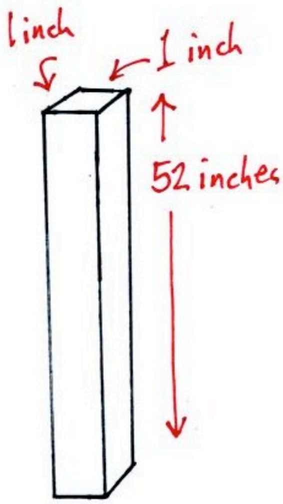
Goals for Module 2:

- Define mass, weight, density and pressure.
- Draw the variation of temperature, density and pressure with altitude based on the above concepts.
- Formulate the Ideal gas law, Charles' law.
- Employ these equations to solve simple problems.

Module 2: Lecture 4

If we first understand what pressure is, it will be easy to determine how it changes as you move vertically through the atmosphere. In the lecture version of this class, a 52 inch long, 1 inch by 1 inch iron bar is usually passed around in the classroom at the start of this topic. Students are asked to guess the weight of the bar (they generally overestimate its true weight). We will come back to this later in the lecture.



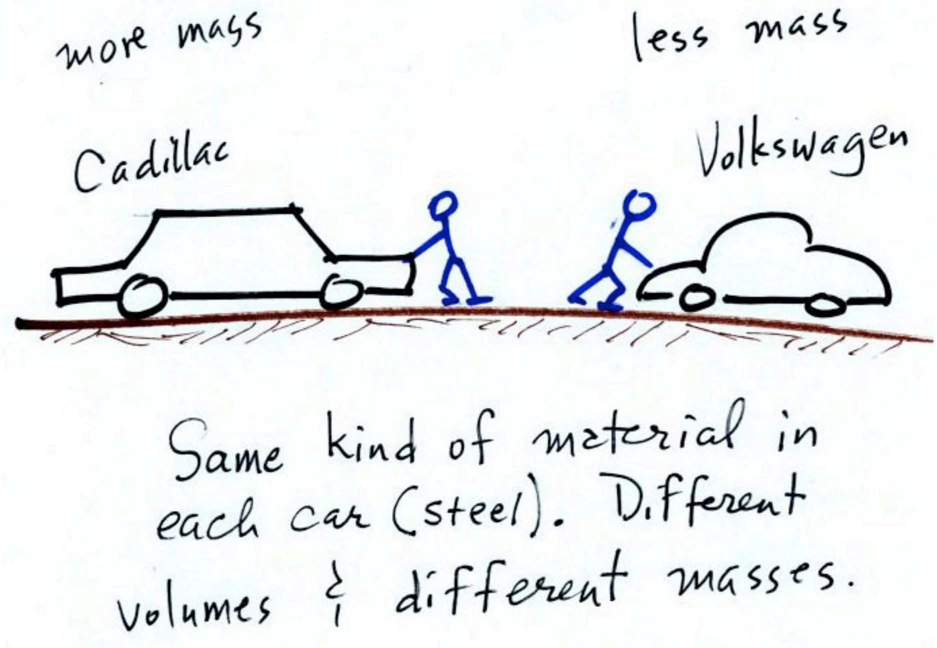
How much does the steel bar weigh?

In some textbooks you'll find mass defined as "amount of stuff" or "amount of a particular material." Other books will define mass as inertia or as resistance to change in motion (this comes from Newton's 2nd law of motion, something we will cover that later in the semester).

MASS = amount of stuff ← not volume, not number of atoms or molecules either.

[Some books define mass as the resistance to change in motion or inertia]

The next picture illustrates both these definitions. A Cadillac and a Volkswagen have both stalled in an intersection. Both cars are made of steel. The Cadillac is larger and has more steel, more stuff, more mass. The Cadillac is also much harder to get moving than the VW, it has a larger inertia (the Cadillac would also be harder to slow down, once it is moving, than the Volkswagen).



Weight is a force and depends on both the mass of an object and the strength of gravity. We tend to use weight and mass interchangeably because we spend all our lives on the earth where gravity never changes.

On earth, a mass is *
pulled downward by gravity,
producing something we can
feel or measure — WEIGHT — a force

Weight = combined effect of
mass & gravity.

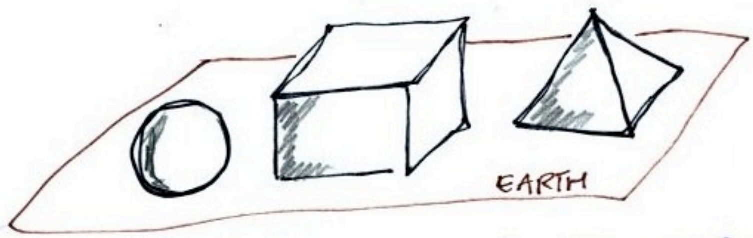
weight = mass x g ← a constant (on earth)

↖ called the "gravitational acceleration"

On the earth where the pull of gravity never changes, any three objects that all have the same mass (even if they had different volumes and were made of different materials) would always have the same weight. There is quite a bit of information hidden in the gravitational acceleration term.

