Week 1

# AP Physics 2

Homework bundle for this week

本周作业合集

exercises.lol

## Contents 目录





AP Physics 2 Name: ______________ Score: ______

1. In kinetic theory, the temperature of a gas is a measure of the particles':
   - ☐ total number
   - ☐ average kinetic energy
   - ☐ colour
   - ☐ total mass
2. A gas at 100 kPa, 2 $m^3$ is squeezed to 0.5 $m^3$ at constant temperature. What is the new pressure, in kPa?

   ______________ kPa
3. Left on their own, in which direction does heat flow?
   - ☐ from cold to hot
   - ☐ from hot to cold
   - ☐ in no particular direction
   - ☐ always upward
4. A gas absorbs 500 J of heat and does 200 J of work. What is its change in internal energy, in joules?

   ______________ J
5. How much heat warms 2 kg of water by 10 °C? ($c = 4200\ \frac{\text{J}}{\text{kg}\cdot{}^\circ\text{C}}$.) Answer in J.

   ______________ J
6. Entropy is a measure of a system's:
   - ☐ total mass
   - ☐ disorder
   - ☐ temperature only
   - ☐ electric charge
7. What causes the pressure a gas exerts on its container?
   - ☐ particles colliding with the walls
   - ☐ gravity pulling the gas down
   - ☐ the colour of the gas
   - ☐ the walls heating up

8. Which is the ideal gas law?

☐ $PV = nRT$

☐ $P = mgh$

☐ $V = IR$

☐ $F = ma$

9. Doubling the kelvin temperature of a gas doubles the average kinetic energy of its particles.

☐ True ☐ False

10. Temperature in the ideal gas law must be in kelvin.

☐ True ☐ False





AP Physics 2

1. **average kinetic energy**

   Temperature is proportional to the average kinetic energy of the particles.

2. **400 kPa**

   $P_1V_1 = P_2V_2 \Rightarrow 200 = 0.5P_2 \Rightarrow P_2 = 400$ kPa.

3. **from hot to cold**

   Heat flows spontaneously from the hotter object to the colder one.

4. **300 J**

   $\Delta U = Q - W = 500 - 200 = 300$ J.

5. **84000 J**

   $Q = mc\Delta T = 2 \times 4200 \times 10 = 84\,000$ J.

6. **disorder**

   Entropy measures how spread-out and disordered a system's energy is.

7. **particles colliding with the walls**

   Each collision with a wall gives a tiny push; together they make the pressure.

8. $PV = nRT$

   $PV = nRT$ links pressure, volume, amount and temperature.

9. **True**

   On the kelvin scale, average kinetic energy is proportional to temperature.

10. **True**

    The law is proportional in kelvin; using °C gives wrong ratios.

AP PHYSICS 2 • EXERCISE SHEET

# 9.1 Kinetic Theory of Temperature and Pressure

Name: ____________ Class: ________ Date: __________ **Total: 9 marks**

**KEY WORDS** pressure 压强 • temperature 温度 • kinetic energy 动能 • random motion 无规则运动 • heat 热量

## Objective

Build the skills to answer exam questions on **the kinetic theory of temperature and pressure**.

**You must be able to:**

- describe a gas as many particles in **random motion** 无规则运动 with negligible volume
- relate **absolute temperature** 绝对温度 to the average **kinetic energy** 动能 of the particles
- explain gas **pressure** 压强 as the result of particle collisions with the walls
- use $\overline{KE} = \frac{3}{2}k_BT$

## 1 Worked examples

Study these first. Each one shows the method for a question type used later.

### ■ The kinetic-theory picture

A gas is a huge number of tiny particles in random motion, with negligible volume and no forces except during brief collisions.

### ■ Temperature and energy

$\overline{KE} = \frac{3}{2}k_BT$, where $k_B = 1.38 \times 10^{-23}$ J K$^{-1}$ and $T$ is the **absolute** temperature (in kelvin). Doubling $T$ doubles the average kinetic energy.

### ■ Pressure

Particles collide with the container walls; faster or more frequent collisions mean a larger force per unit area, i.e. a higher pressure.



## 2 Practice

**2.1** State what causes the pressure a gas exerts on its container. [1]

**2.2** The absolute temperature of a gas doubles. State what happens to the average kinetic energy of its particles. [1]

**2.3** Find the average kinetic energy of a particle at $T = 300$ K (take $k_B = 1.38 \times 10^{-23}$ J K$^{-1}$). [2]

## 3 Exam-style questions

**3.1** The absolute temperature of a gas is a measure of the [1]

- **A** total volume
- **B** average kinetic energy of its particles
- **C** number of particles
- **D** pressure

**3.2** If the average kinetic energy of the gas particles triples, the absolute temperature [1]

- **A** stays the same
- **B** doubles
- **C** triples
- **D** falls to one third

**3.3** A gas in a sealed rigid container is heated from 300 K to 600 K.

(a) State the ratio of the new average kinetic energy to the old. [1]

(b) Explain, in terms of particle motion, why the pressure rises. [2]



## Solutions

**2.1** the collisions of the gas particles with the container walls.

**2.2** it also doubles ($\overline{KE} \propto T$).

**2.3** $\overline{KE} = \frac{3}{2}k_BT = \frac{3}{2}(1.38 \times 10^{-23})(300) = 6.2 \times 10^{-21}$ J.

**3.1** B.

**3.2** C.

**3.3** (a) 2 : 1. (b) higher temperature means faster particles, which hit the walls harder and more often, raising the pressure.

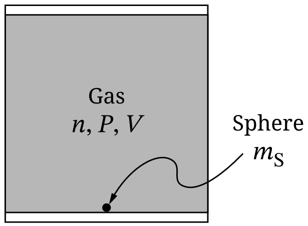
**Question 1: Version J**

## 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**



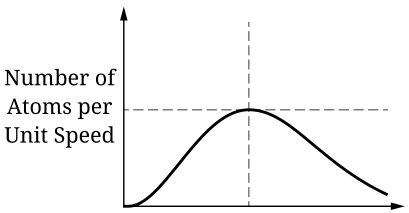

State X

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 $Q_S$.

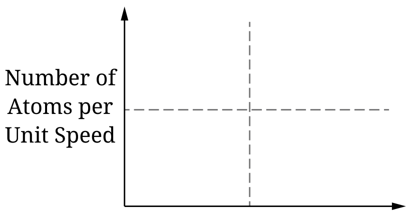
i. The graph in Figure 2 represents the number of atoms per unit speed as a function of atom speed for the gas when the gas is in State X. On Figure 3, **sketch** a curve that could represent the number of atoms per unit speed as a function of atom speed for the gas when the gas is in State Y.

**Figure 2**




State X

**Figure 3**




State Y





ii. **Derive** an expression for the change $\Delta T$ 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.

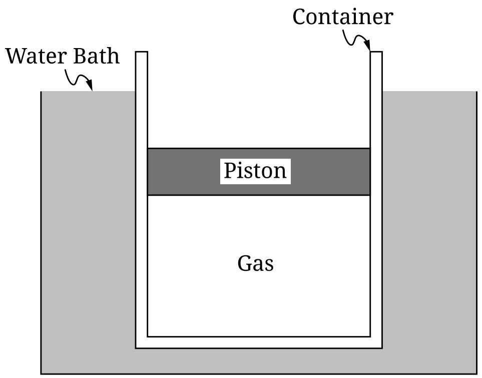
**Indicate** whether $|\Delta T_S|$ is greater than, less than, or equal to $|\Delta T_L|$. Include one of the following relationships in your response.

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

**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 $P_{atm}$.




Side View

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.

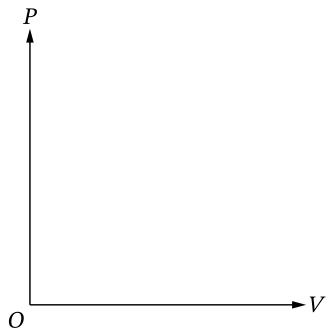


Name: AP Physics 2: 2025

**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 $T_0$.

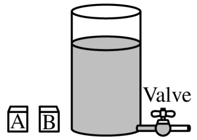
____ $T_{new} > T_0$

____ $T_{new} < T_0$

____ $T_{new} = T_0$

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

Tank X




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.

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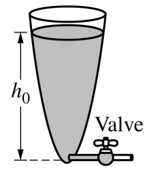
Tank Y




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.

