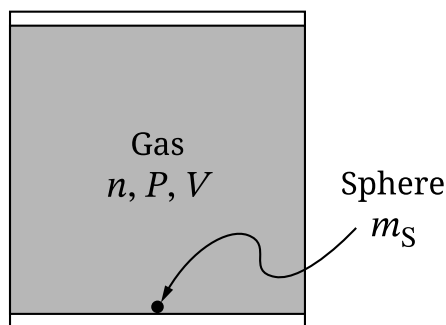


Question 1: Version J**1. Part A**

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.

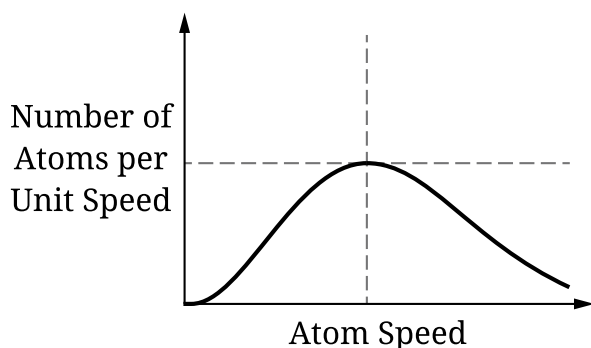
Figure 1

State X

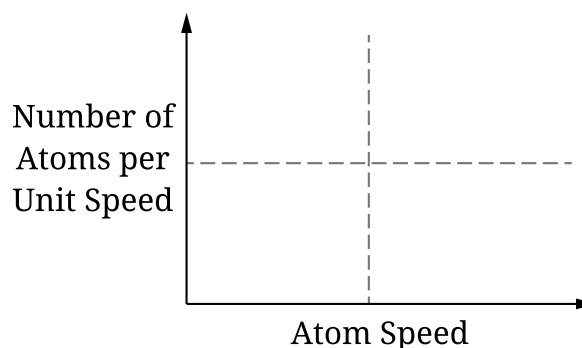
Note: Figure not drawn to scale.

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.

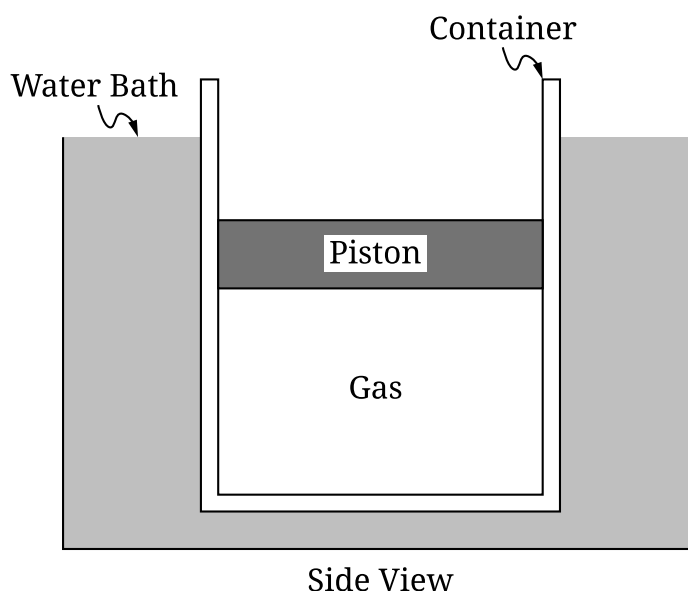
Indicate whether $|\Delta T_S|$ is greater than, less than, or equal to $|\Delta T_L|$. Include one of the following relationships in your response.

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

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} .



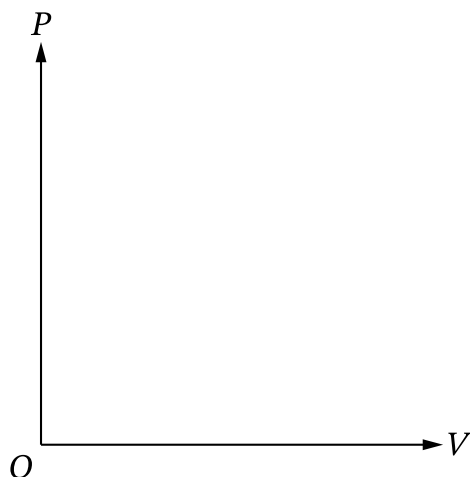
Note: Figure not drawn to scale.

