Past-paper walk-through

The First Law of Thermodynamics ▪ 9.4

eXercise

Questions in this set

- 2026 Q1
- 2025 Q2
- 2024 Q2
- 2021 Q1
- 2019 Q4
- 2016 Q1

Reading the mark scheme

- **B1** a mark that stands on its own – the point is either made or not.
- **M1** a *method* mark: the right approach, even if the number is wrong.
- **A1** an *answer* mark, and it usually needs its M mark first.
- **C1** a working mark on the way to the answer.
- // separates answers the examiner accepts equally.
- **ecf** = error carried forward: a later part is marked on your own earlier answer.
- **owtte** = "or words to that effect" – the wording need not match.

Question 1

2026 ▪ Q1

Part A

A sample of n moles of a monatomic, ideal gas is in a large, sealed, thermally conducting container with fixed volume. A small sphere of mass m_S is in the container. The volume of the sphere is much less than the volume of the container.

The gas is initially in State X with pressure P and volume V, as shown in Figure 1.

[Figure 1: A sealed square container labelled "Gas n, P, V" with a small sphere labelled "Sphere m_S" inside near the bottom, connected by an arrow from the "Sphere" label to a dot inside the container. Caption below the figure: "State X". Note: Figure not drawn to scale.]

The sphere is initially in thermal equilibrium with the gas. The gas undergoes a heating process until the gas is in State Y with pressure $3P$ and the sphere is again in

Question 1

thermal equilibrium with the gas. The total energy transferred to the sphere during the heating process is Q_S.

(i) The graph in Figure 2 represents the number of atoms per unit speed as a function of atom speed for the gas when the gas is in State X. On Figure 3, **sketch** a curve that could represent the number of atoms per unit speed as a function of atom speed for the gas when the gas is in State Y.

[Figure 2: Axes labelled “Number of Atoms per Unit Speed” (vertical) vs. “Atom Speed” (horizontal), captioned “State X”. A Maxwell-Boltzmann-type curve starts at the origin, rises to a single rounded peak (marked with a dashed horizontal line to the peak height and a dashed vertical line to the corresponding atom speed), then decreases back toward the horizontal axis at higher speeds.]

[Figure 3: Blank axes labelled “Number of Atoms per Unit Speed” (vertical) vs. “Atom Speed” (horizontal), captioned “State Y”, with the same dashed reference lines

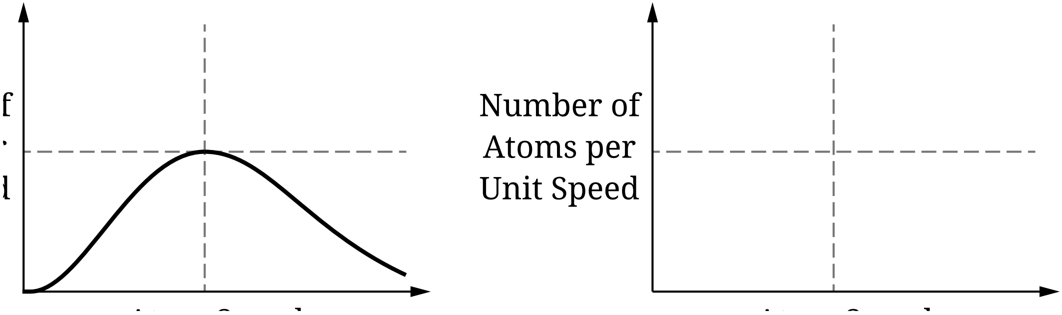
Question 1

(horizontal at the State X peak height, vertical at the State X peak speed) shown for reference, but no curve drawn — to be sketched by the student.]

(ii) **Derive** an expression for the change ΔT in temperature of the gas for the heating process that the gas undergoes as the gas changes from State X to State Y. Express your answer in terms of n, P, V, and physical constants, as appropriate. Begin your derivation by writing a fundamental physics principle or an equation from the reference information.

(iii) **Derive** an expression for the specific heat c_S of the sphere. Express your answer in terms of n, m_S, P, V, Q_S, and physical constants, as appropriate. Begin your derivation by writing a fundamental physics principle or an equation from the reference information.

Question 1



Question 1

2026 ▪ Q1

Part A

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The sphere is initially in thermal equilibrium with the gas. The gas undergoes a heating process until the gas is in State Y with pressure $3P$ and the sphere is again in thermal equilibrium with the gas. The total energy transferred to the sphere during the heating process is Q_S.

(b) Part B

Question 1

An insulated container is filled with a liquid of mass m_L and specific heat c_L. The original sphere is submerged in the liquid. The sphere has mass m_S, where $m_S < m_L$, and specific heat c_S, where $c_S < c_L$. The initial temperature of the sphere is greater than the initial temperature of the liquid. Later, the liquid and the sphere reach thermal equilibrium. The absolute values of the changes in the temperatures of the liquid and the sphere are $|\Delta T_L|$ and $|\Delta T_S|$, respectively.
Indicate whether $|\Delta T_S|$ is greater than, less than, or equal to $|\Delta T_L|$. Include one of the following relationships in your response.
- $|\Delta T_S| > |\Delta T_L|$ - $|\Delta T_S| < |\Delta T_L|$ - $|\Delta T_S| = |\Delta T_L|$
Justify your answer. Your justification may include expressions/equations but must include conceptual reasoning beyond algebraic solutions.

Question 2

2025 ▪ Q2

A sample of a monatomic ideal gas is sealed in a thermally conducting container by a movable piston of mass M and area A. The container is in a large water bath that is held at a constant temperature T_0. The piston is free to move with negligible friction. At the instant shown, the gas is in thermal equilibrium with the water bath, the piston is at rest, and the gas occupies volume V_0. The pressure of the air above the piston is P_{atm}.