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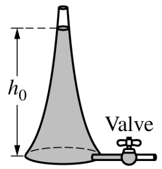
Continue your response to QUESTION on this page.




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).

**GO ON TO THE NEXT PAGE.**





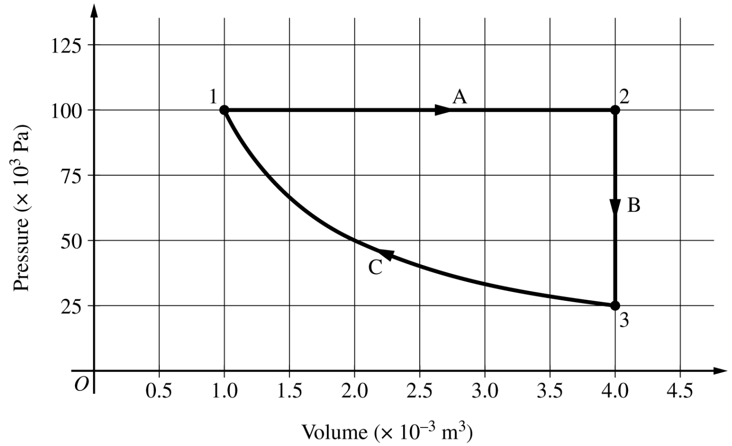
**PHYSICS 2**

**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 $\Delta U$ 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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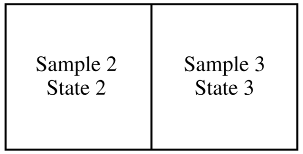
Continue your response to **QUESTION 1** on this page.

(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.

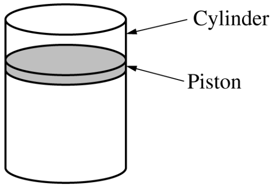



(c) Consider two samples of the gas, each with the same number of gas particles. Sample 2 is in state 2 shown in the graph, and sample 3 is in state 3 shown in the graph. The samples are put into thermal contact, as shown above. Indicate the direction, if any, of energy transfer between the samples. Support your answer using macroscopic thermodynamic principles.





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.

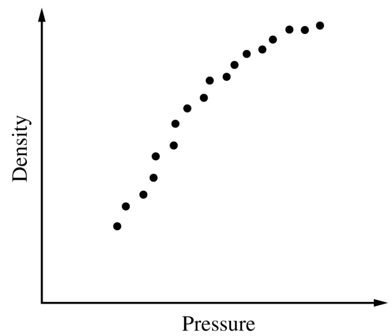
- A sample of the gas of known mass $M_g$ in a sealed, clear, cylindrical container, as shown above, with a movable piston of known mass $m_p$
- A collection of objects each of known mass $m_o$
- A meterstick

(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.

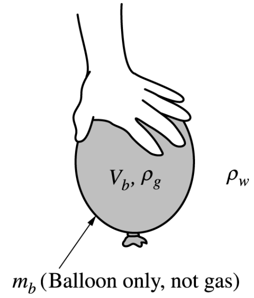
**GO ON TO THE NEXT PAGE.**





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?



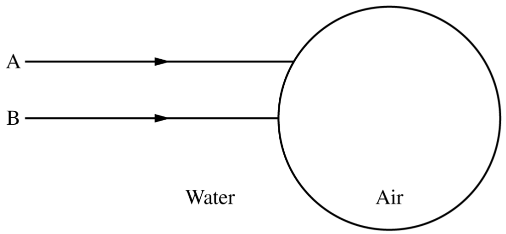

(c) The balloon is kept underwater in the deep pool by a student pushing down on the balloon, as shown above. Let $V_b$ represent the volume of the inflated balloon, $m_b$ represent the mass of just the balloon (not including the mass of the gas), $\rho_g$ represent the density of the gas in the balloon, and $\rho_w$ 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.

**GO ON TO THE NEXT PAGE.**

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 $\rho_A$, and the water around it has density $\rho_W$. 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 $1000\ \mathrm{kg/m^3}$.

i. Determine the absolute pressure in the bubble at this location.

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.

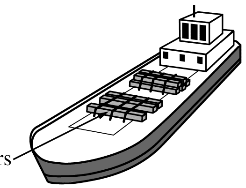
iii. If the air in the bubble cooled as it rose, the volume of the bubble would be less than the value calculated in part (c)(ii). Use physics principles to briefly explain why.

**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 $\rho_{water}$ and is being loaded with steel beams each of density $\rho_{steel}$ 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.

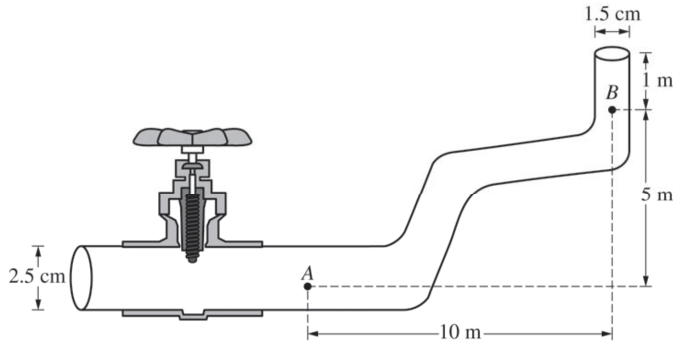
(c) Later the boat is floating down the river with the water current, heading for a town. The river has a width of 60 m and a constant depth and flows at a speed of $5\ \mathrm{km/hr}$. Partway to the town, the river narrows to a width of 30 m while its depth remains the same. Calculate the speed of 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 $0.50\ \text{m/s}$ and a pressure of $2.0 \times 10^5\ \text{Pa}$. The density of water is $1000\ \text{kg/m}^3$.

   (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.

   i. Indicate any aspects of student $Y$'s claim that are correct.

   ii. Indicate any aspects of student $Y$'s claim that are incorrect. Support your answer using appropriate physics principles.

   iii. Indicate any aspects of student $Z$'s claim that are correct.

   iv. Indicate any aspects of student $Z$'s claim that are incorrect. Support your answer using appropriate physics principles.





   (b) Calculate the following at point $B$.

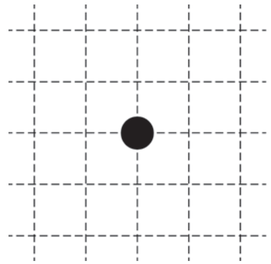
   i. The speed of the water

   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**

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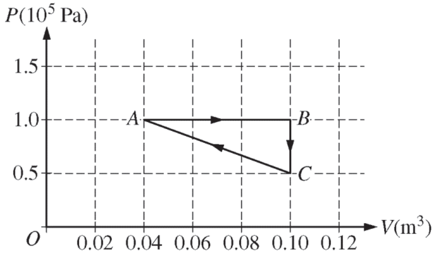



1. (10 points, suggested time 20 minutes)

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)

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.

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.

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*.





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.
___ A pressure sensor
___ A basin that is large enough to hold either cylinder with a lot of extra room
___ A source of hot water
___ A source of mixed ice and water
___ A meterstick
___ A thermometer
___ A stopwatch

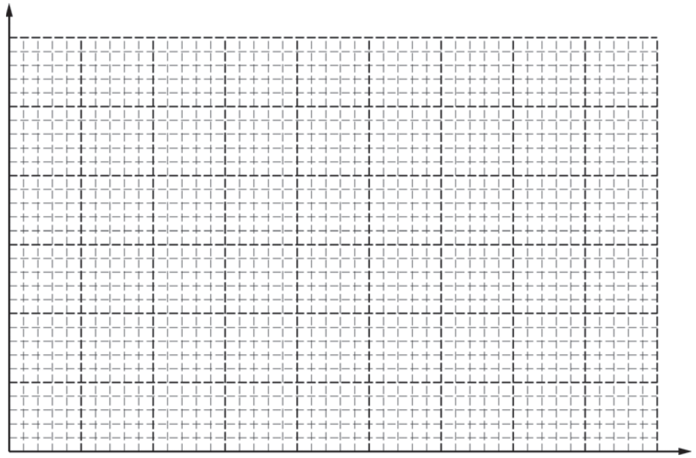
(b) Put a check in the blank next to each of the items above that you would need for your investigation. Outline the experimental procedure you would use to gather the necessary data. Make sure the outline contains sufficient detail so that another student could follow your procedure.

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 $(\text{cm}^3)$ | 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 (°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?



