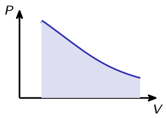
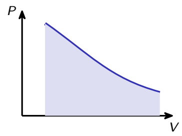
Thermodynamics
AP Physics 2 ▪ Unit 9

AP Physics 2



What we will cover



1 Kinetic theory

Temperature is energy per particle

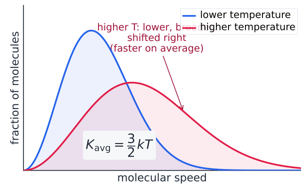
Kinetic theory 分子运动论: matter is countless moving particles.
Temperature 温度 measures their average kinetic energy:

Per particle

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

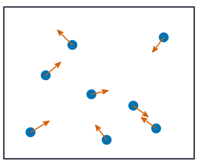
T in **kelvin** 开尔文; $T_K = T_C + 273.15$.

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



Hotter ⇒ 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.

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

2 Ideal gas law

The ideal gas law

Two forms of the same law

$$PV = Nk_BT \qquad PV = nRT$$

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

Comparing two states

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

Heating a gas expands it and can do work

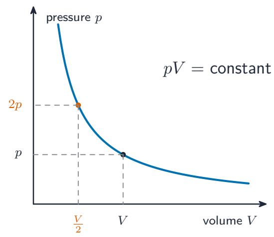
Worked example – heating a rigid container

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** 理想气体 obeys $PV = nRT$, or $PV = Nk_BT$
- 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

3 Heat transfer

Heat transfer and equilibrium

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

Zeroth law 热力学第零定律: A=B and B=C ⇒ A=C – how a thermometer works.

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

Heat flows until temperatures equalise

4 First law

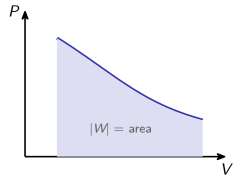
The first law of thermodynamics

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

First law (AP convention)

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

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



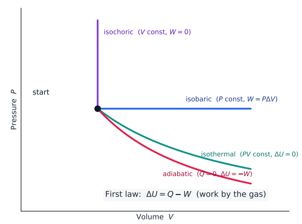
Worked example – the first law, with the sign convention

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
- $= 500 - 200$
- $= +300$ 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

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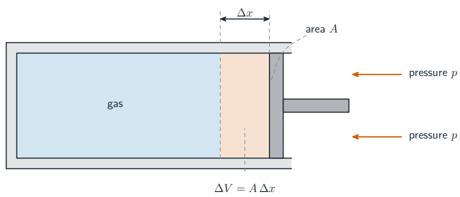
The four thermodynamic processes drawn from – two



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

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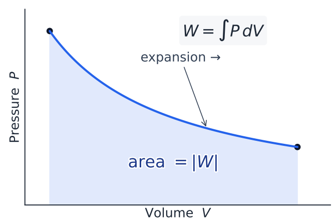
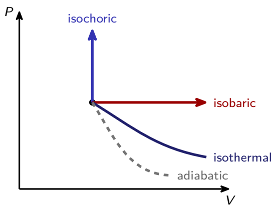
The work done during a volume change



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

Four standard processes



- **isothermal** 等温: $\Delta U = 0$, so $Q = -W$
- **isobaric** 等压: $W = -P\Delta V$
- **isochoric** 等容: $W = 0$, so $\Delta U = Q$
- **adiabatic** 绝热: $Q = 0$, so $\Delta U = W$

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

5 Specific heat

Specific heat and conductivity

Warming a material

$$Q = mc\Delta T$$

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

Water has a large c ($\approx$ 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** 导体
- low k – an **insulator** 绝热体 (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? ($c = 4186$ J/(kg K))

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

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

6 Entropy

Entropy and the second law

Entropy 熵 S measures **disorder** 无序. The **second law** 热力学第二定律: total entropy of an **isolated system** 孤立系统 never decreases.

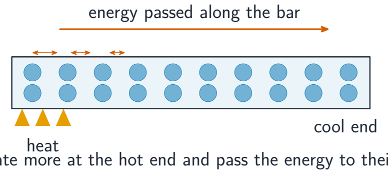
The arrow of time

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

- heat flows hot → 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



particles vibrate more at the hot end and pass the energy to their neighbours

> 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.

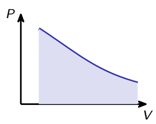
7 Recap

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