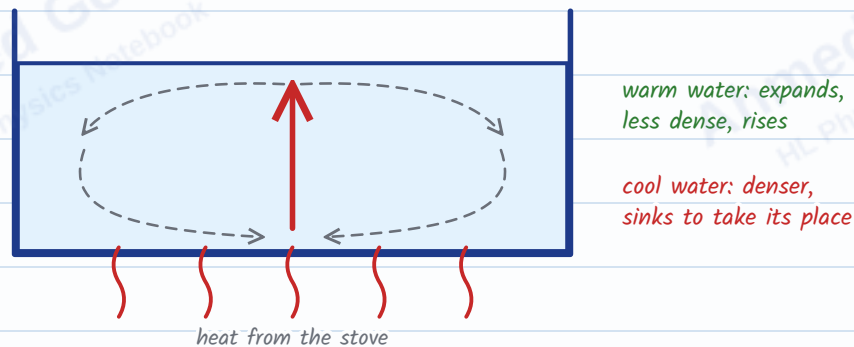
(a) A wall of area 15 m² and thickness 0.25 m has $k = 0.80$ W m⁻¹ K⁻¹. Inside is 21 °C, outside -4 °C. Find the rate of energy loss. (b) Two rods of the same length and area, with conductivities k and $4k$, are joined end to end. The free ends are kept at 120 °C and 20 °C. Find the temperature at the joint.

1. (a) $\Delta T = 21 - (-4) = 25$ K. $\Delta Q/\Delta t = 0.80 \times 15 \times 25/0.25 = 1200$ W. A heater of 1.2 kW keeps the room warm.
2. (b) In the steady state the same rate flows through both rods (energy does not pile up at the joint): $kA(120 - T)/L = 4kA(T - 20)/L$.
3. $120 - T = 4T - 80 \rightarrow 5T = 200 \rightarrow T = 40$ °C.
4. The better conductor needs a smaller temperature difference (20 K) to carry the same rate as the poorer one (80 K).

Why does a tiled floor feel colder than a carpet at the same temperature?

Both are at room temperature, but tile is a much better conductor. It carries energy away from your foot quickly, so your skin cools faster. Your skin senses the rate of energy loss, not the temperature of the floor.

Convection



A convection current in a pan of water.

Learn it word for word.

Convection happens in fluids (liquids and gases). The fluid near the heater warms, **expands** and becomes **less dense**, so it **rises**. Cooler, **denser** fluid sinks to take its place. This sets up a **convection current**: the moving fluid carries the energy.

Examples: a radiator warms the whole room; sea breezes (by day the land warms faster, the air above it rises, and cooler air flows in from the sea); ocean currents and winds. Convection cannot happen in a solid, and it does not happen in space, because there is no fluid to move.

Exam tip

Convection is due to **density differences**. Say “expands, less dense, rises” for the warm fluid and “denser, sinks” for the cool fluid. “Heat rises” scores nothing: it is the warm **fluid** that rises.

Radiation and black bodies

Every body above 0 K emits **electromagnetic waves**, mostly infrared at everyday temperatures. Radiation needs no material: this is how energy from the Sun crosses empty space to reach the Earth.

Learn it word for word.

A **black body** is a perfect absorber: it absorbs all the radiation that falls on it, reflecting and transmitting none. It is also the best possible emitter at any temperature.

Stefan-Boltzmann law (black body): $L = \sigma A T^4$

L : power emitted (luminosity, W) · A : surface area · T : surface temperature in **kelvin** · $\sigma = 5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$

Double $T \rightarrow 2^4 = 16$ times the power · double $A \rightarrow$ twice the power

Worked example 12

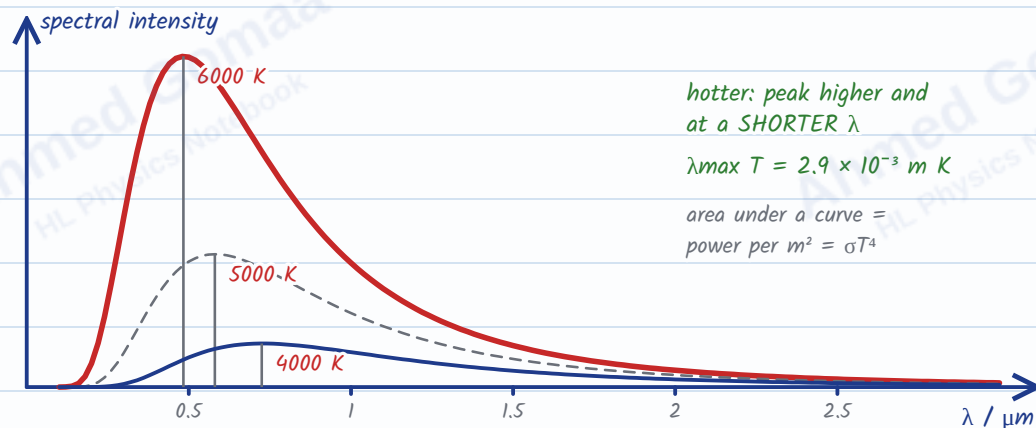
(a) By what factor does the power emitted by a black body increase when it is heated from 50 °C to 250 °C? (b) A black sphere of radius 0.10 m is at 600 K. Find the power it emits.

