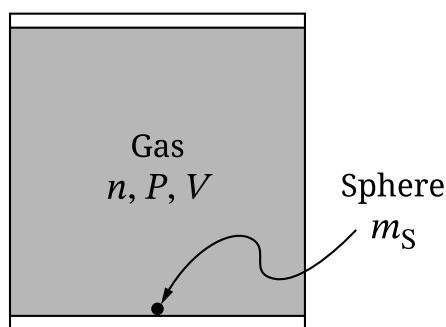


Question 1: Version J**1. Part A**

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.

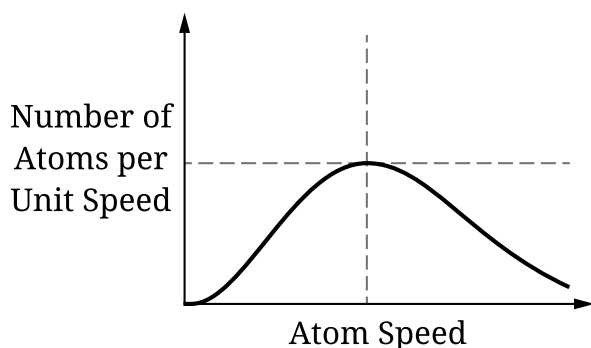
Figure 1

State X

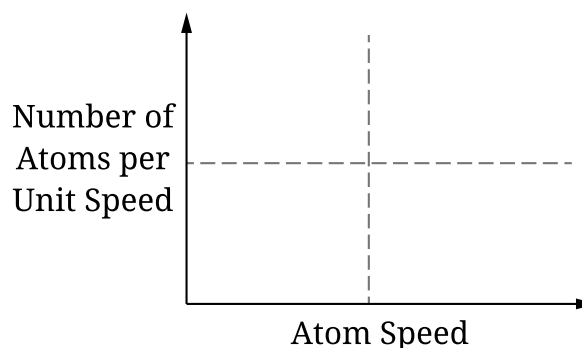
Note: Figure not drawn to scale.

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.

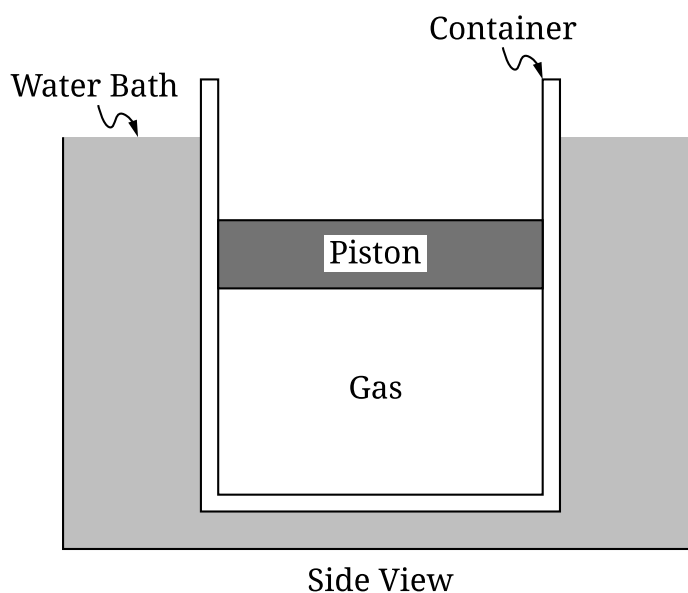
Indicate whether $|\Delta T_S|$ is greater than, less than, or equal to $|\Delta T_L|$. Include one of the following relationships in your response.

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

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} .



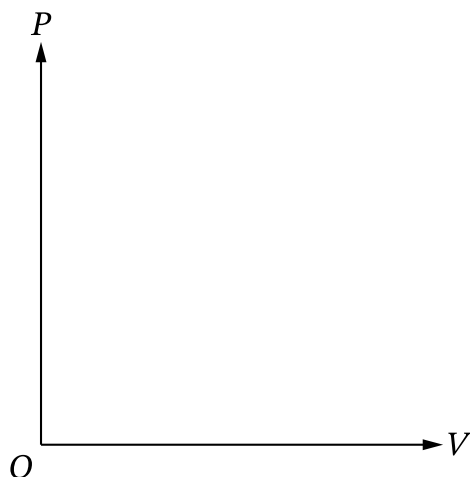
Note: Figure not drawn to scale.

- 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.

