IB DP PHYSICS · THEME B THE PARTICULATE NATURE OF MATTER · B.1 · ~8 MIN READ

B.1 Thermal energy transfers

The particle model, density, Kelvin temperature and internal energy, specific heat capacity and latent heat, conduction, convection and radiation, the Stefan–Boltzmann law, luminosity, apparent brightness and Wien's law.

Particle model · Internal energy · Specific heat & latent heat · Conduction · Convection · Black-body radiation · Luminosity & brightness · Wien's law

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No tag = **SL and HL** HL ONLY HL students only DATA BOOKLET given in the exam

M1 A1 how marks are awarded highlight = comes up again and again Test yourself at the end

IN 30 SECONDS

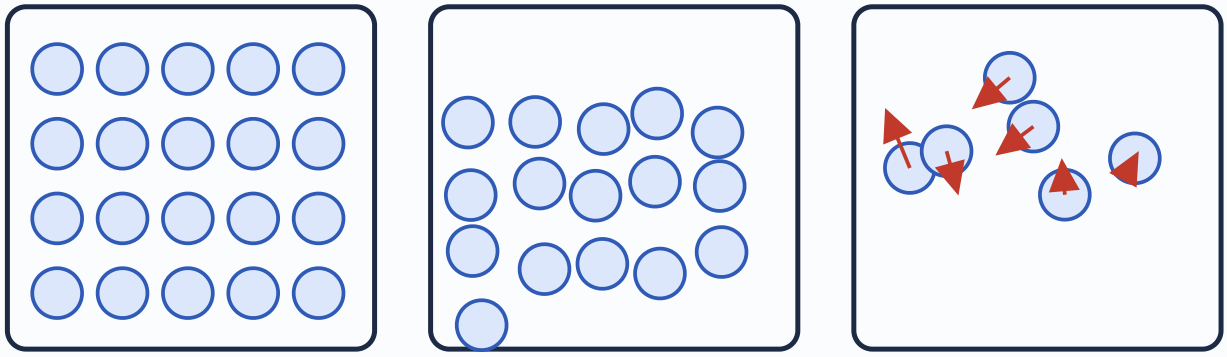
- **Matter is made of particles** in constant random motion. **Temperature in kelvin** measures the average random kinetic energy of the particles: $E_k = \frac{3}{2}k_BT$.
- **Internal energy** = total random kinetic energy + intermolecular potential energy. Heating raises the temperature ($Q = mc\Delta T$) or changes the phase at constant temperature ($Q = mL$).
- Thermal energy flows from hot to cold by **conduction**, **convection** and **radiation**. Conduction rate: $\Delta Q/\Delta t = kA\Delta T/\Delta x$.
- Hot bodies radiate: a black body's power is $\mathbf{L = \sigma AT^4}$, its peak wavelength obeys $\mathbf{\lambda_{max}T = 2.9 \times 10^{-3}\ m\ K}$, and the brightness seen from a distance d is $\mathbf{b = L/4\pi d^2}$.
- **B.1 is the same at SL and HL.**

BY THE END YOU CAN

- Describe solids, liquids and gases with the particle model and use $\rho = m/V$.
- Convert between Celsius and kelvin and relate temperature to average kinetic energy.
- Solve heating and phase-change problems with specific heat capacity and specific latent heat.
- Explain conduction, convection and radiation, and use the conduction equation.
- Use the Stefan–Boltzmann law, apparent brightness and Wien's displacement law.

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1 The particle model



solid
fixed positions, vibrate

liquid
close, slide past

gas
far apart, fast, random

Same particles, different arrangement and energy. Changing phase changes the spacing, not the particles.

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

density in kg m^{-3}

- **Kelvin and Celsius:** T/K = θ/°C + 273. A **change** of 1 K equals a change of 1 °C. Absolute zero (0 K) is the temperature of minimum internal energy.

$$E_k = \frac{3}{2}k_BT$$ DATA BOOKLET

average translational kinetic energy of a particle; $k_B = 1.38 \times 10^{-23}$ J K^{-1}

Internal energy — the total of the random kinetic energies and the intermolecular potential energies of all the particles in a body.

