CHAPTER 13

Gases

BIG Idea **Gases respond in predictable ways to pressure, temperature, volume, and changes in number of particles.**

13.1 The Gas Laws

MAIN Idea For a fixed amount of gas, a change in one variable—pressure, temperature, or volume—affects the other two.

13.2 The Ideal Gas Law

MAIN Idea The ideal gas law relates the number of particles to pressure, temperature, and volume.

13.3 Gas Stoichiometry

MAIN Idea When gases react, the coefficients in the balanced chemical equation represent both molar amounts and relative volumes.

ChemFacts

- The air inside a hot-air balloon is hot enough to boil water.
- In the nineteenth century, scientist Joseph Gay-Lussac used hot air balloon flights for research and experimentation, while scientist Jacques Charles experimented with hydrogen balloons.
- The average hot-air balloon holds 2.5 million liters of gas.

Start-Up Activities

LAUNCH Lab

How does temperature affect the volume of a gas?

In the hot-air balloon at left, the burners raise the temperature of the air inside the balloon to keep it aloft.

Procedure

1. Read and complete the lab safety form.
2. Inflate a **round balloon,** and tie it closed.
3. Pour cold **water** into a **bucket** until it is half full, then add **ice.** Use **paper towels** to wipe up any spilled water.
4. Use **string** to measure the circumference of the balloon.
5. Use a **stirring rod** to stir the water in the bucket to equalize the temperature. Submerge the balloon in the ice water for 15 min.
6. Remove the balloon from the water. Measure the circumference again.

Analysis

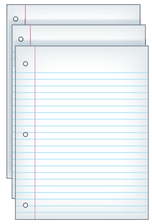
1. **Describe** what happened to the size of the balloon when its temperature decreased.
2. **Predict** what might happen to the balloon's size if the bucket contained warm water.

Inquiry What do you think would happen if you filled the balloon with helium instead of air and repeated the experiment?

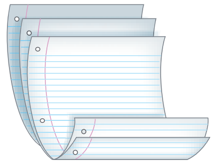
FOLDABLES™ Study Organizer

The Gas Laws Make the following Foldable to help you organize your study of the gas laws.

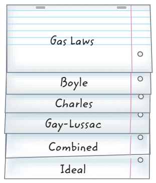
STEP 1 Stack three sheets of paper with the top edges about 2 cm apart vertically.



STEP 2 Fold up the bottom edges of the paper to form five equal tabs. Crease the fold to hold the tabs in place.



STEP 3 Staple along the fold. Label from top to bottom as follows: *Gas Laws, Boyle, Charles, Gay-Lussac, Combined,* and *Ideal.*



FOLDABLES **Use this Foldable with Sections 13.1 and 13.2.** As you read the sections, summarize the gas laws in your own words.

Chemistry Online

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- **find the Try at Home Lab, Under Pressure**

Matt Meadows

Section 13.1

Objectives

- **State** the relationships among pressure, temperature, and volume of a constant amount of gas.
- **Apply** the gas laws to problems involving the pressure, temperature, and volume of a constant amount of gas.

Review Vocabulary

scientific law: describes a relationship in nature that is supported by many experiments

New Vocabulary

Boyle's law
absolute zero
Charles's law
Gay-Lussac's law
combined gas law

The Gas Laws

MAIN Idea For a fixed amount of gas, a change in one variable—pressure, temperature, or volume—affects the other two.

Real-World Reading Link What might happen to the gas in a balloon if you decreased its volume by squeezing it? You would feel increasing resistance as you squeeze and might see part of the balloon bulge.

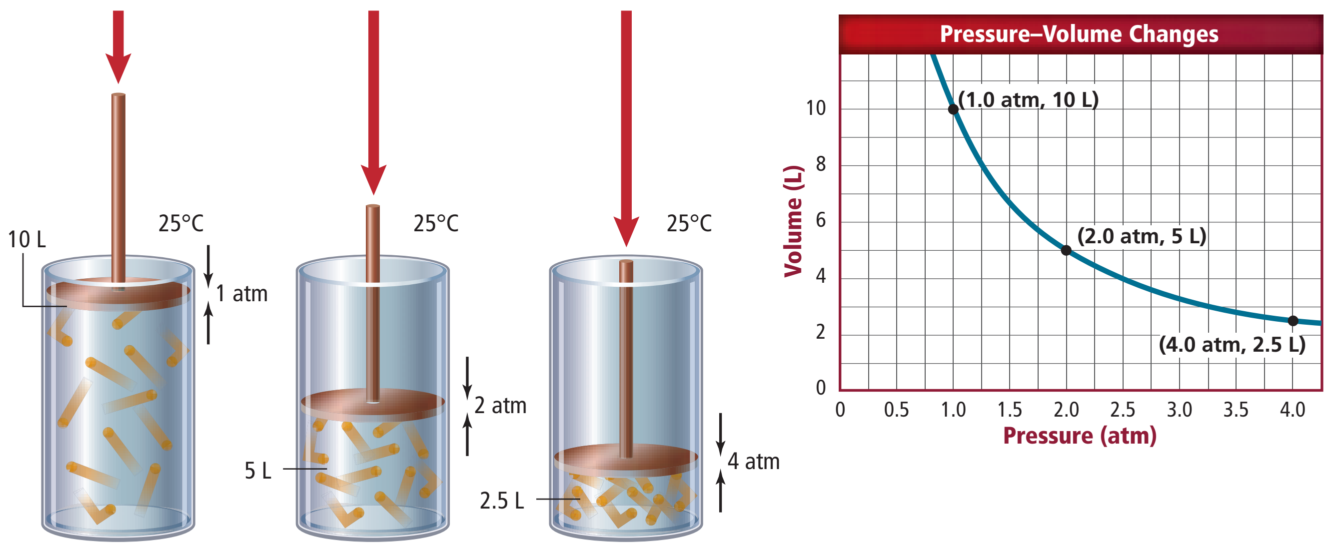
Boyle's Law

As the balloon example illustrates, the pressure of a gas and its volume are related. Robert Boyle (1627–1691), an Irish chemist, described this relationship between the pressure and the volume of a gas.

How are pressure and volume related? Boyle designed experiments like the one shown in **Figure 13.1.** He showed that if the temperature and the amount of gas are constant, doubling the pressure decreases the volume by one-half. On the other hand, reducing the pressure by one-half doubles the volume. A relationship in which one variable increases proportionally as the other variable decreases is known as an inversely proportional relationship.

Boyle's law states that the volume of a fixed amount of gas held at a constant temperature varies inversely with the pressure. Look at the graph in **Figure 13.1,** in which pressure versus volume is plotted for a gas. The plot of an inversely proportional relationship results in a downward curve.

■ **Figure 13.1** As the external pressure on the cylinder's piston increases, the volume inside the cylinder decreases. The graph shows the inverse relationship between pressure and volume.



$P_1V_1 = (1\text{ atm})(10\text{ L})$
$= 10\text{ atm} \cdot \text{L}$
$= \text{constant}$

$P_2V_2 = (2\text{ atm})(5\text{ L})$
$= 10\text{ atm} \cdot \text{L}$
$= \text{constant}$

$P_3V_3 = (4\text{ atm})(2.5\text{ L})$
$= 10\text{ atm} \cdot \text{L}$
$= \text{constant}$

Graph Check
Apply Use the graph to determine the volume if the pressure is 2.5 atm.

Note that the product of the pressure and the volume for each point in **Figure 13.1** is 10 atm·L. Boyle's law can be expressed mathematically as follows.

Boyle's Law

$$P_1V_1 = P_2V_2$$

***P* represents pressure. *V* represents volume.**

For a given amount of gas held at constant temperature, the product of pressure and volume is a constant.

P_1 and V_1 represent the initial conditions, and P_2 and V_2 represent new conditions. If you know any three of these values, you can solve for the fourth by rearranging the equation.

EXAMPLE Problem 13.1

Math Handbook
Inverse Relationships
page 961

Boyle's Law A diver blows a 0.75-L air bubble 10 m under water. As it rises to the surface, the pressure goes from 2.25 atm to 1.03 atm. What will be the volume of air in the bubble at the surface?

1 Analyze the Problem

According to Boyle's law, the decrease in pressure on the bubble will result in an increase in volume, so the initial volume should be multiplied by a pressure ratio greater than 1.

Known	Unknown
$V_1 = 0.75$ L	$V_2 = ?$ L
$P_1 = 2.25$ atm	
$P_2 = 1.03$ atm	

2 Solve for the Unknown

Use Boyle's law. Solve for V_2, and calculate the new volume.

$P_1V_1 = P_2V_2$ — **State Boyle's law.**

$V_2 = V1\left(\frac{P_1}{P_2}\right)$ — **Solve for V_2.**

$V_2 = 0.75\text{ L}\left(\frac{2.25\text{ atm}}{1.03\text{ atm}}\right)$ — **Substitute $V_1 = 0.75$ L, $P_1 = 2.25$ atm, and $P_2 = 1.03$ atm.**

$V_2 = 0.75\text{ L}\left(\frac{2.25\cancel{\text{ atm}}}{1.03\cancel{\text{ atm}}}\right) = 1.6\text{ L}$ — **Multiply and divide numbers and units.**

3 Evaluate the Answer

The pressure decreases by roughly half, so the volume should roughly double. The answer is expressed in liters, a unit of volume, and correctly contains two significant figures.

PRACTICE Problems

Extra Practice Page 984 and glencoe.com

Assume that the temperature and the amount of gas are constant in the following problems.

1. The volume of a gas at 99.0 kPa is 300.0 mL. If the pressure is increased to 188 kPa, what will be the new volume?
2. The pressure of a sample of helium in a 1.00-L container is 0.988 atm. What is the new pressure if the sample is placed in a 2.00-L container?
3. **Challenge** Air trapped in a cylinder fitted with a piston occupies 145.7 mL at 1.08 atm pressure. What is the new volume when the piston is depressed, increasing the pressure by 25%?

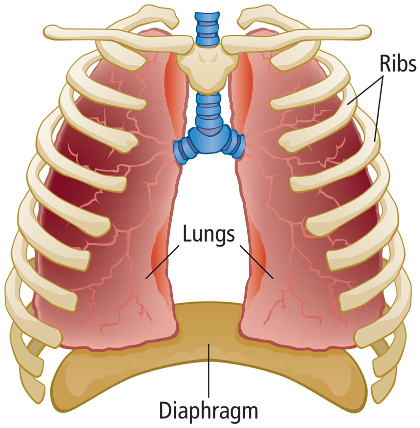
PROBLEM-SOLVING LAB

Apply Scientific Explanations

What does Boyle's law have to do with breathing? You take a breath about 20 times per minute, exchanging carbon dioxide gas for life-sustaining oxygen. How do pressure and volume change in your lungs as you breathe?

Analysis

The spongy, elastic tissue that makes up your lungs allows them to expand and contract in response to movement of the diaphragm, a strong muscle beneath the lungs. As your diaphragm moves downward, increasing lung volume, you inhale. As your diaphragm moves upward, decreasing lung volume, you exhale.



Think Critically

1. **Apply** Boyle's law to explain why air enters your lungs when you inhale and leaves when you exhale.
2. **Explain** what happens inside the lungs when a blow to the abdomen knocks the wind out of a person. Use Boyle's law to determine your answer.
3. **Infer** Parts of the lungs lose elasticity and become enlarged when a person has emphysema. From what you know about Boyle's law, why does this condition affect breathing?
4. **Explain** why beginning scuba divers are taught never to hold their breath while ascending from deep water.

Charles's Law

In the Launch Lab, you observed that a balloon's circumference decreased after the balloon was submerged in ice water. Why did this happen? After a cool evening, a rubber pool raft can appear partially inflated. During a sunny afternoon, the same raft can appear fully inflated. Why did the appearance of the raft change? These questions can be answered by applying a second gas law—Charles's law.

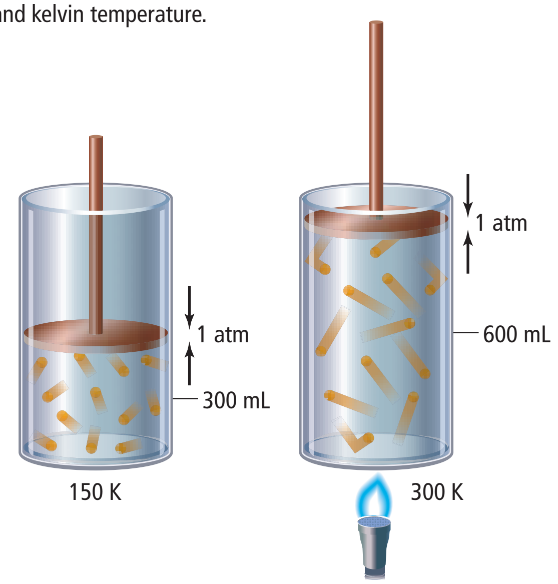
How are temperature and volume related? Jacques Charles (1746–1823), a French physicist, studied the relationship between volume and temperature. He observed that as temperature increases, so does the volume of a gas sample when the amount of gas and the pressure remain constant. This property is explained by the kinetic-molecular theory: as temperature increases, gas particles move faster, striking the walls of their container more frequently and with greater force. Because pressure depends on the frequency and force with which gas particles strike the walls of their container, this would increase the pressure. For the pressure to stay constant, volume must increase so that the particles have farther to travel before striking the walls. Having to travel farther decreases the frequency with which the particles strike the walls of the container.

