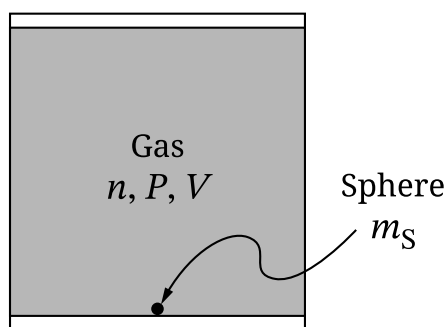


Question 1: Version J**1. Part A**

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.

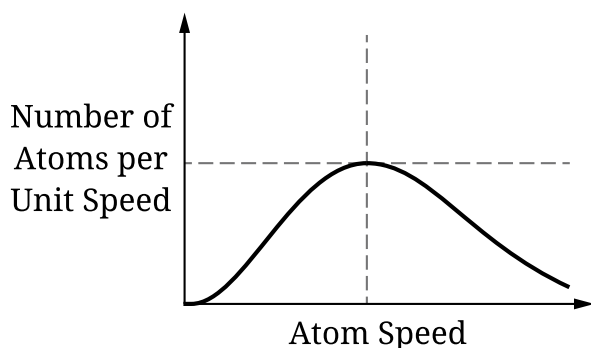
Figure 1

State X

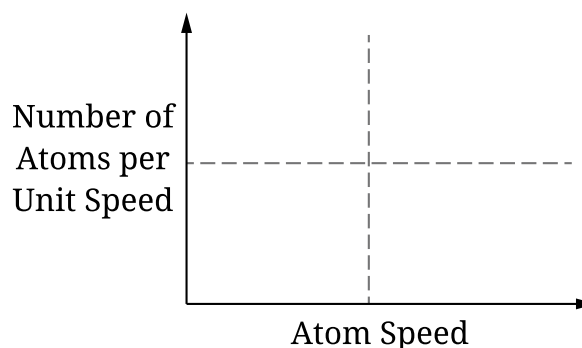
Note: Figure not drawn to scale.

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 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

State X

Figure 3

State Y

- 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.

Part B

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.

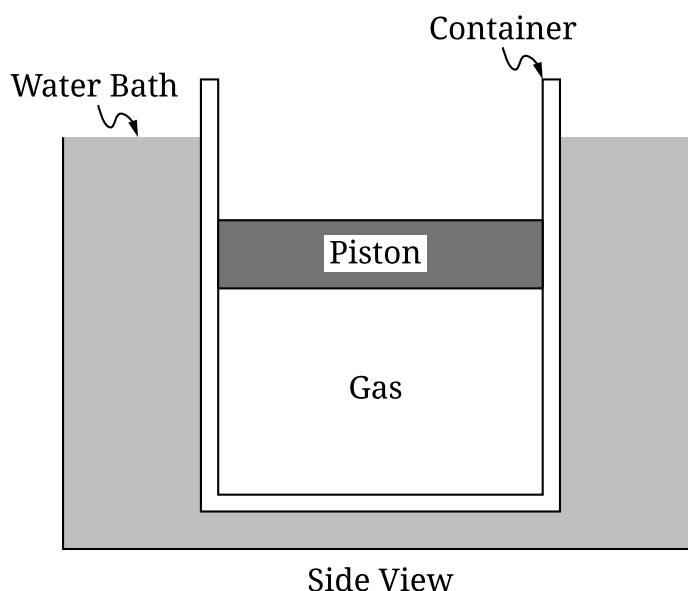
Indicate whether $|\Delta T_S|$ is greater than, less than, or equal to $|\Delta T_L|$. Include one of the following relationships in your response.

- $|\Delta T_S| > |\Delta T_L|$
- $|\Delta T_S| < |\Delta T_L|$
- $|\Delta T_S| = |\Delta T_L|$

Justify your answer. Your justification may include expressions/equations but must include conceptual reasoning beyond algebraic solutions.

Question 2: Version J

2. 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} .



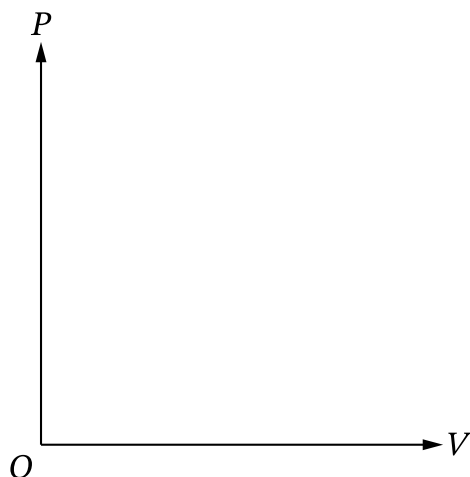
Note: Figure not drawn to scale.

