Physics 2010 (Schroeder) Name ______________________________
spring 2004

Problem Set 15

(due Thursday, April 29)

1. A liter of helium, at room temperature and atmospheric pressure, is in a cylinder with a movable piston. Because a helium molecule contains only a single atom, it has no other (relevant) forms of energy besides translational kinetic energy.

   (a) What is the total kinetic energy of the helium?

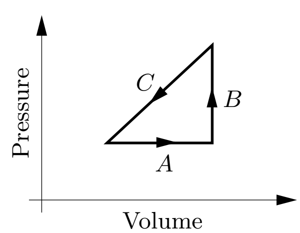
   (b) Suppose now that the helium is somehow made to expand, at *constant pressure*, while the piston is let out. The final volume is 3 liters. How much work does the helium perform during this process? Sketch a PV diagram for this process.

   (c) What is the total kinetic energy of the helium after it has expanded?

   (d) Use the results of parts (b) and (c) to calculate the amount of heat that must have been added to the helium during this process.

2. By applying a pressure of 200 atm, you can compress water to 99% of its usual volume. Sketch this process (not necessarily to scale) on a PV diagram, and estimate the work required to compress a liter of water by this amount. Does the result surprise you?

3. An ideal gas is made to undergo the cyclic process shown in the figure below. For each of the steps A, B, and C, determine whether each of the following quantities is positive, negative, or zero: (a) the work done by the gas; (b) the change in the energy content of the gas; (c) the heat added to the gas. Then determine the sign of each of these three quantities for the *whole* cycle. What does this process accomplish?



4. Imagine that I have a quantity of gas in a cylinder with a movable piston. My job is to compress the gas to half its initial volume. Being lazy, I wish to perform as little work as possible. Should I compress the gas quickly, so there is no time for heat to escape from the gas, or slowly, with the cylinder in thermal contact with a tank of water so the gas is always at the same temperature as the water? Explain your answer completely, with reference to a PV diagram showing each alternative process. Which of the two processes is "adiabatic" and which is "isothermal"?

5. A certain heat engine performs 10 kJ of work and dissipates 8.5 kJ of waste heat during a cyclical process. (a) What is the heat input to this engine during this time? (b) What is the efficiency of the engine?

6. A certain air conditioner removes 5000 Btu's of heat from a building in one hour, while consuming electrical energy at a rate of 500 watts. (a) How much electrical energy does it consume in one hour? (Please express your answer in kilowatt-hours, joules, in Btu's. Look

up the conversion factors in your textbook.) (b) How much heat does this air conditioner dump into the outdoors during this hour? (c) What is the COP of this air conditioner?

7. Explain why you cannot cool off your kitchen (at least over the long term) by leaving the refrigerator door open.

8. An ice cube (mass 30 g) at 0°C is left sitting on the kitchen table, where it gradually melts. The temperature of the kitchen is 25°C.

   (a) How much heat is absorbed by the ice cube as it melts into water at 0°C?

   (b) Calculate the change in the entropy of the ice cube during this process.

   (c) Calculate the change in the entropy of the kitchen during this process.

   (d) Discuss how your answers to parts (b) and (c) compare, and how this relates to the Second Law of Thermodynamics.

9. At a large coal-fired power plant, the steam absorbs heat at a rate of 1 GW (10^9 watts). The temperature of the furnace is 500°C.

   (a) What is the *minimum* amount of entropy gained by the steam due to its absorbing heat during one second?

   (b) Explain why your answer to part (a) is a *minimum*.

   (c) In order to get rid of this entropy, the system expels waste heat into a river at 20°C. What is the *minimum* amount of waste heat that must be expelled in each second?

   (d) Under the most ideal conditions, how much work can this engine perform in one second? What is its efficiency?

   (e) Discuss how the maximum efficiency of this engine would differ, if the temperatures of the steam and the river were different.

10. Name three of your favorite (or least favorite) irreversible processes. For each, explain in what way the number of arrangements of something is greater afterwards than before, and hence how you can tell that the total entropy of the universe has increased. For example, burning gasoline in an automobile converts a smaller number of large molecules into a larger number of small molecules, which can be arranged in more different ways. It also converts chemical energy to thermal energy, which can be arranged in many ways among the molecules in the exhaust gases. Because entropy is related to the number of possible molecular arrangements, both of these effects cause the entropy of the gaseous mixture to increase.

Study Guide for Quiz 15

The law of conservation of energy tells us that during any process, the energy content (U) of a system changes by

$$\Delta U = Q - W,$$

where Q is the net heat that enters the system and W is the net work that it performs. (If heat exits, Q is negative; if work is performed *on* the system, W is negative.) This equation is usually called the **first law of thermodynamics**.

The work performed by an expanding fluid is

$$W = P\,\Delta V,$$

where P is the pressure and ΔV is the change in volume. If the volume decreases, ΔV and W are negative. If the pressure changes by a significant amount during the process, you should plot a graph of P vs. V and calculate W as the area under the graph.

An **isothermal** process is one in which the temperature of the system doesn't change; an **adiabatic** process is one in which no heat enters or leaves the system. These are not the same thing! For instance, the compression of air inside a diesel engine is approximately adiabatic, but definitely not isothermal.

A **heat engine** is a machine that converts heat into work. Every heat engine has a "working substance" (such as air or steam) that undergoes a cyclic process: absorbing heat, performing work, and expelling waste heat before the cycle repeats. The **efficiency** of an engine is defined as the ratio of work performed to heat absorbed (benefit/cost), not counting any waste heat expelled.

A **refrigerator** is a machine that extracts heat from a cool place and expels it into a warmer place. In order for this to occur, some work must be performed on the refrigerator's working substance ("freon" or a similar fluid in most refrigerators and air conditioners). The **coefficient of performance** of a refrigerator is the ratio of heat removed from the cooler place to work input (benefit/cost).

In order to explain why heat flows from hot objects to cold objects, and why engines and refrigerators cannot be as efficient as one might hope, we need a new Big Idea: In addition to energy, every object also has a property called **entropy**. The most important property of entropy is that it flows along with heat. More precisely, whenever heat Q flows into an object, its entropy (S) increases by an amount equal to Q/T, where T is its temperature in kelvins:

$$\Delta S = \frac{Q}{T}.$$

If heat flows *out* of an object, then Q is negative and its entropy decreases. An object's entropy can also increase when no heat is flowing into it, but there is no other way to decrease an object's entropy.

The **second law of thermodynamics** says that entropy tends to increase. More precisely, heat flows in whatever direction tends to increase the total entropy of the system; and more generally, spontaneous processes are those that tend to increase the total entropy. It is impossible to destroy entropy (though it can be moved around via heat flow).

Although entropy was originally defined as "the thing that increases by Q/T when heat Q flows into an object at temperature T," we now know that entropy is really a measure of the number of possible microscopic arrangements of the atoms and energy in a system. The more arrangements, the greater the entropy. (The precise formula, which you need not memorize, is $S = k_B \ln \Omega$, where Ω is the number of possible microscopic states of the system.)