The cylinders in **Figure 13.2** show how the volume of a fixed amount of gas changes as the gas is heated. Unlike **Figure 13.1,** where pressure in addition to that of the atmosphere was applied to the piston, the piston in **Figure 13.2** is free to float. This means that the piston will be supported by the gas inside the cylinder at a level where the pressure of the gas exactly matches that of the atmosphere. As you can see, the volume occupied by a gas at 1 atm increases as the temperature in the cylinder increases. The distance the piston moves is a measure of the increase in volume of the gas as it is heated.

Graphing the relationship of temperature and volume **Figure 13.2** also shows graphs of the relationship between the temperature and the volume of a fixed amount of gas at constant pressure. The plot of temperature versus volume is a straight line. Note that you can predict the temperature at which the volume will reach 0 L by extrapolating the line to temperatures below the values that were measured.

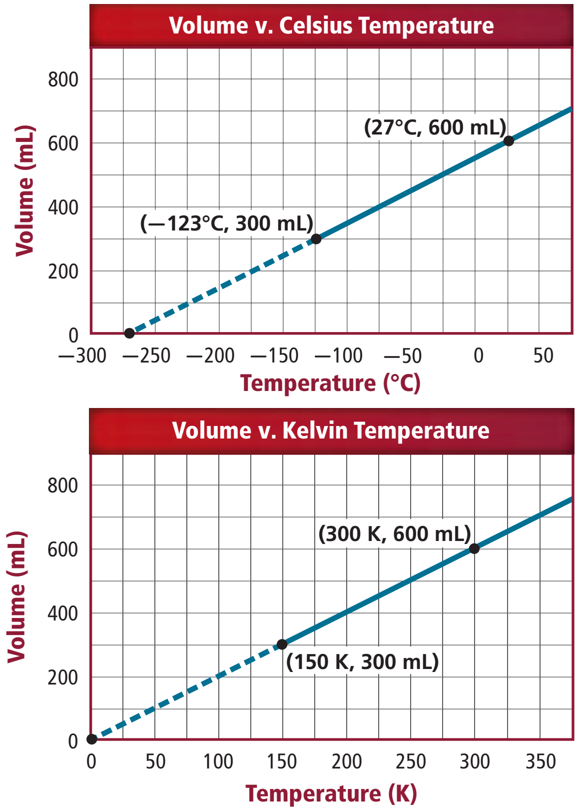
In the first graph, the temperature that corresponds to 0 L is −273.15°C. This relationship is linear, but it is not a direct proportion. For example, you can see that the graph of the line does not pass through the origin and that doubling the temperature from 25°C to 50°C does not double the volume.

■ **Figure 13.2** When the cylinder is heated, the kinetic energy of the gas particles increases, causing them to push the piston outward. The graphs show the relationship of volume to Celsius and kelvin temperature.



$$\frac{V_1}{T_1} = \frac{300\text{ mL}}{150\text{ K}} = 2\text{ mL/K} = \text{constant}$$

$$\frac{V_2}{T_2} = \frac{600\text{ mL}}{300\text{ K}} = 2\text{ mL/K} = \text{constant}$$



The second graph in **Figure 13.2,** which plots the kelvin (K) temperature against volume, does show a direct proportion. A temperature of 0 K corresponds to 0 mL, and doubling the temperature doubles the volume. Zero on the Kelvin scale is also known as **absolute zero.** Absolute zero represents the lowest possible theoretical temperature. At absolute zero, the atoms are all in the lowest possible energy state.

Graph Check **Explain** why the second graph in **Figure 13.2** shows a direct proportion, but the first graph does not.

Using Charles's law **Charles's law** states that the volume of a given amount of gas is directly proportional to its kelvin temperature at constant pressure. Charles's law can be expressed as follows.

Charles's Law

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

V **represents volume.**
T **represents temperature.**

For a given amount of gas at constant pressure, the quotient of the volume and kelvin temperature is a constant.

In the equation above, V_1 and T_1 represent initial conditions, while V_2 and T_2 are new conditions. As with Boyle's law, if you know three of the values, you can calculate the fourth.

The temperature must be expressed in kelvins when using the equation for Charles's law. As you read in Chapter 2, to convert a temperature from Celsius degrees to kelvins, add 273 to the Celsius temperature: $T_K = 273 + T_C$.

FOLDABLES Incorporate information from this section into your Foldable.

EXAMPLE Problem 13.2

Math Handbook
Significant Digits
pages 949–953

Charles's Law A helium balloon in a closed car occupies a volume of 2.32 L at 40.0°C. If the car is parked on a hot day and the temperature inside rises to 75.0°C, what is the new volume of the balloon, assuming the pressure remains constant?

1 Analyze the Problem

Charles's law states that as the temperature of a fixed amount of gas increases, so does its volume, assuming constant pressure. Therefore, the volume of the balloon will increase. The initial volume should be multiplied by a temperature ratio greater than 1.

Known	Unknown
$T_2 = 40.0°C$	$V_2 = ?\ L$
$V_1 = 2.32\ L$	
$T_2 = 75.0°C$	

2 Solve for the Unknown

Convert degrees Celsius to kelvins.

$T_K = 273 + T_C$ — **Apply the conversion factor.**

$T_1 = 273 + 40.0°C = 313.0\ K$ — **Substitute T_1 = 40.0°C.**

$T_2 = 273 + 75.0°C = 348.0\ K$ — **Substitute T_2 = 75.0°C.**

Use Charles's law. Solve for V_2, and substitute the known values into the rearranged equation.

$$\frac{V_1}{T_1} = \frac{V_2}{T_2}$$ **State Charles's law.**

$$V_2 = V_1\left(\frac{T_2}{T_1}\right)$$ **Solve for V_2.**

$$V_2 = 2.32\ L\left(\frac{348.0\ K}{313.0\ K}\right)$$ **Substitute V_1 = 2.32 L, T_1 = 313.0 K, and T_2 = 348.0 K.**

$$V_2 = 2.32\ L\left(\frac{348.0\ \cancel{K}}{313.0\ \cancel{K}}\right) = 2.58\ L$$ **Multiply and divide numbers and units.**

3 Evaluate the Answer

The increase in kelvins is relatively small, so the volume should show a small increase. The unit of the answer is liters, a volume unit, and there are three significant figures.

PRACTICE Problems

Extra Practice Page 984 and glencoe.com

Assume that the pressure and the amount of gas remain constant in the following problems.

4. What volume will the gas in the balloon at right occupy at 250 K?

5. A gas at 89°C occupies a volume of 0.67 L. At what Celsius temperature will the volume increase to 1.12 L?

6. The Celsius temperature of a 3.00-L sample of gas is lowered from 80.0°C to 30.0°C. What will be the resulting volume of this gas?

7. Challenge A gas occupies 0.67 L at 350 K. What temperature is required to reduce the volume by 45%?

Gay-Lussac's Law

In the Launch Lab, you saw Charles's law in action as the balloon's volume changed in response to temperature. What would have happened if the balloon's shape were rigid? If volume is constant, is there a relationship between temperature and pressure? The answer to that question is found in Gay-Lussac's law.

How are temperature and pressure of a gas related?

Pressure is a direct result of collisions between gas particles and the walls of their container. An increase in temperature increases collision frequency and energy, so raising the temperature should also raise the pressure if the volume is not changed. Joseph Gay-Lussac (1778–1850) found that a direct proportion exists between kelvin temperature and pressure, as illustrated in **Figure 13.3.** **Gay-Lussac's law** states that the pressure of a fixed amount of gas varies directly with the kelvin temperature when the volume remains constant. It can be expressed mathematically as follows.

Gay-Lussac's Law

$$\frac{P_1}{T_1} = \frac{P_2}{T_2}$$

***P* represents pressure.**
***T* represents temperature.**

For a given amount of gas held at constant volume, the quotient of the pressure and the kelvin temperature is a constant.

As with Boyle's and Charles's laws, if you know any three of the four variables, you can calculate the fourth using this equation. Remember that temperature must be in kelvins whenever it is used in a gas law equation.

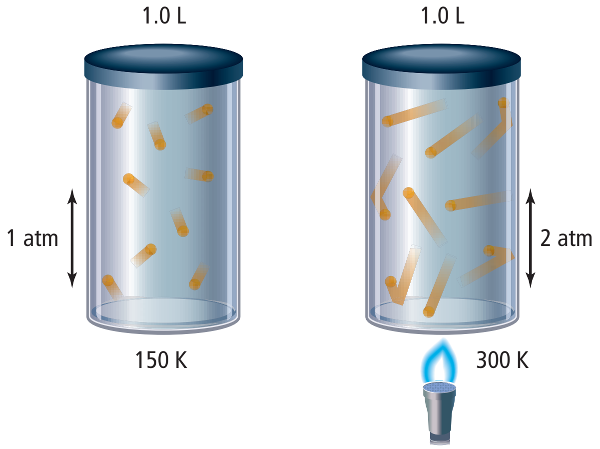
CAREERS IN CHEMISTRY

Meteorologist Relationships among pressure, temperature, and volume of air help meteorologists understand and predict the weather. For example, winds and fronts result from pressure changes caused by the uneven heating of Earth's atmosphere by the Sun. For more information on chemistry careers, visit glencoe.com.

Figure 13.3 When the cylinder is heated, the kinetic energy of the particles increases, increasing both the frequency and energy of the collisions with the container wall. The volume of the cylinder is fixed, so the pressure exerted by the gas increases.

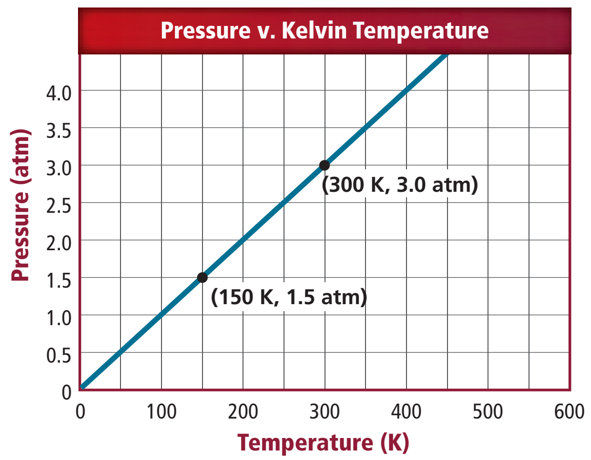
Concepts In Motion

Interactive Figure To see an animation of the gas laws, visit glencoe.com.



$$\frac{P_1}{T_1} = \frac{1.5\text{ atm}}{150\text{ K}} = 0.01\text{ atm/K} = \text{constant}$$

$$\frac{V_2}{T_2} = \frac{3.0\text{ atm}}{300\text{ K}} = 0.01\text{ atm/K} = \text{constant}$$



Graph Check
Compare and contrast the graphs in **Figures 13.2** and **13.3.**

EXAMPLE Problem 13.3

Gay-Lussac's Law The pressure of the oxygen gas inside a canister is 5.00 atm at 25.0°C. The canister is located at a camp high on Mount Everest. If the temperature there falls to −10.0°C, what is the new pressure inside the canister?

1 Analyze the Problem

Gay-Lussac's law states that if the temperature of a gas decreases, so does its pressure when volume is constant. Therefore, the pressure in the oxygen canister will decrease. The initial pressure should be multiplied by a temperature ratio less than 1.

Known	Unknown
$P_1 = 5.00$ atm	$\mathbf{P_2 = ?}$ **atm**
$T_1 = 25.0°C$	
$T_2 = -10.0°C$	

2 Solve for the Unknown

Convert degrees Celsius to kelvins.

$T_K = 273 + T_C$ — **Apply the conversion factor.**

$T_1 = 273 + 25.0°C = 298.0$ K — **Substitute $T_1 = 25.0°C$.**

$T_2 = 273 + (-10.0°C) = 263.0$ K — **Substitute $T_2 = -10.0°C$.**

Use Gay-Lussac's law. Solve for P_2, and substitute the known values into the rearranged equation.

$$\frac{P_1}{T_1} = \frac{P_2}{T_2}$$

State Gay-Lussac's law.

$$P_2 = P_1\left(\frac{T_2}{T_1}\right)$$

Solve for P_2.

$$P_2 = 5.00\text{ atm}\left(\frac{263.0\text{ K}}{298.0\text{ K}}\right)$$

Substitute $P_1 = 5.00$ atm, $T_1 = 298.0$ K, and $T_2 = 263.0$ K.

$$P_2 = 5.00\text{ atm}\left(\frac{263.0\ \cancel{\text{K}}}{298.0\ \cancel{\text{K}}}\right) = \mathbf{4.41\ atm}$$

Multiply and divide numbers and units.

3 Evaluate the Answer

Kelvin temperature decreases, so the pressure should decrease. The unit is atm, a pressure unit, and there are three significant figures.

