Topic B.1

THERMAL ENERGY TRANSFERS

Every Formula, Trick & Trap on a Page
& IB-Style Quick Reference

Topics Covered

Temperature, Internal Energy & Heat
Specific Heat Capacity
Phase Change & Latent Heat
Conduction, Convection & Radiation
Black-body Radiation (Wien, Stefan)

Exam Relevance

P1 & P2 (with & without GDC)
$Q = mc\Delta T$ calorimetry
$Q = mL$, heating curves
Three mechanisms compared
$\lambda_{\max}T$ & $L = \sigma A T^4$

The Big Picture — How B.1 Fits Together

THERMAL ENERGY TRANSFERS
heat is energy in transit — mind temperature vs energy

- **Temperature & U**: $\bar{E}_k = \frac{3}{2}k_B T$; U = KE + PE
- **Specific Heat**: $Q = mc\Delta T$ (temperature change)
- **Latent Heat**: $Q = mL$ (phase change, constant T)
- **Heat Transfer**: conduction, convection, radiation
- **Radiation Laws**: $L = \sigma A T^4$; $\lambda_{\max} T$ = const

§1 — Molecular Theory & Density
Topic B.1

Key Formulae: Density & Pressure

$$\rho = \frac{m}{V}\ [\mathrm{kg\,m^{-3}}] \qquad P = \frac{F}{A}\ [\mathrm{Pa}]$$

$1\,\mathrm{Pa} = 1\,\mathrm{N\,m^{-2}};\ \ 1\,\mathrm{atm} \approx 1\times10^5\,\mathrm{Pa}$

State	Motion	Forces
Solid	Vibrate (fixed)	Strong (binding)
Liquid	Vibrate + flow	Moderate
Gas	Rapid random	Negligible

TRICK Density of gas $\ll$ density of solid/liquid — gas molecules are far apart ($\sim 10\times$ further than solids).

TRAP Density is a scalar — it has no direction. Don't confuse units: $\mathrm{g\,cm^{-3}}$ and $\mathrm{kg\,m^{-3}}$ differ by 1000.

NOTE At a phase change: density changes discontinuously (esp. gas $\leftrightarrow$ liquid).

§2 — Temperature Scales & Average KE
Topic B.1

Key Formulae

$$T(\mathrm{K}) = t(\mathrm{C}) + 273$$
$$\Delta T\,(\mathrm{K}) = \Delta t\,(\mathrm{C})$$
$$\bar{E}_k = \tfrac{3}{2}k_B T$$
$$k_B = 1.38\times10^{-23}\,\mathrm{J\,K^{-1}}\ \text{(Boltzmann const.)}$$

TRICK ΔT is the *same* in K and °C. You can use either in $Q = mc\Delta T$ — just be consistent.

TRICK **Two views of temperature:** macroscopic (a thermometer reading; heat flows hot→cold to thermal equilibrium) AND microscopic ($\bar{E}_k = \frac{3}{2}k_B T$, average KE per molecule).

TRAP Do NOT add 273 to a temperature *difference*. Only add 273 when converting an *absolute* temperature.

NOTE At $T = 0\,\mathrm{K}$ (absolute zero): $\bar{E}_k = 0$ and all molecular motion ceases. It is physically impossible to go below $0\,\mathrm{K}$.

§3 — Internal Energy
Topic B.1

Definition

U = total random KE + total intermolecular PE of all molecules.
Heating $\Rightarrow\uparrow U$. Doing work on gas $\Rightarrow\uparrow U$.

TRAP Temperature = *average* KE per molecule. Internal energy = *total* energy of all molecules. A large cold lake can have greater U than a hot cup of tea!

NOTE During phase change: T is constant (KE unchanged), only PE changes. Internal energy still increases.

TRICK U **= two stores:** KE (raise it $\Rightarrow$ temperature up, use $Q = mc\Delta T$) + PE (change it $\Rightarrow$ phase change, use $Q = mL$).

NOTE Two ways to change U: **heating** (transfer due to ΔT, random molecular collisions) and **working** (force $\times$ distance, ordered). Heat is energy *in transit* — a body does not "contain heat".