**AP PHYSICS 2 • EXERCISE SHEET**

# 9.2 The Ideal Gas Law

Name: ____________ Class: ________ Date: __________ **Total: 11 marks**

**KEY WORDS** ideal gas law 理想气体定律 • temperature 温度 • pressure 压强 • ideal gas 理想气体 • heat 热量

## Objective

Build the skills to answer exam questions on **the ideal gas law**.

**You must be able to:**

- state and apply the **ideal gas law** 理想气体定律 $PV = nRT$ (and $PV = Nk_BT$)
- analyse changes in pressure, volume, and temperature of a fixed amount of gas
- explain when a real gas behaves approximately as an **ideal gas**

## 1 Worked examples

Study these first. Each one shows the method for a question type used later.

■ **The ideal gas law**

$PV = nRT$, with $R = 8.31\ \text{J mol}^{-1}\,\text{K}^{-1}$ and $T$ in kelvin. For a **fixed** amount of gas, $\frac{PV}{T}$ is constant.

■ **The combined gas law**

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}.$$

At constant $T$, doubling $P$ halves $V$ (Boyle's law).

■ **When a real gas is ideal**

Low pressure and high temperature — the particles are far apart and their forces are weak.

## 2 Practice

**2.1** A gas at constant temperature has its pressure doubled. State what happens to its volume. [1]

**2.2** Find the volume of 2.0 mol of gas at 300 K and $1.0 \times 10^5$ Pa (take $R = 8.31$ J mol$^{-1}$ K$^{-1}$). [2]

**2.3** State two conditions under which a real gas behaves like an ideal gas. [2]

## 3 Exam-style questions

**3.1** The ideal gas law is [1]

- **A** $PV = nRT$
- **B** $P = \rho g h$
- **C** $PV = \frac{1}{2}mv^2$
- **D** $V = IR$

**3.2** A fixed amount of gas is heated at constant volume. Its pressure [1]

- **A** falls
- **B** rises
- **C** stays constant
- **D** halves

**3.3** A sealed rigid 0.020 m$^3$ container holds gas at $2.0 \times 10^5$ Pa and 300 K. It is heated to 450 K.

(a) Find the new pressure. [3]

(b) State the assumption you made about the volume. [1]



## Solutions

**2.1** it halves (Boyle's law, $PV$ constant at fixed $T$).

**2.2** $V = \dfrac{nRT}{P} = \dfrac{2.0 \times 8.31 \times 300}{1.0 \times 10^5} = 0.050$ m$^3$.

**2.3** low pressure; high temperature.

**3.1** **A**.

**3.2** **B**.

**3.3** (a) $\dfrac{P_1}{T_1} = \dfrac{P_2}{T_2} \Rightarrow P_2 = 2.0 \times 10^5 \times \dfrac{450}{300} = 3.0 \times 10^5$ Pa. (b) the volume stays constant (the container is rigid).

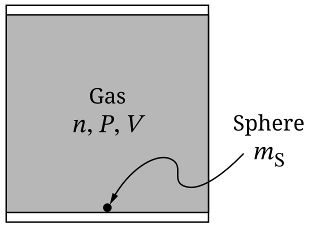
**Question 1: Version J**

## 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**



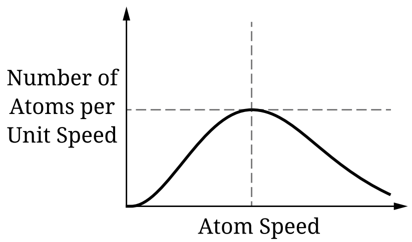

State X

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 $Q_S$.

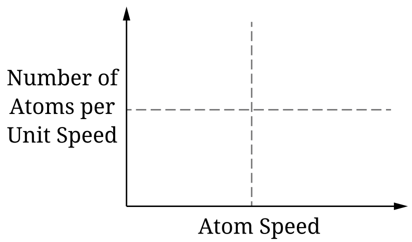
i. The graph in Figure 2 represents the number of atoms per unit speed as a function of atom speed for the gas when the gas is in State X. On Figure 3, **sketch** a curve that could represent the number of atoms per unit speed as a function of atom speed for the gas when the gas is in State Y.

**Figure 2**




State X

**Figure 3**




State Y



Name: AP Physics 2: **2026**

ii. **Derive** an expression for the change $\Delta T$ 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.

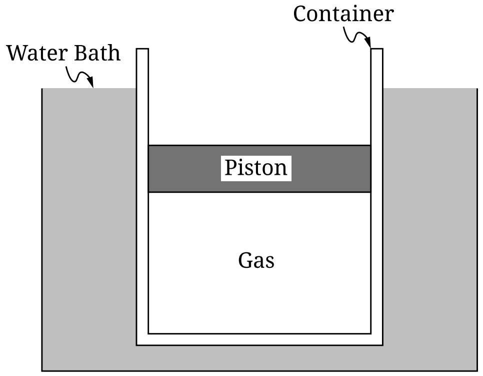
**Indicate** whether $|\Delta T_S|$ is greater than, less than, or equal to $|\Delta T_L|$. Include one of the following relationships in your response.

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

**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 $P_{atm}$.




Side View

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.

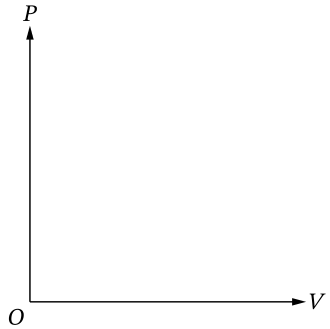




**B.** **Derive** an expression for the internal energy of the gas in terms of $M$, $A$, $V_0$, $P_{atm}$, and physical constants, as appropriate. Begin your derivation by writing a fundamental physics principle or an equation from the reference information.

**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 $T_0$.

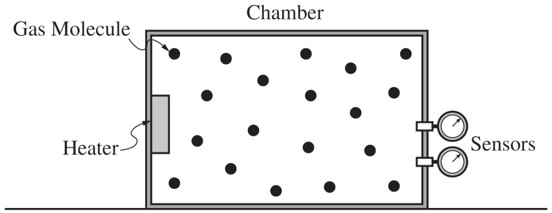
____ $T_{new} > T_0$

____ $T_{new} < T_0$

____ $T_{new} = T_0$

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

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.

**GO ON TO THE NEXT PAGE.**

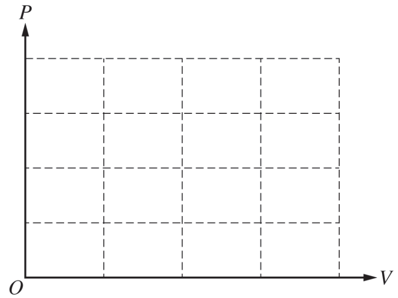




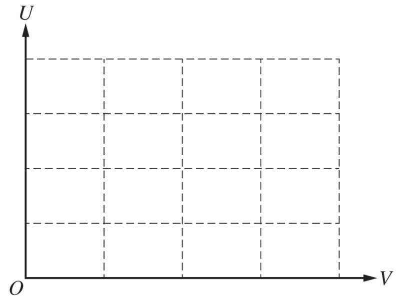
Continue your response to **QUESTION 2** on this page.

(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.

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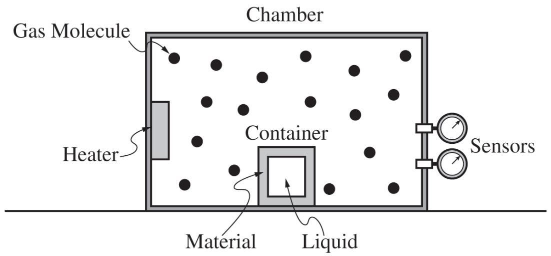
Continue your response to **QUESTION 2** on this page.




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 $0.06\ \text{m}^2$ 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.

**GO ON TO THE NEXT PAGE.**



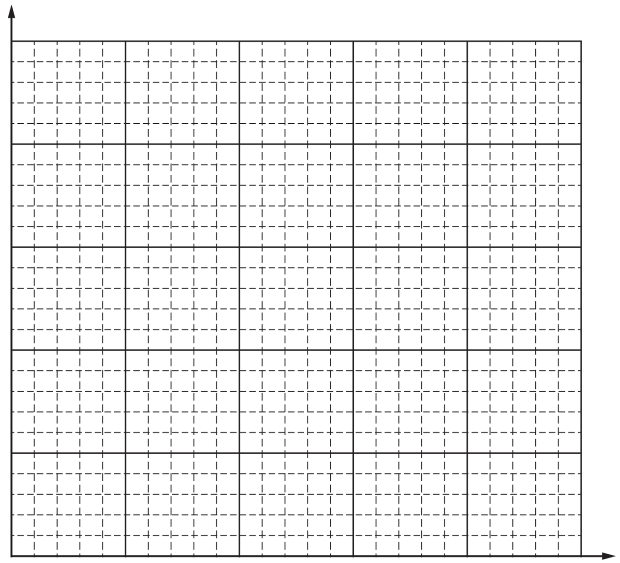


Continue your response to **QUESTION 2** on this page.

