41: The Big Squeeze

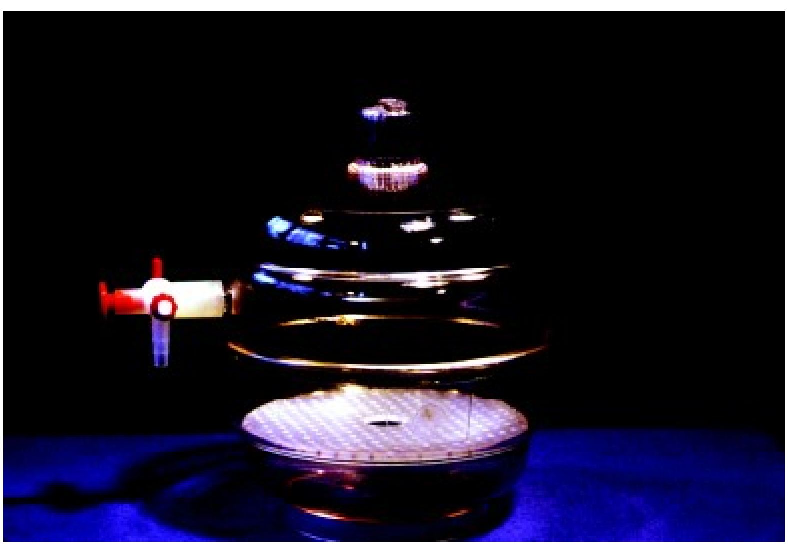
What are the properties of gases that make them different from liquids and solids? We have spoken of their loose arrangement of particles that causes them to move freely about their container. Implied in this loose arrangement is a lot of space among molecules. Because of this "intermolecular space" gases are *compressible*—that is, they can be forced together to occupy less space.

Because gases have low density, and are usually invisible, we might mistakenly think that gases have no mass—simply untrue. To prove this you could just do the following:

1) Place a lid on a container that is open to the air.
2) Weigh the container, including the air inside.
3) Use a vacuum pump to remove all the air from it.
4) Weigh it again.

You'll see that the container weighs less after the air is pumped out than it did before (see Figure 1). This is a clear demonstration that air has mass. Its density is approximately 1.293 g/L at 0°C and 1 atm pressure. These conditions are commonly referred to as "**standard temperature and pressure**," or "STP."

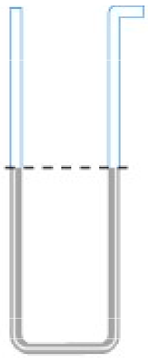
Figure 1. With air in it, this small desiccator weighs 150 g; with the air pumped out it weighs about 149 g. Air has mass, but because your body relies on its pressure all around you, you hardly notice it. If it suddenly went away, you'd notice (about the time your blood started boiling)!



If you accept that gases have mass, then you will be struck by the fact that you have tens of miles of atmospheric gases above you being pulled toward the earth by gravity. That thickness of gas is compressing every square centimeter of your body's surface. The column of air extending directly above you applies the same amount of pressure as a column of water 10.3 m high or a column of liquid mercury 760 mm high.

Because mercury is such a dense liquid, it makes a good tool for measuring and comparing pressures. You will often hear of a **mercury manometer**, also called a **U-tube manometer**, that is used to measure gaseous pressures. Check out the illustration in Figure 2. If a piece of glass tubing were bent in the shape of a U and filled with mercury, the level of the mercury on both ends of the U would experience the same amount of pressure from the atmosphere above it, so they would be at the same height. However, if we were to suck the air out one end with a vacuum pump so that there were no air pressure on that end of the tube, the mercury would rise in that side of the tube. The height of the rise would balance against the pressure exerted by the air on the open side of the tube. At the same time, the mercury level on the other side of the tube would fall.

The difference between the two mercury levels in opposite sides of the tube represents a mass of mercury. That mass of mercury is equal to the mass that can be pushed upward by that amount of atmospheric pressure. The place where the two levels of mercury come to rest would be at balance against the pressure of the atmosphere on the open side. This would demonstrate that the pressure of the atmosphere is equal to that of a column of mercury approximately 760 mm high.