All 3 objects have 1 kg mass

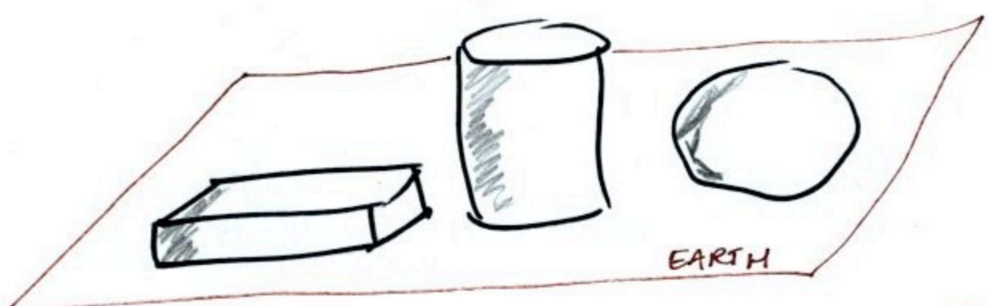
weight = mass × g



They would all weigh 2.2 pounds. It doesn't matter what their volume is or what they're made of.

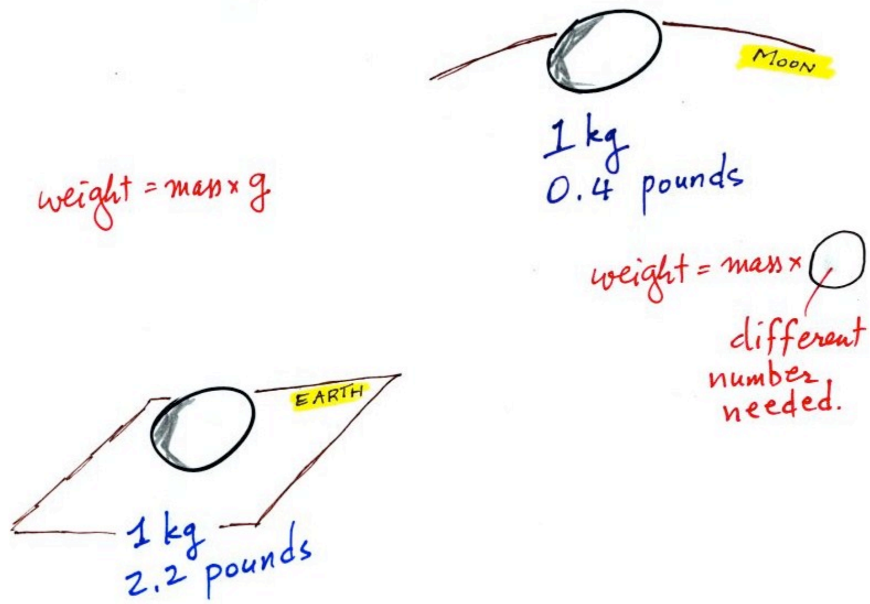
Conversely when gravity is always the same, three objects with the same weight would also have the same mass.

Each object weighs 2.2 pounds

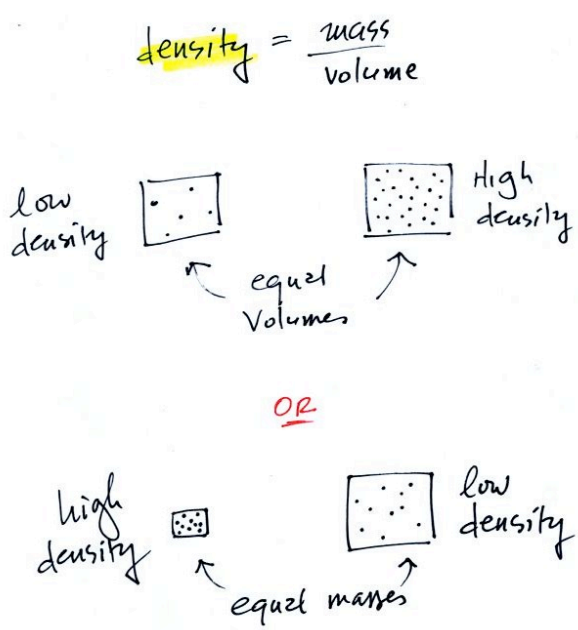


Each object must have a mass of 1 kg.