PRACTICE Problems

Extra Practice Page 984 and glencoe.com

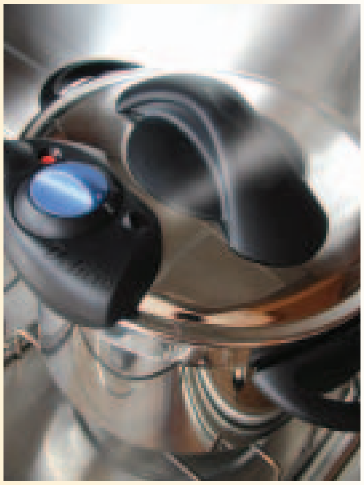
Assume that the volume and the amount of gas are constant in the following problems.

8. The pressure in an automobile tire is 1.88 atm at 25.0°C. What will be the pressure if the temperature increases to 37.0°C?

9. Helium gas in a 2.00-L cylinder is under 1.12 atm pressure. At 36.5°C, that same gas sample has a pressure of 2.56 atm. What was the initial temperature of the gas in the cylinder?

10. Challenge If a gas sample has a pressure of 30.7 kPa at 0.00°C, by how many degrees Celsius does the temperature have to increase to cause the pressure to double?

Real-World Chemistry
Gay-Lussac's Law



Pressure Cookers A pressure cooker is a pot with a lid that locks into place. This seals the container, which keeps its volume constant. Heating the pot increases the pressure in the cooker. As pressure increases, the temperature continues to increase and foods cook faster.

Figure 13.4 Tethers attached at the sides of a weather balloon hold it in place while it is being filled with helium or hydrogen gas. Weather balloons carry instruments that send data, such as air temperature, pressure, and humidity, to receivers on the ground. As the balloon rises, its volume responds to changes in temperature and pressure, expanding until the sides burst. A small parachute returns the instruments to Earth.

The Combined Gas Law

In a number of applications involving gases, such as the weather balloon in **Figure 13.4,** pressure, temperature, and volume might all change. Boyle's, Charles's, and Gay-Lussac's laws can be combined into a single law. This **combined gas law** states the relationship among pressure, temperature, and volume of a fixed amount of gas. All three variables have the same relationship to each other as they have in the other gas laws: pressure is inversely proportional to volume and directly proportional to temperature, and volume is directly proportional to temperature. The combined gas law can be expressed mathematically as follows.

The Combined Gas Law

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

P **represents pressure.** ***V*** **represents volume.**
T **represents temperature.**

For a given amount of gas, the product of pressure and volume, divided by the kelvin temperature, is a constant.

Using the combined gas law The combined gas law enables you to solve problems involving change in more than one variable. It also provides a way for you to remember the other three laws without memorizing each equation. If you can write out the combined gas law equation, equations for the other laws can be derived from it by remembering which variable is held constant in each case.

For example, if temperature remains constant as pressure and volume vary, then $T_1 = T_2$. After simplifying the combined gas law under these conditions, you are left with $P_1V_1 = P_2V_2$, which you should recognize as the equation for Boyle's law.

Reading Check **Derive** Charles's and Gay-Lussac's laws from the combined gas law.

Chemistry Online
Personal Tutor To learn how to derive the equation for the combined gas law, visit glencoe.com.

EXAMPLE Problem 13.4

The Combined Gas Law A gas at 110 kPa and 30.0°C fills a flexible container with an initial volume of 2.00 L. If the temperature is raised to 80.0°C and the pressure increases to 440 kPa, what is the new volume?

1 Analyze the Problem

Both pressure and temperature change, so you will need to use the combined gas law. The pressure quadruples, but the temperature does not increase by such a large factor. Therefore, the new volume will be smaller than the starting volume.

Known

$P_1 = 110$ kPa $P_2 = 440$ kPa

$T_1 = 30.0°C$ $T_2 = 80.0°C$

$V_1 = 2.00$ L

Unknown

$\mathbf{V_2 = ?\ L}$

2 Solve for the Unknown

Convert degrees Celsius to kelvins.

$T_K = 273 + T_C$ **Apply the conversion factor.**

$T_1 = 273 + 30.0°C = 303.0$ K **Substitute $T_1 = 30.0°C$.**

$T_2 = 273 + 80.0°C = 353.0$ K **Substitute $T_2 = 80.0°C$.**

Use the combined gas law. Solve for V_2, and substitute the known values into the rearranged equation.

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$ **State the combined gas law.**

$$V_2 = V_1\left(\frac{P_1}{P_2}\right)\left(\frac{T_2}{T_1}\right)$$ **Solve for V_2.**

$$V_2 = 2.00\ \text{L}\left(\frac{110\ \text{kPa}}{440\ \text{kPa}}\right)\left(\frac{353.0\ \text{K}}{303.0\ \text{K}}\right)$$ **Substitute $V_1 = 2.00$ L, $P_1 = 110$ kPa, $P_2 = 440$ kPa, $T_2 = 353.0$ K, and $T_1 = 303.0$ K.**

$$V_2 = 2.00\ \text{L}\left(\frac{110\ \text{k}\cancel{\text{Pa}}}{440\ \text{k}\cancel{\text{Pa}}}\right)\left(\frac{353.0\ \cancel{\text{K}}}{03.0\ \cancel{\text{K}}}\right) = \mathbf{0.58\ L}$$ **Multiply and divide numbers and units.**

3 Evaluate the Answer

Because the pressure change is much greater than the temperature change, the volume undergoes a net decrease. The unit is liters, a volume unit, and there are two significant figures.

PRACTICE Problems

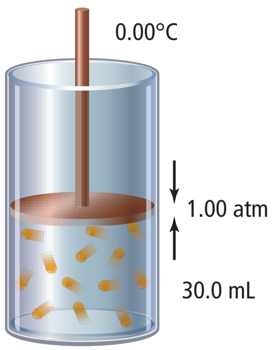
Extra Practice Page 984 and glencoe.com

Assume that the amount of gas is constant in the following problems.

11. A sample of air in a syringe exerts a pressure of 1.02 atm at 22.0°C. The syringe is placed in a boiling-water bath at 100.0°C. The pressure is increased to 1.23 atm by pushing the plunger in, which reduces the volume to 0.224 mL. What was the initial volume?

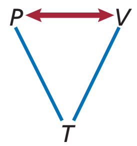
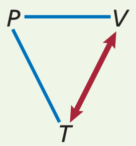
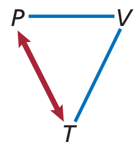
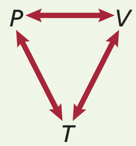
12. A balloon contains 146.0 mL of gas confined at a pressure of 1.30 atm and a temperature of 5.0°C. If the pressure doubles and the temperature decreases to 2.0°C, what will be the volume of gas in the balloon?

13. Challenge If the temperature in the gas cylinder at right increases to 30.0°C and the pressure increases to 1.20 atm, will the cylinder's piston move up or down?



Concepts In Motion

Interactive Table Explore the gas laws at glencoe.com.

Table 13.1	**The Gas Laws**			
Law	**Boyle's**	**Charles's**	**Gay-Lussac's**	**Combined**
Formula	$P_1V_1 = P_2V_2$	$\frac{V_1}{T_1} = \frac{V_2}{T_2}$	$\frac{P_1}{T_1} = \frac{P_2}{T_2}$	$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$
What is constant?	amount of gas, temperature	amount of gas, pressure	amount of gas, volume	amount of gas
Graphic organizer				

Temperature scales and the gas laws You might have noticed that the work done by Charles and Gay-Lussac preceded the development of the Kelvin scale, yet their laws require the use of temperature in kelvins. In the 1700s and early 1800s, scientists worked with several different scales. For example, a scale called the Réaumur scale was often used in France around Charles's time. On this scale—or any scale not based on absolute zero—the expression for Charles's law is more complex, requiring two constants in addition to V and T. The Kelvin scale simplified matters, resulting in the familiar gas laws presented here.

You have now seen how pressure, temperature, and volume affect a gas sample. You can use the gas laws, summarized in **Table 13.1,** as long as the amount of gas remains constant. But what happens if the amount of gas changes? In the next section, you will add the fourth variable, amount of gas present, to the gas laws.

Section 13.1 Assessment

Section Summary

- Boyle's law states that the volume of a fixed amount of gas is inversely proportional to its pressure at constant temperature.
- Charles's law states that the volume of a fixed amount of gas is directly proportional to its kelvin temperature at constant pressure.
- Gay-Lussac's law states that the pressure of a fixed amount of gas is directly proportional to its kelvin temperature at constant volume.
- The combined gas law relates pressure, temperature, and volume in a single statement.

14. **MAIN Idea** **State** the relationship among pressure, temperature, and volume of a fixed amount of gas.
15. **Explain** Which of the three variables that apply to equal amounts of gases are directly proportional? Which are inversely proportional?
16. **Analyze** A weather balloon is released into the atmosphere. You know the initial volume, temperature, and air pressure. What information will you need to predict its volume when it reaches its final altitude? Which law would you use to calculate this volume?
17. **Infer** why gases such as the oxygen used at hospitals are compressed. Why must compressed gases be shielded from high temperatures? What must happen to compressed oxygen before it can be inhaled?
18. **Calculate** A rigid plastic container holds 1.00 L of methane gas at 660 torr pressure when the temperature is 22.0°C. How much pressure will the gas exert if the temperature is raised to 44.6°C?
19. **Design** a concept map that shows the relationships among pressure, volume, and temperature in Boyle's, Charles's, and Gay-Lussac's laws.

Section 13.2

Objectives

- **Relate** number of particles and volume using Avogadro's principle.
- **Relate** the amount of gas present to its pressure, temperature, and volume using the ideal gas law.
- **Compare** the properties of real and ideal gases.

Review Vocabulary

mole: an SI base unit used to measure the amount of a substance; the amount of a pure substance that contains 6.02×10^{23} representative particles

New Vocabulary

Avogadro's principle
molar volume
ideal gas constant (R)
ideal gas law

The Ideal Gas Law

MAIN Idea The ideal gas law relates the number of particles to pressure, temperature, and volume.

Real-World Reading Link You know that adding air to a tire causes the pressure in the tire to increase. But did you know that the recommended pressure for car tires is specified for cold tires? As tires roll over the road, friction causes their temperatures to increase. This also causes the pressure to increase.

Avogadro's Principle

The particles that make up different gases can vary greatly in size. However, kinetic-molecular theory assumes that the particles in a gas sample are far enough apart that size has very little influence on the volume occupied by a gas. For example, 1000 relatively large krypton gas particles occupy the same volume as 1000 smaller helium gas particles at the same temperature and pressure. It was Avogadro who first proposed this idea in 1811. **Avogadro's principle** states that equal volumes of gases at the same temperature and pressure contain equal numbers of particles. **Figure 13.5** shows equal volumes of carbon dioxide, helium, and oxygen.

Volume and moles Recall from Chapter 10 that 1 mol contains 6.02×10^{23} particles. The **molar volume** of a gas is the volume that 1 mol occupies at 0.00°C and 1.00 atm pressure. The conditions of 0.00°C and 1.00 atm are known as standard temperature and pressure (STP). Avogadro showed experimentally that 1 mol of any gas occupies a volume of 22.4 L at STP. Because the volume of 1 mol of a gas at STP is 22.4 L, you can use 22.4 L/mol as a conversion factor whenever a gas is at STP.

For example, suppose you want to find the number of moles in a sample of gas that has a volume of 3.72 L at STP. Use the molar volume to convert from volume to moles.

$$3.72 \text{ L} \times \frac{1 \text{ mol}}{22.4 \text{ L}} = 0.166 \text{ mol}$$

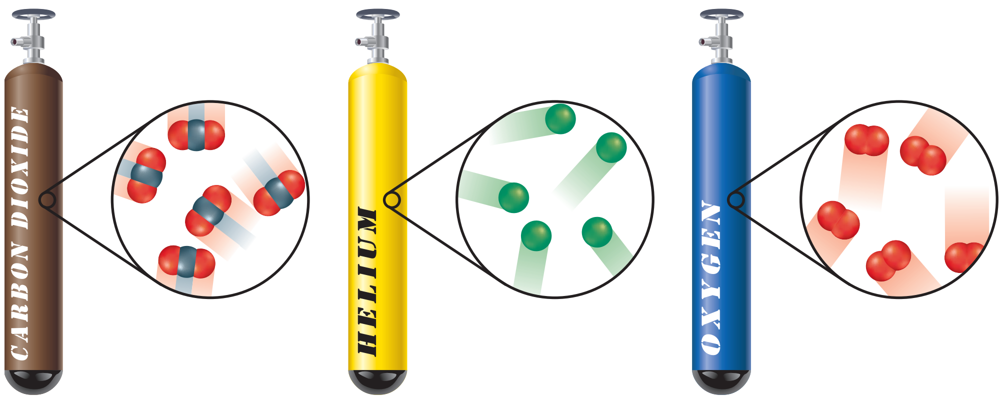


Figure 13.5 Gas tanks of equal volume that are at the same pressure and temperature contain equal numbers of gas particles, regardless of which gas they contain.
Infer *Why doesn't Avogadro's principle apply to liquids and solids?*

EXAMPLE Problem 13.5

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Unit Conversion
page 957

Molar Volume The main component of natural gas used for home heating and cooking is methane (CH_4). Calculate the volume that 2.00 kg of methane gas will occupy at STP.

