We all know the difference between solids, liquids and gases – at least we think we do. We learned about the states of matter as children: solids have a fixed size and shape; liquids have a fixed size but their shape changes to fit the container; and gases fill both their size and shape to fit their container. Another thing we know about solids, liquids and gases is how to change them: if you heat a solid it melts and if you heat a liquid it evaporates. You can reverse this by cooling a gas to condense it and cooling a liquid to freeze it. Those of us who have played with dry ice (frozen CO₂) know that heating certain solids causes them to 'sublimate', which means to go directly from solid to vapor.

But in the real world things aren't always so simple – not all solids are the same. Solids made of different materials can have very different properties. For example rubber is less rigid than iron – but iron is less brittle than most crystals. There is much variation in liquids, too – honey flows slower than water (when a liquid flows slowly it has a high viscosity). Cold honey flows so slowly you have to wait a long time to see it change shape – it has a very high viscosity.

**Particles, Bonds and Motions:**

Solids, liquids and gases are made of particles and their properties depend on how the particles are assembled. To understand solids, liquids and gases they must be viewed as a bunch of particles (this is called the "microscopic view" and uses "kinetic theory" which is the model of how particles move around in solids, liquids and gases).

**Everything is made of particles**

Particles are the building blocks of matter and we can think of them as tiny balls. For now, we don't need to know what the particles are (they can be atoms, ions, molecules, electrons ... the list is very long), we just need to know that different types of particles can have different types of connections between them and how they are connected affects the states of matter.

**Bonds are the connections between particles.**

The connections between particles are called 'bonds' – we can think of them as little springs sticking out of each particle which can attach to the springs of other particles. Just like real springs, bonds can vary in length and strength. Also the number of bonds and how they are arranged on a particle depend on the material. The number and position of these springs determines what types of patterns the particles can make and those patterns influence the properties of the material. For example the bonds of water molecules are very different than those of carbon dioxide molecules – these differences explain many of the differences in the properties of water and carbon dioxide. One key way the bonds influence the properties of the matter is by determining what motions are possible for each individual particle.

**Particles are always in motion**

When attached to other particles by spring-like bonds, particles have little freedom to move – they can typically move back and forth (or "vibrate"). The amount they move depends on temperature: if you crank up the heat the particles vibrate faster (in fact "heat" is a measure of the total energy of the moving particles). If the particles vibrate hard enough they can break some of the bonds and move more freely. The amount of motion of the particles (temperature) limits the possible bonds and that tells it whether it is a solid, liquid or gas.

**Inside Solids and Liquids**

Solids and liquids have their particles arranged with different internal structures and that makes them different. In solids, the particles are ordered in a fixed pattern with strong bonds so they can only vibrate – this gives solids a fixed shape and size. Solids only change shape when subjected to a force (i.e. to break, bend or cut them). In liquids, the bonds between particles are still important but weaker so they have enough energy to move about, so liquids do not have a fixed shape.

**Solids are well organized.**

In solids particles are ordered in a regular pattern called a "lattice". A lattice is like a Greek Phalanx (which is a military formation you may have seen in the movies). A phalanx has rows and columns of soldiers each carrying a spear and shield. For maximum protection the soldiers overlap their shields so each soldier benefits from his own shield as well as his neighbor's and they hold their spears so they pass between soldiers in the rows in front to provide a multi-pronged attack.

In a solid, the particles are held together by their bonds, and the pattern of the lattice depends on the type of bonds the particles have. Not all lattices have square grids with rows and columns, some may be triangular or hexagonal (some even look like the patterns on soccer balls). The bonds and lattice pattern determine properties of the material, like hardness, brittleness and melting point. Usually, stronger bonds between particles make a stronger solid but the geometry of the lattice is important, too, for example more interconnections between particles make stronger lattices. Also, some lattices are stronger in one direction than the others (jewelers take advantage of this to cut gems). The details are complicated so we will skip them but the bottom line is this: the way the particles are stuck together (i.e. the types of bonds and the pattern of particles) determines how they behave as a group.

Going back to the military analogy, not all military formations have the same structure and strength as a phalanx – its strength comes from its
rigidity and interlocking structure. This is good for a phalanx but does not suit, for example, archers and cavalry. They use different formations which match their needs and abilities (e.g. Archers need to concentrate fire on one target and switch to other targets; cavalry needs to move quickly and be able change direction quickly. We won't get into the formations used to accomplish this, but there are many references for the budding war-buff). This is analogous to how solids made of different particles have different properties – as the earlier examples of iron and rubber.

Some materials can form solids with different properties (this is called “polymorphism”). For example graphite, coal and diamond are all made of carbon. What’s the difference? The carbon atoms are arranged in different formations with different bonds. Going back to the army, we can compare polymorphism to reforming a phalanx into a long column better suited for marching down winding roads but much weaker in combat.