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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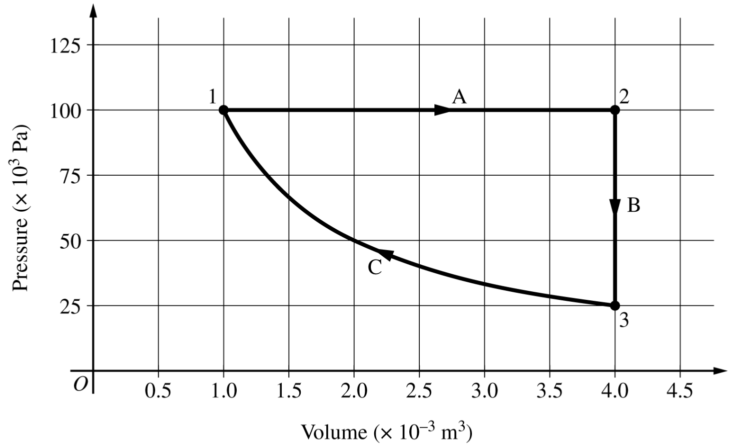
**PHYSICS 2**

**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 $\Delta U$ of the gas
- The net work $W$ done on the gas
- The net energy $Q$ transferred to the gas by heating

**GO ON TO THE NEXT PAGE.**





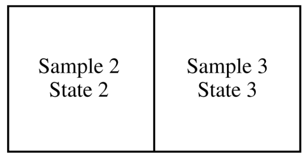


Continue your response to QUESTION 1 on this page.

(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.

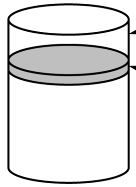
ii. Explain how the microscopic behavior of the gas particles and changes in the size of the container affect interactions on the microscopic level and produce the observed pressure difference between the beginning and end of process C.




(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.

**GO ON TO THE NEXT PAGE.**

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)

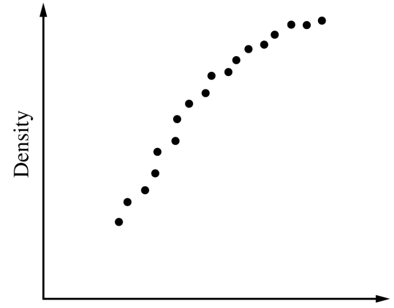
i. Describe the measurements the students should take and a procedure they could use to collect the data needed to create the graph. Specifically indicate how the students could keep the temperature constant. Include enough detail that another student could follow the procedure and obtain similar data.

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.





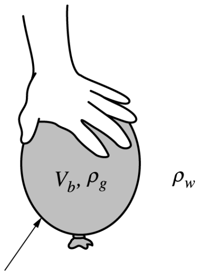
iii. Determine an expression for the density of the gas in terms of measured quantities, given quantities, and physical constants, as appropriate. Define any symbols used that are not already defined.




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.

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), $\rho_g$ represent the density of the gas in the balloon, and $\rho_w$ 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.

**GO ON TO THE NEXT PAGE.**

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

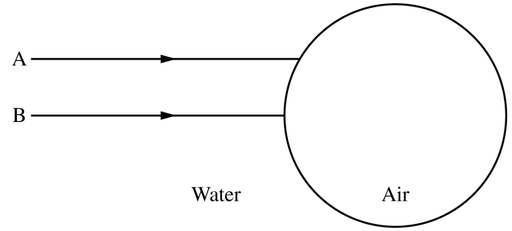




4. (10 points, suggested time 20 minutes)

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 $\rho_A$, and the water around it has density $\rho_W$. 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 $1000\ \mathrm{kg/m^3}$.

i. Determine the absolute pressure in the bubble at this location.

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.

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.

**STOP**

**END OF EXAM**

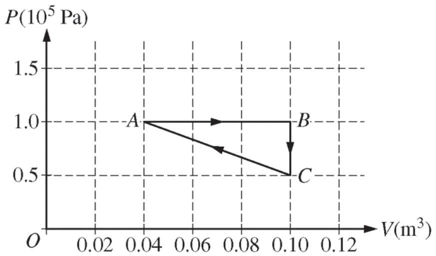
# PHYSICS 2

## 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)

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.

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.

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 $A$.



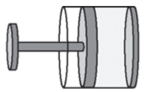


3. (12 points, suggested time 25 minutes)

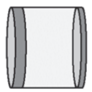
Students are watching a science program about the North Pole. The narrator says that cold air sinking near the North Pole causes high air pressure. Based on the narrator's statement, a student makes the following claim: "Since cold air near the North Pole is at high pressure, temperature and pressure 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.
___ A pressure sensor
___ A basin that is large enough to hold either cylinder with a lot of extra room
___A source of hot water
___ A source of mixed ice and water
___ A meterstick
___ A thermometer
___ A stopwatch

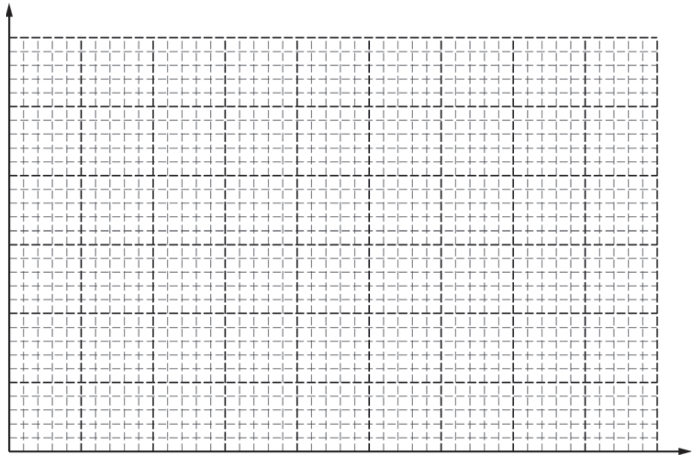
(b) Put a check in the blank next to each of the items above that you would need for your investigation. Outline the experimental procedure you would use to gather the necessary data. Make sure the outline contains sufficient detail so that another student could follow your procedure.

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 $(\text{cm}^3)$ | 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 (°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?



**AP PHYSICS 2 • EXERCISE SHEET**

# 9.3 Thermal Energy Transfer and Equilibrium

Name: ____________ Class: ________ Date: __________ **Total: 9 marks**

**KEY WORDS** thermal equilibrium 热平衡 • heat 热量 • conduction 传导 • convection 对流 • radiation 辐射

## Objective

Build the skills to answer exam questions on **thermal energy transfer and equilibrium**.

**You must be able to:**

- describe thermal energy transfer by **conduction** 传导, **convection** 对流, and **radiation** 辐射
- explain that objects in contact reach **thermal equilibrium** 热平衡 at a common temperature
- relate the direction of **heat** 热量 flow to the temperature difference

## 1 Worked examples

Study these first. Each one shows the method for a question type used later.

### Three ways heat moves

- **Conduction** — through a solid, by particle collisions passing on energy.
- **Convection** — bulk currents in a fluid, as warm fluid rises and cool fluid sinks.
- **Radiation** — electromagnetic waves; needs **no** medium (how the Sun's energy reaches us).

### Thermal equilibrium

Two objects in contact exchange heat until they reach a **common temperature**; then the net heat flow is zero.

### Direction of heat flow

Heat always flows from **hotter** to **colder**.

