

Thermal Physics

Begin with temperature and the motion of particles, then retain the original phases-and-calorimetry lesson before developing the gas model. Follow the original work-on-the-gas sign convention through processes and cycles.

TEACHING ROUTE

The explanations follow the original lesson sequence. Connections, analogies and worked reasoning remain together. Syllabus additions appear beside the ideas they support.

Lesson group	Focus
Temperature and matter	Kelvin scale, rms speed, distributions, phases and calorimetry
The gas model	Ideal-gas variables, transfer mechanisms and conduction
Energy and processes	First-law signs, isobaric and isothermal changes, constant volume, cycles and adiabatic changes
Microscopic reasoning	Entropy, pressure from collisions and experimental evidence
Practice and reference	Class questions, worked review and the process summary

Predict first, draw the situation, then calculate. Use the class questions for discussion and the chapter review for independent practice. Unless stated otherwise, numerical examples use idealized models and the assumptions given on the page.

Source keys N01, N02, and so on refer to the original PDF files listed near the end of this chapter. Source page numbers count PDF pages. CED means the supplied 2026 AP Physics 2 Course and Exam Description.

Temperature, energy & rms speed

Quantity	Meaning	Unit
Temperature T	Describes the thermal state; for an ideal gas it measures average translational kinetic energy per particle.	K
Internal energy U	Microscopic kinetic and configuration potential energy contained in a system.	J
Heat Q	Energy transferred across a boundary because of a temperature difference. It is a transfer, not a stored substance.	J

RELATIONSHIP AND CONDITIONS

$$T \text{ (K)} = T \text{ (}^\circ\text{C)} + 273.15$$

$$K_{\text{avg}} = (1/2)m\langle v^2 \rangle = (3/2)k_B T$$

$$v_{\text{rms}} = \sqrt{\langle v^2 \rangle} = \sqrt{(3k_B T/m)}$$

m is the mass of one particle in kg. The average translational kinetic energy depends on T , not on particle mass. At the same T , lighter particles have larger rms speeds. Temperature differences have the same numerical value in kelvins and Celsius degrees, but gas-law ratios require kelvins.

Worked example | equal temperature, different mass

Helium and neon are at 300 K. Approximate their atomic masses as 4u and 20u. Then

$$v_{\text{rms,He}}/v_{\text{rms,Ne}} = \sqrt{(m_{\text{Ne}}/m_{\text{He}})} = \sqrt{5} = 2.24.$$

Their average translational kinetic energies are equal: $K_{\text{avg}} = (3/2)(1.38 \times 10^{-23})(300) = 6.21 \times 10^{-21} \text{ J}$.

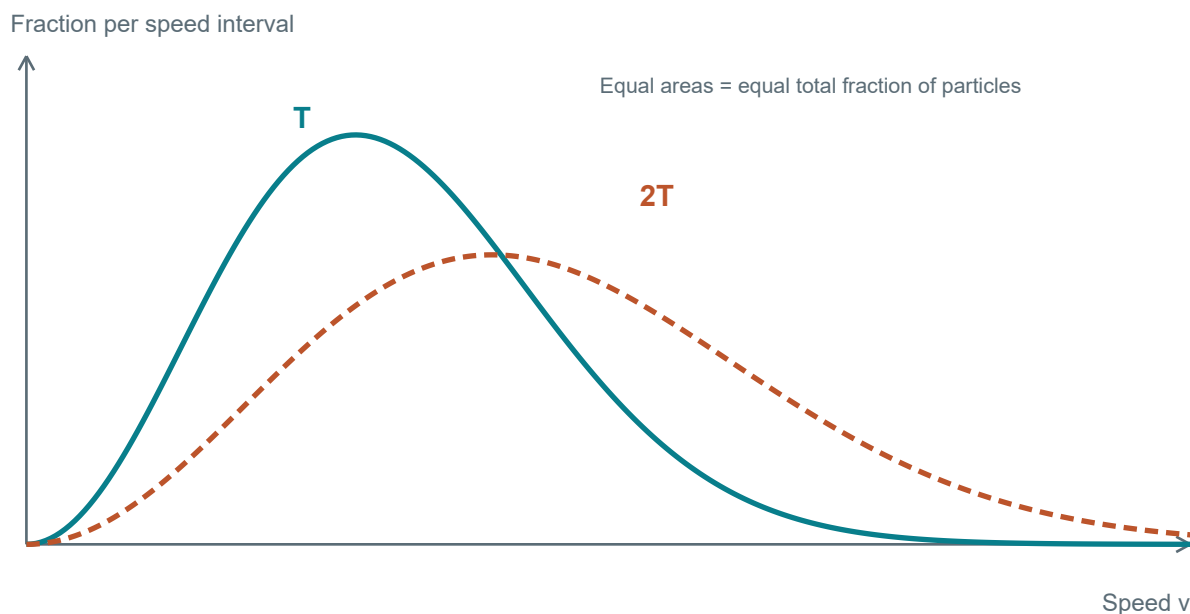
Rms is not the arithmetic mean

For speeds 1, 2, 3, 4, 5 m/s: average speed = 3 m/s, but $v_{\text{rms}} = \sqrt{[(1^2 + 4 + 9 + 16 + 25)/5]} = \sqrt{11} = 3.32 \text{ m/s}$. In a gas at rest, average *velocity* can be zero while rms speed is nonzero.

Pause and predict 1

A fixed sample warms from 300 K to 600 K. By what factors do K_{avg} and v_{rms} change? Explain why the factors differ.

Reading a speed distribution



Normalized Maxwell-Boltzmann speed distributions for the same gas at T and $2T$. Both curves enclose the same area; axes show a qualitative comparison.

When temperature increases...	What the graph tells you
Peak shifts right	The most probable speed becomes larger.
Peak becomes lower; curve broadens	Speeds are spread over a wider range. More particles occupy the high-speed tail.
Area stays the same for normalized curves	The total probability remains 1. If the vertical axis counts particles, equal areas require the same number of particles.

At the same temperature: a lighter gas has a speed distribution shifted toward higher speeds. Its average translational kinetic energy is still the same as that of a heavier gas. Do not treat a graph of speed as though its horizontal axis were kinetic energy.

Explain in words

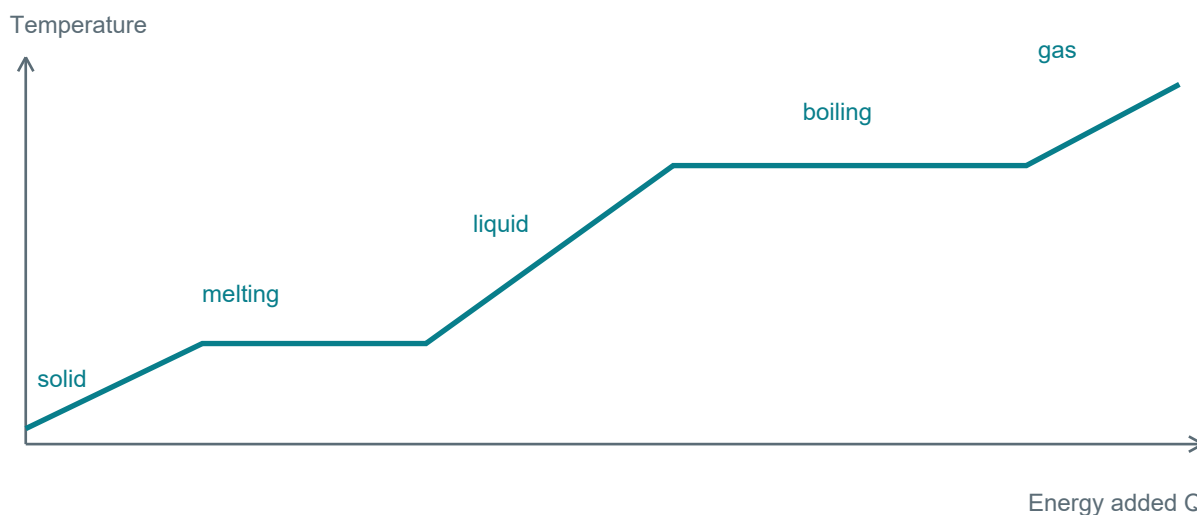
“When the absolute temperature rises, the average translational kinetic energy rises. The speed distribution broadens and shifts toward higher speeds; the particles do not all acquire the same speed.”

Pause and predict 2

A sealed, rigid container is warmed. Sketch the new speed distribution and predict the pressure change. Name two microscopic reasons for the pressure change.

Extension: phases & heating curves

Phase	Particle picture	Macroscopic behavior
Solid	Particles vibrate about relatively fixed positions.	Fixed shape and approximately fixed volume.
Liquid	Particles remain close but rearrange and move past one another.	Approximately fixed volume; shape follows container.
Gas	Particles are widely separated in the dilute-gas model.	Fills available volume and is readily compressed.



Idealized heating curve for a pure substance at fixed pressure. Plateau widths depend on the energy needed for each transition; this sketch is not to scale.

RELATIONSHIP AND CONDITIONS

Single phase: $Q = mc\Delta T$

Phase change at the transition temperature: $|Q| = mL_{\text{phase}}$

Melting / freezing: solid $\leftrightarrow$ liquid. **Vaporization / condensation:** liquid $\leftrightarrow$ gas. **Sublimation / deposition:** solid $\leftrightarrow$ gas. Latent heat L_{phase} has units J/kg. Energy enters during melting or vaporization and leaves during freezing or condensation.

During a plateau, temperature and average thermal kinetic energy do not rise, even though energy is transferred. Energy changes the microscopic configuration and interactions. A flat temperature segment therefore does **not** mean that heat transfer or internal-energy change is zero.

Keep the symbols distinct

L in the conduction equation means **thickness** (m). L_f or L_v means **specific latent heat** (J/kg). A time axis can replace the energy axis only when the net heating power is constant.