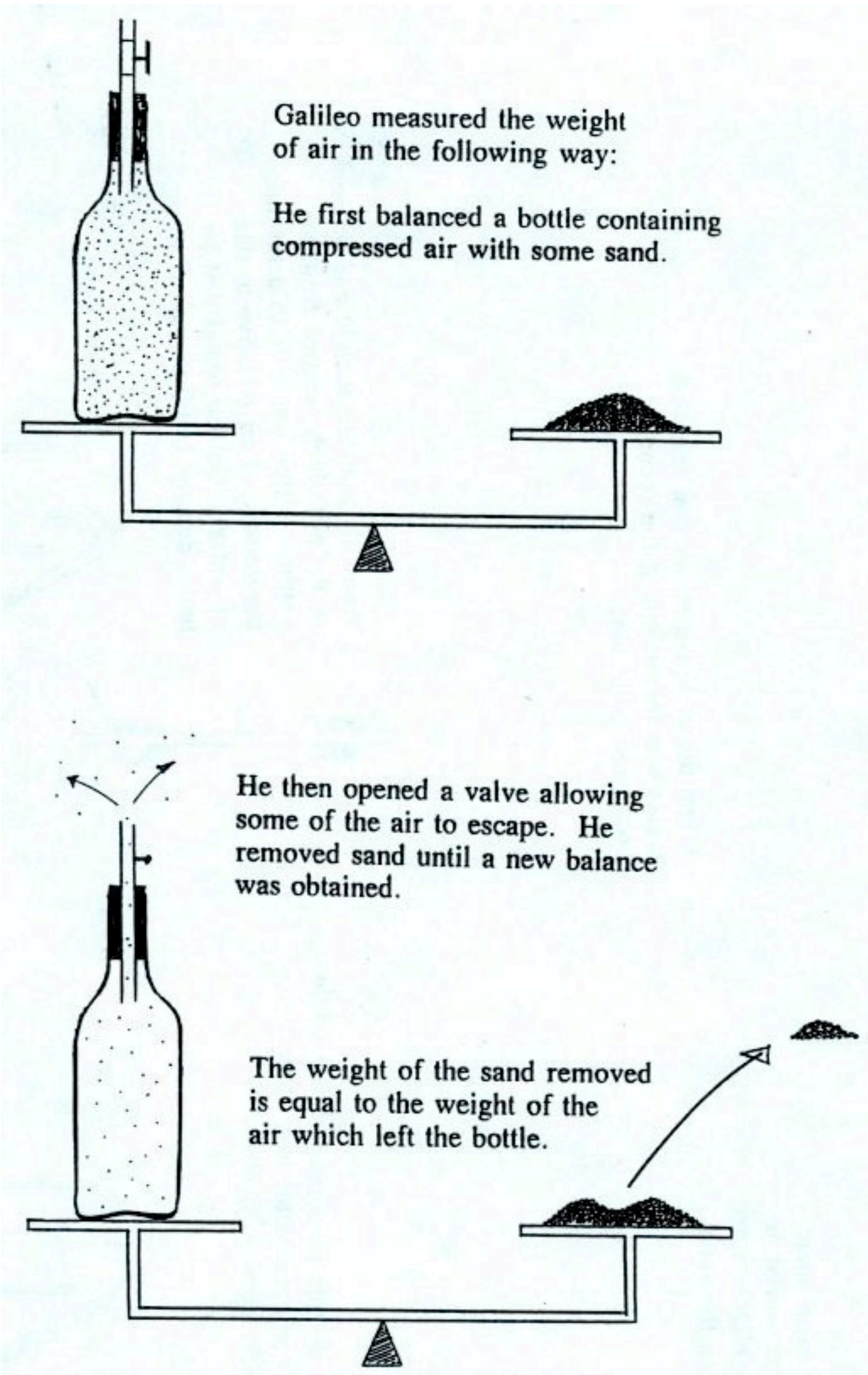
The difference between mass and weight is clearer (perhaps) if you compare the situation on the earth and on the moon. An object carried from the earth to the moon will have the same mass. However the gravitational attraction between the object and the moon is less than on the earth. So the object weighs less on the moon.



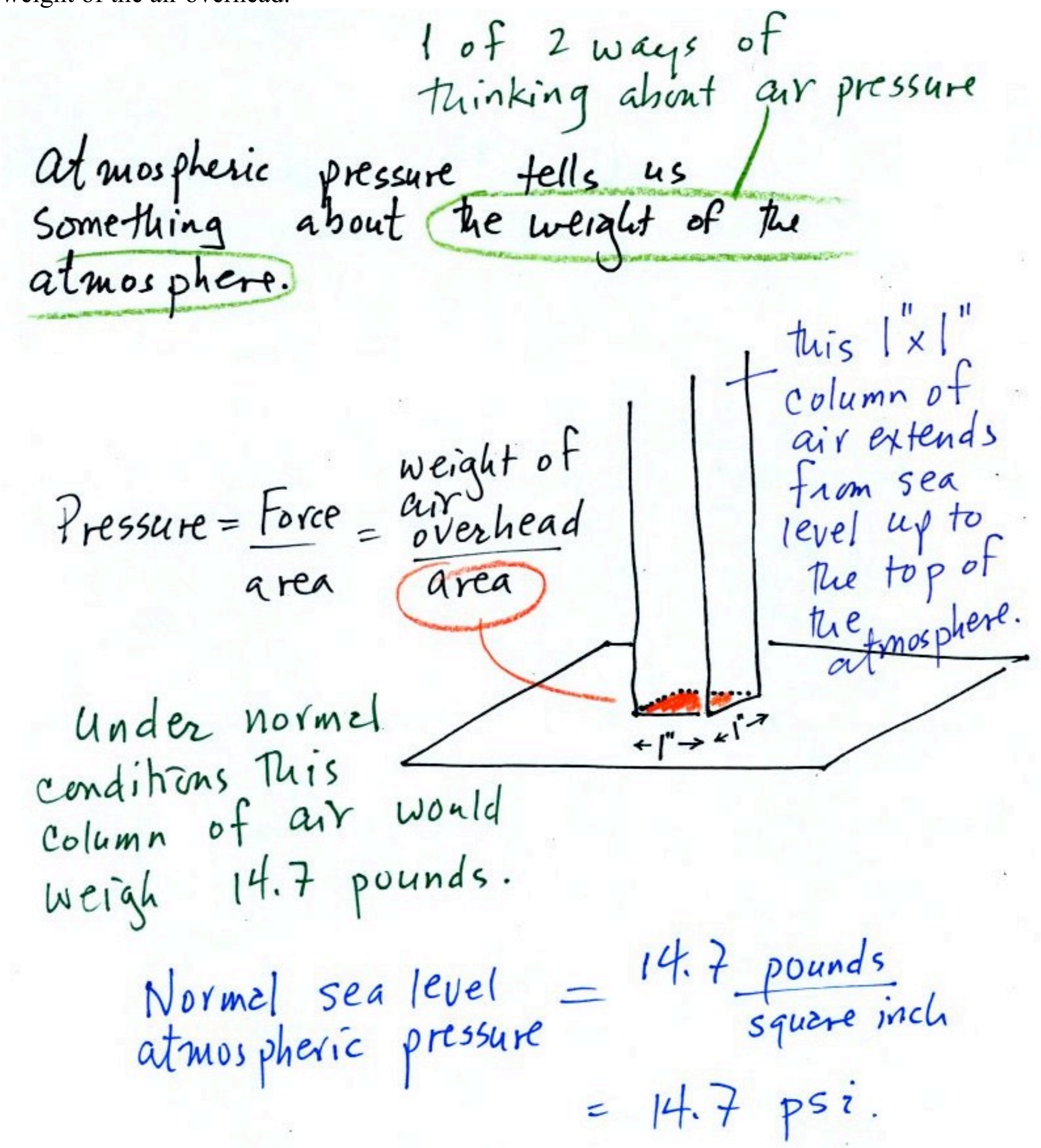
Air density will come up frequently in this class. Density is defined as mass divided by volume. In the first example there is more mass (more dots) in the right box than in the left box. Since the two volumes are equal the box at right has higher density. Equal masses are squeezed into different volumes in the bottom example. The box with smaller volume has higher density.