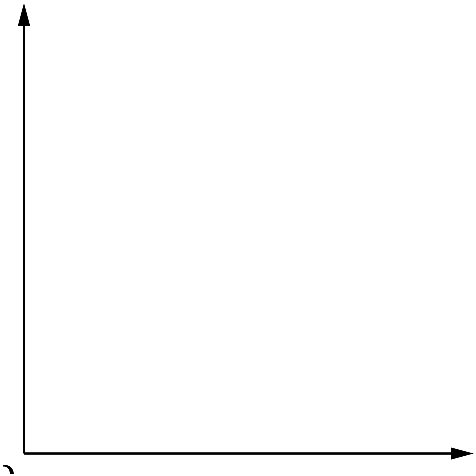
[Figure: Side View. A container (open at the top) sits inside a larger tank labeled "Water Bath". Inside the container, a horizontal bar labeled "Piston" sits partway up, with the region below it labeled "Gas" and the region above it open to the air. The tank surrounding the container is filled with the water bath.]

Note: Figure not drawn to scale.

Question 2

(a) On the dot shown, representing the piston, **draw** and **label** the forces that are exerted on the piston. Each force must be represented by a distinct arrow starting on, and pointing away from, the dot.
[Figure: a single dot representing the piston, for the student to draw force vectors from.]

Question 2



Question 2

2025 ▪ Q2

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Note: Figure not drawn to scale.

(b) Derive an expression for the internal energy of the gas in terms of M, A, V_0, P_{atm}, and physical constants, as appropriate. Begin your derivation by writing a fundamental physics principle or an equation from the reference information.

Question 2

2025 ▪ Q2

A sample of a monatomic ideal gas is sealed in a thermally conducting container by a movable piston of mass M and area A. The container is in a large water bath that is held at a constant temperature T_0. The piston is free to move with negligible friction. At the instant shown, the gas is in thermal equilibrium with the water bath, the piston is at rest, and the gas occupies volume V_0. The pressure of the air above the piston is P_{atm}.
[Figure: Side View. A container (open at the top) sits inside a larger tank labeled "Water Bath". Inside the container, a horizontal bar labeled "Piston" sits partway up, with the region below it labeled "Gas" and the region above it open to the air. The tank surrounding the container is filled with the water bath.]

Note: Figure not drawn to scale.

(c) A block, also of mass M, is placed on the piston at time $t = t_0$ and is slowly lowered. The piston comes to rest at $t = t_f$ when the block is completely released.

Question 2

On the axes provided, **sketch** the expected relationship between the pressure P and volume V of the gas for the thermodynamic process that the gas undergoes during time interval $t_0 \leq t \leq t_f$. **Draw** an arrow on your sketch to represent the direction of the thermodynamic process.
[Graph: axes with vertical axis P (origin labeled O) and horizontal axis V; both axes unlabeled with values — a blank grid for the student to sketch the P-V process and direction arrow.]

Question 2

2025 ▪ Q2

A sample of a monatomic ideal gas is sealed in a thermally conducting container by a movable piston of mass M and area A. The container is in a large water bath that is held at a constant temperature T_0. The piston is free to move with negligible friction. At the instant shown, the gas is in thermal equilibrium with the water bath, the piston is at rest, and the gas occupies volume V_0. The pressure of the air above the piston is P_{atm}.
[Figure: Side View. A container (open at the top) sits inside a larger tank labeled “Water Bath”. Inside the container, a horizontal bar labeled “Piston” sits partway up, with the region below it labeled “Gas” and the region above it open to the air. The tank surrounding the container is filled with the water bath.]

Note: Figure not drawn to scale.

(d) With the block still on the piston, the temperature of the water bath is changed to a new constant temperature T_{new}. The gas occupies the original volume V_0 when the sample of gas and the water bath come to thermal equilibrium.

Question 2

Indicate whether T_{new} is greater than, less than, or equal to T_0.

________ $T_{new} > T_0$

________ $T_{new} < T_0$

________ $T_{new} = T_0$

Briefly **justify** your answer by referencing at least one feature of your answers to parts A, B, or C.

Solution 2

(a)

Mark scheme

- Three forces act on the piston, each drawn as a distinct arrow starting on the dot: F_g (gravity/weight of the piston) points downward; F_atm (force of the atmosphere pushing down on the top of the piston) points downward; F_gas (force of the gas pushing up on the bottom of the piston) points upward. All three arrows must be correctly labeled with the correct direction (F_g down, F_atm down, F_gas up) to earn full credit – one point per correctly drawn/labeled force.

Solution 2

(b) Mark scheme

- Derive U starting from Newton's second law for the piston in equilibrium and the ideal gas law. a_sys = sum(F)/m_sys = F_net/m_sys, and since the piston is in equilibrium sum(F) = 0. Using P = F_perp/A on the piston: P*A - P_atm*A - F_g = 0, i.e. P*A - P_atm*A - Mg = 0, so P - P_atm - Mg/A = 0, giving P = P_atm + Mg/A. Then using U = (3/2)nRT together with PV = nRT gives U = (3/2)PV. Substituting the pressure found above and the original volume V0: U = (3/2)*(P_atm + Mg/A)*V0. Full credit requires: (1) a multistep derivation that includes U=(3/2)nRT (or U=(3/2)N*kB*T), PV=nRT (or PV=N*kB*T), and Newton's second law / P=F_perp/A, or equivalent relevant equations; (2) correctly relating U to PV, e.g. U=(3/2)PV; (3) a correct expression for the

Solution 2

absolute pressure $P = P\_atm + Mg/A$ (or consistent with an incorrect force diagram from part A); (4) the final expression for U consistent with that pressure, e.g. $U = (3/2)(P\_atm + Mg/A)*V0$. A correct isolated final expression alone earns the last three points.

Solution 2

(c) Mark scheme

- On the P-V axes, sketch a curve/line connecting a point in the lower-right region of the diagram (larger V, smaller P – the initial state before the block's weight is fully added) to a point in the upper-left region (smaller V, larger P – the final state once the block is completely resting on the piston), i.e. the gas is compressed as pressure increases. The curve should be concave up. Draw an arrow on the curve pointing from the larger-volume/lower-pressure point toward the smaller-volume/higher-pressure point (i.e., from lower-right to upper-left), showing volume decreasing (or pressure increasing) as the process proceeds. Full credit requires: (1) a line/curve connecting lower-right to upper-left; (2) the curve

Solution 2

is concave up; (3) an arrow indicating volume decreasing / pressure increasing along the curve.