1 Analyze the Problem

The number of moles can be calculated by dividing the mass of the sample, *m*, by its molar mass, M. The gas is at STP (0.00°C and 1.00 atm pressure), so you can use the molar volume to convert from the number of moles to the volume.

Known

$m = 2.00$ kg
$T = 0.00°C$
$P = 1.00$ atm

Unknown

$V = ?$ **L**

2 Solve for the Unknown

Determine the molar mass for methane.

$$M = 1\text{ C }\cancel{\text{atom}}\left(\frac{12.01\text{ amu}}{1\text{ C }\cancel{\text{atom}}}\right) + 4\text{ H }\cancel{\text{atoms}}\left(\frac{1.01\text{ amu}}{1\text{ H }\cancel{\text{atom}}}\right)$$

Determine the molecular mass.

$$= 12.01\text{ amu} + 4.04\text{ amu} = 16.05\text{ amu}$$
$$= 16.05\text{ g/mol}$$

Express the molecular mass as g/mol to arrive at the molar mass.

Determine the number of moles of methane.

$$2.00\ \cancel{\text{kg}}\left(\frac{1000\text{ g}}{1\ \cancel{\text{kg}}}\right) = 2.00 \times 10^3\text{ g}$$

Convert the mass from kg to g.

$$\frac{m}{M} = \frac{2.00 \times 10^3\ \cancel{\text{g}}}{16.05\ \cancel{\text{g}}/\text{mol}} = 125\text{ mol}$$

Divide mass by molar mass to determine the number of moles.

Use the molar volume to determine the volume of methane at STP.

$$V = 125\ \cancel{\text{mol}} = \frac{22.4\text{ L}}{1\ \cancel{\text{mol}}} = \mathbf{2.80 \times 10^3\text{ L}}$$

Use the molar volume, 22.4 L/mol, to convert from moles to the volume.

3 Evaluate the Answer

The amount of methane present is much more than 1 mol, so you should expect a large volume, which is in agreement with the answer. The unit is liters, a volume unit, and there are three significant figures.

PRACTICE Problems

Extra Practice Page 984 and glencoe.com

20. What size container do you need to hold 0.0459 mol of N_2 gas at STP?

21. How much carbon dioxide gas, in grams, is in a 1.0-L balloon at STP?

22. What volume in milliliters will 0.00922 g of H_2 gas occupy at STP?

23. What volume will 0.416 g of krypton gas occupy at STP?

24. Calculate the volume that 4.5 kg of ethylene gas (C_2H_4) will occupy at STP.

25. Challenge A flexible plastic container contains 0.860 g of helium gas in a volume of 19.2 L. If 0.205 g of helium is removed at constant pressure and temperature, what will be the new volume?

■ **Figure 13.6** The volume and temperature of this tire stay the same as air is added. However, the pressure in the tire increases as the amount of air present increases.

The Ideal Gas Law

Avogadro's principle and the laws of Boyle, Charles, and Gay-Lussac can be combined into a single mathematical statement that describes the relationship among pressure, volume, temperature, and number of moles of a gas. This formula works best for gases that obey the assumptions of the kinetic-molecular theory. Known as ideal gases, their particles occupy a negligible volume and are far enough apart that they exert minimal attractive or repulsive forces on one another.

From the combined gas law to the ideal gas law The combined gas law relates the variables of pressure, volume, and temperature for a given amount of gas.

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

For a specific sample of gas, this relationship of pressure, volume, and temperature is always the same. You could rewrite the relationship represented in the combined gas law as follows.

$$\frac{PV}{T} = \text{constant}$$

As **Figure 13.6** illustrates, increasing the amount of gas present in a sample will raise the pressure if temperature and volume are constant. Likewise, if pressure and temperature remain constant, the volume will increase as more particles of a gas are added. In fact, we know that both volume and pressure are directly proportional to the number of moles, n, so n can be incorporated into the combined gas law as follows.

$$\frac{PV}{nT} = \text{constant}$$

FOLDABLES Incorporate information from this section into your Foldable.

Experiments using known values of P, T, V, and n have determined the value of this constant. It is called the **ideal gas constant,** and it is represented by the symbol R. If pressure is in atmospheres, the value of R is 0.0821 L·atm/mol·K. Note that the units for R are simply the combined units for each of the four variables. **Table 13.2** shows the numerical values for R in different units of pressure.

Reading Check **Explain** why the number of moles, *n*, was added to the denominator of the equation above.

Substituting R for the constant in the equation above and rearranging the variables gives the most familiar form of the ideal gas law. The **ideal gas law** describes the physical behavior of an ideal gas in terms of the pressure, volume, temperature, and number of moles of gas present.

Table 13.2 Values of R

Value of R	Units of R
0.0821	$\frac{\text{L·atm}}{\text{mol·K}}$
8.314	$\frac{\text{L·kPa}}{\text{mol·K}}$
62.4	$\frac{\text{L·mmHg}}{\text{mol·K}}$

The Ideal Gas Law

$$PV = nRT$$

P **represents pressure.** ***V*** **represents volume.**
n **represents number of moles. R is the ideal gas constant.**
T **represents temperature.**

For a given amount of gas held at constant temperature, the product of pressure and volume is a constant.

If you know any three of the four variables, you can rearrange the equation to solve for the unknown.

EXAMPLE Problem 13.6

The Ideal Gas Law Calculate the number of moles of ammonia gas (NH_3) contained in a 3.0-L vessel at 3.00×10^2 K with a pressure of 1.50 atm.

1 Analyze the Problem

You are given the volume, temperature, and pressure of a gas sample. Use the ideal gas law, and select the value of R that contains the pressure units given in the problem. Because the pressure and temperature are close to STP, but the volume is much smaller than 22.4 L, it would make sense if the calculated answer were much smaller than 1 mol.

Known

$V = 3.0$ L

$T = 3.00 \times 10^2$ K

$P = 1.50$ atm

$R = 0.0821 \frac{L \cdot atm}{mol \cdot K}$

Unknown

$n = ?$ mol

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Significant Digits
page 949

2 Solve for the Unknown

Use the ideal gas law. Solve for n, and substitute the known values.

$$PV = nRT$$
State the ideal gas law.

$$n = \frac{PV}{RT}$$
Solve for n.

$$n = \frac{(1.50 \text{ atm})(3.0 \text{ L})}{\left(0.0821 \frac{L \cdot atm}{mol \cdot K}\right)(3.00 \times 10^2 \text{ K})}$$
Substitute $V = 3.0$ L, $T = 3.00 \times 10^2$ K, $P = 1.50$ atm, and $R = 0.0821$ L•atm/mol•K.

$$n = \frac{(1.50 \cancel{\text{atm}})(3.0 \cancel{\text{L}})}{\left(0.0821 \frac{\cancel{L \cdot atm}}{mol \cdot \cancel{K}}\right)(3.00 \times 10^2 \cancel{\text{K}})} = 0.18 \text{ mol}$$
Multiply and divide numbers and units.

3 Evaluate the Answer

The answer agrees with the prediction that the number of moles present will be significantly less than 1 mol. The unit of the answer is the mole, and there are two significant figures.

PRACTICE Problems

Extra Practice Page 985 and glencoe.com

26. Determine the Celsius temperature of 2.49 mol of a gas contained in a 1.00-L vessel at a pressure of 143 kPa.

27. Calculate the volume of a 0.323-mol sample of a gas at 265 K and 0.900 atm.

28. What is the pressure, in atmospheres, of a 0.108-mol sample of helium gas at a temperature of 20.0°C if its volume is 0.505 L?

29. If the pressure exerted by a gas at 25°C in a volume of 0.044 L is 3.81 atm, how many moles of gas are present?

30. **Challenge** An ideal gas has a volume of 3.0 L. If the number of moles of gas and the temperature are doubled, while the pressure remains constant, what is the new volume?

VOCABULARY
WORD ORIGIN
Mole
comes from the German word *Mol,* which is short for *Molekulargewicht,* meaning *molecular weight*

The Ideal Gas Law— Molar Mass and Density

The ideal gas law can be used to solve for the value of any one of the four variables *P, V, T,* or *n* if the values of the other three are known. However, you can also rearrange the $PV = nRT$ equation to calculate the molar mass and density of a gas sample.

Molar mass and the ideal gas law To find the molar mass of a gas sample, the mass, temperature, pressure, and volume of the gas must be known. Recall from Chapter 10 that the number of moles of a gas *(n)* is equal to the mass *(m)* divided by the molar mass (M). Therefore, the *n* in the equation can be replaced by *m*/M.

$$PV = nRT \quad \xrightarrow{\text{substitute } n = \frac{m}{M}} \quad PV = \frac{mRT}{M}$$

You can rearrange the new equation to solve for the molar mass.

$$\boxed{M = \frac{mRT}{PV}}$$

Density and the ideal gas law Recall from Chapter 2 that the density *(D)* of a substance is defined as mass *(m)* per unit volume *(V).* After rearranging the ideal gas equation to solve for molar mass, you can substitute *D* for *m*/*V.*

$$M = \frac{mRT}{PV} \quad \xrightarrow{\text{substitute } \frac{m}{V} = D} \quad M = \frac{DRT}{P}$$

You can rearrange the new equation to solve for density.

$$\boxed{D = \frac{MP}{RT}}$$

Why might you need to know the density of a gas? Consider the requirements to fight a fire. One way to put out a fire is to remove its oxygen source by covering it with another gas that will neither burn nor support combustion, as shown in **Figure 13.7.** This gas must have a greater density than oxygen so that it will displace the oxygen at the source of the fire. You can observe a similar application of density by doing the MiniLab on the next page.

■ **Figure 13.7** To extinguish a fire, you need to take away fuel, oxygen, or heat. The fire extinguisher at right contains carbon dioxide, which displaces oxygen but does not burn. It also has a cooling effect due to the rapid expansion of the carbon dioxide as it is released from the nozzle.
Explain *Why does carbon dioxide displace oxygen?*

MiniLab

Model a Fire Extinguisher

Why is carbon dioxide used in fire extinguishers?

Procedure

1. Read and complete the lab safety form.
2. Measure the temperature with a **thermometer.** Obtain the air pressure with a **barometer** or **weather radio.** Record your data.
3. Roll a 23-cm × 30-cm piece of **aluminum foil** into a cylinder that is 30 cm long and roughly 6 cm in diameter. Tape the edges with **masking tape.**
4. Use **matches** to light a **candle.**
   WARNING: *Run water over the extinguished match before throwing it away. Keep hair and clothing away from the flame.*
5. Place 30 g of **baking soda ($NaHCO_3$)** in a large **beaker.** Add 40 mL of **vinegar (5% CH_3COOH).**
6. Quickly position the foil cylinder at about 45° up and away from the top of the candle flame.
   WARNING: *Do not touch the end of the aluminum tube that is near the burning candle.*
7. While the reaction in the beaker is actively producing carbon dioxide gas, carefully pour the gas, but not the liquid, out of the beaker and into the top of the foil tube. Record your observations.

Analysis

1. **Apply** Calculate the molar volume of carbon dioxide gas (CO_2) at room temperature and atmospheric pressure.
2. **Calculate** the room-temperature densities in grams per liter of carbon dioxide, oxygen, and nitrogen gases. Recall that you will need to calculate the molar mass of each gas in order to calculate densities.
3. **Interpret** Do your observations and calculations support the use of carbon dioxide gas to extinguish fires? Explain.

Real Versus Ideal Gases

What does the term *ideal gas* mean? Ideal gases follow the assumptions of the kinetic-molecular theory, which you studied in Chapter 12. An ideal gas is one whose particles take up no space. Ideal gases experience no intermolecular attractive forces, nor are they attracted or repelled by the walls of their containers. The particles of an ideal gas are in constant, random motion, moving in straight lines until they collide with each other or with the walls of the container. Additionally, these collisions are perfectly elastic, which means that the kinetic energy of the system does not change. An ideal gas follows the gas laws under all conditions of temperature and pressure.

In reality, no gas is truly ideal. All gas particles have some volume, however small, and are subject to intermolecular interactions. Also, the collisions that particles make with each other and with the container are not perfectly elastic. Despite that, most gases will behave like ideal gases at a wide range of temperatures and pressures. Under the right conditions, calculations made using the ideal gas law closely approximate experimental measurements.

Reading Check **Explain** the relationship between the kinetic-molecular theory and an ideal gas.

Matt Meadows

Problem-Solving Strategy

Deriving Gas Laws

If you master the following strategy, you will need to remember only one gas law—the ideal gas law. Consider the example of a fixed amount of gas held at constant pressure. You need Charles's law to solve problems involving volume and temperature.

1. Use the ideal gas law to write two equations that describe the gas sample at two different volumes and temperatures. (Quantities that do not change are shown in **red**.)
2. Isolate volume and temperature—the two conditions that vary—on the same side of each equation.
3. Because n, R, and P are constant under these conditions, you can set the volume and temperature conditions equal, deriving Charles's law.

$$PV_1 = n\mathrm{R}T_1 \qquad PV_2 = n\mathrm{R}T_2$$

$$\frac{{}_1}{T_1} = \frac{\mathbf{R}}{P} \qquad \frac{V_2}{{}_2} = \frac{\mathbf{R}}{P}$$

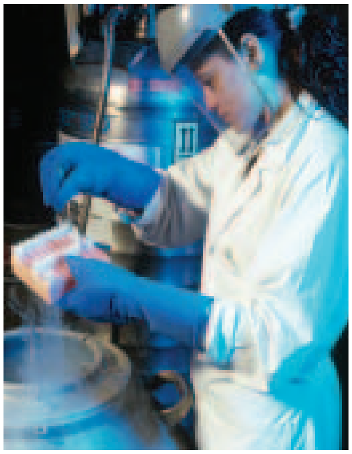
$$\frac{V_1}{T_1} = \frac{V_2}{T_2}$$

Apply the Strategy

Derive Boyle's law, Gay-Lussac's law, and the combined gas law based on the example above.

