unit 2

Gases as a Form of Matter

Modern science has a relatively short history of just a few hundred years. An important goal of modern science is to acquire empirical and theoretical knowledge about aspects of the natural world such as the air. This is usually accomplished by systematically reducing nature into categories that are studied in ever-increasing detail. This method has not been the only way of knowing about our world. For example, Aboriginal peoples developed an indigenous knowledge of nature as evidenced by tens of thousands of years of survival. From an Aboriginal perspective, air is one of the four inter-connected "elements" of nature—earth, air, fire, and water. Aboriginal peoples traditionally had a knowledge of and respect for the air in which we live. They recognized that air plays an important role in maintaining the balance of nature. Their way of knowing did not include experimenting with air; systematic experimentation is more in the tradition of modern science.

According to modern scientific knowledge, air is a mixture of gases. The most important gas for humans is oxygen, which is produced by photosynthesis. This now common-place knowledge required some time to develop. Even at the heyday of alchemy, no one had conceived of the idea that a gas might be produced from a chemical reaction.

The study of gases was essential to the development of many chemical theories and quantitative descriptions. Advancements in the study of gases progressed hand-in-hand with the development of technologies that enabled more precise measurements of temperature and pressure. Today, the study of gases is crucial to our understanding of natural and technological phenomena. We need to understand gases to study natural phenomena such as weather patterns. Scientific knowledge of gases helps us understand modern technologies such as air bags, gas turbines, and lasers.

As you progress through the unit, think about these focusing questions:

- How do familiar observations of gases relate to modern scientific models describing the behaviour of gases?
- What is the relationship between the pressure, temperature, volume, and chemical amount of a gas?

GENERAL OUTCOME

In this unit, you will

- explain molecular behaviour using models of the gaseous state of matter

Unit 2
Gases as a Form of Matter

Prerequisites

Concepts

- states of matter
- empirical and theoretical knowledge
- chemical names and formulas
- mole concept and calculations
- balanced chemical reaction equations

Skills

- scientific problem solving
- WHMIS symbols
- laboratory safety rules
- graphing

You can review prerequisite concepts and skills in the Chemistry Review Unit and in the Appendices.

A Unit Pre-Test is also available online.

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ARE YOU READY?

These questions will help you find out what you already know, and what you need to review, before you continue with this unit.

Knowledge

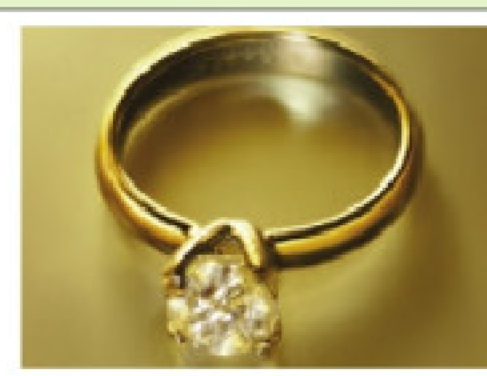
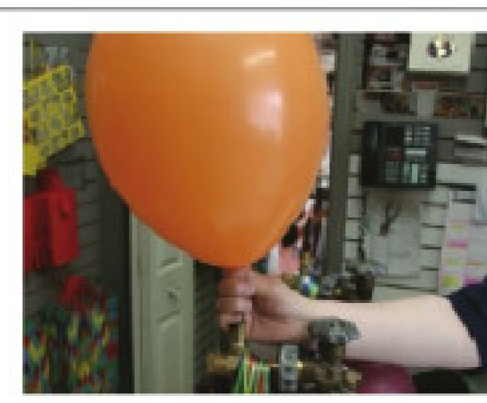
1. This unit is about gases. Evidence shows that the state of a substance (solid, liquid, or gas) is determined by temperature and pressure. Copy and complete **Table 1** by indicating the state of each substance for the given temperature at standard ambient pressure. The melting and boiling points of the elements can be referenced on the periodic table.

Table 1 States of Matter of Substances at Different Temperatures

Substance	State at −150 °C	State at 25 °C	State at 150 °C
argon			
bromine			
chlorine			
sulfur			
water			

2. Copy **Table 2** and, using your own experience, complete the Empirical properties column by describing the shape and volume, compressibility, and ability to flow for each state of matter.

Table 2 Empirical Properties of States of Matter

State	Empirical properties	Example
solid		 **Figure 1** A diamond ring
liquid		 **Figure 2** Coloured liquids
gas		 **Figure 3** A helium-filled balloon

3. Scientists have empirically determined that the production of sulfur dioxide is a significant factor in the formation of acid rain. Sulfur dioxide is oxidized in air (oxygen) to form sulfur trioxide. The sulfur trioxide readily combines with water to form sulfuric acid.
   (a) Write the balanced chemical equations to communicate the conversion of sulfur dioxide gas to sulfur trioxide gas, and sulfur trioxide gas to sulfuric acid.
   (b) Translate each chemical reaction equation in (a) into an English sentence. Include chemical names and chemical amounts.

STS Connections

4. Distinguish between the two main types of scientific knowledge. Which type usually comes first?

5. Research a local weather forecast, then copy and complete **Table 3**.

Table 3 Meteorological Information

Information	Value/Description	Technology (instrument)
date		
location		
high/low temperatures (°C)		
local atmospheric pressure (kPa)		
local relative humidity (%)		

Skills

6. Scientists frequently communicate empirical knowledge with tables and graphs. In many jobs, the salary (without deductions) is directly related to the time spent on the job.
   (a) Using axes like those in **Figure 4**, sketch a line graph for the direct variation between these two variables. (No numbers are required.)
   (b) Like many relationships in science, the slope of the graph has a specific meaning. What does the slope of your graph in (a) represent?
   (c) Suppose that the salary varied inversely with the time spent. Using axes like those in (a), draw the graph for this inverse relationship. Would you want a job that pays this way?

