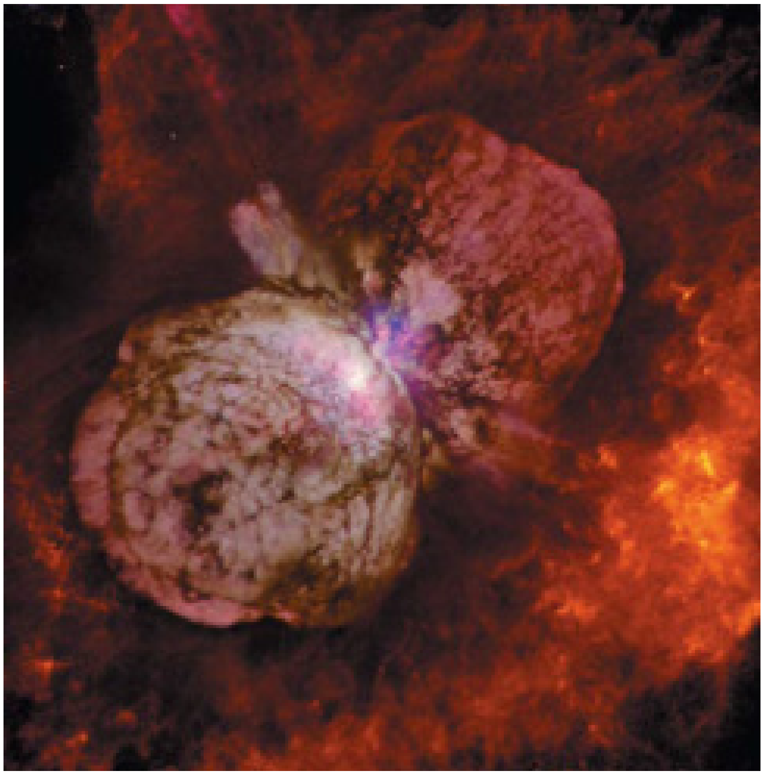


Chapter 2

Particles of Matter

THE MAIN IDEA

Matter is made of particles called atoms

2.1 The Submicroscopic
2.2 Discovering the Atom
2.3 Mass and Volume
2.4 Density: Mass to Volume
2.5 Energy Moves Matter
2.6 Temperature and Heat
2.7 Phase of Matter
2.8 Gas Laws

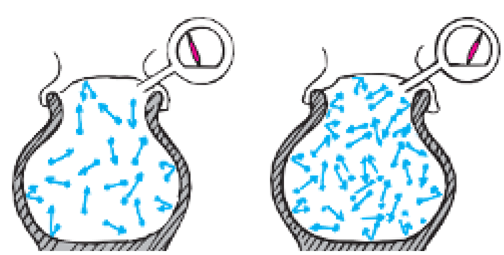
2.8 Gas Laws

Scientists of the 17th, 18th, and 19th centuries investigated the relationships among the pressure, volume, and temperature of gaseous materials. Their observations are summed up by a set of gas laws named in their honor. These laws help us to understand the behavior of gases, including the air we breathe.

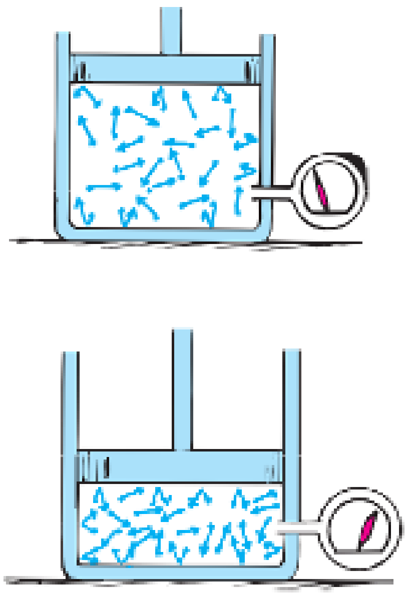
Boyle's Law: Pressure and Volume

Think of the molecules of air inside the inflated tire of an automobile. Inside the tire, the molecules behave like zillions of tiny Ping-Pong balls, perpetually moving helter-skelter and banging against the inner walls. Their impacts on the inner surface of the tire produce a jittery force that appears to our coarse senses as a steady outward push. Averaging this pushing force over a unit of area gives the pressure of the enclosed air.

