Unit 5 · Second Law of Thermodynamics

STUDY NOTES

WHAT NEB'S GRADE 12 EXAM ASKS

- **CDC's grid (2078):** Heat and Thermodynamics (Units 4–5 together): 7 of 75 marks
- **The paper:** 11 MCQs × 1 · 8 short × 5 · 3 long × 8; 3 hours; 1 mark per expected point
- **CDC's model paper:** an MCQ: COP of an ideal refrigerator between 0 °C and 27 °C (273/27 ≈ 10); a short question (5 marks): state the second law; why a refrigerator doesn't break it; an engine's efficiency, and when it would be zero ($T_1 = T_2$)
- **MCQ (1 mark)**
  - what the second law says
  - entropy statements
  - Carnot efficiency depends on both temperatures
  - COP defined; from heat and work
  - Otto efficiency depends on r
  - Carnot efficiency, heat or work from temperatures
  - diesel efficiency (needs the cut-off ratio)
- **Short (5 marks, in parts)**
  - Kelvin–Planck and Clausius; first law vs second
  - parts of a heat engine; block diagram; efficiency; never 100%
  - Carnot cycle on a P–V diagram; derive its efficiency
  - Otto vs Diesel with P–V diagrams
  - refrigerator as a reversed engine; COP
  - entropy and disorder; why it rises
  - no engine beats Carnot; real engines' limits
  - numericals: W, η, Q_2, source temperature, COP

Key terms

Second law: gives the direction of natural processes and the limit to turning heat into work.

Kelvin–Planck statement: no engine working in a cycle can take heat from one reservoir and turn all of it into work.

Clausius statement: heat can't flow by itself from a colder body to a hotter one; external work is needed.

Heat engine: turns heat into work in a cycle, between a hot **source** and a cold **sink**.

Working substance: what takes in heat, does work and gives out the rest (steam; air and fuel gases).

Thermal efficiency η: work done ÷ heat taken from the source.

Carnot's theorem: no engine between two reservoirs beats a reversible one; all reversible ones are equally efficient.

Carnot's engine: ideal, reversible, ideal gas; two isothermal and two adiabatic steps.

Refrigerator: a heat engine in reverse; work moves heat from cold to hot.

Coefficient of performance β: heat taken from the cold body ÷ work done.

Internal combustion engine: fuel burns inside the cylinder (petrol, diesel); **external**: outside (steam engine).

Compression ratio r: largest volume ÷ smallest, V_1/V_2.

Cut-off ratio ρ_c: volume at the end of burning ÷ at its start (diesel).

Knocking: mixture catching fire by itself before the flame arrives; limits a petrol engine's r.

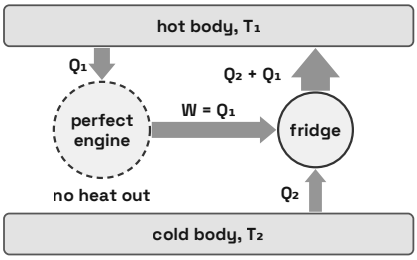
Entropy: measure of disorder, how spread out energy is; a state variable, J/K.

Formulas

$W = Q_1 - Q_2$	Q_1 from source, Q_2 to sink **Use:** engine in a cycle
$\eta = \frac{W}{Q_1} = 1 - \frac{Q_2}{Q_1}$	always < 1 **Use:** any engine
$\eta = 1 - \frac{T_2}{T_1}$	kelvin **Use:** Carnot engine
$\frac{Q_2}{Q_1} = \frac{T_2}{T_1}$	reversible **Use:** Carnot
$W = nR(T_1 - T_2)\ln\frac{V_2}{V_1}$	adiabatic works cancel **Use:** Carnot work
$\beta = \frac{Q_2}{W} = \frac{Q_2}{Q_1 - Q_2}$	$Q_1 = Q_2 + W$ **Use:** refrigerator
$\beta = \frac{T_2}{T_1 - T_2}$	ideal; often > 1 **Use:** Carnot refrigerator
$\eta = 1 - \frac{1}{r^{\gamma-1}}$	$r = V_1/V_2$ **Use:** Otto (petrol)
$\eta = 1 - \frac{1}{r^{\gamma-1}} \cdot \frac{\rho_c^{\gamma}-1}{\gamma(\rho_c-1)}$	$\rho_c = V_D/V_C$ **Use:** Diesel
$dS = \frac{dQ}{T}$	reversible heat; J/K **Use:** entropy
$\Delta S_{\text{total}} \geq 0$	$= 0$ reversible **Use:** second law

The second law

- first law: **how much** energy; second: **which way**, and how much can be used
- first law alone would allow heat cold → hot, and a 100% engine
- "in a cycle" matters: an isothermal expansion turns all its heat into work once, but ends at a larger volume
- refrigerator doesn't break Clausius: its motor does the external work



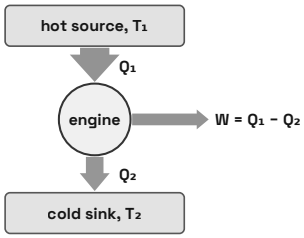
A perfect engine driving a refrigerator: Q_2 flows cold → hot with no work.