## 2 Practice

**2.1** Name the three methods of thermal energy transfer. [2]

**2.2** State the direction heat flows between a hot object and a cold object in contact. [1]

**2.3** Two objects have reached thermal equilibrium. State what is true about their temperatures. [1]

## 3 Exam-style questions

**3.1** The method of heat transfer that needs no medium is [1]

- **A** conduction
- **B** convection
- **C** radiation
- **D** none of these

**3.2** When two objects reach thermal equilibrium, the net heat flow between them is [1]

- **A** from hot to cold
- **B** from cold to hot
- **C** zero
- **D** at its maximum



**3.3** A hot metal spoon is placed in a cup of cold water.

(a) State the direction of the heat flow. [1]

(b) Name the main method of transfer within the metal spoon. [1]

(c) Describe the final state of the spoon and water. [1]

## Solutions

**2.1** conduction, convection, radiation.

**2.2** from the hot object to the cold object.

**2.3** their temperatures are equal.

**3.1** C.

**3.2** C.

**3.3** (a) from the spoon to the water. (b) conduction. (c) both reach the same temperature (thermal equilibrium).





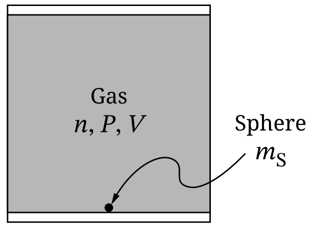
**Question 1: Version J**

### 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**



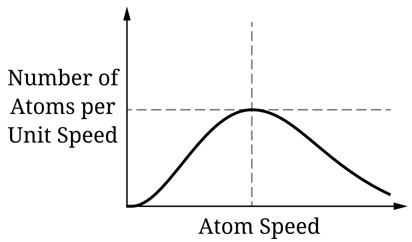

State X

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 $Q_S$.

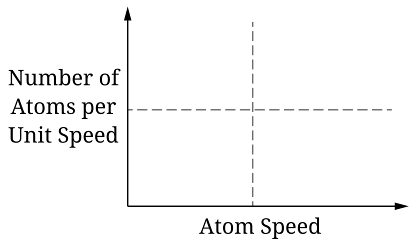
i. The graph in Figure 2 represents the number of atoms per unit speed as a function of atom speed for the gas when the gas is in State X. On Figure 3, **sketch** a curve that could represent the number of atoms per unit speed as a function of atom speed for the gas when the gas is in State Y.

**Figure 2**




State X

**Figure 3**




State Y

ii. **Derive** an expression for the change $\Delta T$ 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.

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

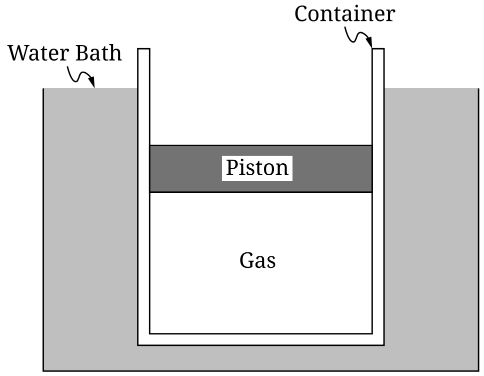
**Justify** your answer. Your justification may include expressions/equations but must include conceptual reasoning beyond algebraic solutions.





**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 $P_{atm}$.




Side View

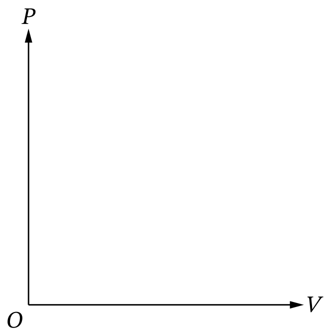
Note: Figure not drawn to scale.

**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 $t_0 \le t \le t_f$. **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 $T_0$.

_____ $T_{new} > T_0$

_____ $T_{new} < T_0$

_____ $T_{new} = T_0$

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





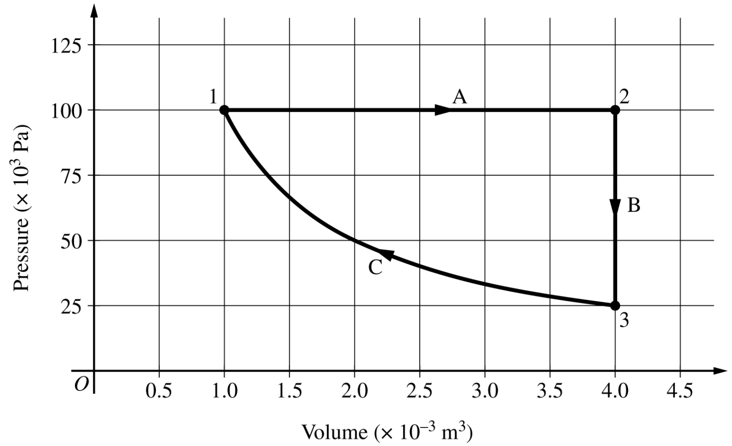
**PHYSICS 2**

**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 $\Delta U$ of the gas
- The net work $W$ done on the gas
- The net energy $Q$ transferred to the gas by heating

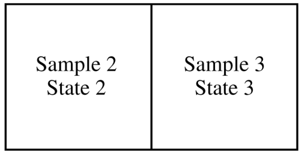
**GO ON TO THE NEXT PAGE.**

Continue your response to **QUESTION [illegible]** on this page.

(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.



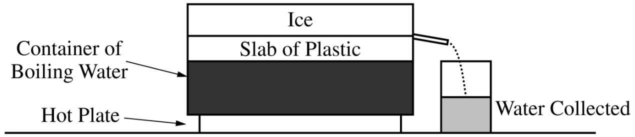

(c) Consider two samples of the gas, each with the same number of gas particles. Sample 2 is in state 2 shown in the graph, and sample 3 is in state 3 shown in the graph. The samples are put into thermal contact, as shown above. Indicate the direction, if any, of energy transfer between the samples. Support your answer using macroscopic thermodynamic principles.

**GO ON TO THE NEXT PAGE.**









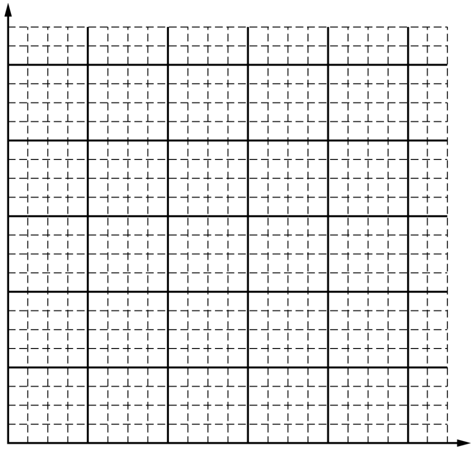

3. (12 points, suggested time 25 minutes)

A group of students use the apparatus shown above to determine the thermal conductivity of a certain type of plastic. A hot plate is used to keep water in a container boiling at a temperature of $100°C$. They place a slab of the plastic with area $0.025\ m^2$ and thickness 0.010 m above the container so that the bottom surface of the slab is at a temperature of $100°C$. They put a large block of ice with temperature $0°C$ on top of the plastic slab. Some of the ice melts, and the students measure the amount of water collected during a time $\Delta t$. The students correctly calculate the amount of energy $Q$ delivered to the ice and thus determine $Q/\Delta t$. They repeat this experiment several times, each time adding an identical slab to increase the total thickness $L$ of plastic. Their results are shown in the table below.

| | | | | | |
|---|---|---|---|---|---|
| Energy flow rate $Q/\Delta t$ (J/s) | 97 | 53 | 31 | 27 | 18 |
| Total thickness of plastic $L$ (m) | 0.010 | 0.020 | 0.030 | 0.040 | 0.050 |
| | | | | | |
| | | | | | |

(a) The students want to create a graph to yield a straight line whose slope could be used to calculate the thermal conductivity of the plastic.

i. Label the axes below to indicate a pair of quantities that could be graphed to yield a straight line. Include units for the quantities.



ii. On the grid on the previous page, create a linear graph using the values for the quantities indicated in part (a)(i). Be sure to do the following.
- Add to the data table the values of any quantities to be plotted that are not already given.
- Scale the axes.
- Plot the data from the table.
- Draw a line that best represents the data.

iii. Use the graph to calculate the thermal conductivity of the plastic.

(b) Indicate one potential problem with the setup that could lead to an experimental value for the thermal conductivity that is different from the actual value. Use physics principles to explain the effect this problem could have on the experimental value.

(c) The rectangle below represents a side view of the plastic slab. Draw a single arrow on the diagram representing the direction of the net flow of energy through the plastic.






(d) Describe what occurs in the plastic at the microscopic level that explains the energy flow you indicated in part (c).