- 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.



- 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.
- 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.

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.



- 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.

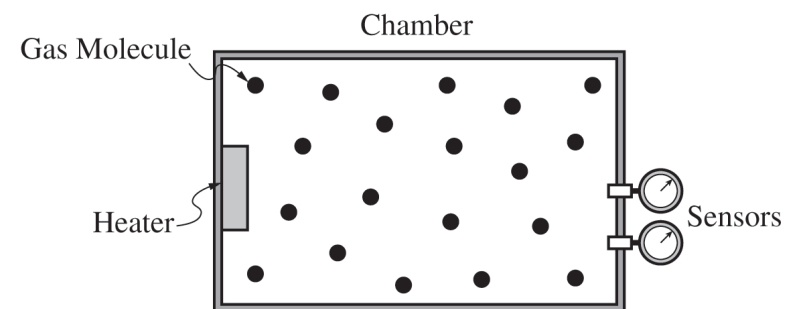
Indicate whether T_{new} is greater than, less than, or equal to T_0 .

_____ $T_{\text{new}} > T_0$

_____ $T_{\text{new}} < T_0$

_____ $T_{\text{new}} = T_0$

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

Begin your response to **QUESTION 2** on this page.

Note: Figure not drawn to scale.

Figure 1

2. (12 points, suggested time 25 minutes)

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.

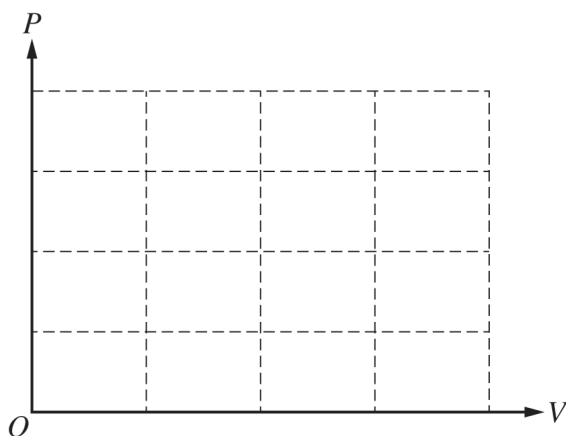
- (a) **Describe** a procedure for collecting data that would allow the student to determine an experimental value for N . Provide enough detail so that a student could replicate the experiment, including any steps necessary to reduce experimental uncertainty.

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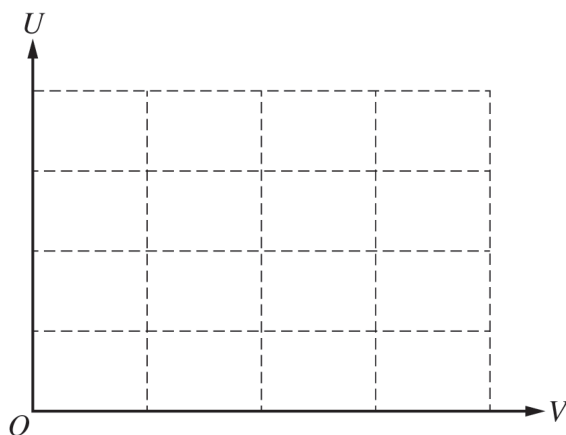
Continue your response to **QUESTION 2** on this page.

(b)

- i. On the following axes, **sketch** a curve or line to represent the expected relationship between the pressure P 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.

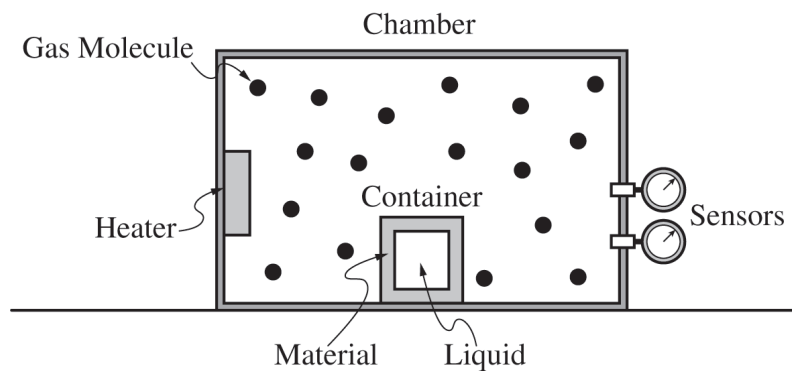


- ii. On the following axes, **sketch** a curve or line to represent the expected relationship between the internal energy U and the volume V of the gas while the heater is on. **Draw** an arrow on the curve or line to represent the direction of the resulting thermal process.