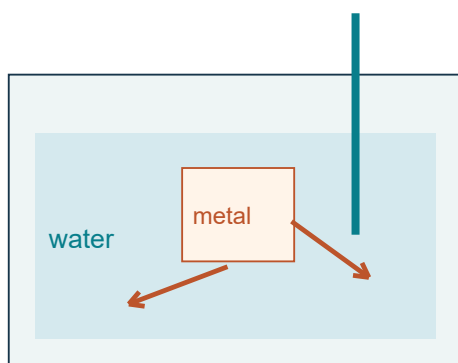
Specific heat & calorimetry

RELATIONSHIP AND CONDITIONS

$$Q = mc\Delta T \quad \text{and} \quad C = mc$$

c : specific heat [$\text{J}/(\text{kg}\cdot\text{K})$] • C : heat capacity [J/K]

Specific heat c is a material property related to microscopic arrangement and interactions. Heat capacity C depends on how much material is present. For a Q -versus- ΔT graph, the slope is mc . For temperature versus added energy, the slope is $1/(mc)$. These relations assume heating changes temperature without significant other energy transfers.



Hot metal loses energy.
Cool water gains energy.

At equilibrium:

$$T_{\text{metal}} = T_{\text{water}} = T_f$$

Calorimetry uses conservation of energy for an approximately insulated combination of objects.

Worked example | hot metal in water

Place 0.200 kg of metal at 90.0°C into 0.300 kg of water at 20.0°C . Let $c_{\text{metal}} = 900 \text{ J}/(\text{kg}\cdot\text{K})$ and $c_{\text{water}} = 4180 \text{ J}/(\text{kg}\cdot\text{K})$. Neglect the cup's heat capacity and transfer to the room.

$\Sigma Q = 0$:

$$0.200(900)(T_f - 90.0) + 0.300(4180)(T_f - 20.0) = 0$$

$$(180 + 1254)T_f = 180(90.0) + 1254(20.0)$$

$T_f = 28.8^\circ\text{C}$. The metal loses about 11.0 kJ and the water gains it.

Model checks before trusting the answer

The final temperature must lie between the starting temperatures when only these two objects exchange energy and no phase change occurs. If the cup also warms, include $C_{\text{cup}}(T_f - T_{\text{cup},i})$. If a material changes phase, use a staged energy balance (pp. 6-7).

Pause and predict 3

Equal masses of materials A and B receive the same energy. If $c_A = 2c_B$, compare their temperature increases.

Extension: multi-stage calorimetry

Worked example | ice at -10 °C to water at 20 °C

For 0.100 kg of ice, use $c_{\text{ice}} = 2100 \text{ J/(kg}\cdot\text{K)}$, $L_f = 3.34 \times 10^5 \text{ J/kg}$, and $c_{\text{water}} = 4180 \text{ J/(kg}\cdot\text{K)}$. Assume constant pressure and negligible losses.

Stage	Energy calculation	Result
Warm ice to 0 °C	$Q_1 = 0.100(2100)(10)$	2100 J
Melt ice at 0 °C	$Q_2 = 0.100(3.34 \times 10^5)$	33400 J
Warm water to 20 °C	$Q_3 = 0.100(4180)(20)$	8360 J
Total	$Q = Q_1 + Q_2 + Q_3$	43860 J $\approx$ 43.9 kJ

Do not assume that all the ice melts

Mix 0.100 kg of ice at 0 °C with 0.200 kg of water at 30 °C in an insulated cup. Cooling the water to 0 °C releases $0.200(4180)(30) = \mathbf{25080 \text{ J}}$. Melting all the ice requires **33400 J**, so there is not enough energy.

Melted mass = $25080/(3.34 \times 10^5) = \mathbf{0.0751 \text{ kg}}$.

Final state: **0 °C**, with approximately **0.0249 kg of ice remaining**.

Preserved setup | molten metal placed in water

The original notes use hot liquid lead. If a metal starts above its freezing temperature T_m , fully solidifies, and ends at $T_f < T_m$, the energy it releases is:

$$m_M c_{\text{liq}}(T_i - T_m) + m_M L_f + m_M c_{\text{sol}}(T_m - T_f).$$

Set this equal to the water's gain $m_w c_w (T_f - T_{w,i})$, adding the cup if necessary. Then verify that the assumed final phases are possible.

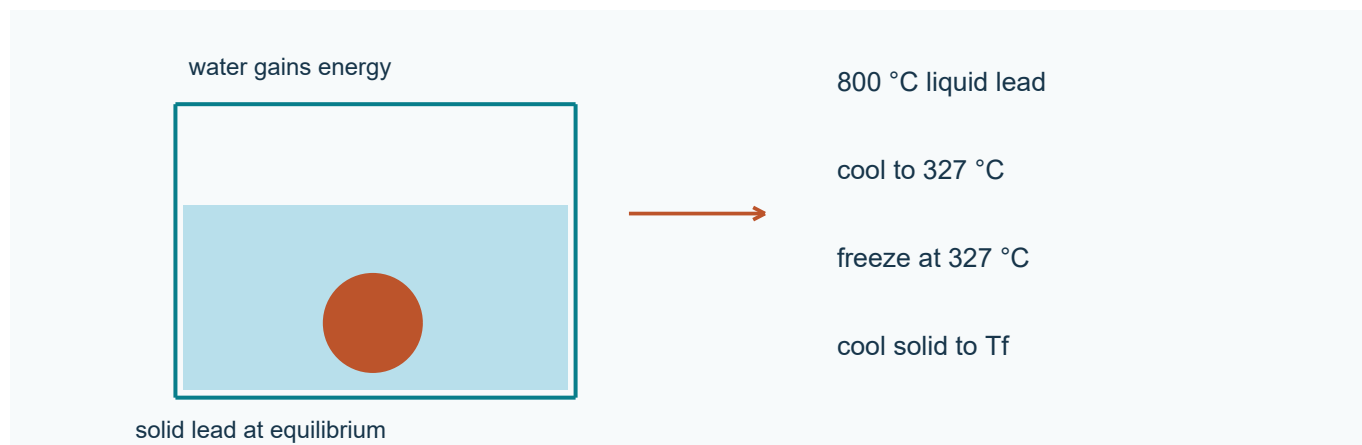
Phase-aware problem solving

1. Find the energy available to reach the nearest transition.
2. Compare it with the latent energy needed to complete the transition.
3. Only then decide whether to solve for a new temperature or a remaining phase fraction.

The molten-metal example is an energy-accounting model, not a classroom demonstration procedure.

Molten lead and water: account for every stage

The original lesson places hot liquid lead into cooler water. The lead may cool as a liquid, freeze, and then cool as a solid. The final-state assumption must be checked after the energy balance.



Ideal insulated calorimeter. The model neglects heat loss, the container and evaporation.

RELATIONSHIP AND CONDITIONS

$$Q_{\text{lead,lost}} = m c_{\text{liquid}}(800 - 327) + mL_f + m c_{\text{solid}}(327 - T_f)$$

$$Q_{\text{water,gained}} = m_w c_w (T_f - 10)$$

Worked completion with stated data: take 1.00 kg of lead, 2.00 kg of water, $c_{\text{liquid}} = 159 \text{ J}/(\text{kg}\cdot\text{K})$, $c_{\text{solid}} = 128 \text{ J}/(\text{kg}\cdot\text{K})$, $L_f = 23,000 \text{ J/kg}$, and $c_w = 4180 \text{ J}/(\text{kg}\cdot\text{K})$. These supplied values complete the original symbolic setup.

$$159(473) + 23,000 + 128(327 - T_f) = 8360(T_f - 10).$$

$$223,663 = 8488T_f, \text{ so } T_f = \mathbf{26.4\text{ }^\circ\text{C}}.$$

CHECK THE FINAL STATE

26.4 °C lies below the lead melting point and within the liquid-water range. The assumed final phases are consistent. If the calculation instead crossed a transition temperature, rebuild the balance with the actual final phases.

The ideal gas law

The ideal-gas model assumes random motion, negligible particle volume compared with the container, elastic collisions, and negligible interaction forces except during collisions. Real gases are often closer to ideal at low density and sufficiently high temperature, away from condensation.

RELATIONSHIP AND CONDITIONS

$$PV = nRT = Nk_B T$$

$$N = nN_A \quad \text{and} \quad R = N_A k_B$$

$$\text{For fixed } n: P_1 V_1 / T_1 = P_2 V_2 / T_2$$

Symbol	Meaning / useful conversion
n / N	n = amount in mol; N = number of particles (a count).
R / k_B	$R = 8.31 \text{ J}/(\text{mol}\cdot\text{K})$; $k_B = 1.38 \times 10^{-23} \text{ J/K}$.
Pressure / volume	$1 \text{ kPa} = 1000 \text{ Pa}$; $1 \text{ L} = 10^{-3} \text{ m}^3$; $1 \text{ kPa}\cdot\text{L} = 1 \text{ J}$.
Absolute pressure	$P_{\text{abs}} = P_{\text{atm}} + P_{\text{gauge}}$. A vacuum corresponds to zero absolute pressure.

Worked example | three state variables

A sealed 2.00 L sample has $P_1 = 100 \text{ kPa}$ and $T_1 = 300 \text{ K}$. It reaches $V_2 = 1.50 \text{ L}$ and $T_2 = 450 \text{ K}$.

$$P_2 = P_1 (V_1/V_2)(T_2/T_1) = 200 \text{ kPa}.$$

Initially, $n = PV/(RT) = (100 \times 2.00)/(8.31 \times 300) = 0.0802 \text{ mol}$.