Why the statements are equivalent

1. suppose an engine turns all of Q_1 into W
2. W drives a refrigerator: takes Q_2 from cold, gives $Q_2 + Q_1$ to hot
3. together: hot gains Q_2, cold loses Q_2, no work in → Clausius broken
4. likewise a Clausius-breaker makes a Kelvin–Planck-breaker: both true or neither

	First law	Second law
heat flow	either way, if energy balances	only hot → cold by itself
efficiency	could be 100%	always < 100%
about	quantity (conservation)	direction, entropy

Heat engine



Block diagram: Q_1 in, W out, Q_2 to the sink.

Parts

1. source: hot, so large its temperature doesn't fall (boiler, burning fuel)
2. sink: cold, so large its temperature doesn't rise (atmosphere, river)
3. working substance: steam; air and fuel gases

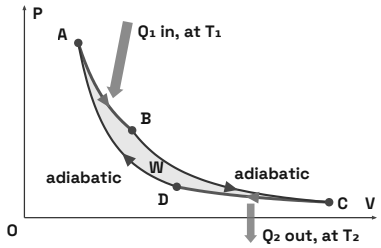
- cycle: $\Delta U = 0 \rightarrow W = Q_1 - Q_2$
- 100% would need $Q_2 = 0$: forbidden by Kelvin–Planck
- $\eta = 0$ when $T_1 = T_2$: no temperature difference, no work
- real: petrol 25–35%, diesel 35–45%, power station steam turbines about 40%

Carnot's engine and cycle

Parts: source at T_1, sink at T_2 (both of infinite heat capacity); insulating stand; ideal gas; cylinder with insulating walls and piston, **conducting base**

Carnot's theorem: why

1. suppose X beats a reversible R between the same reservoirs
2. X drives R backwards (as a refrigerator)
3. no net work, yet heat goes cold → hot: Clausius broken
4. so no engine beats R; reversible engines can't beat each other



A → B isothermal at T_1, B → C adiabatic, C → D isothermal at T_2, D → A adiabatic; loop area = net work.

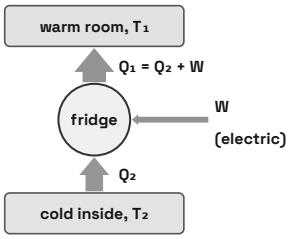
1. AB, on the source: $W_1 = Q_1 = nRT_1 \ln \frac{V_2}{V_1}$
2. BC, on the stand: cools to T_2; $W_2 = \frac{nR(T_1 - T_2)}{\gamma - 1}$
3. CD, on the sink: $Q_2 = nRT_2 \ln \frac{V_3}{V_4}$ given out
4. DA, on the stand: warms to T_1; $W_4 = -W_2$

Efficiency

1. $W = Q_1 - Q_2$ (adiabatic works cancel)
2. $T_1 V_2^{\gamma-1} = T_2 V_3^{\gamma-1}$, $T_1 V_1^{\gamma-1} = T_2 V_4^{\gamma-1} \rightarrow \frac{V_2}{V_1} = \frac{V_3}{V_4}$
3. $W = nR(T_1 - T_2) \ln \frac{V_2}{V_1}$
4. $\eta = \frac{W}{Q_1} = 1 - \frac{T_2}{T_1}$

- depends only on T_1, T_2 (kelvin): not the gas or the design
- hotter source or colder sink → higher η; 100% only at $T_2 = 0$ K, unreachable
- lowering the sink by 100 K beats raising the source by 100 K
- Celsius in the formula: 100 °C and 0 °C would give 100%; in kelvin, 26.8%
- real engines fall short: friction, heat leaks, fast (irreversible) steps

Refrigerator



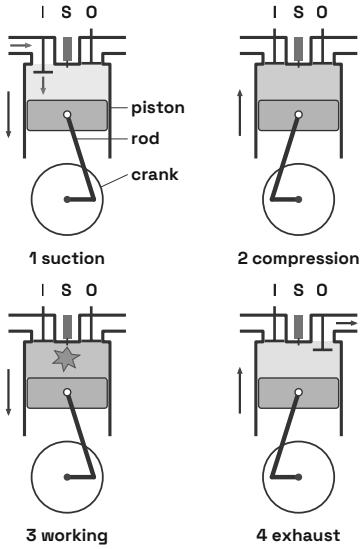
Work W moves Q_2 out of the cold inside; the room gets $Q_1 = Q_2 + W$.