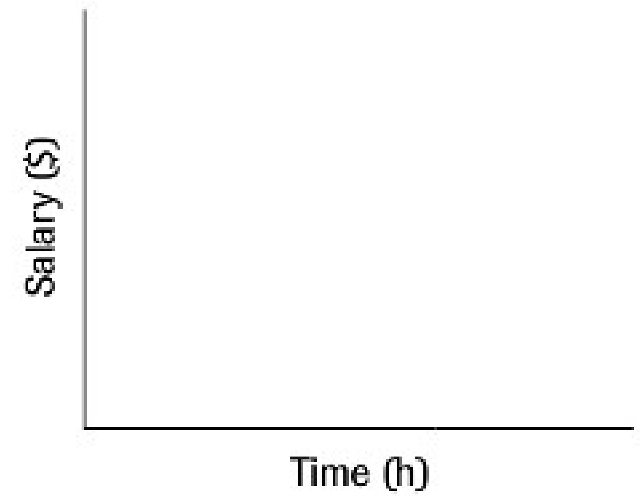


Figure 4
Salary–time axes

7. Flammable and combustible materials require special attention in a laboratory.
   (a) What do the WHMIS symbols in **Figure 5** represent?
   (b) Copy and complete **Table 4** by using check marks to indicate the types of fire extinguishers that are suitable for the various classes of fire.

Figure 5
WHMIS symbols (Appendix E.2)

Table 4 Classes of Fire and Extinguishers

Class of fire	Water	Carbon dioxide	Dry chemical
Class A (wood, paper, cloth)			
Class B (flammable liquids)			
Class C (live electrical equipment)			

chapter

4 Gases

In this chapter

- Exploration: Creating and Testing Ideas about Gases
- Lab Exercise 4.A: A Thought Experiment about Gas Properties
- Investigation 4.1: Pressure and Volume of a Gas
- Investigation 4.2: Temperature and Volume of a Gas
- Biology Connection: Gas-Dependent Processes
- Web Activity: The Combined Gas Law
- Web Activity: Malcolm King
- Case Study: Compressed Gases
- Web Activity: Elizabeth MacGill
- Web Activity: "Designer Air" for Tires
- Case Study: Weather Forecasts
- Web Activity: The Ideal Gas Law
- Lab Exercise 4.B: Evaluating an Experimental Design
- Investigation 4.3: Using the Ideal Gas Law

The scientific study of the properties of gases has led not only to a better understanding of the natural world, but also to many modern technologies that involve gases. The photograph in **Figure 1** is a dramatic depiction of how a gas can save a human life. In a car crash, an air bag, especially in combination with a seat belt, can protect an adult occupant from serious injury. Upon collision, sensors in the steering column and in the bumper initiate the decomposition of sodium azide into sodium metal and nitrogen gas. This reaction is extremely fast. Nitrogen gas is produced and expands into the bag in less than 0.04 s. After cushioning the impact, the air bag quickly deflates as the nitrogen gas escapes through the permeable fabric. Instead of taking a trip to the hospital, the driver takes a trip to the automobile body shop to have the air bag mechanism recharged and the triggering devices reset.

Air bags are not the only use of gases in the operation of automobiles. Tires and shock absorbers are inflated with pressurized air to provide a safe and comfortable ride. Air enters through the car's vents and is either cooled by the air conditioner to keep us comfortable on hot summer days or heated by the car engine to keep us warm in winter. Inside the combustion cylinder of the engine, a gasoline and oxygen explosion produces a gas at a high temperature, which moves a piston. This is an example of converting chemical energy into kinetic energy (motion). Finally, the gases emitted by the exhaust, such as carbon oxides and nitrogen oxides, diffuse into the atmosphere as pollutants.

As you can see, gases play an important role in both technology and our environment. The study of gases illustrates how empirical descriptions and advances in technology have led to a better understanding of gases in both natural and technological phenomena.

STARTING Points

Answer these questions as best you can with your current knowledge. Then, using the concepts and skills you have learned, you will revise your answers at the end of the chapter.

1. Since many gases are invisible, how do you think we can study them?
2. When you are solving problems, the gas laws are like tools. How do you know which gas law to use?
3. Do all gases have the same physical properties? Why or why not?

Career Connections:
Respiratory Therapist; Meteorologist

Figure 1
Empirical and theoretical knowledge of gas properties have useful applications. Air bags are a good example of how gas concepts are used in a life-saving technology.

Exploration — *Creating and Testing Ideas about Gases*

Coming up with ideas to explain the results of experiments with gases requires some imagination, because most gases are invisible. Try to figure out what is happening to the aluminium cans and the water vapour (a gas in our atmosphere) in this activity.

Materials: water, 5 aluminium pop cans, 5 large beakers or containers, hot plate, beaker tongs, ice cubes, eye protection, heat-proof gloves or mitts

Use care when handling hot items. Steam can scald skin. Switch off the hot plate immediately after use.

- Place about 20 mL of water in an empty aluminium pop can.
- Heat the can on a hot plate until steam rises steadily out of the top for a couple of minutes.
- Fill a large beaker to near the top with cold water.
- Using the tongs, lift the can off the hot plate.
- Invert the can, and dip the top rim of the can just under the surface of the water in the beaker.
- Record your observations.

(a) Create a Hypothesis for what happens.

- Repeat the Procedure without placing any water in the can. (Heat the can for a few minutes.)

(b) What happened? Does this support or refute your Hypothesis?

(c) Using your original or revised Hypothesis, predict the results if you repeat the Procedure inverting the steaming can into ice water and warm water.

(d) Try each of these tests, then judge your Predictions and Hypotheses.

- Recycle the cans.

4.1 Empirical Properties of Gases

CAREER CONNECTION

Respiratory Therapist
As vital members of a medical team, respiratory therapists help diagnose and treat patients with breathing problems.
Discover more about the responsibilities and working conditions of respiratory therapists.