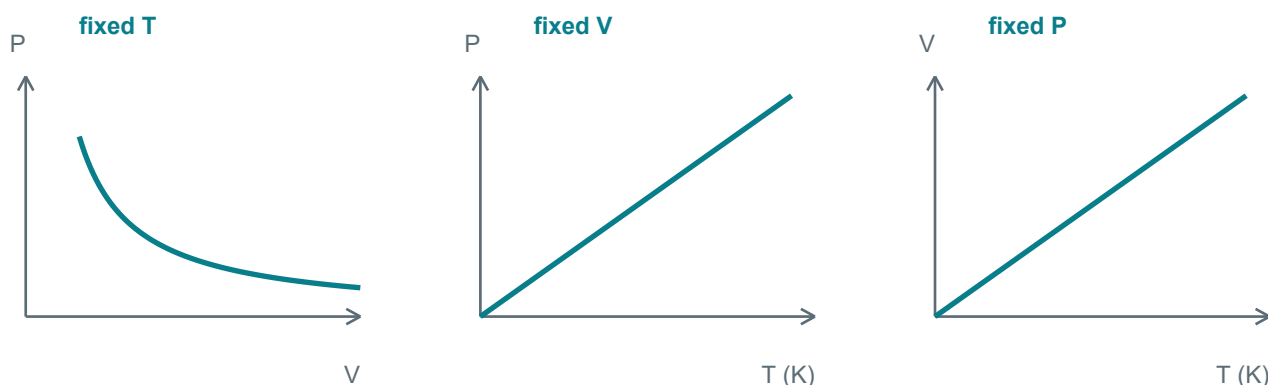
Piston or lid: include the atmosphere

For a horizontal, frictionless piston at rest under added downward force F , $P_{\text{gas}} A = P_{\text{atm}} A + F$. Include the piston's own weight in F when relevant. Example: $A = 0.0050 \text{ m}^2$ and $F = 500 \text{ N}$ give $P_{\text{gas}} = 100 \text{ kPa} + 100 \text{ kPa} = 200 \text{ kPa}$.

Pause and predict 4

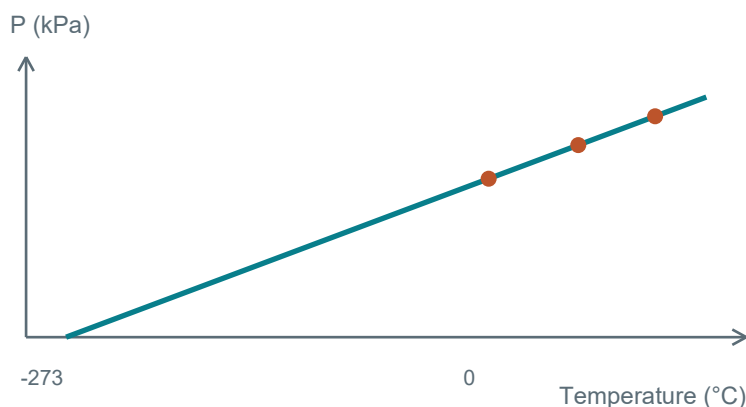
A fixed sample changes to $2T$ and $4V$. Find its final pressure as a multiple of its initial pressure.

Gas graphs & absolute zero



For a fixed amount of gas: $P \propto 1/V$ at fixed T , $P \propto T$ at fixed V , and $V \propto T$ at fixed P . The temperature axes here are in kelvins.

Process (fixed n)	PV graph	PT graph (T horizontal)	VT graph (T horizontal)
Constant P	Horizontal line	Horizontal line	Straight line through origin
Constant V	Vertical line	Straight line through origin	Horizontal line
Constant T	Hyperbola	Vertical line	Vertical line



Extrapolation of the ideal-gas model:
 $P = 0$ at $T = 0$ K.

A real gas usually condenses before reaching this intercept.

Pressure against Celsius temperature has a negative temperature intercept. This is a model extrapolation, not a method for making a real gas reach 0 K.

Worked graph interpretation

At fixed V and n , the line $P = aT_C + b$ has an intercept $T_{C,0} = -b/a$. If $a = 0.366 \text{ kPa/}^\circ\text{C}$ and $b = 100 \text{ kPa}$, then $T_{C,0} \approx -273^\circ\text{C}$. On a graph against kelvins, the slope is nR/V when SI units are used.

Pause and predict 5

A constant-pressure sample doubles its volume. Draw its path on PV, PT, and VT axes, and predict the change in average kinetic energy.

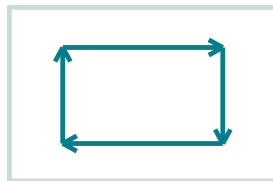
Heat transfer & thermal equilibrium

CONDUCTION



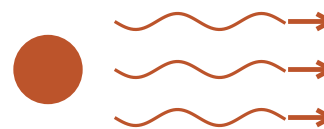
Microscopic interactions

CONVECTION



Bulk flow of a fluid

RADIATION



Electromagnetic waves

Conduction and convection require matter. Radiation can carry energy through a vacuum.

Mechanism	Microscopic or bulk description	Everyday example
Conduction	Energy passes through interactions between neighboring particles. Mobile electrons also contribute in metals. There is no bulk transport of the material.	A metal spoon warms in hot water.
Convection	Bulk motion of a fluid transports energy. In natural convection, density differences under gravity produce circulation.	Warmer water rises while cooler water sinks.
Radiation	Energy is emitted and absorbed as electromagnetic waves. Objects exchange radiation even when their temperatures are equal.	Sunlight warms a surface across space.

Equilibrium means zero net transfer

When two systems can exchange energy by thermal processes, they are in thermal contact. Net spontaneous transfer is from higher temperature to lower temperature. Across many particle interactions, this reduces the temperature difference. At thermal equilibrium, their temperatures are equal and the **net** thermal transfer is zero; microscopic exchanges continue.

Zeroth-law connection: if A and B are each in equilibrium with a thermometer, A and B have equal temperatures. This does not imply equal total internal energies or equal speeds for different species.

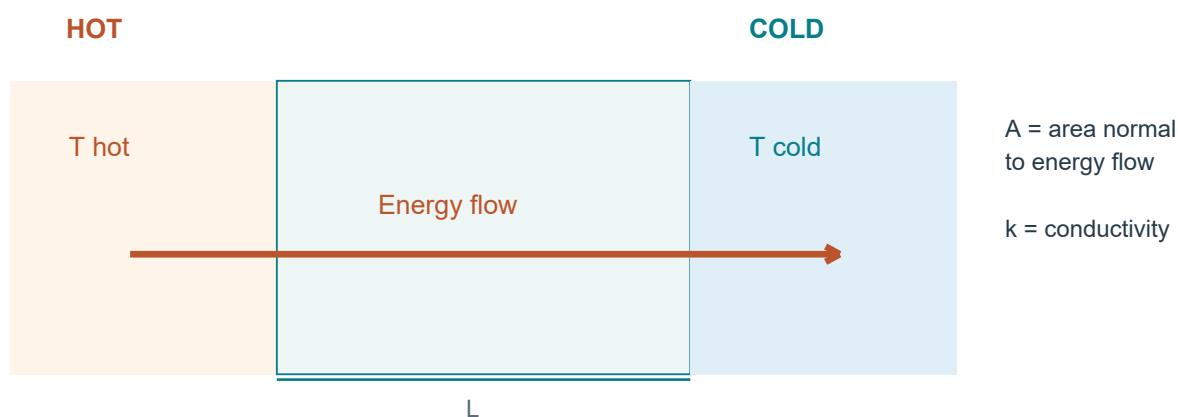
Why does metal feel colder than wood?

At the same room temperature below skin temperature, metal usually removes energy from your hand more rapidly. The sensation reports a transfer rate, not a direct measurement of the object's temperature. The contact and material properties matter.

Pause and predict 6

Can a small hot metal block transfer energy to a large cooler water tank even if the tank has more total internal energy? Explain the direction of transfer.

Thermal conductivity & transfer rate



A uniform slab connects reservoirs whose face temperatures are held fixed. The steady net transfer runs from the hot face to the cold face.

RELATIONSHIP AND CONDITIONS

$$H = Q/\Delta t = kA(T_{\text{hot}} - T_{\text{cold}})/L$$

H: transfer rate [W] • k: conductivity [W/(m·K)]

This model assumes steady, approximately one-dimensional conduction through a uniform material, with constant k and negligible energy leakage through the sides. L is the distance along the direction of transfer; A is the perpendicular cross-sectional area. Here Q is the magnitude transferred from hot to cold.

Change, with other quantities fixed	Effect on H
Double k , A , or the face-to-face temperature difference	Doubles
Double L	Halves
Double both A and L	Unchanged
Make the two face temperatures equal	Zero net conduction

Worked example | energy conducted through a panel

For $k = 0.20 \text{ W/(m·K)}$, $A = 0.50 \text{ m}^2$, $L = 0.020 \text{ m}$, and $\Delta T = 20 \text{ K}$:

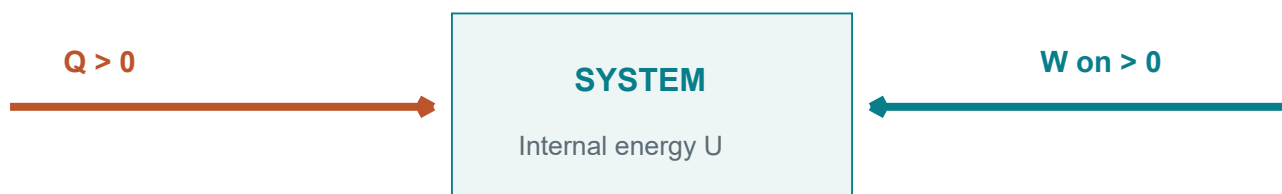
$$H = (0.20)(0.50)(20)/0.020 = 100 \text{ W.}$$

If the boundary temperatures stay constant for 60 s, $Q = H\Delta t = 6000 \text{ J}$. A single use of this rate is not valid if the face temperatures change substantially.

Pause and predict 7

A replacement slab has twice the conductivity and three times the thickness, with unchanged area and face temperatures. What is $H_{\text{new}}/H_{\text{old}}$?

Internal energy & the first law



Positive heat and positive work transfer energy into the system. Either mechanism can increase its internal energy.

