Thermodynamics

AP Physics 2 ▪ Unit 9

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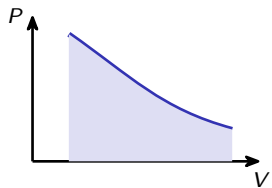
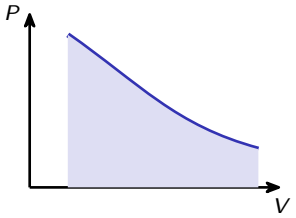


What we will cover

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



1 Kinetic theory

Temperature is energy per particle

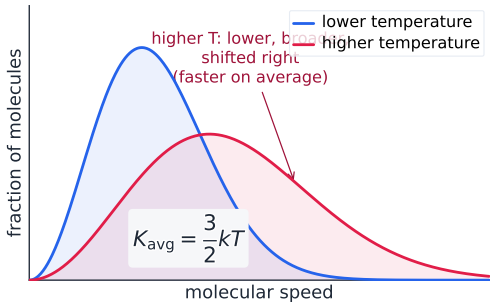
Kinetic theory 分子运动论: matter is countless moving particles.
Temperature 温度 measures their average kinetic energy:

Per particle

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

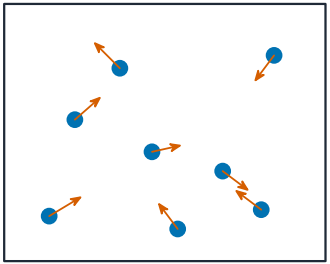
T in **kelvin** 开尔文; $T_K = T_C + 273.15$.

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.

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

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; $R = N_Ak_B$.

Comparing two states

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

Heating a gas expands it and can do work

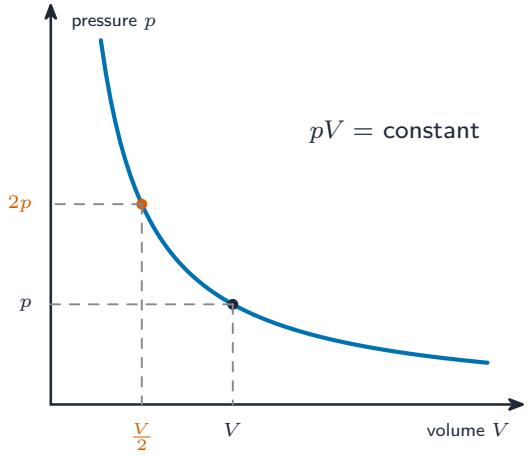
Worked example – heating a rigid container

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: $\dfrac{P_1}{T_1} = \dfrac{P_2}{T_2}$
- $P_2 = 1.0 \times 10^5 \times \dfrac{450}{300} = 1.5 \times 10^5$ 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 $\Rightarrow$ A=C – how a thermometer works.

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

Heat flows until temperatures equalise

4 First law

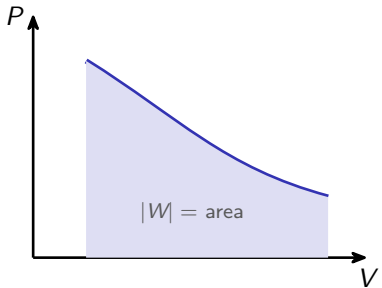
The first law of thermodynamics

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)



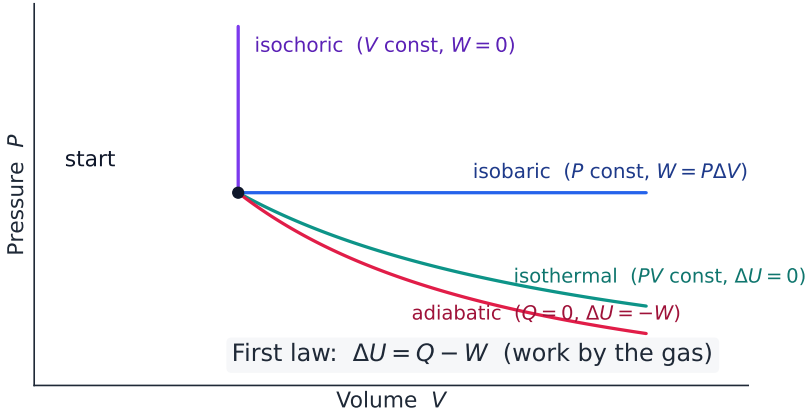
Worked example – the first law, with the sign convention