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

GO ON TO THE NEXT PAGE.

Continue your response to **QUESTION 2** on this page.

Note: Figure not drawn to scale.

Figure 2

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 $\frac{Q}{\Delta t}$ of energy transfer are collected.

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

- (c) 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.

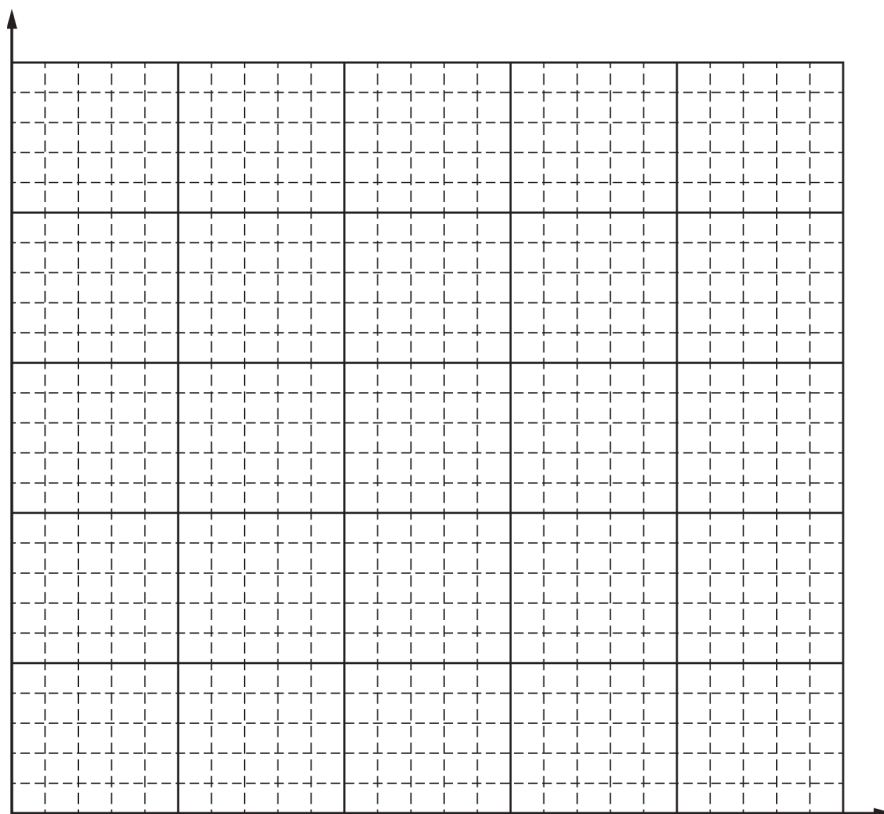
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Continue your response to **QUESTION 2** on this page.

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: _____

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.



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

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

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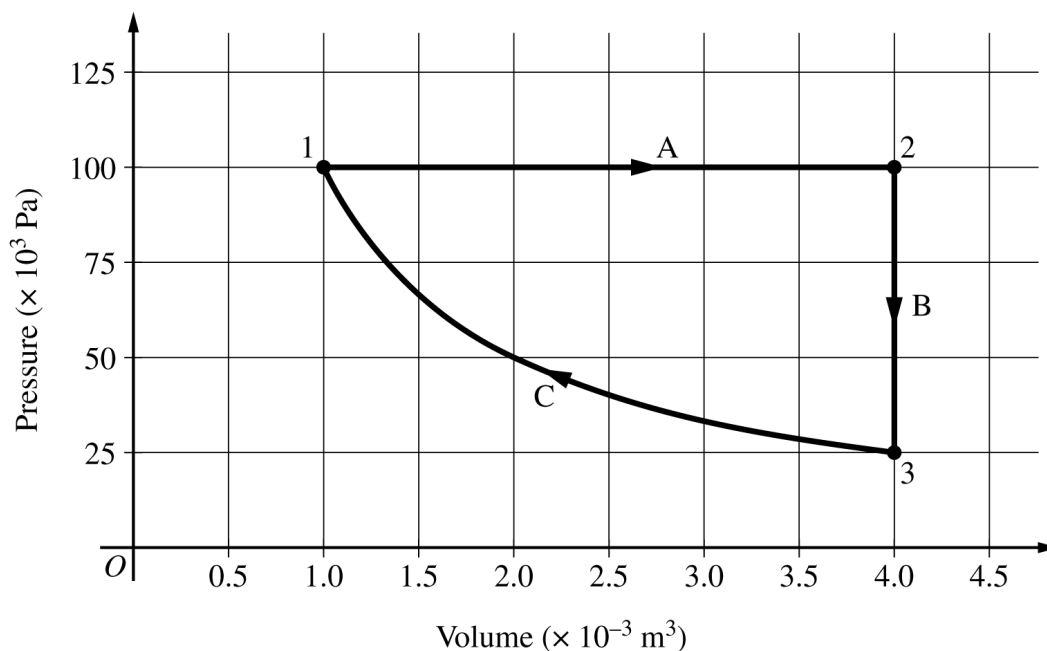
PHYSICS 2