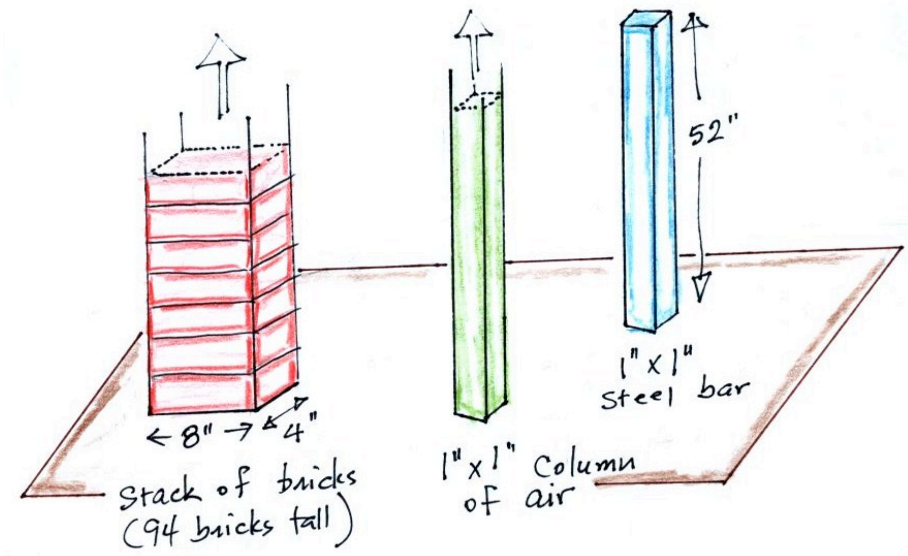
The air that surrounds the earth has mass. Gravity pulls downward on the atmosphere giving it weight. Galileo conducted a simple experiment in the 1600s to prove that air has weight.



Pressure is defined as force divided by area. Air pressure is the weight of the atmosphere overhead divided by the area the air is resting on. Atmospheric pressure is determined by the weight of the air overhead.



Under normal conditions a 1 inch by 1 inch column of air stretching from sea level to the top of the atmosphere will weigh 14.7 pounds. Normal atmospheric pressure at sea level is 14.7 pounds per square inch (psi, the units you use when you fill up your car or bike tires with air).



Now here is where the steel bar comes in. The steel bar also weighs exactly 14.7 pounds. Steel is a lot denser than air, so a steel bar only needs to be 52 inches tall to have the same weight as an air column that is 100 miles or more tall. Because the base of the bar has dimensions of 1" x 1" (1 square inch) the pressure at the bottom of the bar is 14.7 psi. A stack of 94, 5 pound bricks weighs 470 pounds. The pressure at the base of the brick pile would be 470 pounds divided by 32 square inches or about 14.7 psi. Here are some of the other commonly used pressure units.

14.7 psi = 1000 millibars = 1 bar

= 30 inches of mercury

= 1 atmosphere

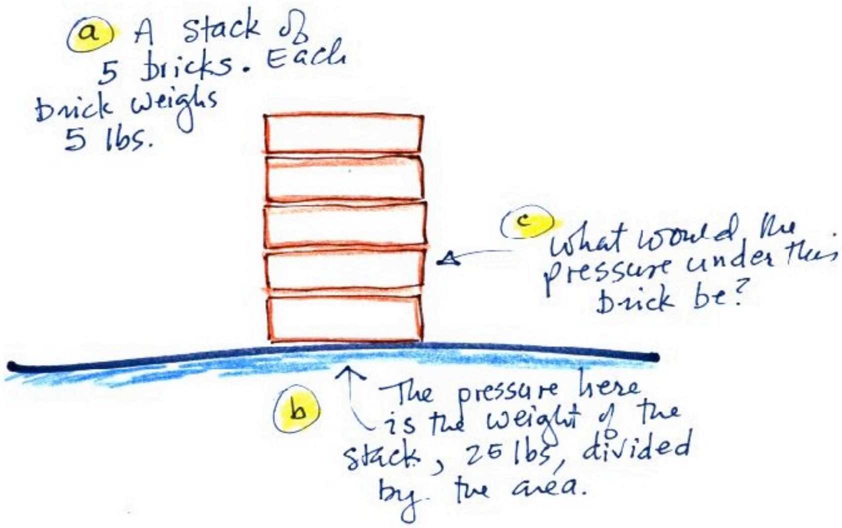
Pressure at sea level is determined by the weight of the air overhead. What happens to pressure as you move upward in the atmosphere? We can use a shorter pile of bricks to help answer this question. You can think of the bricks representing layers of air in the atmosphere. The word "bar" basically means pressure and is used in a lot of meteorological terms.

1000 millibars – pressure units.

