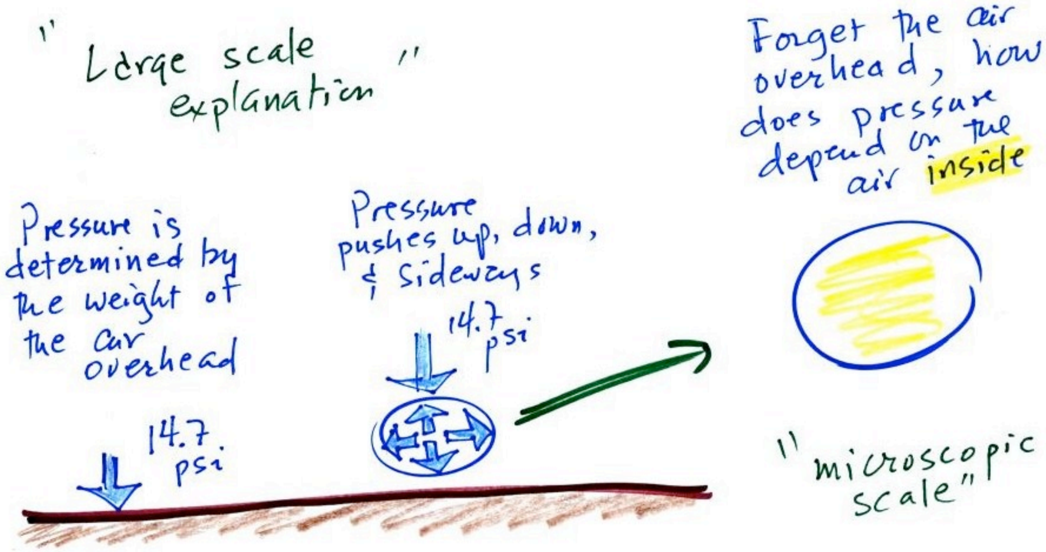
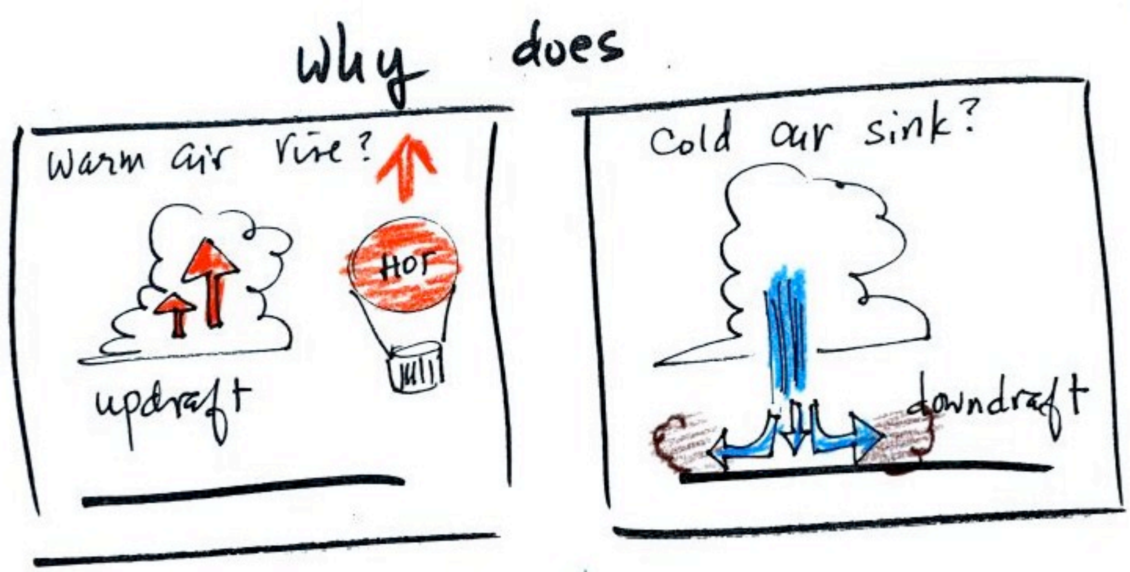
Module 2: Lecture 6

Up to this point, we have been thinking of pressure as being determined by the weight of the air overhead. Air pressure pushes down against the ground at sea level with 14.7 pounds of force per square inch. If you imagine the weight of the atmosphere pushing down on a balloon sitting on the ground you realize that the air in the balloon pushes back with the same force. Air everywhere in the atmosphere pushes upwards, downwards, and sideways.



The relatively warm air in a thunderstorm updraft is warmer than the air around it and rises just like a hot air balloon. Conversely cold air sinks. The surface winds caused by a thunderstorm downdraft (as shown above) can reach speeds of 100 MPH and are a serious weather hazard.

.

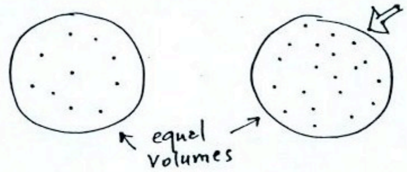


Understanding the ideal gas law is the first step in explaining what actually causes air to rise or sink. The ideal gas law equation is another way of thinking about air pressure on a microscopic scale view. We ignore the atmosphere and instead concentrate on just the air inside a small volume or balloon or parcel of air. We are going to "derive" an equation that shows how pressure (P) depends on certain properties of the air inside the balloon. The word "parcel" means a small volume of air.

$$P = \frac{?}{?}$$

IDEAL GAS LAW

(A) Pressure depends on the number, N, of air molecules.



