

In lecture 22, we learned that INTERNAL ENERGY (U) of a system of particles is all of the energy in the system *except* the macroscopic KE and the PE_G and PE_S due to interactions with external objects. So we at least know what the internal energy is NOT. In required reading 22, you also read about TEMPERATURE; the reading described how temperature is measured but did not say what temperature is. In other words, what does it mean when we say that one object is hotter than a second object? In lecture 23, we will begin by trying to understand what the internal energy IS, instead of what it is not. Then, we will apply our understanding of impulse and momentum to the problem of a system of particles consisting of the gas molecules in an enclosed box; we will learn that both the temperature in the box and the pressure in the box are directly related to the translational kinetic energy of the gas molecules.

So what is INTERNAL ENERGY? Basically, U is all of the *microscopic* sources of energy taken together. For example, nuclear energy is stored in the atomic nuclei of each of the atoms, so one part of U is $PE_{nuclear}$, another kind of potential energy. Another part of U is a chemical potential energy, $PE_{chemical}$, which I need to describe carefully. There is an attractive electromagnetic interaction between any two atoms; placed near each other, with zero velocities, the two atoms will fall together much like a ball falls to the surface of the Earth. So when the atoms are far apart, as in a gas, they have a maximum chemical potential energy; when they are close together, as in a solid, their chemical potential energy is a minimum. When the two atoms are swirling around each other in a liquid, their chemical potential energy is bigger than in the solid case but smaller than in the gas. There are still more types of energy -- if we want to include everything, then we also have to consider the kinetic energies of the electrons orbiting about the atomic nuclei and of the protons and neutrons moving about within the atomic

nuclei, etc. (So you can see why it is easier to say what U is not, than it is to say what U is!) But the part of U with which we will be most concerned is the THERMAL ENERGY; this is the part of U that increases with increasing temperature. This thermal energy is the sum of two parts, one is kinetic and one is potential. To understand the kinetic part, first you must eliminate all translations of the system (v_{CM} must be zero) and all rotations of the system, about any axis; the remaining kinetic energy of all the moving atoms and/or molecules is the kinetic part of the thermal energy. For a gas, this kinetic part is 100% of the thermal energy, but for liquids and solids the atoms (or molecules) are connected by chemical bonds, either temporary (for liquids) or permanent (for solids -- see the picture in our text on page 282). As the atoms (or molecules) move around, these bonds are alternately compressed and stretched; potential energy is stored in these temporarily compressed and stretched bonds -- it is this potential energy that makes up the rest of thermal energy.

For most cases, the only part of U with which we need be concerned is the thermal energy; in most cases when we say "internal energy" we are thinking only of the thermal energy, because in most cases any change in internal energy is a change in thermal energy. The most important cases for which another part of the internal energy is important are the cases of PHASE CHANGES. Please refer to the graph at the bottom of page 353 in your text. The horizontal axis is for the total heat inflow, in units of J (not shown on the graph -- in fact, the horizontal axis of this graph is not to scale). The heat is flowing into a block of water ice. The vertical axis gives the temperature of the water, in $^{\circ}\text{C}$, as it first melts and then boils. The ice starts at a temperature of -30°C , and the inflow of heat increases the temperature of the ice to 0°C ; during this part of the experiment the heat inflow directly increases the thermal energy

of the ice. But once the ice reaches $0\text{ }^{\circ}\text{C}$, the additional heat inflow no longer increases the temperature; instead, all of that incoming energy goes into breaking the permanent bonds between the H_2O molecules in the ice. In other words, the $PE_{chemical}$ of the H_2O molecules is increased as the H_2O molecules get farther apart. This PHASE CHANGE is from the solid phase to the liquid phase and is called "melting". Once the water is in the liquid form, the heat inflow once again increases only the thermal energy of the water; this continues until the water reaches $100\text{ }^{\circ}\text{C}$. At that point, the incoming energy goes into breaking the temporary bonds between the H_2O molecules in the liquid water; the $PE_{chemical}$ of the H_2O molecules is again increased as the H_2O molecules get very far apart (essentially infinitely far apart for something so small). This PHASE CHANGE from the liquid phase to the gas phase is called "evaporation" (or "boiling" if it takes place at the boiling point). Once all the water has been vaporized, the heat inflow again all goes to increase the thermal energy of the water vapor. Therefore, in cases of phase changes, the $PE_{chemical}$ is an important part of U ; in any other case that we deal with, the only important part of U is the thermal energy. Please learn the terms used to describe phase changes as presented in Figure 12.27 of our text on page 353.

We handle problems involving phase changes with the idea of LATENT HEAT (or hidden heat, referring to the fact that heat inflow causing a phase change doesn't change the temperature). Learn the following two definitions:

DEFs The LATENT HEAT OF FUSION (L_f) of a material is the amount of energy per unit mass that must be added (or removed) from the material to make it melt (or fuse). The LATENT HEAT OF VAPORIZATION (L_v) of a material is the amount of energy per unit mass that must be added (or removed) from the material to make it evaporate (or condense). The units of latent heat are J/kg. Latent heats are positive-only scalars.

