

THEME B · THE PARTICULATE NATURE OF MATTER

SL & HL ≈ 35 min read

IB Physics B.1 Thermal Energy Transfers — Notes (SL & HL)

Written by Evan Kotronis for the IB Diploma Physics course (first assessment 2025). B.1 is identical for SL and HL — there is no additional HL content in this sub-topic.



SL B.1 questions



HL B.1 questions



Flashcards



Heating & phase change simulation

What this page covers

- ✓ How the molecular model explains the differences between solids, liquids and gases
- ✓ Density, $\rho = m/V$
- ✓ Temperature on the Celsius and Kelvin scales, converting between them, and why a temperature change is the same on both
- ✓ Absolute temperature as a measure of the average kinetic energy of the particles, $\bar{E}_k = \frac{3}{2}k_B T$
- ✓ Internal energy: total random kinetic energy plus total intermolecular potential energy
- ✓ Why a temperature difference sets the direction of the net thermal energy transfer
- ✓ Phase changes at constant temperature, and the terms melting, freezing, boiling, condensing and evaporation
- ✓ Calculations with specific heat capacity and specific latent heat, $Q = mc\Delta T$ and $Q = mL$
- ✓ Conduction, convection and thermal radiation as the main mechanisms of thermal energy transfer

- ✓ Conduction explained by particle kinetic energy, and the rate of conduction $\frac{\Delta Q}{\Delta t} = kA \frac{\Delta T}{\Delta x}$
- ✓ Convection as a result of differences in fluid density (qualitative)
- ✓ Radiation from a black body: the Stefan–Boltzmann law $L = \sigma AT^4$, apparent brightness $b = \frac{L}{4\pi d^2}$ and Wien's displacement law

In one minute

- Solids, liquids and gases differ in particle **spacing, arrangement, motion and intermolecular forces**.
- $T/\text{K} = \theta/^{\circ}\text{C} + 273$. A change of 1°C is a change of 1 K. The **average kinetic energy** of the particles is proportional to the kelvin temperature: $\bar{E}_k = \frac{3}{2}k_B T$.
- **Internal energy** = total random kinetic energy + total intermolecular potential energy of all the particles.
- Thermal energy always flows (net) from higher to lower temperature, until thermal equilibrium.
- Heating changes temperature: $Q = mc\Delta T$. At a phase change the temperature stays constant and only the potential energy changes: $Q = mL$.
- Conduction: $\frac{\Delta Q}{\Delta t} = kA \frac{\Delta T}{\Delta x}$. Convection: bulk movement of fluid driven by density differences. Radiation: electromagnetic waves, $L = \sigma AT^4$.
- Brightness falls with the inverse square of distance, $b = \frac{L}{4\pi d^2}$; a black body's peak wavelength gives its temperature, $\lambda_{\text{max}} T = 2.9 \times 10^{-3} \text{ m K}$.

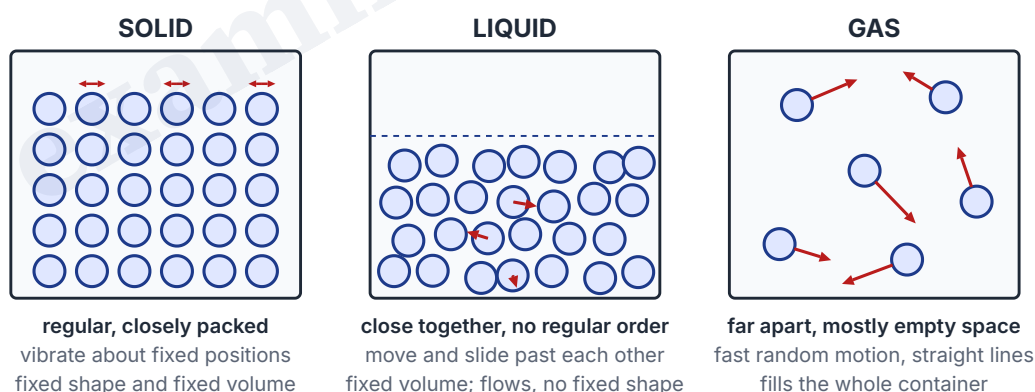
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How does the molecular model explain solids, liquids and gases?

In the molecular (kinetic) model, all matter is made of particles (atoms or molecules) in constant random motion, with attractive and repulsive forces between them. The state of a substance depends on how strongly these intermolecular forces hold the particles together compared with how much kinetic energy the particles have.



red arrows: random motion of particles (kinetic energy)

Particle models of the three states of matter. Particle spacing in the gas is not to scale: in a real gas at room conditions the particles are about ten diameters apart.

	Solid	Liquid	Gas
Arrangement	regular (lattice), fixed positions	disordered, no fixed positions	random, widely spaced
Separation	about one particle diameter	about one particle diameter	about ten particle diameters
Motion	vibrate about fixed equilibrium positions	vibrate and move past one another	fast, random, straight lines between collisions
Intermolecular forces	strong	strong enough to keep particles together	negligible, except during collisions
Macroscopic result	fixed shape and volume; hard to compress	fixed volume, takes the shape of its container; hard to compress	fills its container; easily compressed
Density	high	high (usually slightly less than the solid)	low (about 1/1000 of the liquid)

This is a beautiful example of a **model**: macroscopic observations (shape, compressibility, density, flow) are explained by microscopic behaviour that cannot be seen directly. For example, when water boils its volume increases by a factor of about 1600 at atmospheric pressure. Since volume scales as the cube of particle spacing, the spacing increases by about $\sqrt[3]{1600} \approx 12$ — which is why gas particles are described as "about ten diameters apart".

What is density?

Density is the mass per unit volume of a substance.

$$\rho = \frac{m}{V}$$

- ρ = density (kg m^{-3})
- m = mass (kg)

- V = volume (m^3)

This equation is in the data booklet. Watch the units: $1 \text{ g cm}^{-3} = 1000 \text{ kg m}^{-3}$, and $1 \text{ cm}^3 = 10^{-6} \text{ m}^3$.

Substance (about 20 °C and atmospheric pressure unless stated)	Approximate density / kg m^{-3}
Air	1.2
Steam (100 °C)	0.6
Ice (0 °C)	920
Water	1000
Aluminium	2700
Copper	8960

Water is unusual: ice is less dense than liquid water, so ice floats. For most substances the solid is slightly denser than the liquid.

How are the Kelvin and Celsius scales related, and what does temperature measure?

The Kelvin (absolute) temperature of a substance is proportional to the average random kinetic energy of its particles: $\bar{E}_k = \frac{3}{2} k_B T$.

Celsius and Kelvin

$$T/\text{K} = \theta/^{\circ}\text{C} + 273$$

- The conversion is in the data booklet ("unit conversions"). Use 273 in IB answers.
- The two scales have the same size of degree, so a **temperature change** has the same value on both: a rise from 20 °C to 35 °C is a rise of 15 °C *and* of 15 K. In $Q = mc\Delta T$ you can use either.

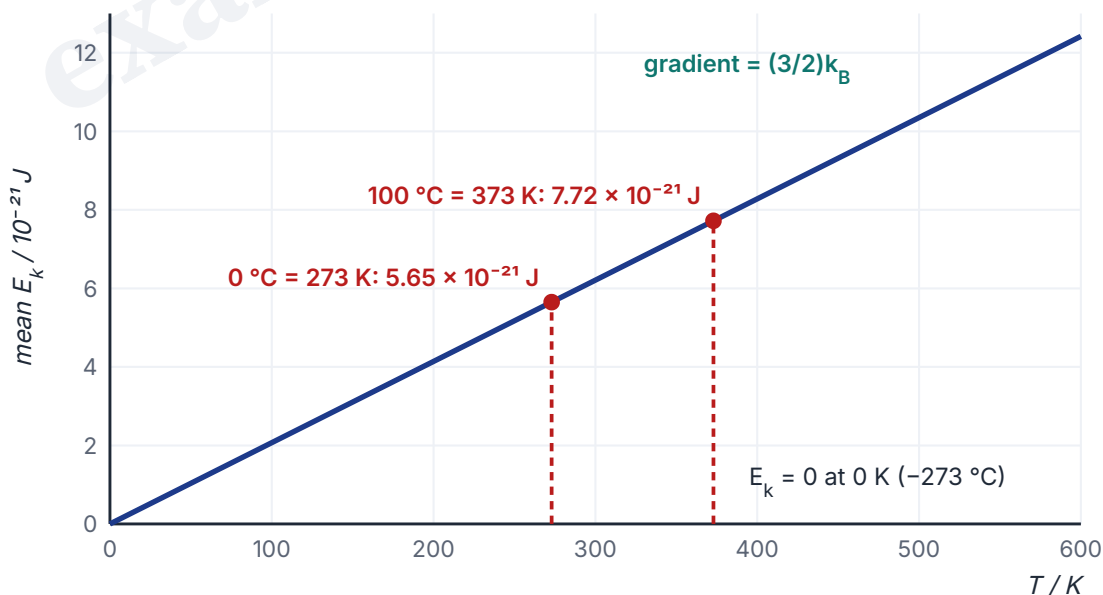
- **Absolute zero**, 0 K (−273 °C), is the lowest possible temperature: the temperature at which the particles have their minimum possible kinetic energy. There are no negative kelvin temperatures.
- Any equation that uses T itself rather than ΔT — such as $\bar{E}_k = \frac{3}{2}k_B T$, $L = \sigma AT^4$ and Wien's law — needs the temperature **in kelvin**.