§4 — Specific Heat Capacity

Topic B.1

Key Formula

$$Q = mc\Delta T$$

c: specific heat capacity ($\mathrm{J\,kg^{-1}\,K^{-1}}$)

Heat capacity of an object: $C = \dfrac{Q}{\Delta T}$ ($\mathrm{J\,K^{-1}}$), and $c = C/m$.

Electrical method: $c = \dfrac{VIt}{m\,(T_2 - T_1)}$

Method of mixtures (no heat loss):

$$m_1 c_1 \Delta T_1 = m_2 c_2 \Delta T_2$$

Selected c values:
Water: 4200, Ice: 2100, Al: 900, Cu: 390 $\mathrm{J\,kg^{-1}\,K^{-1}}$

TRAP Don't forget: if the container has significant mass, you must include its heat capacity too in real experiments.

TRICK In method of mixtures: energy lost by hot = energy gained by cold. Set up $m_{\text{hot}}c_{\text{hot}}(T_{\text{hot}} - T_f) = m_{\text{cold}}c_{\text{cold}}(T_f - T_{\text{cold}})$ and solve for T_f.

NOTE Steeper slope on heating curve ⇒ smaller c. The slope $= P/(mc)$ where P is constant power input.

FROM THE PHOTON QUESTION BANK

Calorimetry: "heat lost by hot = heat gained by cold", $Q = mc\Delta T$ each side. Constant heating rate ⇒ $P = \dfrac{mc\Delta T}{\Delta t}$; rearrange for c.

§5 — Latent Heat & Phase Changes

Topic B.1

Key Formula

$$Q = mL \qquad [\mathrm{J\,kg^{-1}}]$$

Fusion (L_f): solid ↔ liquid
Vaporisation (L_v): liquid ↔ gas
Water: $L_f = 334\,\mathrm{kJ\,kg^{-1}}$, $L_v = 2260\,\mathrm{kJ\,kg^{-1}}$

Electrical (L_v): $L_v = \dfrac{VIt}{m_1 - m_2}$ (mass boiled off)

Phase change terms:

melting	solid → liquid
freezing	liquid → solid
boiling	liquid → gas (at BP)
condensing	gas → liquid
evaporation	liquid → gas (below BP)

TRICK $L_v > L_f$ always, because going gas←liquid requires breaking *all* intermolecular bonds, while melting only partially disrupts them.

TRICK $Q = mc\Delta T$ **or** $Q = mL$**?** Sloped part of the heating curve (temp changing) → $mc\Delta T$; flat plateau (phase changing) → mL. Crossing both (ice→steam) → *add* every piece.

TRAP During phase change: temperature is **constant**. No KE change. Molecules do NOT speed up during melting/boiling.

NOTE On a cooling curve for water placed in a freezer: initial steep drop (specific heat of water), then plateau at 0°C (latent heat of fusion), then gentler drop (specific heat of ice, $c_{\text{ice}} = c_{\text{water}}/2$).

FROM THE PHOTON QUESTION BANK

Mixed ice-in-water: melt-water must *also* be warmed ($+mc\Delta T$) after fusion. Plateau length on a constant-power curve $\propto L$: $P = \dfrac{mL}{\Delta t}$.

§6 — Conduction

Topic B.1

Fourier's Law

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

k: thermal conductivity ($\mathrm{W\,m^{-1}\,K^{-1}}$)
A: cross-sectional area ($\mathrm{m^2}$)
$\Delta T/\Delta x$: temperature gradient ($\mathrm{K\,m^{-1}}$)
In series (steady state, same rate through both):

$$\tfrac{\Delta Q}{\Delta t} = k_1 A \tfrac{T_3 - T_2}{x_1} = k_2 A \tfrac{T_2 - T_1}{x_2}$$

TRICK Higher k = better conductor. Metals have high k (free electrons). Air has very low k — that's why insulation works by trapping air.

TRAP Conduction occurs in *any* material — solids, liquids, gases. But it is most efficient in solids (especially metals).

NOTE Same maths as electrical conduction: $\frac{\Delta q}{\Delta t} = \sigma A \frac{\Delta V}{\Delta \ell}$; T-gradient ↔ V-gradient, $k \leftrightarrow \sigma$. Steeper gradient across the poorer conductor.

FROM THE PHOTON QUESTION BANK

Rate $\propto A$: circular rod $A = \frac{1}{4}\pi d^2$, so doubling d quadruples the rate (parabola through origin). In series, "same rate through both" fixes the interface temperature.