WORKED EXAMPLE

Find the average kinetic energy of a gas molecule at 27 °C.

1. T = 27 + 273 = 300 K A1
2. $E_k = 1.5 \times 1.38 \times 10^{-23} \times 300$ M1
3. **$= 6.2 \times 10^{-21}$ J** A1

COMMON MISTAKE

Using °C in $E_k = \frac{3}{2}k_BT$, PV = nRT or σT^4. Every thermal equation with T in it needs **kelvin**.

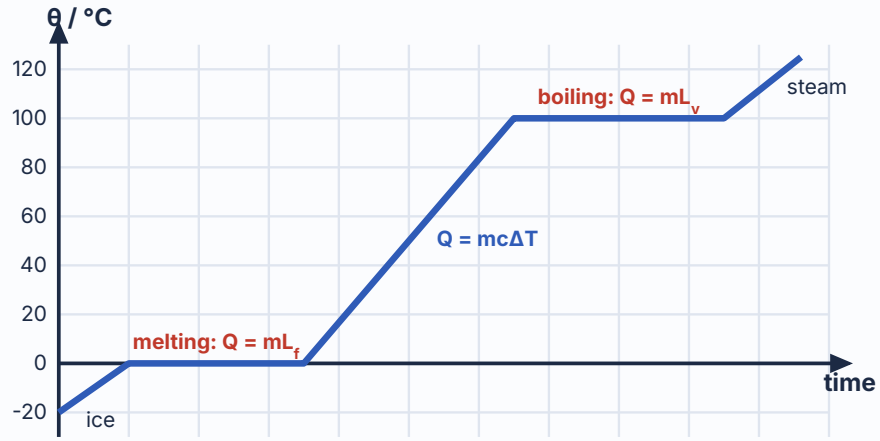
2 Heating and phase change

$$Q = mc\Delta T$$ DATA BOOKLET

c = specific heat capacity, J kg^{-1} K^{-1}

$$Q = mL$$ DATA BOOKLET

L = specific latent heat (fusion or vaporisation), J kg^{-1}



Flat parts: energy goes into breaking bonds, so temperature is constant.

Heating ice at a steady rate. The temperature only rises when the phase is not changing.

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- **During a phase change** the energy supplied increases the **potential** energy of the particles (bonds are broken), so the average kinetic energy, and therefore the temperature, stays constant.

WORKED EXAMPLE

A 2.0 kW kettle heats 1.5 kg of water from 20 °C to 100 °C ($c = 4200$ J kg^{-1} K^{-1}). How long does it take if no energy is lost?

1. $Q = 1.5 \times 4200 \times 80 = 5.04 \times 10^5$ J M1 A1
2. $t = Q/P = 5.04 \times 10^5/2000 = 252$ s (about 4 minutes) A1

WORKED EXAMPLE

0.30 kg of water at 80 °C is mixed with 0.20 kg of water at 20 °C. Find the final temperature.

1. energy lost by hot water = energy gained by cold water M1
2. $0.30 \times c \times (80 - T) = 0.20 \times c \times (T - 20)$ A1
3. $24 - 0.30T = 0.20T - 4 \Rightarrow T = 56$ °C A1

WORKED EXAMPLE

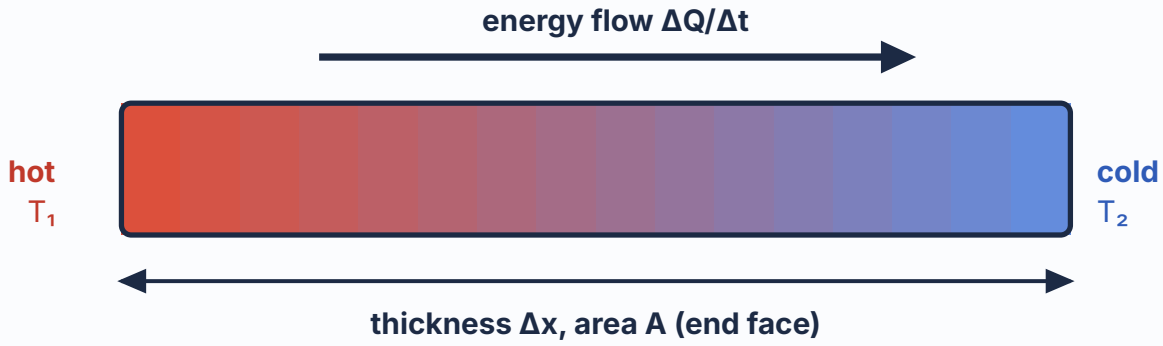
How much energy melts 0.20 kg of ice at 0 °C and then warms it to 10 °C? ($L_f = 3.34 \times 10^5$ J kg^{-1})

