Chapter 3:

Solids, Liquids, and Gases

The Lament Configuration is a box that's used to summon Cenobites that will drag you into Hell. It is also a solid.

3.1: Solids, Liquids, and Gases

Unless you're a huge idiot, you're already well aware that there are three main states of matter: Solids, liquids, and gases. If you are a huge idiot, then here's some news for you: The three states of matter are solids, liquids, and gases.

Solids are materials that have a defined shape and volume. For example, if you have a solid that's shaped like a bunny rabbit and has a volume of 50 cubic centimeters, you'll have the same bunny rabbit-shaped solid with a volume of 50 cubic centimeters when you look at it tomorrow.

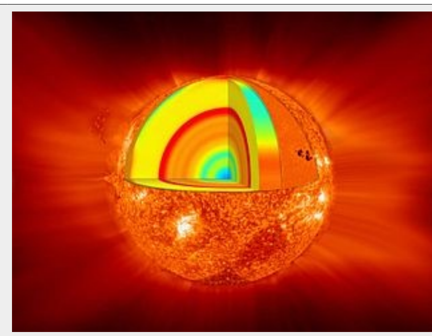
Liquids have defined volumes, but no defined shape. If you've got 50 mL of water in a glass and turn the cup upside down, the shape of the water will change as it splatters all over the place. However, the overall volume of the liquid will stay the same.

Gases have neither defined shapes nor volumes. If you pop a 1 L balloon full of helium, the helium will fly around all over the place, eventually filling the room you're in.

Gases are one of the main causes of people getting ejected from Thanksgiving dinner.

What about other states of matter?

In addition to solids, liquids, and gases, there exist other states of matter. Namely, plasma, Bose-Einstein condensates, neutron-degenerate matter, and quark-gluon plasma. Of these, plasma is the most common, with stars being made almost entirely of plasma. However, because plasma is an extremely high-energy state of matter and shares some similarities with gases, we're not going to talk about it.



This is what the sun would look like if you cut it open like an orange.

The Kinetic Molecular Theory of Gases

The **kinetic molecular theory of gases** states that you can figure out the properties of gases is you understand the motion of gas particles. The “kinetic” part of this theory's name refers to the constant motion of gas particles.

Here are the underlying assumptions we use in the kinetic molecular theory, and their implications for the observed behavior of gases.

- **Gas particles are always moving around in random directions**. If you think of gas particles as being really fast bouncing balls, this should give you an idea of what they look like. If you've got a gas, the molecules are always flying around at very high speed[1], and they fly around completely at random.

When children play they also move around in random directions.

- **Gas particles don't interact with each other**. If gas molecules are flying around at high speed, they won't interact much. Because of this, we can assume that all gas molecules follow the same rules, regardless of what gas we're talking about.

- **Gas particles are infinitely small**. Since gas molecules tend to be really really far away from each other, it's not unreasonable for us to make the simplifying assumption that their volume is insignificant when compared to that of the overall volume of the gas.

- **Gas particles move faster when their temperature increases**. When you put energy into a gas, the molecules have to do *something* with it. That *something* in this case is that they move faster.[2]

To summarize, gas molecules are infinitely tiny particles that don't interact with each other but bounce all over the place at speeds proportional to their temperatures. Gases that behave like this are called **ideal gases**.

---

1 *The particles in dry air move at approximately 450 m/s (~1,000 mph).*
2 *Depending on how much energy you put into them, that is. If you put enough energy into them they start losing electrons, forming a plasma. Which makes it no longer a gas, exactly.*

An example of an ideal gas:

Ideal gases don't exist. They're fictional, like the island of Atlantis or Donald Trump. It's important, however, to remember than even if there are no ideal gases in the world, most gases in the real world behave almost exactly as if they were ideal. The kinetic molecular theory of gases may not be completely right, but it does an astonishingly good job of making a complicated phenomenon understandable.