Extreme pressure and temperature When is the ideal gas law not likely to work for a real gas? Real gases deviate most from ideal gas behavior at high pressures and low temperatures. The nitrogen gas in the tanks shown in **Figure 13.8** behaves as a real gas. Lowering the temperature of nitrogen gas results in less kinetic energy of the gas particles, which means their intermolecular attractive forces are strong enough to affect their behavior. When the temperature is low enough, this real gas condenses to form a liquid. The propane gas in the tanks shown in **Figure 13.8** also behaves as a real gas. Increasing the pressure on a gas forces the gas particles closer together until the volume occupied by the gas particles themselves is no longer negligible. Real gases such as propane will liquefy if enough pressure is applied.

Figure 13.8 Real gases do not follow the ideal gas law at all pressures and temperatures.



Nitrogen gas turns to liquid at −196°C. At this temperature, scientists can preserve biological specimens, such as body tissues, for future research or medical procedures.

About 270 times more propane can be stored as a liquid than as a gas in the same amount of space. Your family might use small tanks of liquid propane as fuel for your barbecue grill or larger tanks for heating and cooking.

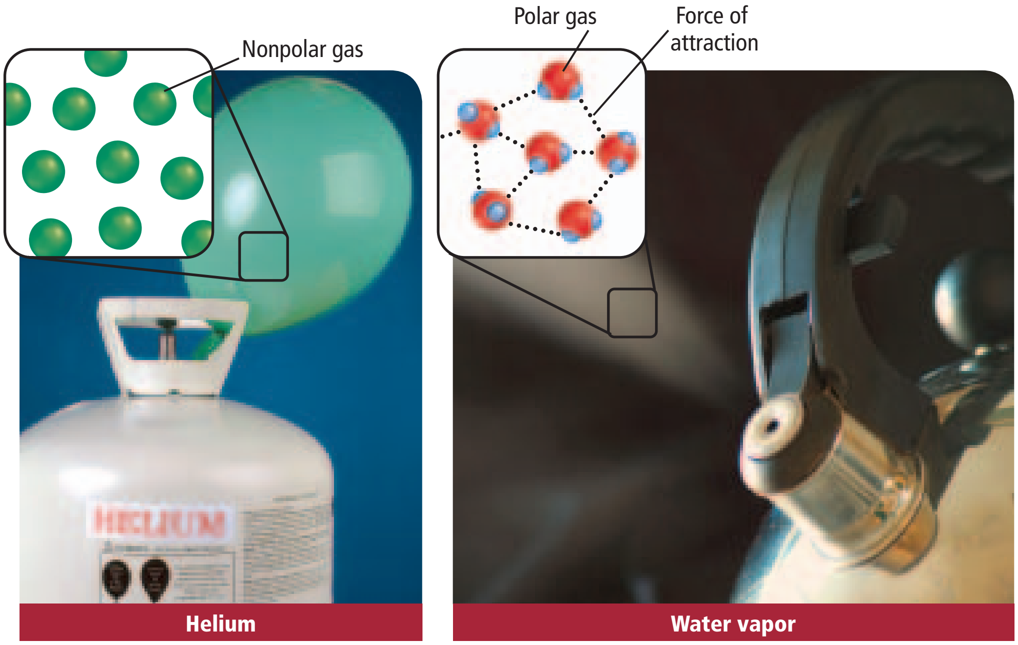


Figure 13.9 In a nonpolar gas, there is minimal attraction between particles. However, polar gases, such as water vapor, experience forces of attraction between particles.

Infer *Assuming the volume of the particles is negligible, how will the measured pressure for a sample of gas that experiences significant intermolecular attractive forces compare to the pressure predicted by the ideal gas law?*

Polarity and size of particles The nature of the particles making up a gas also affects how ideally the gas behaves. For example, polar gas molecules, such as water vapor, generally have larger attractive forces between their particles than nonpolar gases, such as helium. The oppositely charged ends of polar molecules are pulled together through electrostatic forces, as shown in **Figure 13.9.** Therefore, polar gases do not behave as ideal gases. Also, the particles of gases composed of larger nonpolar molecules, such as butane (C_4H_{10}), occupy more actual volume than an equal number of smaller gas particles in gases such as helium (He). Therefore, larger gas particles tend to exhibit a greater departure from ideal behavior than do smaller gas particles.

Section 13.2 Assessment

Section Summary

- Avogadro's principle states that equal volumes of gases at the same pressure and temperature contain equal numbers of particles.
- The ideal gas law relates the amount of a gas present to its pressure, temperature, and volume.
- The ideal gas law can be used to find molar mass if the mass of the gas is known, or the density of the gas if its molar mass is known.
- At very high pressures and very low temperatures, real gases behave differently than ideal gases.

31. MAIN Idea **Explain** why Avogadro's principle holds true for gases that have small particles and for gases that have large particles.
32. **State** the equation for the ideal gas law.
33. **Analyze** how the ideal gas law applies to real gases using the kinetic-molecular theory.
34. **Predict** the conditions under which a real gas might deviate from ideal behavior.
35. **List** common units for each variable in the ideal gas law.
36. **Calculate** A 2.00-L flask is filled with propane gas (C_3H_8) at a pressure of 1.00 atm and a temperature of −15.0°C. What is the mass of the propane in the flask?
37. **Make and Use Graphs** For every 6°C drop in temperature, the air pressure in a car's tires goes down by about 1 psi (14.7 psi = 1.00 atm). Make a graph illustrating the change in tire pressure from 20°C to −20°C (assume 30.0 psi at 20°C).

Section 13.3

Objectives

- **Determine** volume ratios for gaseous reactants and products by using coefficients from chemical equations.
- **Apply** gas laws to calculate amounts of gaseous reactants and products in a chemical reaction.

Review Vocabulary

coefficient: the number written in front of a reactant or product in a chemical equation, which tells the smallest number of particles of the substance involved in the reaction

Gas Stoichiometry

MAIN Idea When gases react, the coefficients in the balanced chemical equation represent both molar amounts and relative volumes.

Real-World Reading Link To make a cake, it is important to add the ingredients in the correct proportions. In a similar way, the correct proportions of reactants are needed in a chemical reaction to yield the desired products.

Stoichiometry of Reactions Involving Gases

The gas laws can be applied to calculate the stoichiometry of reactions in which gases are reactants or products. Recall that the coefficients in chemical equations represent molar amounts of substances taking part in the reaction. For example, hydrogen gas can react with oxygen gas to produce water vapor.

$$2H_2(g) + O_2(g) \rightarrow 2H_2O(g)$$

From the balanced chemical equation, you know that 2 mol of hydrogen gas reacts with 1 mol of oxygen gas, producing 2 mol of water vapor. This tells you the molar ratios of substances in this reaction. Avogadro's principle states that equal volumes of gases at the same temperature and pressure contain equal numbers of particles. Thus, for gases, the coefficients in a balanced chemical equation represent not only molar amounts but also relative volumes. Therefore, 2 L of hydrogen gas would react with 1 L of oxygen gas to produce 2 L of water vapor.

Stoichiometry and Volume–Volume Problems

To find the volume of a gaseous reactant or product in a reaction, you must know the balanced chemical equation for the reaction and the volume of at least one other gas involved in the reaction. Examine the reaction in **Figure 13.10,** which shows the combustion of methane. This reaction takes place every time you light a Bunsen burner.

Because the coefficients represent volume ratios for gases taking part in the reaction, you can determine that it takes 2 L of oxygen to react completely with 1 L of methane. The complete combustion of 1 L of methane will produce 1 L of carbon dioxide and 2 L of water vapor.

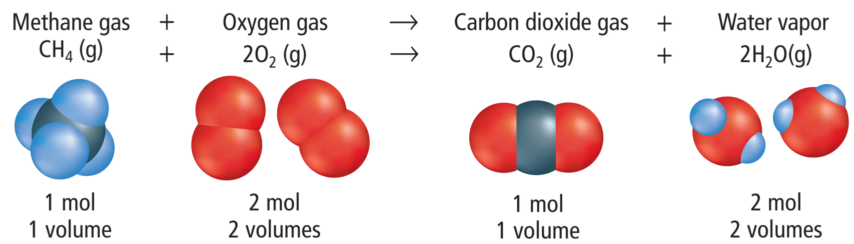


Figure 13.10 The coefficients in a balanced equation show the relationships among numbers of moles of all reactants and products, and the relationships among volumes of any gaseous reactants or products. From these coefficients, volume ratios can be set up for any pair of gases in the reaction.

Note that no conditions of temperature and pressure are listed. They are not needed as part of the calculation because after mixing, both gases are at the same temperature and pressure. The temperature of the entire reaction might change during the reaction, but a change in temperature would affect all gases in the reaction the same way. Therefore, you do not need to consider pressure and temperature conditions.

EXAMPLE Problem 13.7

Math Handbook
Ratios
page 964

Volume–Volume Problems What volume of oxygen gas is needed for the complete combustion of 4.00 L of propane gas (C_3H_8)? Assume that pressure and temperature remain constant.

1 Analyze the Problem

You are given the volume of a gaseous reactant in a chemical reaction. Remember that the coefficients in a balanced chemical equation provide the volume relationships of gaseous reactants and products.

Known
$V_{C_3H_8} = 4.00\ L$

Unknown
$V_{O_2} = ?\ L$

2 Solve for the Unknown

Use the balanced equation for the combustion of C_3H_8. Find the volume ratio for O_2 and C_3H_8, then solve for V_{O_2}.

$C_3H_8(g) + 5O_2(g) \rightarrow 3CO_2(g) + 4H_2O(g)$ **Write the balanced equation.**

$\frac{5\ \text{volumes}\ O_2}{1\ \text{volume}\ C_3H_8}$ **Find the volume ratio for O_2 and C_3H_8.**

$VO_2 = (4.00\ L\ \cancel{C_3H_8}) \times \frac{5\ \cancel{\text{volumes}}\ O_2}{1\ \cancel{\text{volume}\ C_3H_8}}$ **Multiply the known volume of C_3H_8 by the volume ratio to find the volume of O_2.**

$= \mathbf{20.0\ L\ O_2}$

3 Evaluate the Answer

The coefficients in the combustion equation show that a much larger volume of O_2 than C_3H_8 is used up in the reaction, which is in agreement with the calculated answer. The unit of the answer is liters, a unit of volume, and there are three significant figures.

PRACTICE Problems

Extra Practice Page 985 and glencoe.com

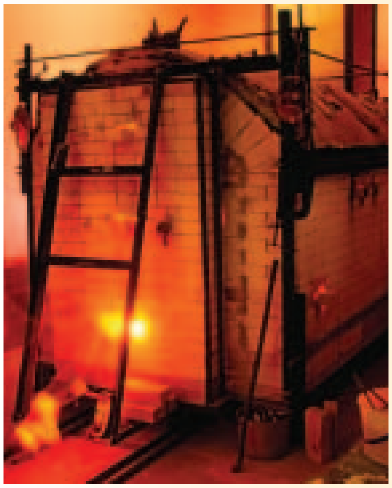
38. How many liters of propane gas (C_3H_8) will undergo complete combustion with 34.0 L of oxygen gas?

39. Determine the volume of hydrogen gas needed to react completely with 5.00 L of oxygen gas to form water.

40. What volume of oxygen is needed to completely combust 2.36 L of methane gas (CH_4)?

41. **Challenge** Nitrogen and oxygen gases react to form dinitrogen oxide gas (N_2O). What volume of O_2 is needed to produce 34 L of N_2O?

Real-World Chemistry
Using Stoichiometry



Kilns Correct proportions of gases are needed for many chemical reactions. Although many pottery kilns are fueled by methane, a precise mixture of propane and air can be used to fuel a kiln if methane is unavailable.

Figure 13.11 Ammonia is essential in the production of fertilizers containing nitrogen. Proper levels of soil nitrogen lead to increased crop yields.

Stoichiometry and Volume–Mass Problems

Connection to Biology What you have learned about stoichiometry can be applied to the production of ammonia (NH_3) from nitrogen gas (N_2). Fertilizer manufacturers use ammonia to make nitrogen-based fertilizers. Nitrogen is an essential element for plant growth. Natural sources of nitrogen in soil, such as nitrogen fixation by plants, the decomposition of organic matter, and animal wastes, do not always supply enough nitrogen for optimum crop yields. **Figure 13.11** shows a farmer applying fertilizer rich in nitrogen to the soil. This enables the farmer to produce a crop with a higher yield.