**Liquids are very flexible**

Liquids are not like rigid military formations which do not change shape easily – they are like ever-changing crowds of people, such as mosh pits. The rigid order of a phalanx provides strength but each individual is fixed in their relative position and they move how the phalanx moves. In a mosh pit each person can, with effort, move around and change position within the group making the whole mosh more adaptable and flexible.

In a liquid, there are weak, flexible bonds between the particles, which can be broken and reconnected to other particles. This allows individual particles to move around and means that they are not organized in a large, fixed lattice. They are in a random mish-mash (like a mosh). Changing one part of a lattice requires changes to the whole group (or at least to a lot of it) but with the randomness of a liquid, local changes do not always affect the whole. Liquids can change shape more easily because they can change bit by bit, breaking and changing a few bonds at a time rather than changing them all at once like a solid.

Although the particles are not tightly bound in place, their motion within the group is slowed by the resistance of the crowd. Each particle has to slide past the others, breaking and reforming bonds as it goes. The resistance to motion increases the viscosity of the liquid (how slow it flows) and depends on the types of bonds between particles. This is why some liquids flow more easily than others.

The flexible bonds of liquids give them the unique ability of being a solvent: particles of another material can mix in with the liquid particles and swim about going where ever the crowd goes. The loose bonds can accommodate particles with different sizes or shapes. The other material can start out as a solid, liquid or a gas but after dissolving, it joins the rest of the liquid solvent – and goes where the solvent goes. A solid’s particles are fixed in a lattice pattern and the particles of another material cannot mix in (but a solid can be melted, mixed with something and then be frozen – incorporating the new particles in its lattice ... but that is another story). Things cannot dissolve in a gas, normally, although different kinds of gases can mix. For example, the Earth’s atmosphere, which contains Nitrogen, Oxygen, a tiny bit of water vapor and traces of other stuff. But when the temperature drops, the water vapor turns liquid and rains down – the other gases cannot prevent this (every gas is on its own). Solvents are very important for chemistry (especially biochemistry) because dissolving different materials in a liquid brings them together so they can react.

**Some things are solidy-liquids or liquidy-solids.**

Solids which form lattice patterns are called “crystalline solids”, but some materials do not form crystalline solids, they form another type of solid (or are they liquids?). These are more random than solids but without the individual mobility like liquids and are called “glassy solids” or “super-cooled liquids” (see, even scientists cannot decide if these are solids or liquids!). They have properties of both a solid and a liquid – they look solid in the day to day world, but they flow but v-e-r-y s-l-o-w, so over millions of years (“geologic timescales”) they change shape. When heated, a glassy solid flows more quickly getting gradually softer until it is obviously liquid – like household honey, which is seemingly solid when cold and gets very runny when heated. This is different than crystalline solids which change from solid to liquid very distinctly: water is either solid (ice) or liquid (water) it does not gradually soften.

Glass, which is made of Silicon and Oxygen (it is a “silicate”), is a glassy solid (gee, no duh). Rocks and the Earth’s mantle are silicates and glassy solids, too, so they are glassy solids - and that helps explain how the continents can move around (called “plate tectonics”) over millions of years. [Note: maybe you heard that windows in old churches are thicker at the bottom because glass flows? Sorry, glass flows way too slowly for that to happen in a few hundred years – it is more likely that they just couldn’t make uniform window glass back in those days. Still, that urban legend had its heart in the right place.]

**Motion shapes structure.**

As mentioned before, particles are always in motion – or at least vibrating - and the amount of motion depends on temperature. Really, temperature is just a measurement of how much motion and vibration is going on. Particle motion affects the bonds and the structure of particles - the structure does not really limit the motion. If you increase the temperature, the motion (or vibration) increases and if it gets too much, the structure can change or fall apart. So raising the temperature of a solid can melt it, by breaking up the structure, allowing particles to move more freely. Heating a liquid can cause the particles to move so much that the loose flexible bonds will break and the particles will fly apart, moving freely and independently – as a gas.

**INSIDE GASES AND PLASMAS**

**Gases – the ultimate freedom of motion**

In a gas, the particles move so fast and are so far apart that bonds have little effect (in the case of an ideal gas they have absolutely no effect). Although they collide often, particles bounce off of each other without bonding, letting a gas change shape and volume freely to fill the entire container. Plasmas are another state of matter, very much like gases. Most of this discussion applies to both gases and plasmas. We will discuss the special properties of plasmas at the end of this section.

If solids are like military formations and liquids are like mosh pits, gases are like children on a playground running around and using all the room they can. Playground children run freely mixing with each other without sticking together in tight groups (at least in this analogy, there is no cliquish behavior). The bonds do not matter because the particles move freely so it doesn't matter much what they are made of. Gases can change shape and size, but they follow the ideal gas law: \( PV = nRT \) To understand gas, we need to start with what each letter stands for.
P is pressure, which is how hard the gas pushes or presses on its container and itself.