(e) An extra plastic slab sits on a wood surface, with both the plastic slab and the wood surface at room temperature. A student touches each and finds that the plastic slab feels cooler than the wood surface. Explain what causes this observation.

AP PHYSICS 2 • EXERCISE SHEET

# 9.4 The First Law of Thermodynamics

Name: ____________ Class: ________ Date: __________ **Total: 11 marks**

**KEY WORDS** internal energy 内能 • first law 热力学第一定律 • pressure 压强 • heat 热量 • temperature 温度

## Objective

Build the skills to answer exam questions on **the first law of thermodynamics**.

**You must be able to:**

- state the **first law of thermodynamics** 热力学第一定律 as $\Delta U = Q + W$
- analyse the **internal energy** 内能 change of a gas from the heat added and work done
- interpret **work** as the area under a curve on a pressure-volume ($PV$) diagram
- describe **isothermal**, **isobaric**, **isochoric**, and **adiabatic** processes

## 1 Worked examples

Study these first. Each one shows the method for a question type used later.

### ■ The first law

$\Delta U = Q + W$, where $Q$ is the heat **added to** the gas and $W$ is the work done **on** the gas. It is just conservation of energy for a gas.

### ■ Work on a $PV$ diagram

The work is the **area** under the process curve. Compressing a gas (volume decreasing) does **positive** work on it.

### ■ Four processes

- **Isothermal** — constant temperature ($\Delta U = 0$).
- **Isobaric** — constant pressure.
- **Isochoric** — constant volume ($W = 0$).
- **Adiabatic** — no heat exchange ($Q = 0$).



## 2 Practice

**2.1** State the first law of thermodynamics. [1]

**2.2** A gas absorbs 500 J of heat while 200 J of work is done on it. Find the change in internal energy. [2]

**2.3** State which of $Q$ or $W$ is zero in an isochoric (constant-volume) process, and why. [2]

## 3 Exam-style questions

**3.1** In $\Delta U = Q + W$, the quantity $Q$ is the [1]

- **A** work done
- **B** heat added
- **C** internal energy
- **D** temperature

**3.2** An adiabatic process is one in which [1]

- **A** $Q = 0$
- **B** $W = 0$
- **C** $\Delta U = 0$
- **D** $\Delta T = 0$

**3.3** A gas is compressed: 300 J of work is done on it while it releases 100 J of heat.

(a) Find the change in internal energy. [3]

(b) State whether its temperature rises or falls. [1]



## Solutions

**2.1** the change in internal energy equals the heat added plus the work done on the gas, $\Delta U = Q + W$.

**2.2** $\Delta U = Q + W = 500 + 200 = 700$ J.

**2.3** $W = 0$ — no volume change means no work is done on or by the gas.

**3.1** **B**.

**3.2** **A**.

**3.3** (a) $\Delta U = Q + W = (-100) + (+300) = +200$ J. (b) it rises ($\Delta U > 0$).

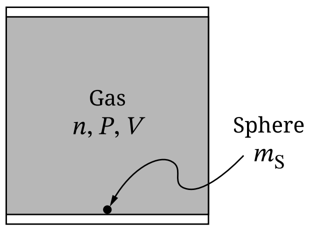
**Question 1: Version J**

### 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**



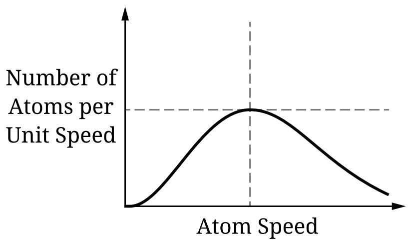

State X

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 $Q_S$.

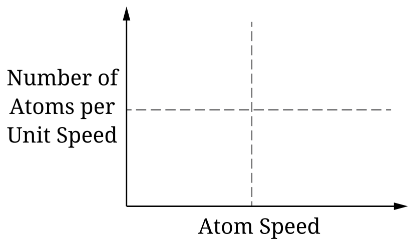
i. The graph in Figure 2 represents the number of atoms per unit speed as a function of atom speed for the gas when the gas is in State X. On Figure 3, **sketch** a curve that could represent the number of atoms per unit speed as a function of atom speed for the gas when the gas is in State Y.

**Figure 2**




State X

**Figure 3**




State Y





ii. **Derive** an expression for the change $\Delta T$ 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.

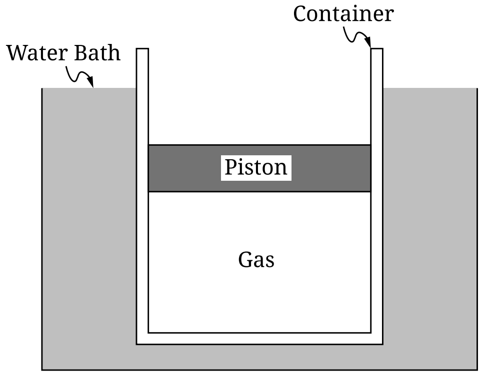
**Indicate** whether $|\Delta T_S|$ is greater than, less than, or equal to $|\Delta T_L|$. Include one of the following relationships in your response.

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

**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 $P_{atm}$.




Side View

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.

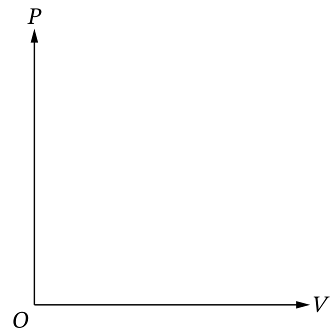




**B.** **Derive** an expression for the internal energy of the gas in terms of $M$, $A$, $V_0$, $P_{atm}$, and physical constants, as appropriate. Begin your derivation by writing a fundamental physics principle or an equation from the reference information.

**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 $T_0$.

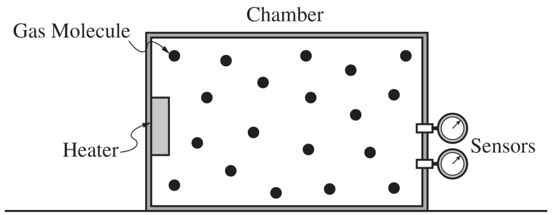
_____ $T_{new} > T_0$

_____ $T_{new} < T_0$

_____ $T_{new} = T_0$

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

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.

**GO ON TO THE NEXT PAGE.**

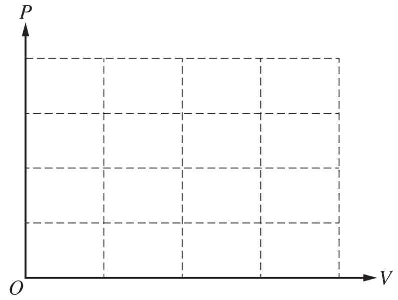




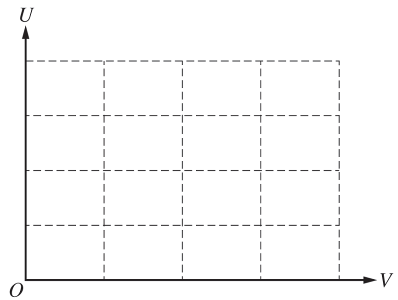
Continue your response to **QUESTION 2** on this page.

(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.



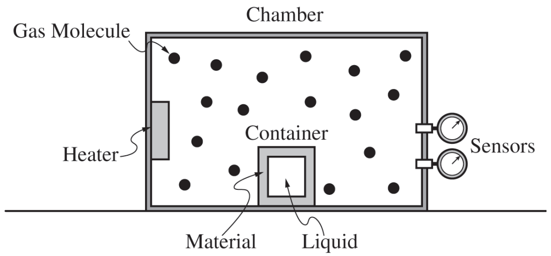

ii. On the following axes, **sketch** a curve or line to represent the expected relationship between the internal energy $U$ and the volume $V$ of the gas while the heater is on. **Draw** an arrow on the curve or line to represent the direction of the resulting thermal process.




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 $0.06\ \text{m}^2$ 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.