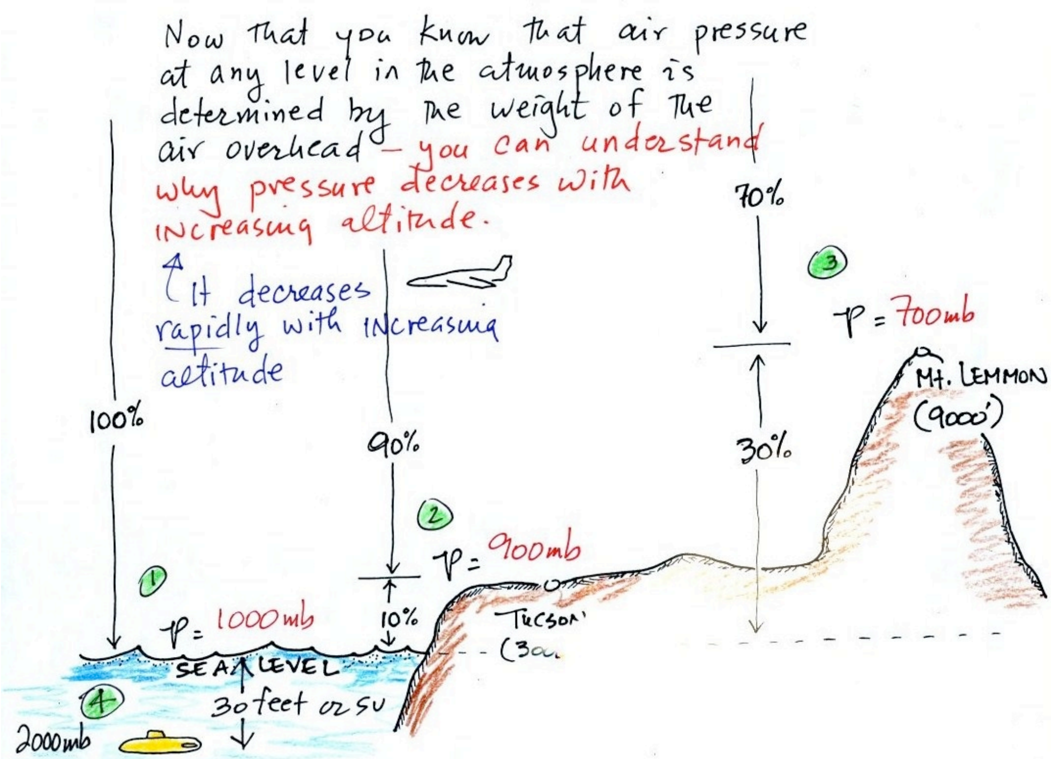
barometer – used to measure pressure

isobars – contours of pressure

The atmosphere can be compared to a stack of bricks which weigh 5 pounds each. At the bottom of the 5 brick high pile you would measure a weight of 25 pounds. If you moved up a brick you would measure a weight of 20 pounds, the weight of the four bricks still above. To get the pressure you would need to divide by the area. It should be clear that weight and pressure will decrease as you move up the pile.



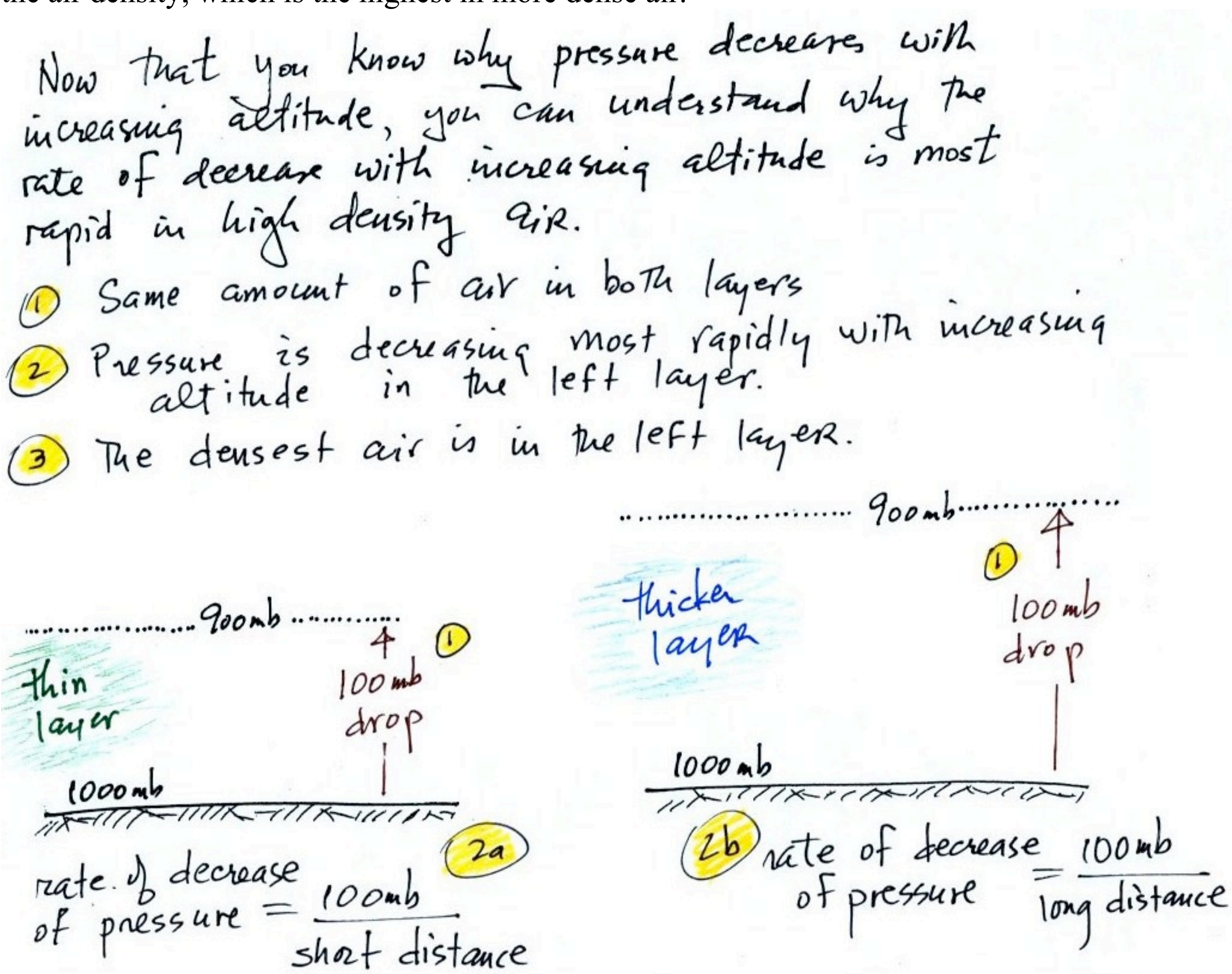
Pressure decreases rapidly with increasing altitude. **We will find that pressure changes more slowly if you move horizontally. But the small horizontal changes are what cause the wind to blow and storms to form.**