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Gases have always been important to us—we need them to breathe, after all. Aboriginal peoples recognize that air provides a physical interconnection, linking us with everything else in the world. The wind is important for survival, bringing information about weather and game, so it is highly valued. As Western society has advanced technologically, the importance of gases has been expanding. We use gases in our daily lives—natural gas as fuel, gases as refrigerants, and anesthetic gases for surgery. We also generate gases for special uses. For example, we create artificial atmospheres for deep-sea diving and for the exploration of outer space. It is not surprising, then, that the study of gases has quite a long history in chemistry. People studied many empirical properties of gases long before the development of our modern understanding of the composition and molecular motion of substances. In fact, it was the large body of empirical knowledge about gases that made possible the development of some important ideas, such as atomic theory, kinetic molecular theory, and the mole concept. Let's now look more closely at the empirical properties of gases. Keep in mind that any empirical knowledge in science can be communicated in several ways: simple descriptions like observations, tables of evidence, graphs, empirical hypotheses, empirical definitions, generalizations, and scientific laws.

LAB EXERCISE 4.A

A Thought Experiment about Gas Properties

Report Checklist

- ○ Purpose
- ○ Problem
- ○ Hypothesis
- ○ Prediction
- ○ Design
- ○ Materials
- ○ Procedure
- ○ Evidence
- ● Analysis
- ● Evaluation (1, 3)

Imagine that you have five gas cylinders that have the volumes and temperatures listed in **Table 1** and contain the same mass of nitrogen gas. Complete the Analysis by proposing a hypothesis (with reasoning) to answer the Problem. In the Evaluation, identify any difficulties you had in answering the question, state how certain you are about your answer, and list some additional information you think you need to improve the certainty.

Purpose

The purpose of this exercise is to create a hypothesis based on differing gas properties.

Problem

What is the order of gas cylinders, from most likely to explode to least likely to explode?

Evidence

Table 1 Comparison of Nitrogen Gas Cylinders

Cylinder number	Volume (L)	Temperature (°C)
1	1.0	800
2	2.0	200
3	2.0	300
4	4.0	200
5	4.0	800

Pressure

We now understand that we live at the bottom of an ocean of air. Air has many properties that can be altered experimentally in a laboratory, including temperature and pressure (familiar to us from weather reports), volume, and chemical amount of gas.

In any controlled experiment, the plan is to manipulate one variable and observe its effect on another variable while keeping all other properties constant. We begin our study of gases by looking at the relationship between pressure and volume with temperature and chemical amount of gas kept constant.

Your weight, due to Earth's gravity, is the force you exert on the ground, and the ground pushes back with an equal but opposite force. However, the force you exert can be distributed over a larger or smaller area. The area is larger when you lie down and smaller when you stand on the tips of your toes. The greater the area, the lower the **pressure**, or force per unit area. This observation was put to practical use by many Aboriginal groups as they developed snowshoes (**Figure 1**). The pressure of a gas is also a measure of force per unit area, but in this case, according to modern scientific theories, the force is exerted by the moving molecules as they collide with objects in their path, particularly the walls of a container.

Figure 1
When you wear snowshoes, the force is distributed over the surface area of the snowshoes, so you exert less pressure on the ground than you would if you were wearing regular shoes. This allows you to walk over snow instead of sinking into it.

Scientists have agreed, internationally, on units, symbols, and standard values for pressure. The SI unit for pressure, the pascal (Pa), represents a force of 1 N (newton) on an area of 1 m^2; 1 Pa = 1 N/m^2. Atmospheric pressure and the pressure of many gases are conveniently measured in kilopascals (kPa); 1 kPa = 1000 Pa = 1 kN/m^2 (exactly).

Atmospheric pressure is the force per unit area exerted by air on all objects. At sea level, average atmospheric pressure is about 101 kPa. Scientists used this value as a basis to define one standard atmosphere (1 atm), or *standard pressure*, as exactly 101.325 kPa. For many years, standard conditions for work with gases were a temperature of 0 °C and a pressure of 1 atm (101.325 kPa); these conditions are known as **standard temperature and pressure (STP)**. However, 0 °C is not a convenient temperature, because laboratory temperatures are not close to 0 °C. Scientists have since agreed to use another set of standard conditions, not only for gases but also for reporting the properties of other substances. The new standard is called **standard ambient temperature and pressure (SATP)**, defined as 25 °C and 100 kPa. The new standard is much closer to laboratory conditions and therefore more convenient.

Since the empirical properties of gases were measured long before the development of SI, the pressure of gas has been expressed in a bewildering variety of units over the years. In 1643, Evangelista Torricelli (1608–1647), following up on a suggestion from Galileo, accidentally invented a way of measuring atmospheric pressure. He was investigating Aristotle's notion that a vacuum cannot exist in nature. Torricelli's experimental design involved inverting a glass tube filled with mercury and placing it into a tub also containing mercury (**Figure 2**). Noticing that the mercury level changed from day to day, he realized that his device, which came to be called a mercury barometer, was a means of measuring atmospheric pressure. In Torricelli's honour, standard pressure was at one time defined as 760 torr, or 760 mm Hg. (Mercury vapour is toxic. In modern mercury barometers, a thin film of water or oil is added to prevent the evaporation of mercury from the open reservoir, as shown in Figure 2.)

