Heat and Calorimetry

In the last class we distinguished between *heat* and *temperature*. In particular, we defined heat as the energy transferred between objects of different temperatures that are in thermal contact. The hotter object loses energy and its temperature drops (it "cools down"). At the same time, the cooler object gains energy and its temperature rises (it "heats up"). This allows us to come up with a working definition of temperature as the tendency for an object to spontaneously give up energy to its surroundings.

Internal Energy

The first conclusion you should draw from the characterization of heat as the amount of energy transferred between two objects is that these objects must contain some amount of energy. Last semester you learned about types of energy like gravitational potential energy and kinetic energy. These forms of energy are defined in terms of the relationship between an object and its surroundings.

The energy related to heat transfer is *internal* to the object and is independent of its surroundings. We call this **internal energy** or **thermal energy**. It is hard to visualize thermal energy on the macroscopic scale, but we can visualize it on the microscopic scale. At the microscopic level, the molecules in a substance (be it solid, liquid or gas) will undergo random motions and therefore have kinetic energies. In a solid, the bonds between the molecules store potential energy, as well. The internal energy of the object is the sum total of all these microscopic bits of kinetic and potential energy.

The second conclusion you should draw is that the amount of internal energy is related to the temperature of the object. Adding heat to an object increases its temperature. Adding heat to an object increases its internal energy, the microscopic kinetic and potential energies of all the molecules that comprise the object. Therefore, temperature can be used to determine the

internal energy of an object and the average kinetic energy of its molecules. We will see the quantitative relationship in the next class.

Heat Capacity and Specific Heat

When an object gains an amount of heat Q, its temperature increases in proportion to the amount of heat. If some amount of heat raises the object's temperature by 10°C, twice that heat will raise its temperature by 20°C. (Remember, we're talking about *change in temperature* here.)

However, as you will see in lab, the temperature increase will also depend on the mass of the object and its composition. The heavier the object, the more heat is required to achieve a certain increase in temperature. Furthermore, it takes more heat to raise the temperature of a certain amount of water than it does to heat an equivalent mass of rock by the same amount.

Mathematically, we can express these relationships by the formula

$$Q = m\,c\,\Delta T\ ,$$

where Q is the heat added to an object (positive value) or taken away (negative value), m is the mass of the object, and ΔT is its temperature change (positive for an increase, negative for a decrease in temperature). The proportionality constant c is called the **specific heat** or **specific heat capacity** of the material that comprises the object. It does not vary too much with temperature for most materials.

In fact, the calorie is a unit of energy defined to make the specific heat of water equal to 1 in appropriate units. The calorie is the amount of heat needed to raise the temperature of 1 g of water by 1°C. Using the formula above, this gives

$$c = \frac{Q}{m\Delta T} = \frac{(1\,\text{cal})}{(1\,\text{g})(1^\circ\text{C})} = 1\,\text{cal/g}^\circ\text{C}\ .$$

The BTU, or "British Thermal Unit" (which, of course, the British no longer use) is defined similarly. It is the amount of heat required to raise the temperature of 1 pound of water by 1°F.

In this course we deal exclusively with SI units, so we will define the specific heat of substances in terms of Joules and kilograms. The specific heat of water is $4186\,\text{J/kg}^\circ\text{C}$, or $4186\,\text{J/kg K}$. (Remember, a temperature change in °C is equivalent to the same temperature change in K.)

Again, pay special note that specific heat is a property of the material that an object is made of, not the object itself. The quantity $m\,c$, however, is a property of the object. It is sometimes

known as the **Heat Capacity**. Ten kilograms of water will have ten times the heat capacity of one kilogram of water, but both will have the same specific heat. You wouldn't refer to the "heat capacity of water", but you would refer to the "heat capacity of that bucket of water" if it's appropriate to the problem you're studying.

Finally, it is worth noting that "specific heat" is a poor choice of terms. Recall that the internal energy of an object is related to its temperature, so the temperature will increase when the internal energy increases. You can do this not only by adding heat, but also (as we will see in another class) by doing work on the object.

Latent Heat

Some materials undergo **phase changes**, or changes in form, as heat is added to or taken from them. For example, adding heat to water causes its temperature to increase until (at one atmosphere of pressure) it reaches a temperature of 100°C. At that point, as more heat is added, some of the liquid water will be converted to gaseous water (steam). If the heat is added slowly and everything is well mixed, the water's temperature will not increase above 100°C. The addition of heat will simply contribute to the phase change.

If you add some amount of heat to water at 100°C, you will get a certain amount of steam at 100°C. If you add twice as much energy to the water, you will get twice as much steam—twice as much water will have been converted from liquid to gas. Therefore, the amount of material that changes phase is proportional to the heat added at the phase change temperature. Let Q represent the heat added to the substance, and let m be the mass of the material that has changed phase (not the total mass of the material!) Then we can write

$$Q = m\,L\,,$$

where m is the **latent heat** of the material.

There are different kinds of latent heat, depending on the phase change. The **latent heat of fusion**, L_f, tells how much material will melt or freeze as heat is added or taken away. For water, $L_f = 334\,\mathrm{kJ/kg}$. Similarly, the **latent heat of vaporization**, L_v, tells how much material will boil or condense as heat is added or taken away. For water, $L_v = 2260\,\mathrm{kJ/kg}$.

Calorimetry

When two objects of different temperature are brought into thermal contact, energy will transfer between them in the form of heat. If the two objects are isolated from their surroundings, so

neither will gain or lose thermal energy from external sources, the energy lost by the hotter object will equal the energy gained by the cooler object. (This is a statement of the law of conservation of energy.)

If the objects are left in thermal contact and isolated from their surroundings for long enough time, they will come into thermal equilibrium with each other, i.e. they will reach the same final temperature. Given the masses, compositions, and initial temperatures of the objects, you can use conservation of energy to predict the final temperature of the pair. To do the calculation, all you really need to do is the same kind of conservation of energy bookkeeping you did last term. You need to make sure you account both for heat associated with temperature changes and heat associated with phase changes.