Latent heats are different for different materials because different atoms have chemical attractions of different strengths. You will find a table of latent heats in our text on page 354. L_v 's are bigger than L_f 's because, in melting, the atoms (or molecules) only get a little farther apart, while in evaporating, the atoms (or molecules) go from being relatively close together in the liquid to infinitely far apart in the gas. In this table, the L_v 's are given at the boiling point; L_v depends sensitively on temperature because of thermal expansion in the liquid -- when the atoms (or molecules) of the liquid are farther apart the temporary chemical bonds holding them together are weaker and require less energy to break. For example, at 100 °C, L_v for H₂O is 22.6×10^5 J/kg; while at body temperature, about 37 °C, L_v for H₂O is a larger value of 24.2×10^5 J/kg.

Problems with latent heat are straightforward applications of conservation of energy, similar to the examples that we did in lecture 22 with specific heat. Test your abilities on such problems with questions 1-4 (specific heat problems) and 6-8 (latent heat and/or specific heat) from Self-Assessment Test 12.2 available at the C&J 6th Ed. link on our course home page.

We are going to skip Chapter 13. The most important topic in this Chapter is Conduction in Section 13.2. Architecture and construction students may be interested in this section because of its direct relation to building insulation. Also, conduction is frequently a topic on the MCATs. An understanding of this section, particularly of Equation 13.1, will also help you in 112, because heat conduction through a slab of material is exactly analagous to conduction of current through a wire. Rearranging Eq. 13.1 on page 376 to yield $\Delta T = (Q/t)(L/kA)$ makes it directly analagous to $V = IR$ (Eq. 20.2 on page 581) with electrical resistance $R = \rho L/A$ (Eq. 20.3 on the same page). Thermal conductivity is k and electrical conductivity is $(1/\rho)$.

In 111, you are not responsible for thermal conduction (or anything else in Chapter 13) in any way.

We are going to cover Chapter 14 in lecture, but there are several DEFs that you need to learn to get us started.

DEFs One MOLE (mol) of a substance contains as many elementary particles (either atoms or molecules) as there are in 12 grams of carbon-12 (carbon-12 has 6 protons and 6 neutrons). The number of particles per mole is determined experimentally and is known as AVOGADRO'S NUMBER (N_A).

To four significant figures, $N_A = 6.022 \times 10^{23} \text{ mol}^{-1}$. This number will appear on your equation sheet.

DEFs The ATOMIC MASS UNIT (u) is 1/12 of the mass of carbon-12.

In kilograms, $1.0 \text{ u} = 1.6605 \times 10^{-27} \text{ kg}$. This number will also appear on your equation sheet. Combining these DEFs gives us a very useful result for u:

$$\begin{aligned} N_A \text{ atoms} \equiv 12.0 \text{ g of carbon-12} &\Rightarrow 1.0 \text{ u} \equiv \frac{1}{12} (\text{the mass of carbon-12}) \\ &= \frac{1}{12} \left(\frac{12.0 \text{ g}}{N_A \text{ atoms}} \right) \\ &= \frac{1.0 \text{ g}}{N_A \text{ atoms}} \\ &\Rightarrow 1.0 \text{ u} = 1.0 \text{ g/mol} \end{aligned}$$

In the periodic table (see the inside of the back cover of our text) the masses of the elements are given in atomic mass units. These numbers can thus be taken as the number of g/mol or else multiplied by $1.6605 \times 10^{-27} \text{ kg/u}$ to convert to kg.

Everyone should be familiar with the Ideal Gas Law from high school chemistry. I mentioned it during lecture 22 in connection with the constant-volume gas thermometer and the measurement of absolute zero. The Ideal Gas Law is a statement of the experimental fact that, for an ideal gas in an enclosed

container, the product of pressure (P) and volume (V) is always found to be proportional to the "amount of gas" times the Kelvin temperature (T_K) of the gas, i.e. $PV \propto (\text{amount of gas})T_K$. To express the "amount of gas", we can either choose to use the number of molecules N or the number of moles n . The proportionality constant depends on our choice. Here are the DEFs:

DEFs The UNIVERSAL GAS CONSTANT (R) is the proportionality constant for the ideal gas law when the amount of gas is expressed in moles, i.e. $PV = R(nT_K)$. The measured value of R is $8.31 \text{ J}/(\text{mol}\cdot\text{K})$. The BOLTZMANN CONSTANT (k_B) is the proportionality constant for the ideal gas law when the amount of gas is expressed as the number of molecules, i.e. $PV = k_B(NT_K)$.

The BOLTZMANN CONSTANT k_B can thus be calculated from the measured value of R . Since $nR = Nk_B$, therefore

$$\begin{aligned} k_B &= \frac{nR}{N} = \frac{R}{(N/n)} = \frac{R}{N_A} \\ &= \left(\frac{8.31 \text{ J}/(\text{mol}\cdot\text{K})}{6.022 \times 10^{23} \text{ mol}^{-1}} \right) \\ &= 1.38 \times 10^{-23} \text{ J/K} \end{aligned}$$

Both R and k_B will appear on your equation sheet.

I will give a demonstration or two of the ideal gas law during lecture. Then we will use the ideal gas law, in combination with our understanding of impulse and momentum, to work out the pressure and temperature of an ideal gas in an enclosed container in terms of the average speed of the molecules in the gas. We will do this by considering a collision between an "average" molecule and a wall of the container!