PHYSICS 151 – Notes for Online Lecture #32

Specific Heat

Joule found that there is a relationship between how much heat is necessary to change the temperature of a given material by a certain amount.

If we use Q to denote heat flow, we expect that:

- Q should be proportional to ΔT - the larger the change in temperature, the more heat must flow
- Q should be proportional to the mass: a larger mass takes longer to warm or cool
- Finally, there must be something accounting for the fact that it is easier to change the temperature of some types of materials than it is to change the temperature of others.

$$Q = mc\Delta T$$

where c is the **specific heat** of a quantity and has units J/kg-°C or sometimes kcal/kg-°C. Specific heats vary from material to material. The specific heat tells you how easy it is to warm or cool different things. A large specific heat means that more heat must be added to warm a fixed quantity of the material than if I warm the same quantity of a material with a lower specific heat.

Material	c(cal/g-°C) or (kcal/kg-°C)	c (J/kg-°C)
Water(0°C - 100°C)	1.00	4187
Human Body	0.83	3470
Water (-10°C - 0°C)	0.50	2090
Wood	0.40	1700
Aluminum	0.22	900
Marble	0.21	860
Copper	0.09	390
Lead	0.03	130

The specific heat values given in the table in your book are good at 1 atm constant pressure and 20°C. c may depend on the temperature and/or on pressure.

More Conservation Laws!

Assume we have an isolated system – meaning that no heat can enter or escape from our system. If we think about adding milk to coffee, for example, the system would be the coffee plus the milk. We have to assume that all heat transfer is between those two things and not to the outside atmosphere. Heat will be lost from the coffee and will flow to the milk, thus warming the milk. The net effect is that the milk will become warmer and the coffee will become cooler. There is nowhere else for heat to go, as the system is isolated.

Note: You have to be **very** careful with signs when doing heat transfer problems. I will always take ΔT to be T_f - T_i. As usual, the signs mean something physical

　　If $T_f < T_i$, Q is negative and there has been a net loss of heat.
　　If $T_f > T_i$, Q is positive and there has been a net gain of heat.

Since no heat escapes, we must have:

$$\text{heat gained} + \text{heat lost} = 0$$

If we mix two liquids together, one at a warmer temperature (a) and one at a cooler temperature (b), they arrive at a common temperature T_f. T_f is cooler than T_{ia} and warmer than T_{ib}.

Material a will decrease in temperature (lose heat)　　　　　$Q_a = m_a c_a (T_f - T_{ia}) < 0$

The second material will increase its temperature　　　　　$Q_b = m_b c_b (T_f - T_{ib}) > 0$

$$\text{such that } Q_a + Q_b = 0$$

Ex. 32-1: In automatic faucets (like at airports), the water temperature is controlled by how much hot and cold water is mixed together. We measure the temperatures and find that the hot-water heater puts out water at a temperature of 80 °C and the cold water source is 15°C. The builder must feed water from both sources into a holding tank so that they come to thermal equilibrium. What must the proportion of hot to cold water be to assure that the final temperature at the tap is 55°C.

Since we don't know masses, we'll call m_H the mass of hot water and m_C the mass of cold water. We're interested in a ratio of the amount of hot water to the amount of cold water, so we don't really need to know the actual numbers.

The change in heat of the hot water will be $Q_H = m_H c(55°C - 80°C)$

The change in heat of the cold water will be $Q_C = m_C c(55°C - 15°C)$

$$m_H c\left(55°C - 80°C\right) + m_C c\left(55°C - 15°C\right) = 0$$

$$m_H\left(1.0\tfrac{kcal}{kg-°C}\right)\left(-25°C\right) + m_C\left(1.0\tfrac{kcal}{kg-°C}\right)\left(40°C\right) = 0$$

$$m_H\left(1.0\tfrac{kcal}{kg-°C}\right)\left(-25°C\right) = -m_C\left(1.0\tfrac{kcal}{kg-°C}\right)\left(40°C\right)$$

$$m_H\left(-25°C\right) = -m_C\left(40°C\right)$$

$$\frac{m_H}{m_C} = \frac{40°C}{25°C}$$

$$\frac{m_H}{m_C} = 1.6$$

Of course, builders don't measure water in mass – they would use the volume, where mass = volume x density.

We can apply conservation of heat in systems with more than two components. The system we use to isolate things so that conservation of energy can be applied is called a *calorimeter* - a meter for calories. One way to determine specific heats is to place a hot object into a water calorimeter and wait for them to come to equilibrium. The heat gained by the water and the calorimeter will equal the heat lost by the object. This allows you to figure out the specific heat of a material.

Another type of calorimeter is one that is used to figure out how many calories are in a particular piece of food. It is called a bomb calorimeter. A sample of the food – usually a small piece that is very, very accurately weighed, is place into the calorimeter with an excess amount of oxygen at high pressure. The calorimeter is sealed and placed in the water of the calorimeter. A fine wire leading to the bomb is heated, which causes the mixture to ignite and burn completely. Again, the heat rise in the water and the calorimeter can tell how much heat was transferred from the food and thus, how many calories it contains. You have to be careful in defining your system, because the calorimeter is now part of the system.