Solution 2

(d) Mark scheme

- T_new > T0 (or an indication consistent with incorrect features of parts A, B, or C). Justification: with the block's weight now supported by the gas but the gas back at the original volume V0, the pressure of the gas must be greater than the original pressure (to support the added weight of the block in equilibrium) – e.g. using the part B derivation, since U = (3/2)*P*V and V = V0 is unchanged while P has increased (due to the block's added weight, P = P_atm + Mg/A becomes larger with the extra weight), the internal energy – and hence temperature – increases. Therefore T_new > T0. (Any justification consistent with the student's own diagram in part A, derivation in part B, or graph in part C that correctly relates a pressure increase at equal volume, or a volume increase at equal

Solution 2

pressure, to a temperature increase earns full credit; a justification consistent with an incorrect earlier part is also accepted for the reasoning point.)

Question 2

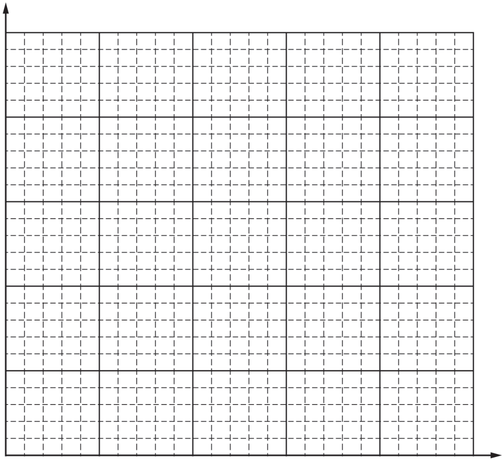
2024 ▪ Q2

[Figure 1: A rectangular sealed chamber labeled "Chamber" with thin, rigid walls. Inside are many small dots labeled "Gas Molecule" scattered throughout the interior. On the left wall is a component labeled "Heater". On the right wall are two circular components labeled "Sensors". Note: Figure not drawn to scale.]

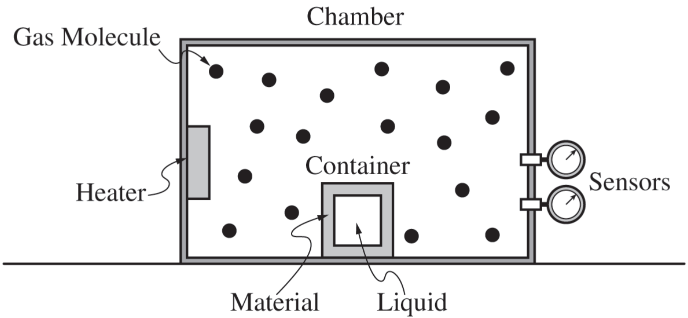
In Experiment 1, shown in Figure 1, a sample of an ideal gas is contained in an insulated, sealed chamber with thin, rigid walls. The chamber contains a heater and sensors that measure the temperature and pressure of the gas. A student is asked to design an experiment to determine the number N of molecules of the gas contained in the chamber.

(a) Describe a procedure for collecting data that would allow the student to determine an experimental value for N. Provide enough detail so that a student could replicate the experiment, including any steps necessary to reduce experimental uncertainty.

Question 2



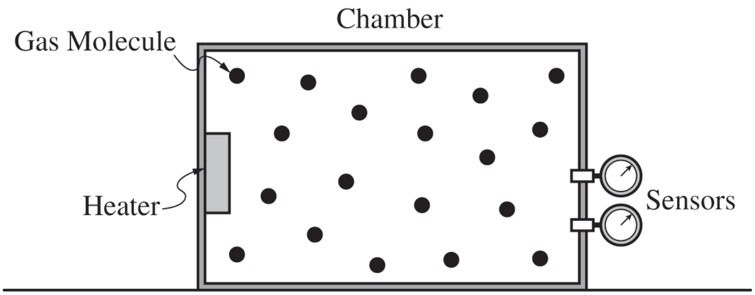
Question 2



Note: Figure not drawn to scale.

Figure 2

Question 2



Note: Figure not drawn to scale.

Figure 1

Question 2

2024 ▪ Q2

[Figure 1: A rectangular sealed chamber labeled "Chamber" with thin, rigid walls. Inside are many small dots labeled "Gas Molecule" scattered throughout the interior. On the left wall is a component labeled "Heater". On the right wall are two circular components labeled "Sensors". Note: Figure not drawn to scale.]

In Experiment 1, shown in Figure 1, a sample of an ideal gas is contained in an insulated, sealed chamber with thin, rigid walls. The chamber contains a heater and sensors that measure the temperature and pressure of the gas. A student is asked to design an experiment to determine the number N of molecules of the gas contained in the chamber.

(b)(i) On the following axes, **sketch** a curve or line to represent the expected relationship between the pressure P and volume V of the gas while the heater is on. **Draw** an arrow on the curve or line to represent the direction of the resulting thermal process.

Question 2

[Graph with vertical axis P and horizontal axis V, both starting at origin O; empty dashed gridded axes for the student to sketch on.]

(b)(ii) On the following axes, **sketch** a curve or line to represent the expected relationship between the internal energy U and the volume V of the gas while the heater is on. **Draw** an arrow on the curve or line to represent the direction of the resulting thermal process.

[Graph with vertical axis U and horizontal axis V, both starting at origin O; empty dashed gridded axes for the student to sketch on.]

(b)(iii) Briefly **justify** why the curve or line drawn in part (b)(ii) has the shape that you sketched.

Question 2

2024 ▪ Q2

[Figure 1: A rectangular sealed chamber labeled “Chamber” with thin, rigid walls. Inside are many small dots labeled “Gas Molecule” scattered throughout the interior. On the left wall is a component labeled “Heater”. On the right wall are two circular components labeled “Sensors”. Note: Figure not drawn to scale.]

