PHYSICS 151 – Notes for Online Lecture #31

Temperature

You probably have an intuitive feeling for temperature – you know when something is warm or hot or cold. Now we want to examine what it is about matter that changes when an object changes temperature. Let's look at a balloon. I can fill the balloon with air. When I do this, why does the balloon stay inflated?

The answer is that there is a greater density of air inside the balloon than outside the balloon - but what does that mean?

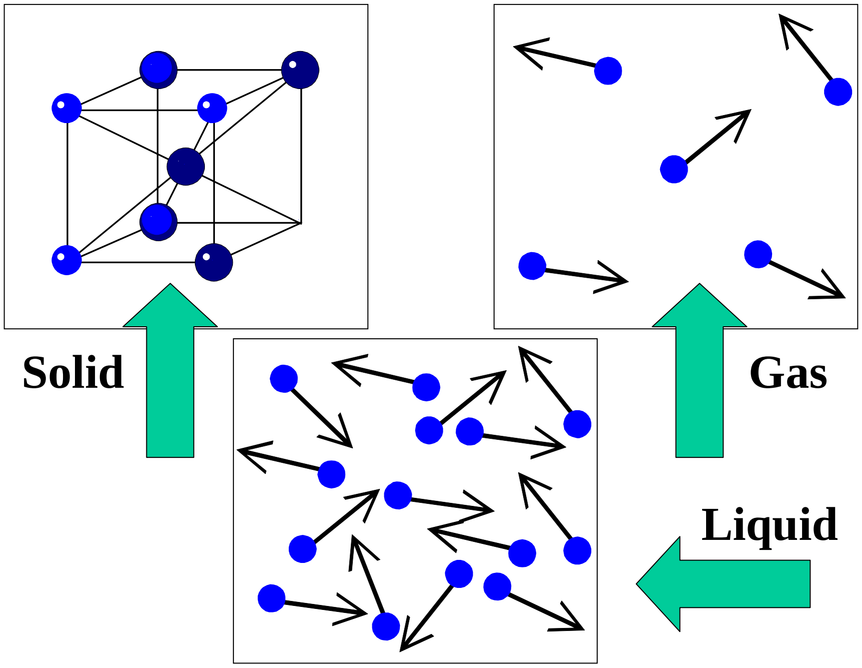
Some Greek philosophers believe that if you cut something into a hundred pieces, then took one of those pieces and cut *it* into a hundred pieces and so on, eventually, you would come up with something that couldn't be divided any further. They called this part the **atom.** **Atom** is the Greek word for indivisible. Of course, today, we know that atoms can indeed be divided into even smaller pieces, but for the sake of discussing temperature, that isn't relevant. Everything is made up of atoms. Atoms combine to form molecules, so we have air molecules, balloon molecules, etc. Air molecules are what is inside the balloon right now – so how do they keep the balloon inflated? The answer is that molecules are always moving. All molecules are moving, even though it doesn't really look like they are. The amount that they move depends on how they are connected to each other.

You have probably heard about the three forms of matter: solids, liquids and gases (and plasma). Solids, liquids, and gases are all composed of atoms or molecules.

In a **solid**, the molecules are very well connected to each other. They are very densely packed. You can think of the interactions between the atoms as being as if they were connected by springs (and in fact, everything we learned about springs in the previous chapters can be used to study the behavior of solids.) Solids hold their own shape.

In a **liquid**, the molecules are less well connected. A liquid fills the shape of the container it is in. Compare, for example, ice and liquid water. They are made up of the exact same molecule, but they behave very differently. The molecules in the liquid move around past each other in a sort of jiggling type of way.

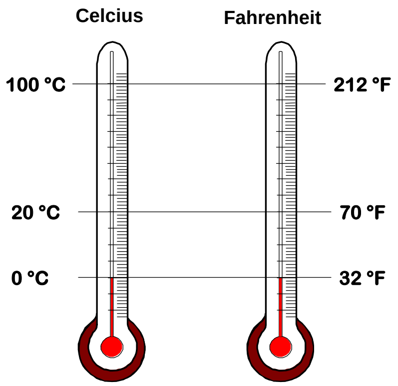
In a **gas**, the molecules are much more spread out. They don't interact with each other as much and spend most of their time bouncing around.