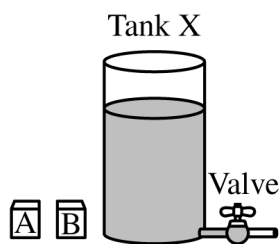
Indicate whether T_{new} is greater than, less than, or equal to T_0 .

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

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

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

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



Note: Figure not drawn to scale.

Figure 1

. (12 points, suggested time 25 minutes)

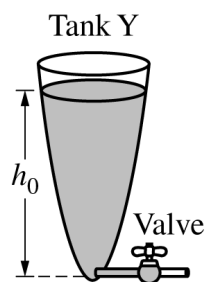
Tank X is a large cylindrical tank that is partially filled with water, as shown in Figure 1. The bottom of Tank X is connected to a short horizontal pipe. A valve that is initially closed can be opened to allow water to flow through the pipe and exit through the other end of the pipe.

(a) Two blocks, A and B, have identical dimensions and are placed in the tank. Both blocks float at rest and are partially submerged in the water.

i. The water and air can be modeled as consisting of individual particles that are in continuous random motion. In terms of interactions with both water and air particles, explain why there is an upward buoyant force exerted on each block.

ii. The valve is then opened, and water flows out through the pipe. The surface of the water moves downward. When Block A touches the bottom of Tank X, Block B is still above the bottom of Tank X. Which block has a greater density? Briefly explain your reasoning.

GO ON TO THE NEXT PAGE.

Continue your response to **QUESTION 3** on this page.

Note: Figure not drawn to scale.

Figure 2

Tank Y is a large tank with the top open to the air, as shown in Figure 2. The bottom of Tank Y is connected to a short horizontal pipe of radius r with a closed valve. Tank Y is filled with water to height h_0 above the horizontal pipe. Tank Y is specially designed so that when the valve is opened, the surface of the water moves downward at constant speed v_s .

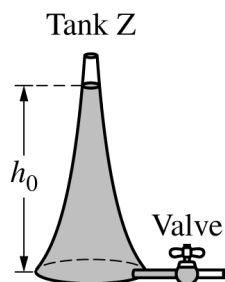
(b) At time $t = 0$, the valve is opened.

i. Derive the relationship between the speed v_p at which water exits the pipe and the changing height h of the surface of the water above the pipe to show that $v_p = \sqrt{v_s^2 + 2gh}$.

ii. Derive the relationship between v_p and the changing radius R of the top surface of the water to show that $v_p = \frac{R^2}{r^2} v_s$.

iii. When the radius R of the tank is sufficiently greater than r , the speed v_p can be approximated as $v_p = \sqrt{2gh}$. Justify this claim.

GO ON TO THE NEXT PAGE.



Note: Figure not drawn to scale.

Figure 3

Tank Z is a large tank whose top is open to the air and is shaped as shown in Figure 3. The bottom of Tank Z is connected to a short horizontal pipe with a closed valve. Tank Z is filled with water to a height h_0 above the horizontal pipe.

At time $t = 0$, the valve of Tank Z is opened.

- (c) Does the speed v_s at which the surface of the water moves downward increase, decrease, or remain the same over time as water exits the other end of the pipe? Justify your answer by using or referencing equations from both part (b)(i) and part (b)(ii).

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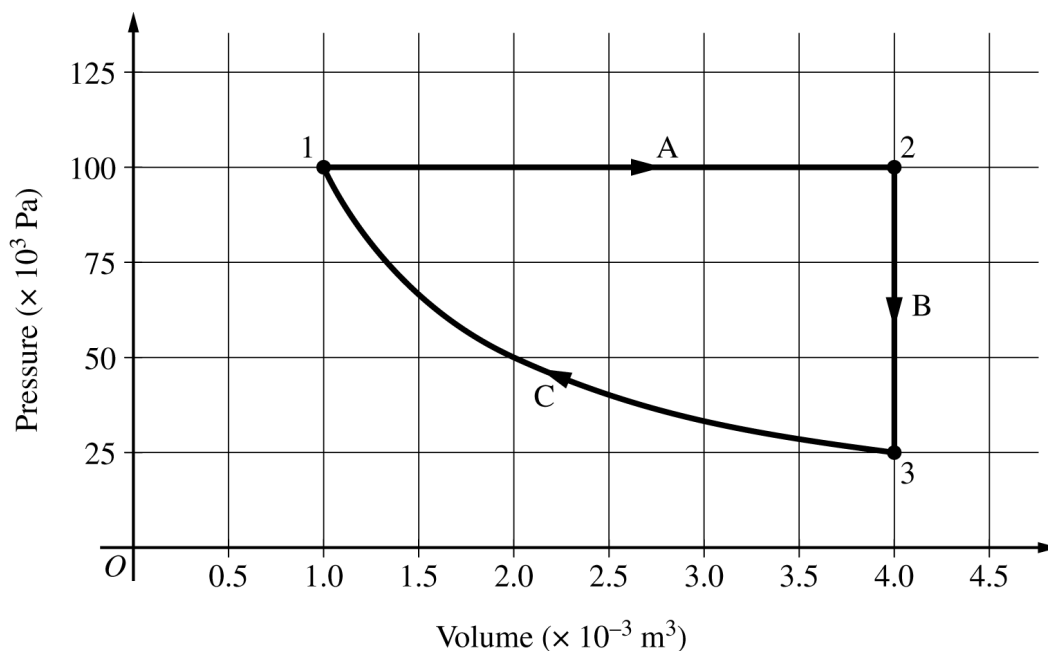
PHYSICS 2