Temperature and particle kinetic energy

$$\bar{E}_k = \frac{3}{2}k_B T$$

- $\bar{E}_k$ = average (mean) random kinetic energy of a particle (J); the data booklet writes it simply as E_k
- k_B = Boltzmann constant, $1.38 \times 10^{-23} \text{ J K}^{-1}$ (data booklet)
- T = absolute temperature (K)

The equation is in the data booklet. It describes the *average*: at any instant individual particles have a wide range of speeds. It connects a macroscopic measurement (a thermometer reading) to a microscopic quantity (particle energy) — a model you will develop for gases in B.3.



The average kinetic energy of the particles is directly proportional to the absolute temperature. On a Celsius axis the same line would not pass through the origin, so $\bar{E}_k$ is not proportional to the Celsius temperature.

WORKED EXAMPLE 1 Easy · State / Calculate

A sample of gas is heated from 27 °C to 127 °C.

(a) State the change in temperature in kelvin. (b) Calculate the average kinetic energy of the gas particles at 27 °C. (c) Determine the ratio $\frac{\bar{E}_k \text{ at } 127^\circ\text{C}}{\bar{E}_k \text{ at } 27^\circ\text{C}}$. (d) Determine the Celsius temperature at which the average kinetic energy is double its value at 27 °C.

(a) A change of 100 °C is a change of **100 K**.

(b) $T = 27 + 273 = 300 \text{ K}$; $\bar{E}_k = \frac{3}{2}(1.38 \times 10^{-23})(300) = \mathbf{6.21 \times 10^{-21} \text{ J}}$

(c) $\bar{E}_k \propto T$ in kelvin: $\frac{127 + 273}{27 + 273} = \frac{400}{300} = \mathbf{1.33}$

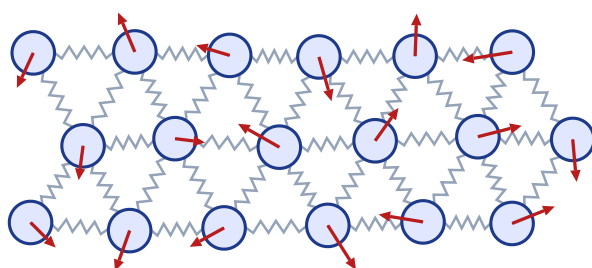
Using Celsius gives $127/27 = 4.70$ — a classic wrong answer.

(d) Double the kinetic energy needs double the kelvin temperature: $T = 600 \text{ K}$, so $\theta = 600 - 273 = \mathbf{327^\circ\text{C}}$ (not 54 °C).

What is internal energy?

The internal energy of a system is the total intermolecular potential energy arising from the forces between its molecules plus the total random kinetic energy of its molecules arising from their random motion.

$$U = \sum E_p + \sum E_k$$



arrows: random velocities
 → total random kinetic energy ΣE_k

springs: intermolecular forces
 → total potential energy ΣE_p

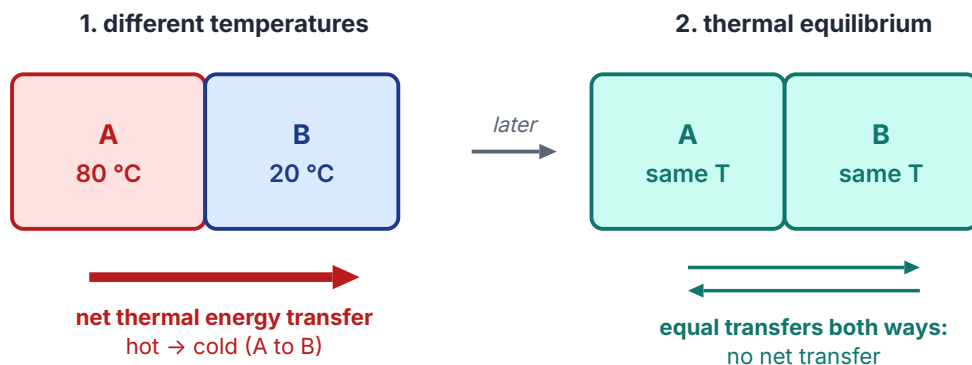
$$\text{internal energy } U = \Sigma E_k \text{ (random motion)} + \Sigma E_p \text{ (intermolecular forces)}$$

The springs represent intermolecular forces (potential energy store); the arrows represent random motion (kinetic energy store). Internal energy is the sum over all the particles.

- **Random kinetic energy** comes from translational, vibrational and rotational motion of particles. Its average per particle is linked to temperature.
- **Intermolecular potential energy** depends on the separation of the particles. It changes significantly when the particles move further apart, as in melting and especially boiling.
- Internal energy is **not** the same as temperature. A bath of warm water has far more internal energy than a cup of boiling water, because it has many more particles — even though its temperature is lower.
- The kinetic energy of the body moving as a whole (or its gravitational potential energy) is *not* part of its internal energy: only *random* motion counts.
- In an ideal gas (B.3) the intermolecular forces are assumed to be zero, so its internal energy is purely random kinetic energy.

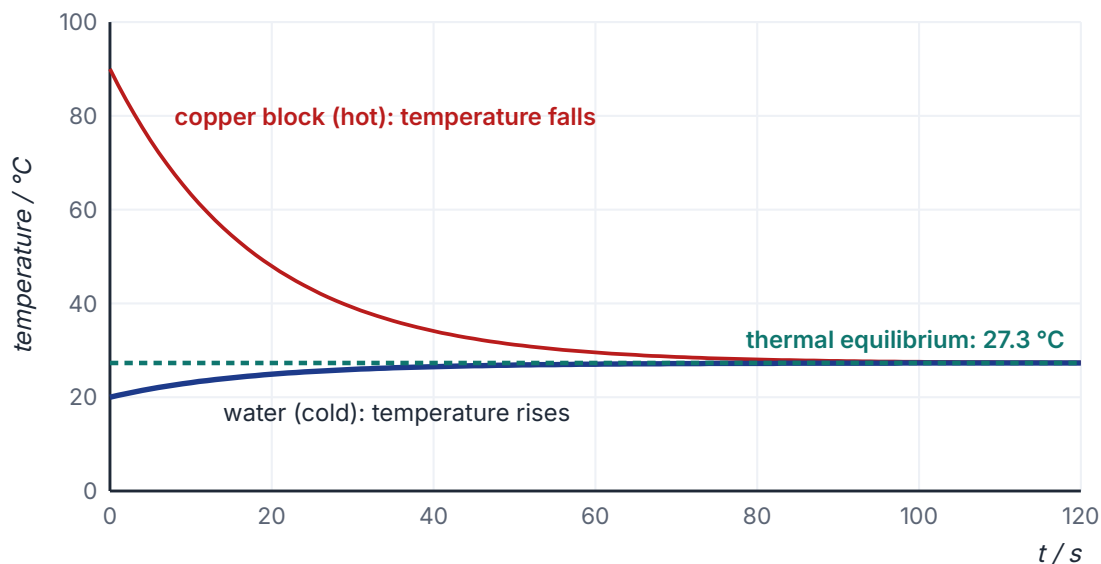
What determines the direction of thermal energy transfer?

When two bodies are in thermal contact, the net thermal energy transfer is always from the body at the higher temperature to the body at the lower temperature. When their temperatures are equal there is no net transfer: the bodies are in thermal equilibrium.



The direction of the net transfer depends only on the temperatures — not on which body has more internal energy.