Suppose the temperature is kept constant and twice as many molecules are pumped into the same volume, as shown in **Figure 2.28**. Then the air density—the number of molecules per given volume—is doubled. If the molecules move with the same average kinetic energy, or, equivalently, if their temperature is the same, then, to a close approximation,



Λ Figure 2.28
When the density of gas in the tire is doubled, the pressure is doubled.



Λ Figure 2.29
When the volume of gas is decreased, the density, and therefore the pressure, are increased.

the number of collisions will be doubled. This means that the pressure is doubled

We can also double the air density by compressing air to half its volume. Consider the cylinder with the movable piston in **Figure 2.29**. If the piston is pushed downward so that the volume is half the original volume, the density of molecules will double and the pressure will correspondingly double. In general, a lessening of the volume means a correspondingly greater pressure (because the gas density is greater), while a larger volume means a correspondingly smaller pressure (because the gas density is less

Notice in the example involving the piston that volume and pressure are inversely proportional—as one gets bigger, the other gets smaller. This can be represented as

$$V \propto \frac{1}{\mathrm{P}}$$

This relationship is known as **Boyle's Law**, after the 17th-century scientist Robert Boyle (1627–1691) who first described it. Boyle discovered that as volume decreases, pressure increases, and as volume increases, pressure decreases. Similarly, an increase in pressure results in a smaller volume, while a decrease in pressure results in a larger volume. Boyle's Law, however, holds true only assuming that the temperature and number of gas particles remain the same.

CONCEPT **CHECK**

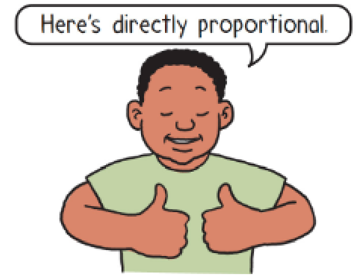
1. You bring a long snorkel with you to the bottom of a deep swimming pool. The snorkel provides a direct path between your lungs and the air above, but you still can't breathe through it. Why?

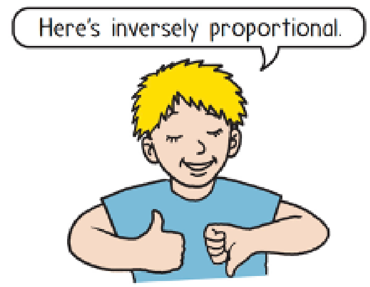
2. A scuba diver swimming underwater breathes compressed air, which counteracts the water pressure, allowing her to breathe. She then holds her breath while returning to the surface. What happens to the volume of air in her lungs?

CHECK YOUR ANSWER The weight of the water above you squeezes you from all directions. This water is very heavy, and your lungs are not strong enough to expand against all this pressure. That's why all snorkels are short.

As she rises to the surface, the water pressure decreases, which allows the compressed air in her lungs to expand in accordance with Boyle's Law. Rising 10 m to the surface results in half the pressure, which results in a doubling of the volume. This is enough to burst the lungs. A first lesson in scuba diving is not to hold your breath while ascending—to do so can be fatal.

Charles's Law: Volume and Temperature





The 18th-century French scientist and daring balloon aviator Jacques Charles (1746–1823) discovered the direct relationship between the volume of a gas and its temperature at constant pressure. Charles showed that the volume of a gas increases as its temperature increases. Likewise, the volume of a gas decreases as its temperature decreases, as is shown in **Figure 2.30**.

Remarkably, when the volume and temperature of various gases at constant pressure are plotted on a graph, it appears that at a rather cold temperature, –273.15°C, the volume of any gas dwindles down to zero, as shown in **Figure 2.31**.