RELATIONSHIP AND CONDITIONS

$$\Delta U = Q + W \quad (W = \text{work done on the system})$$

$$\text{Ideal monatomic gas: } U = \left(\frac{3}{2}\right)nRT = \left(\frac{3}{2}\right)Nk_B T = \left(\frac{3}{2}\right)PV$$

Internal energy includes microscopic motion and configuration energy, but excludes kinetic energy of the center of mass. A stationary object can gain U . For a **fixed amount of ideal monatomic gas**, $\Delta U = \left(\frac{3}{2}\right)nR\Delta T$, so ΔU and ΔT have the same sign.

System boundary	What may cross?	Consequence
Closed system	Energy, but no matter	Use $\Delta U = Q + W$ when these are the relevant transfers.
Isolated system	Neither matter nor energy	Total energy remains constant.
Open system	Matter and energy	Energy carried by matter must also be accounted for.

Worked example | heating while doing work

A gas absorbs 500 J and does 180 J of work on its surroundings. For the gas, $Q = +500 \text{ J}$ and $W = -180 \text{ J}$. **$\Delta U = 500 - 180 = +320 \text{ J}$** . If the gas instead lost 500 J while being compressed by 180 J of work, ΔU would be -320 J.

Do not overextend the monatomic formula

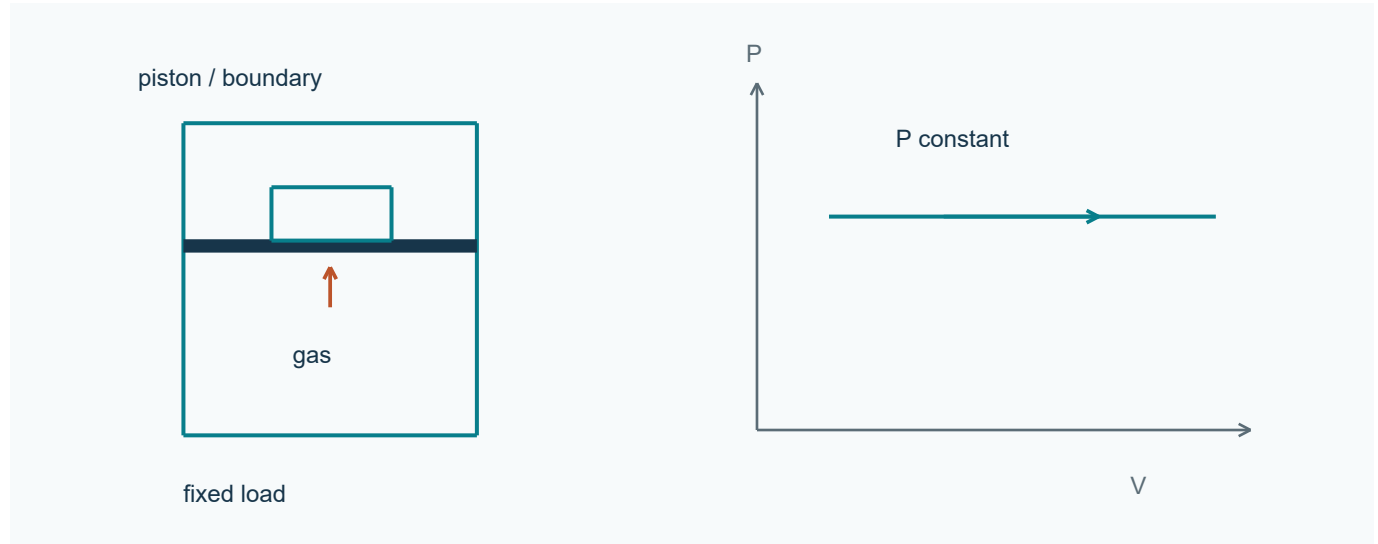
The coefficient $3/2$ applies to the ideal monatomic model. Molecular gases may store rotational and vibrational energy; use the model the problem specifies. **Q and W depend on the path; U is a state function.**

Pause and predict 8

An insulated gas is compressed, and 90 J of work is done on it. Determine Q , ΔU , and the direction of the temperature change.

Isobaric expansion: the loaded piston

A frictionless piston carrying a constant load moves slowly enough that the gas remains close to mechanical equilibrium. The load and atmospheric pressure fix the gas pressure. Heating then makes the piston rise and the volume increase.



The piston picture and the horizontal PV path describe the same expansion.

RELATIONSHIP AND CONDITIONS

$$P_{\text{gas}} = P_{\text{atm}} + F_{\text{load}}/A$$

$$W_{\text{on}} = -P\Delta V; \Delta U = (3/2)P\Delta V; Q = \Delta U - W_{\text{on}}$$

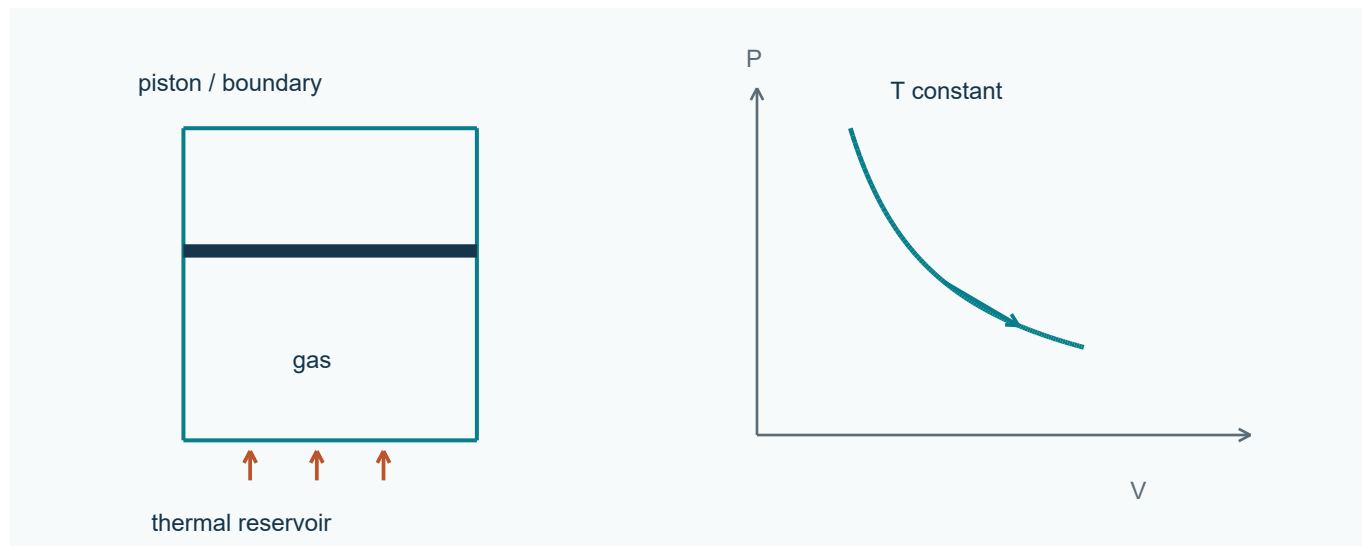
Example: a monatomic gas expands from 1.0 L to 3.0 L at 100 kPa. Since $1 \text{ kPa} \cdot \text{L} = 1 \text{ J}$, $W_{\text{on}} = -200 \text{ J}$, $\Delta U = +300 \text{ J}$ and $Q = +500 \text{ J}$. Some input energy raises internal energy and some becomes work done by the gas.

PAUSE AND EXPLAIN

Why is Q larger than ΔU ? The gas must also supply the 200 J of work to lift the load. A movable piston alone does not guarantee constant pressure: the external load must stay constant.

Isothermal change: heat can enter at constant T

Keep a fixed ideal-gas sample in thermal contact with a temperature reservoir and change its volume slowly. At constant temperature the gas stays on one PV isotherm. Higher-temperature isotherms lie farther from the origin.



An expansion follows one hyperbola. The energy supplied by heat replaces the energy leaving as work.

RELATIONSHIP AND CONDITIONS

$$PV = nRT = \text{constant}$$

$$\Delta U = 0; Q = -W_{\text{on}} = W_{\text{by}}$$

If the gas delivers 60 J of work while expanding isothermally, $W_{\text{on}} = -60 \text{ J}$ and $Q = +60 \text{ J}$. A compression with 60 J done on the gas requires $Q = -60 \text{ J}$ to maintain the same temperature.

MICROSCOPIC EXPLANATION

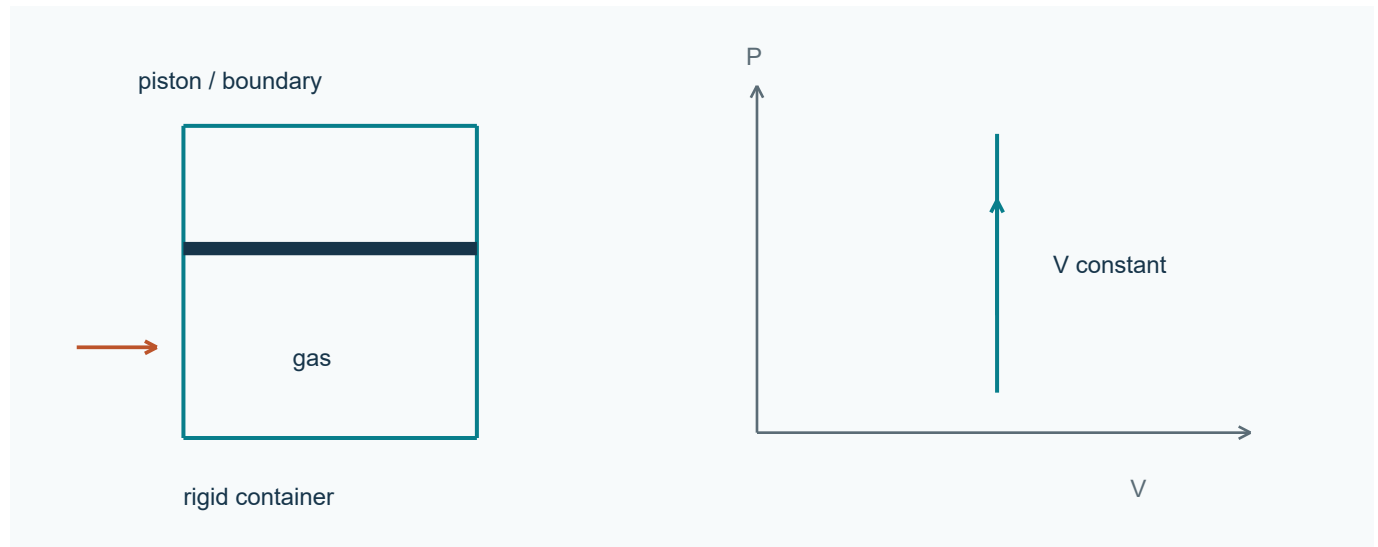
Average translational kinetic energy stays constant. The expanding gas transfers energy through the moving piston, while interactions with the warmer boundary replace that energy. Constant temperature does not mean that no energy crosses the boundary.