In Experiment 1, shown in Figure 1, a sample of an ideal gas is contained in an insulated, sealed chamber with thin, rigid walls. The chamber contains a heater and sensors that measure the temperature and pressure of the gas. A student is asked to design an experiment to determine the number N of molecules of the gas contained in the chamber.

(c) [Figure 2: The same rectangular sealed chamber, labeled ”Chamber”, with ”Gas Molecule” dots scattered throughout. On the left wall is ”Heater”. On the right wall are two ”Sensors”. Inside the chamber is a smaller rectangular ”Container” that is

Question 2

completely wrapped, holding a "Material" layer and a "Liquid" layer inside it. Note: Figure not drawn to scale.]

In Experiment 2, shown in Figure 2, a liquid-filled container that is completely wrapped with a material of uniform thickness 0.01 m is inside the sealed chamber that is filled with an ideal gas. The material has a total area of 0.06 m^2 in contact with the gas. The heater is turned on. As the temperature T_G of the gas increases, the following data for the temperature T_L of the liquid and the rate $\dfrac{Q}{\Delta t}$ of energy transfer are collected.

T_G (K)	T_L (K)	$\dfrac{Q}{\Delta t}$ (J/s)
295	295	0.0
371	303	26.3
425	308	43.1
475	313	60.0
528	323	75.0

The student is asked to determine an experimental value of the thermal conductivity k of the material used to wrap the container inside the sealed chamber.

Question 2

(c)(i) Indicate what measured and/or calculated quantities could be graphed to yield a straight line that could be used to calculate an experimental value for the thermal conductivity k of the material. Use the blank columns in the table to list any calculated quantities you graph in addition to the data provided.

Vertical Axis: ______________________ Horizontal Axis: ______________________

(c)(ii) Plot the data points for the quantities indicated in part (c)(i) on the graph provided. Clearly scale and **label** all axes, including units, as appropriate.

[Empty gridded graph with axes to be scaled and labeled by the student, with tick marks along both axes for plotting data points.]

(c)(iii) Draw the best-fit line for the data graphed in part (c)(ii).

Question 2

2024 ▪ Q2

[Figure 1: A rectangular sealed chamber labeled “Chamber” with thin, rigid walls. Inside are many small dots labeled “Gas Molecule” scattered throughout the interior. On the left wall is a component labeled “Heater”. On the right wall are two circular components labeled “Sensors”. Note: Figure not drawn to scale.]

In Experiment 1, shown in Figure 1, a sample of an ideal gas is contained in an insulated, sealed chamber with thin, rigid walls. The chamber contains a heater and sensors that measure the temperature and pressure of the gas. A student is asked to design an experiment to determine the number N of molecules of the gas contained in the chamber.

(d) Using the best-fit line, **calculate** an experimental value for k.

Solution 2

(a) Mark scheme

- Procedure: measure the length, width, and height of the chamber to determine the volume of the gas (measurements of the heater's own dimensions/volume may also earn credit). Activate the heater. Starting at time $t = 0$, use the pressure and temperature sensors to record the pressure and temperature of the gas at multiple times — e.g., every 10 s until $t = 60$ s — so that a temperature/pressure trend over time can be established. Scoring: 1 pt for indicating measurements that could be used to determine the gas volume; 1 pt for indicating the sensors are used to record the gas's temperature and pressure; 1 pt for indicating that multiple different temperature and pressure measurements are recorded (not just one).

Solution 2

(b)(i)

Mark scheme

- Sketch on the P vs. V axes: a vertical line segment (constant V) that never touches either axis, with an arrow pointing upward — pressure increases while volume stays constant as the heater raises the gas's pressure at fixed volume (isochoric heating). Scoring: 1 pt for sketching an upward vertical line/arrow that never touches the horizontal or vertical axes.

Solution 2

(b)(ii)

Mark scheme

- Sketch on the U vs. V axes: a vertical line segment (constant V) that never touches either axis, with an arrow pointing upward — internal energy increases while volume stays constant, consistent with the heater adding thermal energy to the sealed, fixed-volume gas. Scoring: 1 pt for sketching an upward vertical line/arrow that never touches the horizontal or vertical axes.

Solution 2

(b)(iii)

Mark scheme

- Justification (either is acceptable, must be consistent with the part (b)(ii) sketch): 'The heater transfers energy to the gas by heating, so the internal energy of the gas increases.' OR 'The gas has a constant volume [the chamber is sealed/rigid], so all the energy added goes into internal energy, but volume does not change.' Scoring: 1 pt for a justification that correctly relates the (fixed) volume of the chamber to the sketch, or relates the heater's energy transfer to the increase in internal energy shown in the sketch.

Solution 2

(c)

Mark scheme

- This is introductory/stem text (with Figure 2) describing the Experiment 2 setup: a liquid-filled container, completely wrapped in a material of uniform thickness 0.01 m, placed inside the same heated, sensor-equipped chamber. It sets up the thermal-conductivity determination carried out in parts (c)(i)-(c)(iii) and (d). No points are allocated to this stem text itself in the official scoring guidelines; all points for part (c) are attached to leaves 2ci, 2cii, and 2ciii.

Solution 2

(c)(i) Mark scheme

- Vertical axis: $\dfrac{Q}{\Delta t}$ — the rate of heat transfer through the material (heat current). Horizontal axis: $\Delta T = T_G - T_L$ — the temperature difference between the gas side and the liquid side of the material's surfaces. Plotting $Q/\Delta t$ vs. ΔT gives a straight line through the origin whose slope equals kA/L, which can be used to extract the thermal conductivity k. Scoring: 1 pt for correctly indicating the quantities (measured and/or calculated) that, when graphed, yield a straight line usable to find k.