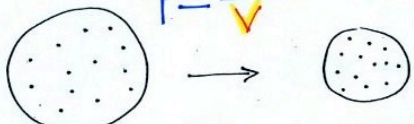
more molecules, more collisions = higher pressure.

$$P = \frac{N}{\quad}$$

Pressure, P, is directly proportional to N.

(B) A gas can be compressed or may expand. The volume, V, can change while N remains constant.

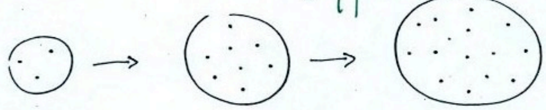
$$P = \frac{N}{V}$$



more frequent collisions with smaller surface area = higher pressure.

Pressure is inversely proportional to V.

Note: If N & V change in such a way that the ratio $\left(\frac{N}{V}\right)$ remains constant, P will not change. Note: This is exactly what happens in Expt. #1



Expt 1

Part A of Figure

The pressure produced by the air molecules inside a balloon will first depend on the number of air molecules, N, in the balloon. As you add more and more air to a fixed volume (like a bicycle tire), the pressure increases. If there were no air molecules there would be no pressure. Pressure is directly proportional to N so that an increase in N causes an increase in P. If N doubles, P also doubles (as long as the other variables in the equation do not change).

Part B of Figure

Air pressure inside a balloon also depends on the size of the balloon. Pressure is inversely proportional to volume, V . If V were to double, P would drop to 1/2 its original value.

(C) Temperature*, T, is a measure of the average speed of the gas molecules.

incr. in temp. → increased speed → more force per collision, more frequent collisions = higher pressure.

P is directly proportional to T.

* The absolute or Kelvin scale (K) must be used. Temperature is never negative on this scale.

$$P = \frac{NT}{V}$$

(D) Mass of the molecules? No mass doesn't appear in the equation.

$\left.\begin{array}{l}\text{Large molecules move slowly} \\ \\ \text{Small molecules move rapidly}\end{array}\right\}$ The two effects compensate. The pressure of a gas does not depend on the type of gas.

Part C of Figure

Increasing the temperature of the gas in a balloon will cause the gas molecules to move more quickly. They will collide with the walls of the balloon more frequently and rebound with greater force, thereby increasing the pressure. Propane tanks are very hazardous to firefighters because the heat can cause the tank to explode.

Surprisingly, as explained in **Part D**, the pressure does not depend on the mass of the molecules or the composition of the gas. Gas molecules with a lot of mass will move slowly while the less massive molecules will move more quickly. They both will collide with the walls of the container with the same force.

Note
It is possible to keep pressure constant by changing N and V together in just the right kind of way. This is what happens to the oxygen concentration described in the following experiment. Oxygen in a graduated cylinder reacts with steel wool to form rust. Oxygen is removed from the air sample which decreases N. As oxygen is removed, water rises up into the cylinder decreasing the air sample volume. N and V both decrease in the same relative amounts and the air sample pressure remains constant. If you were to remove 20% of the air molecules, V would decrease to 20% of its original value and pressure would stay constant.

The figure below shows two forms of the ideal gas law. The top equation is the one we just derived and the bottom is a second slightly different version. You can ignore the constants k and R if you are just trying to understand how a change in one of the variables would affect the pressure. You only need the constants when you are doing a calculation involving numbers (which we will not be doing).

$$p = \frac{kNT}{V}$$

k and R are constants

ρ = density

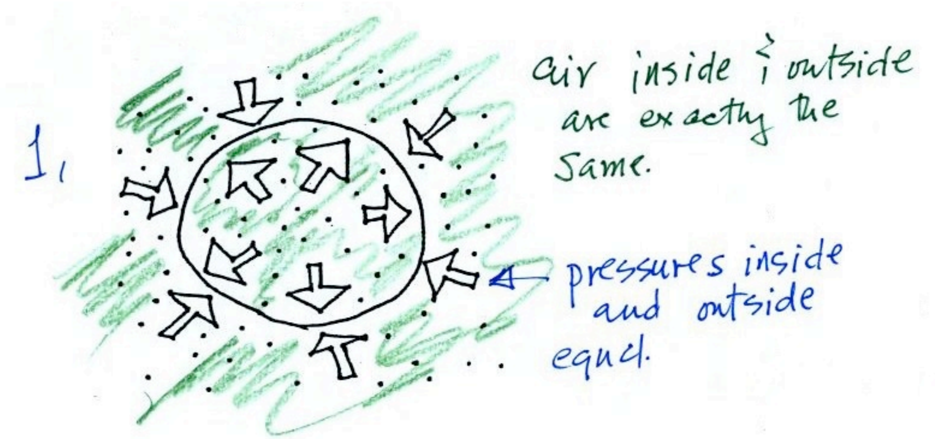
"rho"