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.

***** your response is requested ***** on this page.

- 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.

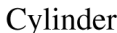
Sample 2 State 2	Sample 3 State 3
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- (c) Consider two samples of the gas, each with the same number of gas particles. Sample 2 is in state 2 shown in the graph, and sample 3 is in state 3 shown in the graph. The samples are put into thermal contact,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



Piston

2. (12 points, suggested time 25 minutes)

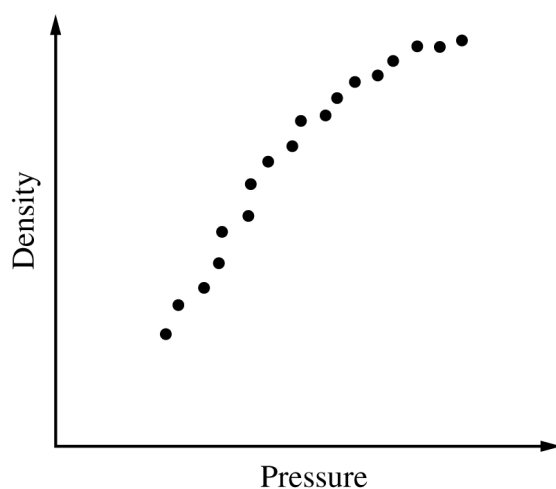
A group of students design an experiment to investigate the relationship between the density and pressure of a sample of gas at a constant temperature. The gas may or may not be ideal. They will create a graph of density as a function of pressure. They have the following materials and equipment.

- 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.



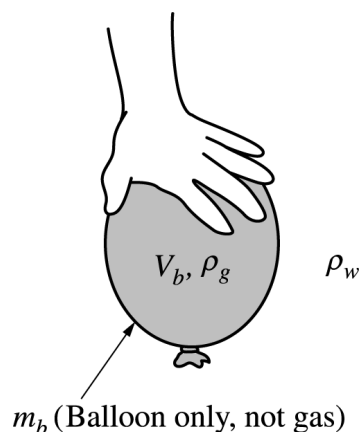
- iv. The graph above represents the students' data. Does the data indicate that the gas is ideal? Describe the application of physics principles in an analysis of the graph that can be used to arrive at your answer.

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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.

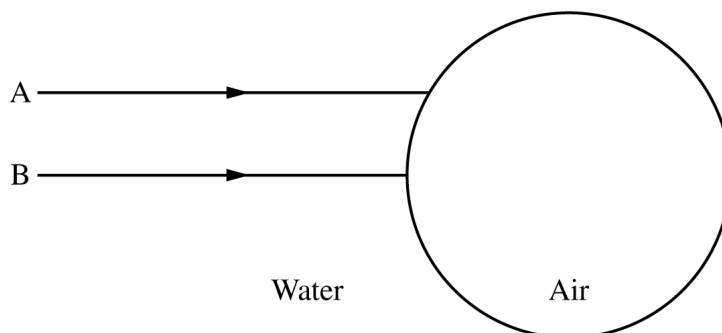
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4. (10 points, suggested time 20 minutes)

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

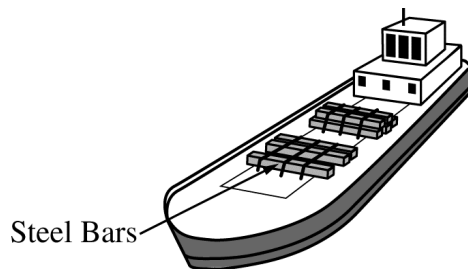
- (a) In the figure below, the circle represents one such air bubble, and two incoming rays of light, A and B, are shown. Ray B points toward the center of the circle. On the diagram, draw the paths of rays A and B as they go through the bubble and back into the water. Your diagram should clearly show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



4. (10 points, suggested time 20 minutes)

A large boat like the one shown above has a mass M_b and can displace a maximum volume V_b . The boat is floating in a river with water of density ρ_{water} and is being loaded with steel beams each of density ρ_{steel} and volume V_{steel} . The boat owners want to be able to carry as many beams as possible.