Solution 2

(c)(ii) Mark scheme

- Label the vertical axis $Q/\Delta t$ in J/s and the horizontal axis ΔT in K, each on an evenly spaced linear scale chosen so the plotted data fill roughly half the grid area. Plot each data point at its corresponding $(\Delta T,\ Q/\Delta t)$ value from the experiment's data table (the reference plot shows points increasing roughly linearly from near the origin, e.g. near $(60\,\mathrm{K}, 25\,\mathrm{J/s})$, $(110, 42)$, $(160, 60)$, and $(200, 75)$). Scoring: 1 pt for correctly labeling both axes (including units) on a linear scale sized so the data span about half the graph; 1 pt for plotting the data points correctly at their given values.

Solution 2

(c)(iii)

Mark scheme

- Draw a single straight best-fit line through the plotted points that approximates the overall trend of the data — starting near the origin and increasing with a roughly constant positive slope, with roughly equal numbers of points above and below the line. Scoring: 1 pt for drawing a straight line that reasonably approximates the trend of the plotted data.

Solution 2

(d) Mark scheme

- Relate the graph's slope to the model: since $\dfrac{Q}{\Delta t} = \dfrac{kA\Delta T}{L} = \left(\dfrac{kA}{L}\right)\Delta T$, the slope of the best-fit line equals kA/L. Reading two well-separated points from the best-fit line, e.g. slope $= \dfrac{(80-44)\ \mathsf{J/s}}{(220-120)\ \mathsf{K}} = 0.36\ \dfrac{\mathsf{J}}{\mathsf{s}\cdot\mathsf{K}}$. Then $k = \dfrac{L}{A}(\text{slope}) = \dfrac{0.01\ \mathsf{m}}{0.06\ \mathsf{m}^2}\left(0.36\ \dfrac{\mathsf{J}}{\mathsf{s}\cdot\mathsf{K}}\right) \approx 0.06\ \dfrac{\mathsf{J}}{\mathsf{s}\cdot\mathsf{K}\cdot\mathsf{m}}$. Scoring: 1 pt for correctly relating the slope of the line to $Q/\Delta t = kA\Delta T/L$ (i.e., slope $= kA/L$); 1 pt for calculating an experimental value of k approximately equal to $0.06\ \mathsf{J}/(\mathsf{s}\cdot\mathsf{K}\cdot\mathsf{m})$, using the student's own graph and $A = 0.06\ \mathsf{m}^2$, $L = 0.01\ \mathsf{m}$.

Question 1

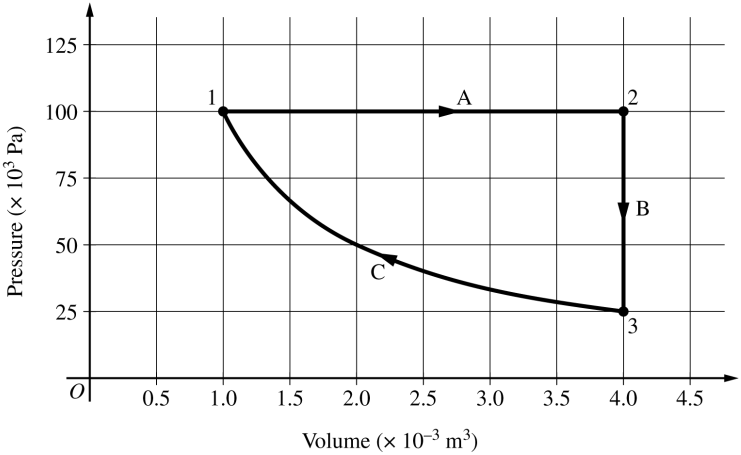
2021 ▪ Q1

A sample of ideal gas is taken through the thermodynamic cycle shown above. Process C is isothermal.
[Graph: Pressure ($\times 10^3$ Pa) on the y-axis (gridlines at 25, 50, 75, 100, 125) vs. Volume ($\times 10^{-3}$ m^3) on the x-axis (gridlines at 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5). State 1 is at approximately $(1.0, 100)$. Process A is a horizontal arrow from state 1 at $(1.0, 100)$ to state 2 at $(4.0, 100)$, pointing right. Process B is a vertical arrow from state 2 at $(4.0, 100)$ down to state 3 at $(4.0, 25)$, pointing down. Process C is a curve from state 3 at $(4.0, 25)$ back to state 1 at $(1.0, 100)$, passing through a labeled point near $(2.1, 42)$, with an arrow pointing up and to the left toward state 1.]
(a) Consider the portion of the cycle that takes the gas from state 1 to state 3 by processes A and B. Calculate the magnitude of the following and indicate the sign of any nonzero quantities.

Question 1

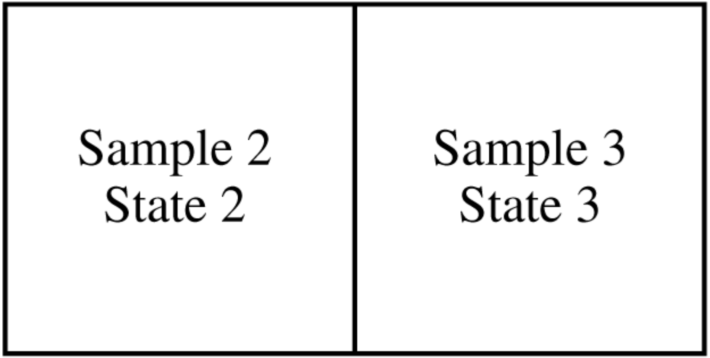
- The net change in internal energy ΔU of the gas - The net work W done on the gas - The net energy Q transferred to the gas by heating

Question 1



125
100
75
50
25
Pressure (× 10^3 Pa)
O
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
Volume (× 10^{-3} m^3)
1
2
3
A
B
C

Question 1



Question 1

2021 ▪ Q1

A sample of ideal gas is taken through the thermodynamic cycle shown above. Process C is isothermal.

