Science-1A Lab: Week 4, Wednesday, September 1, 2021

Temperature Scales

The textbook devoted its Chapter 4 to heat and temperature with a particular nice section entitled "Temperature Scales" that explains the Fahrenheit scale we use in the US, the Celsius scale used in the rest of the world and in medicine and science, and the Kelvin scale which has a zero point determined by nature and must be used in many physics equations involving temperature.

Converting between these scales is done by the following equations shown on the 2nd page of the Equation Sheet at the start of the Chapter 4 section in the middle of the page:

$$T_F = \frac{9}{5} T_C + 32\,^{\mathrm{o}}\mathrm{F} \qquad T_C = \frac{5}{9}\left(T_F - 32\,^{\mathrm{o}}\mathrm{F}\right) \qquad T_{\mathrm{K}} = T_{\mathrm{C}} + 273\,^{\mathrm{o}}\mathrm{C} = T_{\mathrm{C}} + 273\,\mathrm{K} \qquad \Delta T_C = \Delta T_K$$

Here, T_{F}, T_{C}, and T_{K} represent values in the Fahrenheit, Celsius, and Kelvin scales, respectively. The first two of these equations deal with the Fahrenheit scale which we do not use in science. The Celsius scale has a comfortable room temperature at 22 $^{\mathrm{o}}$C, normal body temperature at about 37 $^{\mathrm{o}}$C, water freezing at 0 $^{\mathrm{o}}$C, water boiling at 100 $^{\mathrm{o}}$C, and the coldest possible temperature at −273.15 $^{\mathrm{o}}$C. The last equation shows that the Celsius and Kelvin scales use the same interval size; they only differ where their zero point is set. The 3rd equation shows how their zero points differ.

That coldest possible temperature is called **absolute zero**. At that temperature, atoms and molecules move as little as the laws of physics (specifically, quantum mechanics) allow. They cannot stop moving, but must wiggle a bit (called zero-point motion). This lowest temperature was discovered by watching what happened when gasses and solids were cooled down. When the absolute zero limit was recognized, it was decided to call that the zero of temperature and use Celsius size degree units above that zero for a new temperature scale called the Kelvin scale. It was also decided to use a capital letter K for its temperature unit abbreviation **without** any degree symbol.

On the Kelvin scale, room temperature is about 295 K, normal body temperature is 310 K, water freezes at 273 K (actually closer to 273.15 K), water boils at 373 K, and absolute zero is at 0 K.

During my 30 years of doing low-temperature physics research, I usually did experiments at 4.2 K and below, occasionally as low as 0.02 K. Very interesting quantum effects are observable at those temperatures where the randomness of thermal agitation has nearly been eliminated.

How atomic motion relates to gas temperature and pressure

A short handout entitled "Chapter 4" discusses temperature by analogy with kindergarten kids. It is at
https://yosemitefoothills.com/Science-1A/Handouts/Week-04/Chapter-4-Notes.pdf
That handout also discusses the "Ideal Gas Law" which connects pressure, temperature, volume and number of atoms or molecules. Your textbook does not talk about it, but nearly all other texts do so I gave it a few words.

Although we cannot see atoms, we know how they behave. To show their behavior, I wrote a computer program to create animations of atoms bouncing against walls and colliding with each other under different conditions.

First, look at the following animated gif of 100 helium atoms in a small 2-dimensional box at a temperature of 12 K. It is at *https://yosemitefoothills.com/Science-1A/Handouts/Week-04/GasAt12K100He.gif* .

These atoms collide with each other and the box walls while obeying the laws of conservation of energy and momentum. Their random collisions cause some to temporarily move faster or slower than others, but the average speed of them all is characterized by the temperature of close to 12 K. **The Kelvin temperature of a group of atoms is proportional to their average kinetic energy**.

When they recoil off the walls of the box, they exert a pressure on its walls, just as happens in a bounce house for kids or in the imaginary kindergarten room I talked about in the Chapter 4 notes mentioned above. **The pressure of the group of atoms is the average recoil force per unit area of atoms hitting a wall**.

The next animation is at a much higher temperature of 300 K:
https://yosemitefoothills.com/Science-1A/Handouts/Week-04/GasAt300K100He.gif
At 300 K, the atoms have more energy and therefore are moving faster. They hit the walls more often and recoil harder so the pressure is greater. It turns out that the pressure on the walls is proportional to the Kelvin temperature.

If there are more atoms at the same temperature, collisions with the walls will happen more often. There will therefore be a greater pressure in proportion to the increase in the number of atoms.