Ex. 32-2: 15.0 g of water at a temperature of $1.00 \times 10^2°C$ is placed in a calorimeter made of aluminum with of mass 1.0×10^2 g at a temperature of 20.0°C. The system is allowed to come to thermal equilibrium. What is the final temperature of the mixture?

$c_{Al} = 0.22$ kcal/kg °C $\qquad\qquad$ $c_{water} = 1.0$ kcal/kg °C

Heat change of calorimeter is $\qquad Q_c = m_c c_c (T_f - T_{ic})$

Heat change of water is: $\qquad Q_w = m_w c_w (T_f - T_{iw})$

The final temperature of both materials will be the same, so we don't have to subscript it.
The total heat gained by the calorimeter will have to equal the total heat lost by the water.
Another way of saying this is that the two heats have to add to zero.

$$Q_c + Q_w = 0$$
$$m_c c_c (T_f - T_{ic}) + m_w c_w (T_f - T_{iw}) = 0$$

$$m_c c_c (T_f - T_{ic}) + m_w c_w (T_f - T_{iw}) = 0$$
$$m_c c_c T_f - m_c c_c T_{ic} + m_w c_w T_f - m_w c_w T_{iw} = 0$$
$$m_c c_c T_f + m_w c_w T_f = m_c c_c T_{ic} + m_w c_w T_{iw}$$
$$(m_c c_c + m_w c_w) T_f = m_c c_c T_{ic} + m_w c_w T_{iw}$$
$$T_f = \frac{m_c c_c T_{ic} + m_w c_w T_{iw}}{(m_c c_c + m_w c_w)}$$
$$T_f = \frac{(0.100\,kg)(0.22\,\tfrac{kcal}{kg\,°C})(20.0°C) + (0.015\,kg)(1.0\,\tfrac{kcal}{kg\,°C})(100°C)}{((0.100\,kg)(0.22\,\tfrac{kcal}{kg\,°C}) + (0.015\,kg)(1.0\,\tfrac{kcal}{kg\,°C}))} = 52.4°C$$

Thermal Transport

So far, we've spent all of our time discussing the magnitudes of heat transferred from one object to another – we haven't discussed at all how the heat is transferred.
There are three ways to transfer heat:
- conduction
- convection
- radiation

In most situations, more than one of these can be working, but we'll consider them one at a time

Conduction

Let's consider what happens when you are cooking. You can't find a wooden spoon, so you grab a metal spoon to start stirring your dinner. After a few moments, you realize that your hand is getting very warm. But your hand is not in contact with the food in the pot, or the pot, or the stove. Why is your hand warm?
This is the process of conduction. Let's think about the spoon. One end of the spoon is at a higher temperature than the other end of the spoon. If we think back to what temperature means, you'll recall that it has to do with the average kinetic energy of the molecules. So if this end of the spoon is at a higher temperature, on average the molecules in this end are moving faster than those in the other end. When the molecules move around, they engage in collisions. You should remember from back when we studied collisions that momentum is always conserved. In some collisions, the faster moving molecules will impart some of their momentum to the slower moving molecules, causing the slower

molecules to move around more. These in turn hit other, colder molecules, and eventually, the whole spoon is heated up.

Conduction cannot occur without a difference in temperature.

In fact, the rate at which heat flows is found experimentally to be directly proportional to the temperature difference.

$$\frac{\Delta Q}{\Delta t} = KA\frac{\Delta T}{l}$$

where l is the length of the object, A is the cross-sectional area and K is a proportionality constant called the **thermal conductivity**. The units of k are kcal/s-m-°C or J/s-m-°C.

$$\frac{\Delta Q}{\Delta t}$$ is a rate of energy transfer

ΔT/l represents a temperature gradient – how the temperature varies along the length of the object. If one end is at a very high temperature and the other is at a lower temperature, conduction will occur at a higher rate than if the ends are at similar temperatures. If the material has a large cross sectional area, the rate is higher. K tells us that some materials are better conductors than others.

Material	J/m-s-°C
silver	420
copper	380
aluminum	200
steel	40
glass	.84
brick/concrete	.84
water	.56
people (not including blood)	.2
Asbestos	.16
wood	.08-.16
down	.025
air	.023

Ex. 32-3: What is the rate of heat flow along a copper bar 1.5 m long having a cross sectional area of 0.50 cm^2 if one end of the bar is at 25 °C and the other is at 110 °C?