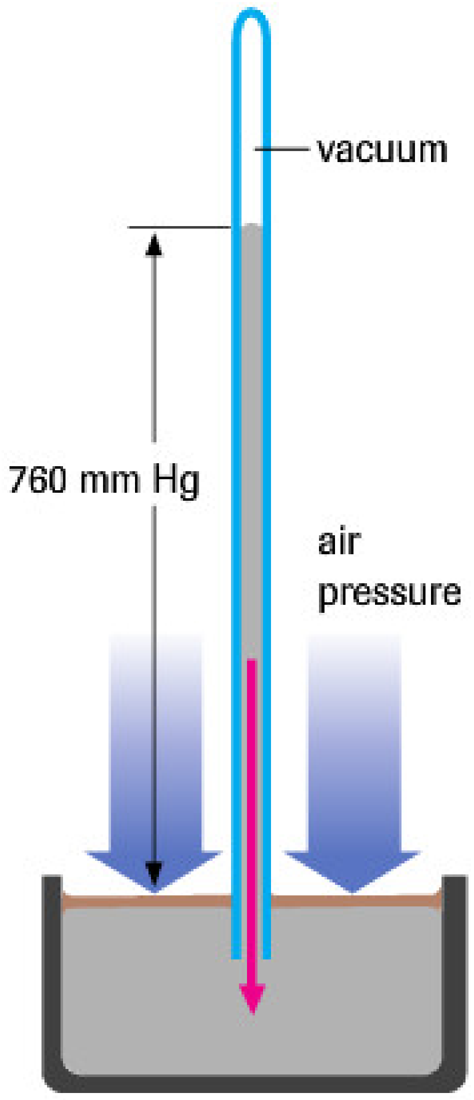

Figure 2
When a tube filled with mercury is inverted, the weight of the column of mercury pulls it toward Earth. However, the weight of the air directly above the open dish pushes down on the surface of the mercury and prevents all of the mercury from falling out of the tube. The two opposing forces balance each other when the height of mercury is about 760 mm. If the vertical mercury-filled tube is longer than 760 mm, the mercury drops to 760 mm. This leaves a vacuum above the liquid.

Many areas of study that use gases, such as medicine and meteorology, and several technological applications, such as deep-sea diving, still use non-SI units (**Table 2**). Using the definitions in **Table 2**, we can convert between SI and non-SI units.

Table 2 SI and Non-SI Units of Gas Pressure

Unit name	Unit symbol	Definition/Conversion
pascal (SI unit)	Pa	1 Pa = 1 N/m^2
atmosphere	atm	1 atm = 101.325 kPa (exactly)
millimetres of mercury	mm Hg	760 mm Hg = 1 atm = 101.325 kPa
torricelli	torr	1 torr = 1 mm Hg

COMMUNICATION example 1

Standard ambient pressure is defined as 100 kPa. Convert this value to the corresponding values in atmospheres and millimetres of mercury.

Solution

$$100\ \cancel{\text{kPa}} \times \frac{1\ \text{atm}}{101.325\ \cancel{\text{kPa}}} = 0.987\ \text{atm}$$

$$100\ \cancel{\text{kPa}} \times \frac{760\ \text{mm Hg}}{101.325\ \cancel{\text{kPa}}} = 750\ \text{mm Hg}$$

Learning Tip

When converting units, multiply the given quantity by a ratio obtained from the definition in **Table 2**. Make sure the ratio is oriented so that the unit of the given quantity is cancelled out, as shown in the example.

Practice

1. Define STP and SATP. What is the advantage of using SATP over STP?
2. Copy and convert the measured values of pressure in **Table 3**. Show your work using appropriate conversion factors from **Table 2**.

Table 3 Converting between Pressure Units

	Pressure (kPa)	Pressure (atm)	Pressure (mm Hg)
(a)	96.5		
(b)			825
(c)		2.50	

3. What are the advantages of having only one SI unit for pressure?
4. When using a medicine dropper or a meat baster, you squeeze the rubber bulb and insert the end of the tube into a liquid. Why does the liquid rise inside the dropper or baster when you release the bulb?

EXTENSION

Mars Dead or Alive

You may think of parachutes and airbags as useful emergency technologies here on Earth, but they are also being put to work in the exploration of Mars. These two video segments show you some applications of gases that are real-world—but not *this* world!

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The Relationship between Pressure and Volume

An important goal of science is to obtain knowledge about the natural world. One common method for accomplishing this goal is a controlled experiment involving known variables. Investigation 4.1 is such an experiment.

INVESTIGATION 4.1 *Introduction*

Pressure and Volume of a Gas

This investigation is a replication of a famous experiment first done by Robert Boyle in 1662. Write your Design using the information given and remember to include a plan and identify the variables. Include a graph and a word statement describing the relationship as part of your Analysis.

Report Checklist

- ○ Purpose
- ○ Problem
- ○ Hypothesis
- ○ Prediction
- ● Design
- ○ Materials
- ○ Procedure
- ● Evidence
- ● Analysis
- ○ Evaluation

Purpose

The purpose of this investigation is to create a general relationship between the pressure and volume of a gas.

Problem

What effect does increasing the pressure have on the volume of a gas?

To perform this investigation, turn to page 177.

Analysis of the evidence produced in an investigation similar to Investigation 4.1 suggests an inverse variation between the pressure and volume of a gas; that is, as the pressure increases, the volume decreases (**Figure 3**). Using the evidence given in SI units in **Table 4**, you can see that, when the pressure is doubled (100 kPa to 200 kPa), the volume is reduced to about one-half (3.00 L to 1.52 L). If the pressure is tripled, the volume is reduced to one-third. Test this hypothesis by checking the other values in Table 4.