- **Heat** (symbol Q) means energy transferred *because of a temperature difference*. A body does not "contain heat"; it contains internal energy. In answers, say "thermal energy is transferred".
- Particle explanation: where the particles of the hotter body meet those of the colder body, the faster particles on average lose kinetic energy in collisions and the slower ones gain it, so the average kinetic energy evens out.
- A large, cool body can have more internal energy than a small, hot one, yet energy still flows from the small hot body to the large cool one.
- If no energy is exchanged with the surroundings, the energy lost by the hotter body equals the energy gained by the colder body. This is the basis of "method of mixtures" calculations (worked example 4).

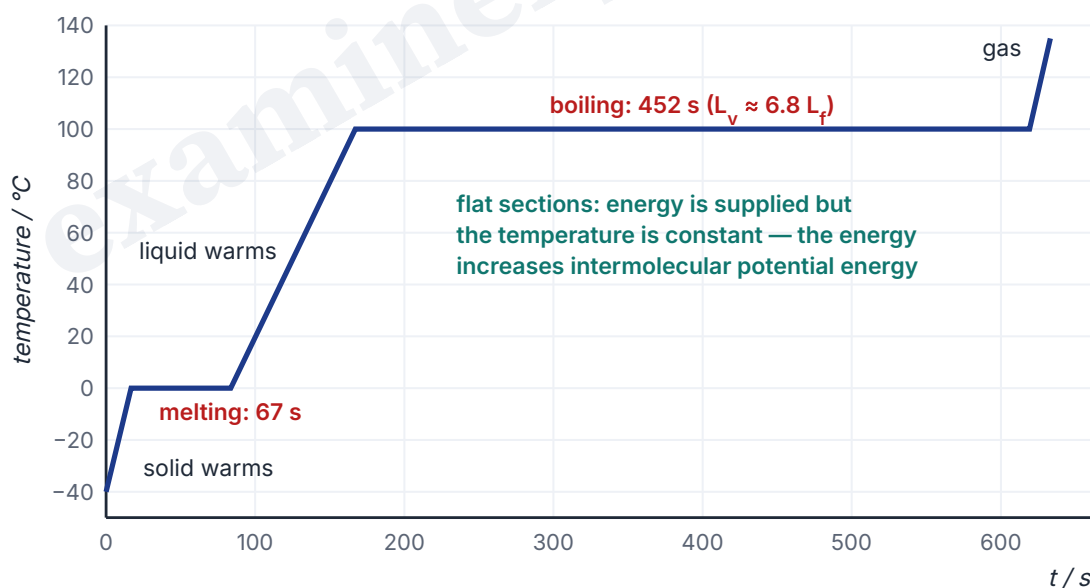


A 0.50 kg copper block at 90 °C is dropped into 0.40 kg of water at 20 °C (no losses). The final temperature, 27.3 °C, follows from energy lost = energy gained; the shape of the curves is illustrative. The water's temperature changes much less because its heat capacity mc is about 8.6 times larger.

What happens to particles during a phase change?

A phase change is a change of state that happens at constant temperature: the energy transferred changes the intermolecular potential energy of the particles (the separation and arrangement of the particles change), while their average kinetic energy stays the same.

Term	Change	Energy	What the particles do
Melting	solid → liquid at the melting point	absorbed	break free of fixed lattice positions; potential energy increases
Freezing (solidifying)	liquid → solid at the melting point	released	settle into fixed positions; potential energy decreases
Boiling	liquid → gas throughout the liquid at the boiling point	absorbed	separate completely, overcoming almost all intermolecular attraction
Condensing	gas → liquid	released	come close together again; potential energy decreases
Evaporation	liquid → gas from the surface, at any temperature	absorbed from the liquid	the fastest particles near the surface escape

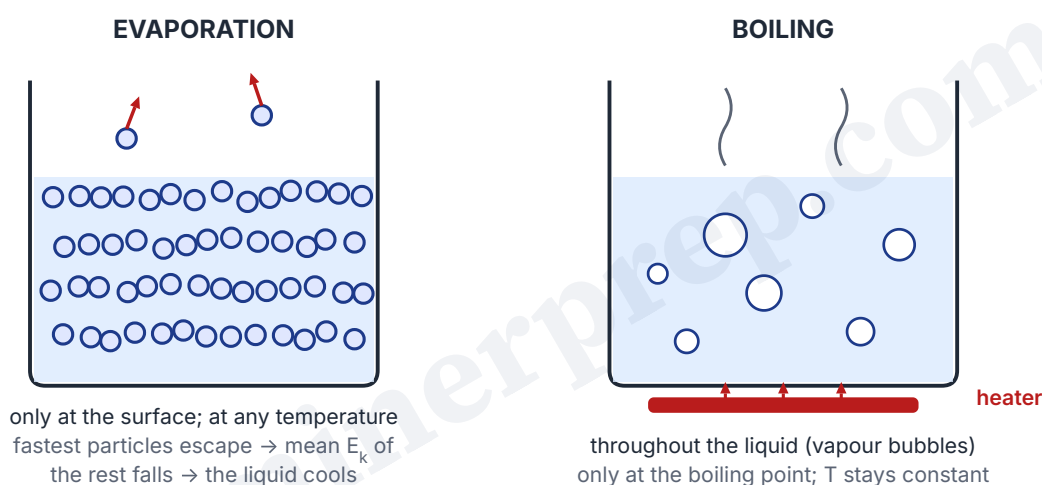


Heating curve for 0.10 kg of ice, initially at $-40\text{ }^{\circ}\text{C}$, heated at a constant 500 W with no losses (computed from typical values of c and L). Sloping sections: kinetic energy increases, so the temperature rises. Flat sections: potential energy increases at constant temperature. Boiling takes almost seven times longer than melting.

- Why is the temperature constant? The average **kinetic** energy of the particles, and so the temperature, does not change; all the energy supplied goes into

increasing the intermolecular **potential** energy as bonds are broken or weakened.

- Why is L_v much bigger than L_f ? Melting only loosens the structure (particles stay about as close as before), but boiling separates the particles completely and work must also be done pushing back the atmosphere as the volume increases enormously.
- A **cooling curve** is the mirror image: the temperature stays constant while the substance freezes or condenses, because energy is released by the decrease in potential energy.



Evaporation happens only at the surface, at any temperature, and cools the remaining liquid.

Boiling happens throughout the liquid, at one fixed temperature for a given pressure.

Evaporation cools because only the particles with the highest kinetic energies can overcome the attraction of their neighbours and escape. The average kinetic energy of those left behind falls, so the temperature of the liquid falls — this is why sweating cools you. Evaporation is faster at a higher temperature, with a larger surface area and when air flow removes the vapour.

TRY IT YOURSELF

B.1 Heating and Phase Change simulation: heat a substance at constant power, watch the heating curve build up and see which sections change the kinetic energy and which change the potential energy of the particles.

How do you calculate thermal energy transfers with c and L ?

The specific heat capacity c of a substance is the energy required to raise the temperature of 1 kg of the substance by 1 K. The specific latent heat L is the energy required to change the phase of 1 kg of the substance at constant temperature.

$$Q = mc\Delta T$$

$$Q = mL$$

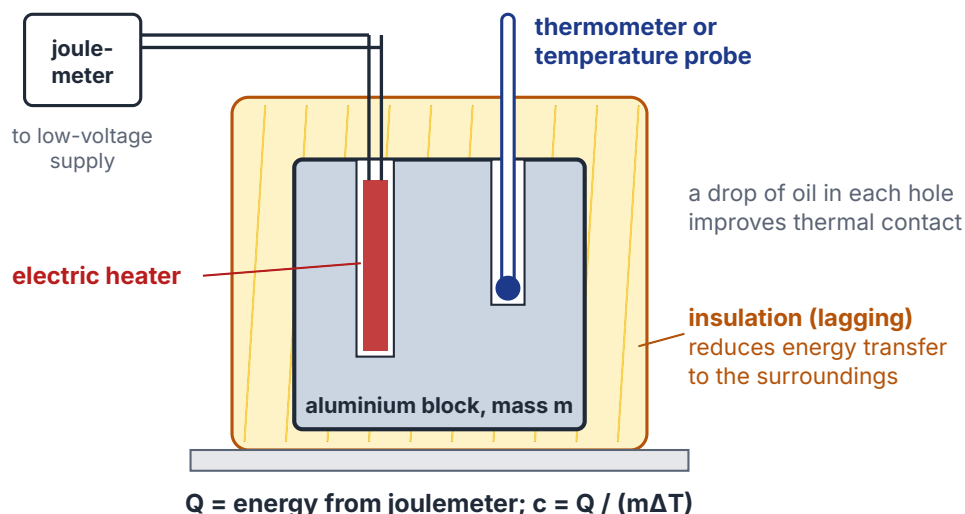
- Q = thermal energy transferred (J)
- m = mass (kg)
- c = specific heat capacity ($\text{J kg}^{-1} \text{K}^{-1}$)
- ΔT = change in temperature (K or $^{\circ}\text{C}$ — the values are the same)
- L = specific latent heat (J kg^{-1}): L_f for fusion (melting/freezing), L_v for vaporization (boiling/condensing)

Both equations are in the data booklet. Use $Q = mc\Delta T$ when the temperature changes and there is no change of phase; use $Q = mL$ during a change of phase, when the temperature is constant. Values of c and L are always given in the question.

