Names & Picture:

3.2 EVAPORATION

Most people are familiar with the fact that a small puddle of water on the ground will eventually disappear. This happens because of a process called evaporation. To begin our investigation of evaporation, we will first examine a quantity called the "wet-bulb" temperature.

Activity 3.2.1 What is Room Temperature?

a) Suppose two electronic temperature sensors are sitting in a room (22°C). One is initially surrounded by a piece of paper towel that has been soaked in warm (30°C) water, the other is open to the air. Sketch below your prediction for the temperature of the two thermometers over ten or so minutes.

Wrap the end of the sensor with just one layer of paper toweling, folded over, then taped closer to the handle than the tip.

If the stable temperature is 5-10 degrees higher, you can start data collection and take the thermometer out…

b) Now try the experiment. Set up the software to run for at least ten minutes. Then, get a cup of water that is warmer than room temperature (at least 5ºC warmer) and wrap the end of one of the temperature sensors with a small piece of paper towel and tape it securely in place. Place this sensor in the water and stir it around till the temperature stabilizes. When the temperature is stable and only about 5 degrees higher than the thermometer that's not in the water, start the program and take the thermometer out of the water and lay it down on the table (on top of some paper towels so the table doesn't get wet). When the program has finished running, print out a copy of your graph. Describe what happens. What is the lowest temperature reached by either thermometer?

c) Which of the thermometers do you think gives a better indication of "room temperature?" Why.

d) Based on your observation, what would happen if a thermometer wrapped in a towel soaked in 22°C water were left open to 22°C air. Do you think the temperature would drop below ~~27~~°C? Discuss this with your group and come to a consensus. **Hint:** was the paper towel in the last experiment ever at 22°C?

Should be
"…would drop below 22 C?"

e) Using your knowledge of temperature, what can you conclude about the motion of the molecules in the wet paper towel versus the room air?

"Wet" and "Dry" Temperatures

The temperatures you just took are referred to as "dry-bulb" and "wet-bulb" temperatures. You will have noticed that the wet-bulb temperature reading drops down below the dry-bulb temperature reading and then levels off to a constant value. It is this constant value that it called the wet-bulb temperature. Most students find it surprising that the wet-bulb temperature drops below the dry bulb. Why does this happen and what stops it from continuing to drop? The answer must have something to do with the wetness of the paper towel, since that is the only difference between the two thermometers. The following thought experiment will help you understand why this happens.

Activity 3.2.2 Evaporating Water

a) Consider a glass of water that has no lid on it. If you wait for a really long time, the water in the glass will have *evaporated*. Where must the water molecules be going.

b) Since boiling water also disappears (although at a much faster rate), do you think these processes (boiling and evaporating) are related? Explain briefly.

c) What causes specific water molecules to leave the water? Can *any* water molecule leave or only certain ones? Explain. **Hint:** When water is boiling, lots of molecules are leaving the water.

d) Remember that temperature is actually a measure of molecular motion. If the wet-bulb reading is lower than the dry-bulb reading, what does that tell you about the average motion of the molecules? Use this to explain how evaporation could be the cause of the wet-bulb reading being lower than the dry-bulb reading.

Checkpoint Discussion: Before proceeding, discuss your ideas with your instructor.

We have developed the idea that temperature is a measure of the average speed of the molecules. This means that the lower wet-bulb reading must be a result of slower moving molecules. However, the wet-bulb reading was originally at a higher temperature, which is a result of faster moving molecules. Clearly the average speed of the molecules around the wet-bulb thermometer is decreasing. Now, one way for the faster moving (water) molecules to slow down, is though collisions with the slower moving (air) molecules. The wet paper towel and the air are in *thermal contact* with each other, so at some point they should reach *thermal equilibrium* (i.e., they would reach the same temperature). However, this is not what we observed. Something *else* must be happening to cool the wet-bulb reading below the dry-bulb reading. This “something” is called evaporative cooling and is an example of a dynamic equilibrium (as opposed to thermal equilibrium).

