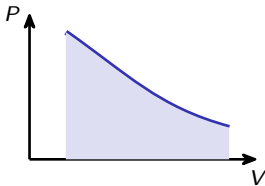


Thermodynamics

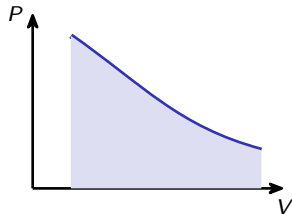
AP Physics 2 ■ Unit 9

AP Physics 2



What we will cover

- 1 Kinetic theory of temperature and pressure
- 2 The ideal gas law
- 3 Heat transfer and equilibrium
- 4 The first law of thermodynamics
- 5 Specific heat and conductivity
- 6 Entropy and the second law





Temperature is energy per particle

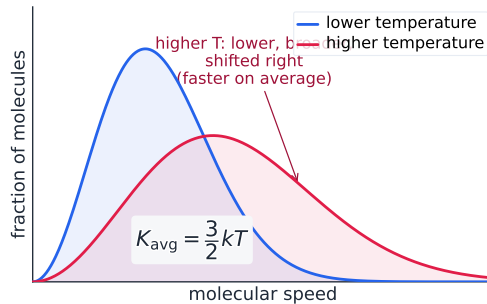
Kinetic theory : matter is countless moving particles. **Temperature** measures their **average kinetic energy**:

Per particle

$$\bar{K} = \frac{3}{2} k_B T$$

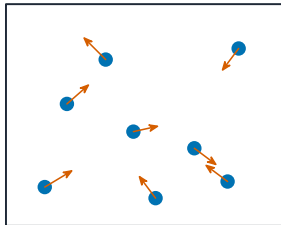
T in **kelvin** ; $T_K = T_C + 273.15$.

Pressure comes from particles striking the walls – $P = F/A$.



Hotter $\Rightarrow$ the speed distribution shifts right.

Kinetic Theory of Temperature and Pressure



1. many identical molecules, in continuous **random motion**
2. their own volume is **tiny** next to the container
3. straight lines between hits - intermolecular forces **ignored**
4. collisions are **elastic**: no kinetic energy is lost

poor at very high pressure (volume matters) or very low temperature (forces matter)

The key assumptions of the kinetic theory of an ideal gas

Worked example – the average kinetic energy of a molecule

Find the average kinetic energy of a gas molecule at 300 K, with $k_B = 1.38 \times 10^{-23}$ J/K.

- $K_{\text{avg}} = \frac{3}{2} k_B T$
- $= \frac{3}{2} (1.38 \times 10^{-23}) (300)$
- $= 6.2 \times 10^{-21}$ J

Temperature *is* average kinetic energy per molecule – and it depends on **neither** the gas's identity **nor** its pressure. Two gases at the same T have the same K_{avg} and different speeds.



The ideal gas law

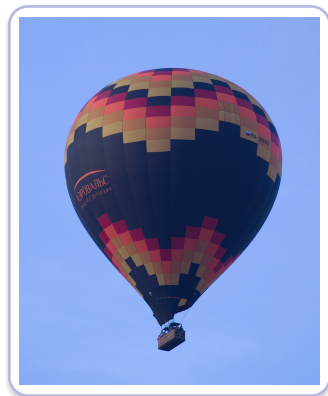
Two forms of the same law

$$PV = Nk_B T \quad PV = nRT$$

N particles, or n **moles** ; $R = N_A k_B$.

Comparing two states

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$



Heating a gas expands it and can do work

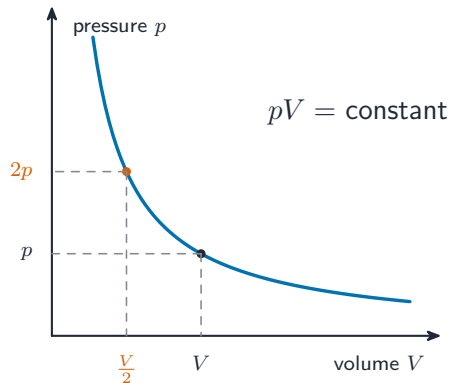
Worked example – heating a rigid container

A sealed container of gas is at 1.0×10^5 Pa and 300 K. It is heated to 450 K. Find the new pressure.

- an **ideal gas** obeys $PV = nRT$, or $PV = Nk_B T$
- rigid and sealed, so V and n are fixed:
$$\frac{P_1}{T_1} = \frac{P_2}{T_2}$$
- $P_2 = 1.0 \times 10^5 \times \frac{450}{300} = 1.5 \times 10^5$ Pa

Always identify **what is held constant** before choosing the form of the law – and always use **kelvin**, since the ratio is meaningless in Celsius.