Substance	$c / \text{J kg}^{-1} \text{K}^{-1}$	$L_f / \text{J kg}^{-1}$	$L_v / \text{J kg}^{-1}$
Water	4180 (liquid); 2100 (ice)	3.34×10^5	2.26×10^6
Aluminium	900	4.0×10^5	1.1×10^7
Copper	390	2.1×10^5	4.7×10^6

Typical values. Water's very large specific heat capacity is why it is used in central-heating systems and car cooling systems, and why coastal climates change temperature slowly.

Measuring specific heat capacity: the electrical method



A heater of known power warms an insulated metal block. The energy supplied is $Q = Pt$ (or read from a joulemeter); the temperature rise is measured with a thermometer or probe.

WORKED EXAMPLE 2 Medium · Calculate / Suggest

In the apparatus above, a 48.0 W heater is switched on for 5.00 min. The temperature of the 1.00 kg aluminium block rises from 19.0 °C to 34.0 °C.

(a) Calculate the energy supplied by the heater. (b) Determine the specific heat capacity of aluminium given by these data. (c) The accepted value is $900 \text{ J kg}^{-1} \text{ K}^{-1}$. Suggest why the experimental value is larger, and estimate the energy transferred to the surroundings.

(a) $Q = Pt = 48.0 \times (5.00 \times 60) = 1.44 \times 10^4 \text{ J}$

(b) $c = \frac{Q}{m\Delta T} = \frac{1.44 \times 10^4}{1.00 \times 15.0} = 960 \text{ J kg}^{-1} \text{ K}^{-1}$

(c) Some of the energy supplied is transferred to the surroundings (and to the heater and thermometer) instead of to the block, so the temperature rise is smaller than it would be with no losses, and $c = Q/(m\Delta T)$ comes out too large.

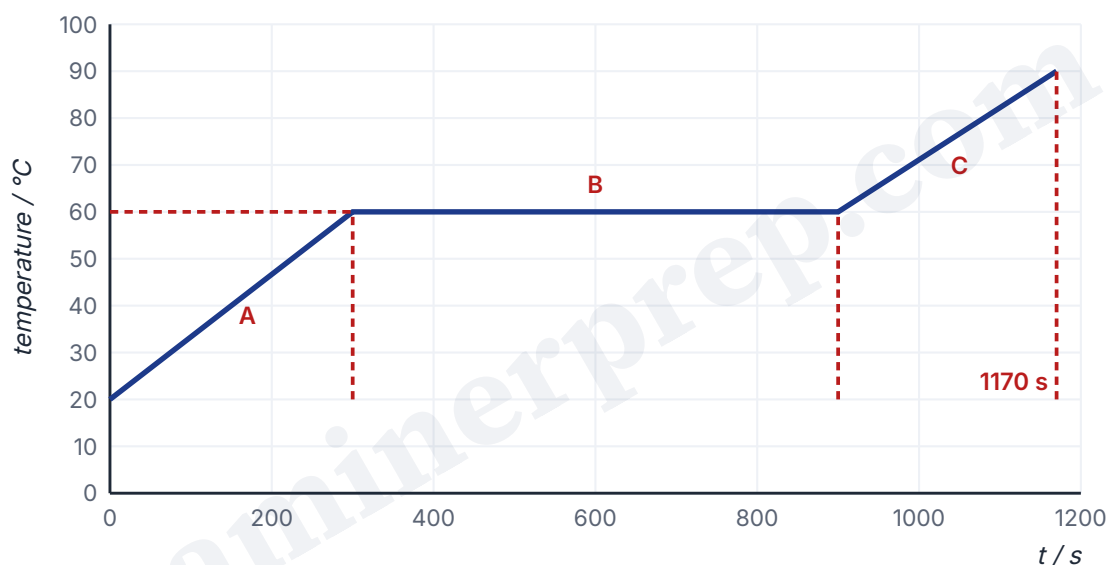
Energy actually absorbed by the block $= 1.00 \times 900 \times 15.0 = 1.35 \times 10^4 \text{ J}$; energy transferred elsewhere $\approx 1.44 \times 10^4 - 1.35 \times 10^4 = 900 \text{ J}$ (about 6 % of the input).

Improvements: better lagging, oil in the holes, and starting a few degrees below room temperature and finishing the same amount above, so that energy gained from and lost to

the surroundings roughly cancel.

Using a heating curve

When a substance is heated at constant power P , $Q = Pt$. On a temperature–time graph the gradient of a sloping section is $\frac{\Delta T}{\Delta t} = \frac{P}{mc}$, so a **shallower gradient means a larger specific heat capacity**. The length of a flat section gives the latent heat: $L = \frac{Pt}{m}$.



Worked example 3: wax heated at a constant 40.0 W. A — solid warms; B — melting; C — liquid warms.

WORKED EXAMPLE 3 Medium · Determine (graph)

A 0.150 kg sample of solid wax in a well-insulated container is heated by a 40.0 W heater. The graph above shows how its temperature varies with time. Assume all the energy from the heater goes into the wax.

- (a) State the melting point of the wax. (b) Determine the specific heat capacity of solid wax. (c) Determine the specific latent heat of fusion of wax. (d) Deduce, using the graph, whether the specific heat capacity of liquid wax is greater or smaller than that of solid wax, and calculate it.

(a) The temperature is constant during melting (section B): **60 °C**

(b) Section A: $Q = Pt = 40.0 \times 300 = 1.20 \times 10^4 \text{ J}$ for $\Delta T = 60 - 20 = 40 \text{ K}$.

$$c = \frac{Q}{m\Delta T} = \frac{1.20 \times 10^4}{0.150 \times 40} = 2.0 \times 10^3 \text{ J kg}^{-1} \text{ K}^{-1}$$

(c) Section B lasts $900 - 300 = 600 \text{ s}$: $Q = 40.0 \times 600 = 2.40 \times 10^4 \text{ J}$.

$$L_f = \frac{Q}{m} = \frac{2.40 \times 10^4}{0.150} = 1.6 \times 10^5 \text{ J kg}^{-1}$$

(d) Gradient of A = $40/300 = 0.133 \text{ K s}^{-1}$; gradient of C = $30/270 = 0.111 \text{ K s}^{-1}$. The gradient is $P/(mc)$ with P and m the same, so the smaller gradient means the liquid has the **greater** specific heat capacity:

$$c = \frac{40.0 \times 270}{0.150 \times 30} = 2.4 \times 10^3 \text{ J kg}^{-1} \text{ K}^{-1}$$

Method of mixtures

When two substances at different temperatures are mixed in an insulated container, they reach a common final temperature. With no losses:

energy lost by the hotter substance = energy gained by the colder substance

Write each side as a sum of $mc\Delta T$ and mL terms, one for each stage, with every ΔT taken as a positive temperature *change*. If ice is involved, first check whether there is enough energy available to melt all of it.

WORKED EXAMPLE 4 Hard · Determine

A student adds 0.050 kg of ice at -10.0°C to 0.300 kg of lemonade at 24.0°C in an insulated cup. Treat lemonade as water.

Data: $c_{\text{water}} = 4180 \text{ J kg}^{-1} \text{ K}^{-1}$, $c_{\text{ice}} = 2100 \text{ J kg}^{-1} \text{ K}^{-1}$, $L_f = 3.34 \times 10^5 \text{ J kg}^{-1}$.

(a) Show that all the ice melts. (b) Determine the final temperature of the drink.