So if you think about why the balloon stays inflated in terms of molecules, we can reason that the molecules inside the balloon are bouncing off the sides of the balloon, pushing them outward. There are, of course, molecules hitting the balloon from the outside, too, but we've squished in a whole bunch of molecules inside the balloon, so the pressure exerted by the molecules inside the balloon is greater than that exerted outside the balloon, and the balloon stays inflated.

Temperature Scales

So what does this discussion of atoms have to do with temperature? I'll make it more clear in a moment, but before I do, I have to discuss temperature scales. There are three temperature scales with which we will concern ourselves:



The one you're used to using is the **Fahrenheit** scale. In this scale, water boils at 212°F and freezes at 32°F. The **Celsius** scale was developed by someone who thought, "These are really dopey numbers to have to memorize. Why not make them something simpler, like, say, 0° and 100°?" What resulted was the Celsius scale. The two fixed points – water boiling and water freezing – were picked because they occur at a very precise temperature and it is very easy to reproduce them. If you compare the two scales, we find that one degree F is 9/5 of one degree Celsius – roughly twice the size. So to convert from one scale to another, we use

$$T(^\circ C) = \frac{5}{9}\left[T(^\circ F) - 32\right]$$

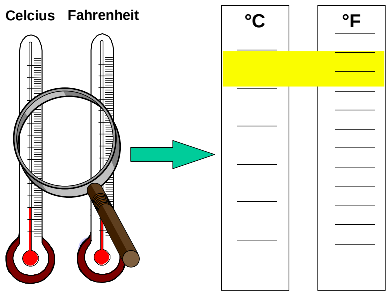
$$T(^\circ F) = \frac{9}{5}\left[T(^\circ C)\right] + 32$$

If you can't remember these relationships – and some of you have calculators that do this for you – you can always figure them out based on knowing the equivalent temperatures:
212°F = 100°C and 32°F = 0°C. We know that the equation is a straight line and we have two points.

°F	**°C**
212	100
32	0

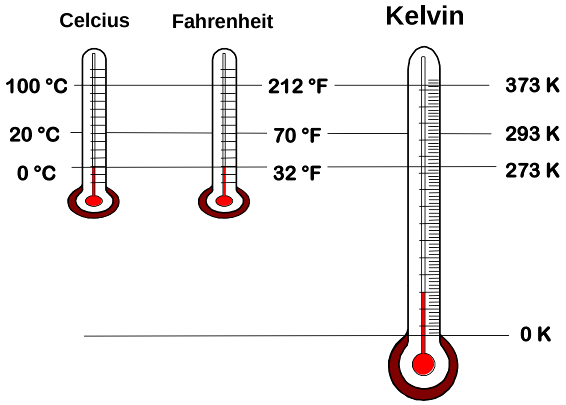
$$\text{then } m = \frac{y_2 - y_1}{x_2 - x_1} = \frac{100-0}{212-32} = \frac{100}{180} = \frac{5}{9}$$

$$\text{and } b = y_2 - mx_2 = 0 - \frac{5}{9}(32) = -\frac{5}{9}(32)$$



This shows us that one degree Celsius is equal to approximately two (actually 1.8) Fahrenheit degrees.

Kelvin



The third scale – which we will not use right away, but which will become very important later, is the **Kelvin** scale, which is the scale most scientists use. The big difference you'll notice here is that the Kelvin scale goes down to zero and stops. There is no such thing as a negative temperature in the Kelvin scale.

The relationship between the Kelvin and Celsius scales is simple:

°C=K-273.

You'll note that there is no degree sign in Kelvin measurements. We got tired of writing it and voted to drop it a few years ago.

Can you identify any other points of reference between the temperature scales?

Body Temperature?

Is there a common value of temperature where the Celsius and Fahrenheit scales are equal?

Is there a common value of temperature where the Fahrenheit and Kelvin scales are equal?

Is there a common value of temperature where the Celsius and Kelvin scales are equal?

