Topic B.4

THERMODYNAMICS

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

Topics Covered

First Law $\Delta U = Q + W$
Work Done by a Gas
p–V Diagrams & Processes
Second Law & Entropy
Heat Engines & Efficiency

Exam Relevance

HL only — P1 & P2
Sign conventions for Q, W
Area under a p–V curve
Isothermal / adiabatic
Carnot efficiency, $\Delta S \geq 0$

The Big Picture — How B.4 Fits Together

THERMODYNAMICS
energy (1st law) and disorder (2nd law) of gases

- **First Law** — $Q = \Delta U + W$ energy conserved
- **Work** — $W = P\Delta V$ = area under P–V
- **Entropy & 2nd Law** — $\Delta S = \frac{Q}{T}$; $S = k_B \ln \Omega$; $S_{\text{total}} \uparrow$
- **Four Processes** — isovol / isobar / isotherm / adiabatic
- **Heat Engines** — $\eta = 1 - \frac{Q_C}{Q_H}$; Carnot $1 - \frac{T_C}{T_H}$

§1 — First Law of Thermodynamics B.4

First Law: Energy Conservation for Closed Systems

$$\boxed{Q = \Delta U + W}$$

Q Thermal energy **into** system (positive = heat added)
ΔU Change in internal energy
W Work done **by** the system ($W = P\Delta V$, positive = expansion)

Work done ON system $= -W$ (negative in Clausius convention).

Work done by gas (constant or variable P): $W = P\,\Delta V$ (area under P–V curve)

Work done on gas electrically (heater): $W = VIt$

Internal energy — monatomic ideal gas: $U = \frac{3}{2}Nk_BT = \frac{3}{2}nRT$ $\Delta U = \frac{3}{2}nR\,\Delta T$

NOTE **Closed system:** no matter in/out, but energy (heat/work) can transfer. **Isolated system:** neither matter nor energy transfers. Internal energy U = random KE + intermolecular PE (excludes bulk KE and gravitational PE).

FROM THE PHOTON QUESTION BANK
Photon bank hotspots: track the signs of Q and W, convert temperatures to kelvin, and use $\Delta U = \frac{3}{2}nR\,\Delta T$ (or $U = \frac{3}{2}PV$) for monatomic gases.

TRICK For any cyclic process: $\Delta U = 0$, so $Q_{\text{net}} = W_{\text{net}}$ = area enclosed by cycle on P–V diagram.

TRICK **Two ways to get work:** $W = P\Delta V$ only if P is *constant* (isobar); otherwise W = *area under the P–V curve* (isothermal/adiabatic). Expansion $\Rightarrow W > 0$.

TRAP Work done ON gas is negative ($W < 0$). If a piston is pushed in, $\Delta V < 0$, so $W < 0$ and internal energy increases (gas warms). Do not write W as a positive compression value in the first law.

§2 — Entropy B.4

Entropy — Two Definitions

Macroscopic:

$$\Delta S = \frac{\Delta Q}{T} \quad \text{[J/K]}$$

ΔQ = heat added reversibly at absolute temperature T.

Microscopic (Boltzmann):

$$S = k_B \ln \Omega$$

Ω = number of microstates; $k_B = 1.38 \times 10^{-23}$ J/K.
Higher $\Omega \Rightarrow$ more disorder $\Rightarrow$ higher entropy.

Entry difference from microstates: $S_2 - S_1 = k_B \ln\left(\frac{\Omega_2}{\Omega_1}\right)$

Coin Microstate Example ($N = 4$ coins)

Macrostate	$\Omega = \binom{N}{n_H}$	Relative entropy
4H 0T	1	lowest
3H 1T	4	
2H 2T	6	highest
1H 3T	4	
0H 4T	1	lowest

System evolves toward the most probable macrostate (maximum Ω).

NOTE If entropy is S when microstates $= \Omega$, then entropy $= S/2$ when microstates $= \sqrt{\Omega}$, and entropy $= 2S$ when microstates $= \Omega^2$.

§3 — Second Law of Thermodynamics

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Second Law

$\Delta S_{\text{total}} \geq 0$ for any isolated system.

- **Real processes:** irreversible, $\Delta S_{\text{total}} > 0$
- **Reversible (ideal) processes:** $\Delta S_{\text{total}} = 0$
- **Non-isolated systems:** local ΔS can be negative, but surroundings compensate: $|\Delta S_{\text{surroundings}}| \geq |\Delta S_{\text{system}}|$

TRICK A refrigerator running in a sealed room always *increases* total room entropy. The fridge reduces entropy inside, but the motor heat to the room increases surroundings entropy by more.

