Lecture 21

- Temperature
- Thermal Expansion
- Heat and Internal Energy

Cutnell+Johnson: 12.1-12.7, 14.3

Temperature

So far in this class we've usually talked about large objects, and we've treated the object as moving uniformly. In other words, if you push on the block, all of the block moves in the same way. We did talk a little about stretching and compressing (chapter 10), but still we're talking about the properties of the object as a whole.

However, we know that objects are made up of tiny molecules. The fact that we treat it uniformly doesn't mean that the individual molecules are really moving uniformly. This can be seen directly with a microscope. The molecules themselves are still too small to see, but if there are slightly larger objects in the system, the molecules bump into them, and make them move around randomly. This sort of motion is called Brownian motion, and when people saw this, it was really the first direct experimental observation of the fact that materials are made up of small entities called molecules. In a gas, the molecules are moving all over the place. In a liquid, they are doing the same thing, although they don't move as far. In a solid, they are more or less held in place (you can think of a solid as a bunch of balls coupled by a bunch of springs). However, they are still wiggling back and forth.

For most examples, treating objects as uniform is perfectly correct. However, there are certainly times when we do need to take into account this molecular motion. Certainly we can't possibly compute the motion of each individual molecule. But we can take into account the *average* motion. The way we do this is to introduce *temperature*.

The temperature measures how fast the molecules are moving. In fact, there's a precise statement you can make about this for *ideal gases*. An ideal gas is a gas dilute enough so that the molecules don't interact with each other very much. For an ideal gas, the average kinetic energy of a molecule is proportional to temperature:

$$KE_{average} \propto T$$

where T is measured in Kelvin. This formula only applies to ideal gases, but for any kind of material, the more the molecules are moving around, the higher the temperature.

So what's the Kelvin scale? There are three temperature scales we use: Fahrenheit, Celsius (sometimes called centigrade), and Kelvin. They all work in the same way, and it's easy to convert between them. Celsius is defined so that water freezes at 0^o C and boils at 100^o C. On the Fahrenheit scale, water freezes at 32^o F and boils at 212^oF Thus a temperature change of 100^o C is the same as 180^o F. This means that if you raise the temperature by one degree celsius, that is the same as raising the temperature by $9/5^o$ F. This equation applies only to temperature *differences*: it does not meant that a thermometer reading 1^oC is the same as one reading $9/5^o$ F. The equation relating the two is therefore

$$T(\text{ in }^oF) = 1.8 \times T(\text{ in }^oC) + 32$$

Problem What will a Fahreinheit thermometer measure if a celsius thermometer is measuring 1^o C?

Answer 1^o C means one celsius degree above freezing, which means $9/5^o$ F above freezing. ("Above freezing" is a temperature difference, so the above equality applies.) On the Fahrenheit scale, $9/5^o$ F above freezing means $32^o + 9/5^oF = 33.8^oF$.

The third scale is the Kelvin scale. The Kelvin scale is the same as Celsius, except for an overall shift. In a formula,

$$T_{Kelvin} = T_{Celsius} + 273.15$$

There is a reason for this. The point is that on the Kelvin scale, there are no negative temperatures When the temperature is 0^o K (or equivalently, -273.15^o C), all molecular motion stops (the kinetic energy of the particles is zero). This is called absolute zero. Once you've stopped moving altogether, you can't get any colder. You may have read a few years ago about something called "Bose-Einstein Condensation". The story was that they've managed to cool some materials so that some of it effectively is at zero temperature. The properties of these materials had been predicted a long time ago by Einstein, hence the name.

Problem What is absolute zero on the Fahrenheit scale?