Evaporative Cooling

Evaporation occurs when molecules leave the bulk liquid and move off into the air. As we saw when boiling water, the ability of molecules to leave the liquid is enhanced when the liquid temperature is greater. This should make sense, since faster moving molecules (and temperature is a measure of molecular speed) are more likely to have the necessary energy to break away from surrounding molecules. But the temperature of a liquid is only the measure of the *average* speed of the molecules. This means that some molecules are moving *faster* than average, while others are moving more slowly. Which are more likely to break free from the liquid? In fact, only the fastest moving molecules are in a position to break away. You observed this earlier when boiling the liquid. If all of the molecules could break free, then the entire cup of water would suddenly vaporize into steam. This in fact, is not what happened. It took some time for the water to boil away. So what happens as the faster moving molecules leave? The *average* speed goes down. Since temperature is a measure of this *average* speed, the temperature goes down as well. This is called *evaporative cooling*, since the evaporation process itself lowers the temperature.

Since heating the water hastens evaporation, one might wonder if qualities of the air (other than temperature) also affect evaporation. The answer, as you will soon discover, is yes. A clue is found in how we cool ourselves during exercise. Sweating uses the idea of evaporative cooling to lower your body’s temperature. If you are from New Orleans or another humid city, you might know from first-hand experience that this doesn’t always work. Sometimes sweating only makes you wetter. In particular, on a very humid day, sweating is a very inefficient means of cooling off. We’ll see why in the next section.

3.3 RELATIVE HUMIDITY AND DYNAMIC EQUILIBRIUM

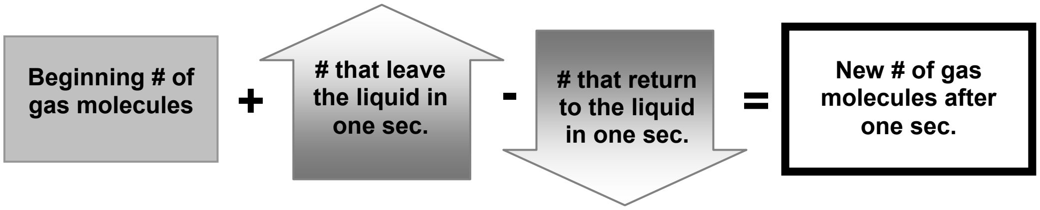
It is well known that placing a lid on a glass of water will prevent it from evaporating. The act of covering the water prevents molecules from leaving the glass. This seems reasonable enough, however, the cover is not in contact with the surface of the water so how can it possibly prevent molecules from leaving the water? Shouldn’t the water continue to evaporate? This question is the addressed in the following activity.

Activity 3.3.1 Dynamic Equilibrium

a) If the cover on the glass of water cannot prevent molecules from leaving the water, what do you think happens to the molecules that *do* leave the water? Where do they go?

b) We observe that in a sealed container the water level does not change. This means that the total number of molecules in the liquid is not changing. However, some water molecules are leaving the liquid (the fastest moving ones). How can you reconcile these two seemingly contradictory facts? **Hint:** What must be happing in order for the number of molecules in the liquid to remain constant?

c) If the total number of molecules in the liquid is not changing, yet some molecules are *leaving* the liquid, then it must be the case that some of the gaseous water molecules are *returning* to the liquid. In fact, if the total number of molecules in the liquid is not changing, then the number that leave must be equal to the number that return. If more molecules leave the liquid than return, then the water will slowly disappear. If we know how many molecules are leaving and returning to the liquid each second, then we can determine how the number of gaseous water molecules changes as shown schematically in the figure below.



Now, imagine a glass of water that is sealed with a lid. Imagine further that at the instant the lid is placed on the glass, there are no water molecules in the gaseous state (they are all still in the liquid). After a short time, some of the liquid molecules have evaporated and become gaseous water molecules above the liquid. Since the surface of the liquid water does not change its size, it is reasonable to assume that the same number of water molecules leave the liquid every second. Let’s assume for the moment that 100 molecules leave the liquid every second.[7] We need to devise a model for how the molecules might return to the liquid. We could assume that this process is similar to evaporation. That is, every second a certain number of molecules return to the liquid, regardless of other factors. On the other hand, we could assume that the number of molecules that return to the liquid depends on the number of gaseous water molecules above the liquid. Discuss with your group which of these two ideas seems more realistic. Explain your reasoning below.

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[7] In fact, the number of molecules evaporating each second depends critically on how much of the water is exposed to the air. Still, a more realistic estimate of this number would be one hundred million billion or 10^{17} molecules every second.

d) Most students find it more realistic to assume that when there are a small number of gaseous water molecules, there will be a small number returning and when there are a large number of gaseous water molecules, there will be a large number returning. A simple way to model this is to postulate that a certain percentage of the gaseous water molecules will return to the liquid each second. For simplicity, let's assume that 50% of the gaseous molecules return every second. Using these assumptions, we are now in a position to determine the number of gaseous molecules as a function of time. This calculation has been started in the table below. Complete this table, rounding your results to the nearest whole number. Note that the number of gas molecules one second later (right column) becomes the beginning number of gas molecules for the next second.