$$p = R\rho T$$

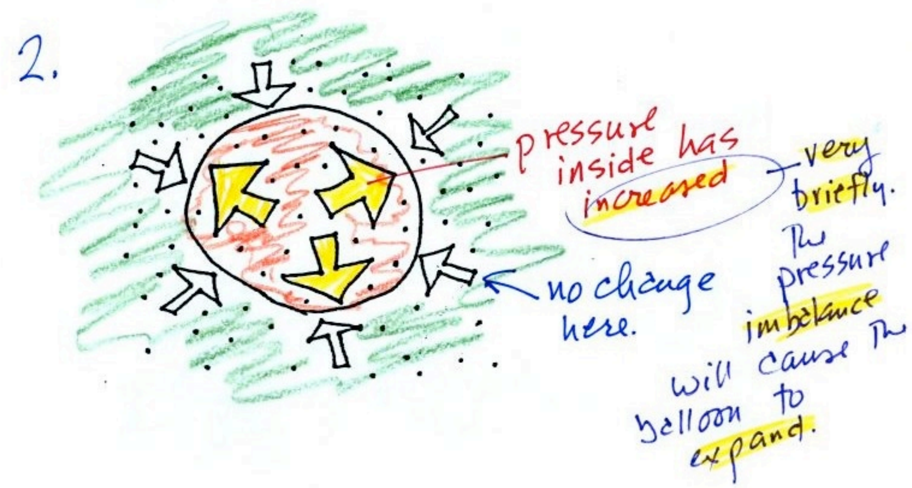
Here is a link to a video which explains the ideal gas law. You may not understand all the terminology, but it is still a helpful tool.

Charles' Law is a special case involving the ideal gas law. Charles' Law requires that the pressure in a volume of air remain constant. T, V, and density can change but they must do so in a way that keeps P constant. This is what happens in the atmosphere. Volumes of air in the atmosphere are free to expand or shrink. They do so to keep the pressure inside the air volume constant (the pressure inside the volume is staying equal to the pressure of the air outside the volume).

Air in the atmosphere behaves like air in a balloon. A balloon can grow or shrink in size depending on the pressure of the air inside. When a balloon is not getting bigger or smaller, it means the force inside that is pushing out is balanced by the force outside that is pushing in.

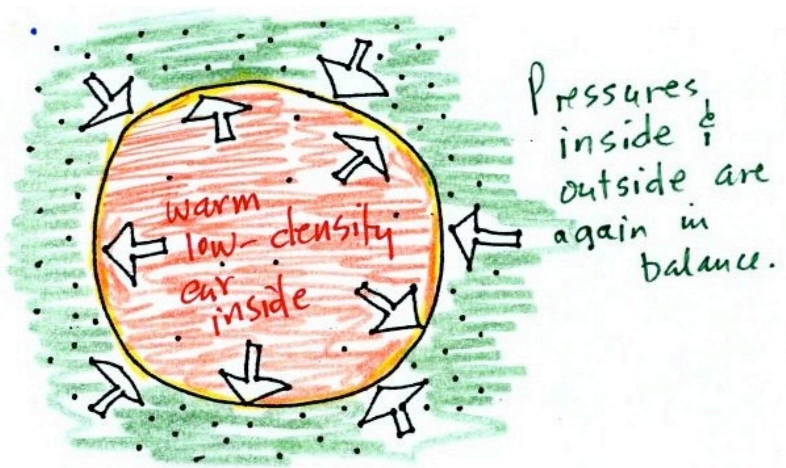


Heat up the air inside the balloon.

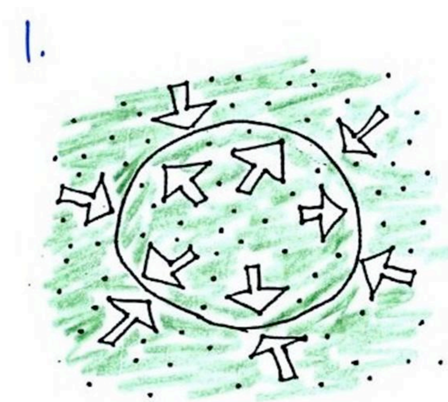


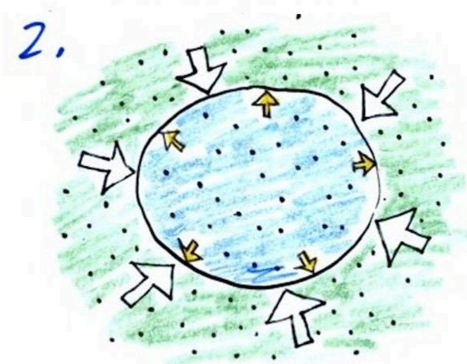
We start in the above figure with air inside a balloon exactly the same as the air outside (**Part 1** above). The air inside and outside have been colored green. The pressure of the air inside pushing outward and the pressure of the outside air surrounding pushing inward are equal. When we warm the air in the balloon (**Part 2** above), the ideal gas law equation tells us that the pressure of the air in the balloon will increase. The increase is short-lived because the pressure inside is now greater (the big yellow arrows) than the pressure outside. The balloon expands and the pressure of the air inside the balloon decreases.

Eventually the balloon will expand just enough that the pressures inside and outside are again in balance. You end up with a balloon of warm low density air that has the same pressure as the air surrounding it.



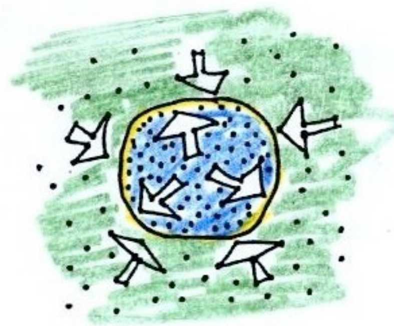
You can use the same reasoning to understand what happens when you cool the air in a balloon. The air inside and outside are the same in **Part 1** (below). Cooling the air inside the balloon in **Part 2** (below) causes a momentary drop in the inside pressure (small yellow colored arrows) and creates a pressure imbalance. The outside air has a higher pressure and compresses the balloon. As the balloon volume decreases, pressure inside the balloon increases until it is equal to the outside air pressure.