(a) Energy to warm the ice to 0°C : $0.050 \times 2100 \times 10.0 = 1050 \text{ J}$

Energy to melt the ice: $0.050 \times 3.34 \times 10^5 = 16\,700 \text{ J}$

Total needed = $17\,750 \text{ J}$. Energy released if the lemonade cools all the way

to 0 °C: $0.300 \times 4180 \times 24.0 = 30\,100 \text{ J}$.

Since $30\,100 \text{ J} > 17\,750 \text{ J}$, **all the ice melts** and the final temperature is above 0 °C.

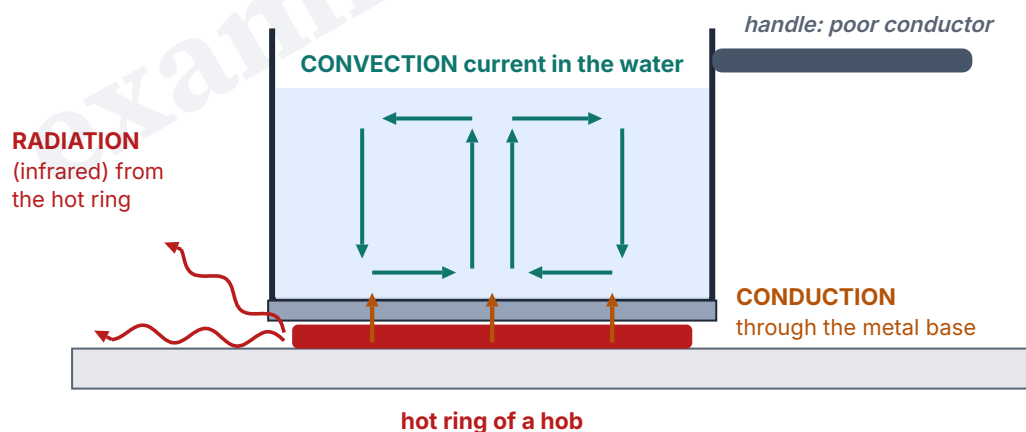
(b) Let the final temperature be T (in °C). Energy lost by lemonade = energy gained by ice, then by the melted ice water:

$$0.300 \times 4180 \times (24.0 - T) = 1050 + 16\,700 + 0.050 \times 4180 \times (T - 0)$$
$$30\,096 - 1254T = 17\,750 + 209T \Rightarrow T = \frac{12\,346}{1463} = \mathbf{8.4 \text{ °C}} \text{ (8.44 °C)}$$

Forgetting the latent heat gives 19.9 °C; forgetting to warm the melted ice from 0 °C to T gives 9.8 °C. Both are common errors.

What are conduction, convection and radiation?

Thermal energy is transferred mainly in three ways: conduction, convection and thermal radiation. Conduction and convection need a medium; radiation does not.



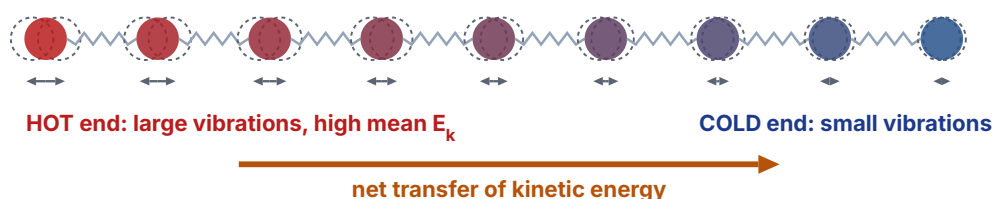
All three mechanisms at once: radiation from the hot ring, conduction through the metal base of the pan, convection in the water.

Mechanism	How the energy moves	Where it is important
Conduction	kinetic energy passed between neighbouring particles (and by free electrons in metals); no bulk movement of matter	mainly solids, especially metals; poor in liquids, very poor in gases
Convection	bulk movement of a fluid caused by density differences carries internal energy with it	liquids and gases only
Thermal radiation	emission of electromagnetic waves (mainly infrared at everyday temperatures) from the surface of a body	everywhere, including a vacuum; dominant for very hot bodies and in space

How does conduction work, and how fast is it?

Conduction is the transfer of thermal energy through a material from a region of higher temperature to a region of lower temperature by collisions between particles: particles with a higher average kinetic energy pass kinetic energy to neighbouring particles with a lower average kinetic energy.

All solids: energy passed on by collisions between vibrating neighbouring particles



Metal: free (delocalised) electrons also carry kinetic energy quickly through the lattice



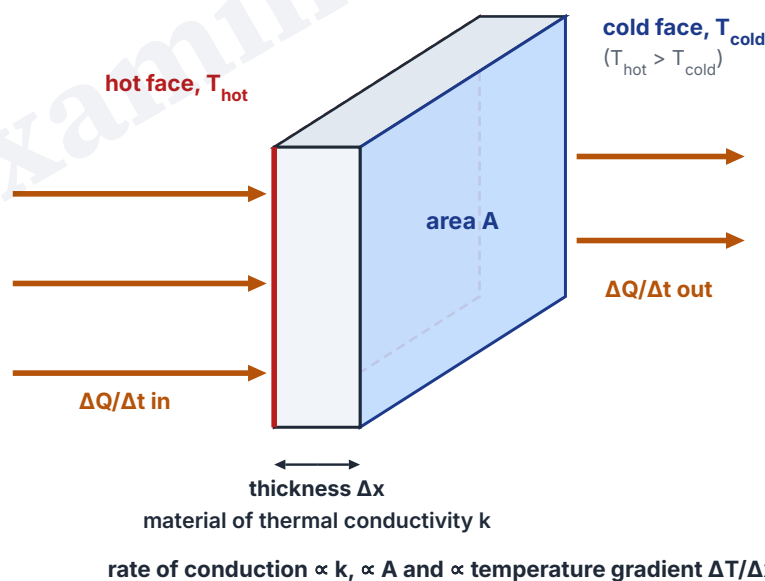
Top: in all solids, vibrating particles at the hot end pass kinetic energy to their neighbours. Bottom: in metals, mobile free electrons also carry kinetic energy rapidly through the material, which is why metals are good thermal conductors.

The rate of conduction

$$\frac{\Delta Q}{\Delta t} = kA \frac{\Delta T}{\Delta x}$$

- $\frac{\Delta Q}{\Delta t}$ = rate of thermal energy transfer (W)
- k = thermal conductivity of the material ($\text{W m}^{-1} \text{K}^{-1}$)
- A = cross-sectional area through which the energy flows (m^2)
- $\frac{\Delta T}{\Delta x}$ = temperature gradient: temperature difference ΔT across a thickness Δx (K m^{-1})

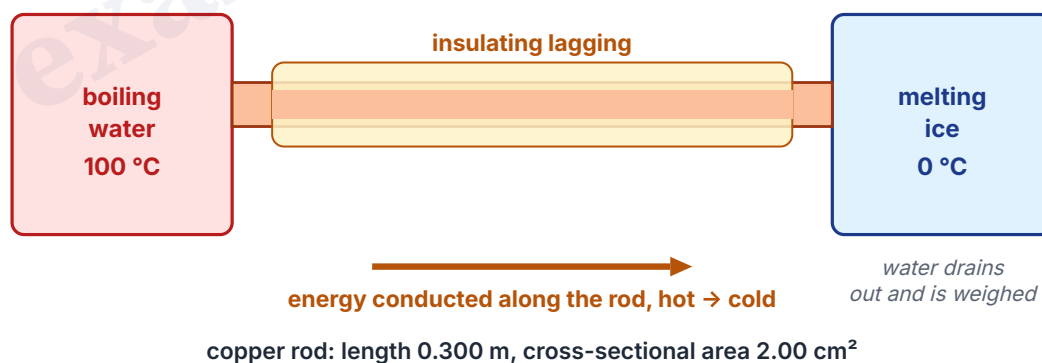
This equation is in the data booklet. The rate of conduction is greater for a better conductor (larger k), a larger cross-sectional area and a steeper temperature gradient (larger temperature difference or thinner material). Strictly the energy flows *down* the gradient, from hot to cold; use magnitudes in calculations and state the direction in words.



Quantities in the conduction equation. Energy is conducted perpendicular to the faces, from the hot face to the cold face.

Material	Approximate $k / \text{W m}^{-1} \text{K}^{-1}$	Comment
Copper	390	excellent conductor: free electrons
Aluminium	240	cooking pans, heat sinks
Stainless steel	16	much poorer than most metals
Glass	0.8	windows
Water	0.6	liquids conduct poorly
Wood	0.1–0.2	pan handles
Air	0.025	trapped air is an excellent insulator (wool, foam, double glazing)

A metal bench and a wooden bench in the same park are at the same temperature, but the metal feels colder: it conducts energy away from your hand much faster, so your skin cools faster.