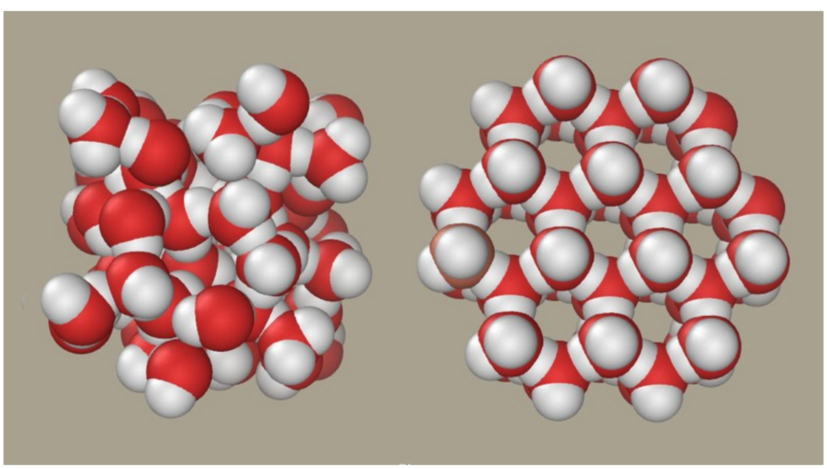
Unicorns breathe ideal gases and poop solid gold.

Why Liquids Behave the Way They Do

As mentioned earlier, liquids flow around all over the place but don't change their volume. This is because, unlike gases, their particles experience intermolecular forces. **Intermolecular forces** are attractive forces between the particles in a liquid, and they keep the particles in a liquid close enough together that they can puddle together. Though intermolecular forces are strong enough to keep liquid particles bound loosely together, they're not strong enough to lock everything permanently in place as in a solid.

The Deal With Solids

If the forces between them are strong enough, the particles in a material won't just hang around each other, but will lock into place.[3] This locked-together bunch of particles is called a solid.



Water molecules are relatively unstructured in liquid water (left), but are aligned by attractive intermolecular forces to form an ordered crystal in ice (right).

3 *Depending on the type of solid, these forces can either be intermolecular forces, electrostatic forces, or covalent bonds.*

3.2: Gases

If you sit on a balloon, you probably already know that it pops. That's not exactly rocket science. However, let's explore *why* a balloon pops when you sit on it.

Pressure:

Pressure is equal to the force something has exerted upon it divided by the area over which it pushes. This may sound kind of complicated, so let's do a little experiment to see how it works.

- Step 1: Lie down and press a baking sheet on your stomach. Have somebody push on the baking sheet and record how it feels.
- Step 2: Replace the baking sheet with a knife and have somebody push on the knife.

Now for the big question: Why did the knife poke through your intestines while the baking sheet merely squished you a little? The answer: Pressure.

Here's how it works: If you apply some amount of force to the large area of a baking sheet, the amount of pressure on any particular spot isn't very high. However, if you put exactly the same amount of force on the point of a knife, the pressure is much higher because the area over which that force is exerted is much less. This is why the experiment killed you in Step 2 and not Step 1.

In retrospect, I probably shouldn't have made this a do-it-yourself experiment.

The SI unit of pressure is the pascal (Pa)[4], with the average air pressure at sea level equal to 101,325 Pa, or 101.325 kPa.

Other units of pressure

Though the pascal is the SI unit of pressure, there are a lot of other units in common usage. Meteorologists use the bar to measure air pressure, where 1 bar = 100 kPa. Chemists frequently use the atmosphere (atm), which is equal to 101.325 kPa. Torr and mm Hg (both of which are 1/760 of 1 atm) have been used in both chemistry and physics, while pounds per square inch (psi) are sometimes used in engineering and in Hg is still used in weather prediction and aviation. Just use Pa or kPa and save us all a lot of trouble.

This barometer is calibrated in dekatorr. As if life isn't hard enough.

4 *1 Pa is equal to one newton per square meter (1 N/m^2)*

How To Change The Pressure Of A Gas

My Uncle Henry passes a lot of gas after Thanksgiving dinner. When we were kids, we used to think it was funny to jump on him as he relaxed afterward because he'd always pass gas. Then one day he barfed instead and things were a lot less funny.

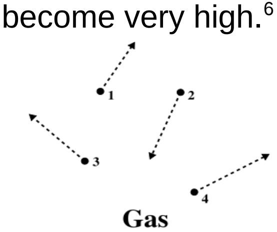
Uncle Henry now spends Thanksgiving with the birds in the park.