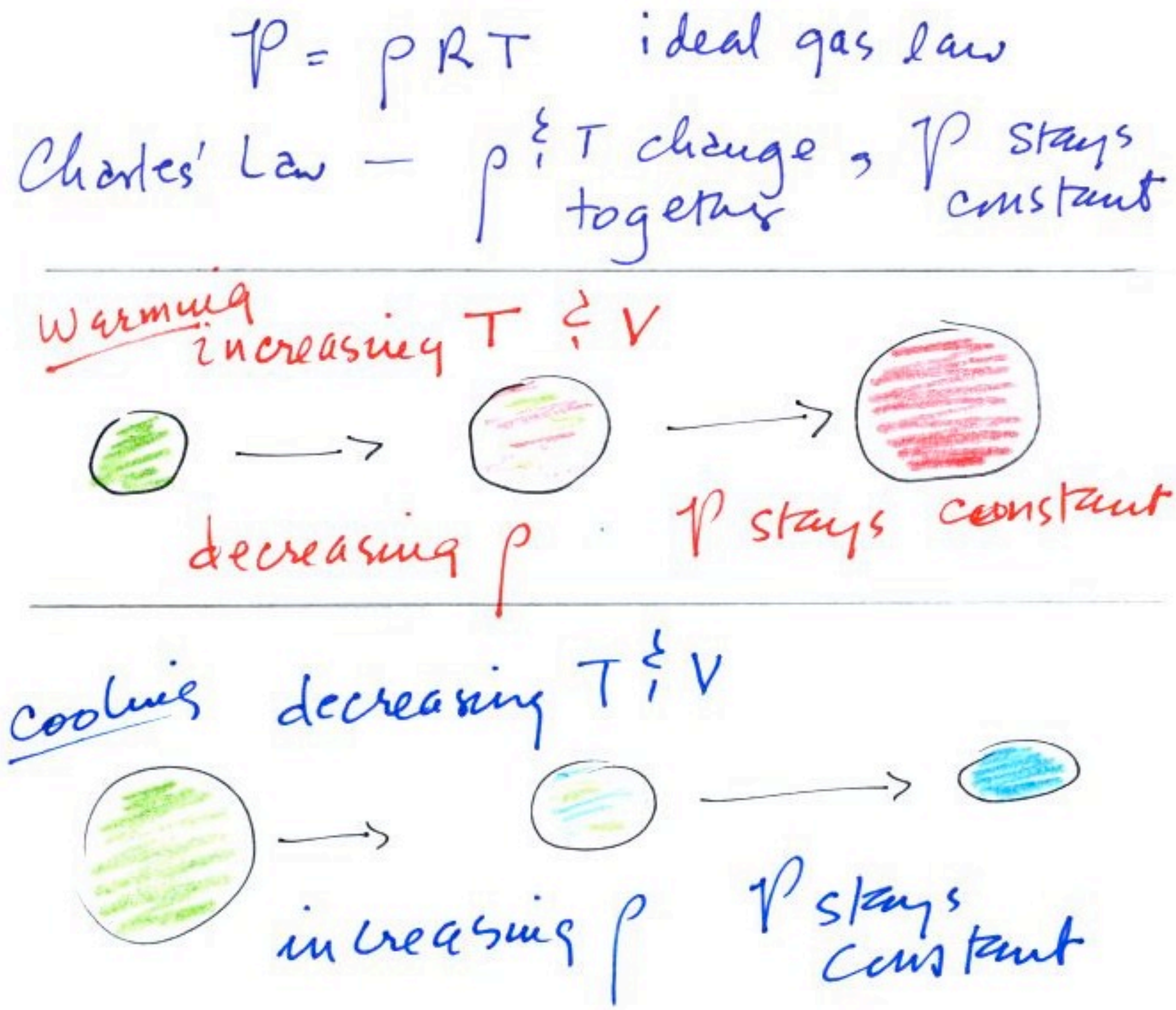


You end up with a balloon filled with cold high density air (**Part 3** below).

3.

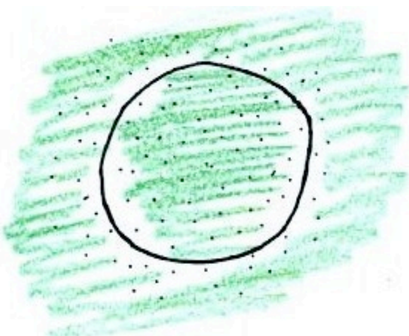


Charles' Law can be summarized in two sentences. If you warm air it will expand and its density will decrease until the pressure inside and outside the parcel are equal. If you cool air the parcel will shrink and its density will increase until the pressures balance. Below is a visual summary of Charles' Law.



These two associations:
(i) warm air = low density air
(ii) cold air = high density air
are important and will come up a lot during the remainder of the semester.