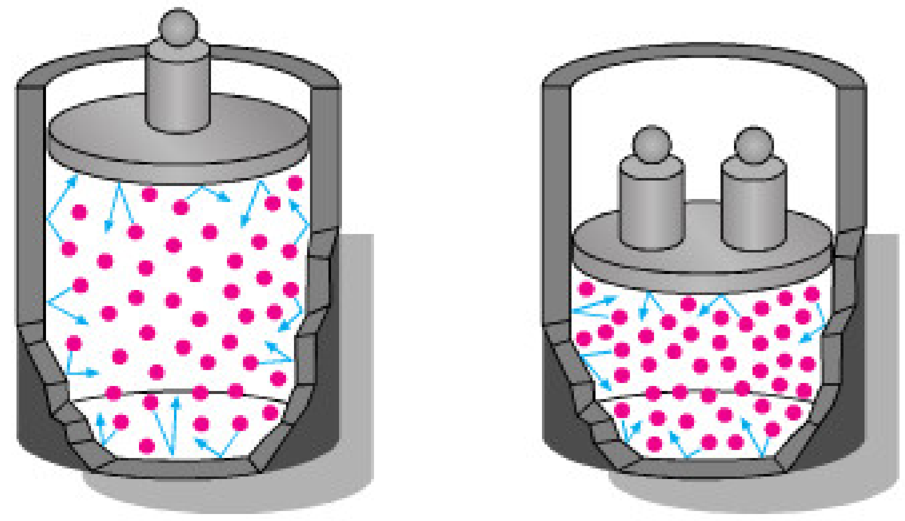

Figure 3
As the pressure on a gas increases, the volume decreases, as illustrated by this combined empirical-theoretical model.

Boyle's Law

If P_1 and V_1 represent the initial conditions of pressure and volume of a gas, the other values of pressure and volume from Table 4 may be stated as follows:

$$(P_1, V_1) \quad \left(2P_1, \tfrac{1}{2}V_1\right) \quad \left(3P_1, \tfrac{1}{3}V_1\right) \quad \left(4P_1, \tfrac{1}{4}V_1\right) \quad \left(5P_1, \tfrac{1}{5}V_1\right)$$

For all the conditions listed above, the product of the pressure and volume is equal to P_1V_1. Mathematically, the relationship is represented as $PV = k$, where k is a constant. This simple quantitative relationship was first determined by Robert Boyle in 1662 (**Figure 4**). Boyle's hypothesis was tested many times and, after successful replication by others, is now accepted as a scientific law. **Boyle's law** states that ***as the pressure on a gas increases, the volume of the gas decreases proportionally, provided that the temperature and chemical amount of gas remain constant***. In other words, the volume of a gas is inversely proportional to the pressure of the gas, providing that the temperature and chemical amount of gas are held constant. Boyle's law can be conveniently written comparing any two sets of pressure and volume measurements:

$$P_1V_1 = P_2V_2 \quad \textbf{(Boyle's law)}$$

Table 4 Pressure and Volume of Gas Samples

Pressure (kPa)	Volume (L)	*PV* (kPa·L)
100	3.00	300
200	1.52	304
300	1.01	303
400	0.74	296
500	0.60	300

COMMUNICATION example 2

A 2.0 L party balloon at 98 kPa is taken to the top of a mountain where the pressure is 75 kPa. Assume that the temperature and chemical amount of the gas remain the same. Use Boyle's law to determine the new volume of the balloon.

Solution

$$P_1V_1 = P_2V_2$$

$$V_2 = \frac{P_1V_1}{P_2}$$

$$= \frac{98\ \cancel{\text{kPa}} \times 2.0\ \text{L}}{75\ \cancel{\text{kPa}}}$$

$$= 2.6\ \text{L}$$

or $\quad V_2 = 2.0\ \text{L} \times \dfrac{98\ \cancel{\text{kPa}}}{75\ \cancel{\text{kPa}}} = 2.6\ \text{L}$

According to Boyle's law, the balloon would have a new volume of 2.6 L.

Figure 4
Anglo-Irish chemist Robert Boyle (1627–1691) was a founding member of the Royal Society of London. He is reported to have coined its anti-Aristotelian motto: "Nothing by Authority."

Practice

5. Write an empirical definition of atmospheric pressure.
6. A bicycle pump contains 0.650 L of air at 101 kPa. If the pump is closed, what pressure is required to change the volume to 0.250 L?
7. A weather balloon containing 35.0 L of helium at 98.0 kPa is released and rises. Assuming that the temperature is constant, find the volume of the balloon when the atmospheric pressure is 25.0 kPa at a height of about 25 km.
8. A small oxygen canister contains 110 mL of oxygen gas at a pressure of 3.0 atm. All of the oxygen is released into a balloon with a final pressure of 2.0 atm.
   (a) Predict whether the final volume will be smaller, greater, or the same. Justify your answer.
   (b) What is the final volume of the balloon?
9. A diving bell contains 32 kL of air at a pressure of 98 kPa at the surface. About 5 m below the surface, the volume of air trapped inside the bell is 21 kL (**Figure 5**). What is the pressure of the air in the bell, if you assume that the temperature remains constant?
10. Why does atmospheric pressure depend on your location or vary over time at your location?

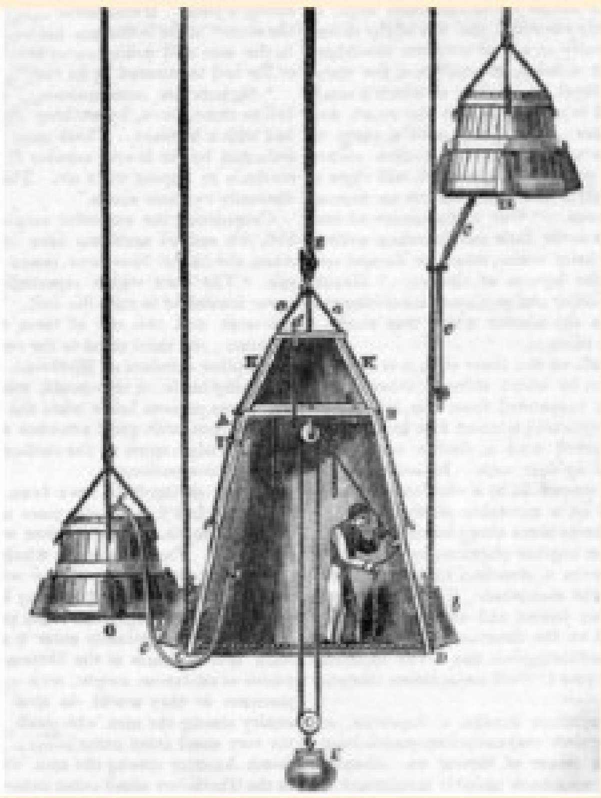

Figure 5
Before underwater diving apparatus became common, divers used a diving bell to explore underwater.