V is volume, which is how big the container is or how much space the gas has to move in.

n is the number of particles, or how much gas is in the container. It doesn't matter if the particles are atoms, molecules or even protons or neutrons n is the number of them.

R is the gas constant, which is important to do calculations and make all the numbers work out right, but we just want to understand the concepts so we can ignore it and we will from now on!

T is temperature, which is "how hot it is." This is what thermometers measure but although we all known about temperature it is tricky to define exactly what it is.

These basic descriptions are fine on the general level, but we need more to truly understand gases. Fortunately, volume and number are pretty simple so the basic understanding is all we really need to know. We just need to dig a little deeper into pressure and temperature.

Macroscopic view of pressure

This is what we measure with pressure gages, it is force per unit area – or how concentrated a force is. In the United States we measure gas pressure in pounds per square inch (PSI) – one PSI is one pound of force on each square inch (Wait – a 'pound' is a force? I thought it was weight! It's both: an object which weighs one pound, sitting on a bathroom scale pushes on it with a force of one pound – which is why it can compress the spring and make the scale register one pound.) At sea level, the Earth's atmosphere has a pressure of 14.7 PSI – yes, almost 15 pounds is pressing down on every square inch of you. (No wonder it is so hard to get out of bed!) Pressure isn't only used for gases – we can talk about the amount of pressure of a shark bite. Or, consider if a 100 pound woman steps on your foot with stiletto heels (with an area of \( \frac{3}{4}'' \times \frac{3}{4}'' = 0.0625 \) sq in) – the pressure is 1600 psi. For comparison, urban legends claim that a Pit Bull's bite is 1800 psi (weaker sex, yeah, right!) We don't always use PSI to measure pressure, we can use "bars" (1 bar = 14.7 PSI) or millimeters of Mercury, etc. However we measure it, pressure is how much gases push on each square inch of the walls of their containers.

Microscopic view of pressure (from the kinetic theory of gases)

Kinetic theory is a model of a lot of particles moving and bouncing around and the effects of their motions and bounces. The effect of the particles hitting the container walls (and each other) is called pressure. The harder they hit and the more frequently they hit, the more they push on the walls; IOW: the greater the pressure. When looking at it this way, pressure is simple.

Macroscopic view of temperature:

Temperature is "how hot something is." But what does it mean to be 'hot'? One of the most common misconceptions about temperature is that it is the same as "heat" – which is a form of energy. For example, to melt ice we need to add energy in the form of heat. We can see that heat and temperature are not the same by putting some ice in hot air and in hot water – both with the same temperature. The ice in the hot water will melt faster because water contains more heat than air does (if they are at the same temperature).

Actually, this isn't the best test, it would be better to measure how much ice can be melted with hot water vs. hot air – the higher amount of heat in hot water can melt more ice than that in hot air. So if temperature is not heat what is it? Temperature 'tells heat where to go. Heat always goes from a high temperature object to low temperature one – even if the low temperature one already has more heat (remember the example with air and water?) This little fact about temperature makes it easier to air-condition buildings.

It is easily to confuse heat and temperature – we think our body senses temperature (hot and cold) but really it senses heat flow (we gain heat or lose it) To see that this is true, note that when walking on a cold tile floor we feel the cold, but when we step on the rug (which has been sitting on the floor day after day so it has to be at the same temperature) we don't feel the cold. Why? Because heat doesn't flow from our feet into a rug as well as it flows into tile. Tile conducts heat but rugs don't. So we cannot actually feel the temperature of things which are good insulators.

Microscopic view temperature (from kinetic theory)

The particle definition of temperature is a bit more straightforward than the every-day macroscopic view: temperature depends on the average speed of the particles. Specifically, temperature is the average kinetic energy of the particles in the gas (times a constant). Kinetic energy is the energy of motion: a fast moving object carries a lot of energy with it, the faster it goes the more energy it has. This is why high speed car accidents cause more damage than low speed ones. But kinetic energy depends on more than speed – it depends on mass. This is why having a train hit you causes more damage than having a car hit (at the same speed). When we're dealing with gases made out of one type of particle we don't have to worry about the mass of the particles - temperature is how fast the particles are moving. When we're dealing with a mixture of particles, we just need to remember that the lighter particles are moving faster than the heavier ones.

Putting it all together: \( PV = nT \)

The gas law tells us how pressure, volume, number and temperature of a gas are interrelated, especially that if we change any one of these properties of a gas, at least one other one must change. There are two ways to understand this about gases, using the equation and thinking about particles. People who understand equations don't really need much explanation how to interpret the gas law, but everyone can benefit from thinking about what the particles are actually doing.