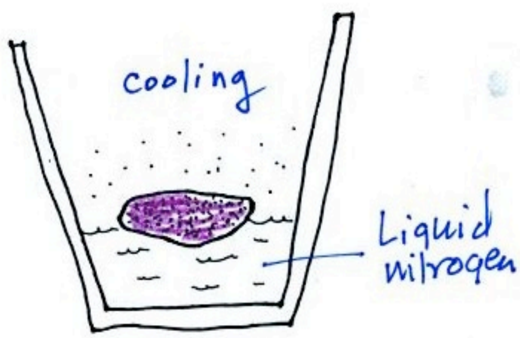
Charles Law is demonstrated in the classroom version of this course by dipping a balloon in liquid nitrogen. The balloon becomes very small when pulled from the liquid nitrogen because it is filled with very cold high density air. As the balloon warms the balloon expands and the density of the air inside the balloon decreases. The volume and temperature kept changing in a way that kept pressure constant. Eventually the balloon ends up back at room temperature, although it often pops before that happens.

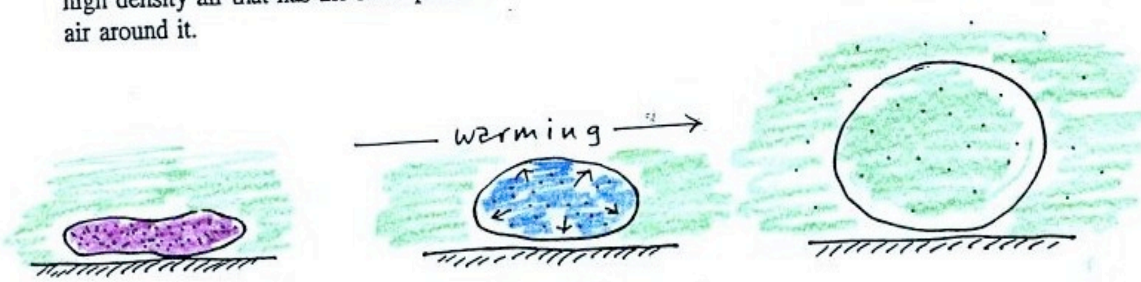


Charles' Law

Start with a balloon filled with air. The temperature (T) and density (ρ) inside and outside the balloon are the same. A balloon will change size in order to keep the air pressure inside and outside equal.

Next we will cool the balloon (a lot by immersing it in liquid nitrogen). As the air cools, the pressure decreases momentarily. This creates a pressure imbalance - the greater outside air pressure compresses the balloon. The reduction in balloon volume increases the air density which raises the air pressure inside the balloon. The balloon will continue to shrink in size until its pressure is again the same as the surrounding air. We end up with a balloon filled with very cold, high density air that has the same pressure as the air around it.





Once we remove the balloon from the liquid nitrogen it will begin to warm and we will be able to see the process in reverse. The air warms, its density decreases, but the air pressure remains constant.

Another classroom demonstration is performed using balloons filled with helium or hydrogen. Helium is less dense than air even at the same temperature, so a helium-filled balloon does not need to be warmed up in order to rise. We dunk the helium-filled balloon into liquid nitrogen to cool it and the density of the helium increases. When the balloon is removed from the liquid nitrogen, it sinks because the cold helium gas is denser than the surrounding air. As the helium in the balloon warms and expands, its density decreases. The balloon at some point has the same density as the air around it and is neutrally buoyant. Eventually the helium becomes less dense that the surrounding air and the balloon floats up to the ceiling.

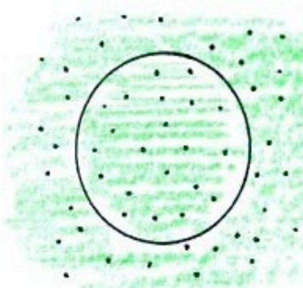
Now we are in a position to evaluate the forces that can cause parcels of air to rise or sink. There are two forces acting on a parcel of air in the atmosphere.

1. Gravity pulls downward. The strength of the gravity force depends on the mass of the air **inside** the parcel. This force is just the weight of the parcel.

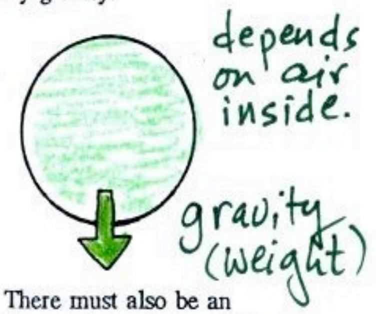
2. There is a pressure differential or buoyant force that points upward. This force is caused by the air **outside** the parcel. Because pressure decreases with increasing altitude, the air pressure at the bottom of a parcel pushing upward is slightly stronger than the pressure of the air at the top of the balloon that is pushing downward. The overall effect is an upward pointing force.

When the air inside a parcel is exactly the same as the air outside, the two forces are equal in strength and cancel out. The parcel is neutrally buoyant and does not rise or sink. If you replace the air inside the balloon with warm low density air, it will not weigh as much and the gravity force is weaker. The upward pressure difference force does not change, because it is determined by the air outside the balloon. The gravity force is now weaker than the upward force and the balloon will rise. Conversely if the air inside is cold, high density air, the air now weighs more. The gravity force is stronger than the upward pressure difference force and the balloon will sink.