Figure 6
Jacques Charles (1746–1823) applied Archimedes' concept of buoyancy, Henry Cavendish's calculations for the density of hydrogen, and his own observations to invent the hydrogen balloon. His first flight was in 1783. His experiences and experiments led to the formulation of Charles' law in 1787.

The Relationship between Temperature and Volume

More than a century after Boyle had determined the relationship between the pressure and volume of a gas, French physicist Jacques Charles (**Figure 6**) determined the relationship between the temperature and volume of a gas. Charles became interested in the effect of temperature on gas volume after observing the hot air balloons that had become popular as flying machines. This is another example in which a technological development (hot air balloons) led to advances in science.

INVESTIGATION 4.2 *Introduction*

Temperature and Volume of a Gas

This investigation, like Investigation 4.1, is a controlled experiment in which all variables are kept constant except the two variables being investigated, in this case temperature and volume. Include a graph and a word statement describing the relationship as part of your Analysis. In your Evaluation, pay particular attention to the sources of experimental uncertainties (see Appendix B.2).

Report Checklist

○ Purpose	○ Design	● Analysis
○ Problem	○ Materials	● Evaluation (1, 3)
○ Hypothesis	○ Procedure	
○ Prediction	● Evidence	

Purpose

The purpose of this investigation is to create a general relationship between the temperature and volume of a gas.

Problem

What effect does increasing the temperature have on the volume of a gas?

Design

A volume of air is sealed inside a syringe, which is then placed in a water bath. As the temperature of the water is manipulated, the volume of the air is measured as the responding variable. Two controlled variables are the chemical amount of gas inside the syringe and the pressure on the gas.

To perform this investigation, turn to page 178.

Absolute Temperature Scale

The mathematical equation describing the relationship between volume and temperature may not be apparent from the graph you created in Investigation 4.2; however, if you draw a graph of the two variables, as in **Figure 7(a)**, you get a straight line. This is evidence that a simple relationship does exist. When the line is extrapolated backwards, it crosses the horizontal axis at –273 °C. It appears that, if the gas did not liquefy, its volume would become zero at –273 °C. If this experiment is repeated with different quantities of gas or with samples of different gases, straight-line relationships between temperature and volume are also observed. When the lines are extrapolated, they all meet at –273 °C, as shown in **Figure 7(b)**. This temperature, called **absolute zero**, is the lowest possible temperature. Scientists with sophisticated technology are coming within an increasingly smaller fraction of a degree from absolute zero.