[Graph: Pressure ($\times 10^3$ Pa) on the y-axis (gridlines at 25, 50, 75, 100, 125) vs. Volume ($\times 10^{-3}$ m^3) on the x-axis (gridlines at 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5). State 1 is at approximately $(1.0, 100)$. Process A is a horizontal arrow from state 1 at $(1.0, 100)$ to state 2 at $(4.0, 100)$, pointing right. Process B is a vertical arrow from state 2 at $(4.0, 100)$ down to state 3 at $(4.0, 25)$, pointing down. Process C is a curve from state 3 at $(4.0, 25)$ back to state 1 at $(1.0, 100)$, passing through a labeled point near $(2.1, 42)$, with an arrow pointing up and to the left toward state 1.]

(b)(i) Consider isothermal process C.

Question 1

Compare the magnitude and sign of the work W done on the gas in process C to the magnitude and sign of the work in the portion of the cycle in part (a). Support your answer using features of the graph.

(b)(ii) Explain how the microscopic behavior of the gas particles and changes in the size of the container affect interactions on the microscopic level and produce the observed pressure difference between the beginning and end of process C.

Question 1

2021 ▪ Q1

A sample of ideal gas is taken through the thermodynamic cycle shown above. Process C is isothermal.
[Graph: Pressure ($\times 10^3$ Pa) on the y-axis (gridlines at 25, 50, 75, 100, 125) vs. Volume ($\times 10^{-3}$ m^3) on the x-axis (gridlines at 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5). State 1 is at approximately $(1.0, 100)$. Process A is a horizontal arrow from state 1 at $(1.0, 100)$ to state 2 at $(4.0, 100)$, pointing right. Process B is a vertical arrow from state 2 at $(4.0, 100)$ down to state 3 at $(4.0, 25)$, pointing down. Process C is a curve from state 3 at $(4.0, 25)$ back to state 1 at $(1.0, 100)$, passing through a labeled point near $(2.1, 42)$, with an arrow pointing up and to the left toward state 1.]

(c) Consider two samples of the gas, each with the same number of gas particles. Sample 2 is in state 2 shown in the graph, and sample 3 is in state 3 shown in the graph. The samples are put into thermal contact, as shown above.

Question 1

[Diagram: two adjacent boxes labeled "Sample 2 State 2" and "Sample 3 State 3", placed in contact with each other.]
Indicate the direction, if any, of energy transfer between the samples. Support your answer using macroscopic thermodynamic principles.

Solution 1

(a) Mark scheme

- $\Delta U = 0$ J (temperatures at states 1 and 3 are equal, so internal energy is unchanged). Net work done ON the gas: $W = -P\Delta V = -(100\times10\hat{}3$ Pa)($3\times10\hat{}-3$ m^3) $= -300$ J (volume increases from $1\times10\hat{}-3$ m^3 to $4\times10\hat{}-3$ m^3 at constant pressure $100\times10\hat{}3$ Pa; answer must show the negative sign or state the work is done BY the gas). Applying the first law $\Delta U = Q + W$ with $\Delta U=0$ and $W=-300$ J gives $Q = +300$ J transferred TO the gas by heating (or equivalently, showing $|Q|=|W|$ with opposite sign). Award 1 point each for: $\Delta U=0$; $W=-300$ J with correct sign/units; correctly using the first law to obtain Q.

Solution 1

(b)(i)

Mark scheme

- The magnitude of the work in isothermal process C is LESS than in part (a) ($|W\_C| < 300$ J), because there is less area under the P–V curve for process C than for the combined processes A+B (1 point, must reference area under the curve). The sign is OPPOSITE that of part (a): in part (a) the volume increased so W (on gas) was negative; in process C the volume decreases (shown by the arrow direction on the graph), so the work done ON the gas is POSITIVE (1 point, must reference the sign of ΔV or the direction of the process on the graph).

Solution 1

(b)(ii) Mark scheme

- Process C is isothermal, so temperature is constant and the average kinetic energy/average speed of the gas molecules does NOT change (1 point). The volume of the container decreases, which changes something relevant to the collision rate — acceptable references include volume, surface area, or time to traverse the container (1 point). With unchanged molecular speed but decreased volume, molecules collide with the container walls more frequently, producing more net force per unit area on the walls — the response must explicitly refer to collisions with the walls (1 point). Example: temperature (and thus molecular speed) is unchanged; smaller volume increases the density of gas molecules, so they collide with the walls more often, giving more net force due to wall collisions

Solution 1

(and the smaller volume also means less wall surface area), producing higher pressure.

Solution 1

(c)

Mark scheme

- The temperature of the gas in state 2 (sample 2) is HIGHER than the temperature in state 3 (sample 3), as read from their positions on the P–V diagram/isotherms (1 point). When placed in thermal contact, energy spontaneously flows from the hotter sample to the cooler sample, so energy transfers from sample 2 to sample 3 (1 point, must reference the macroscopic principle that heat flows hot$\rightarrow$cold).

Question 4

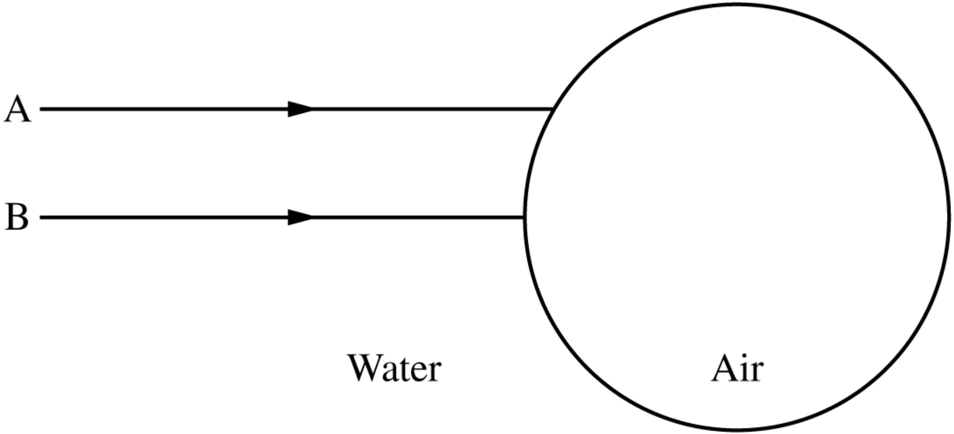
2019 ▪ Q4

A student notices many air bubbles rising through the water in a large fish tank at an aquarium.