In any case, what we learned is that we could affect the pressure of the gas in Uncle Henry's colon by jumping on him. Let's figure out what else would have this effect.

- **Temperature affects pressure:** If you make a gas very hot, the particles of gas move more quickly. Because fast particles will hit the walls of their container harder than slow ones, the pressure inside will increase[5]. Instead of jumping on him, we could have made Uncle Henry pass gas by heating him up.

- **Volume affects pressure:** If you squish a gas, the particles get all crammed together. Because there's less space for the molecules to move around in, they'll hit the walls of the container more often, resulting in higher gas pressure. By squishing Uncle Henry, we decreased the volume of his colon, which resulted in an increase of pressure. Until he farted, that is.

- **Number of gas particles affects pressure:** If you've got a lot of gas particles in a container, they'll hit the walls more often than if you didn't have as many of them. An example of this is found in scuba tanks, where pushing a whole lot of gas into the tank causes the pressure inside to become very high.[6]



Science textbooks always contain a diagram like this. Enjoy!

5 *Imagine throwing a tennis ball at a wall vs. shooting it at the wall with a cannon. Clearly, the one shot through a cannon will exert more pressure on the wall.*

6 *The pressure inside an 80 cubic foot scuba cylinder is approximately 3,000 psi, or 20,000 kPa.*

The Combined Gas Law

Now that we've said that the pressure, volume, and temperature of gases are related to each other, it's time to write it down in the form of cool, solvable equations. Because who doesn't love equations? Especially one that combines them all. Like the combined gas law:

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

In this equation, P_1 is the initial pressure of the gas, V_1 is its initial volume of the gas, and T_1 is its original temperature (in Kelvin). Likewise, P_2 is the final pressure of the gas, V_2 is its final volume, and T_2 is its final temperature (also in Kelvin).[7]

Example: If I have 2.0 liters of a gas at a temperature of 280 K and a pressure of 110 kPa, what will the new volume be if the temperature is raised to 330 K and the pressure is decreased to 95 kPa?

Answer: 2.0 L is our initial volume (V1), 110 kPa is our initial pressure (P_1), and 280 K is our initial temperature (T_1). Likewise, we have 330 K as our final temperature (T_2) and 95 kPa as our final pressure (P_2), while V_2 is what we're solving for. If we plug these into the equation, we get the following:

$$\frac{(110\,kPa)(2.0\,L)}{280\,K} = \frac{(95\,kPa)V_2}{330\,K}$$

and solving for V_2, we find the answer of 2.7 L

Why "Combined" Gas Law?

When three other gas laws are put together, we get the combined gas law. These laws are Boyle's law (which compares pressure and volume), Charles's law (which compares volume and temperature), and Gay-Lussac's law (which compares pressure and temperature). If your teacher makes you memorize all of these laws, don't worry too much about it – the combined gas law can be used to solve all of them.

Joseph Louis Gay-Lussac (1778-1850) believed in wearing the most ridiculous clothes available.

7 In case you forgot, you add 273 to degrees Celsius to find Kelvin. As a result, a temperature of 25 degrees Celsius would be equal to (25 +273) or 298 K.

3.3: Phase Changes

Ice turns to water. Water turns to steam. Steam turns to, well, nothing. It just kind of stays all steamy. Unless it condenses back to water. Which can be frozen again. One great big cycle of ice, water, and steam, conducted for no particular reason.

Phase changes occur when a material goes from being one state of matter to another, through either a net gain or loss of energy. Examples of phase changes include the following pairs of reversible processes:

- **Melting**: A transition from solid to liquid, as in the case of ice melting.
- **Freezing**: A transition from liquid to solid, as when ice is formed from water.

- **Vaporization**: A transition from liquid to gas, as when water boils. Vaporization occurs through boiling or evaporation.
- **Condensation**: When a gas cools to form a solid. Condensation happens on your bathroom mirror when water vapor condenses on the cooler mirror.