Some examples:

Consider putting a sealed air tank in a fire. The tank is rigid which means it has a fixed volume and being sealed, the number of particles cannot change. The fire raises the temperature, which means the particles move more rapidly, this means when the collisions with the walls are stronger. So the pressure increases. Looking at the equation, we see that this is true - if the temp doubles so much the pressure.

Now consider the same situation except the air tank is equipped with a pressure relief valve. The valve vents excess pressure by letting gas escape and keeps the pressure constant. The volume is, again, constant. Now when the temperature goes up, the more energetic particles push against the relief valve and it lets out some gas, lowering the number of particles. From the equation, if
Suppose you fill an air tank while keeping the temperature from changing (you could fill it slowly while keeping it partially immersed in a liquid which would add or remove heat to compensate for any temperature changes). Temp and volume are constant. Adding gas increases n so there are more particles to collide with the walls of the container. More collisions mean higher pressure. Again, this is consistent with the equation, if T & V are constant, increasing n, causes an increase in P.

Now let's switch to examples using a cylinder with a moving piston which allows the volume to change to keep the pressure constant. Let's heat it and let the piston slide so the pressure remains constant. As the particles speed up and collide with the piston, which will move until the pressure returns to the original level. Clearly the volume will increase with temperature as the equation requires: if P & n are constant, V & T must increase the same.

We can push in the piston keeping the temperature constant (we could use a chiller), then as the volume decreases the particles hit the walls more frequently and as a result the pressure increases. Again, this is what we expect from the equation.

There are many other examples, but these are enough to show how gases respond to changes and that you have to know what happens to three properties to figure out what happens to the fourth.

The problem with using this equation with planetary atmospheres, it is hard to measure the volume and number of particles in a planet's atmosphere. We can use \( \rho \) (this is the Greek letter "rho" which represents density) in place of \( n/V \), giving us \( P = \rho \, T \). This is better for working with atmospheres first because density is easier to measure than \( V \) & \( n \) and the density at lower levels is greater than that in higher levels so we can more easily deal with those variations.

Additionally, with this simplification, we only need to know what happens to TWO properties to figure out the third. If the temperature is constant (the isothermal condition) then pressure and density do the same thing. If pressure is constant (isobaric) then density and temperature change in the opposite direction. If the density is constant (isochoric), then P & T vary together.

This simplification of the gas law also helps us understand the concepts of gas behavior -- it all depends on how fast the particles are moving (temperature), how hard they hit the walls (pressure) and how spread out they are (density). Most importantly, these three properties depend on each other.

**Plasmas – Just Ionized Gas.**

The fourth state of matter is plasma, which is an ionized gas. The gas law applies to plasmas, too, so we can treat plasmas just like regular gas most of the time. The main difference is ionized gases conduct electricity very well -- they should, because they have a bunch of free electrons moving around (and moving electrons make up electric currents). Any time you see a gas with electricity running through it you can bet it is a plasma: fluorescent lamps, sodium vapor lights, and halogen lamps all contain plasma.

Along with conducting electricity well (actually, because they conduct electricity well) plasmas have a special relationship to magnetic fields. Plasmas cannot cross a magnetic field line -- but it can move along one. This is because of the free electrons zipping around in plasmas but the details get very technical very fast so we won't delve into them.

Plasmas usually have a high temperature, because if the particles are not moving around quickly, the electrons are likely to rejoin the atoms and ‘de-ionize.’ So the way to turn a gas into a plasma is to heat it up (and the higher particle speed means that collisions will 'knock loose' electrons and ionize the gas). There is a trend from solids (at low temperatures), to liquids, gases, and finally plasmas (at high temperatures). As the temperature rises the particles move faster and faster -- breaking more bonds until the electrons break free of the atoms. (So it should be noted that plasmas don’t usually have any molecules because they break up before the electrons break free).

**PHASE DIAGRAMS: MAKING SENSE OF IT ALL**

Temperature has a role in the states of matter, but so does pressure. Anyone who has used a pressure cooker knows that water stays liquid at a higher temperature if it is at higher pressure (and the flip side is that mountaineers know that water boils are a lower temperature at high altitudes, where the pressure is lower -- this means it is harder to brew your morning cup of java in the mountains).

To sort out how temperature and pressure both affect the states of matter, scientists came up with the "phase diagram" which shows the ranges of P & T where a material is solid, liquid or gas. The figure shown below is a phase diagram for water (H2O). The colored regions are marked for solid, liquid or gas. There are many, many things we could study in a phase diagram to help us understand the properties of the material, but we are only going to take a look a few of them.

First there is a point where the curved line bordering the vapor region connects with the straight(ish) line separation solids and liquids. At this point, H2O can exist as ice, water and vapor all in equilibrium (balance) -- it is called the triple point. It is often near the lowest temperature that the material can possibly be liquid, and is at the lowest pressure that it can be liquid.