1. (a) Kelvin: 323 K and 523 K. Power $\propto T^4$, so the factor is $(523/323)^4 = 6.9$. (Using °C would give $5^4 = 625$; wrong.)
2. (b) $A = 4\pi r^2 = 4\pi \times 0.10^2 = 0.126 \text{ m}^2$.
3. $L = \sigma A T^4 = 5.67 \times 10^{-8} \times 0.126 \times 600^4 = 920 \text{ W}$.

× Mistake

Using °C in $\sigma A T^4$. The law only works with the absolute temperature: always add 273 first.

The black-body spectrum and Wien's law



Black-body spectra at three temperatures (calculated, not sketched). Hotter means more power at every wavelength and a peak at a shorter wavelength.

Wien's displacement law: $\lambda_{\text{max}} T = 2.9 \times 10^{-3} \text{ m K}$

λ_{max} : the wavelength at the peak of the spectrum · T in kelvin

Double $T \rightarrow$ the peak moves to half the wavelength

A black body emits a continuous range of wavelengths. As it gets hotter, the curve gets **higher** everywhere (more power) and the **peak moves to shorter wavelengths**. A heated piece of iron goes from dull red to orange to yellow-white. Blue stars are hotter than red stars.

The **area under the curve** is the power emitted per square metre of surface, σT^4 . If the same body has a **bigger area** at the same temperature, it emits more power, but each square metre still gives the same curve: the graph of power per m^2 does not change.

Worked example 13

Find the peak wavelength for (a) human skin at 33 °C, (b) a star with surface temperature 9700 K, (c) a lamp filament at 2900 K.

Name the part of the spectrum each time.

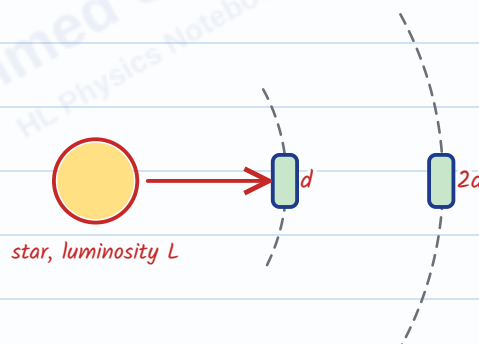
1. (a) $T = 306 \text{ K}$: $\lambda_{\max} = 2.9 \times 10^{-3} / 306 = 9.5 \times 10^{-6} \text{ m}$: infrared
(this is what thermal cameras detect).
2. (b) $\lambda_{\max} = 2.9 \times 10^{-3} / 9700 = 3.0 \times 10^{-7} \text{ m} = 300 \text{ nm}$: ultraviolet.
The star looks blue-white.
3. (c) $\lambda_{\max} = 2.9 \times 10^{-3} / 2900 = 1.0 \times 10^{-6} \text{ m}$: infrared. A filament lamp gives out most of its energy as infrared, not light.

Luminosity and apparent brightness

Learn it word for word.

Luminosity L : the total power radiated by a star (W). For a star modelled as a black body, $L = \sigma AT^4 = \sigma 4\pi R^2 T^4$.

Apparent brightness b : the power received per unit area at the observer (W m^{-2}).



$$b = L / (4\pi d^2)$$

power received per m^2

twice as far $\rightarrow$ area $4\times$
 $\rightarrow b$ is $1/4$ as big

unit: W m^{-2}

The star's power spreads out over bigger and bigger spheres, so the apparent brightness falls as $1/d^2$.

$$b = L / (4\pi d^2) \quad \cdot d: \text{distance from the star}$$

Luminosity is a property of the star. Apparent brightness also depends on how far away we are. Luminosity can also be given in units of the Sun's luminosity, $L_{\odot}$.

Worked example 14

(a) A star 25 ly away has an apparent brightness of $2.0 \times 10^{-9} \text{ W m}^{-2}$. Find its luminosity (1 ly = $9.46 \times 10^{15} \text{ m}$). (b) Another star has $L = 3.8 \times 10^{27} \text{ W}$ and $b = 1.2 \times 10^{-9} \text{ W m}^{-2}$. Find its distance.

1. (a) $d = 25 \times 9.46 \times 10^{15} = 2.37 \times 10^{17} \text{ m}$.

2. $L = 4\pi d^2 b = 4\pi \times (2.37 \times 10^{17})^2 \times 2.0 \times 10^{-9} = 1.4 \times 10^{27} \text{ W}$.

3. (b) $d = \sqrt{L/(4\pi b)} = \sqrt{(3.8 \times 10^{27} / (4\pi \times 1.2 \times 10^{-9}))} = 5.0 \times 10^{17} \text{ m}$.