Pause and predict 9

An ideal gas delivers 60 J of work. Find Q and ΔU for an isothermal change. Compare with an adiabatic change delivering the same work.

Constant volume: heating with no boundary work

A rigid sealed container prevents volume change. Thermal energy transfer changes the gas temperature and pressure, but the fixed boundary has no displacement and therefore no pressure-volume work.



The path is vertical on a PV graph, so its horizontal width and its boundary work are zero.

RELATIONSHIP AND CONDITIONS

$$\Delta V = 0; W_{\text{on}} = 0; Q = \Delta U$$

Fixed n and V : $P/T = \text{constant}$

Example: 1.0 mol of ideal monatomic gas warms from 300 K to 400 K. $\Delta U = (3/2)(1.0)(8.31)(100) = 1246.5 \text{ J}$. Thus $Q \approx +1.25 \text{ kJ}$, while the pressure increases by a factor of 4/3.

PAUSE AND EXPLAIN

A vertical PV segment has a nonzero length but encloses no area under a volume interval. Explain why the visual height of the segment is not the work.

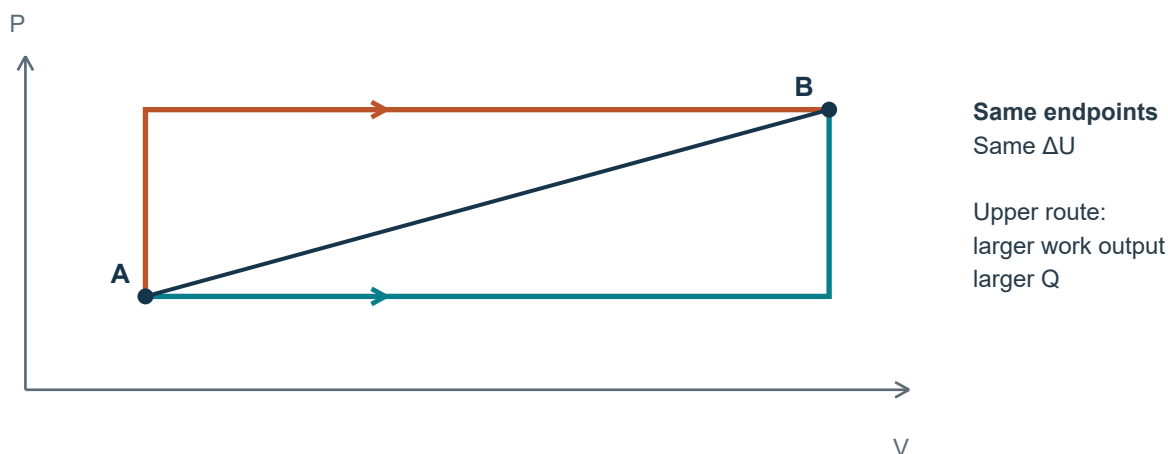
Work, PV area & path dependence

RELATIONSHIP AND CONDITIONS

$W = -P_{\text{ext}}\Delta V$ for constant external pressure

$W_{\text{by}} = -W$ and $Q = \Delta U - W$

For a quasistatic piston process, gas pressure closely matches external pressure, so the area under the gas's PV curve gives the magnitude of the boundary work. Expansion gives $W < 0$; compression gives $W > 0$. For an arbitrary rapid process, use the external pressure to evaluate boundary work; a gas-state curve alone may be insufficient.



Three paths take the same fixed sample from A to B. Every path has the same ΔT and ΔU . Expansion at a higher pressure produces a larger magnitude of work.

Worked example | a straight-line path

A gas expands from (1.0 L, 100 kPa) to (3.0 L, 300 kPa) along a straight line. The work magnitude is a trapezoid area:

$$W = -[(100 + 300)/2](3.0 - 1.0) = -400 \text{ J.}$$

For an ideal monatomic gas, $\Delta U = (3/2)[(300)(3.0) - (100)(1.0)] = 1200 \text{ J}$. Therefore $Q = 1200 - (-400) = 1600 \text{ J}$.

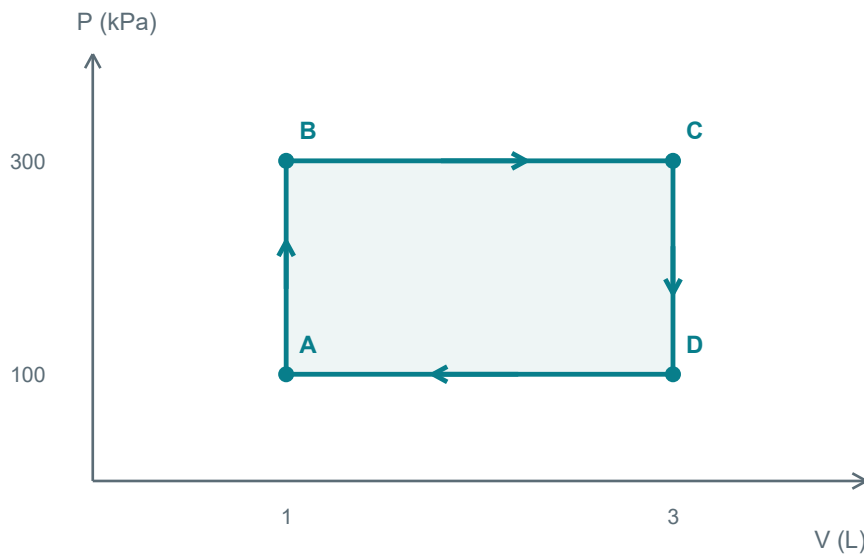
A complete cycle

The system returns to its initial state, so $\Delta U_{\text{cycle}} = 0$ and $Q_{\text{net}} = -W_{\text{net}}$. A clockwise PV loop has net work output: $W_{\text{net}} < 0$. A counterclockwise loop requires net work input: $W_{\text{net}} > 0$. The enclosed area gives the magnitude.

Pause and predict 10

Two paths connect the same A and B. One has a larger expansion area under its PV curve. Which path requires more heat input? Justify with the first law.

A complete cycle: signs before numbers



Clockwise cycle

$$\begin{aligned}\text{Area} &= (300 - 100) \text{ kPa} \\ &\times (3 - 1) \text{ L}\end{aligned}$$

400 J

Read each leg separately. For this plot, multiplying kPa by L gives joules directly.

Leg	$\Delta U = (3/2)\Delta(PV)$	W on gas	$Q = \Delta U - W$
A $\rightarrow$ B	+300 J	0	+300 J
B $\rightarrow$ C	+900 J	-600 J	+1500 J
C $\rightarrow$ D	-900 J	0	-900 J
D $\rightarrow$ A	-300 J	+200 J	-500 J
Cycle	0	-400 J	+400 J

State comparison: $T \propto PV$ for fixed n . Therefore $T_A : T_B : T_C : T_D = 100 : 300 : 900 : 300 = 1 : 3 : 9 : 3$. States B and D have equal temperatures, even though neither P nor V is the same.

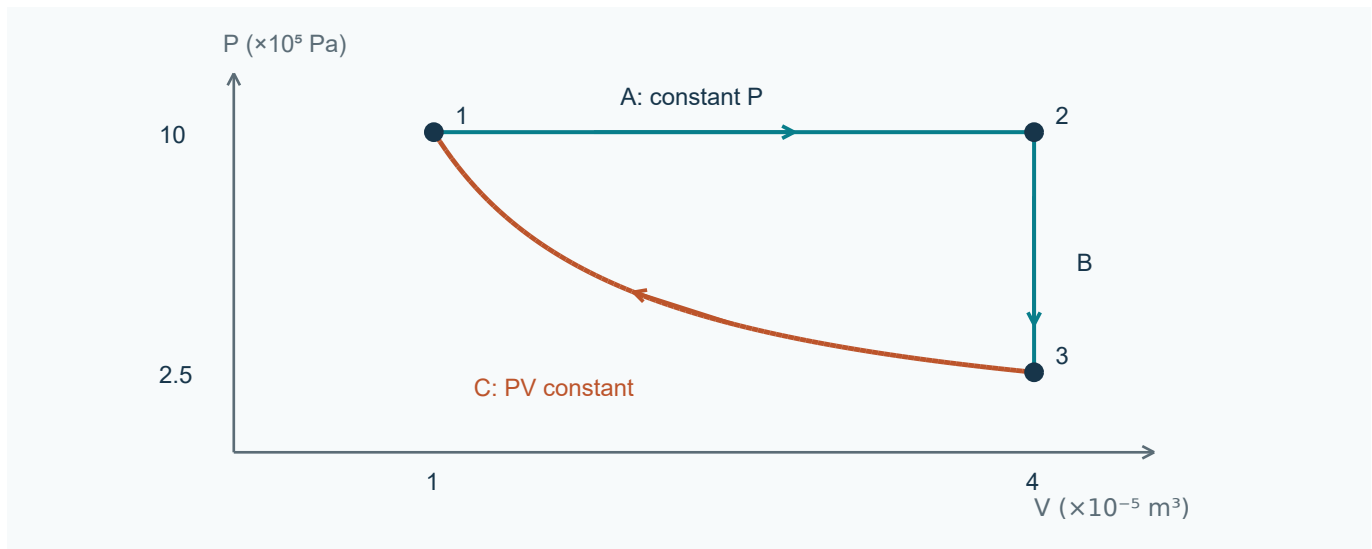
An energy audit of the cycle

The gas absorbs 1800 J on $A \rightarrow B \rightarrow C$ and releases 1400 J on $C \rightarrow D \rightarrow A$. The difference, 400 J, is the work delivered to the surroundings. Net heat is not the same as total heat absorbed. No energy is created during the cycle.