Example Problem 13.8 shows how to use a volume of nitrogen gas to produce a certain amount of ammonia. In doing this type of problem, remember that the balanced chemical equation allows you to find ratios for only moles and gas volumes, not for masses. All masses given must be converted to moles or volumes before being used as part of a ratio. Also, remember that the temperature units used must be kelvin.

VOCABULARY

ACADEMIC VOCABULARY

Ratio

the relationship in quantity between two things

In a water molecule, the ratio of hydrogen to oxygen is 2:1.

EXAMPLE Problem 13.8

Volume–Mass Problems Ammonia is synthesized from hydrogen and nitrogen.

$$N_2(g) + 3H_2(g) \rightarrow 2NH_3(g)$$

If 5.00 L of nitrogen reacts completely with hydrogen at a pressure of 3.00 atm and a temperature of 298 K, how much ammonia, in grams, is produced?

1 Analyze the Problem

You are given the volume, pressure, and temperature of a gas sample. The mole and volume ratios of gaseous reactants and products are given by the coefficients in the balanced chemical equation. Volume can be converted to moles and thus related to mass by using molar mass and the ideal gas law.

Known	Unknown
$V_{N_2} = 5.00$ L	$m_{NH_3} = ?$ g
$P = 3.00$ atm	
$T = 298$ K	

2 Solve for the Unknown

Determine how many liters of gaseous ammonia will be made from 5.00 L of nitrogen gas.

$$\frac{1 \text{ volume } N_2}{2 \text{ volumes } NH_3}$$ **Find the volume ratio for N_2 and NH_3 using the balanced equation.**

$$5.00 \text{ L } \cancel{N_2} \left(\frac{2 \text{ } \cancel{\text{volumes}} \text{ } NH_3}{1 \text{ } \cancel{\text{volume}} \text{ } \cancel{N_2}}\right) = 10.0 \text{ L } NH_3$$ **Multiply the known volume of N_2 by the volume ratio to find the volume of NH_3.**

Use the ideal gas law. Solve for n, and calculate the number of moles of NH_3.

$$PV = nRT$$ **State the ideal gas law.**

$$n = \frac{PV}{RT}$$ **Solve for *n*.**

$$n = \frac{(3.00 \text{ atm})(10.0 \text{ L})}{\left(0.0821 \frac{\text{L·atm}}{\text{mol·K}}\right)(298 \text{ K})}$$ **Substitute $V_{N_2} = 5.00$ L, $P = 3.00$ atm, and $T = 298$ K.**

$$n = \frac{(3.00 \text{ } \cancel{\text{atm}})(10.0 \text{ } \cancel{\text{L}})}{\left(0.0821 \frac{\cancel{\text{L·atm}}}{\text{mol·}\cancel{\text{K}}}\right)(298 \text{ } \cancel{\text{K}})} = 1.23 \text{ mol } NH_3$$ **Multiply and divide numbers and units.**

$$M = \left(\frac{1 \text{ } \cancel{\text{N atom}} \times 14.01 \text{ amu}}{1 \text{ } \cancel{\text{N atom}}}\right) + \left(\frac{3 \text{ } \cancel{\text{H atoms}} \times 1.01 \text{ amu}}{1 \text{ } \cancel{\text{H atom}}}\right)$$ **Find the molecular mass of NH_3.**

$$= 17.04 \text{ amu}$$

$$M = 17.04 \text{ g/mol}$$ **Express molar mass in units of g/mol.**

Convert moles of ammonia to grams of ammonia.

$$1.23 \text{ } \cancel{\text{mol } NH_3} \times \frac{17.04 \text{ g } NH_3}{1 \text{ } \cancel{\text{mol } NH_3}} = \mathbf{21.0 \text{ g } NH_3}$$ **Use the molar mass of ammonia as a conversion factor.**

3 Evaluate the Answer

To check your answer, calculate the volume of reactant nitrogen at STP. Then, use molar volume and the mole ratio between N_2 and NH_3 to determine how many moles of NH_3 were produced. The unit of the answer is grams, a unit of mass. There are three significant figures.

PRACTICE Problems

Extra Practice Page 985 and glencoe.com

42. Ammonium nitrate is a common ingredient in chemical fertilizers. Use the reaction shown to calculate the mass of solid ammonium nitrate that must be used to obtain 0.100 L of dinitrogen oxide gas at STP.

$$NH_4NO_3(s) \rightarrow N_2O(g) + 2H_2O(g)$$

43. When solid calcium carbonate ($CaCO_3$) is heated, it decomposes to form solid calcium oxide (CaO) and carbon dioxide gas (CO_2). How many liters of carbon dioxide will be produced at STP if 2.38 kg of calcium carbonate reacts completely?

44. When iron rusts, it undergoes a reaction with oxygen to form iron(III) oxide.

$$4Fe(s) + 3O_2(g) \rightarrow 2Fe_2O_3(s)$$

Calculate the volume of oxygen gas at STP that is required to completely react with 52.0 g of iron.

45. **Challenge** An excess of acetic acid is added to 28 g of sodium bicarbonate at 25°C and 1 atm pressure. During the reaction, the gas cools to 20°C. What volume of carbon dioxide will be produced? The balanced equation for the reaction is shown below.

$$NaHCO_3(aq) + CH_3COOH(aq) \rightarrow NaCH_3COO(aq) + CO_2(g) + H_2O(l)$$

Figure 13.12 To effectively manufacture a product, such as these plastics, it is essential to answer the following questions. How much of a reactant should be purchased? How much of a product will be produced?

Stoichiometric problems, such as the ones in this section, are considered in industrial processes. For example, ethene gas (C_2H_4), also called ethylene, is the raw material for making polyethylene polymers. Polyethylene is produced when numerous ethene molecules join together in chains of repeating $—CH_2–CH_2—$ units. These polymers are used to make many everyday items, such as the ones shown in **Figure 13.12.** The general formula for this polymerization reaction is shown below. In this formula, n is the number of units used.

$$n(C_2H_4)(g) \rightarrow —(CH_2 – CH_2)_n(s)—$$

If you were a process engineer for a polyethylene manufacturing plant, you would need to know about the properties of ethene gas and the polymerization reaction. Knowledge of the gas laws would help you calculate both the mass and volume of raw material needed under different temperature and pressure conditions to make different types of polyethylene.

Section 13.3 Assessment

Section Summary

- The coefficients in a balanced chemical equation specify volume ratios for gaseous reactants and products.
- The gas laws can be used along with balanced chemical equations to calculate the amount of a gaseous reactant or product in a reaction.

46. MAIN Idea **Explain** When fluorine gas combines with water vapor, the following reaction occurs.

$$2F_2(g) + 2H_2O(g) \longrightarrow O_2(g) + 4HF(g)$$

If the reaction starts with 2 L of fluorine gas, how many liters of water vapor react with the fluorine, and how many liters of oxygen and hydrogen fluoride are produced?

47. **Analyze** Is the volume of a gas directly or inversely proportional to the number of moles of a gas at constant temperature and pressure? Explain.

48. **Calculate** One mole of a gas occupies a volume of 22.4 L at STP. Calculate the temperature and pressure conditions needed to fit 2 mol of a gas into a volume of 22.4 L.

49. **Interpret Data** Ethene gas (C_2H_4) reacts with oxygen to form carbon dioxide and water. Write a balanced equation for this reaction, then find the mole ratios of substances on each side of the equation.

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Health Under Pressure

You live, work, and play in air that is generally about 1 atm in pressure and 21% oxygen. Have you ever wondered what might happen if the pressure and the oxygen content of the air were greater? Would you recover from illness or injury more quickly? These questions are at the heart of hyperbaric medicine.

Hyperbaric medicine The prefix *hyper-* means *above* or *excessive,* and a bar is a unit of pressure equal to 100 kPa, roughly normal atmospheric pressure. Thus, the term *hyperbaric* refers to pressure that is greater than normal. Patients receiving hyperbaric therapy are exposed to pressures greater than the pressure of the atmosphere at sea level.

The oxygen connection Greater pressure is most often combined with an increase in the concentration of oxygen a patient receives. The phrase *hyperbaric oxygen therapy* (HBOT) refers to treatment with 100% oxygen. **Figure 1** shows a chamber that might be used for HBOT. Inside the hyperbaric chamber, pressures can reach five to six times normal atmospheric pressure. At hyperbaric therapy centers across the country, HBOT is used to treat a wide range of conditions, including burns, decompression sickness, slow-healing wounds, anemia, and some infections.

Figure 1 During HBOT, the patient lies in a hyperbaric chamber. A technician controls the pressure and oxygen levels.

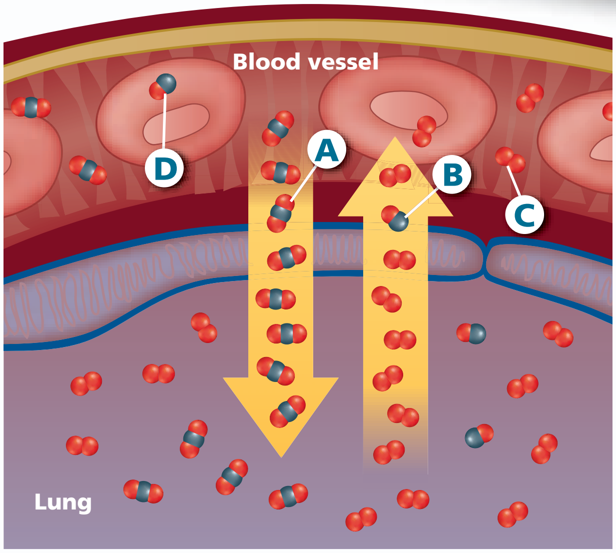


Figure 2 Gases are exchanged between the lungs and the circulatory system.

Carbon-monoxide poisoning Use **Figure 2** to help you understand how HBOT aids in the treatment of carbon-monoxide poisoning.

Normal gas exchange Oxygen (O_2) moves from the lungs to the blood and binds to the hemoglobin in red blood cells. Carbon dioxide (CO_2) is released, as shown by **A.**

Abnormal gas exchange If carbon monoxide (CO) enters the blood, as shown by **B,** it, instead of oxygen, binds to the hemoglobin. Cells in the body begin to die from oxygen deprivation.

Oxygen in blood plasma In addition to the oxygen carried by hemoglobin, oxygen is dissolved in the blood plasma, as shown by **C.** HBOT increases the concentration of dissolved oxygen to an amount that can sustain the body.

Eliminating carbon monoxide Pressurized oxygen also helps remove any carbon monoxide bound to hemoglobin, as shown by **D.**

WRITING in Chemistry

Research and prepare an informational pamphlet about the use of HBOT to treat slow-healing wounds. For more information about hyperbaric oxygen therapy, visit glencoe.com.

CHEMLAB

INTERNET: DETERMINE PRESSURE IN POPCORN KERNELS

Background: When the water vapor pressure inside a popcorn kernel is great enough, the kernel bursts and releases the water vapor. The ideal gas law can be used to find the pressure in the kernel as it bursts.

Question: *How much pressure is required to burst a kernel of popcorn?*

Materials

popcorn kernels (18–20)
vegetable oil (1.5 mL)
wire gauze squares (2)
Bunsen burner
ring stand
small iron ring
10-mL graduated cylinder
250-mL beaker
beaker tongs
balance
distilled water
paper towels

Safety Precautions

Procedure

1. Read and complete the lab safety form.
2. Create a table to record your data.
3. Place approximately 5 mL of distilled water in the graduated cylinder, and record the volume.
4. Place 18–20 popcorn kernels in the graduated cylinder with the water. Tap the cylinder to force any air bubbles off the kernels. Record the new volume.
5. Remove the kernels from the graduated cylinder, and dry them.
6. Place the dry kernels and 1.0–1.5 mL of vegetable oil into the beaker.
7. Measure the total mass of the beaker, oil, and kernels.
8. Set up a Bunsen burner with a ring stand, ring, and wire gauze.
9. Place the beaker on the wire gauze and ring. Place another piece of wire gauze on top of the beaker.
10. Gently heat the beaker with the burner. Move the burner back and forth to heat the oil evenly.
11. Observe the changes in the kernels and oil while heating, then turn off the burner when the popcorn has popped and before any burning occurs.
12. Using the beaker tongs, remove the beaker from the ring and allow it to cool completely.

13. Measure the final mass of the beaker, oil, and popcorn once cooling is complete.
14. Post your data at glencoe.com.
15. **Cleanup and Disposal** Dispose of the popcorn and oil as directed by your teacher. Wash and return all lab equipment to its designated location.

Analyze and Conclude

1. **Calculate** the volume of the popcorn kernels, in liters, by the difference in the volumes of distilled water before and after adding popcorn.
2. **Calculate** the total mass of water vapor released using the mass measurements of the beaker, oil, and popcorn before and after popping.
3. **Convert** Use the molar mass of water and the volume of popcorn to find the number of moles of water released.
4. **Use Formulas** Use the temperature of the boiling oil (225°C) as your gas temperature, and calculate the pressure of the gas using the ideal gas law.
5. **Compare and contrast** atmospheric pressure to the pressure of the water vapor in the kernel.
6. **Infer** why all the popcorn kernels did not pop.
7. **Error Analysis** Identify a potential source of error for this lab, and suggest a method to correct it.

INQUIRY EXTENSION

Design an experiment that tests the amount of pressure necessary to burst different types of popcorn kernels.