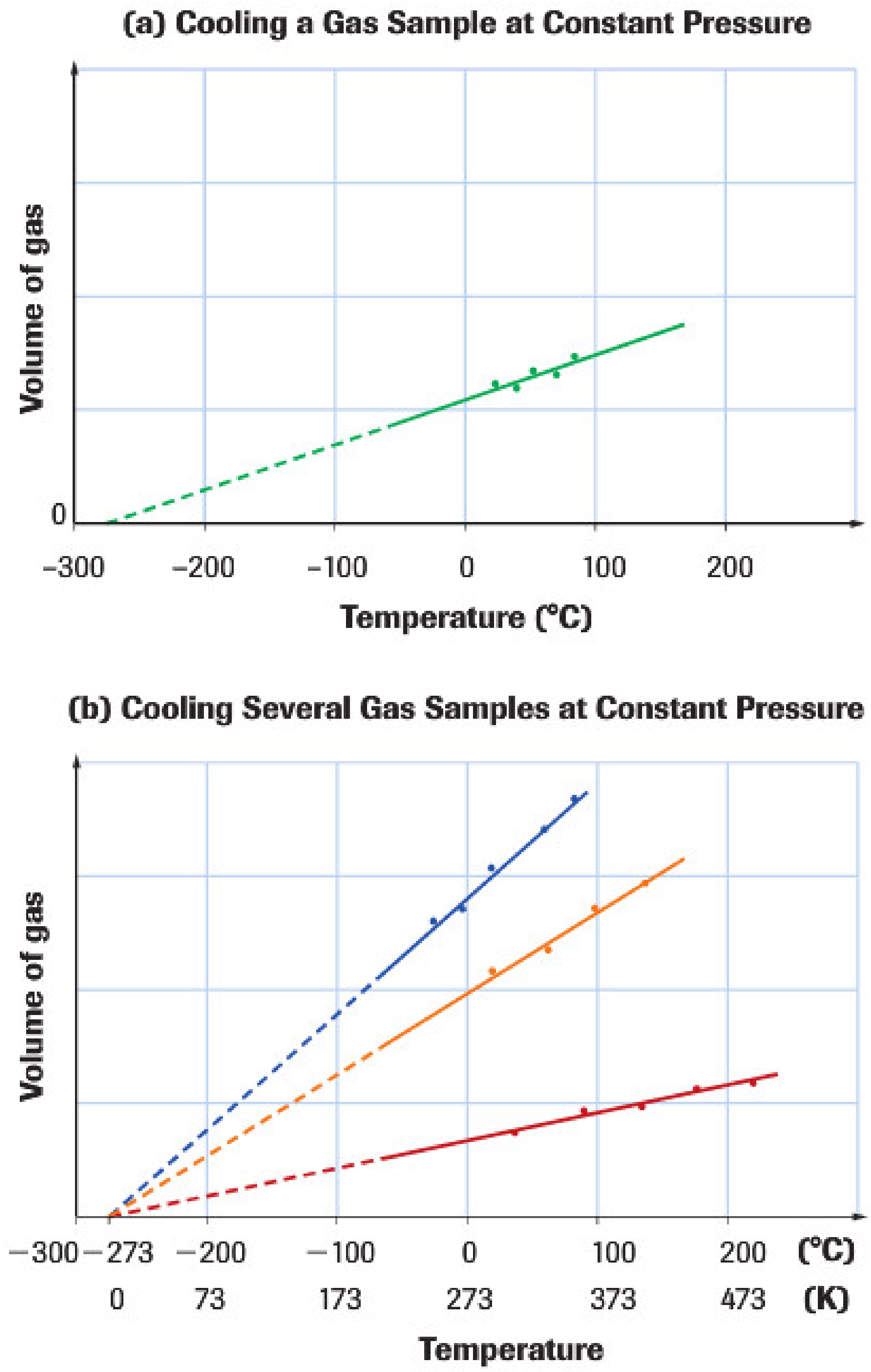

Figure 7
When the graphs from several careful volume–temperature experiments are extrapolated, all the lines meet at what scientists define as absolute zero, –273 °C or 0 K.

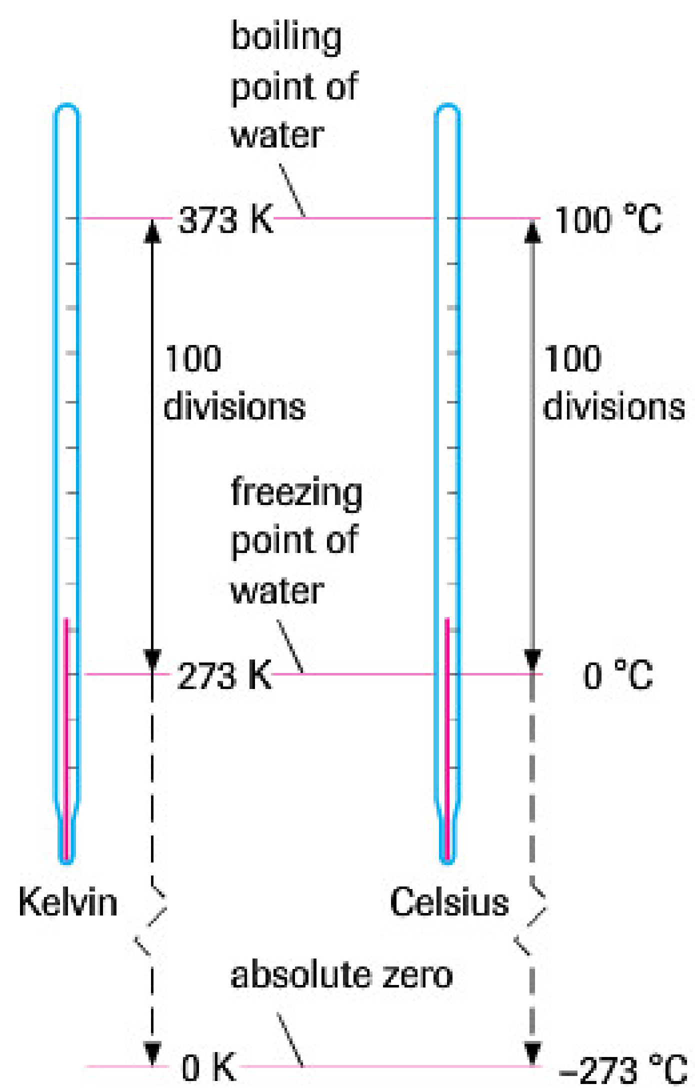

Figure 8
Jacques Charles predicted the absolute zero temperature and Lord Kelvin explained it as the temperature at which the kinetic energy of all entities of solids, liquids, or gases would become zero.

Absolute zero is the basis of another temperature scale, called the **absolute** or Kelvin **temperature scale**. On the absolute temperature scale, absolute zero (–273 °C) is zero kelvin (0 K), as shown in **Figure 7(b).** (Note that no degree symbol is used for kelvin.) The absolute temperature scale has the same size divisions as the Celsius temperature scale. To convert degrees Celsius to kelvin, you add 273 (**Figure 8**). STP and SATP are each defined by two exact values with infinite significant digits. STP is 273.15 K and 101.325 kPa; SATP is 298.15 K and 100 kPa. For convenience, however, use STP as 273 K and 101 kPa and SATP as 298 K and 100 kPa.

DID YOU KNOW ?

Lord Kelvin

Sir William Thomson (1824–1907), also known as Lord Kelvin, was a Scottish engineer, mathematician, and physicist. His work, during his very long and productive life, profoundly influenced the scientific thought of his generation. Thomson started attending Glasgow University when he was only eleven years old. His brilliant mind ranged from the constitution of matter to the age of Earth and the challenges of laying the Atlantic Cable. It was this last challenge that earned him his peerage and the title "Lord Kelvin."

Practice

11. What is the approximate temperature for absolute zero in degrees Celsius and kelvin?

12. Convert the following Celsius temperatures (t) to absolute temperatures (T).

(a) 0 °C
(b) 100 °C
(c) −30 °C
(d) 25 °C

13. Convert the following absolute temperatures (T) to Celsius temperatures (t).

(a) 0 K
(b) 100 K
(c) 300 K
(d) 373 K

Charles' Law

The relationship between the volume and absolute temperature of a gas is shown in **Figure 7(b)**. This relationship is described as a direct variation; that is, as the temperature increases, the volume increases. The simplest mathematical relationship is obtained when the absolute temperature is used. Mathematically, this relationship is represented as:

$$V = kT$$

where T represents the absolute temperature in kelvin. This means that the quotient of the two variables $\left(\frac{V}{T}\right)$ has a constant value (k), which is the slope of the straight-line graph (Figure 7(b) on the previous page). A constant value is clearly shown by the analysis in **Table 5**.