Boyle's law



Boyle's law: at constant temperature, pressure times volume is constant



Heat transfer and equilibrium

Heat Q is energy in transit from hot to cold. Flow stops at **thermal equilibrium** (equal temperatures).

Zeroth law : $A=B$ and $B=C$
 $\Rightarrow A=C$ – how a thermometer works.

Isolated: $Q_{\text{lost}} = Q_{\text{gained}}$.



Heat flows until temperatures equalise



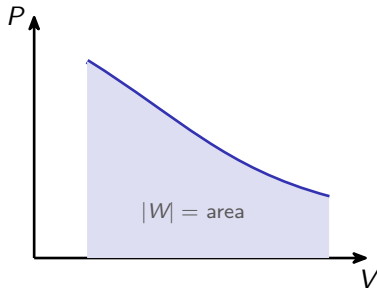
The first law of thermodynamics

Energy conservation for a gas: **internal energy** U changes by heat in plus work in.

First law (AP convention)

$$\Delta U = Q + W, \quad W = -P\Delta V$$

- $Q > 0$: heat **added**
- $W > 0$: gas **compressed** (work done on it)



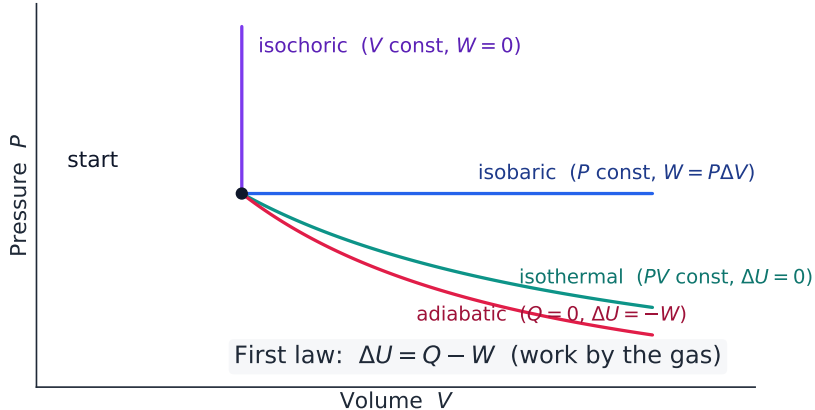
Worked example – the first law, with the sign convention

A gas absorbs 500 J of heat and does 200 J of work . Find the change in internal energy.

- $\Delta U = Q - W$, with W the work done by the gas
- $= 500 - 200$
- $= +300 \text{ J}$

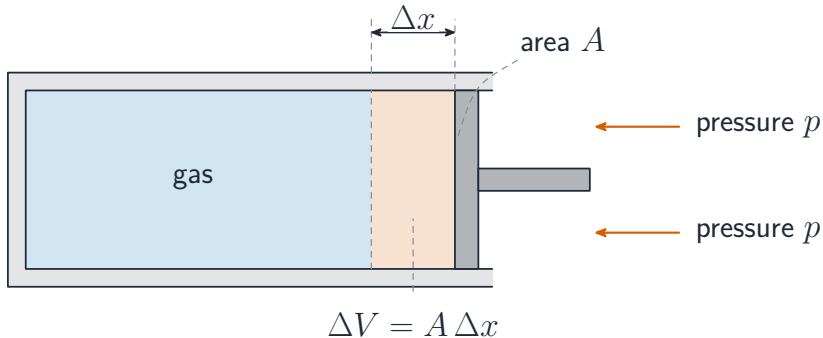
The sign convention is the whole difficulty. Heat **in** is positive; work done **by** the gas is positive and lowers U . State which convention you are using before substituting.

The four thermodynamic processes drawn from – one



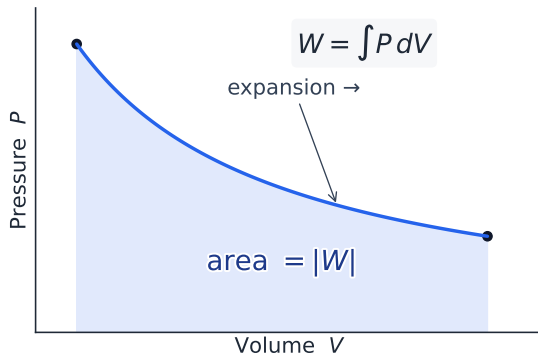
The four thermodynamic processes drawn from a common starting state on a PV diagram