Of course, the volume of a gas never reaches zero. Somewhere along the way the gas transforms into a liquid. Nonetheless, in 1848, William Thomson, also known as Lord Kelvin (1824–1907), recognized that this convergent temperature of –273.15°C would be a convenient zero point for an alternative temperature scale by which the absolute motion of particles could be measured. The number 0 is assigned to this lowest possible temperature—absolute zero. Accordingly, this scale became known as the Kelvin temperature scale, as was introduced in Section 2.6.

According to **Charles's Law**, the volume and absolute temperature (measured in kelvins) of a gas are directly proportional—as one gets bigger, so does the other. This can be represented as

$$P_1V_1 = P$$

Figure 2.30
Evan inflates two balloons to the same size and heats one over some boiling water while the other cools down in the freezer. A quick re-comparison of the two balloons shows that while the heated balloon expanded, the cooled balloon became smaller. What do you suppose happens when an air-filled balloon is dipped into –196°C liquid nitrogen and then pulled back out?

CONCEPT **CHECK**

A perfectly elastic balloon holding helium is warmed. What happens to its volume?

CHECK YOUR ANSWER According to Charles's Law, as a gas is warmed, its volume expands.

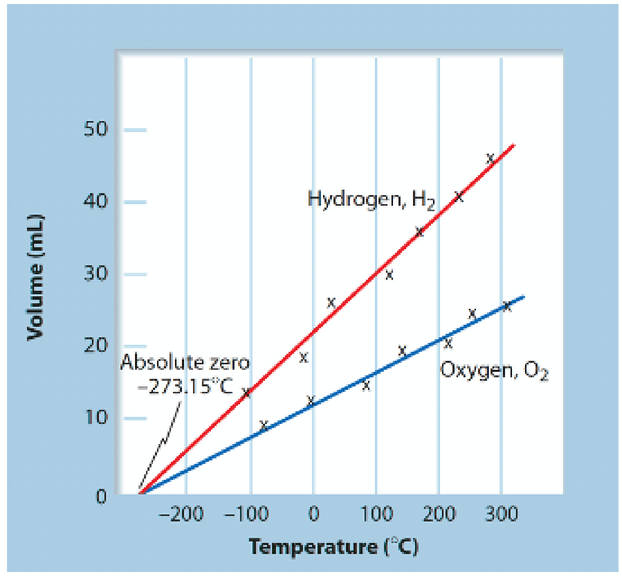


Figure 2.31 > A plot of experimental data showing volume versus the temperature (at constant pressure) for hydrogen, H_2, and oxygen, O_2, in their gaseous phases. Note how the gases converge to zero volume at the same temperature, −273.15°C.

FOR YOUR INFORMATION

In 1783, Jacques Charles was the first to fly in a balloon filled with hydrogen gas, which he created by reacting scrap iron with sulfuric acid. (Two weeks earlier, the Mongolfier brothers had been responsible for the first balloon flight using hot air.) One of Charles's first flights over the French countryside lasted about 45 minutes and took him 15 miles to a small village, where the people were so terrified they tore the balloon to shreds.

Avogadro's Law: Volume and Number of Particles

The 19th-century Italian scientist Amedeo Avogadro hypothesized that the volume of a gas is a function of the number of gas particles it contains. In other words, as the number of gas particles increases, so does the volume, assuming a constant pressure and temperature. This relationship is known as **Avogadro's Law**. An easy way to demonstrate this law is to grasp the opening of an empty plastic bag and blow into it. The more air molecules you blow into the bag, the bigger its volume. This can be represented as

$$P_1V_1 = P$$

CONCEPT **CHECK**

Assuming the same pressure and temperature, which has a greater number of gas particles: 5 liters of gaseous water, H_2O, or 5 liters of gaseous oxygen, O_2?

CHECK YOUR ANSWER According to Avogadro's Law, the same volume means the same number of gas particles. Each particle here refers to a single molecule of either water, H_2O, or oxygen, O_2. There are just as many water gas particles in 5 liters as there are oxygen gas particles. The nature of the gas particles doesn't matter. But can you answer this question: which has a greater number of atoms?