TRAP Entropy of a **non-isolated** system can decrease. Only the **total** (system + surroundings) entropy cannot decrease. Never say "entropy always increases" without specifying the system is isolated.

NOTE **Equivalent statements:** entropy of the Universe never decreases $\equiv$ **Kelvin–Planck** (no engine fully converts heat to work) $\equiv$ **Clausius** (heat won't flow cold→hot unaided) $\equiv$ heat flows hot→cold. Probability all N molecules occupy one half $= (\frac{1}{2})^N$, so gases spread out. As entropy rises, energy is **degraded** — spread out and less available for work.

FROM THE PHOTON QUESTION BANK

Photon bank hotspots: $S = k_B \ln \Omega$ (and $\Delta S = k_B \ln(\Omega_2/\Omega_1)$), per-reservoir $\Delta S = Q/T$ with heat-out negative, and stating the law for an *isolated* system.

§4 — Four Thermodynamic Processes

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Process Summary — Monatomic Ideal Gas

Process	**Fixed**	W	ΔU	Q
Isovolumetric	V	0	$\frac{3}{2}nR\Delta T$	$= \Delta U$
Isobaric	P	$P\Delta V$	$\frac{3}{2}nR\Delta T$	$\Delta U + P\Delta V$
Isothermal	T	area under curve	0	$= W$
Adiabatic	$Q = 0$	$-\Delta U$	$\frac{3}{2}nR\Delta T$	0

Adiabatic relation (monatomic, $\gamma = 5/3$): $PV^{5/3} = \text{constant}$ $\quad TV^{2/3} = \text{constant}$

TRICK To find T after adiabatic process: use $PV^{5/3} = \text{const}$ to find P_2, then apply $PV = nRT$ to get T_2.

TRICK **Analyse any process two ways:** first law — spot the *zero* term (isovol $W=0$; isotherm $\Delta U=0$; adiabatic $Q=0$); *and* the P–V shape (vertical/horizontal/hyperbola/steeper) whose area is W. Cross-check the signs.

TRAP Adiabatic curve is **steeper** than isothermal on P–V diagram. If asked to sketch both through the same point, the adiabat always has larger $|dP/dV|$.

NOTE For isothermal process: $\Delta T = 0 \Rightarrow \Delta U = 0$ for ideal gas. All heat input equals work output. Do NOT say no heat is exchanged (that is adiabatic).

§5 — Heat Engines & Carnot Efficiency

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Heat Engine: Energy Flow

$$Q_H = W + Q_C \qquad \text{(energy conservation)}$$
$$\eta = \frac{W}{Q_H} = 1 - \frac{Q_C}{Q_H}$$

Clockwise P–V cycle $\Rightarrow$ heat engine ($W > 0$ by gas)
Anticlockwise P–V cycle $\Rightarrow$ refrigerator / heat pump (W input)

Carnot (maximum) efficiency: $\eta_{\text{Carnot}} = 1 - \dfrac{T_C}{T_H}$ (T in kelvin)

Carnot Cycle Stages

1. Isothermal expansion at T_H (heat Q_H absorbed)
2. Adiabatic expansion ($T_H \to T_C$, $Q = 0$)
3. Isothermal compression at T_C (heat Q_C expelled)
4. Adiabatic compression ($T_C \to T_H$, $Q = 0$)

All processes reversible $\Rightarrow \Delta S_{\text{total}} = 0 \Rightarrow$ maximum possible efficiency.

TRICK Carnot efficiency trick: if $\eta = 0.4$ at T_C, find $T_H = T_C/0.6$. New $T_C' = T_C/2 \Rightarrow$ new $\eta = 1-(T_C/2)/T_H = 1-0.3 = 0.7$.

TRAP Carnot efficiency uses **absolute temperatures** (kelvin). Using Celsius gives wrong answers. Also: η_{Carnot} is the **maximum** possible efficiency; real engines are always less efficient.

NOTE A heat pump coefficient of performance (not on syllabus in detail) is > 1 because it moves more heat than the work input.

FROM THE PHOTON QUESTION BANK

Photon bank hotspots: kelvin in $\eta = 1 - T_C/T_H$, distinguishing actual W/Q_H from the maximum Carnot value, and $Q_H = W + Q_C$ to find waste heat or work per cycle.