The Earth atmosphere is more dense at sea level and thins out at higher altitudes. The top of Mt. Everest has only 34% of normal pressure. The Earth's gravity tries to pull the atmosphere to the ground, but the random motion caused by temperature counter that tendency. The next animation shows this where 400 helium atoms at 12 K are in a box with an enormously strong gravitational field. It is at
https://yosemitefoothills.com/Science-1A/Handouts/Week-04/GasAt12K400HeGravity4.gif .

The change in atmospheric pressure with altitude is called the Law of Atmospheres. You can see from this simulation how it comes about. As gravity tries to pull the atmosphere to the Earth surface, the atmosphere becomes more dense. The increased collisions between the atoms and molecules of the atmosphere push against the effect of gravity. The result is a balance where the atmospheric pressure is highest at the Earth surface and decreases exponentially with altitude.

Evaporation of a liquid

The next animation simulates what happens when a liquid evaporates. To avoid always needing to say "atom or molecule", I'll just say atom, but you should understand that the same discussion holds for molecules.

Atoms in a liquid are held together by relatively weak forces compared to those that hold atoms themselves together. Random thermal motion occasionally, by chance, gives a particular atom at the liquid surface enough energy to break loose into the void above the liquid. The departure of that extra energetic atom leaves the liquid with less average energy.

We experience this when we feel cooled as we get out of a swimming pool. The evaporating water molecules take energy away from our skin. This is nearly always true in California where the humidity is low, but on the Atlantic Coast in the summer or in a rainforest people do not feel this effect. There are so many water molecules in the air in those places of high humidity that for every water molecule that evaporates taking energy away, another molecule returns adding energy back to our skin. In that case there is a balance, and no net cooling is felt.

Let's watch a simulation of this, and afterwards I'll explain more. It is at
https://yosemitefoothills.com/Science-1A/Handouts/Week-04/EvaporationIntoVacuum-25K.gif .

This simulation starts with 3000 neon atoms in a puddle at the bottom of a box and a vacuum above the puddle. The temperature is about 25 K. As the simulation proceeds, some atoms are kicked into the upper region of the box. The number being kicked out per unit time is only determined by the liquid temperature. The number of atoms in the gas above the puddle grows, and those gas atoms bounce against the walls and each other. The bouncing against the walls causes the walls to experience a pressure.

After a while, some atoms have, by chance, returned to the liquid. The more atoms that are in the gas, the greater the number that will be number returning. Eventually, the rate of returning atoms matches the rate that atoms are being kicked out of the liquid. That is called the vapor pressure equilibrium situation for that temperature. The final pressure is called the **vapor pressure** of the liquid at that temperature. You might watch the simulation a second time now that you have read more about it.

Now, let's watch a similar simulation except that the temperature is 40 K, 15 K higher than in the first simulation. At that higher temperature, there is a great increase in the likelihood of atoms being kicked out of the liquid. As a result, the equilibrium vapor pressure will be higher. This simulation is at
https://yosemitefoothills.com/Science-1A/Handouts/Week-04/EvaporationIntoVacuum-40K.gif .

In these simulations the gas was contained in the box. If it were allowed to escape into the atmosphere, the puddle would keep evaporating without an equivalent replenishment and would eventually disappear. On the other hand, if water vapor were continuously added to the box, the puddle would grow.

We have watched liquid atoms becoming vapor in balance with vapor atoms returning to the liquid. This is a general behavior of collections of atoms or molecules. Chemical reactions can also go both ways and attain a balance unless a positive feedback effect creates an explosion or the addition or removal of reactants or products occurs. We will discuss this in the chemistry half of this course. Understanding evaporation, helps you understand chemical reactions.

Equipartition of Energy between heavy and light atoms

Here is a gas simulation that has two different kinds of atoms, 100 helium atoms and 100 argon atoms. It is at *https://yosemitefoothills.com/Science-1A/Handouts/Week-04/GasAt300K100He100Ar.gif* .

The helium atoms are 10 times lighter than the argon atoms. As a result of the mathematics of collisions, the helium and argon atoms end up with the same amount of average kinetic energy. But from the Chapter 3 section on page 2 of the Equation Sheet, we see that kinetic energy is given by $KE=\frac{1}{2}mv^2$. Since their average kinetic energies are the same, and their masses differ by a factor of 10, their average velocities squared must differ by a factor of 10. That means their average velocities must differ by $\sqrt{10}\approx 3.16$. When you watch the simulation, the light helium atoms colored cyan are, on the average, moving about 3 times faster than the heavier argon atoms colored white. Even if the speeds of the helium and argon atoms were initially set to be equal, they would quickly evolve to the behavior shown in the video as they repeatedly collide. Conservation of energy and momentum during their collisions force their average kinetic energies to become equal. That fact is called **Equipartition of Energy** and is a very general result that applies to many other situations.