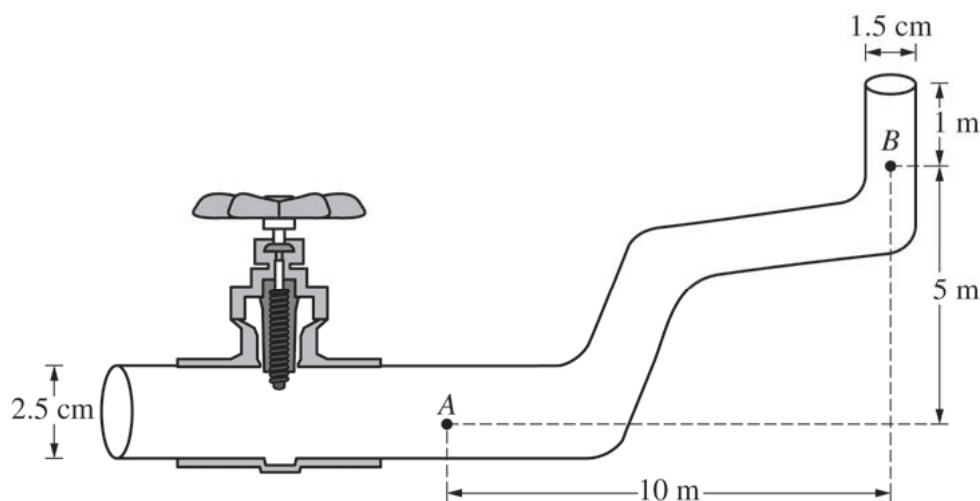
- (a) Derive an expression for the maximum number N of steel beams that can be loaded on the boat without exceeding the maximum displaced volume, in terms of the given quantities and physical constants, as appropriate.
- (b) The captain realizes that oil is leaking from the boat, creating a thin film of oil on the water surface. In one area of the oil film the surface looks mostly green. Explain in detail how constructive interference contributes to the green appearance. Assume the index of refraction of the oil is greater than the index of refraction of the water.
- (c) Later the boat is floating down the river with the water current, heading for a town. The river has a width of 60 m and a constant depth and flows at a speed of 5 km/hr. Partway to the town, the river narrows to a width of 30 m while its depth remains the same. Calculate the speed of the water in the narrow section.

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.



Note: Figure not drawn to scale.

1. (10 points, suggested time 20 minutes)

Two students observe water flowing from left to right through the section of pipe shown above, which decreases in diameter and increases in elevation. The pipe ends on the right, where the water exits vertically. At point A the water is known to have a speed of 0.50 m/s and a pressure of $2.0 \times 10^5 \text{ Pa}$. The density of water is 1000 kg/m^3 .

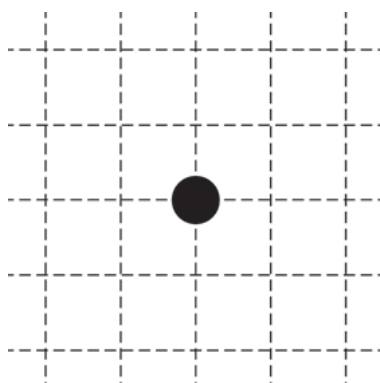
- (a) The students disagree about the water pressure and speed at point B. They make the following claims.
- Student Y claims that the pressure at point B is greater than that at point A because the water is moving faster at point B.
- Student Z claims the speed of the water is less at point B than that at point A because by conservation of energy, some of the water's kinetic energy has been converted to potential energy of the Earth-water system.
- Indicate any aspects of student Y's claim that are correct.
 - Indicate any aspects of student Y's claim that are incorrect. Support your answer using appropriate physics principles.
 - Indicate any aspects of student Z's claim that are correct.
 - Indicate any aspects of student Z's claim that are incorrect. Support your answer using appropriate physics principles.