§7 — Convection & Radiation

Topic B.1

Convection

Bulk movement of fluid due to density differences. Heated fluid expands, density decreases, rises. Cooler fluid sinks. Cannot occur in solids.

Radiation

EM waves (mainly IR). No medium needed. All objects above $0\,\mathrm{K}$ radiate. Dark/rough = good radiator & absorber. Shiny/smooth = poor radiator.

NOTE Evaporation is a 4th mechanism: fastest molecules escape from liquid surface, cooling it. Different from boiling (occurs at all temperatures below BP).

TRICK Remember 3 mechanisms: Conduction (KE transfer by collisions), Convection (bulk fluid movement, needs density gradient), Radiation (EM waves, works in vacuum).

TRAP A thermos flask minimises all three: double-walled vacuum (no convection/conduction), silvered walls (minimise radiation).

§8 — Stefan-Boltzmann & Wien's Laws

Topic B.1

Key Formulae

Stefan-Boltzmann:

$$L = \sigma A T^4, \quad \sigma = 5.67 \times 10^{-8}\,\mathrm{W\,m^{-2}\,K^{-4}}$$

Sphere: $A = 4\pi r^2$

Wien's displacement law:

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

Intensity / inverse square:

$$I = \frac{P}{A} = \frac{P}{4\pi r^2}\ [\mathrm{W\,m^{-2}}], \quad I \propto \frac{1}{r^2}$$

Apparent brightness:

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

Spectral classes (hot→cool):
O B A F G K M — blue → red. Sun = G ($\approx 5800\,\mathrm{K}$).

TRICK If temperature doubles: $L \propto T^4$ so luminosity increases by $2^4 = 16\times$. For area and T changes together: $L \propto r^2 T^4$.

TRAP Wien's law gives the temperature from the peak wavelength — not the average wavelength. Units: λ in metres, T in kelvin.

NOTE Two stars with the same apparent brightness: the more distant one has greater true luminosity. Two stars with the same colour (same $\lambda_{\max}$): same surface temperature.

NOTE Absorption lines (dark "missing" wavelengths) give a star's composition; Doppler shift of those lines gives its motion (red = receding).

FROM THE PHOTON QUESTION BANK

Chain the laws: $\lambda_{\max} \to T$ (Wien), $b, d \to L$, then $L = \sigma(4\pi r^2)T^4 \to r$. Net loss uses $T^4 - T^4_{\text{surr}}$; equilibrium gives $T \propto I^{1/4}$.

B.1 Thermal Energy Transfers

Student Self-Check Table

Ref	Topic	Formulae	Tricks	Confidence
§1	Molecular theory & density	☐	☐	☐☐☐☐☐
§2	Temperature scales & avg KE	☐	☐	☐☐☐☐☐
§3	Internal energy	☐	☐	☐☐☐☐☐
§4	Specific heat capacity	☐	☐	☐☐☐☐☐
§5	Latent heat & phase changes	☐	☐	☐☐☐☐☐
§6	Thermal conduction (Fourier)	☐	☐	☐☐☐☐☐
§7	Convection & radiation	☐	☐	☐☐☐☐☐
§8	Stefan-Boltzmann & Wien	☐	☐	☐☐☐☐☐

Confidence: fill each box for 1–5 (1 = need help, 5 = exam-ready)

IB Exam Quick Checklist for B.1

☐ State $\rho = m/V$ and use it
☐ Convert between K and °C
☐ Know ΔT is same in K and °C
☐ State $\bar{E}_k = \frac{3}{2}k_B T$
☐ Define internal energy (KE + PE)
☐ Apply $Q = mc\Delta T$ to mixing problems
☐ Apply $Q = mL$ to phase changes
☐ Name all 5 phase-change processes
☐ Use Fourier's law $\Delta Q/\Delta t = kA\Delta T/\Delta x$
☐ Explain convection qualitatively
☐ Apply $L = \sigma A T^4$ to stars
☐ Use Wien's law to find T from $\lambda_{\max}$
☐ Apply $b = L/(4\pi d^2)$
☐ Explain why $L_v > L_f$
☐ Interpret heating/cooling curves
☐ Distinguish radiation from other mechanisms

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