(a) In the figure below, the circle represents one such air bubble, and two incoming rays of light, A and B, are shown. Ray B points toward the center of the circle. On the diagram, draw the paths of rays A and B as they go through the bubble and back into the water. Your diagram should clearly show what happens to the rays at each interface.

[Figure: A large circle labeled “Air” on the right side, with “Water” labeled to its left outside the circle. Two horizontal rays labeled A (upper) and B (lower) enter from the left and strike the circle’s boundary; ray B is aimed at the center of the circle. Arrowheads show the rays traveling rightward toward the circle.]

Question 4



Question 4

2019 ▪ Q4

A student notices many air bubbles rising through the water in a large fish tank at an aquarium.

(b) The bubble has a volume V_1, the air inside it has density ρ_A, and the water around it has density ρ_W. The bubble starts at rest and has a speed v_f when it has risen a height h. Assume that the change in the bubble's volume is negligible. Derive an expression for the mechanical energy dissipated by drag forces as the bubble rises this distance. Express your answer in terms of the given quantities and fundamental constants, as appropriate.

Question 4

2019 ▪ Q4

A student notices many air bubbles rising through the water in a large fish tank at an aquarium.

(c)(i) At a particular instant, one bubble is 4.5 m below the water's surface. The surface of the water is at sea level, and the density of the water is 1000 kg/m^3. Determine the absolute pressure in the bubble at this location.

(c)(ii) The bubble has a volume V_1 when it is 4.5 m below the water's surface. Assume that the temperature of the air in the bubble remains constant as it rises. In terms of V_1, calculate the volume of the bubble when it is just below the surface of the water.

(c)(iii) If the air in the bubble cooled as it rose, the volume of the bubble would be less than the value calculated in part (c)(ii). Use physics principles to briefly explain why.

Solution 4

(a) Mark scheme

- Ray B is aimed at the center of the circular bubble, so it strikes the water–air interface along the normal (radial direction) and passes straight through undeviated, continuing in a straight line through the bubble and back into the water on the far side (1 pt for ray B going straight through). Ray A strikes the first interface at an angle to the normal and bends away from the normal as it refracts from water into air (light speeds up going into the lower-index medium, air) (1 pt for ray A bending away from the normal entering the air from the water). At the second interface, as ray A exits the air bubble back into the water, it bends the opposite way relative to the normal there (toward the normal, since it is now going from a lower-index medium, air, into a higher-index medium, water)

Solution 4

compared to how it refracted at the first interface (1 pt for ray A bending the opposite direction relative to the normal on exiting compared to entering).

Solution 4

(b) Mark scheme

- Apply the work-energy theorem to the rising bubble:
  $\Delta K = W_{net} = |W_b| - |W_g| - |W_{diss}|$, where W_b is the work done by the buoyant force, $|W_g|$ is the magnitude of the work done against gravity, and $|W_{diss}|$ is the mechanical energy dissipated by drag (1 pt for a valid application of the work-energy theorem). The buoyant force equals the weight of displaced water, $\rho_W V_1 g$, so the work it does over height h is $W_b = \rho_W V_1 gh$ (1 pt for finding the work done by the buoyant force). Substituting $\Delta K = \frac{1}{2}\rho_A V_1 v_f^2$ (starting from rest) and $|W_g| = \rho_A V_1 gh$ (weight of the bubble's air) with consistent relative signs: $\frac{1}{2}\rho_A V_1 v_f^2 = \rho_W V_1 gh - \rho_A V_1 gh - |W_{diss}|$, so

Solution 4

$|W_{diss}| = \rho_W V_1 gh - \rho_A V_1 gh - \frac{1}{2}\rho_A V_1 v_f^2$ (1 pt for correct substitution into an equation with consistent relative signs for the terms).

Solution 4

(c)(i)

Mark scheme

- $P_{4.5\mathrm{m}} = P_{atm} + \rho_W g d = (1.0 \times 10^5 \text{ Pa}) + (1000 \text{ kg/m}^3)(9.8 \text{ m/s}^2)(4.5 \text{ m})$. $P_{4.5\mathrm{m}} = 1.44 \times 10^5$ Pa (or 1.45×10^5 Pa using $g = 10 \text{ m/s}^2$). (1 pt for a correct answer with units.)

Solution 4

(c)(ii)

Mark scheme

- Applying the ideal gas law at constant temperature between the two locations (so PV is constant): $P_{4.5\text{m}} V_1 = P_{atm} V_{surface}$, giving $V_{surface} = P_{4.5\text{m}} V_1 / P_{atm}$ (1 pt for applying the ideal gas law at two locations to determine the new bubble volume). Substituting the pressure from part (c)(i): $V_{surface} = (1.44 \times 10^5 \text{ Pa})\, V_1 / (1 \times 10^5 \text{ Pa}) = 1.44\, V_1$ (or $1.45\, V_1$ using $g = 10 \text{ m/s}^2$) (1 pt for substituting pressures consistent with part (i)).

Solution 4

(c)(iii) Mark scheme

- By the ideal gas law, $P_{4.5\mathrm{m}} V_1 / T_1 = P_{atm} V_{surface} / T_{surface}$, so $V_{surface} = P_{4.5\mathrm{m}} V_1 T_{surface} / (P_{atm} T_1)$; the pressures are the same as before, but now $T_{surface} < T_1$ (the air cooled), so the volume at the surface comes out smaller than the constant-temperature value found in part (c)(ii). (Equivalent microscopic explanation: as the bubble cools, its air molecules move slower and exert less outward force on the bubble's inner surface; the resulting unbalanced inward force from the water causes the bubble to expand less than — i.e., contract relative to — the constant-temperature case.) Full credit for a correct explanation, whether qualitative or quantitative, macroscopic or microscopic. (1 pt.)