**GO ON TO THE NEXT PAGE.**



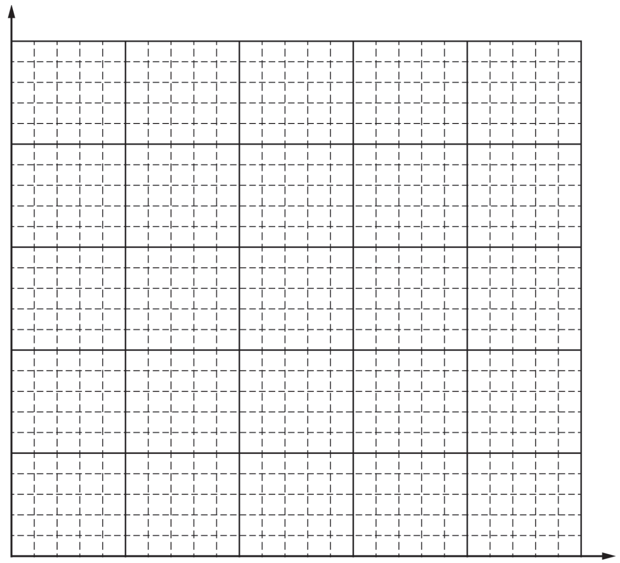


Continue your response to **QUESTION 2** on this page.

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 $k$.

**GO ON TO THE NEXT PAGE.**

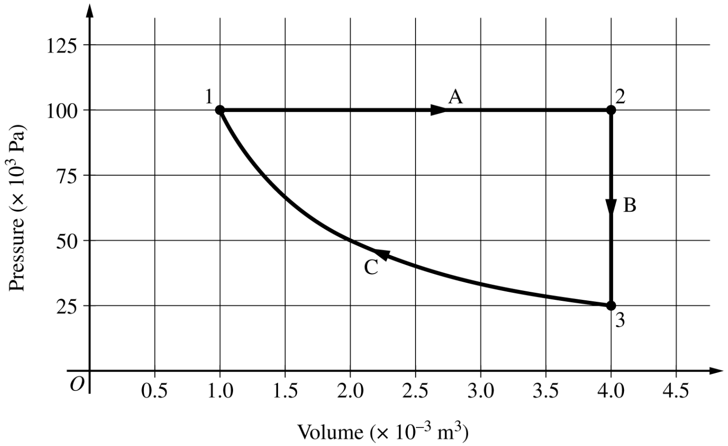
**PHYSICS 2**

**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 $\Delta U$ of the gas
- The net work $W$ done on the gas
- The net energy $Q$ transferred to the gas by heating

**GO ON TO THE NEXT PAGE.**



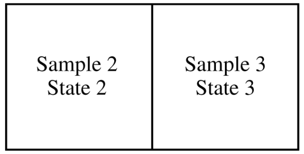


Continue your response to **QUESTION 1** on this page.

(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.



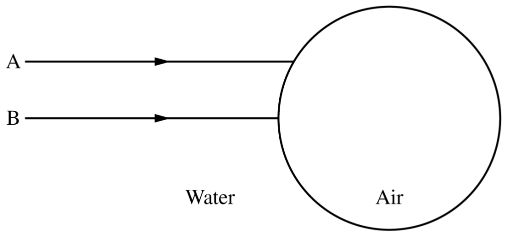

(c) Consider two samples of the gas, each with the same number of gas particles. Sample 2 is in state 2 shown in the graph, and sample 3 is in state 3 shown in the graph. The samples are put into thermal contact, as shown above. Indicate the direction, if any, of energy transfer between the samples. Support your answer using macroscopic thermodynamic principles.

**GO ON TO THE NEXT PAGE.**

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 $\rho_A$, and the water around it has density $\rho_W$. 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 $1000\ \mathrm{kg/m^3}$.

i. Determine the absolute pressure in the bubble at this location.

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.

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.

**STOP**

**END OF EXAM**





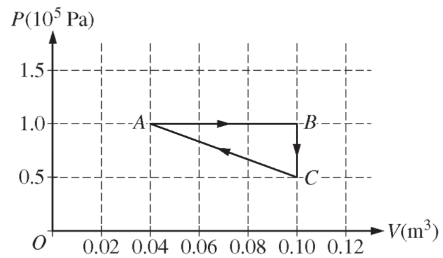
**PHYSICS 2**

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

(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.

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.

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 $A$.

AP PHYSICS 2 • EXERCISE SHEET

# 9.5 Specific Heat and Thermal Conductivity

Name: ____________ Class: _________ Date: ___________ **Total: 10 marks**

**KEY WORDS** thermal conductivity 热导率 • specific heat 比热容 • temperature 温度 • heat 热量

## Objective

Build the skills to answer exam questions on **specific heat and thermal conductivity**.

**You must be able to:**

- use $Q = mc\Delta T$ with **specific heat** 比热容 to find the heat needed for a temperature change
- explain how **thermal conductivity** 热导率 governs the rate of heat transfer
- compare how different materials store and conduct thermal energy

## 1 Worked examples

Study these first. Each one shows the method for a question type used later.

**Specific heat**

$Q = mc\Delta T$, where $c$ is in J kg$^{-1}$ K$^{-1}$. Water's large $c \approx 4200$ means it takes a lot of heat to warm up.

**Thermal conductivity**

A **high** conductivity (metals) transfers heat quickly; a **low** conductivity (wood, air, foam) makes a good insulator.

**Example**

To warm 2.0 kg of water by 10 K: $Q = 2.0 \times 4200 \times 10 = 8.4 \times 10^4$ J.

## 2 Practice

**2.1** Find the heat needed to raise 0.50 kg of water by 20 K (take $c = 4200$ J kg$^{-1}$ K$^{-1}$). [2]



**2.2** State what a high thermal conductivity means for the rate of heat transfer. [1]

**2.3** Two blocks receive the same heat. State which has the greater temperature rise — the one with the larger or smaller specific heat. [1]

## 3 Exam-style questions

**3.1** The equation $Q = mc\Delta T$ gives the [1]

- **A** power
- **B** heat transferred
- **C** temperature
- **D** conductivity

**3.2** A good thermal insulator has a [1]

- **A** high thermal conductivity
- **B** low thermal conductivity
- **C** high specific heat only
- **D** zero mass

**3.3** A 0.30 kg metal block ($c = 900$ J kg$^{-1}$ K$^{-1}$) is heated from 20 °C to 70 °C.

(a) Find the heat needed. [3]

(b) State the heat needed if the mass were doubled. [1]

## Solutions

**2.1** $Q = mc\Delta T = 0.50 \times 4200 \times 20 = 4.2 \times 10^4$ J.

**2.2** heat is transferred quickly (a fast rate).

**2.3** the one with the smaller specific heat.

**3.1** B.

**3.2** B.

**3.3** (a) $Q = 0.30 \times 900 \times 50 = 1.35 \times 10^4$ J. (b) $2.7 \times 10^4$ J (double).





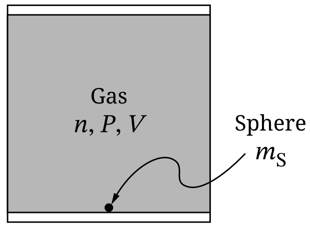
**Question 1: Version J**

### 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**



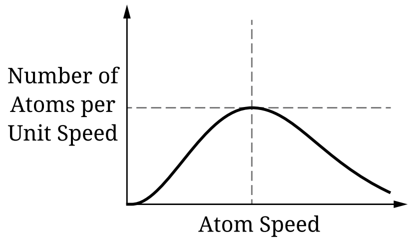

State X

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 $Q_S$.

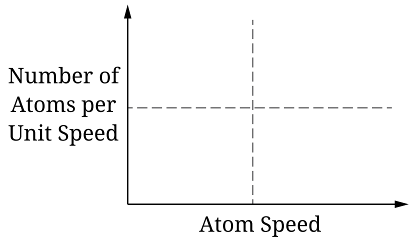
i. The graph in Figure 2 represents the number of atoms per unit speed as a function of atom speed for the gas when the gas is in State X. On Figure 3, **sketch** a curve that could represent the number of atoms per unit speed as a function of atom speed for the gas when the gas is in State Y.

**Figure 2**




State X

**Figure 3**




State Y

ii. **Derive** an expression for the change $\Delta T$ 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.

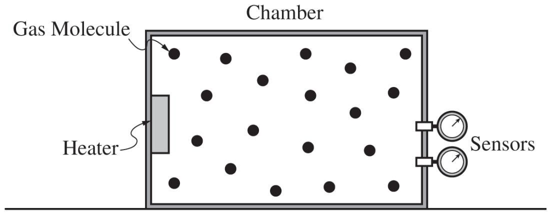
- $|\Delta T_S| > |\Delta T_L|$
- $|\Delta T_S| < |\Delta T_L|$
- $|\Delta T_S| = |\Delta T_L|$

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





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.