The Ideal Gas Law and Kinetic Molecular Theory

The properties of a gas can be described by four interrelated quantities: Boyle's, Charles's, and Avogadro's gas laws each describe how one quantity varies relative to another as long as the remaining two are held constant. Mathematically, these three laws can be combined into a single law, called the **ideal gas law**, which shows the relationship of all these quantities in a single equation:

$$PV = nRT$$

where P is the pressure of the gas, V is its volume, n is the number of gas particles, and T is the temperature. The R in this equation is the gas constant, which is the same no matter what the identity of the gas. Its value depends only upon the chosen units of pressure, volume, and temperature.*

The ideal gas law gets its name from the fact that it accurately describes only an ideal gas. Such a gas is one in which individual gas particles are considered to occupy no volume in their container. Furthermore, the particles of an ideal gas experience no attractions to or repulsions from one another. Each particle of a real gas, however, does have volume, albeit very, very small. Also, these particles do interact with each other. Real gases, therefore, do not follow any of the gas laws perfectly. At normal pressures, however, the contribution of particle size to total volume is insignificant and gas laws are good predictors of gas behavior. Furthermore, when the temperature of the gas is well above its boiling point, the gas particles are moving so fast that they rebound off one another without sticking. The interactions, therefore, are negligible, so the particles closely resemble those of an ideal gas.

READING CHECK

What four interrelated quantities can be used to describe the properties of a gas?

CONCEPT CHECK

Assuming the same pressure and temperature, which has a greater number of gas particles: 5 liters of gaseous water, H_2O, or 5 liters of gaseous oxygen, O_2?

CHECK YOUR ANSWER According to Avogadro's Law, the same volume means the same number of gas particles. Each particle here refers to a single molecule of either water, H_2O, or oxygen, O_2. There are just as many water gas particles in 5 liters as there are oxygen gas particles. The nature of the gas particles doesn't matter. But can you answer this question: which has a greater number of atoms?

*A commonly used value for the gas constant is 0.082057 L atm/K mol. Regarding the units, L is volume in liters, atm is pressure in atmospheres, K is temperature in kelvin, and 1 mole (mol) equals 6.02×10^{23} particles. The concept of the mole is introduced in Chapter 7.

CONCEPT **CHECK**

Which do gas laws describe more accurately: a gas at high pressure and low temperature or a gas at low pressure and high temperature?

CHECK YOUR ANSWER Gas laws work best for gases at low pressures and high temperatures. The air we breathe is a good example. At atmospheric pressure, the distances between air molecules are much greater than the sizes of the air molecules. Also, air is well above its components' boiling points (N_2 boils at –196°C and O_2 at –183°C). This behavior permitted the gas law discoveries of Boyle, Charles, Avogadro, and others.

From the gas laws a model has been developed that gives us insight as to why gases behave as they do. This model, known as the kinetic molecular theory, can be summarized as a set of five postulates:

1. A gas consists of tiny particles, either atoms or molecules or both.

2. Gas particles are in constant random motion, colliding with one another and with the walls of their container.

3. The impacts of gas particles on the walls of the container produce a jittery force that appears as a steady push against the inner surface. This pushing force provides the pressure of the enclosed gas.

4. Deviations from gas laws arise primarily because of the interactions occurring among gas particles and because gas particles are not infinitely small.

5. The average kinetic energy (energy due to motion) of the gas particles is directly proportional to the temperature of the gas.

We can use these postulates to rationalize the various gas laws. For Boyle's Law, pressure decreases with increasing volume because collisions of the gas particles with the walls of the container occur less frequently, and those impacts are spread out over a greater area. For Charles's Law, volume increases with increasing temperatures because faster-moving particles push against the inner sides of the container more forcefully, which causes an expansion. Similarly, for Avogadro's Law, volume increases with an increasing number of particles because each particle produces a force on the inner sides of the container, and when there are a greater number of particles, the net force on the inner surface is also greater.

fyi FOR YOUR INFORMATION

With your mouth wide open, blow air from your lungs onto the palm of your hand. Now repeat the same procedure with your lips puckered so that your breath is compressed within your mouth and expands upon exiting. You'll discover that as air expands, it cools. In more technical terms, as the pressure decreases, so does the temperature. In regard to the weather, as warm air rises, it expands into less dense higher-altitude air and thus cools. This cooling causes atmospheric water vapor to condense into tiny suspended droplets, which is how clouds are formed.