Worked example 15

(a) Star A has 2.5 times the radius and 1.5 times the surface temperature of star B. Find L_A/L_B . (b) The two stars have the same apparent brightness. Find d_A/d_B . (c) A star has 0.6 times the Sun's surface temperature and 250 times its luminosity. Find its radius in solar radii.

1. (a) $L \propto R^2 T^4$; $L_A/L_B = 2.5^2 \times 1.5^4 = 6.25 \times 5.06 = 32$.

2. (b) Same b means L/d^2 is the same: $d_A/d_B = \sqrt{L_A/L_B} = \sqrt{32} = 5.6$.

3. (c) $250 = (R/R_{\odot})^2 \times 0.6^4 \rightarrow R/R_{\odot} = \sqrt{250/0.6^2} = 15.8/0.36 = 44$.

A cool, very luminous star must be huge: a red giant.

Ratio problems

Write $L \propto R^2 T^4$ and $b \propto L/d^2$, then put in the ratios. The constants σ and 4π cancel, so you never need them.

Writing the explanations

"Define internal energy" (2 marks)

- ✓ the **total random kinetic energy** of the **molecules** (atoms / particles)
- ✓ plus the **total intermolecular potential energy** of the **molecules** (from the forces between them)

The answer must mention molecules, atoms or particles: "KE + PE" on its own scores 0. Also not "average".

"Explain why the temperature stays constant while a substance melts (or boils)" (2–3 marks)

- ✓ the energy supplied increases the **intermolecular potential energy** / breaks the bonds between the molecules / the molecules move further apart
 - ✓ the **average (random) kinetic energy** of the molecules does **not** change
 - ✓ temperature measures the average kinetic energy, so the temperature is constant (the internal energy still increases)
- For freezing: bonds form, potential energy decreases and energy is released; the kinetic energy does not change.

"Explain, in terms of molecules, why evaporation cools a liquid" (2 marks)

- ✓ the **fastest** (most energetic) molecules escape from the surface
- ✓ so the **average kinetic energy** of the remaining molecules decreases, and temperature is a measure of the average kinetic energy

Use "average kinetic energy", not "the liquid loses heat".

"Explain how thermal energy is transferred through a metal by conduction" (2 marks)

- ✓ particles at the hot end have a **higher average kinetic energy**
- ✓ they pass energy to neighbouring particles in **collisions**; **free electrons** carry energy quickly through the metal

Energy flows from high to low temperature; the material itself does not move.

"Explain why there is a temperature difference across a layer that energy is conducted through" (2 marks)

- ✓ energy is conducted through the layer at a rate $\Delta Q/\Delta t = kA\Delta T/\Delta x$
- ✓ a **temperature gradient** ($\Delta T/\Delta x$) is needed for energy to flow; the faster the energy flows (or the poorer the conductor), the bigger the temperature difference

In the steady state the rate is the same through every layer in series.

"Describe how convection transfers energy" (2–3 marks)

- ✓ the fluid near the heat source warms, **expands**, becomes **less dense** and rises
- ✓ cooler, **denser** fluid sinks to replace it, forming a **convection current**

Always mention density. Only fluids show convection.

"Determine the surface temperature of a star from its spectrum" (2 marks)

- ✓ read the **peak wavelength** $\lambda_{\max}$ from the graph (check the unit: nm or μm)
- ✓ use Wien's law: $T = 2.9 \times 10^{-3} / \lambda_{\max}$, with $\lambda_{\max}$ in metres; the answer is in kelvin

Peak wavelength, not the wavelength where the curve ends.

Common mistakes

✗ Ten traps in B.1

1. Using $^{\circ}\text{C}$ in $\bar{E}_k = (3/2)k_B T$, $\sigma A T^4$ or Wien's law. All three need kelvin.
2. Converting a temperature **change** to kelvin by adding 273. A change of 10°C is a change of 10 K.
3. Defining internal energy as "kinetic energy plus potential energy" without saying it is the energy of the **molecules (atoms, particles)**, and without total, random and intermolecular.
4. Saying a hotter body always has more internal energy. Internal energy also depends on the number of particles (and the phase).
5. Saying the temperature rises during melting, or that the kinetic energy increases during a phase change. The potential energy changes; the temperature is constant.
6. Missing a step in a mixing problem with ice (warm the ice $\rightarrow$ melt it $\rightarrow$ warm the water), or forgetting the container.
7. In mixtures, writing ΔT as (final – initial) for the hot body, which gives a negative term. Use (higher – lower) on both sides of "lost = gained".
8. Forgetting that the rate through rods in series is the same in each rod.
9. "Heat rises." The warm, less dense **fluid** rises.
10. Mixing up luminosity (W , a property of the star) and apparent brightness (W m^{-2} , depends on the distance).

Practise next

You have read the notes. Now practise, in this order:

1. **Levelled practice**: first a ★ at Level 2 in every topic (the goal), then Levels 3 and 4 for a 6 or 7. Hints and worked answers help you as you go.
2. **IB-format practice** ([Paper 1A](#) · [Paper 2](#)): timed, one attempt, and your report goes to your teacher. Do these when the practice goal is reached.

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