Unit 17 *Homework Problems*

Learning Goals:

F.17 State the first law of thermodynamics and the ideal gas law and apply them qualitatively to a physical process.

A.17 Quantitatively apply the first law of thermodynamics and the definitions of latent and specific heat to a system that may include multiple phase changes, mixtures of substances of different temperatures, thermal energy transferred to a system, and work done by a system.

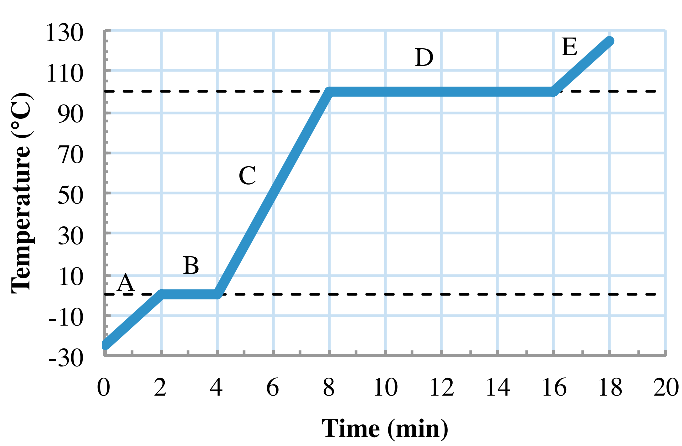
17-1) Joseph Black (1728-1799) was a Scottish physician who was a leading researcher in the middle of the eighteenth century. He refined and sharpened the concepts of temperature and heat and was probably the first to recognize the significance of the thermal interactions taking place during the processes of melting and freezing. He wrote:

> "Melting has been universally considered as produced by the addition of a very small quantity of heat to a solid body, once it has been warmed up to its melting point … It was believed that this small addition of heat during melting was needed to produce a small rise in temperature as indicated by a thermometer."
>
> The opinion I formed is as follows. When ice or any other solid substance is melted … a large quantity of heat enters it … without making it apparently warmer … I affirm that this large addition of heat [without change in temperature] is the principal and most immediate cause of the liquefaction induced …"
>
> "If the common opinion had been well founded—if the complete change of ice and snow into water required only the addition of a very small quantity of heat—the mass … ought to be all melted within a few minutes or seconds by the heat incessantly communicated from the surrounding air … the consequences of it would be dreadful … This sudden liquefaction does not actually happen. The masses of ice and snow require a long time to melt."

(a) Discuss Black's argument by translating it into your own words and connecting it to your own experiences.

(b) From a modern perspective what is wrong with Black's choice of words when referring a "… quantity of heat entering a solid body …" . What misimpression does this phraseology give about the nature of heat?

17-2) Suppose an experiment was conducted in which a solid block of subzero ice was placed in a thermally insulated container and warmed at a constant rate from a temperature of -25^{o}C to a temperature greater than 100^{o}C. You should interpret the following graph of ideal experimental data. (A graph of real data would show scatter due to experimental uncertainties and deviations from constant and uniform warming.)



(a) Explain what is happening to the ice during each of the first four segments, A through D, of the graph. For example, a good answer for part (a) is: in segment A the temperature of the solid block of ice is increasing linearly with time from -25°C to 0°C during a two minute span of time. No ice has melted.

(b) Now, look carefully at segment E. What do you think could be happening to the H_2O during that time?

(c) What would happen after the 18-minute period if the container were opened to the atmosphere?

17-3) Now let's put the concepts of latent heat and specific heat together to solve a problem. What will be the final result (final temperature and amount (mass) of ice, water, and/or steam) when equal amounts (mass) of ice at 0°C and steam at 100°C are mixed together in a closed thermally insulated container.

17-4) A disposable medical syringe with the needle removed and the tip plugged up makes a good piston. Consider a syringe that has a diameter of 1.8 cm.

(a) If you compress the air trapped in the piston by pushing on the syringe's plunger with an average force of 2.0 N for a distance of 0.55 cm, how much mechanical work do you do on the gas?

(b) What is the pressure exerted on the syringe?

(c) How much does the volume of the trapped air change as a result of the distance the plunger moves?

(d) Use the pressure and volume change to calculate the work.

(e) Are the answers to part (a) and (d) the same? Did you expect them to be the same? Why or why not?

17-5) A system does 31 J of work while it has 67 J of thermal energy transferred to it.

(a) What is the change in its internal energy?

(b) If the initial internal energy is 553 J what is its final internal energy?

17-6) *A simplified microscopic model of thermal energy transfer with no work:* Consider six atoms consisting of little tiny spheres that obey the laws of Newtonian mechanics as they ping around in a container of a fixed size. Let's place a thin thermal conductor on the bottom wall of the container and put a candle under it so thermal energy can be transferred to the gas. According to the First Law $\Delta E^{\text{int}} = Q - W$ but if $W = 0$ J then $\Delta E^{\text{int}} = Q$ for this special situation. Examine the QuickTime movie entitled "Qtransfer.mov". There is no need to do quantitative calculations.