Worked example 5: a lagged copper rod conducts energy from boiling water to melting ice.

WORKED EXAMPLE 5 Medium · Show that / Determine

A copper rod of length 0.300 m and cross-sectional area 2.00 cm² is lagged along its length. One end is in boiling water at 100 °C and the other in melting ice at 0 °C. The thermal conductivity of copper is 390 W m⁻¹ K⁻¹; the specific latent heat of fusion of ice is 3.34 × 10⁵ J kg⁻¹.

(a) Show that the rate of thermal energy transfer along the rod is about 26 W. (b) Determine the mass of ice melted by the rod in 10.0 minutes. (c) Determine the temperature of the rod 0.100 m from the hot end. (d) Explain why the rod is lagged.

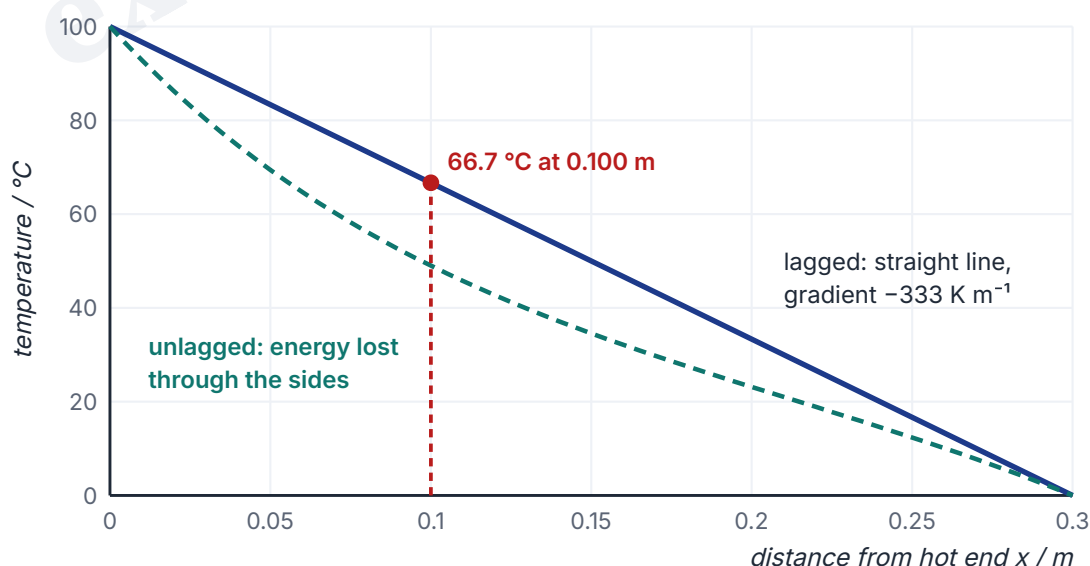
(a) $A = 2.00 \text{ cm}^2 = 2.00 \times 10^{-4} \text{ m}^2$.

$$\frac{\Delta Q}{\Delta t} = kA \frac{\Delta T}{\Delta x} = 390 \times 2.00 \times 10^{-4} \times \frac{100}{0.300} = \mathbf{26.0 \text{ W} \approx 26 \text{ W}}$$

(b) $Q = 26.0 \times 600 = 1.56 \times 10^4 \text{ J}; m = \frac{Q}{L_f} = \frac{1.56 \times 10^4}{3.34 \times 10^5} = \mathbf{0.047 \text{ kg}}$
(47 g)

(c) With lagging, the same power passes through every cross-section, so the temperature gradient is uniform: $\frac{100}{0.300} = 333 \text{ K m}^{-1}$. At 0.100 m:
 $100 - 333 \times 0.100 = \mathbf{66.7 \text{ }^\circ\text{C}}$

(d) Without lagging, energy would be transferred from the sides of the rod to the surroundings, so less energy would reach the ice and the temperature gradient would not be uniform (see the graph below). The equation assumes all the energy flows along the rod.

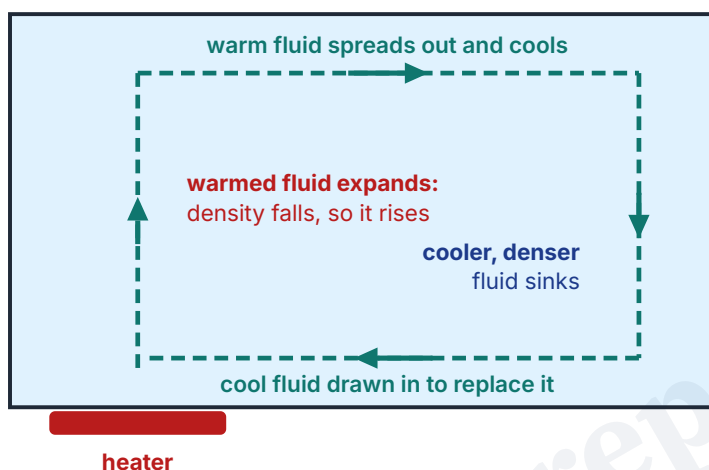


Temperature along the rod in worked example 5. Lagged: a straight line (uniform gradient).

Unlagged: energy leaks out through the sides, so the curve sags and the gradient at the cold end — and therefore the power reaching the ice — is smaller (illustrative curve).

What causes convection?

Convection is the transfer of thermal energy by the bulk movement of a fluid, caused by differences in density within the fluid.



the fluid itself moves and carries its internal energy

not possible in solids or a vacuum

A convection current. Fluid near the heater is warmed, expands and becomes less dense, so it rises; cooler, denser fluid sinks to take its place, setting up a continuous circulation.

1. Fluid near a hot surface gains internal energy; its particles move faster and spread further apart, so the fluid **expands**.
 2. Its **density decreases**, so it is less dense than the surrounding fluid and rises (it is buoyed up by the surrounding denser fluid).
 3. Cooler, denser fluid sinks and flows in to replace it, and is in turn heated.
 4. The circulating fluid carries internal energy from the hot region to the cooler regions.
- Convection needs a fluid (liquid or gas) and gravity. It cannot happen in a solid, whose particles cannot flow, or in a vacuum.
 - Examples: a room radiator warming a room (mostly by convection, despite the name); sea and land breezes; the heating element at the bottom of a kettle; ocean currents and weather systems.
 - Say "the warm fluid rises because it is less dense" — not "heat rises". Thermal energy itself does not rise; the fluid moves.
 - Only a qualitative treatment of convection is required.

How is energy radiated, and what are luminosity and apparent brightness?

Thermal radiation is the emission of electromagnetic waves from the surface of a body because of its temperature. A black body is an idealised body that absorbs all radiation falling on it and is the best possible emitter at any temperature.

- Every body above 0 K emits thermal radiation. A body at room temperature emits mostly infrared; a body above about 800 K glows visibly.
- A body also absorbs radiation from its surroundings. Its temperature is steady when the power absorbed equals the power emitted (energy balance, B.2).
- Stars are modelled very well as black bodies. Real surfaces emit less than a black body at the same temperature (emissivity, B.2).