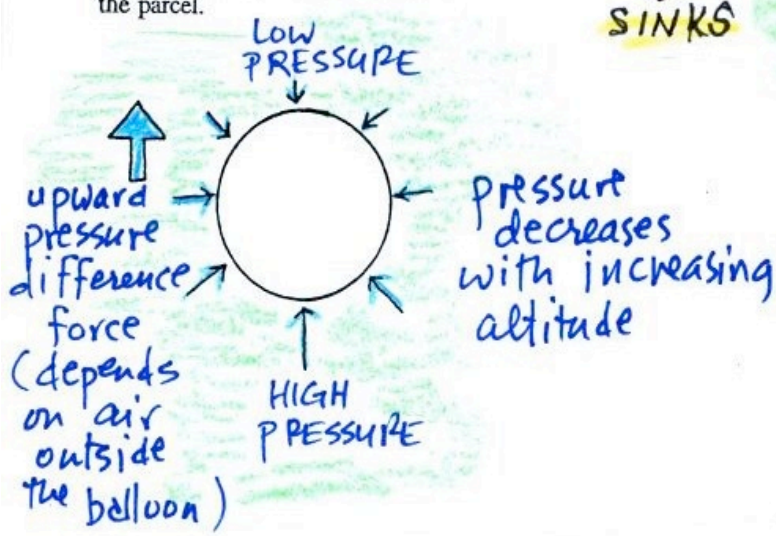
1. A small volume of the atmosphere has been isolated in this picture. The air density inside and outside are the same; the air parcel is not moving.



2. The air in the parcel has mass, so there is a downward force caused by gravity.

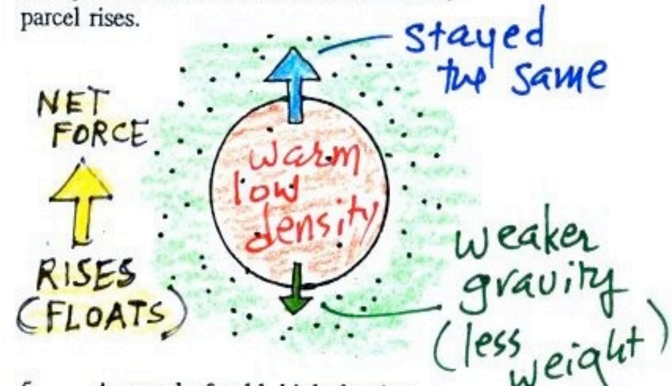


3. There must also be an upward force of equal strength in order for the parcel to remain in place. This upward force is supplied by the pressure difference between the top and the bottom of the parcel.

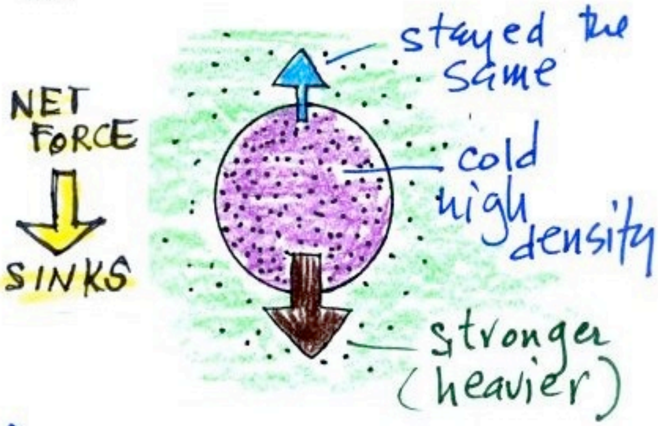


4. The air in this parcel is warmer than the surroundings. Its density must be lower in order for the pressures inside and outside to be equal.

The mass and weight of the air in this parcel have decreased. The upward pressure force has not changed (the surrounding atmospheric conditions are the same). The upward force is now stronger than the downward force and the parcel rises.