Matt Meadows

Study Guide

BIG Idea Gases respond in predictable ways to pressure, temperature, volume, and changes in number of particles.

Section 13.1 The Gas Laws

MAIN Idea For a fixed amount of gas, a change in one variable—pressure, temperature, or volume—affects the other two.

Vocabulary

- absolute zero (p. 445)
- Boyle's law (p. 442)
- Charles's law (p. 445)
- combined gas law (p. 449)
- Gay-Lussac's law (p. 447)

Key Concepts

- Boyle's law states that the volume of a fixed amount of gas is inversely proportional to its pressure at constant temperature.

$$P_1V_1 = P_2V_2$$

- Charles's law states that the volume of a fixed amount of gas is directly proportional to its kelvin temperature at constant pressure.

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

- Gay-Lussac's law states that the pressure of a fixed amount of gas is directly proportional to its kelvin temperature at constant volume.

$$\frac{P_1}{T_1} = \frac{P_2}{T_2}$$

- The combined gas law relates pressure, temperature, and volume in a single statement.

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

Section 13.2 The Ideal Gas Law

MAIN Idea The ideal gas law relates the number of particles to pressure, temperature, and volume.

Vocabulary

- Avogadro's principle (p. 452)
- ideal gas constant (p. 454)
- ideal gas law (R) (p. 454)
- molar volume (p. 452)

Key Concepts

- Avogadro's principle states that equal volumes of gases at the same pressure and temperature contain equal numbers of particles.
- The ideal gas law relates the amount of a gas present to its pressure, temperature, and volume.

$$PV = n\mathrm{R}T$$

- The ideal gas law can be used to find molar mass if the mass of the gas is known, or the density of the gas if its molar mass is known.

$$\mathrm{M} = \frac{m\mathrm{R}T}{PV} \qquad D = \frac{\mathrm{M}P}{\mathrm{R}T}$$

- At very high pressures and very low temperatures, real gases behave differently than ideal gases.

Section 13.3 Gas Stoichiometry

MAIN Idea When gases react, the coefficients in the balanced chemical equation represent both molar amounts and relative volumes.

Key Concepts

- The coefficients in a balanced chemical equation specify volume ratios for gaseous reactants and products.
- The gas laws can be used along with balanced chemical equations to calculate the amount of a gaseous reactant or product in a reaction.

Section 13.1

Mastering Concepts

50. State Boyle's law, Charles's law, Gay-Lussac's law, and the combined gas law in words and equations.

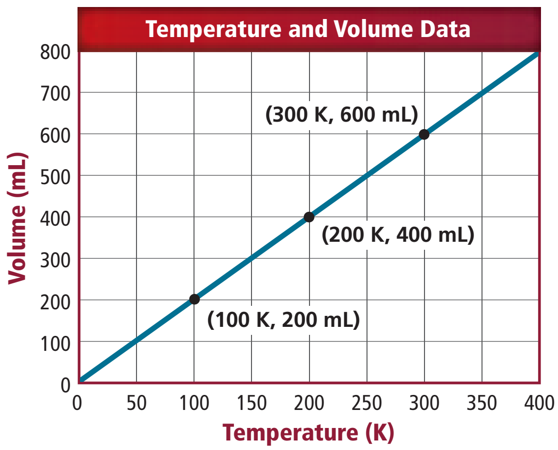
51. If two variables are inversely proportional, what happens to the value of one as the value of the other increases?

52. If two variables are directly proportional, what happens to the value of one as the value of the other increases?

53. List the standard conditions for gas measurements.

54. Identify the units most commonly used for *P*, *V*, and *T*.

Mastering Problems



■ **Figure 13.13**

55. Use Charles's law to determine the accuracy of the data plotted in **Figure 13.13.**

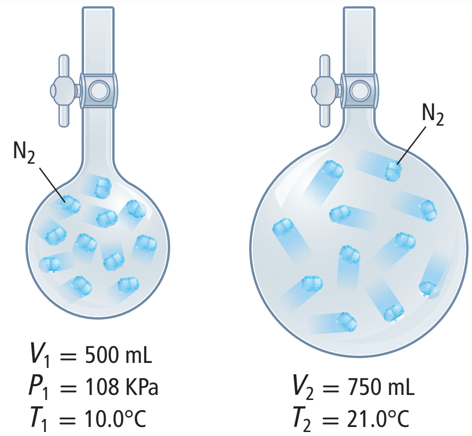
56. Weather Balloons A weather balloon is filled with helium that occupies a volume of 5.00×10^4 L at 0.995 atm and 32.0°C. After it is released, it rises to a location where the pressure is 0.720 atm and the temperature is −12.0°C. What is the volume of the balloon at the new location?

57. Use Boyle's, Charles's, or Gay-Lussac's law to calculate the missing value in each of the following.

a. $V_1 = 2.0$ L, $P_1 = 0.82$ atm, $V_2 = 1.0$ L, $P_2 = ?$
b. $V_1 = 250$ mL, $T_1 = ?$, $V_2 = 400$ mL, $T_2 = 298$ K
c. $V_1 = 0.55$ L, $P_1 = 740$ mm Hg, $V_2 = 0.80$ L, $P_2 = ?$

58. Hot-Air Balloons A sample of air occupies 2.50 L at a temperature of 22.0°C. What volume will this sample occupy inside a hot-air balloon at a temperature of 43.0°C? Assume that the pressure inside the balloon remains constant.

59. What is the pressure of a fixed volume of hydrogen gas at 30.0°C if it has a pressure of 1.11 atm at 15.0°C?



■ **Figure 13.14**

60. A sample of nitrogen gas is transferred to a larger flask, as shown in **Figure 13.14.** What is the pressure of nitrogen in the second flask?

Section 13.2

Mastering Concepts

61. State Avogadro's principle.

62. State the ideal gas law.

63. What volume is occupied by 1 mol of a gas at STP? What volume does 2 mol occupy at STP?

64. Define the term *ideal gas,* and explain why there are no true ideal gases in nature.

65. List two conditions under which a gas is least likely to behave ideally.

66. What units must be used to express the temperature in the equation for the ideal gas law? Explain.

Mastering Problems

67. Home Fuel Propane (C_3H_8) is a gas commonly used as a home fuel for cooking and heating.

a. Calculate the volume that 0.540 mol of propane occupies at STP.
b. Think about the size of this volume and the amount of propane that it contains. Why do you think propane is usually liquefied before it is transported?

68. Careers in Chemistry A physical chemist measured the lowest pressure achieved in a laboratory—about 1.0×10^{-15} mm Hg. How many molecules of gas are present in a 1.00-L sample at that pressure if the sample's temperature is 22.0°C?

69. Calculate the number of moles of O^2 gas held in a sealed, 2.00-L tank at 3.50 atm and 25.0°C. How many moles would be in the tank if the temperature was raised to 49.0°C and the pressure remained constant?

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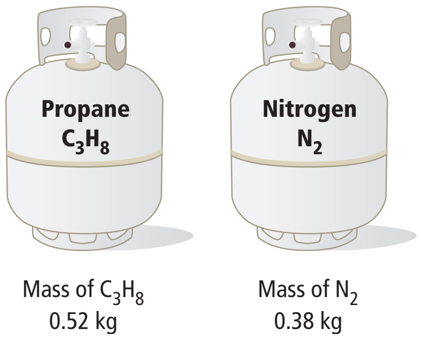
70. **Perfumes** Geraniol is a compound found in rose oil that is used in perfumes. What is the molar mass of geraniol if its vapor has a density of 0.480 g/L at a temperature of 260.0°C and a pressure of 0.140 atm?

71. Find the volume that 42 g of carbon monoxide gas occupies at STP.

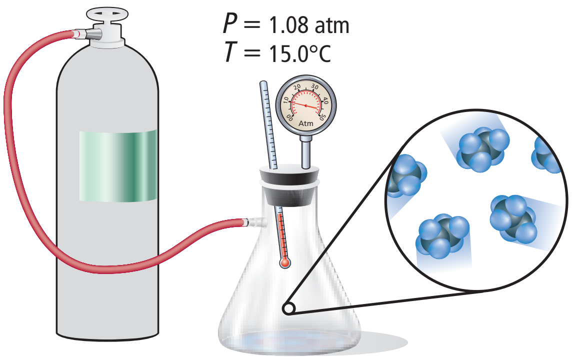
72. Determine the density of chlorine gas at 22.0°C and 1.00 atm.



■ **Figure 13.15**

73. Which of the gases in **Figure 13.15** occupies the greatest volume at STP? Explain your answer.

74. If the containers in **Figure 13.15** each hold 4.00 L, what is the pressure inside each? Assume ideal behavior.



■ **Figure 13.16**

75. A 2.00-L flask is filled with ethane gas (C_2H_6) from a small cylinder, as shown in **Figure 13.16.** What is the mass of the ethane in the flask?

76. What is the density of a sample of nitrogen gas (N_2) that exerts a pressure of 5.30 atm in a 3.50-L container at 125°C?

77. How many moles of helium gas (He) would be required to fill a 22-L container at a temperature of 35°C and a pressure of 3.1 atm?

78. Before a reaction, two gases share a container at a temperature of 200 K. After the reaction, the product is in the same container at a temperature of 400 K. If both V and P are constant, what must be true of n?

Section 13.3

Mastering Concepts

79. Why must an equation be balanced before using it to determine the volumes of gases involved in a reaction?

80. It is not necessary to consider temperature and pressure when using a balanced equation to determine relative gas volume. Why?

81. What information do you need to solve a volume-mass problem that involves gases?

82. Explain why the coefficients in a balanced chemical equation represent not only molar amounts but also relative volumes for gases.

83. Do the coefficients in a balanced chemical equation represent volume ratios for solids and liquids? Explain.

Mastering Problems

84. **Ammonia Production** Ammonia is often formed by reacting nitrogen and hydrogen gases. How many liters of ammonia gas can be formed from 13.7 L of hydrogen gas at 93.0°C and a pressure of 40.0 kPa?

85. A 6.5-L sample of hydrogen sulfide is treated with a catalyst to promote the reaction shown below.

$$2H_2S(g) + O_2(g) \longrightarrow 2H_2O(g) + 2S(s)$$

If the H_2S reacts completely at 2.0 atm and 290 K, how much water vapor, in grams, is produced?

86. To produce 15.4 L of nitrogen dioxide at 310 K and 2.0 atm, how many liters of nitrogen gas and oxygen gas are required?

87. Use the reaction shown below to answer these questions.

$$2CO(g) + 2NO(g) \longrightarrow N_2(g) + 2CO_2(g)$$

a. What is the volume ratio of carbon monoxide to carbon dioxide in the balanced equation?

b. If 42.7 g of CO is reacted completely at STP, what volume of N_2 gas will be produced?

88. When 3.00 L of propane gas is completely combusted to form water vapor and carbon dioxide at 350°C and 0.990 atm, what mass of water vapor results?

89. When heated, solid potassium chlorate ($KClO_3$) decomposes to form solid potassium chloride and oxygen gas. If 20.8 g of potassium chlorate decomposes, how many liters of oxygen gas will form at STP?

90. **Acetylene** The gas acetylene, often used for welding, burns according to the following equation.

$$2C_2H_2(g) + 5O_2(g) \longrightarrow 2H_2O(g) + 4CO_2(g)$$

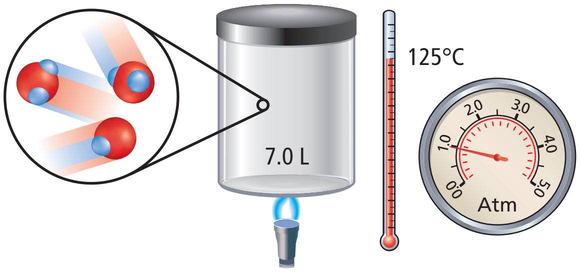
If you have a 10.0-L tank of acetylene at 25.0°C and 1.00 atm pressure, how many moles of CO_2 will be produced if you burn all the acetylene in the tank?

Mixed Review

91. Gaseous methane (CH_4) undergoes complete combustion by reacting with oxygen gas to form carbon dioxide and water vapor.

a. Write a balanced equation for this reaction.

b. What is the volume ratio of methane to water in this reaction?



■ **Figure 13.17**

92. Calculate the amount of water vapor, in grams, contained in the vessel shown in **Figure 13.17.**

93. Television Determine the pressure inside a television picture tube with a volume of 3.50 L that contains 2.00×10^{-5} g of nitrogen gas at 22.0°C.

94. Determine how many liters 8.80 g of carbon dioxide gas would occupy at:

a. STP

b. 160°C and 3.00 atm

c. 288 K and 118 kPa

95. Oxygen Consumption If 5.00 L of hydrogen gas, measured at a temperature of 20.0°C and a pressure of 80.1 kPa, is burned in excess oxygen to form water, what mass of oxygen will be consumed? Assume temperature and pressure remain constant.

96. A fixed amount of oxygen gas is held in a 1.00-L tank at a pressure of 3.50 atm. The tank is connected to an empty 2.00-L tank by a tube with a valve. After this valve has been opened and the oxygen is allowed to flow freely between the two tanks at a constant temperature, what is the final pressure in the system?