At an altitude of sea level (**Point 1** in the figure above); the weight of the entire atmosphere determines the air pressure which is normally about 1000 mb. Some parts of Tucson (**Point 2** in the figure above) are 3000 feet above sea level. Most of the valley is a little lower with an elevation of about 2500 feet. At 3000 feet about 10% of the atmosphere is below and 90% is still overhead. The atmospheric pressure is caused by the weight of the 90% that is still above. If 100% of the atmosphere produces a pressure of 1000 mb, then 90% will produce a pressure of 900 mb. The atmospheric pressure is typically about 700 mb at the summit of Mt. Lemmon (9000 feet altitude at **Point 3**) and 70% of the atmosphere is overhead.

Point 4 shows a submarine at a depth of about 30 feet. The total pressure under water is determined by the weight of the air and the weight of the water overhead. Water is much denser and much heavier than air. At 33 ft., the pressure is already twice what it would be at the surface of the ocean (2000 mb instead of 1000 mb).

Air pressure decreases with increasing altitude. The rate of the pressure decrease depends upon the air density, which is the highest in more dense air.



Here is a summary of the information in the above figure.

Point 1 - There is a 100 mb pressure drop in both air layers. In order for this to be true, both layers must have the same weight. In order for both layers to have the same weight they must contain the same amount of air and have the same mass.

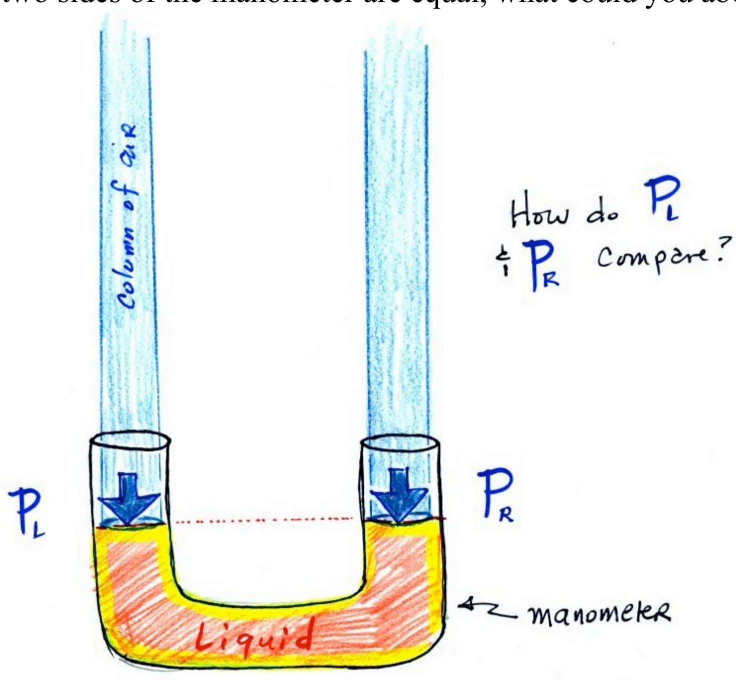
Point 2a - The pressure decreases 100 mb in a relatively short distance. This produces a relatively rapid rate of pressure decrease with increasing altitude.

Point 2b - The pressure also decreases 100 mb but over a longer distance. Pressure is decreasing at a slower rate in this layer.