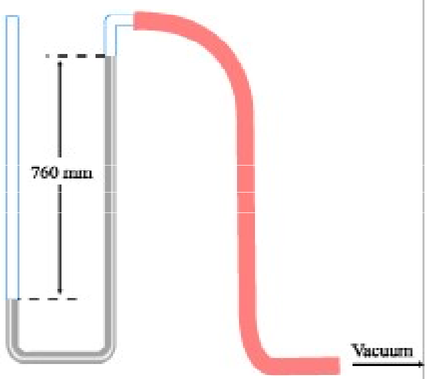
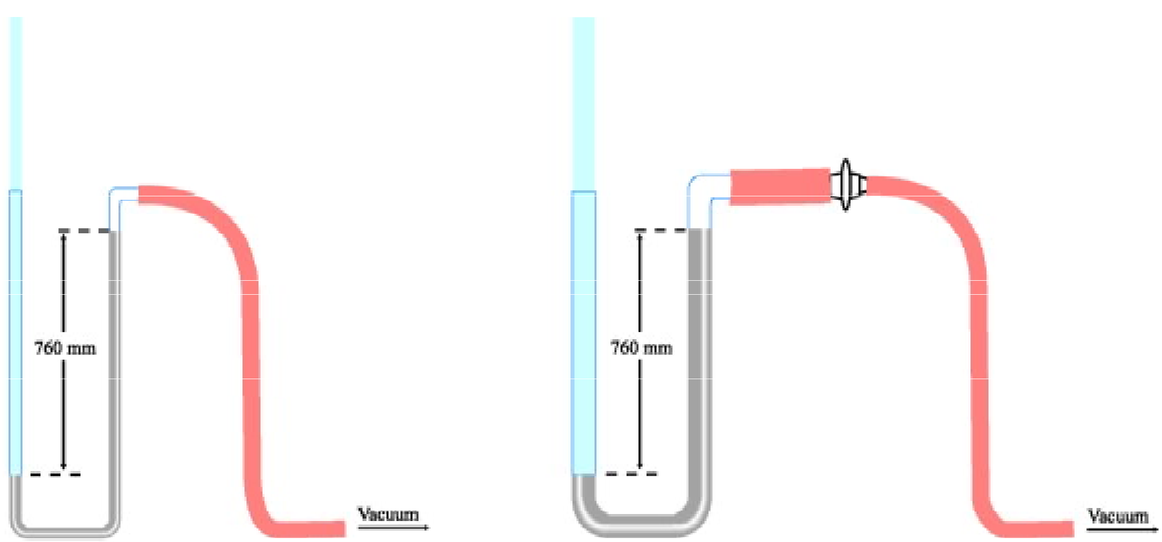


Figure 2. (Left, above) If mercury any fluid is placed in an open U-tube its level will be the same on both sides. (Left, below) If a vacuum is drawn on one side, the mercury will rise to the level where the mass of the liquid is balanced by the pressure of the atmosphere. That rise is 760 mm under the Earth's atmosphere. Of course, the atmospheric pressure varies with your altitude and changes slightly over time. 760 torr is "normal" atmospheric pressure at sea level.

Because millimeters of mercury—mmHg—is such a common expression of pressure, it has come to be called by its own name. That name is **torr**. From now on, when you see 760 torr, you may interpret this to mean the pressure applied by a column of mercury 760 mm high.

Well, what if we changed the diameter of the glass tube? Would that change the height of the mercury column? No, because the diameter of the atmospheric column above the mercury will also have changed. (See Figure 3.) No matter how big the tubing is, the height will still be 760 mmHg. The *mass* of mercury will be greater in a larger-diameter piece of tubing than in a smaller one. But the *height* of the mercury will be the same. Furthermore the pressure applied by that amount of mercury per amount of area will be the same.

Figure 3. The diameter of the U-tube is of no consequence in the measurement of atmospheric pressure. A wider U-tube means a greater capacity for mercury, but it also means a greater area of atmosphere above it.