The kinetic molecular theory was developed from the study of gases, but this theory also nicely sums up what we know about liquids and solids. As discussed earlier in this chapter, liquids and solids are also made of tiny particles, either atoms or molecules. These particles are in constant random motion. This motion is confined, however, because the particles are held together by electrical attractions. We'll be discussing the nature of these electrical attractions in later chapters. In the liquid phase, the particles can tumble over one another like marbles in a bag, which gives the liquid its fluid character. In the solid phase, the particles are held together so strongly that they can only vibrate about fixed positions. Kinetic molecular theory also tells us that the higher the temperature, the faster the movement of the particles, as was discussed in Section 2.6. This explains why liquids and solids, like gases, also tend to expand when heated and contract when cooled, as illustrated in **Figure 2.32**.

Λ Figure 2.32
This gap in the roadway of a bridge is called an expansion joint; it allows the bridge to expand and contract. (Can you tell whether this photo taken on a warm day or a cold day?)

CONCEPT **CHECK**
Assuming a constant volume and number of particles, as the temperature of a gas increases, what happens to the pressure? Why?

CHECK YOUR ANSWER As the temperature increases in a gas, so does the average kinetic energy (speed) of its particles. Faster-moving particles collide more frequently with the inner surface of a container and strike it harder. More frequent and more forceful impacts mean greater pressure. So, as the temperature of a gas increases, so does its pressure, provided the volume and number of gas particles remain constant. Understanding this, can you explain why the pressure inside an automobile tire is greatest just after driving?

CALCULATION CORNER
SCUBA Diving and Hot Air Balloon Calculations

We can express Boyle's Law and Charles's Law mathematically as follows:

$$P_1V_1 = P_2V_2$$

Boyle's Law

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

Charles's Law

Here P_1, V_1, and T_1 represent an original pressure, volume, and temperature, respectively, while P_2, V_2, and T_2 represent a new pressure, volume, and temperature, respectively. Each of the preceding equations contains four variables. For such equations, if three of the variables are known we can calculate the fourth (assuming all temperatures are expressed in kelvins).

EXAMPLE

What would be the new volume of a 1.00 liter balloon if it were brought from sea level, where the air pressure is 1.00 atmosphere, to an altitude of 2500 meters, where air pressure is about 0.743 atmospheres? Assume there is no change in temperature. (As we explore in Chapter 16, the "atmosphere" is a common unit of pressure and is equal to the average atmospheric pressure at sea level.)

P_1 = 1.00 atm
P_2 = 0 .743 atm
V_1 = 1.00 liter
V_2 = ?

Use algebra to rearrange the equation for Boyle's Law to solve for V_2:

$V_2 = (P_1)(V_1) / (P_2)$

= (1.00 atm)(1.00 liter) / (0 .743 atm)

= 1.35 liters

YOUR TURN

1. A scuba diver swimming underwater in the ocean breathes compressed air at a pressure of 2 atmospheres. If she holds her breath while returning to the surface, show that the volume of her lungs will double.

2. A 5.00-liter rubber balloon is submerged 5.00 meters under ocean water, where its new volume is measured to be 3.38 liters. Show that the pressure at this depth is 1.48 atmospheres.

3. A perfectly elastic 419-liter balloon is heated from 25°C (298 K) to 50°C (323 K). Show that the volume expands to 454 liters.

4. A hot air balloon 401,000 liters in volume is warmed from 298 K to 398 K. As the air inside the balloon expands, it is unable to stretch the fabric, which is not very elastic. Instead, the expanded air escapes out of a hole placed at the top of the balloon. Show that 135,000 liters of air escapes.

5. Air has a density of 1.18 g/L. Show that the hot air balloon in the previous question is now lighter by 159 kilograms, which helps the balloon to rise.