- **Sublimation**: When a solid turns directly into a gas, as is the case when dry ice disappears.
- **Deposition**: When a gas turns directly into a solid (see box below):

Sublimation and Deposition

If you've ever found an old container of ice cream in the fridge, you've probably noticed that some of it is all gummy and gross while ice crystals are all over the lid. The reason that this happens is that the solid water molecules in the ice cream undergo sublimation into the gas phase, and then are deposited again on the lid of the container as ice crystals. This process is called freezer burn.

These peas are freezer burned. Not that anybody would have eaten them anyway.

How Phase Changes Occur

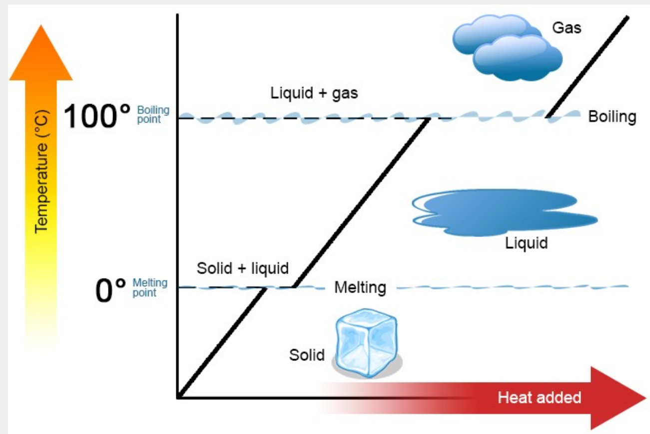
The idea behind phase changes is actually pretty simple. Let's say that we start with a big block of ice. The molecules of water in ice are all organized so that the forces between the molecules are maximized. Nothing much goes anywhere and the water molecules just wiggle around and chill.[8]

8 *Yeah, I said it.*

Now, let's say that we start increasing the temperature, which puts energy into the block of ice. As the ice heats up, the wiggling of the water molecules increases. Once there's enough energy added to the ice, the forces that are holding the water molecules together are no longer strong enough to lock them tightly in place, and the water melts into a liquid. The amount of energy that's absorbed by 18.0 grams of water when it melts is called its heat of fusion.

Temperature and Energy

As you add energy to ice, the temperature of the ice increases. However, once you hit the melting point of ice and the ice starts melting, extra energy doesn't keep heating up the ice/water mixture. Instead, the temperature of this mixture stays the same until the water has completely melted because all of the energy is used to disrupt intermolecular forces. Once this has been done, heating resumes.



This graph shows how the temperature water increases as energy is added to it. Note that during the melting and boiling steps, the temperature doesn't increase until the phase change is completed.

Likewise, if we add energy to liquid water, the molecules wiggle even more. When enough energy is added to the water, this wiggling becomes energetic enough to disrupt the forces between the molecules even more, causing the material to boil into a gas. The amount of energy it takes to vaporize 18.0 grams of water is called its heat of vaporization.

In a gas, there are essentially no intermolecular forces anymore. As a result, you can keep dumping as much additional energy into the steam as you want and no more phase changes will occur.

Vaporization, evaporating, and boiling

There are two ways that water can vaporize from the liquid to the gas phase: Evaporation and boiling. Here's how they work.

When water is heated, energy is dumped into it. This energy causes the water molecules to bounce around and overcome the forces holding them to each other.

As the temperature increases, some of the molecules get enough energy to overcome the forces faster than others. The molecules that vaporize early are said to evaporate and the pressure of these evaporated molecules is said to be the liquid's vapor pressure. As more energy is added, more molecules evaporate and the vapor pressure goes up. Eventually, when this vapor pressure becomes equal or greater to that of the surrounding air, all of the molecules start boiling.

Bathroom mirrors get steamy during hot showers and not cold ones because hot water has a higher vapor pressure (i.e. evaporates more) than cold water.

The Main Ideas In Chapter 3:

- The three states of matter we most often interact with are solids, liquids, and gases. On a molecular scale, they differ mostly in how tightly the particles are held to each other via intermolecular forces.

- The kinetic molecular theory of gases says that if you understand how gas molecules move around, you can understand the properties and behavior of the gases.