1. melting: $0.20 \times 3.34 \times 10^5 = 66\,800$ J M1
2. warming: $0.20 \times 4200 \times 10 = 8\,400$ J M1
3. total = 7.5×10^4 J A1

EXAM TIP

"Explain why the temperature stays constant during melting" needs two ideas: energy goes into **potential energy** (breaking bonds) and the **kinetic energy**, which temperature measures, does not change.

3 Conduction, convection and radiation



$\Delta Q/\Delta t = kA\,\Delta T/\Delta x$: better conductor (large k), bigger area, steeper gradient ⇒ faster

Fast-vibrating particles at the hot end pass energy to slower neighbours. In metals, free electrons carry most of it.

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

k = thermal conductivity, W m^{-1} K^{-1}

WORKED EXAMPLE

A window has area 1.5 m^2 and glass 4.0 mm thick (k = 0.80 $W\ m^{-1}\ K^{-1}$). Inside is 20 °C, outside 5 °C. Find the rate of energy loss.

1. $\Delta T/\Delta x = 15/0.0040 = 3750\ K\ m^{-1}$ M1
2. $\Delta Q/\Delta t = 0.80 \times 1.5 \times 3750$ M1
3. **= 4.5 kW (double glazing traps air, k ≈ 0.025, to cut this)** A1

- **Convection** happens in fluids: the heated fluid expands, its density falls, and it rises; cooler, denser fluid sinks to replace it. No convection in solids or in a vacuum.
- **Radiation** is electromagnetic (mostly infrared at everyday temperatures). It needs no medium, which is how the Sun's energy reaches the Earth.

Black-body radiation

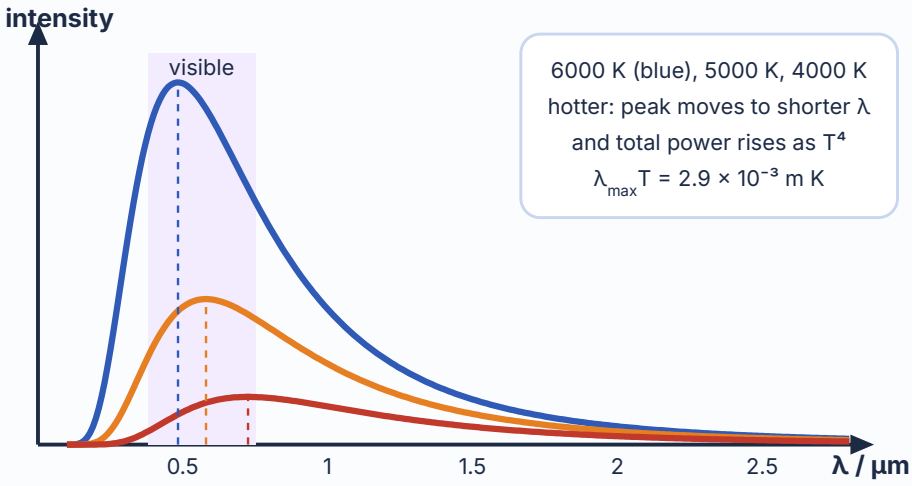
Black body — an ideal object that absorbs all radiation falling on it and emits the maximum possible radiation for its temperature.

$$L = \sigma A T^4$$ DATA BOOKLET

luminosity (total power emitted); σ = 5.67 × 10^{-8} W m^{-2} K^{-4}

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

Wien's displacement law



6000 K (blue), 5000 K, 4000 K
hotter: peak moves to shorter λ
and total power rises as T^4
$\lambda_{max} T = 2.9 \times 10^{-3}$ m K