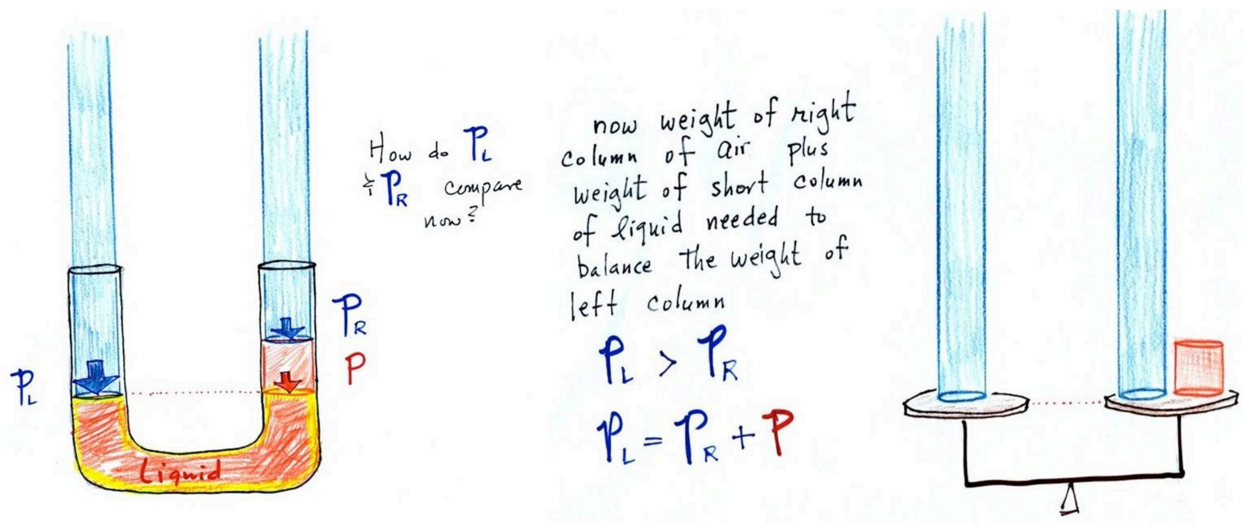
Point 3 - The left layer contains more dense air than the right layer. The same amount of air is squeezed into a thinner layer and a smaller volume in the left layer, resulting in a denser layer.

The fact that the rate of pressure decrease with increasing altitude depends on air density is a fairly subtle but important concept. This concept will come up 2 or 3 more times later in the semester. For example, we will use this concept to explain why hurricanes can intensify and become so strong.

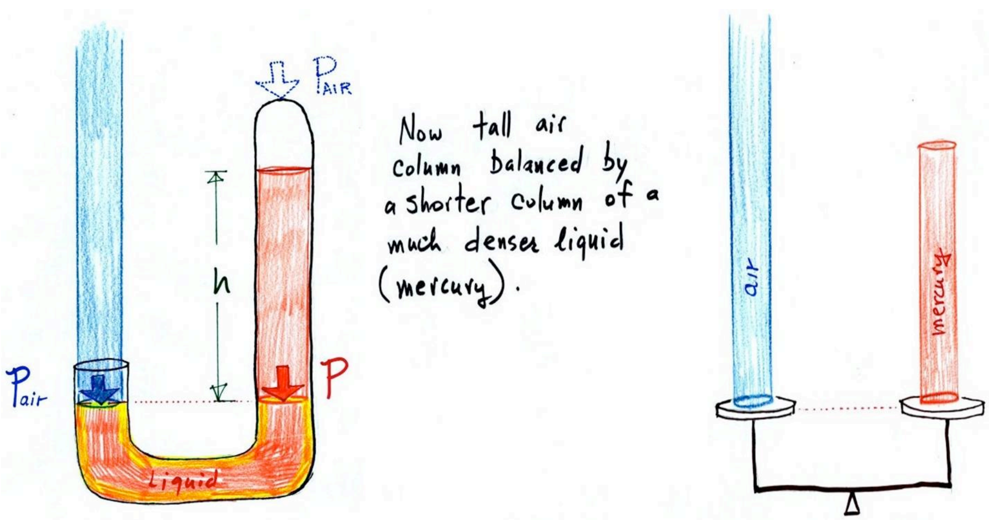
The instrument in the figure below measures pressure **differences** and is called a manometer. A manometer is a u-shaped glass tube filled with a liquid of some kind. The two ends of the tube are open so that air can get inside and press upon the liquid. Given that the liquid levels on the two sides of the manometer are equal, what could you about P_L and P_R?



The manometer liquid can slosh back and forth in the same way that the pans on a balance can move up and down. In the picture below the liquid levels are no longer equal. You probably realize that the air pressure on the left, P_L, is a little higher than the air pressure on the right, P_R. P_L is now being balanced by P_R + P acting together, where P is the pressure produced by the weight of the extra fluid on the right hand side of the manometer. The height of extra liquid provides a measure of the difference between P_L and P_R.

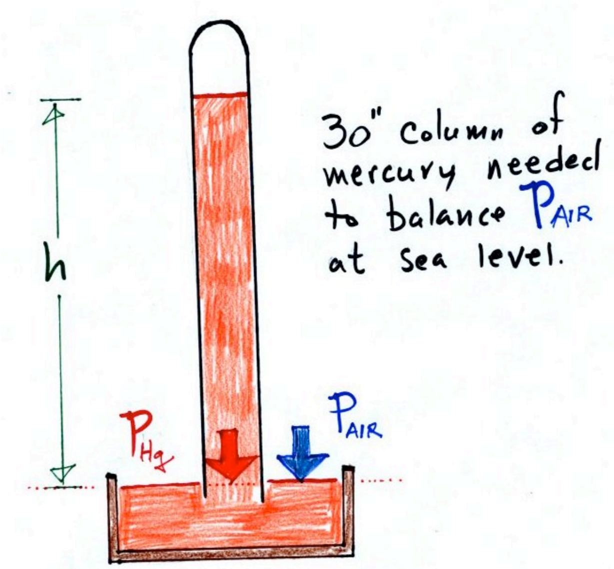


Now we will close off the right hand side of the manometer. Air cannot get into the right tube anymore, so the air pressure above the liquid is zero. Now at the level of the dotted line the balance is between P_{air} and P (pressure by the extra liquid on the right). If P_{air} changes, the height of the right column (h) will also change.