So then, the pressure applied by a column of fluid (liquid or gas) may be expressed in several ways. It may be expressed as:

- the mass of fluid divided by the surface area over which it applies pressure (any units of mass per unit surface area could be used.)
- some conversion of those values to a standard unit of pressure, such as lb/in^2 (PSI)
- the height of a column of a standard fluid, such as mmHg (Torr) or meters of water

The Table shows several standard units for pressure. Conversion factors to change from one set of units to another are provided inside the back cover of your text.

Boyle's Law

In the mid-1600's, Robert Boyle of Great Britain was one of the first people who began to understand matter as it is understood today. He performed a series of experiments concerning the behavior of gases under different conditions. What he did was simple, but what he learned was profound. Boyle placed different amounts of pressure on a column of air trapped in a U-tube. Figure 4 is an apparatus that we might make today that is similar to what he made. He then measured the air volume under compression. He found that the *pressure and the volume of the air were inversely related by a constant value*. In other words, as he applied greater pressure, the volume of the trapped air decreased predictably. Mathematically written, the volume of the air could be calculated as:

$$V = k/P$$

This equation states that the volume and the pressure are related by a factor k. As pressure on the gas increases, the value of k/P decreases, so the volume decreases

Table. Expressions for pressure and their equivalents in torr.

Unit	Abbr.	Torr
atmosphere	atm	760
bar	NA	750
torr (millimeter of mercury)	mm Hg	1
meter water	m H_2O	73.6
pascal	pa	7.50 E(-3)*
pound per square inch	PSI, PPSI	51.7

* The expression 7.50 E(-3) is shorthand for 7.50×10^{-3}. This form of shorthand is often used in tabular data. The E stands for "exponent" of ten.

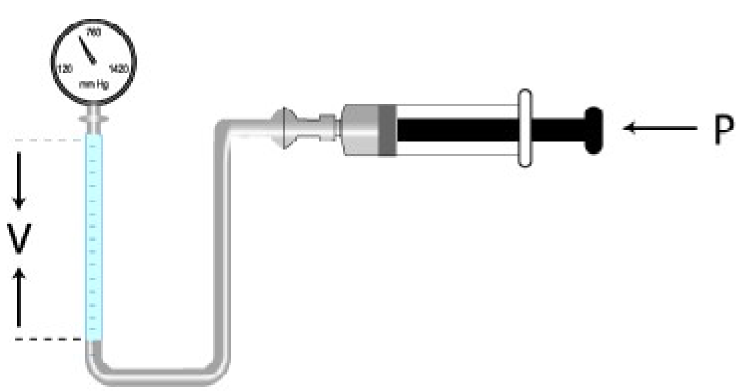


Figure 4. This apparatus demonstrates the principle of Boyle's law. As the pressure on the inside of the tube increases, the volume of gas trapped at the opposite end of the tube decreases in proportion. The volume is inversely proportional to the pressure.

where k is a constant for a specific amount of any gas at a given temperature. By rearranging this equation, it's clear that the volume of gas, times the pressure applied, would be equal to that constant value:

$$VP = k$$

Since k is constant for all values of pressure, if the volume (V_1) were measured at any specific pressure (P_1), the product of P and V would be equal to their product at any other volume (V_2) and pressure (P_2). That is:

$$P_1 V_1 = P_2 V_2$$

This mathematical relationship, in whichever form you prefer, is now called **Boyle's Law**. This was the first of several historical steps that would lead to a much broader understanding of gases. Soon, you'll see the big picture, but for now...

Exercises

1) What volume will 3.89 L of a gas occupy if the pressure is reduced from 921 mmHg to standard atmospheric pressure?

2) A given mass of Ar gas has a volume of 25.0 L at 600 torr. What volume will the same quantity of gas occupy at 6.00 atm?

3) A nitrogen sample occupies a volume of 7.43 L at 1100.0 torr. At what pressure would the volume be 5.00 L?

4) In an experiment, the pressure on a 7.0-L sample of H_2 is increased from standard atmospheric pressure to 1,750 mmHg. At the final pressure, assuming the temperature doesn't change, what is the volume?