Pause and predict 11

Reverse the direction of every arrow. What are the signs and magnitudes of net W and net Q ? Does the cycle's ΔU change?

The original cycle: compare areas before calculating



The source cycle expands at $10 \times 10^5 \text{ Pa}$ from 1.0×10^{-5} to $4.0 \times 10^{-5} \text{ m}^3$, then cools at fixed volume. The return path is isothermal.

Leg A, horizontal expansion: $W_{\text{on}} = -(10 \times 10^5)(3 \times 10^{-5}) = -30 \text{ J}$. PV rises, so temperature and internal energy rise. Q must be positive and larger than 30 J.

Leg B, constant-volume cooling: $W_{\text{on}} = 0$. Pressure, temperature and internal energy fall. Therefore Q is negative.

Leg C, isothermal compression: $\Delta U = 0$. Work on the gas is positive, so Q is negative. Its PV area is smaller than the 30 J expansion rectangle. Therefore the net work on the gas over the cycle is negative.

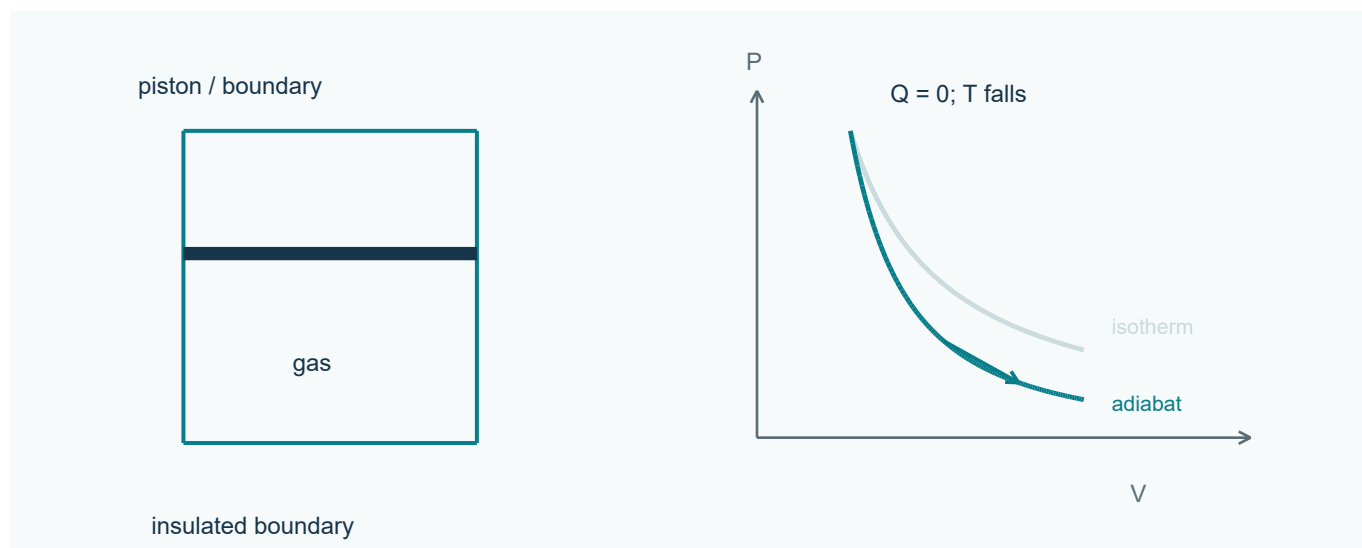
THE MICROSCOPIC PART OF THE ORIGINAL QUESTION

Compare equal-particle-number samples in states 2 and 3. State 2 has the larger PV and therefore the higher temperature. Thermal contact produces net energy transfer from state 2 toward state 3. During the isothermal compression, typical molecular speed stays constant while collision frequency rises.

For a monatomic model, $\Delta U_A = (3/2)(40 - 10) = +45 \text{ J}$ and $Q_A = 75 \text{ J}$. These energy values supplement the source's area argument.

Adiabatic change: temperature changes without heat

Insulate the gas, or change its volume quickly enough that thermal transfer is negligible during the change. $Q = 0$ is the defining condition. Compression then raises internal energy through work. Expansion lowers it.



An adiabatic expansion drops below the isotherm through the same initial state. A compression reaches higher-temperature isotherms.

RELATIONSHIP AND CONDITIONS

$$Q = 0; \Delta U = W_{\text{on}}$$

Expansion: $W_{\text{on}} < 0$ and T decreases.

Compression: $W_{\text{on}} > 0$ and T increases.

Example: 0.50 mol of monatomic gas undergoes insulated compression with 90 J of work done on it. $\Delta T = 90 / [(3/2)(0.50)(8.31)] = 14.4$ K.

ISOTHERMAL AND ADIABATIC COMPARED

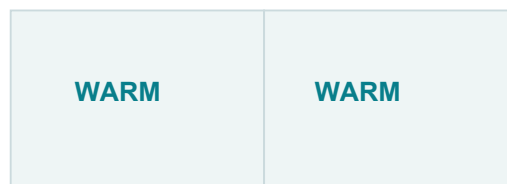
Isothermal fixes T and allows Q to balance work. Adiabatic fixes Q at zero and allows T to change. For a reversible ideal-gas extension, PV^γ is constant, with $\gamma = 5/3$ for a monatomic gas. The supplied CED does not require that extra process equation.

Entropy & the second law

Before contact



At equilibrium



Isolated combined system: energy conserved; entropy increases.

For two bodies in an isolated combination, spontaneous energy redistribution brings them toward a common temperature.

Entropy S is a state function: it depends on the current macroscopic state, not the path taken to reach it. Qualitatively, increasing entropy describes energy spreading among more accessible microscopic arrangements and a reduction in its availability to produce useful work.

The second law

The total entropy of an **isolated system cannot decrease**. It increases for irreversible processes and remains constant for an ideal reversible process. At thermodynamic equilibrium, the isolated system has maximum entropy subject to its constraints.

Situation	Correct conclusion
Hot and cold bodies brought into contact	The hot body can lose entropy, but the combined isolated system gains entropy.
An object cools in a large room	The object is not isolated. Its entropy may decrease while total entropy increases.
A refrigerator cools its interior	Work input allows energy to be transferred from colder to hotter regions; the surroundings must be included.
An ideal reversible change	Total entropy of system plus surroundings stays constant. Reversible is an ideal limiting condition.

Heat-engine connection: a cyclic device cannot take energy solely by heating from one reservoir and convert all of that energy into work with no other effect. It must reject energy or produce another compensating change. This is more precise than saying “no machine is 100% efficient.” No numerical entropy or Carnot formula is required by the supplied Unit 9 boundary.

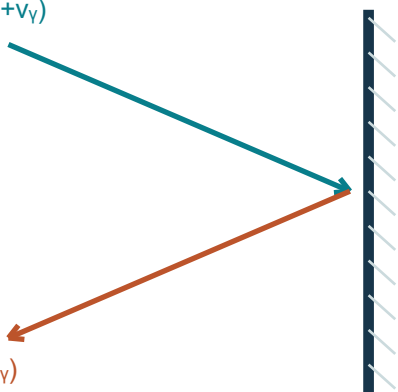
Pause and predict 12

A cup of hot water cools. A student says, “The water’s entropy decreases, so the second law is violated.” Identify the missing system boundary and correct the claim.

Pressure comes from momentum transfer

before: $(+v_x, +v_y)$

after: $(-v_x, +v_y)$



A smooth, fixed wall reverses the **normal** velocity component. The tangential component is unchanged.

Particle: $\Delta p_x = -2mv_x$
 Wall: impulse = $+2mv_x$
 Axes: +x right; +y downward.

Oblique elastic collision: only the velocity component perpendicular to a smooth fixed wall reverses. The drawn vertical direction is the tangential direction.

RELATIONSHIP AND CONDITIONS

$$P = F_{\perp, \text{avg}} / A$$

$$F_{\perp, \text{avg}} = (\text{total perpendicular impulse delivered to wall}) / \Delta t$$

If N_{hit} identical impacts deliver impulse $2mv_{\perp}$ each in time Δt , then $P = 2N_{\text{hit}}mv_{\perp} / (A\Delta t)$. For unequal speeds, add the impulses individually. Pressure exists throughout a gas, not only at the wall.