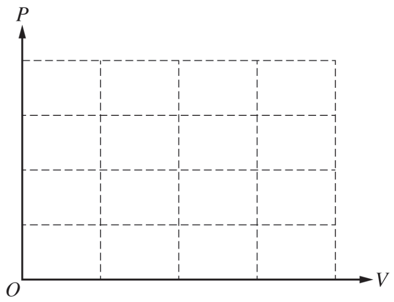
(a) **Describe** a procedure for collecting data that would allow the student to determine an experimental value for $N$. Provide enough detail so that a student could replicate the experiment, including any steps necessary to reduce experimental uncertainty.

**GO ON TO THE NEXT PAGE.**

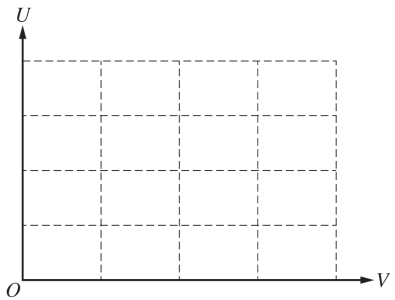
Continue your response to **QUESTION 2** on this page.

(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.

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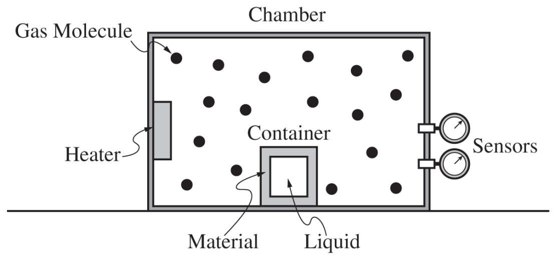
Continue your response to **QUESTION 2** on this page.




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 $0.06\ \text{m}^2$ 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.

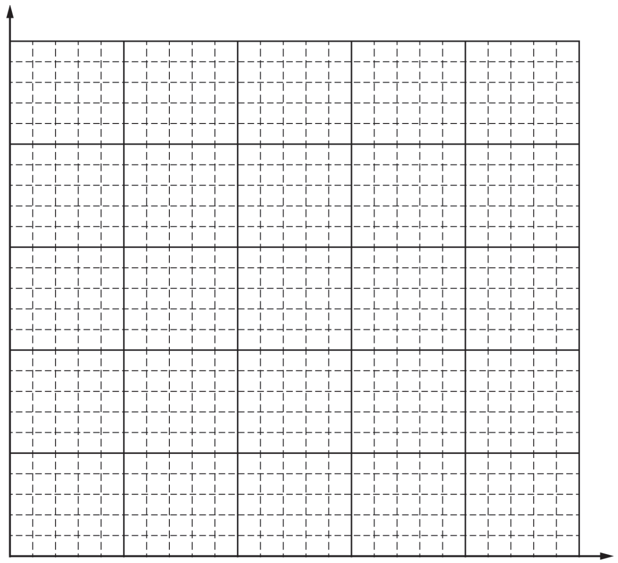
**GO ON TO THE NEXT PAGE.**

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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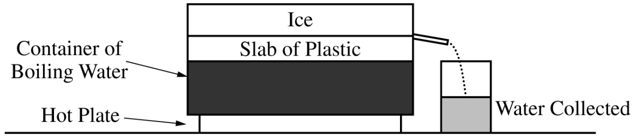


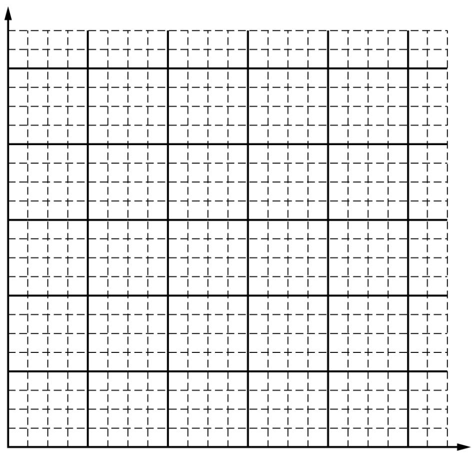

3. (12 points, suggested time 25 minutes)

A group of students use the apparatus shown above to determine the thermal conductivity of a certain type of plastic. A hot plate is used to keep water in a container boiling at a temperature of $100°C$. They place a slab of the plastic with area $0.025\ m^2$ and thickness 0.010 m above the container so that the bottom surface of the slab is at a temperature of $100°C$. They put a large block of ice with temperature $0°C$ on top of the plastic slab. Some of the ice melts, and the students measure the amount of water collected during a time $\Delta t$. The students correctly calculate the amount of energy $Q$ delivered to the ice and thus determine $Q/\Delta t$. They repeat this experiment several times, each time adding an identical slab to increase the total thickness $L$ of plastic. Their results are shown in the table below.

| | | | | | |
|---|---|---|---|---|---|
| Energy flow rate $Q/\Delta t$ (J/s) | 97 | 53 | 31 | 27 | 18 |
| Total thickness of plastic $L$ (m) | 0.010 | 0.020 | 0.030 | 0.040 | 0.050 |
| | | | | | |
| | | | | | |

(a) The students want to create a graph to yield a straight line whose slope could be used to calculate the thermal conductivity of the plastic.

i. Label the axes below to indicate a pair of quantities that could be graphed to yield a straight line. Include units for the quantities.



ii. On the grid on the previous page, create a linear graph using the values for the quantities indicated in part (a)(i). Be sure to do the following.

- Add to the data table the values of any quantities to be plotted that are not already given.
- Scale the axes.
- Plot the data from the table.
- Draw a line that best represents the data.

iii. Use the graph to calculate the thermal conductivity of the plastic.

(b) Indicate one potential problem with the setup that could lead to an experimental value for the thermal conductivity that is different from the actual value. Use physics principles to explain the effect this problem could have on the experimental value.

(c) The rectangle below represents a side view of the plastic slab. Draw a single arrow on the diagram representing the direction of the net flow of energy through the plastic.




Name: AP Physics 2: **2019**

(d) Describe what occurs in the plastic at the microscopic level that explains the energy flow you indicated in part (c).

(e) An extra plastic slab sits on a wood surface, with both the plastic slab and the wood surface at room temperature. A student touches each and finds that the plastic slab feels cooler than the wood surface. Explain what causes this observation.

AP PHYSICS 2 • EXERCISE SHEET

# 9.6 Entropy and the Second Law of Thermodynamics

Name: ____________ Class: ________ Date: __________ **Total: 9 marks**

**KEY WORDS** entropy 熵 • second law 热力学第二定律 • heat 热量 • thermodynamics 热力学 • pressure 压强

## Objective

Build the skills to answer exam questions on **entropy and the second law of thermodynamics**.

**You must be able to:**

- describe **entropy** 熵 as a measure of disorder (the number of microstates)
- state the **second law of thermodynamics** 热力学第二定律: total entropy tends to increase
- explain why thermal energy flows spontaneously from hot to cold

## 1 Worked examples

Study these first. Each one shows the method for a question type used later.

### ■ Entropy

Entropy measures **disorder** — the number of ways (microstates) the particles can be arranged. More disorder means higher entropy.

### ■ The second law

The **total** entropy of an isolated system tends to **increase** over time.

### ■ Direction of heat flow

Heat flows from hot to cold on its own because that **raises** the total entropy. The reverse (cold to hot) needs external work — that is what a refrigerator does.

## 2 Practice

**2.1** State what entropy measures. [1]



**2.2** State the second law of thermodynamics. [1]

**2.3** Explain why heat does not flow from a cold object to a hot one on its own. [2]

## 3 Exam-style questions

**3.1** Entropy is a measure of a system's [1]

- **A** temperature
- **B** energy
- **C** disorder
- **D** pressure

**3.2** In an isolated system, the total entropy tends to [1]

- **A** decrease
- **B** increase
- **C** stay exactly constant
- **D** fall to zero

**3.3** A block of ice melts in a warm room.

(a) State whether the entropy of the water increases or decreases. [1]

(b) Explain your answer in terms of disorder. [2]

## Solutions

**2.1** the disorder of a system (the number of microstates).

**2.2** the total entropy of an isolated system tends to increase.

**2.3** that would **decrease** the total entropy, which the second law forbids without external work being done.

**3.1** **C**.

**3.2** **B**.

**3.3** (a) increases. (b) liquid water is more disordered than solid ice — its particles move more freely, so there are more microstates and higher entropy.