The refrigerant's cycle

1. evaporator (inside): boils, takes Q_2
2. compressor: work W; vapor gets hot
3. condenser (at the back): gives Q_1 to the room, turns liquid
4. expansion valve: pressure drops, it cools

- thermostat switches the compressor on and off
- β usually > 1: it **moves** heat, it doesn't make cold
- smaller $T_1 - T_2 \to$ larger β
- 0 °C to 27 °C: $\beta = 273/27 \approx 10$

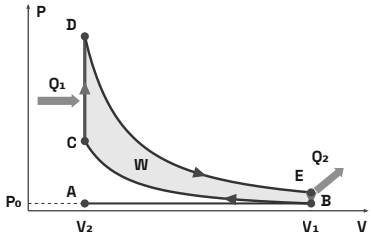
Petrol and diesel engines



Suction, compression, working stroke, exhaust: I intake, S spark plug, O outlet.

Petrol (Otto) strokes

1. suction: mixture in at constant pressure (AB)
2. compression: adiabatic (BC); spark: heat Q_1 at **constant volume** (CD)
3. working: adiabatic expansion (DE), the only stroke doing work
4. exhaust: valve opens, Q_2 out at constant volume (EB); gas pushed out (BA)

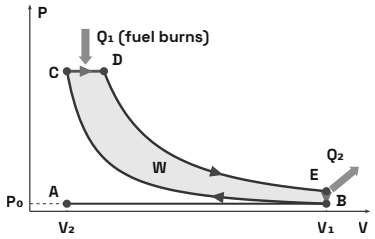


Otto cycle: work = loop BCDE (AB and BA cancel).

Otto efficiency

1. $Q_1 = nC_V(T_D - T_C)$, $Q_2 = nC_V(T_E - T_B)$
2. adiabats: $T_C = T_B r^{\gamma-1}$, $T_D = T_E r^{\gamma-1}$
3. $\eta = 1 - \frac{T_E - T_B}{T_D - T_C} = 1 - \frac{1}{r^{\gamma-1}}$

- r 8–12 (knocking): ideal 56–63%, real 25–35%
- diesel: **air only**, r 14–25, air at 500 °C+ lights the injected fuel (no spark); heat in at **constant pressure** (CD)



Diesel cycle: heat Q_1 at constant pressure CD.

	Petrol	Diesel
takes in	air–petrol	air only
ignition	spark plug	heat of compression
heat added	constant volume	constant pressure
r	8–12	14–25
real η	25–35%	35–45%
build	lighter, cheaper	heavier, dearer

- same r: diesel cycle a little **less** efficient; higher r makes the diesel engine better
- uses: petrol in cars, motorbikes, small generators; diesel in buses, lorries, tractors, ships, locomotives

Entropy

- $dS = dQ/T$: the same heat raises S more at low T
- gas > liquid > solid
- reversible adiabatic: $dS = 0$; irreversible adiabatic (free expansion): S rises
- tea cooling: tea loses entropy, the room gains more
- heat Q hot $\to$ cold: $-\frac{Q}{T_1} + \frac{Q}{T_2} > 0$
- Carnot: $Q_1/T_1 = Q_2/T_2$, no net change (reversible)
- entropy of the universe keeps rising: energy spread out, less able to work (degradation of energy; "heat death")

COMMON MISTAKES

✗ an engine can be 100% efficient without friction
✓ needs $T_2 = 0$ K; $Q_2 > 0$ always.

✗ Carnot η depends on $T_1 - T_2$ alone
✓ on $1 - T_2/T_1$: 500/300 K gives 40%, 1000/800 K 20%.

✗ temperatures in °C
✓ in **kelvin**.

✗ a refrigerator breaks the second law
✓ its motor does the work Clausius asks for.

✗ COP > 1 makes energy
✓ it moves existing heat; the room gets $Q_2 + W$.

✗ diesel $\eta = 1 - 1/r^{\gamma-1}$
✓ that's Otto; diesel also needs ρ_c (the Otto value is an upper limit).

✗ entropy is constant in any adiabatic process
✓ only a reversible one.

✗ the entropy of a system never falls
✓ the **total** of system and surroundings never falls.