From one particle to the whole gas

For a cube of side L , one particle returns to the same wall after $2L/|v_x|$. Its average force on that wall is $m v_x^2 / L$. For random motion, $\langle v_x^2 \rangle = \langle v_y^2 \rangle = \langle v_z^2 \rangle = \langle v^2 \rangle / 3$. Summing over all N particles gives:

$$PV = (1/3)Nm\langle v^2 \rangle = (2/3)N K_{\text{avg}}. \text{ Combining this with } PV = Nk_B T \text{ gives } K_{\text{avg}} = (3/2)k_B T.$$

Collisions between particles: conserve components

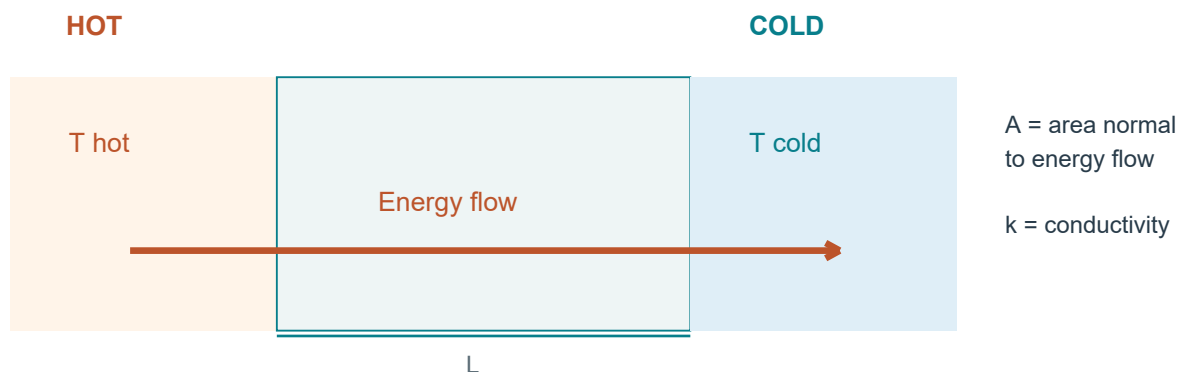
For an isolated pair, total momentum is conserved separately along x and y . An elastic collision also conserves the pair's total kinetic energy; each particle's kinetic energy may change. Example: two equal masses, initially $(v, 0)$ and $(0, 0)$, may leave with $(v/2, v/2)$ and $(v/2, -v/2)$. The total momentum remains $(mv, 0)$, and the total kinetic energy remains $\frac{1}{2}mv^2$.

Pause and predict 13

At fixed volume, why does increasing T raise P ? At fixed T , why does compressing the gas raise P ? Use impulse and collision rate, not only $PV = nRT$.

The original conduction experiment

The original apparatus keeps boiling water above one face of a plastic slab and ice near 0 °C on the other face. Area $A = 0.025 \text{ m}^2$ and $\Delta T = 100 \text{ K}$ stay fixed while slab thickness L changes. After steady transfer develops, the melt rate gives the energy-transfer rate H .



Energy moves through the slab from the hot reservoir to the melting ice.

L (m)	0.010	0.020	0.030	0.040	0.050
H (J/s)	95	53	31	27	18
1/L (m^{-1})	100	50	33.3	25	20

RELATIONSHIP AND CONDITIONS

$$H = kA\Delta T(1/L)$$

Plot H vertically against $1/L$ horizontally. Slope = $kA\Delta T$.

A fitted slope near $1.0 \text{ W}\cdot\text{m}$ gives $k \approx 1.0/(0.025 \times 100) = \mathbf{0.40 \text{ W/(m}\cdot\text{K)}}$. Use all points and show a best-fit line. Measurement scatter need not put every point exactly on the line.

EXPLANATIONS RETAINED FROM THE SOURCE

Plastic transfers energy through interactions and vibrations of its particles. Do not explain plastic conduction by mobile metal electrons. Equal-temperature wood and plastic can feel different because they remove energy from a hand at different rates. A lower actual face-to-face ΔT than assumed biases the inferred k downward.

Two experiments you can explain and defend

A | Test the ideal gas law with a sealed syringe

Question: Is P proportional to $1/V$ at fixed temperature and fixed amount of gas?

Equipment: sealed syringe, absolute pressure sensor, volume scale, thermometer, and a clamp or force control. Keep the connection volume in the model.

Procedure: seal a fixed amount of air; select at least five volumes over a useful range; change volume slowly; wait for temperature and pressure to stabilize; record P , total gas volume, and T ; repeat each setting.

Prediction & analysis

Plot absolute **P vertically against $1/V$ horizontally**. For constant n and T , slope = nRT , with units $\text{Pa} \cdot \text{m}^3 = \text{J}$. A systematic curve may indicate unaccounted tubing volume, temperature drift, leaks, or a nonideal apparatus. Do not interpret a gauge reading as absolute pressure.

Improve the test: include syringe plus tubing volume; check leaks; take repeated readings; compare compression and expansion readings for hysteresis. If a weighted piston is used instead of a sensor, calculate $P = P_{\text{atm}} + F/A$ and consider friction. A rapid compression raises T , making P temporarily too large for an isothermal model.

B | Determine specific heat from electrical heating

Question: What is c for a sample of known mass m ?

Equipment: insulated sample, low-voltage heater, temperature probe, timer, voltmeter and ammeter.

Procedure: measure m ; place the heater and probe in good thermal contact; stir if the sample is a liquid; measure electrical power $P_{\text{elec}} = IV$; record T at regular intervals over a modest range; repeat. Insulate the container and avoid any phase change.

RELATIONSHIP AND CONDITIONS

$$P_{\text{elec}} t \approx mc\Delta T$$

$$\text{Slope } s \text{ of } \Delta T \text{ versus } t = P_{\text{elec}}/(mc)$$

$$c = P_{\text{elec}}/(ms)$$

Interpret an error: if heat escapes to the room, the measured slope is too small. Using all electrical power as though it heats the sample makes the inferred c too large. A warming container also adds heat capacity; measure or correct for it. Measure power rather than assuming it stays constant.

Practice: connect the representations

1 | Temperature and speed. A helium sample warms from 200 K to 800 K. Find the factors of change in average translational kinetic energy and rms speed. Describe the changes to a normalized speed distribution.

2 | Collision and pressure. An atom of mass 5.0×10^{-26} kg hits a smooth fixed wall with normal speed 400 m/s and tangential speed 300 m/s. Find the impulse magnitude delivered to the wall. If 1.0×10^{20} such impacts occur on 0.010 m^2 each second, calculate the average pressure.

3 | Gas states. A sealed 2.0 L gas sample is initially at 100 kPa and 300 K. It is compressed to 1.0 L and warmed to 450 K. Find its final pressure and its initial amount in moles.

4 | Energy signs. A gas releases 80 J by cooling while 130 J of work is done on it. Calculate ΔU . For a fixed ideal monatomic sample, state whether T rises or falls.

5 | Calorimetry. A 0.100 kg solid with $c = 400 \text{ J}/(\text{kg}\cdot\text{K})$ at 100°C is placed in 0.200 kg of water at 20°C . Use $c_w = 4200 \text{ J}/(\text{kg}\cdot\text{K})$. Neglect the cup and losses. Find the final temperature.

6 | Conduction scaling. A slab is replaced by one with half the conductivity, twice the area, and three times the thickness. Face temperatures are unchanged. Find the ratio of new to old transfer rate.

7 | Entropy claim. “Every object’s entropy must increase whenever anything happens.” Correct the claim and give a counterexample consistent with the second law.

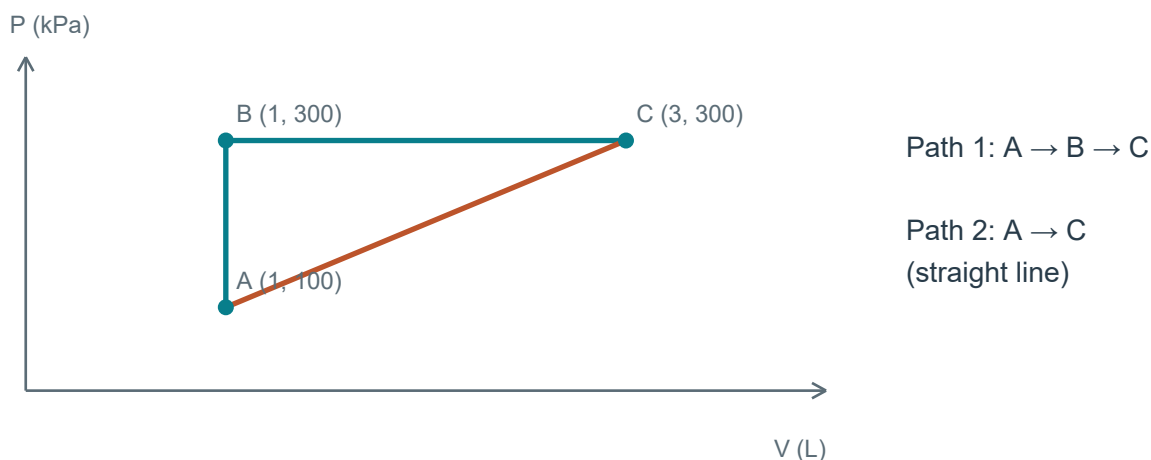
8 | Extension. How much energy is needed to change 0.050 kg of ice at 0°C into water at 10°C ? Use $L_f = 3.34 \times 10^5 \text{ J/kg}$ and $c_w = 4180 \text{ J}/(\text{kg}\cdot\text{K})$.

Before you move on

For every numerical answer, check units and order of magnitude. For every explanation, name the system, the constraint, and the physical relationship. A correct equation alone is not a complete explanation of a microscopic mechanism.

Practice: two extended responses

A | Two paths, one pair of endpoints



A fixed ideal monatomic sample starts at A. All shown paths are quasistatic. Path 1 goes vertically to B, then horizontally to C. Path 2 is the straight segment AC.

- Find T_C/T_A and the change in internal energy from A to C.
- Calculate W and Q for each path. Explain the difference using areas.
- Return from C to A along the straight segment. Find net W , net Q , and ΔU for the loop $A \rightarrow B \rightarrow C \rightarrow A$.
- During $A \rightarrow B$, explain the increase in pressure in terms of particle-wall collisions.

B | Measure a material property

A student heats a 0.250 kg sample with a constant measured electrical power of 20.0 W. The table contains illustrative measurements. There is no phase change.

Time t (s)	0	30	60	90
Temperature rise ΔT (K)	0	2.4	4.8	7.2

- State the axes and expected form of a graph used to find c .
- Find the slope, including units, and calculate c .
- If 10% of the electrical power actually heats the cup rather than the sample, is the value in (b) too high or too low? Calculate the corrected c under this assumption.
- Describe one procedural improvement and explain why it helps.

What a strong response contains

A symbolic relationship, a graph feature or data trend, units, a conclusion, and a causal explanation. For an error question, say both **which way the result changes** and **why**.