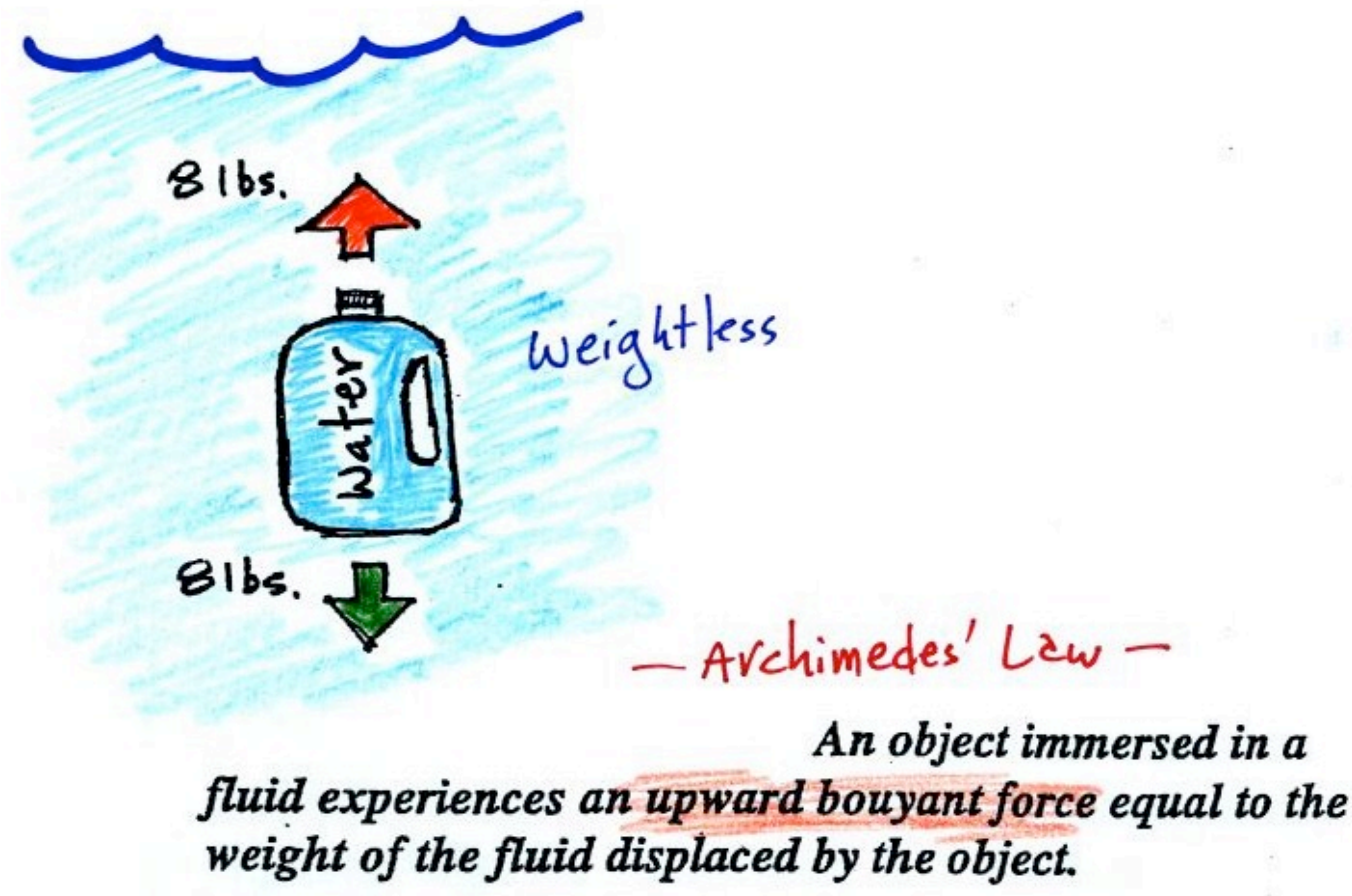


5. A parcel of cold, high-density airwill sink because the gravitational force will be larger than the upward pressure force.



Archimedes' Law describes how the relative strengths of the downward gravitational force and the upward pressure difference force determine whether a parcel of air will rise or sink. Archimedes was an ancient Greek scientist who is considered one of the greatest mathematicians of all time.

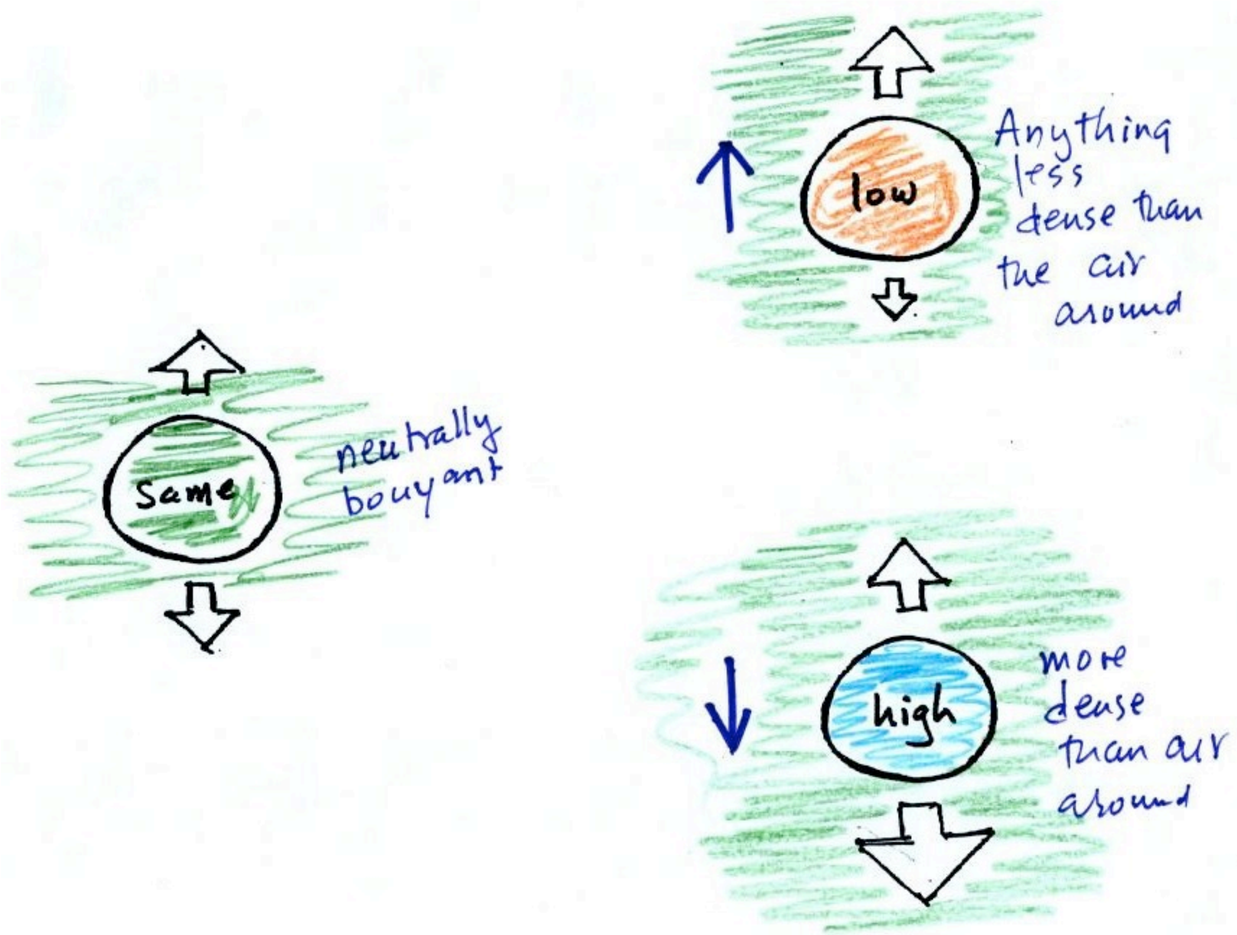
A gallon of water weighs about 8 pounds. But if you submerge a 1 gallon jug of water in a swimming pool, the jug becomes, for all intents and purposes, weightless. Archimedes' Law explains why this is true. A 1 gallon bottle will displace 1 gallon of pool water. One gallon of pool water weighs 8 pounds (the downward force due to gravity). The upward buoyant force will be 8 pounds, the same as the downward force on the jug due to gravity. The two forces are equal and opposite.