- 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.

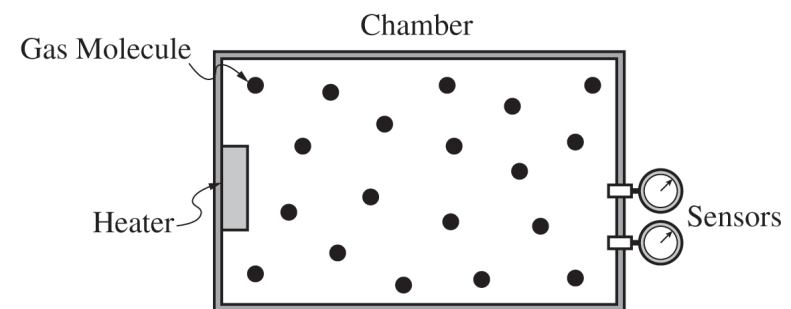
Indicate whether T_{new} is greater than, less than, or equal to T_0 .

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

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

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

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.

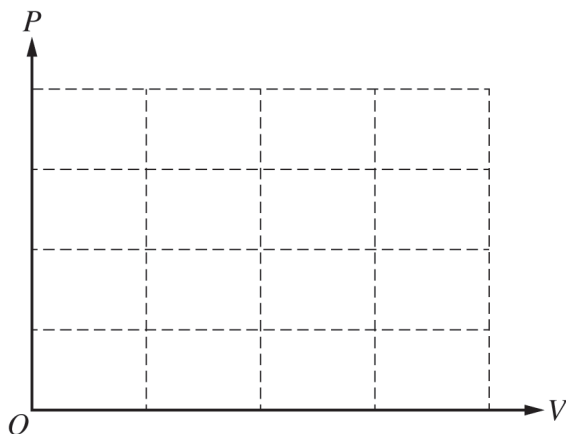
- (a) **Describe** a procedure for collecting data that would allow the student to determine an experimental value for N . Provide enough detail so that a student could replicate the experiment, including any steps necessary to reduce experimental uncertainty.

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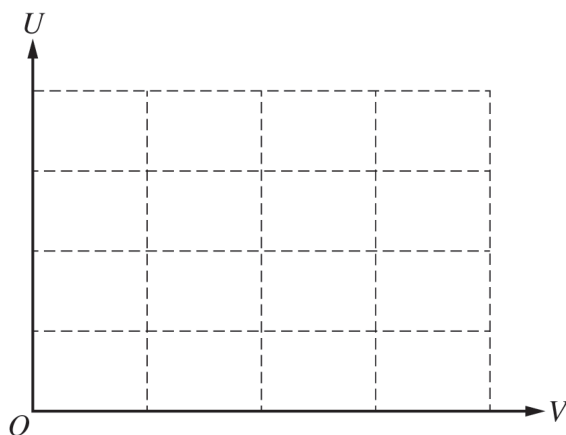
Continue your response to **QUESTION 2** on this page.

(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.



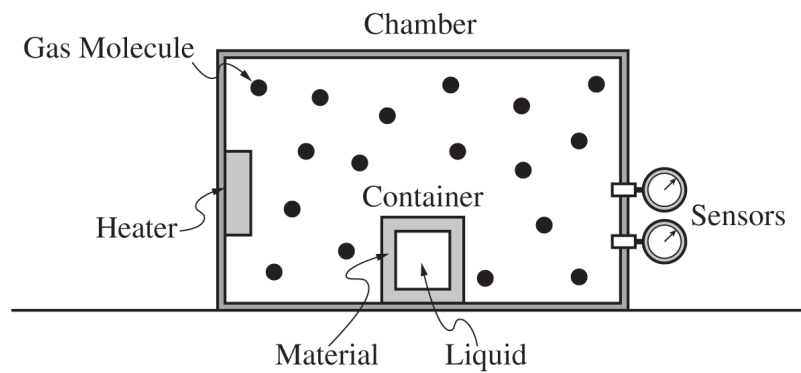
- ii. On the following axes, **sketch** a curve or line to represent the expected relationship between the internal energy U and the volume V of the gas while the heater is on. **Draw** an arrow on the curve or line to represent the direction of the resulting thermal process.