Answers: pause & predict

Check	Answer and reasoning
1	K_{avg} doubles; v_{rms} increases by $\sqrt{2}$. Energy is proportional to T , while speed is proportional to $\sqrt{T}$ for a fixed particle mass.
2	The distribution broadens, its peak lowers and shifts right, and its normalized area stays 1. Pressure rises: impacts are more frequent and have larger typical perpendicular impulse.
3	$\Delta T_A = \Delta T_B/2$, because $\Delta T = Q/(mc)$.
4	$P_2/P_1 = (T_2/T_1)(V_1/V_2) = 2/4 = 1/2$.
5	T doubles and K_{avg} doubles. PV: horizontal rightward path. PT: horizontal rightward path. VT: up-right along $V \propto T$.
6	Yes. The temperature difference sets the direction of net thermal transfer, not the total internal energy of each object.
7	$H_{new}/H_{old} = 2/3$.
8	$Q = 0$; $W = +90$ J; $\Delta U = +90$ J. The temperature rises.
9	Isothermal: $W = -60$ J, $\Delta U = 0$, $Q = +60$ J. Adiabatic with the same work output: $Q = 0$ and $\Delta U = -60$ J.
10	The larger-area expansion has more negative W . Since ΔU is the same, $Q = \Delta U - W$ is larger.
11	Reversed: $W_{net} = +400$ J and $Q_{net} = -400$ J. ΔU_{cycle} remains zero.
12	Water alone is not isolated. Include the surroundings: their entropy increase exceeds the water's decrease for this spontaneous process.
13	At fixed V , greater T raises both typical impulse per collision and collision rate. At fixed T , compression leaves the speed distribution unchanged but increases wall-collision rate per unit area.

Teaching use: ask students to identify the conserved or constrained quantity before displaying the answer. For gas reasoning, request both a macroscopic equation and a microscopic explanation.

Solutions: short practice

1-3 | Particle motion and gas variables

1. $T_2/T_1 = 4$, so $K_{\text{avg},2}/K_{\text{avg},1} = 4$ and $v_{\text{rms},2}/v_{\text{rms},1} = 2$. The normalized speed curve broadens and shifts right, with a lower peak and unchanged total area.

2. The wall receives only perpendicular impulse:

$$J = 2mv_{\perp} = 2(5.0 \times 10^{-26})(400) = 4.0 \times 10^{-23} \text{ N}\cdot\text{s}.$$

$$\text{Force} = (\text{impact rate})J = 4.0 \times 10^{-3} \text{ N}.$$

$P = F/A = 0.0040/0.010 = 0.40 \text{ Pa}$. The 300 m/s tangential component does not contribute to the normal impulse at a smooth wall.

$$3. P_2 = 100(2.0/1.0)(450/300) = 300 \text{ kPa}.$$

$$n = P_1 V_1 / (RT_1) = 200 / (8.31 \times 300) = 0.0802 \text{ mol}.$$
 Use kelvins for the temperature ratio.

4-6 | Energy accounting and material response

4. $Q = -80 \text{ J}$ and $W = +130 \text{ J}$. $\Delta U = Q + W = +50 \text{ J}$. For the stated gas, T rises even though energy leaves by thermal transfer.

5. Use signed energy changes:

$$0.100(400)(T_f - 100) + 0.200(4200)(T_f - 20) = 0.$$

$$40T_f - 4000 + 840T_f - 16800 = 0.$$

$T_f = 20800/880 = 23.6 \text{ }^\circ\text{C}$. The final temperature is closer to $20 \text{ }^\circ\text{C}$ because the water has the greater heat capacity.

$$6. H \propto kA/L, \text{ so } H_{\text{new}}/H_{\text{old}} = (1/2)(2)/3 = 1/3.$$

7-8 | Second law and phase changes

7. The total entropy of an **isolated system** cannot decrease. An individual nonisolated object can lose entropy, as when hot water cools into a cooler room. The combined entropy increases. Ideal reversible processes have zero total entropy change.

8. First melt, then warm:

$$Q = mL_f + mc_w \Delta T = 0.050(334000) + 0.050(4180)(10)$$

$$= 16700 + 2090 = 18790 \text{ J} \approx 18.8 \text{ kJ}.$$

Solutions: extended responses

A | State changes, path changes, and a loop

(a) For fixed n , $T \propto PV$, so $T_C/T_A = (300 \times 3)/(100 \times 1) = 9$.

$\Delta U = (3/2)\Delta(PV) = (3/2)(900 - 100) = +1200 \text{ J}$.

Path	Work on the gas	Heat transferred to gas
$A \rightarrow B \rightarrow C$	$0 - (300)(3 - 1) = -600 \text{ J}$	$1200 - (-600) = +1800 \text{ J}$
$A \rightarrow C$, straight	$-[(100 + 300)/2](3 - 1) = -400 \text{ J}$	$1200 - (-400) = +1600 \text{ J}$

(b) The upper route has a greater area under its PV path. It delivers 200 J more work to the surroundings, so it requires 200 J more heat input to produce the same internal-energy change.

(c) On $C \rightarrow A$, $W = +400 \text{ J}$, $\Delta U = -1200 \text{ J}$, and $Q = -1600 \text{ J}$. For $A \rightarrow B \rightarrow C \rightarrow A$, $W_{\text{net}} = -200 \text{ J}$, $Q_{\text{net}} = +200 \text{ J}$, and $\Delta U = 0$. The triangular enclosed area is $\frac{1}{2}(200 \text{ kPa})(2 \text{ L}) = 200 \text{ J}$.

(d) At fixed volume, T rises. The particles have greater average kinetic energy, so their wall impacts have larger typical perpendicular impulse and occur more often. The average normal force per area therefore rises.

B | Specific heat from a slope

(a) Plot ΔT (K) vertically against t (s) horizontally. With constant net heating power and c , expect a straight line; the ideal ΔT intercept is zero.

(b) $s = (7.2 - 0)/(90 - 0) = 0.080 \text{ K/s}$.

$c = P/(ms) = 20.0/(0.250 \times 0.080) = 1000 \text{ J/(kg}\cdot\text{K)}$.

(c) The original value is **too high**: it attributes the cup's heating energy to the sample. Sample power = $0.90(20.0) = 18.0 \text{ W}$. Corrected $c = 18.0/(0.250 \times 0.080) = 900 \text{ J/(kg}\cdot\text{K)}$.

(d) Measure the cup's heat capacity and subtract its energy increase, or use a lower-heat-capacity container. Insulating the apparatus reduces a different error: heat loss to the room.

Consistency check

Changing the path changes work and heat, but not the endpoints' ΔU . Changing an experimental assumption changes which energy belongs in the model. In both cases, an explicit system boundary prevents sign and interpretation errors.

Original notes and syllabus map

The source sequence determines the teaching order. Repeated examples are consolidated while distinct reasoning, diagrams and comparisons are retained.

Original source	Content retained
N11, pp.1-8 Thermal 9.1-9.2, 9.5 - Phase Changes.pdf	Temperature, speed distributions, phases, calorimetry and ideal-gas model
N12, pp.1-9 Thermal 9.2-9.5.pdf	Gas variables, conduction, work convention and piston processes
N13, pp.1-10 Thermal 9.1-9.4, 9.6.pdf	Cycles, adiabatic changes, entropy and annotated cycle question
N14, pp.1-9 Thermal 9.1-9.5.pdf	Pressure derivation, rms arithmetic and conduction experiment
N34, p.5 Magnetism 12.3-12.4 + Electrostatics 10.1 + Thermal 9.3.pdf	Conduction, convection and radiation
N35, pp.1-4 Problem Solving - Thermal 9.1-9.2, 9.4 + Electrostatics 10.1-10.5, 10.7.pdf	Gas properties, collisions and adiabatic reasoning

Curriculum: supplied *AP Physics 2 Course and Exam Description*, 2026, Unit 9. Topic labels on each content page show where the syllabus connects to the original lesson. Extensions remain labeled.

Clarifications and independent references

Point checked	Treatment in this chapter
Work sign	W means work on the gas throughout. Expansion has $W < 0$.
Elastic collisions	Total kinetic energy of the colliding pair is conserved. One particle may gain or lose energy.
Entropy	The isolated total has nondecreasing entropy. A subsystem may lose entropy.
Piston pressure	A movable piston gives constant pressure only under an appropriate constant load and quasistatic conditions.
Scope	Phase changes, numerical latent heat and the reversible adiabatic equation are retained as extensions.

Independent checks

[OpenStax: pressure, temperature and rms speed](#)

[OpenStax: first law](#)

[OpenStax: entropy](#)

Constants and calculations use the values stated in each example. Historical practice provides context and reasoning patterns. New worked questions and corrected explanations are distinguished from an official answer key.

Master summary: gas processes and energy signs

Process	Constraint	PV shape	W on gas during expansion	ΔU for fixed ideal gas	Heat Q
Isobaric	P constant	Horizontal	$-P\Delta V$	Positive as T rises	Positive; supplies ΔU and work output
Isothermal	T constant	Hyperbola	Negative	0	Positive, equal to $-W$
Isochoric	V constant	Vertical	0	Tracks T	$Q = \Delta U$
Adiabatic	$Q = 0$	Steeper than isotherm for reversible gas	Negative	Negative as T falls	0
Closed cycle	Final state = initial state	Closed loop	Clockwise: negative net W	0 over cycle	$Q_{\text{net}} = -W_{\text{net}}$

Quantity	Relationship	Interpretation
Temperature	$K_{\text{avg}} = (3/2)kBT$; $v_{\text{rms}} = \sqrt{(3kBT/m)}$	Average energy per particle; use absolute T
State and energy	$PV = nRT$; $U = (3/2)nRT$ for monatomic gas	For fixed n, T ranks with PV
First law	$\Delta U = Q + W$	U is a state function; Q and W depend on the path
Material response	$Q = mc\Delta T$; $H = kA\Delta T/L$	Specific heat and conductivity describe different properties
Second law	$\Delta S_{\text{total}} \geq 0$ for an isolated total	Equilibrium and reversibility determine the direction

For compression, reverse the work sign and follow the actual temperature change. A single process constraint does not imply all other quantities stay constant.