Answer A temperature difference of -273.15^oC is the same as a temperature difference of $-273.15^o \times \frac{9}{5} = 491.67^o$ F. This is below the freezing temperature of water, so the temperature in Fahrenheit is

$$T_F = 32 - 491.67 = 459.67^o\text{F}$$

Thermal Expansion

One major effect of heat is that it causes substances to change size and/or density. This is true for solids, liquids, and gases. The effect is extremely important for buildings. A long girder appreciably expands. You've probably noticed that there are these gaps in bridges in larger bulidings, with maybe some rubber to fill the hole. This is to allow the buildng to expand and contract. These are called *expansion joints*. There's a great photo in the book of some buckled train tracks, which is what can happen if you don't take into account thermal expansion. Another thing which can happen is that sidewalks can buckle upwards.

The formula for linear thermal expansion of a solid is

$$\Delta L = \alpha L_0 \Delta T$$

In other words, a change in temperature ΔT causes an increase of length ΔL. L_0 is the original length, and the constant of proportionality α is called the coefficient of linear expansion. This depends on the material; there's a table in your book.

This expansion in a building can result in enormous stresses. Recall out stress/strain relations from chapter 10. One of them related a force to the change in length. There we discussed how an external force causes a change in length. The reverse is true as well. If you change the length by changing the temperature, this causes a stress.

Problem A steel beam of cross-sectional area $.10\,m^2$ is mounted between two pieces of concrete at 23^o C. Say no room was left for expansion. What force does the concrete need to put to keep the beam from expanding when the temperature rises to 42^o C?

Answer The stress is related to the change in length (the strain) by the formula

$$\frac{F}{A} = Y \frac{\Delta L}{L_0}$$

where Y is Young's modulus, which for steel is $2.0 \times 10^{11} N/m$. If the beam were free to expand when the temperature changes, then it would stretch a distance

$$\Delta L = \alpha L_0 \Delta T$$

Plugging this into the first equation gives

$$\frac{F}{A} = Y\frac{\alpha L_0 \Delta T}{L_0} = Y\alpha\Delta T$$

Using the fact that $\alpha = 12 \times 10^{-6}\ /^oC$ for steel, and $\Delta T = 19^o$ C here gives

$$\frac{F}{A} = 4.6 \times 10^7 N/m^2$$

This pressure is enormous. To get the force, multiply by the total area $.01m^2$:

$$F = 4.6 \times 10^7 N/m^2(.10m^2) = 4.6 \times 10^6 N$$

This is about a million pounds.

The entire volume changes as well. The formula for volume expansion is nearly the same. It is

$$\Delta V = \beta V_0 \Delta T$$

where β is the coefficient of volume expansion.

Notice in these examples, we've used celsius. The reason we can do this is that all the formulas in this lecture involve temperature differences, and the temperature difference is the same in celsius and in kelvin. If you're ever in doubt, use Kelvin – that won't be wrong.

Heat and Internal Energy

So how does temperature change? We're used to discussing *heat*. When you heat something, its temperature increases, when you extract heat from it, its temperature decreases. But what is heat? Back before they knew about molecules, they thought that heat itself was some sort of fluid (which isn't so ridiculous – heat does indeed flow). However, we've already seen that temperature is what can be called the *internal energy* of some matter. When heat flows from one place to another, it means that the kinetic energy of some molecules is being transferred to some other molecules. In other words, one system is losing internal energy, while the other is gaining.

So it makes sense to say that heat is transferred. We can now write a formula which relates the energy transferred to the change in temperature. If an amount of energy ΔQ is transferred into some body of mass m, the body's temperature changes by some ΔT. The two are related by

$$Q = cm\Delta T$$

where c is called the *specific heat capacity*. The specific heat capacity is different for different materials. For water, $c = 4186 J/(kg\,^oC)$. For copper, it's $387 J/(kg\,^oC)$. It's much easier to heat up copper (or any metal) than it is water. Note also that there is another unit of energy commonly used in temperature problems. This is called the calorie, and is defined so that 4.186 calories = 1 Joule. Thus the specific heat of water is 1000 cal /(kg ^oC), the reason for this unit calorie.

The "strength" of food is measured in calories. What it means is the amount of energy you get when you "burn" the food, that is convert the energy from the food to the energy body uses. When you read the cereal box, what they call a calories is actually 1000 calories, a kilocalorie.