The four thermodynamic processes drawn from – two



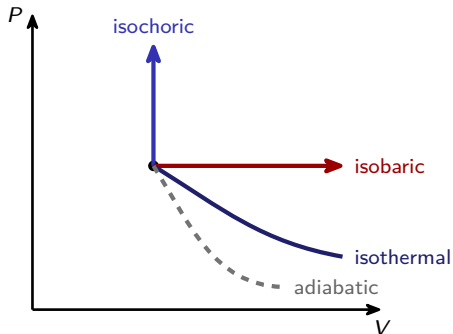
A gas pushing a piston out by a small distance does work equal to p times the volume change

The work done during a volume change



The work done during a volume change equals the area under the P-V curve

Four standard processes



■ **isothermal** : $\Delta U = 0$, so $Q = -W$

■ **isobaric** : $W = -P\Delta V$

■ **isochoric** : $W = 0$, so $\Delta U = Q$

■ **adiabatic** : $Q = 0$, so $\Delta U = W$

A **cycle** returns to its state: $\Delta U = 0$, net heat = net work – a **heat engine** .



Specific heat and conductivity

Warming a material

$$Q = mc\Delta T$$

Specific heat c : heat to warm 1 kg by 1 K.

Water has a large c (≈ 4186) – it resists temperature change, so coasts stay mild.

Rate of conduction

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

- high k – a metal **conductor**
- low k – an **insulator** (air, foam)

Worked example – heating water, and how heat travels

How much heat raises 2.0 kg of water from 20 °C to 80 °C? ($c = 4186 \text{ J/(kg K)}$)

- $Q = mc\Delta T = (2.0)(4186)(60)$
- $= 5.0 \times 10^5 \text{ J}$
- the three transfer modes: **conduction** (through a solid), **convection** (bulk fluid motion), **radiation** (electromagnetic, needing no medium)

A temperature *difference* in kelvin equals the same difference in Celsius, so ΔT needs no conversion – unlike an absolute temperature.



Entropy and the second law

Entropy S measures **disorder** . The **second law** : total entropy of an **isolated system** never decreases.

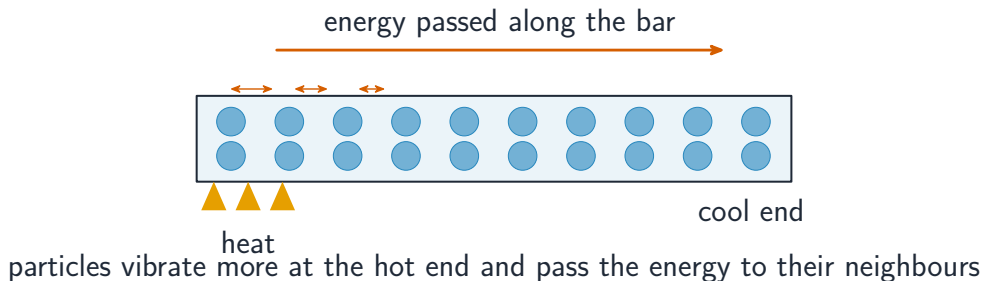
The arrow of time

$$\Delta S_{\text{total}} \geq 0$$

- heat flows hot $\rightarrow$ cold on its own
- ink spreads, glass shatters – never reverse

No heat engine is 100% efficient
– some heat is always dumped as waste.

Specific Heat and Thermal Conductivity



Conduction: vibrating particles pass energy along a metal bar

Exam tips

- Always convert temperatures to **kelvin** ($T_K = T_C + 273$) before using any gas law.
- In the first law $\Delta U = Q + W$, get the **sign of W right**: **work done on** the gas is positive; when the gas expands and does work on its surroundings, W is negative.
- **Temperature** measures the average kinetic energy of particles, so at the same T lighter molecules move faster.
- On a **PV diagram** the work done by the gas is the **area** under the process curve.
- Use $Q = mc\Delta T$ for temperature change; the **second law** fixes the direction – heat flows hot→cold and total entropy never decreases.



Unit 9 – key takeaways

1

Kinetic theory

T = average particle KE; $PV = nRT$ in kelvin

2

First law

$\Delta U = Q + W$; $|W|$ is the area under a PV curve

3

Processes

iso-thermal / -baric / -choric /
adiabatic

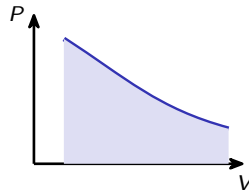
4

Second law

$\Delta S \geq 0$; no engine is fully efficient

Check yourself

- 1 What does temperature measure at the particle level?
- 2 Halve a gas's volume at constant T – what happens to P ?
- 3 In an isochoric process, what is the work done?
- 4 Can any heat engine be 100% efficient?



Answers 1. average kinetic energy of particles 2. it doubles 3. zero 4. no