Back to our balloon – we're still trying to figure out what temperature is. Liquid nitrogen is the liquid form of nitrogen gas. The air we breathe is about 73% nitrogen. Air is to liquid nitrogen as steam is to water. The difference is that liquid nitrogen has a temperature of 77 K, which is (77-273)= –196°C. This is cold enough to cause frostbite almost immediately.

When we dunk the balloon in liquid nitrogen, it shrinks. How do we relate what we've learned about molecules to temperature?

The answer is that **temperature is a measure of how fast the molecules in a material move**. When a material gets cold, the molecules slow down. When a material gets hot, the molecules speed up. The balloon stays inflated because the molecules inside are constantly banging around against the walls of the balloon. When their temperature is decreased, they slow down and don't bang so hard, so the balloon deflates.

The reason that there is no zero on the Kelvin scale is that the Kelvin scale measures the motion of molecules on an absolute scale. 0 K corresponds to absolutely no molecular motion. You can't have negative molecular motion; therefore, you can't have negative Kelvin temperatures. This definition will be important in the next few lectures.

In the thermometer discussed above, the thermometer acts as a **transducer**: the expansion of the liquid mercury is used to determine the temperature. Here are some other temperature transducers

Length - bimetalic strip

Volume - liquid (mercury or alcohol) in class

Volume - gas (at constant pressure)

Pressure - gas (at constant volume)

Electric Potential between two metals - thermocouple

Electric Resistance (metal) - Resistance Thermometer

Electric Resistance (semi-conductor) - thermistor

Color - pyrometer

Chemical - Thermograph

Thermal Expansion

We're going to return to the idea of how temperature is related to molecular motion later, but first let's look at what happens to materials when they change temperature. Let's say that you've got a jar lid that's stuck and you want to get it off. How can you do this? One common way is by running the jar under hot water so that the jar lid expands and can come off the jar. Thinking back to our model of solids, if temperature is a measure of how fast things are moving, when a solid heats up, the molecules vibrate about their normal positions. At higher temperature, they vibrate more and the material actually grows in size. When a material is cooled, the molecules don't move as much and the material shrinks.

If we look at a long strip of metal, with length L_o, we might want to find out what its change in length is under certain conditions. This is important, for instance, in building roads that must undergo temperature extremes. Experimentally, we find that the change in length is directly related to the change in temperature and to the initial length of the bar. The dependence on the initial length of the bar comes about because there are that many more molecules moving, so the change in length will be greater than that of a shorter bar.

$$\Delta L \propto L_o \Delta T$$

But let's think back to the jar. When you heat the lid, you're also heating the glass, too. Doesn't the glass also expand? The answer is that it does, but it expands less than the material from which the lid is made. This means that we somehow have to account for the fact that different materials expand or contract by different amounts under the same temperature change.

Let's try to arrange these materials on a scale. The way we account for the different rates of different materials in out equation is via the **coefficient of linear expansion**, α. α has units of $°C^{-1}$.

Material	**α (x 10^{-6}) $°C^{-1}$**	**β (x 10^{-6}) $°C^{-1}$**
Lead	**29**	**87**
Aluminum	**25**	**75**
Brass	**19**	**56**
Iron or Steel	**12**	**35**
Concrete and Brick	**12**	**36**
Glass	**9**	**27**
Pyrex	**3**	**9**
Marble	**1.4-3.5**	**4-10**
Quartz	**.4**	**1**
Gasoline		**950**
Mercury		**180**
Ethyl Alcohol		**1100**
Glycerin		**500**
Water		**210**
Most gases		**3400**

Some interesting things stand out in this chart.

1) Metals change their length much more than do glass or bricks
2) Note the difference between Glass and Pyrex – this is why a lot of kitchenware is made of Pyrex and not of glass. If you've ever stuck a hot glass dish in the refrigerator, you know why Pyrex can be very useful.

So the final equation we use to determine the change in length of a material with changing temperature is:

$\Delta L = \alpha L_o \Delta T$

Knowing the way in which materials change their length is very important, especially if you want to match two different types of materials together.

Good Example: A bimetallic strip is a strip with one side made of brass and the other of steel. What happens if I cool the strip?

Many thermostats have a coil of bimetallic strip inside of them. How does this allow you to measure the temperature and adjust the furnace or air conditioning?