The Stefan–Boltzmann law

$$L = \sigma AT^4$$

- L = luminosity: the total power radiated by the body (W)
- σ = Stefan–Boltzmann constant, $5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$ (data booklet)
- A = surface area of the body (m^2); for a sphere of radius R , $A = 4\pi R^2$
- T = absolute surface temperature (K)

This equation is in the data booklet. Because of the fourth power, doubling the kelvin temperature multiplies the power emitted by $2^4 = 16$. The luminosity of a star is often given as a multiple of the Sun's luminosity, $L_{\odot}$ (about $3.83 \times 10^{26} \text{ W}$; the value is given in questions when needed). In ratio form, for two spherical bodies:

$$\frac{L_1}{L_2} = \left(\frac{R_1}{R_2}\right)^2 \left(\frac{T_1}{T_2}\right)^4$$

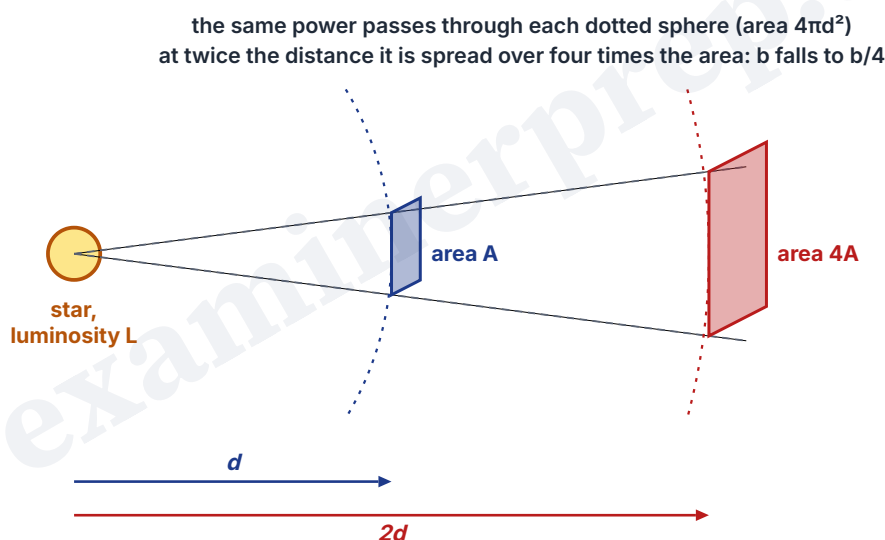
Apparent brightness

The apparent brightness b of a source is the power received per unit area perpendicular to the direction of the radiation, at the observer's position.

$$b = \frac{L}{4\pi d^2}$$

- b = apparent brightness (W m^{-2})
- L = luminosity of the source (W)
- d = distance from the source (m)

This equation is in the data booklet. The source radiates equally in all directions, so the power L is spread over a sphere of area $4\pi d^2$. Brightness obeys an **inverse square law**: doubling the distance quarters the brightness.



The same power passes through each sphere around the source. At twice the distance it is spread over four times the area, so the apparent brightness is a quarter as large.

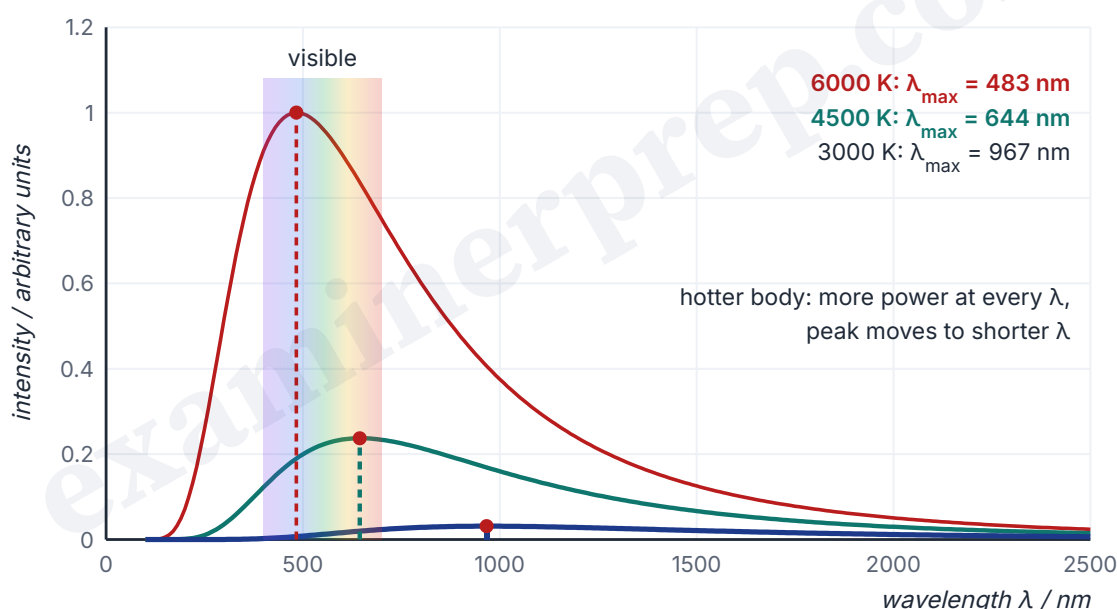
- **Luminosity** is a property of the source (total power emitted). **Apparent brightness** depends also on the distance to the observer. A dim nearby star can look brighter than a luminous distant one.
- Check with the Sun: $b = \frac{3.83 \times 10^{26}}{4\pi(1.50 \times 10^{11})^2} = 1.35 \times 10^3 \text{ W m}^{-2}$ — in agreement with the solar constant $S = 1.36 \times 10^3 \text{ W m}^{-2}$ (data booklet, fundamental constants; used in B.2) to within rounding.
- Astronomers measure b ; if the distance is known (from stellar parallax, E.5), $L = 4\pi d^2 b$ follows, and then $L = \sigma AT^4$ gives the radius of the star.

What does a black-body spectrum show, and how does Wien's law give temperature?

Wien's displacement law: the wavelength at which a black body emits the maximum power per unit wavelength is inversely proportional to its absolute temperature, $\lambda_{\max}T = 2.9 \times 10^{-3} \text{ m K}$.

$$\lambda_{\max}T = 2.9 \times 10^{-3} \text{ m K}$$

- $\lambda_{\max}$ = peak wavelength of the emission spectrum (m)
- T = absolute temperature of the body (K)



Black-body emission spectra at three temperatures (computed, scaled to the peak of the 6000 K curve). The area under each curve is proportional to the total power emitted per unit area, σT^4 .

- The spectrum is **continuous**: all wavelengths are emitted, with a single peak.
- As the temperature increases, the intensity increases at every wavelength (the area under the curve grows as T^4) and the peak moves to **shorter** wavelengths.
- That is why hot bodies change colour as they heat up — dull red, orange, yellow-white, then bluish-white — and why the colour of a star tells you its surface temperature: red stars are cool (about 3000 K), blue-white stars are hot (above 10 000 K).

- The Sun's spectrum peaks at about 500 nm, giving $T = \frac{2.9 \times 10^{-3}}{500 \times 10^{-9}} = 5800 \text{ K}$.

WORKED EXAMPLE 6 Hard · Show that / Determine

The spectrum of a star peaks at a wavelength of 414 nm. The star's luminosity is $25L_{\odot}$ and it is 25 ly from Earth.

Data: $L_{\odot} = 3.83 \times 10^{26} \text{ W}$, radius of the Sun $R_{\odot} = 6.96 \times 10^8 \text{ m}$, $1 \text{ ly} = 9.46 \times 10^{15} \text{ m}$.

- (a) Show that the surface temperature of the star is about 7000 K. (b) Determine the radius of the star, giving your answer as a multiple of $R_{\odot}$. (c) Calculate the apparent brightness of the star at Earth.

$$\text{(a)} \quad T = \frac{2.9 \times 10^{-3}}{414 \times 10^{-9}} = 7.00 \times 10^3 \text{ K} \approx 7000 \text{ K}$$

$$\text{(b)} \quad L = 25 \times 3.83 \times 10^{26} = 9.58 \times 10^{27} \text{ W}.$$

$$L = \sigma(4\pi R^2)T^4 \Rightarrow R = \sqrt{\frac{L}{4\pi\sigma T^4}} = \sqrt{\frac{9.58 \times 10^{27}}{4\pi \times 5.67 \times 10^{-8} \times (7.00 \times 10^3)^4}} = 2.37 \times 10^9 \text{ m}$$

$$\frac{R}{R_{\odot}} = \frac{2.37 \times 10^9}{6.96 \times 10^8} = 3.4, \text{ so } R \approx 3.4 R_{\odot}$$

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

$$b = \frac{L}{4\pi d^2} = \frac{9.58 \times 10^{27}}{4\pi(2.37 \times 10^{17})^2} = 1.4 \times 10^{-8} \text{ W m}^{-2} \quad (1.36 \times 10^{-8} \text{ W m}^{-2})$$

Remember to convert nm to m in (a), use $A = 4\pi R^2$ (the whole surface, not πR^2) in (b), and convert light years to metres in (c).

Exam tips for B.1

EXAM TIP 1 — "THERMAL ENERGY", NOT "HEAT"

When you describe what happens to energy (brakes warming up as a bicycle stops, energy absorbed by a cold drink), write "transferred as thermal energy" or "increases the internal energy". Mark schemes routinely refuse "heat" as the name of an energy store. Use "heat" only as a verb or for a transfer driven by a temperature difference.