(b) Calculate the following at point B .

- i. The speed of the water
- ii. The pressure in the pipe

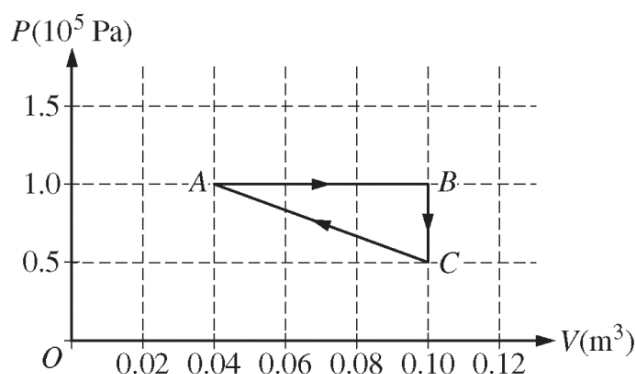
(c) A valve to the left of point A now closes off that end of the pipe. The section of pipe shown is still full of water, but the water is no longer flowing.

- i. Calculate the absolute pressure at point A (the pressure that includes the effect of the atmosphere).
- ii. An air bubble forms at point A . On the figure below, where the dot represents the air bubble, draw a free-body diagram showing and labeling the forces (not components) exerted on the bubble. Draw the relative lengths of all vectors to reflect the relative magnitudes of the forces.



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

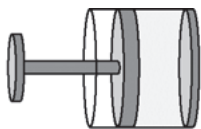
- (a)
- Calculate the force that the gas exerts on the piston in state *A*, and explain how the collisions of the gas atoms with the piston allow the gas to exert a force on the piston.
 - Calculate the temperature of the gas in state *B*, and indicate the microscopic property of the gas that is characterized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

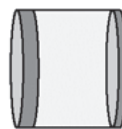
Students are watching a science program about the North Pole. The narrator says that cold air sinking near the North Pole causes high air pressure. Based on the narrator's statement, a student makes the following claim: "Since cold air near the North Pole is at high pressure, temperature and pressure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

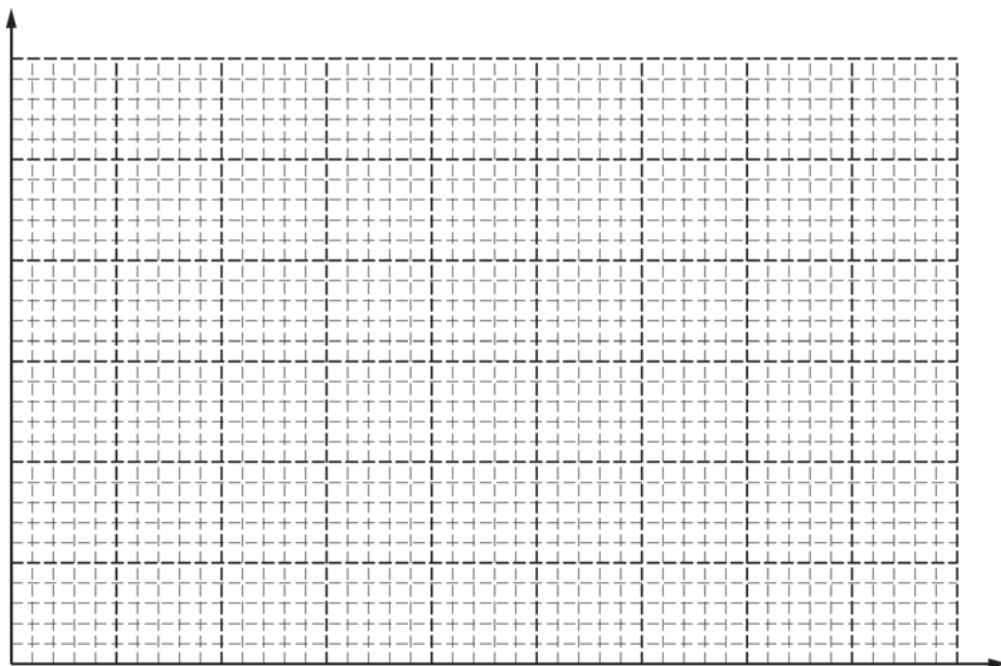
- (b) Put a check in the blank next to each of the items above that you would need for your investigation. Outline the experimental procedure you would use to gather the necessary data. Make sure the outline contains sufficient detail so that another student could follow your procedure.

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?