- 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.

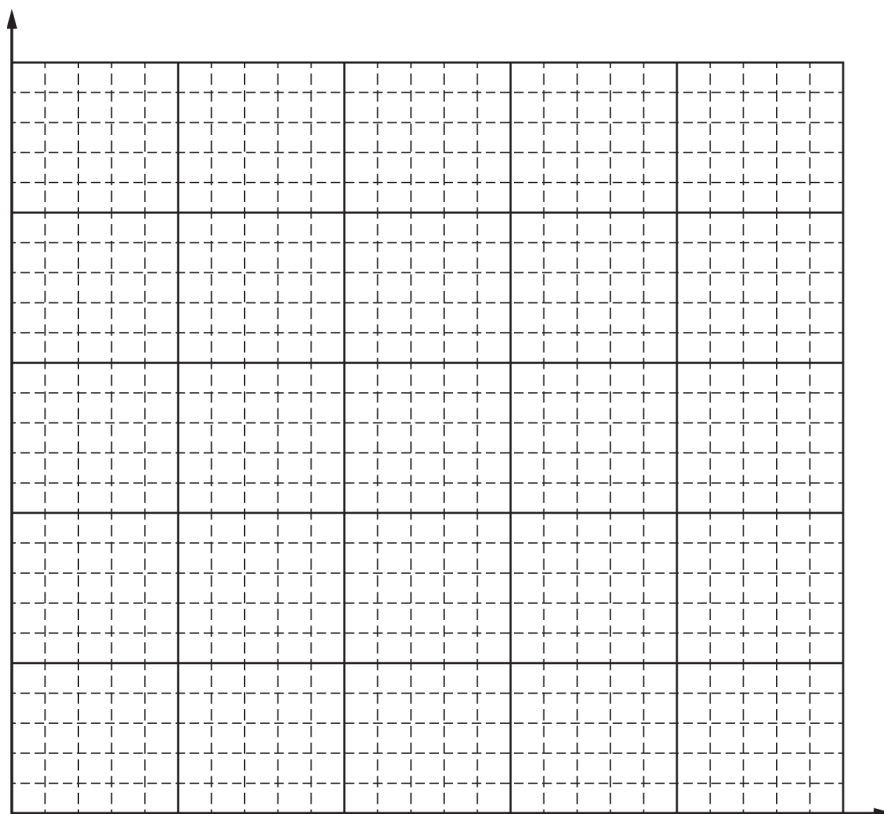
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Continue your response to **QUESTION 2** on this page.

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.