EXAM TIP 2 — EXPLAINING A PHASE CHANGE

A full answer has three parts: (1) energy is still being supplied (or removed); (2) the average kinetic energy of the particles, and so the temperature, is constant; (3) the energy changes the intermolecular **potential** energy as the particle separation/arrangement changes. "Bonds are broken" alone is rarely enough.

EXAM TIP 3 — KELVIN IN T-EQUATIONS, EITHER SCALE IN ΔT -EQUATIONS

In $\bar{E}_k = \frac{3}{2}k_B T$, $L = \sigma AT^4$ and $\lambda_{\max} T = 2.9 \times 10^{-3} \text{ m K}$ the temperature must be in kelvin. In $Q = mc\Delta T$ and $\Delta Q/\Delta t = kA \Delta T/\Delta x$ a difference in $^{\circ}\text{C}$ equals a difference in K. Ratio questions ("by what factor...") are where Celsius errors cost most marks.

EXAM TIP 4 — MAKE DIRECTIONS EXPLICIT

When asked how energy leaves a system, name the mechanism **and** the route: "conduction through the wall of the mug into the air" or "conduction from the pan into the worktop". An answer that does not make the direction of the transfer clear is not credited.

EXAM TIP 5 — USE RATIOS FOR STARS

For comparisons between stars, write $\frac{L_1}{L_2} = \left(\frac{R_1}{R_2}\right)^2 \left(\frac{T_1}{T_2}\right)^4$ and substitute only the ratios — the constants cancel, there are fewer powers of ten to

mistype, and a mark is available for the correctly set-up ratio. Check that a larger radius or temperature really does give a larger luminosity.

Common misconceptions

Misconception	Why it is wrong	Correct idea
Temperature and internal energy are the same thing.	Temperature depends on the <i>average</i> kinetic energy per particle; internal energy is a <i>total</i> over all particles and also includes potential energy.	A large lake at 15 °C has far more internal energy than a cup of tea at 80 °C.
During melting no energy is absorbed because the temperature does not change.	Energy is being supplied all the time.	It increases the intermolecular potential energy; the kinetic energy (temperature) is unchanged.
Energy flows from the body with more internal energy to the body with less.	The direction is set by temperature only.	Net transfer is always from higher to lower temperature.
Metal objects in a room are colder than wooden ones because they feel colder.	Everything in the room has reached thermal equilibrium.	They are at the same temperature; metal conducts energy away from your hand faster.
Heat rises.	Energy has no direction of its own in convection.	Warmer, less dense fluid rises; the moving fluid carries internal energy.
Only hot objects emit radiation; a brighter star is always more luminous.	Every body above 0 K radiates; brightness depends on distance as well.	$L = \sigma AT^4$ for all bodies; $b = L/(4\pi d^2)$.

How this topic connects

Boiling water to make electricity: latent heat in thermal power stations

In most thermal power stations (coal, gas, nuclear) the fuel heats water in a boiler. Because L_v is so large, each kilogram of water absorbs about 2.3 MJ as it boils, and the high-pressure steam drives a turbine connected to a generator, where electromagnetic induction (D.4, HL) produces the electricity. The steam is then condensed back to water in a condenser, releasing its latent heat to cooling water or cooling towers, and is pumped back to the boiler. The cycle is a heat engine whose efficiency is limited by the second law of thermodynamics (B.4, HL) — which is why large cooling towers are needed.

Radiated power at work: sizing stars and estimating solar energy

In astrophysics, Wien's law gives a star's surface temperature from its spectrum, the measured brightness and distance give its luminosity, and $L = \sigma(4\pi R^2)T^4$ then gives its radius — this is how stars are placed on the Hertzsprung–Russell diagram (E.5). For solar energy, the Sun's luminosity spread over a sphere of radius 1 AU gives the solar constant, about 1.36 kW m^{-2} ; this sets the maximum power a solar panel or solar water heater can collect per square metre, and the same energy balance determines the Earth's temperature (B.2).

The $1/d^2$ pattern: spreading from a point source across physics

Any quantity that spreads out uniformly in three dimensions from a point source falls off as $1/d^2$, because the surface area of a sphere is $4\pi d^2$. Apart from apparent brightness, this applies to the intensity of sound and other waves from a point source (C.2), to gravitational field strength and force, $g = GM/r^2$ (D.1), to the electric field and Coulomb force of a point charge (D.2), and to the intensity of gamma radiation from a small radioactive source. The common geometry explains the common mathematics.

Tools & inquiry — thermal experiments

- **Specific heat capacity:** the electrical method above. Plot temperature against time: the gradient of the straight part is $P/(mc)$, which averages out reading errors; losses make the line curve over at higher temperatures.
- **Specific latent heat of fusion of ice:** melt ice with a heater in a funnel and collect the meltwater. Run an identical funnel with no heater (a *control*) and subtract the mass of ice it melts — this corrects for energy gained from the room.
- **Specific latent heat of vaporization:** keep water boiling with an immersion heater on a balance; the rate of loss of mass at constant power gives $L_v = P/(\Delta m/\Delta t)$.
- **Wien's law:** a spectrometer or a light sensor with filters shows how the spectrum of a filament lamp shifts as its voltage (and temperature) is increased.
- **Systematic errors:** energy exchange with the surroundings is the main systematic error in all calorimetry experiments; state its direction (e.g. "energy lost, so measured c too large").

Key equations

Equation	Use	In data booklet?
$\rho = \frac{m}{V}$	density	yes
$T/\text{K} = \theta/^{\circ}\text{C} + 273$	Celsius to kelvin	yes (unit conversions)
$\bar{E}_k = \frac{3}{2}k_B T$	average kinetic energy of a particle	yes
$U = \sum E_p + \sum E_k$	internal energy (definition)	no — learn it
$Q = mc\Delta T$	energy to change temperature	yes
$Q = mL$	energy to change phase at constant temperature	yes
$\frac{\Delta Q}{\Delta t} = kA \frac{\Delta T}{\Delta x}$	rate of conduction	yes
$L = \sigma AT^4$	power radiated by a black body (Stefan–Boltzmann)	yes
$b = \frac{L}{4\pi d^2}$	apparent brightness	yes
$\lambda_{\text{max}} T = 2.9 \times 10^{-3} \text{ m K}$	Wien's displacement law	yes

Check your understanding

1. Liquid nitrogen boils at -196°C . State this temperature in kelvin. A sample of nitrogen gas then warms by 25°C — state this change in kelvin.

$-196 + 273 = 77 \text{ K}$. A change of 25°C is a change of 25 K .

2. A cube of aluminium of side 2.0 cm has a mass of 21.6 g . Calculate its density in kg m^{-3} .

$$V = (0.020)^3 = 8.0 \times 10^{-6} \text{ m}^3; \rho = \frac{0.0216}{8.0 \times 10^{-6}} = 2.7 \times 10^3 \text{ kg m}^{-3}.$$

3. A 2.2 kW kettle contains 1.5 kg of water at 20 °C. Estimate the time to bring it to the boil and the further time to boil it all away ($c = 4180 \text{ J kg}^{-1}\text{K}^{-1}$, $L_v = 2.26 \times 10^6 \text{ J kg}^{-1}$).

To 100 °C: $t = \frac{1.5 \times 4180 \times 80}{2200} = 228 \text{ s} \approx 3.8 \text{ min}$. To boil away: $t = \frac{1.5 \times 2.26 \times 10^6}{2200} = 1.5 \times 10^3 \text{ s} \approx 26 \text{ min}$ — almost seven times longer, assuming no losses.

4. Explain, in terms of particles, why a liquid cools when it evaporates.

Only the particles with the highest kinetic energies near the surface have enough energy to overcome the attractive forces of their neighbours and escape. The particles left behind have a lower average kinetic energy, so the temperature of the liquid falls.

5. Stars A and B have the same surface temperature. B has twice the radius of A and is four times further from Earth. Determine the ratio of apparent brightnesses b_B/b_A .

$$L \propto R^2 T^4, \text{ so } L_B = 4L_A. \quad b \propto L/d^2, \text{ so } \frac{b_B}{b_A} = \frac{4}{4^2} = 0.25.$$

Practise B.1 with exam-style questions

Original Paper 1A, 1B and 2 questions on thermal energy transfers, with full mark schemes. Tick the questions you want and print them as your own test.

SL B.1 questions

HL B.1 questions

Revise and explore

- [Flashcards](#) — choose IB Physics and filter to B.1 Thermal energy transfers. Free, no sign-up.
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SL students: A.4 and A.5 are HL only — the previous SL page is [A.3 Work, energy and power](#).

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