Cold ice becoming hot steam

As heat is added to ice below 0 °C, it warms up, but when it reaches 0 °C, it starts to melt. Continuing to add heat causes more and more of the ice to melt, but the temperature stays at 0 °C until the ice has fully melted. Then, adding still more heat warms the water up to 100 °C at which point it starts to turn to steam. Continuing to add heat causes more and more of the water to become steam, but the temperature stays at 100 °C until the water has all turned to steam. Finally, adding heat simply raises the temperature of the steam above 100 °C.

Your iced drinks stay near 0 °C and boiling water on the stove stays near 100 °C irrespective of the amount of heat added until the ice has melted or the boiling water has all turned to steam.

This is shown at
https://yosemitefoothills.com/Science-1A/Handouts/Week-04/IceToSteam.pdf .
Those equations shown there are on page 2 of the Equation Sheet in the Chapter 4 section. They will be discussed in detail in the lecture of September 13 because they will be part of Quiz-3 given during the week of September 20.

The Laws of Thermodynamics

The way heat energy flows is characterized by 3 laws of thermodynamics, but without the time to study semester courses of thermodynamics and graduate level statistical mechanics, the usual statements of those laws are not very enlightening. Instead, physicists often simplify them into the following semi-joking forms:

1. You can't win - Energy is only converted between different forms, it cannot be created. (We have no idea how it appeared in the first place.)

2. You can't even break even - When energy is converted, the useful work obtainable is always less than the energy put in. The disorder of an isolated system always increases. There can be no perpetual-motion machines.

0 or 3. You must play the game - The disorder of the universe is always increasing and you are part of it.

The 2nd law can be stated many different ways. My freshman chemistry teacher passed out a sheet with about 20 different ways to express that law.

These laws may seem like jokes, but you will definitely be required to cite them on some Quizzes and Tests!

Entropy and Disorder

It is easy to understand the thermodynamic quantities pressure and temperature, but there is a third important quantity called **entropy** that is difficult to explain. Basically it is a measure of disorder in a large collection of atoms or molecules. To fully understand it requires a highly-mathematical graduate physics course called "Statistical Mechanics". Here in Science-1A, we must settle for some vague qualitative descriptions of entropy.

Normal objects settle to an arrangement of minimum energy. A kid's pile of blocks will crash to the floor if not perfectly balanced. Water settles to the bottom of a bowl. A wind-up toy spins down. The blocks needed an energetic kid to carefully pile them up – they do not jump up on each other by themselves. Water does not flow uphill (except as capillary action) without a pump or siphon. Wind-up toys do not wind themselves back up.

Earlier in this note, we watched two simulations where atoms did not settle to the lowest energy. Liquid atoms spontaneously evaporated into a vacuum, and the atmosphere did not fall to the ground when pulled on by gravity. The reason was temperature. At the temperature of absolute zero, these systems would indeed settle to the lowest energy. Temperature, however, causes a random motion of the atoms that opposes the tendency toward minimum energy. Small randomly moving atoms tend to spread out; they have a natural tendency to increasing their disorder. That tendency is greater at higher temperatures. An additional quantity besides energy is needed to describe how thermodynamic systems behave. That quantity is called **entropy**, a measure of disorder in a system. A nicely organized crystal like diamond has a very low entropy, a liquid has some entropy, and a gas has a high entropy.

It is a combination of energy and entropy that determines the state of a thermodynamic system. In our evaporation simulation, some liquid atoms were driven by thermal energy to evaporate and increase the system's entropy. That process continued until there was a balance between the tendency for minimizing energy by being held in the liquid and increasing entropy by flying around in the vapor.

It is easy to mix two colors of paint. Just pour one into the other and stir a bit. Unless the colors chemically react, the energy of the mixture is essentially the same as when they were not mixed. But, the separated paints had a low entropy and the mixture has a higher entropy. Decreasing entropy is hard and requires energy. For example, the blended paint might be separable by using a centrifuge if the molecules of the original colors have different masses, but the centrifuge requires energy. The source of that energy, however, is causing an increase of entropy elsewhere in the Universe.

A living organism uses its food and chemical reactions to keep its entropy low – to stay organized. A living organism is a highly-organized collection of chemicals, but once it dies, it quickly becomes disorganized. It decays to less-organized chemicals. To keep living, an organism takes in organized (low entropy) food and excretes less organized (higher entropy) waste which only bacteria can use. To keep its own entropy low and stay alive, a living organism increases the entropy of its surroundings.