Question 1

2016 ▪ Q1

[Graph: P $(10^5 Pa) ontheverticalaxis, V(m^3) onthehorizontalaxis. Gridlinesontheverticalaxisat 0.5, 1.0, 1.5; gr$
pointAisat(0.04, 1.0); *ahorizontallinewithanarrowpointsrightfromAtopointBat*(0.10, 1.0); *alinewithanarrowpointsdownfromBtopointCat*(0.10, 0.5); *adiagonallinewithanarrowpointsfromCbackuptoA*.]

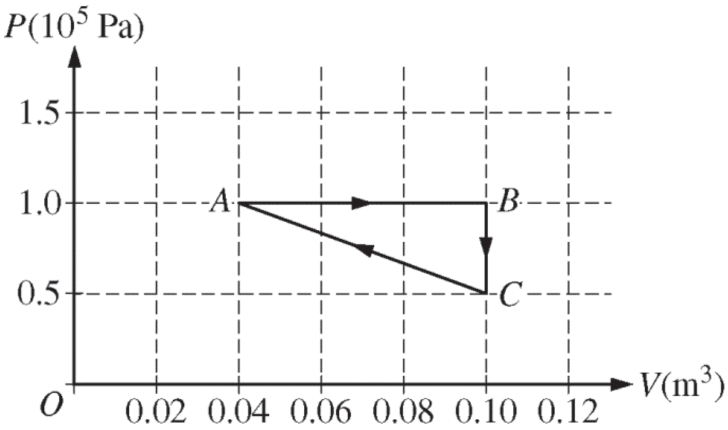
Two moles of a monatomic ideal gas are enclosed in a cylinder by a movable piston. The gas is taken through the thermodynamic cycle shown in the figure above. The piston has a cross-sectional area of 5×10^{-3} m^2.

(a)(i) Calculate the force that the gas exerts on the piston in state *A*, and explain how the collisions of the gas atoms with the piston allow the gas to exert a force on the piston.

Question 1

(a)(ii) Calculate the temperature of the gas in state B, and indicate the microscopic property of the gas that is characterized by the temperature.
(b)(i) Predict qualitatively how the internal energy of the gas changes as it is taken from state A to state B. Justify your prediction.
(b)(ii) Calculate the energy added to the gas by heating as it is taken from state A to state C along the path ABC.
(c) Determine the change in the total kinetic energy of the gas atoms as the gas is taken directly from state C to state A.

Question 1



Solution 1

(a)(i)

Mark scheme

- $F = PA = (1.0\times10\hat{}5 \text{ Pa})(5\times10\hat{}\text{-}3 \text{ m}\hat{}2) = 500$ N. Explanation: the gas atoms colliding with the piston undergo a change in momentum/velocity on each collision; by Newton's third law this momentum exchange means each colliding atom exerts a force on the piston, and the sum of these collisions over time produces the net force on the piston. Full credit needs (1) the calculation with correct units and (2) an explanation that identifies some change in the atoms' momentum or velocity to justify the force between atoms and piston.

Solution 1

(a)(ii)

Mark scheme

- Using PV = nRT: T = PV/(nR) = (1.0×10^5 Pa)(0.10 m^3)/[(2 mol)(8.31 J/mol · K)] = 602 K. Temperature characterizes the AVERAGE speed (equivalently the average kinetic energy or the RMS velocity) of the gas molecules — not the speed of any single molecule. Full credit needs (1) the calculation with correct units and (2) identifying that temperature reflects an average/RMS microscopic quantity.

Solution 1

(b)(i)

Mark scheme

- The internal energy increases from state A to state B. Because the process A$\rightarrow$B occurs at constant pressure while the volume increases, $PV = nRT$ shows the temperature must increase. An increase in temperature means an increase in the average kinetic energy of the gas molecules, i.e., an increase in the total internal energy of the gas. Full credit needs (1) identifying that temperature increases because volume increases at constant pressure and (2) relating that temperature increase to an internal-energy increase.

Solution 1

(b)(ii) Mark scheme

- Work done in process ABC (area under the P-V path): W_AB = -(1.0×10^5 Pa)(0.10 m^3 - 0.04 m^3) = -6000 J, and W_BC = 0 (constant volume). Temperatures: T_A = P_A V_A/(nR) = (1.0×10^5 Pa)(0.04 m^3)/[(2 mol)(8.31 J/mol · K)] = 241 K; T_C = P_C V_C/(nR) = (0.5×10^5 Pa)(0.10 m^3)/[(2 mol)(8.31 J/mol · K)] = 301 K. Internal energy change: ΔU = (3/2)nRΔT = (3/2)(P_C V_C - P_A V_A) = (3/2)[(0.5×10^5 Pa)(0.10 m^3) - (1.0×10^5 Pa)(0.04 m^3)] = 1500 J (equivalently ΔU = (3/2)k_B ΔT n N_0 = (3/2)(1.38×10^-23 J/K)(301 K - 241 K)(2 mol)(6.02×10^23 mol^-1) = 1500 J). First law: Q = ΔU - W = 1500 J - (-6000 J) = 7500 J. The energy added to the gas by heating along ABC is Q = 7500 J. Full credit needs (1) W_AB = -6000

Solution 1

J and W_BC $= 0$, (2) T_A, T_C (or ΔT) used to get $\Delta U = 1500$ J, and (3) correctly substituting ΔU and W into the first law (with units) to get $Q = 7500$ J.

Solution 1

(c)

Mark scheme

- The change in total kinetic energy of the gas atoms for process C$\rightarrow$A has the same magnitude as ΔU found in part (b)(ii) but the opposite sign (since C$\rightarrow$A is the reverse temperature change of A$\rightarrow$C): ΔK_total = (3/2)k_B ΔT n N_0 = (3/2)(1.38$\times$10^-23 J/K)(241 K - 301 K)(2 mol)(6.02$\times$10^23 mol^-1) = -1500 J. So ΔK_total = -1500 J (the kinetic energy of the gas atoms decreases by 1500 J).