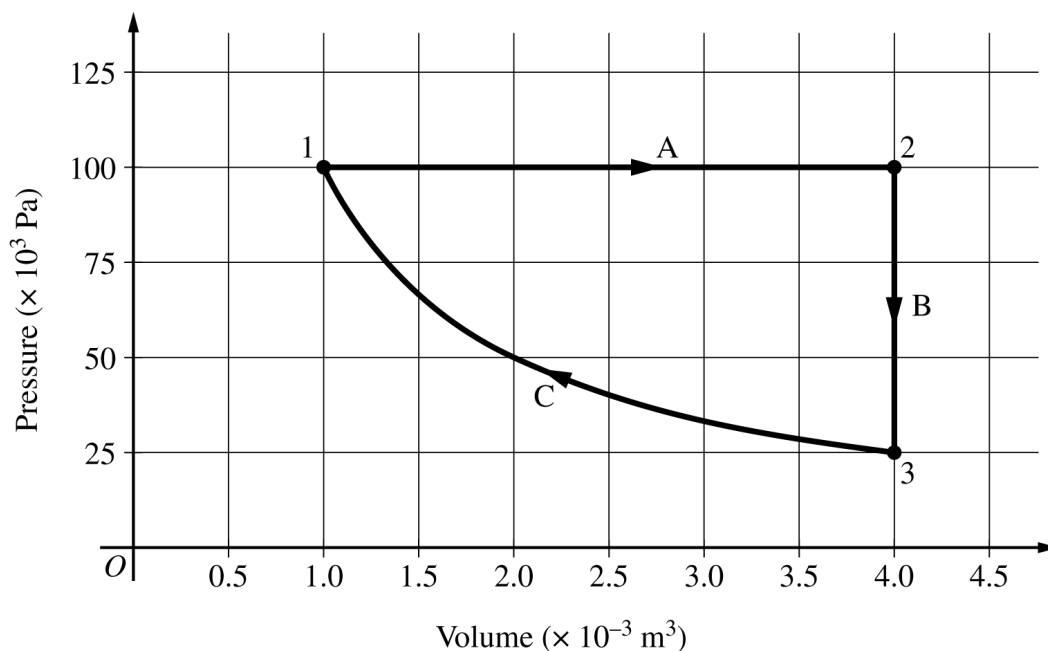
iii. **Draw** the best-fit line for the data graphed in part (c)(ii).

(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.

(b) Consider isothermal process C.

- i. 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.
- 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.

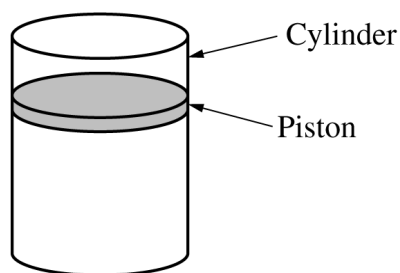
Sample 2 State 2	Sample 3 State 3
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(c) Consider two samples of the gas, each with the same number of gas particles. Sample 2 is in state 2 shown in the graph, and sample 3 is in state 3 shown in the graph. The samples are put into thermal contact, as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

Begin your response to question 2 on this page.



2. (12 points, suggested time 25 minutes)

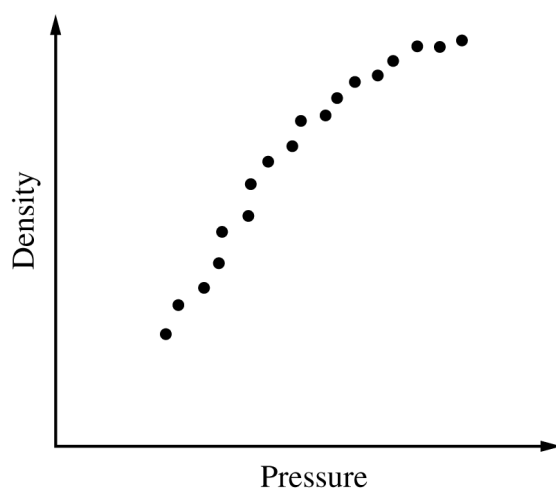
A group of students design an experiment to investigate the relationship between the density and pressure of a sample of gas at a constant temperature. The gas may or may not be ideal. They will create a graph of density as a function of pressure. They have the following materials and equipment.

- A sample of the gas of known mass M_g in a sealed, clear, cylindrical container, as shown above, with a movable piston of known mass m_p
- A collection of objects each of known mass m_o
- A meterstick

(a)

- i. Describe the measurements the students should take and a procedure they could use to collect the data needed to create the graph. Specifically indicate how the students could keep the temperature constant. Include enough detail that another student could follow the procedure and obtain similar data.
- ii. Determine an expression for the absolute pressure of the gas in terms of measured quantities, given quantities, and physical constants, as appropriate. Define any symbols used that are not already defined.

- iii. Determine an expression for the density of the gas in terms of measured quantities, given quantities, and physical constants, as appropriate. Define any symbols used that are not already defined.