97. If 2.33 L of propane at 24°C and 67.2 kPa is completely burned in excess oxygen, how many moles of carbon dioxide will be produced?

98. Respiration A human breathes about 0.50 L of air during a normal breath. Assume the conditions are at STP.

a. What is the volume of one breath on a cold day atop Mt. Everest? Assume −60°C and 253 mm Hg pressure.

b. Air normally contains about 21% oxygen. If the O_2 content is about 14% atop Mt. Everest, what volume of air does a person need to breathe to supply the body with the same amount of oxygen?

Think Critically

99. Apply An oversized helium balloon in a floral shop must have a volume of at least 3.8 L to rise. When 0.1 mol is added to the empty balloon, its volume is 2.8 L. How many grams of He must be added to make it rise? Assume constant *T* and *P*.

100. Calculate A toy manufacturer uses tetrafluoroethane ($C_2H_2F_4$) at high temperatures to fill plastic molds for toys.

a. What is the density (in g/L) of $C_2H_2F_4$ at STP?

b. Find the molecules per liter of $C_2H_2F_4$ at 220°C and 1.0 atm.

101. Analyze A solid brick of dry ice (CO_2) weighs 0.75 kg. Once the brick has fully sublimated into CO_2 gas, what would its volume be at STP?

102. Apply Calculate the pressure of 4.67×10^{22} molecules of CO gas mixed with 2.87×10^{24} molecules of N_2 gas in a 6.00-L container at 34.8°C.

103. Analyze When nitroglycerin ($C_3H_5N_3O_9$) explodes, it decomposes into the following gases: CO_2, N_2, NO, and H_2O. If 239 g of nitroglycerin explodes, what volume will the mixture of gaseous products occupy at 1.00 atm pressure and 2678°C?

104. Make and Use Graphs The data in **Table 13.3** show the volume of hydrogen gas collected at several different temperatures. Illustrate these data with a graph. Use the graph to complete the table. Determine the temperature at which the volume will reach a value of 0 mL. What is this temperature called?

Table 13.3 Volume of H_2 Collected

Trial	*T* (°C)	*V* (mL)
1	300	48
2	175	37
3	110	
4	0	22
5		15
6	−150	11

105. Apply What is the numerical value of the ideal gas constant (R) in $\frac{cm^3 \cdot Pa}{K \cdot mol}$?

106. Infer At very high pressures, will the ideal gas law calculate a pressure that is higher or lower than the actual pressure exerted by a sample of gas? How will the calculated pressure compare to the actual pressure at low temperatures? Explain your answers.

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Challenge Problem

107. Baking A baker uses baking soda as the leavening agent for his pumpkin-bread recipe. The baking soda decomposes according to two possible reactions.

$$2NaHCO_3(s) \longrightarrow Na_2CO_3(s) + H_2O(l) + CO_2(g)$$
$$NaHCO_3(s) + H^+(aq) \longrightarrow H_2O(l) + CO_2(g) + Na+(aq)$$

Calculate the volume of CO_2 that forms per gram of $NaHCO_3$ by each reaction process. Assume the reactions take place at 210°C and 0.985 atm.

Cumulative Review

108. Convert each mass measurement to its equivalent in kilograms. *(Chapter 2)*
a. 247 g
b. 53 mg
c. 7.23 mg
d. 975 mg

109. Write the electron configuration for each atom. *(Chapter 5)*
a. iodine
b. boron
c. chromium
d. krypton
e. calcium
f. cadmium

110. For each element, tell how many electrons are in each energy level and write the electron dot structure. *(Chapter 5)*
a. Kr
b. Sr
c. P
d. B
e. Br
f. Se

111. How many atoms of each element are present in five formula units of calcium permanganate? *(Chapter 7)*

112. You are given two clear, colorless aqueous solutions. One solution contains an ionic compound, and one contains a covalent compound. How could you determine which is an ionic solution and which is a covalent solution? *(Chapter 8)*

113. Write a balanced equation for the following reactions. *(Chapter 9)*
a. Zinc displaces silver in silver chloride.
b. Sodium hydroxide and sulfuric acid react to form sodium sulfate and water.

114. Terephthalic acid is an organic compound used in the formation of polyesters. It contains 57.8% C, 3.64% H, and 38.5% O. The molar mass is approximately 166 g/mol. What is the molecular formula of terephthalic acid? *(Chapter 10)*

115. The particles of which gas have the highest average speed? The lowest average speed? *(Chapter 12)*
a. carbon monoxide at 90°C
b. nitrogen trifluoride at 30°C
c. methane at 90°C
d. carbon monoxide at 30°C

Additional Assessment

WRITING in Chemistry

116. Hot-Air Balloons Many early balloonists dreamed of completing a trip around the world in a hot-air balloon, a goal not achieved until 1999. Write about what you imagine a trip in a balloon would be like, including a description of how manipulating air temperature would allow you to control altitude.

117. Scuba Investigate and explain the function of the regulators on the air tanks used by scuba divers.

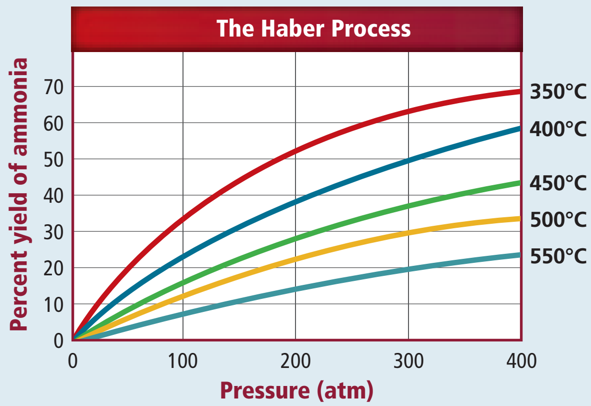
Document-Based Questions

The Haber Process *Ammonia (NH_3) is used in the production of fertilizer, refrigerants, dyes, and plastics. The Haber process is a method of producing ammonia through a reaction of molecular nitrogen and hydrogen. The equation for the reversible reaction is:*

$$N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g) + 92\text{ kJ}$$

Figure 13.18 *shows the effect of temperature and pressure on the amount of ammonia produced by the Haber process.*

Data obtained from: Smith, M. 2004. *Science* 39:1021–1034.



■ **Figure 13.18**

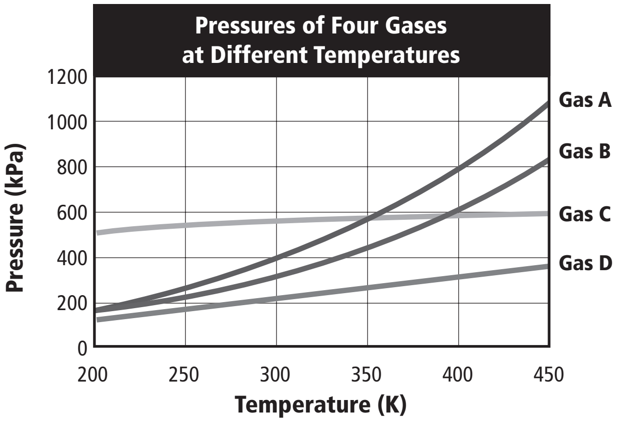
118. Explain how the percent yield of ammonia is affected by pressure and temperature.

119. The Haber process is typically run at 200 atm and 450°C, a combination proven to yield a substantial amount of ammonia in a short time.
a. What effect would running the reaction above 200 atm have on the temperature of the containment vessel?
b. How do you think lowering the temperature of this reaction below 450°C would affect the amount of time required to produce ammonia?

Cumulative
Standardized Test Practice

Multiple Choice

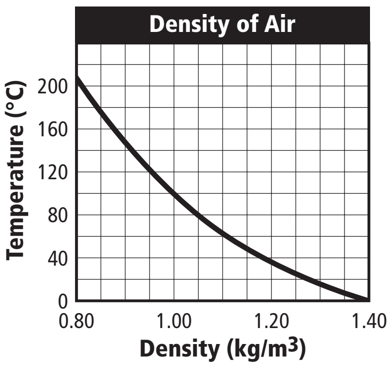
Use the graph below to answer Questions 1 and 2.



1. Which is evident in the graph above?
- **A.** As temperature increases, pressure decreases.
- **B.** As pressure increases, volume decreases.
- **C.** As temperature increases, the number of moles decreases.
- **D.** As pressure decreases, temperature decreases.

2. Which behaves as an ideal gas?
- **A.** Gas A
- **B.** Gas B
- **C.** Gas C
- **D.** Gas D

Use the graph below to answer Question 3.

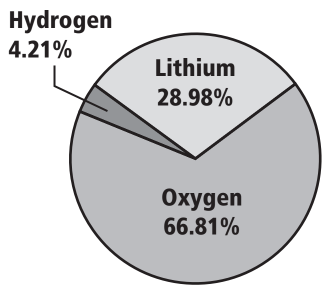


3. The graph shows data from an experiment which analyzed the relationship between temperature and air density. What is the independent variable in the experiment?
- **A.** density
- **B.** mass
- **C.** temperature
- **D.** time

4. Hydrofluoric acid (HF) is used in the manufacture of electronics equipment. It reacts with calcium silicate ($CaSiO_3$), a component of glass. What type of property prevents hydrofluoric acid from being transported or stored in glass containers?
- **A.** chemical property
- **B.** extensive physical property
- **C.** intensive physical property
- **D.** quantitative property

5. Sodium hydroxide (NaOH) is a strong base found in products used to clear clogged plumbing. What is the percent composition of sodium hydroxide?
- **A.** 57.48% Na, 60.00% O, 2.52% H
- **B.** 2.52% Na, 40.00% O, 57.48% H
- **C.** 57.48% Na, 40.00% O, 2.52% H
- **D.** 40.00% Na, 2.52% O, 57.48% H

Use the circle graph below to answer Question 6.



6. What is the empirical formula for this compound?
- **A.** LiOH
- **B.** Li_2OH
- **C.** Li_3OH
- **D.** $LiOH_2$

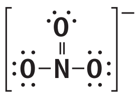
7. While it is on the ground, a blimp is filled with 5.66×10^6 L of He gas. The pressure inside the grounded blimp, where the temperature is 25°C, is 1.10 atm. Modern blimps are nonrigid, which means that their volumes can change. If the pressure inside the blimp remains the same, what will be the volume of the blimp at a height of 2300 m, where the temperature is 12°C?
- **A.** 2.72×10^6 L
- **B.** 5.40×10^6 L
- **C.** 5.66×10^6 L
- **D.** 5.92×10^6 L

Short Answer

8. Describe several observations that provide evidence that a chemical change has occurred.

9. Identify seven diatomic molecules that occur naturally, and explain why the atoms in these molecules share one pair of electrons.

10. The diagram below shows the Lewis structure for the polyatomic ion nitrate (NO_3^-). Define the term *polyatomic ion,* and give examples of other ions of this type.



Extended Response

Use the table below to answer Question 11.

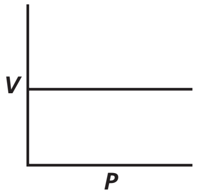
Radon Levels August 2004 through July 2005

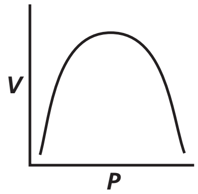
Date	Radon Level (mJ/m^3)	Date	Radon Level (mJ/m^3)
8/04	0.15	2/05	0.05
9/04	0.03	3/05	0.05
10/04	0.05	4/05	0.06
11/04	0.03	5/05	0.13
12/04	0.04	6/05	0.05
1/05	0.02	7/05	0.09

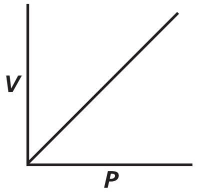
11. Radon is a radioactive gas produced when radium in soil and rock decays. It is a known carcinogen. The data above show radon levels measured in a community in Australia. Select a method for graphing these data. Explain the reasons for your choice, and graph the data.

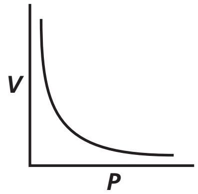
SAT Subject Test: Chemistry

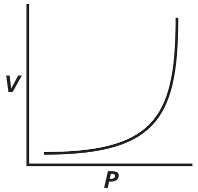
12. Which diagram shows the relationship between volume and pressure for a gas at constant temperature?

A.


D.


B.


E.


C.


13. The reaction that provides blowtorches with their intense flame is the combustion of acetylene (C_2H_2) with oxygen to form carbon dioxide and water vapor. Assuming that the pressure and temperature of the reactants are the same, what volume of oxygen gas is required to completely burn 5.60 L of acetylene?
A. 2.24 L
B. 5.60 L
C. 8.20 L
D. 11.2 L
E. 14.0 L

14. Assuming ideal behavior, how much pressure will 0.0468 g of ammonia (NH_3) gas exert on the walls of a 4.00-L container at 35.0°C?
A. 0.0174 atm
B. 0.296 atm
C. 0.0126 atm
D. 0.00198 atm
E. 0.278 atm

NEED EXTRA HELP?														
If You Missed Question . . .	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Review Section . . .	13.1	13.2	1.3	3.1	10.4	10.4	13.1	3.2	8.1	7.3	2.4	13.1	13.1	13.1