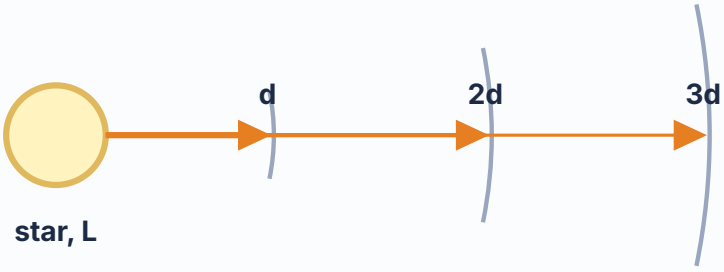
Hotter bodies emit more at every wavelength, and their peak moves towards the blue.

WORKED EXAMPLE

The Sun's surface is at 5800 K and its radius is 6.96 × 10^8 m. Find its luminosity and peak wavelength.

1. $A = 4\pi R^2 = 6.09 \times 10^{18}\ m^2$ M1
2. $L = 5.67 \times 10^{-8} \times 6.09 \times 10^{18} \times 5800^4$ = **3.9×10^{26} W** A1
3. **$\lambda_{max} = 2.9 \times 10^{-3}/5800 = 5.0 \times 10^{-7}$ m (500 nm, visible)** A1

Luminosity and apparent brightness



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

double d:

b falls to ¼

triple d: 1/9

The same power spreads over a sphere of area $4\pi d^2$, so brightness falls with the square of distance.

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

apparent brightness, W m^{-2}

WORKED EXAMPLE

Find the Sun's apparent brightness at the Earth ($d = 1.5 \times 10^{11}$ m).

1. $b = 3.9 \times 10^{26}/(4\pi \times (1.5 \times 10^{11})^2)$ M1
2. **$\approx 1.4 \times 10^3$ W m^{-2}: the solar constant used in B.2** A1

COMMON MISTAKE

Using the radius of the star in $b = L/4\pi d^2$. d is the distance from the star to the observer; R appears only in $L = \sigma(4\pi R^2)T^4$.

LINKING QUESTION

The same black-body ideas power the greenhouse model in B.2 and the stellar HR diagram in E.5, where two stars of the same colour but different brightness must have different radii.

IDEA FOR YOUR IA / EXPLORATION

Measure the specific heat capacity of a metal block with an immersion heater, joulemeter and thermometer. Plot temperature against energy supplied, use the gradient, and discuss heat losses as a systematic error.

Test yourself — cover the answers first

QUICK CHECK

1. Convert −40 °C to kelvin.

2. What happens to the temperature of water while it boils?
3. Which transfer mechanism works in a vacuum?
4. Two stars have the same temperature; one has twice the radius. Ratio of luminosities?
5. A star's peak wavelength halves. What happens to its surface temperature?
6. What is the effect on apparent brightness of tripling the distance?

EXAM-STYLE

7. A 0.50 kg copper block (c = 385 J kg^{-1} K^{-1}) at 200 °C is dropped into 0.40 kg of water at 15 °C. Find the final temperature (ignore losses).
8. A star has luminosity 2.0×10^{28} W and surface temperature 12 000 K. Find its radius.

Show answers

1. 233 K
2. It stays constant (100 °C at standard pressure).
3. radiation
4. 4 ($L \propto R^2$ at fixed T)
5. It doubles.
6. falls to 1/9
7. $0.50 \times 385 \times (200 - T) = 0.40 \times 4200 \times (T - 15)$
   $38\,500 - 192.5T = 1680T - 25\,200$
   $T = 63\,700/1872.5 =$ **34 °C**
8. $R^2 = L/(4\pi\sigma T^4) = 2.0 \times 10^{28}/(4\pi \times 5.67 \times 10^{-8} \times 12\,000^4)$
   $= 1.35 \times 10^{18}$ m^2
   $R =$ **1.2×10^9 m** (about 1.7 solar radii)

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