Time (sec)	Beginning # of gas molecules	# leaving (constant) # returning (50% of # at left)	New # of gaseous molecules one second later
0	0	100 0	100
1	100	100 50	150
2	150	100 75	175
3	175	100	
4			
5			
6			
7			
8			
9			
10			
11			
12			

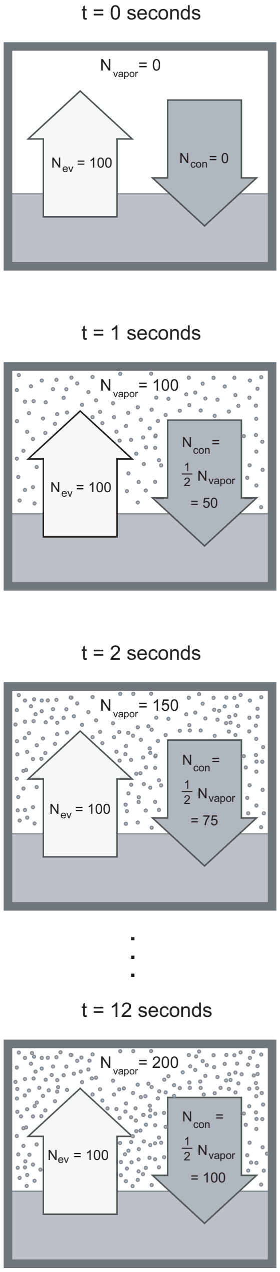

Figure C-11: If molecules leave (evaporate) the liquid at a constant rate N_{ev} each second and return (condense) to the liquid at a rate N_{con} per second proportional to the number of molecules in the gaseous phase, the system will eventually reach a dynamic equilibrium in which the total number of molecules in the gas (vapor) phase (N_{vapor}) is constant.

e) Describe what happens after about 10 minutes, and using the data from your table, make a rough sketch of the number of water molecules in the gaseous state as a function of time.

Gaseous water molecules are also referred to as *water vapor*. Thus, the graph you just made depicts the amount of water vapor in a sealed container as a function of time. Initially, the amount of water vapor increases quite rapidly, but then levels off to a constant value. This happens when the *evaporation rate* (number of molecules leaving the liquid each second) is exactly equal to the *condensation rate* (number of molecules returning to the liquid each second). This is what scientists call a *dynamic equilibrium*. This simply means that although the amount of water in the glass does not appear to be changing, it is actually losing and gaining molecules at exactly the same rate so that the average number of molecules in the liquid does not change. Although the mathematical model we used in the previous activity is quite simple, it captures the main features of evaporation in a closed container. In reality, the actual percentage of molecules evaporating and returning both depend on many factors, such as temperature and the amount of air above the liquid.

When the rate of evaporation is equal to the rate of condensation, we say that the air is *saturated*. This simply means that no more water molecules can coexist with the air. If more water molecules are placed into the air, they simply *condense* back into liquid water. Thus, there is no *net* evaporation. This is why a glass of water that is covered will not disappear. After a little time, there is enough water vapor coexisting with the air above the liquid so that an equal amount is being condensed back into the water as is being evaporated away. The amount of water vapor that can co-exist with the air at saturation is called the *equilibrium value* and must be experimentally determined. It has been observed that the equilibrium value for water vapor in air increases as the temperature increases.

When the amount of water vapor is far from its equilibrium value, the rate of evaporation is much larger than the rate of condensation and there is a net evaporation. But as the amount of water vapor in the air gets closer and closer to its equilibrium value, the number of molecules that condense back into the liquid state increases and this slows down the net rate of evaporation. Thus, things evaporate more quickly when there is a small amount of water vapor in the air and things evaporate more slowly when there is a large amount of water vapor in the air.

Evaporation, Humidity, and "Wet" and "Dry" Temperatures

Remember that this investigation started with the observation that a thermometer surrounded with a damp towel read a *lower* temperature than a dry thermometer. This led to the idea of evaporative cooling and the factors that affected evaporation. We now return to our wet and dry thermometers for a thought experiment.