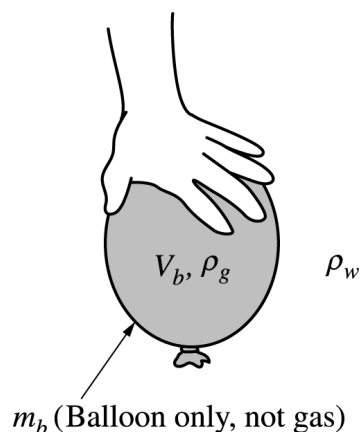
- iv. The graph above represents the students' data. Does the data indicate that the gas is ideal? Describe the application of physics principles in an analysis of the graph that can be used to arrive at your answer.

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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.

Another group of students propose that the relationship between density and pressure could also be obtained by filling a balloon with the gas and submerging it to increasing depths in a deep pool of water.

(b) Why could submerging the balloon to increasing depths be useful for determining the relationship between the density and pressure of the gas?



(c) The balloon is kept underwater in the deep pool by a student pushing down on the balloon, as shown above. Let V_b represent the volume of the inflated balloon, m_b represent the mass of just the balloon (not including the mass of the gas), ρ_g represent the density of the gas in the balloon, and ρ_w represent the density of the water. Derive an expression for the force the student must exert to hold the balloon at rest under the water, in terms of the quantities given in this part and physical constants, as appropriate.

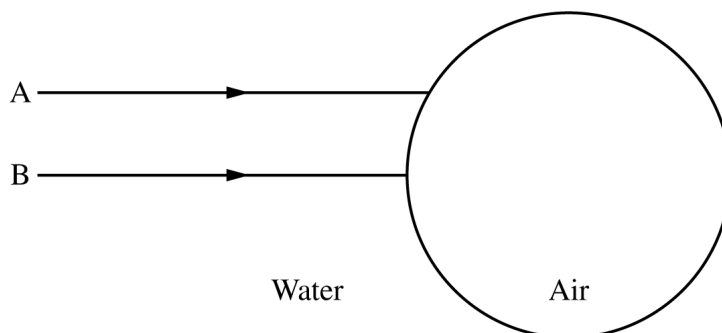
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4. (10 points, suggested time 20 minutes)

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.



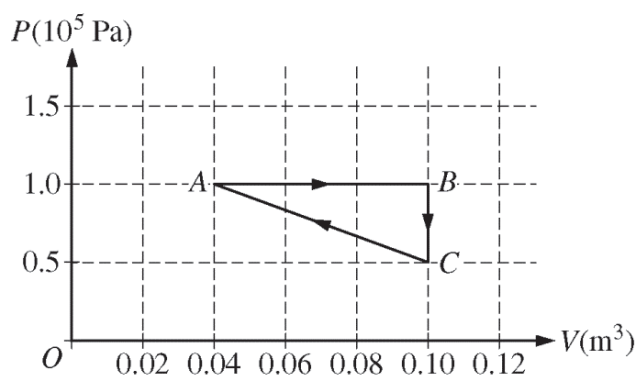
- (b) The bubble has a volume V_1 , the air inside it has density ρ_A , and the water around it has density ρ_W . The bubble starts at rest and has a speed v_f when it has risen a height h . Assume that the change in the bubble's volume is negligible. Derive an expression for the mechanical energy dissipated 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 $5 \times 10^{-3} \text{ m}^2$.

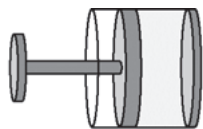
- (a)
- Calculate the force that the gas exerts on the piston in state *A*, and explain how the collisions of the gas atoms with the piston allow the gas to exert a force on the piston.
 - Calculate the temperature of the gas in state *B*, and indicate the microscopic property of the gas that is characterized 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*.

3. (12 points, suggested time 25 minutes)

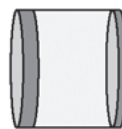
Students are watching a science program about the North Pole. The narrator says that cold air sinking near the North Pole causes high air pressure. Based on the narrator's statement, a student makes the following claim: "Since cold air near the North Pole is at high pressure, temperature and pressure must be inversely related."