(a) Explain what happens to the motion of the atoms as more and more thermal energy is transferred to them.

(b) In terms of the definition of work, why can we say no work is being done on the surroundings by the gas?

(c) What happens to the internal energy of the gas as time goes on and more and more thermal energy is transferred to the gas molecules? Could the First Law of Thermodynamics hold in this situation? Explain!

17-7) *A simplified microscopic model of work with no thermal energy transfer:* In this model we change our container so it is perfectly insulated. What we mean by "perfectly insulated" is that no thermal energy can be transferred to the atoms through the container walls. However, our container has a piston in it that can move if it experiences forces. In order for the piston to remain more or less steady the average upward force exerted on it by the six atoms must be equal and opposite to the average downward force on it due to the gravitational force on the piston and the pressure of the air molecules outside the container. Examine the QuickTime movie entitled "ZeroQ.mov". There is no need to do quantitative calculations.

(a) Explain what happens to the motion of the atoms as they make more and more collisions with the piston causing it to rise?

(b) In terms of the definition of work, can we say work is being done on the surroundings (in this case on the piston) by the gas? Why?

(c) What happens to the internal energy of the gas as time goes on and more and more work is done by the gas on its surroundings? Does the First Law of Thermodynamics seem to hold in this situation? Explain!

17-8) *Modeling Boyle's Law Data:* Data for a Boyle's Law experiment on a volume of air held at a constant temperature in a 10 cc syringe were obtained. The experimental setup is exactly like that shown in Figure 17.7 in the Activity Guide. When the plunger was set to the 5.00 cc mark on the syringe the air was under a pressure of 1.00 atm. The data are shown in the diagram below.

Data A

Pressure Atm	V-syringe cc	Volume cc
0.54	9.00	10.79
0.69	7.00	8.79
0.89	5.00	6.79
1.29	3.00	4.79
2.13	1.00	2.79

Note that the data collection file shows two different volumes, *V-syringe* which is the volume of the syringe at each plunger setting and *V* which is the volume of the syringe at each plunger setting plus the volume of the air in the hose that connects the syringe to the computer-based pressure sensor.

(a) Examine the data. What is the volume of the small length of hose leading to the pressure sensor?

(b) State Boyle's Law in words.

(c) Based on the results obtained by classmates who performed the Boyle's Law experiment, which set of data do you predict will fit Boyle's Law best, *P* vs. *V*-syringe, or *P* vs. *V*. Explain the reason for your prediction. **Note**: Full credit will be given for either prediction as long as the reason you present seems plausible.

(d) Transfer the data to an Excel spreadsheet and test your prediction by creating a Boyle's Law model for how pressure varies with volume for each of the two sets of data. Hand in a printout of each of the models. Include data, parameter(s), and overlay graph with your data and model curve in it.

17-9) If you accept the idea that matter is made up of discrete atoms and molecules, gases can be visualized as consisting of:

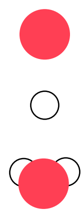
(1) atoms or molecules in continual motion, colliding with each other and the walls of their container, and

(2) very far apart on the average relative to their diameters.

(a) In terms of your observations of gases and of the work you did in section 17.11 what are the justifications for this mental picture or model?

(b) Why does the identical model not work well for liquids and solids? What evidence do you have that the distances between molecules are not far apart relative to their diameters?

17-10) No one really knows what atoms and molecules look like, but water is considered to be a liquid form of H_2O molecules that stick together. H_2O molecules are thought to consist of two hydrogen atoms bonded to a larger oxygen atom. One model that is often used to represent this molecule is shown in the diagram below.


represents an oxygen atom

represents a hydrogen atom

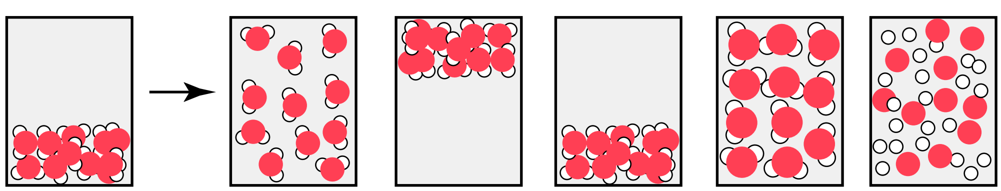
represents an H_2O molecule in which two H atoms are bonded to an O atom

Suppose a tiny container with some water in the bottom of it and air above it is closed so no molecules or atoms can pass in or out of it. In the diagram below the water molecules (but not the air molecules) are depicted on the left. (They should actually be pictured as much smaller relative to the container, but then you couldn't see them.) What do you think will happen if the water is warmed above the boiling point of water?

(a) What do you expect to happen to the pressure in the container?