SECTION II

Time—1 hour and 30 minutes

4 Questions

Directions: Questions 1 and 4 are short free-response questions that require about 20 minutes each to answer and are worth 10 points each. Questions 2 and 3 are long free-response questions that require about 25 minutes each to answer and are worth 12 points each. Show your work for each part in the space provided after that part.



1. (10 points, suggested time 20 minutes)

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

(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.

- 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

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Use a pencil or pen with black or dark blue ink only. Do NOT write your name. Do NOT write outside the box.

Name:

- 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.

Sample 2 State 2	Sample 3 State 3
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- (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. Indicate the direction, if any, of energy transfer between the samples. Support your answer using macroscopic thermodynamic principles.

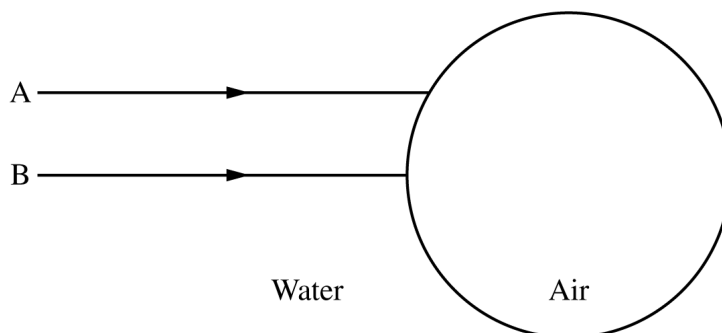
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Use a pencil or pen with black or dark blue ink only. Do NOT write your name. Do NOT write outside the box.

4. (10 points, suggested time 20 minutes)

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.



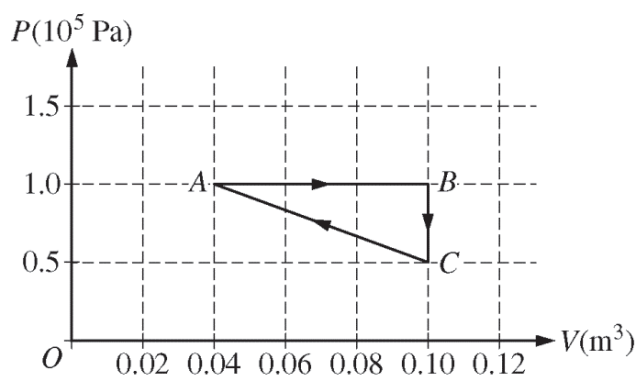
- (b) The bubble has a volume V_1 , the air inside it has density ρ_A , and the water around it has density ρ_W . The bubble starts at rest and has a speed v_f when it has risen a height h . Assume that the change in the bubble's volume is negligible. Derive an expression for the mechanical energy dissipated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

STOP

END OF EXAM

PHYSICS 2**Section II****4 Questions****Time—90 minutes**

Directions: Questions 1 and 4 are short free-response questions that require about 20 minutes each to answer and are worth 10 points each. Questions 2 and 3 are long free-response questions that require about 25 minutes each to answer and are worth 12 points each. Show your work for each part in the space provided after that part.



1. (10 points, suggested time 20 minutes)

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 $5 \times 10^{-3} \text{ m}^2$.

- (a)
- 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.
 - Calculate the temperature of the gas in state *B*, and indicate the microscopic property of the gas that is characterized by the temperature.
- (b)
- Predict qualitatively how the internal energy of the gas changes as it is taken from state *A* to state *B*. Justify your prediction.
 - 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*.