- (a) Do you agree or disagree with the student's claim about the relationship between pressure and temperature? Justify your answer.

After hearing the student's hypothesis, you want to design an experiment to investigate the relationship between temperature and pressure for a fixed amount of gas. The following equipment is available.



Cylinder with Movable Piston



Cylinder with Fixed Lid

- ☐ A cylinder with a movable piston, shown above on the left
☐ A cylinder with a fixed lid, shown above on the right

Note: The two cylinders have gaskets through which measurement instruments can be inserted without gas escaping.

- | | |
|---|---|
| <p>☐ A pressure sensor
☐ A basin that is large enough to hold either cylinder with a lot of extra room
☐ A source of hot water</p> | <p>☐ A source of mixed ice and water
☐ A meterstick
☐ A thermometer
☐ A stopwatch</p> |
|---|---|

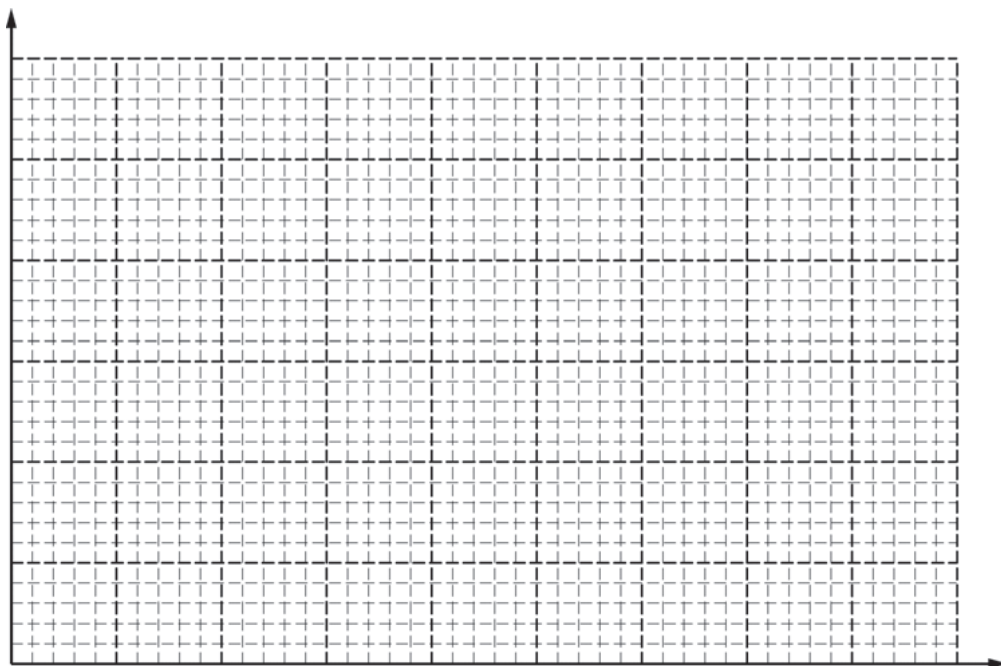
- (b) Put a check in the blank next to each of the items above that you would need for your investigation. Outline the experimental procedure you would use to gather the necessary data. Make sure the outline contains sufficient detail so that another student could follow your procedure.

The table below shows data from a different experiment in which the volume, temperature, and pressure of a sample of gas are varied.

Trial Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Volume (cm^3)	10.0	5.0	4.0	3.0	5.0	4.0	10.0	5.0	3.0	4.0	5.0	10.0	3.0	5.0
Pressure (kPa)	100	200	250	330	220	270	110	230	380	290	240	120	420	250
Temperature ($^{\circ}\text{C}$)	0	0	0	0	20	20	20	40	40	40	60	60	70	70

- (c) What subset of the experimental trials would be most useful in creating a graph to determine the relationship between temperature and pressure for a fixed amount of gas? Explain why the trials you selected are most useful.

- (d) Plot the subset of data chosen in part (c) on the axes below. Be sure to label the axes appropriately. Draw a curve or line that best represents the relationship between the variables.



- (e) What can be concluded from your curve or line about the relationship between temperature and pressure?