(b) Which of the diagrams below are compatible with the assumptions of the kinetic theory of gases? *i.e.*, according to kinetic theory what will happen to the average kinetic energy of the molecules as the temperature and pressure goes up? (Hint: it is possible that more than one of the diagrams is compatible.)

A B C D E



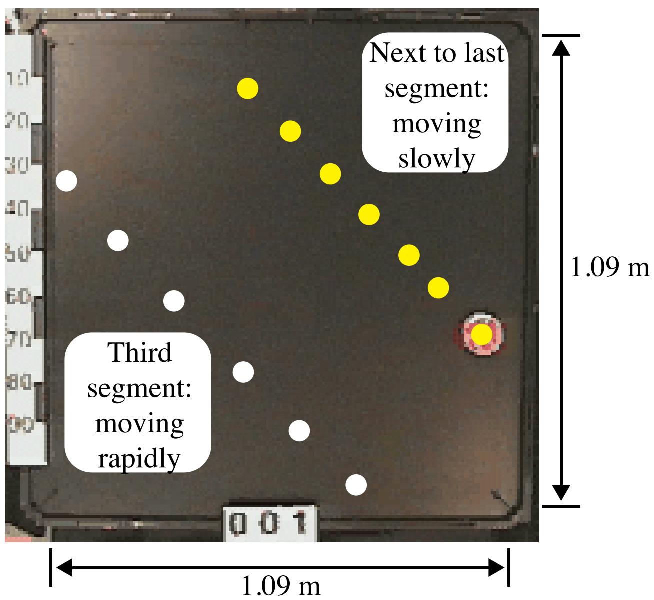
original liquid phase — A: molecules have spread out — B: molecules have moved up — C: no change — D: molecules have expanded — E: molecules have come apart and the atoms have spread out

(c) Which diagram do you think best represents the actual situation? Why?

17-11) *Kinetic Theory and an Ideal Gas:* Argon atoms do not bond chemically with other atoms of any kind. Thus a collection of Argon atoms contained in a box is a monatomic gas (i.e. each gas particle is made up of only one atom.) If we assume that argon atoms have small rotational kinetic energies compared to their translational kinetic energies, then a collection of Argon atoms ought to behave like an ideal gas.

If we made a video move of an Argon atom bouncing around in a box (that just happens to look like an air puck), you could analyze it and use your understanding of kinetic theory and Newtonian mechanics to tell us something about a gas consisting of 1 mole of these Argon atoms. The digital video movie you are to analyze to answer the questions in this problem is entitled *PRU001: Puck Collisions with Air Table Walls*. Suppose that the mass of the Argon atom is $6.63\times10^{-23}\text{kg}$ (I know, I know, this is really the mass of an Argon atom in grams, but for this problem assume it is the mass in kilograms). *Ignore the data on the title frame of the movie indicating a mass of* 49.7g *for the airpuck.*

Before starting this problem, open the Logger Pro software and the movie. Play the movie and watch the molecule bouncing around in the box. Then "analyze" the movie by selecting the location of the center of the atom for Logger Pro frames 5–10 ($t = 0.833$ s to $t = 1.666$ s) and Logger Pro frames 49–55 ($t = 8.166$ s to $t = 9.166$ s) and using the leave trails feature, as shown in the diagram below.



(a) If you move forward from frame one you should be able to determine the edges of the box. Determine the volume of the box assuming that it is a three dimensional cubical box. (**Hint:** the diagram above will help you a lot – what a nice person your instructor is.)

(b) Note that this particular atom happens to be moving entirely in the *x-y* plane so that $v_z = 0\,\text{m/s}$ in all segments of its path. What is the translational kinetic energy of the atom in the third segment of its path (Logger Pro frames 5–10)? In the next to last segment of its path (Logger Pro frames 49–55)? **Hint**: Figure out the speed *v* of the atom in each of these segments.

(c) What is the internal energy of this one atom gas in the third segment? In the next to the last segment?

(d) What is the absolute temperature *T* of this gas in the third segment? In the next to the last segment?

(e) Suppose that instead of containing only one Argon atom, the box contains one mole of Argon gas. How many molecules would be in the box then?

(f) Suppose the average translational kinetic energy of each atom in the gas is the same as the energy you calculated for a single atom. What is the internal energy of the mole of gas at time $t = 1.250\ \mathrm{s}$? How about for $t = 8.667\ \mathrm{s}$?

(g) Assuming that Argon behaves like an ideal gas, what would the temperature and pressure of the gas be at time $t = 1.250\ \mathrm{s}$? How about for $t = 8.667\ \mathrm{s}$?

(h) How much energy is transferred to the surroundings by the heat process between $t = 1.250\ \mathrm{s}$ and $t = 8.667\ \mathrm{s}$?

(i) What is the average cooling rate, $\frac{Q}{\Delta t}$, of the gas over the time period between $t = 1.250\ \mathrm{s}$ to $t = 8.667\ \mathrm{s}$?