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

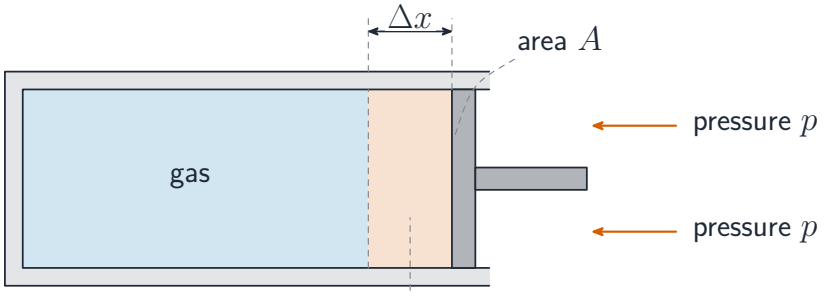
The sign convention is the whole difficulty. Heat in is positive; work done by the gas is positive and lowers U. State which convention you are using before substituting.

Four thermodynamic processes on a PV diagram



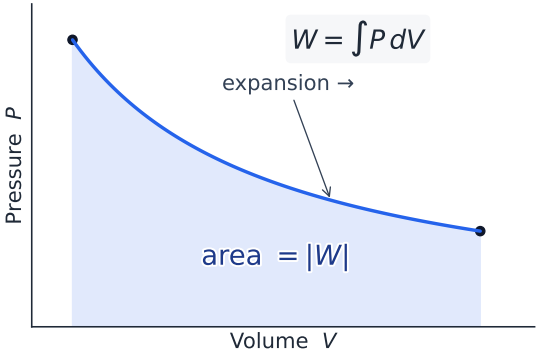
The four thermodynamic processes drawn from a common starting state on a PV diagram

Work done by a gas on a piston



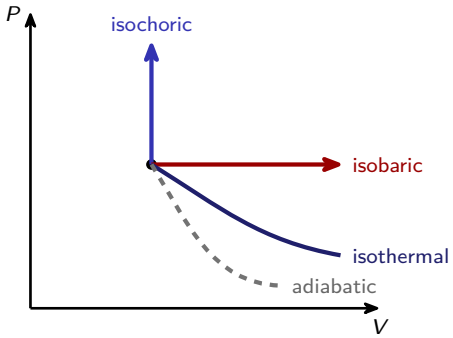
A gas pushing a piston out by a small distance does work equal to p times the volume change

Work is the area under the PV curve



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 $1\,\mathrm{kg}$ by $1\,\mathrm{K}$.

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** 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 $20\,^{\circ}$C to $80\,^{\circ}$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.

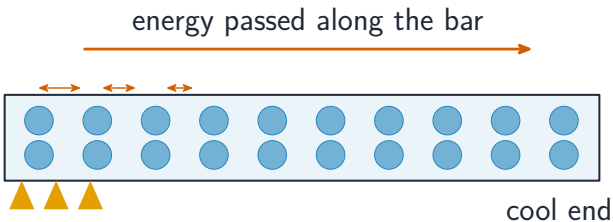
The arrow of time

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

- heat flows hot $\rightarrow$ 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



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** ($T_{\mathrm{K}} = T_{\mathrm{C}} + 273$) 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$\rightarrow$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

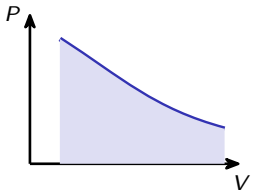
iso-thermal / -baric / -choric / adiabatic

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