Using K = 380 J/m-s-°C and applying the equation

$$\frac{\Delta Q}{\Delta t} = KA\frac{\Delta T}{l}$$

$$\frac{\Delta Q}{\Delta t} = \left(380\tfrac{J}{ms°C}\right)\left(0.50\,cm^2\right)\frac{\left(110°C - 25°C\right)}{150\,cm}$$

$$\frac{\Delta Q}{\Delta t} = 108\frac{Jcm^2°C}{ms°C\,cm}$$

$$\frac{\Delta Q}{\Delta t} = 108\frac{Jcm}{ms}\left(\frac{1m}{100\,cm}\right)$$

$$\frac{\Delta Q}{\Delta t} = 1.1\frac{J}{s}$$

- Windows -   There is cold air outside and warm air inside. The glass conducts the heat to the outside (or the cold to the inside, depending how you look at it).
  - What happens if we instead double the thickness of the glass? The answer is that the heat flow will occur at half the rate ($\Delta Q/\Delta t$ proportional to $1/l$).
  - Now let's separate the glass plates and fill the space between them with air. K for the air is much less than that for glass. So the cold air comes in contact with the outer layer of glass, but the air is a poor thermal conductor, so not much of the cold is transferred to the inner pane of glass. You may even see triple-pane windows in very cold parts of the country. This is called glazing. Note that a thin layer of air is much more effective than just making the glass thicker.
- The difference in thermal conductivity also helps explain things like why a tile floor is colder than carpet - the tile has a higher thermal conductivity, so it pulls the heat away from your foot faster than the carpeting would.
- Clothing is also much more insulating than just the effect of the material. Clothing can trap air and prevent breezes. Layers of clothing are especially good at this.
  - For example, if you think back to our window, if there is no breeze, the cold air, glass and warm air inside will eventually come to some equilibrium temperature; however, if the air outside is constantly moving, the air that is warmed by contact with the window is swept away and replaced with new, colder air. You can see from all of this why putting drapes in front of a window will help cut down on heat loss – it prevents breezes.
  - Down, which is lots of feathers, fluffs up and traps lots of air, providing great thermal insulation.
  - Some of you may have heard of a material called 'Gore-Tex', which is made up of a material that has 9 billion pores per square inch. Each pore is 20,000 times smaller than a droplet of water, but 700 times larger than a molecule of water vapor. This means a couple of things: first, the pockets are great for trapping lots of air. Second, liquid water can't get in, but perspiration can escape.
  - Polar bears have – in addition to all the fat – an underlayer of hollow hairs that are very good at trapping air, thus keeping the bears warm.
  - This is similar idea to why women wear nylons in the winter – the nylons keep you warmer than slacks by trapping air close to your legs.
- We use insulation to reduce the loss of heat. The effectiveness of the insulation is rated by its "R-Value".

$$R = \frac{L}{K}$$

where L is the thickness of the material and K is the thermal conductivity. In this country, the R-value is given in units of ft^{2}h°F/BTU.

Convection

In conduction, heat is transmitted through a solid (or a liquid or gas); however, there is no motion of the molecules themselves. In liquids and gases, the molecules themselves can actually move, which we call convection.

- One place in which convection occurs is in heating water. The water molecules at the bottom of the pan are heated by conduction through the pan. As they are heated, their density decreases and the warm water becomes less dense than the colder water above it. The warmer molecules rise and the colder molecules fall to the bottom of the pan where they are then heated. This is the same phenomena responsible for the phrases, "warmer near the lake" and "cooler near the lake".
- Other examples of where convection is important are in forced-air heating and cooling systems. IN a refrigerator, the coolant gas or liquid moves through the inside of the refrigerator and removes

heat from the inside of the refrigerator, transferring it to the outside. The coolant must be colder when it passes through the inside of the refrigerator so that heat will flow from the inside of the refrigerator to the coolant. Your blood cools your body the same way - it moves heat from the inside of the body to the skin, where it can be exhausted to the air.

- Question: Air is a good thermal insulator; however, you often find that a polymer foam insulation is blown into the spaces between the walls of a house? Why would you do this?

Answer: Although air is a poor conductor, is it still subject to heat transfer by convection. The polymer foam is a solid and therefore doesn't transmit heat by convection.

Radiation

Radiation often has a bad connotation; however radiation is a very important method of energy transfer. Conduction and convection require the presence of a medium -solid, gas or liquid. Radiation is the method of energy transfer that can take place without a medium - in a vacuum.

- This is important because there is a vacuum between the sun and the Earth and if we could only get heat from conduction and convection, we'd be in big trouble.
- If you stand in front of a fireplace, you feel heat through radiation. Although some of the heat is from visible radiation, quite a bit of the heat you feel is from infrared radiation. Infrared lamps are used to heat food in cafeterias.
- People emit infrared radiation and it turns out that the patterns of blood vessels in your face are very unique. Infrared cameras are being developed that use these patterns of blood vessels as a means of identification.

The rate at which an object radiates energy is determined by Stefan's Law:

$P = \sigma AeT^4$

where P is the power (energy per unit time), σ is a constant, e is the emissivity (ranging from 0 to 1) that tells you how efficiently the object radiates or absorbs. T is the temperature.

- Microwave ovens use microwaves (a form of radiation) that are easily absorbed by the water in the food. The metal walls have a high emissivity, so they reflect the microwaves, focusing them back into the food.