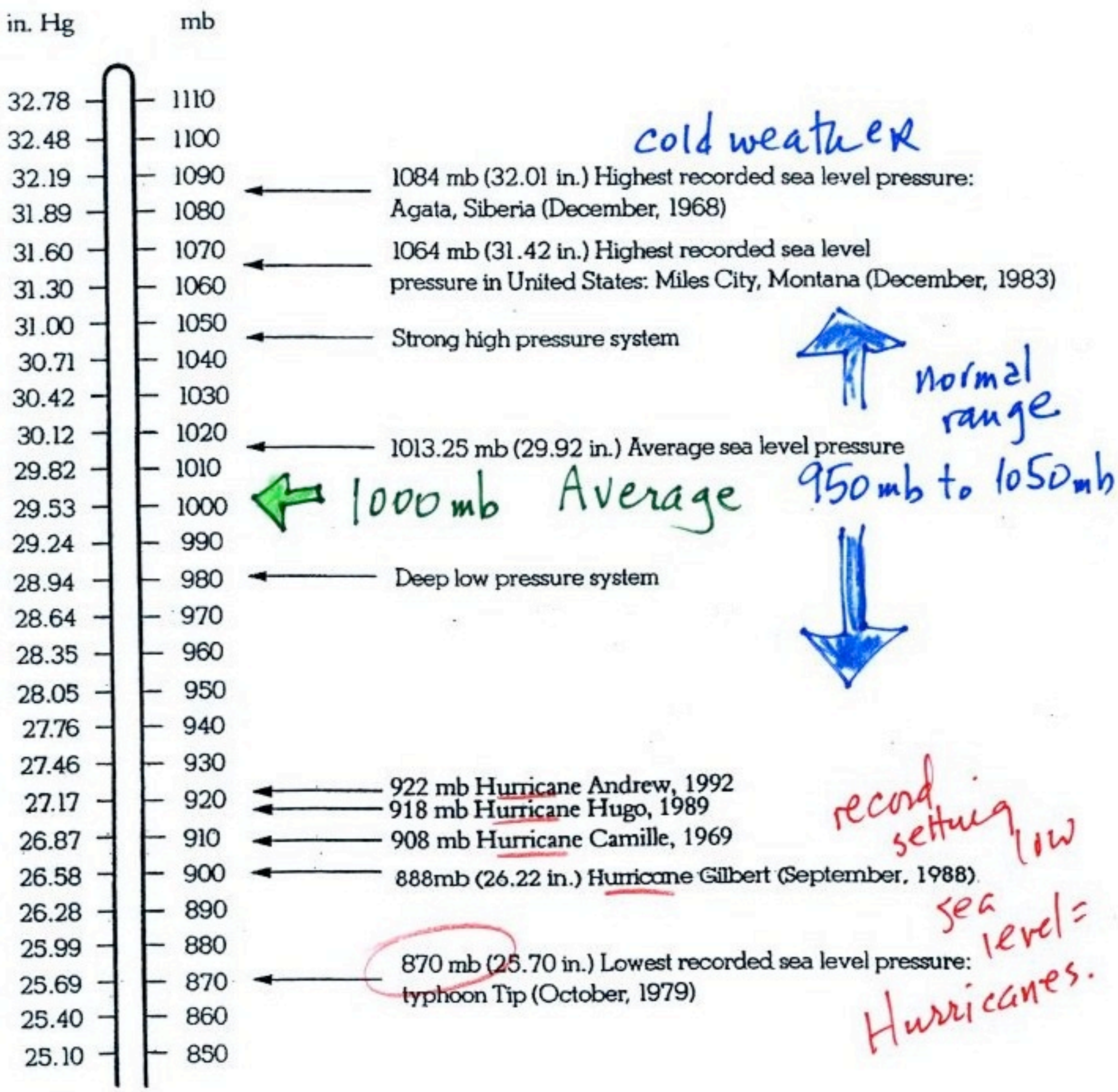
You now have a barometer, an instrument that can measure and monitor the atmospheric pressure. Barometers like this are usually filled with mercury because mercury is a dense liquid. With mercury you will need only a 30 inch tall column to balance the weight of the atmosphere at sea level under normal conditions (remember the 30 inches of mercury pressure units mentioned earlier). A water barometer would need to be over 30 feet tall. Water barometers are used for industrial applications in which very small pressure changes need to be measured. Mercury also has a low rate of evaporation so you do not have much mercury gas at the top of the right tube (it is the mercury vapor that would make a mercury spill in the classroom dangerous).

Below is a typical barometer design. The bowl of mercury is covered in such a way that it can sense changes in pressure without the evaporation of poisonous mercury vapor.



The figure below shows sea level pressure values under various conditions. Sea level pressures usually fall between 950 millibars (mb) and 1050 mb and the average pressure is about 1013 mb. High sea level pressure values generally occur during cold weather. When a TV weather forecast associates hot weather with high pressure, her or she is generally referring to upper level high pressure rather than surface pressure.

Representative and Extreme Values of Sea Level Pressure



Record low pressure values have been caused by intense hurricanes (the record-setting low pressure is the reason these storms became so strong). Hurricane Wilma in 2005 set a new record low sea level pressure reading for the Atlantic. Hurricane Katrina had a pressure of 902 mb. The following table lists some of the information on hurricane strength. Three of the ten strongest N. Atlantic hurricanes occurred in 2005.

Most Intense North Atlantic Hurricanes	Most Intense Hurricanes to hit the US Mainland
Wilma (2005) 882 mb Gilbert (1988) 888 mb Labor Day (1935) 892 mb Rita (2005) 895 mb Allen (1980) 899 Katrina (2005) 902	Labor Day (1935) 892 mb Camille (1969) 909 mb Katrina (2005) 920 mb Andrew (1992) 922 mb Indianola, Texas (1886) 925 mb