Ex. 31-1: If a hole in a aluminum plate is 45.00 cm when it is at room temperature, what size is the hole at 2.00×10^2 °C? What size is the hole when the temperature is -2.00×10^2 °C?

$\alpha = 25.0 \times 10^{-6}$ 1/°C for aluminum

$\Delta L = \alpha L_o \Delta T$

$$\Delta L = \alpha L_o \Delta T$$

$$\Delta L = \left(25 x 10^{-6} \frac{1}{°C}\right) 45\text{cm} (200°C - 20°C)$$

$$\Delta L = .20\text{cm}$$

So L = 45+0.2 = 45.2cm

At -200°C:

$$\Delta L = \alpha L_o \Delta T$$

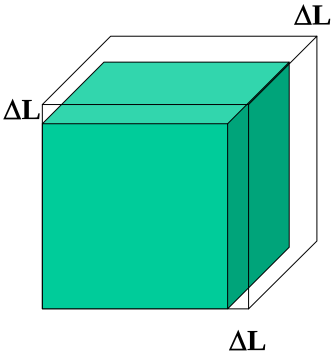
$$\Delta L = \left(25x10^{-6} \frac{1}{°C}\right) 45\text{cm}(-200°C - 20°C)$$

$$\Delta L = -.25\text{cm}$$

So L = 45 -0.25 = 44.75 cm

Expansion of Liquids and Gases

We have a minor problem with our expression for the thermal expansion of solids, which is that it only works for solids. Neither liquids nor gases have a fixed shape when left on their own. The expression also fails if you have to consider the expansion of a solid in all directions. Let's look at a cube of volume L_o^3.



We now have a cube with volume = $(L_o+\Delta L)^3$. So the new volume is V + ΔV

$$V + \Delta V = \left(L_o + \Delta L\right)^3$$

$$V + \Delta V = \left(L_o + \Delta L\right)^2\left(L_o + \Delta L\right) \qquad \Delta$$

$$V + \Delta V = \left[L_o + 2L_o\Delta L + \left(\Delta L\right)^2\right]\left(L_o + \Delta L\right)$$

L is small compared to L_o, so anytime we get a term that goes like ΔL^2, we're going to ignore it.

$$V + \Delta V = \left[L_o + 2L_o\Delta L + \left(\Delta L\right)^2\right]\left(L_o + \Delta L\right)$$

$$V + \Delta V = \left[L_o^2 + 2L_o\Delta L\right]\left(L_o + \Delta L\right)$$

$$V + \Delta V = \left[L_o^3 + 2L_o^2\Delta L\right] + L_o^2\Delta L + 2L_o\left(\Delta L\right)^2$$

$$V + \Delta V = L_o^3 + 3L_o^2\Delta L$$

We know that $V = L_o^3$, so $\Delta V = 3L^2\Delta L$

$$\Delta V = 3L_o^2\Delta L$$

$$\Delta V = 3L_o^2\alpha L_o\Delta T$$

$$\Delta V = 3\alpha L_o^3\Delta T$$

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

β is called the coefficient of volume expansion. For solids, β is approximately equal to 3α. This is true only when ΔV is small compared to V. The problem is that for liquids and gases, β is very large and this formula sometimes won't work. We'll remedy this later.

The Interesting Case of Water

Most materials expand when heated and contract when cooled. Water is an exception. Between 0°C and 4°C, water actually expands when cooled. Above this range, it behaves normally. Water therefore has its greatest density at 4°C. This turns out to be quite important for things that live underwater. In the winter, you notice that the top of a pond always freezes first. As the temperature decreases, there is a temperature gradient in the water. The top will be cooler than the bottom because it is in contact with the cold air. When the water on the top of the lake reaches 4°C, it becomes denser and sinks to the bottom of the lake, being replaced by warmer water from the bottom. The water that is now on top cools to 4°C, and so on, until the whole lake is at 4°C. The surface water cools even more, but now it is less dense than the water below it, so it stays on the top of the lake and turns to ice (which is even less dense than cold water). If the ice sank instead of floating, the lake would freeze all the way through and pretty much everything inside would die. The layer of ice additionally acts as an insulator, keeping the rest of the water away from the surface and the colder environment.