- The pressure, volume, and temperature of a gas are all related to one another according to the relationship in the ideal gas law.

- A phase change is when a material changes its state of matter. These processes are all reversible, and depend on how strongly the particles of the material interact with each other.

Image credits:

- **Gas mask**: By Ethbaal (Own work) [GFDL (http://www.gnu.org/copyleft/fdl.html) or CC-BY-SA-3.0 (http://creativecommons.org/licenses/by-sa/3.0/)], via Wikimedia Commons. A quick check on Wikipedia tells me that farts can be flammable if they contain methane, but that only five out of nine people in a study had methane in their farts. In other words, you've got just over a 50% chance of having flammable farts. Not that you should try it out or anything, because I knew a guy who did that and had some medical issues as a result. And no, it wasn't me.
- **Sun**: By NASA [Public domain or Public domain], via Wikimedia Commons. 98% of the sun is made of either hydrogen or helium.
- **Unicorn**: By Conrad Gesner (National Library of Medicine) [Public domain], via Wikimedia Commons. In the middle ages, alicorns (unicorn horns) were highly prized by European nobility. However, because unicorns are imaginary, these were usually just narwhal tusks.
- **Children playing with Legos**: By Jordiferrer (Own work) [CC BY-SA 4.0 (http://creativecommons.org/licenses/by-sa/4.0)], via Wikimedia Commons. All Legos, from the very first produced to those made now, interlock with each other perfectly.
- **Intestine**: By PPSE15 (Own work) [CC BY-SA 4.0 (http://creativecommons.org/licenses/by-sa/4.0)], via Wikimedia Commons. Shown here is a section of small intestine removed from a Crohn's disease sufferer.
- **Dekatorr barometer**: By Jean-Jacques MILAN, this image was modified by Frederic.marbach at fr.wikipedia (Transferred from fr.wikipedia to Commons.) [GFDL (http://www.gnu.org/copyleft/fdl.html) or CC-BY-SA-3.0 (http://creativecommons.org/licenses/by-sa/3.0/)], from Wikimedia Commons. The first barometer was made by Evangelista Torricelli, for whom the unit “torr” was named.
- **Uncle Henry**: http://www.cgpgrey.com [CC BY 2.0 (http://creativecommons.org/licenses/by/2.0)], via Wikimedia Commons. Uncle Henry is fictional, but for some reason I can't help but think of Henry Rollins when I read “Uncle Henry.” Which is odd, since Henry Rollins isn't at all fat.
- **Water and ice**: By P99am (Own work) [CC BY-SA 3.0 (http://creativecommons.org/licenses/by-sa/3.0) or GFDL (http://www.gnu.org/copyleft/fdl.html)], via Wikimedia Commons. This image, incidentally, does a nice job of showing why the water expands as it freezes, unlike most materials. As you can see, there's more space between the water molecules in the solid, which is why water is about 10% less dense as a solid.
- **Gas**: By User:Closeapple [Public domain], via Wikimedia Commons. Gasoline is called gas in the US and Canada for obvious reasons, and petrol in many other countries because it's a petroleum product. Another very common name for it is some version of “benzine” after the compound benzene (C_6H_6) which used to be more prevalent in gasoline than it is currently.
- **Gay-Lussac**: François Séraphin Delpech [Public domain], via Wikimedia Commons. Gay-Lussac's last name was originally just Gay, but his family owned a great deal of the town of Lussac so it was added to his name.

- **Peas**: By User:Ragesoss (Own work) [CC BY-SA 3.0 (http://creativecommons.org/licenses/by-sa/3.0)], via Wikimedia Commons. Small peas are considered to be more tender than large ones.
- **Heating curve**: By Community College Consortium for Bioscience Credentials (Own work) [CC BY 3.0 (http://creativecommons.org/licenses/by/3.0)], via Wikimedia Commons. If you want a really good view of what these phases look like on a heating curve, check out http://www.kentchemistry.com/links/Matter/HeatingCurve.htm.
- **Bathroom mirror**: By Yvwv (Own work) [Public domain], via Wikimedia Commons. A "looking glass" is a particular type of mirror that's used to admire oneself, as this apparently used to be a thing.