Now we will pour out all the water and the jug will fill with air. Air is about 1000 times less dense than water. If you submerge the jug in a pool it will displace 1 gallon of water and experience an 8 pound upward buoyant force again. Since there is no downward force the jug will float.

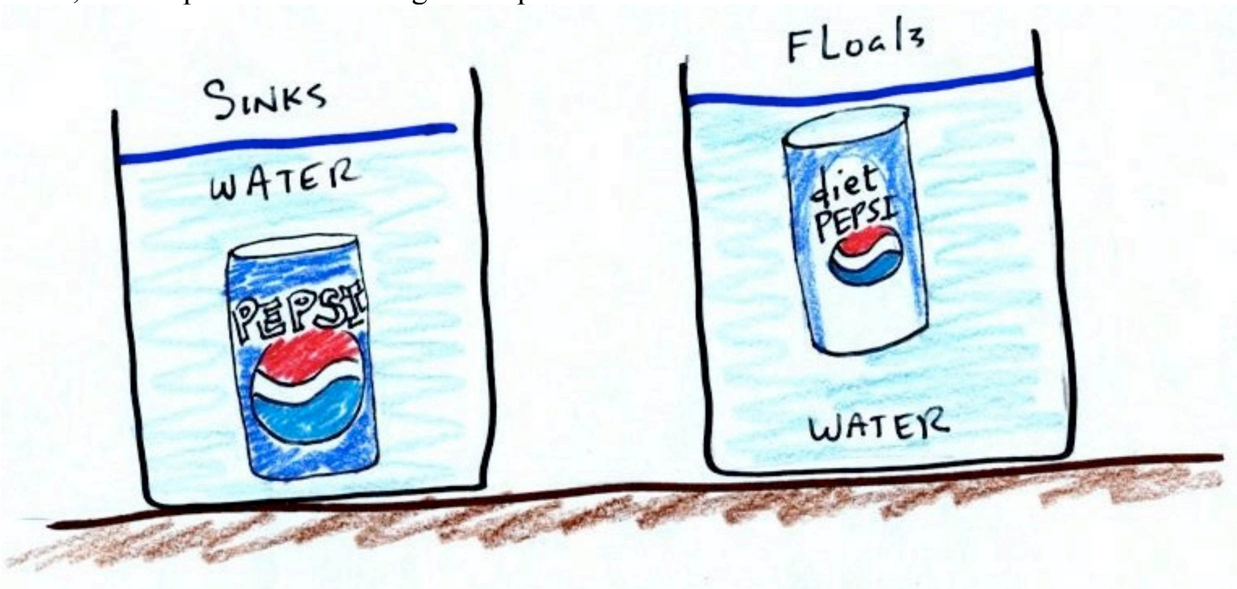
One gallon of sand (which is about 1.5 times denser than water) jug will weigh12 pounds. A jug of sand will sink because the downward force is greater than the upward force.

In summary, anything that is less dense than water will float and anything that is denser than water will sink. The same reasoning applies to air in the atmosphere. Air parcels that are less dense (warmer) than the surrounding air will rise. Air parcels that are more dense (colder) than will sink.



When sunlight reaching the ground is absorbed, the ground becomes warm and in turn warms the air above it. This air is less dense than the surrounding air and begins to rise. The rising air, which is called a thermal, expands and cools. A cloud will become visible if the air is cooled to the dew point. This process is called free convection and is the mechanism for many of Arizona's summer thunderstorms.

Another colorful demonstration of Archimedes' Law can be performed using cans of regular and Diet Pepsi. Coke and Diet Coke can also be used. The cans are made of aluminum which has a density almost three times higher than water and all the beverages contain carbon dioxide. Regular Pepsi and Coke contain a lot of high-fructose corn syrup so that these beverages have a higher density than water. Diet Pepsi or Coke do not contain corn syrup and these beverages are less dense than water because of the dissolved carbon dioxide. The average density of the can of regular Pepsi (water & corn syrup + aluminum + air) ends up being slightly greater than the density of water. The average density of the can of diet Pepsi (water + aluminum + air) is slightly less than the density of water. When the cans of soda are placed in beakers filled with water, Diet Pepsi floats while regular Pepsi sinks.



In some respects people in swimming pools are like cans of regular and diet soda. Some people float (they're a little less dense than water) while other people sink (slightly denser than water). Many people can fill their lungs with air and make themselves float, or they can empty their lungs and make themselves sink.