All systems increase the entropy of the Universe as they perform their local organization. It is often stated that the Universe is headed toward an entropy death where billions of years from now the entropy of the universe will be increased to the point where all its energy will become too spread out to power stars.

Maybe when we understand more about black holes or quantum mechanics, we may learn of a way around these laws. The fundamental laws of particle interactions seem to allow all processes to reverse, but the probability of a disorganized system composed of a huge number of randomly-moving particles adopting an organized configuration is negligibly small. There are just too many possible disorganized configurations. Mixing two colors of paint is easy; separating them again is exceedingly difficult.

Thermal Conductivity

I bring three 20-cm long rods to the lab, one made of glass, one of stainless steel, and one of copper. I also bring a propane torch. A student volunteer holds one end of a rod while I use the torch to heat the other end until it glows a dull red (about 900 ºC). For the stainless steel and glass rods, the student feels no significant heat even after a minute, but for the copper rod heat is felt in about 20 seconds. For each rod, I then take it and very carefully touch closer and closer toward the end that had been heated. For the stainless steel and glass rods, I start to feel a very abrupt increase in heat as I approach to about 2 cm from the heated end. For the copper rod, that point is about half way to the end.

The property of the materials governing their efficiency at carrying heat is called **thermal conductivity**. Clearly, stainless steel and glass have low thermal conductivities while copper has a high thermal conductivity. When building an apparatus to do experiments at temperatures near absolute zero, we use stainless steel where we want thermal isolation and copper where we want uniform temperatures.

Heat Capacity

People desiring overnight warmth use hot water bottles to hold heat. This was very common in older days when houses were only heated by a fireplace. An alternative to hot water was rocks from the fireplace, but experience showed the water held heat much better than the same mass of rock. The measure of how well a material holds heat is called its **heat capacity** (a related term is **specific heat**). For each 1 K of added temperature, 1 kg of water holds 4181 J while 1 kg of granite rock holds about 750 J. Living near a lake shore or the ocean provides a more constant air temperature than living far from large bodies of water.

Heat Engines

Heat engines involve heat flow, work, and temperature differences. A refrigerator uses electrical energy to run a compressor that does work on a gas to move heat from a lower temperature to a higher temperature. A steam engine uses high temperature heat to power a piston doing work while exhausting leftover heat to a lower temperature.

The details of these devices are quite complicated, but the analysis reduces to the following two simple facts:

$$\textbf{Refrigerator:}\quad \textbf{low temperature heat} + \textbf{work received} = \textbf{high temperature heat}$$

$$\textbf{Steam Engine:}\quad \textbf{high temperature heat} - \textbf{work performed} = \textbf{low temperature heat}$$

Heat and work are both measures of energy and usually would have units of joules, but the long history of heat engines causes us to usually often use calories as a heat unit. The conversion factor between calories and joules, 1 cal = 4.186 J, is given on page 2 of the Equation Sheet at the end of the Chapter 4 section.

If a refrigerator takes 3000 calories from its interior and deposits 5000 calories to its exterior, its motor must do the work W_{required} given by

$$\boldsymbol{W_{\text{required}} = \left(4.186\,\frac{\text{J}}{\text{cal}}\right)\cdot\left(Q_{\text{out}} - Q_{\text{in}}\right) = \left(4.186\,\frac{\text{J}}{\text{cal}}\right)\cdot\left(5000\ \text{cal} - 3000\ \text{cal}\right) = 8372\,\text{J}}$$

If a steam engine takes 5000 calories of steam from its boiler and its pistons expel 3000 calories of exhaust steam, it has done an amount of work $W_{\text{performed}}$ given by

$$\boldsymbol{W_{\text{performed}} = \left(4.186\,\frac{\text{J}}{\text{cal}}\right)\cdot\left(Q_{\text{in}} - Q_{\text{out}}\right) = \left(4.186\,\frac{\text{J}}{\text{cal}}\right)\cdot\left(5000\ \text{cal} - 3000\ \text{cal}\right) = 8372\,\text{J}}$$

To earn credit for this lab, report that you have done the following:

1. Read this entire note.
2. Read the Chapter 4 note about the thermodynamics of kindergarten kids.
3. Watched the following animated gifs linked to in the above pages:
    100 helium atoms at 12 K.
    100 helium atoms at 300 K.
    400 helium atoms at 12 K falling in a gravitational field.
    Neon atom puddle evaporating at 25 K
    Neon atom puddle evaporating at 40 K
    100 helium and 100 argon atoms at 300 K
4. Looked over the graph in the handout entitled "Ice to Steam" while reading the related narration in this note.