Lecture 30

- Equilibrium
- Convection
- Conduction

Cutnell+Johnson: 12.9-12.10, 13.1-13.4

Equilibrium

Last time, we studied heat, and how heat can cause a material to either change in temperature, or change in phase. To review, let's first do a problem in temperature change.

Problem A $5\,kg$ chunk of iron at $95.0^o\,C$ is placed in 5.0 liters of water, initially at $20.0^o\,C$. The water and iron reach the same temperature (they *equilibriate*). What is this temperature, given that the heat capacity of iron is $452J/kg\,^oC$?

Answer Because of the conservation of energy, the heat lost by the iron is gained by the water. Thus the iron goes down in temperature and the water goes down in temperature until the temperature is the same for both. The heat lost by the iron is

$$Q_{iron} = (452J/kg\,^oC)(5\,kg)(T_{final} - 95^0C)$$

A liter is $10^{-3}m^3$, so the mass of the water is

$$m_{water} = (1000\,kg/m^3)(.005m^3) = 5kg$$

and the heat gained by the water is

$$Q_{water} = (4186J/kg\,^oC)(20\,kg)(T_{final} - 20^oC)$$

Note that T_{final} is the same for both. To find T_{final}, we use the fact that $Q_{water} = -Q_{iron}$. The reason for the minus sign is that the water is gaining heat, while the iron is losing heat.

$$(4186J/kg\,^oC)(5\,kg)(T_{final} - 20^oC) = (452J/kg\,^oC)(5\,kg)(T_{final} - 95^0C)$$

$$9.26(T_{final} - 20) = 95 - T_{final}$$

$$10.26T_{final} = 95 + 20(9.26)$$

$$T_{final} = 27.3^o\,C$$

So notice the final temperature is much closer to the original temperature of the water than of the iron. The reason is that even though they are both of the same mass, the specific heat capacity of water is much larger.

Now that I've introduced the word equilibrium, we can understand what humidity precisely means. The above problem discusses how two different bodies reach equilibrium. Basically, these reach equilibrium when they are the same temperature. Equilibrium gets trickier if the two different materials are different phases of the same material. In other words, can water and ice be in equilibrium? Can water and water vapor be in equilibrium? The answer is yes. The idea is simple. Let's first consider water and water vapor together. This is in fact our daily situation: we have lakes, and there is always some water vapor in the air (unless you're in Death Valley). The two are in equilibrium if the rate at which water is evaporating is the same as the rate the water vapor is condensing. That's all there is to it. To compute the temperature and pressure at which this is true is more complicated, so we won't do that.

Now to humidity. 100% humidity means that water and water vapor are in equilibrium. Higher than 100% humidity means that more water vapor is condensing than water evaporating. Lower than 100% humidity means that more water is evaporating than water condensing. A precise number (for example 83% relative humidity) means the fraction of water vapor as compared to its maximum value. The maximum value depends on the temperature and pressure. This is why it's convenient to give the humidity as a fraction instead of an overall number.

Convection

We've talked about the effects of heat on materials. Now we'll talk about *how* heat flows. So this in fact goes back to the old way of thinking, where heat was treated as a fluid. It's not a fluid, but it's a reasonable way of thinking about heat flow.

The first main kind of heat flow is called *convection.* This is the most important kind of flow for heating your house, for example. What convection means is the the heat is carried from place to place by the material itself moving. Thus convection in your house occurs from air coming in through windows, doors, or seeping through the walls.

Conduction

Heat can also be transferred by contact. This is called *conduction.* This means the bulk of the material is not moving. Of course, the molecules inside the material are still moving randomly, but there is no net flow of these molecules. In other words, the air is still, the water isn't flowing. Yet heat can still be transferred. This occurs because the molecules in one material collide with the molecules in the other material. In such a collision, kinetic energy can be transferred from one molecule to another, as we saw when we did the chapter on momentum.

Materials which conduct heat well are called thermal conductors, while those which conduct heat poorly are called thermal insulators. Most (but not all) metals are good thermal conductors. This is why metal is usually cold to the touch, even though the metal is the same temperature is the room air. Your body temperature is warmer than room temperature, so heat flows to whatever you're touching. A good thermal conductor takes the heat out of your body quicker, and thus cools your skin off quicker.

Air is a very poor thermal conductor, which is why styrofoam and goose down are thermal insulators. Another famous thermal insulator is asbestos, which (unfortunately) was used in millions of buildings.

A simple formula describes heat conduction. Let's consider a bar of length L and cross-sectional area A. One end held at a temperature T_1, and the other held at a temperature T_2. Heat will flow from the hotter end to the colder end. First of all, you expect that the longer the time, the more heat flows. Thus $Q \propto t$. Second, you expect that that the greater the temperature difference, the quicker the heat will flow. $Q \propto \Delta T$. Third, the wider the bar is, the more heat will flow. Thus $Q \propto A$. Finally, the longer the bar is, the longer it will take heat to flow. Thus $Q \propto 1/L$. Putting this all together gives

$$Q = \frac{\kappa A \Delta T}{L} t$$

where the constant of proportionality κ is called the thermal conductivity. It depends on the material: the larger the κ, the better a conductor the material is. Your book calls the thermal conductivity k instead of κ. I changed the name to avoid confusion with the Boltzmann constant, which is also called k. If there's ever any ambiguity between the two, I'll make it clear which I mean. The MKS units of κ are $J/(s \cdot m \cdot ^o C)$.

Radiation

Another very important way of heating is from radiation. This converts electromagnetic energy to heat. Light, radio, and microwaves are all forms of electromagnetic waves. When these waves hit a material, their energy can be converted to heat. One example you know well is a microwave oven. Another is the heat from the sun.

The other way around is also true. Any material at non-zero temperature emits radiation. You've of course seen this. When a metal gets very hot, it starts to emit light. We say it glows red hot, or white hot. Your body is also emitting heat as well. The reason, you're not visible in the dark is that the light you're emitting is out of the visible range. However, there is some light in the infrared, which is how those fancy night sensore work. The amount of heat radiated is proportional to the time, as before. It is also proportional to the surface area (not the volume of the emitter). You would also expect it to depend on the temperature – the higher the temperature, the more heat a body radiates. It turns out that the heat is proportional to T^4, where T is measured in Kelvin. Thus

$$Q \propto T^4 A t$$

One interesting thing is that in fact there is radiation leftover from the big bang all around us. This is radiation like that coming from a body at $3\,K$. It's not much (it wasn't measured til the '60s), but it's extremely interesting. The reason is that this radiation comes straight from the big bang. Measuring its form is basically doing an experiment on the origins of the universe.