DID YOU KNOW ?

Development of Scientific Laws

Boyle's or Charles' initial experiments led to an empirical hypothesis in their first result and then a generalization after investigating several gases. Only after replication by many other scientists with many examples does the result attain the status of a scientific law.

empirical hypothesis
↓
generalization
↓
scientific law

Table 5 Analysis of Temperature and Volume of a Gas Sample

Temperature, t (°C)	Temperature, T (K)	Volume, V (L)	Constant, V/T (L/K)
25	298	5.00	0.0168
50	323	5.42	0.0168
75	348	5.84	0.0168
100	373	6.26	0.0168
125	398	6.68	0.0168

The relationship between volume and absolute temperature, after verification by other scientists, became known as **Charles' law**. Charles' law states that, ***as the temperature of a gas increases, the volume increases proportionally, provided that the pressure and chemical amount of gas remain constant*** (**Figure 9**). Charles' law can be conveniently written to compare any two sets of volume and temperature measurements at constant pressure and chemical amount:

$$\frac{V_1}{T_1} = k \text{ and } \frac{V_2}{T_2} = k$$

Therefore, $$\frac{V_1}{T_1} = \frac{V_2}{T_2} \quad \textbf{(Charles' law)}$$

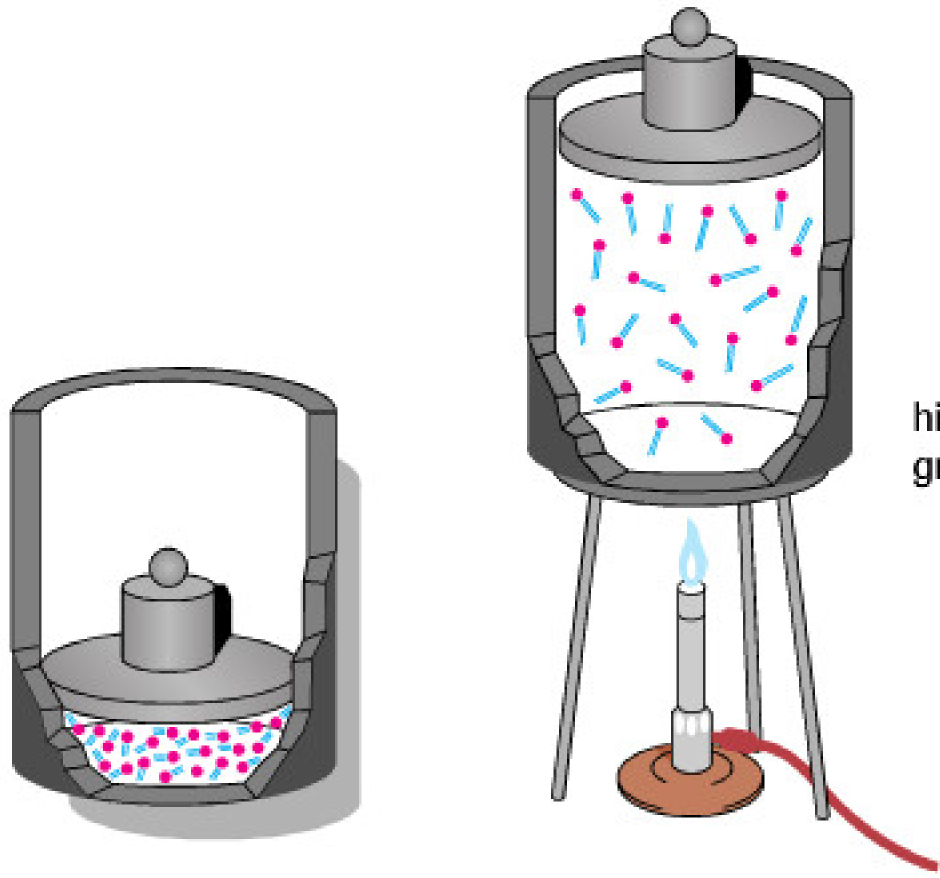

Figure 9
This diagram of cylinders with movable pistons illustrates a combined empirical–theoretical model. The model shows that the volume of a gas increases as the temperature of the gas increases. The pressure, equal to the pressure exerted by the mass, the piston, and the atmosphere, remains constant.

COMMUNICATION example 3

In a test of Charles' law, a gas inside a cylinder with a movable piston (**Figure 9**) is heated to 315 °C. The initial volume of gas in the cylinder is 0.30 L at 25 °C. What will be the final volume when the temperature is 315 °C?

Solution

$T_1 = (25 + 273)\ \text{K} = 298\ \text{K}$

$T_2 = (315 + 273)\ \text{K} = 588\ \text{K}$

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

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

$$= \frac{0.30\ \text{L} \times 588\ \cancel{\text{K}}}{298\ \cancel{\text{K}}}$$

$$= 0.59\ \text{L}$$

or $$V_2 = 0.30\ \text{L} \times \frac{588\ \cancel{\text{K}}}{298\ \cancel{\text{K}}}$$

$$= 0.59\ \text{L}$$

According to Charles' law, the final volume will be 0.59 L.

Learning Tip

- Charles' law only works if you use absolute temperatures (in kelvin). Check the example to see that you get a totally different (and incorrect) answer using Celsius temperatures.
- Some calculators allow you to store (STO) numbers and recall (RCL) them in later calculations. Check your calculator to see if you can calculate and then store the values of T_1 and T_2. Alternatively, you can include the calculation of T_1 and T_2 in the final calculation if you use parentheses around the addition operation.

Temperature Measurement Technologies

The first thermometer in the early 1600s was an air-filled glass bulb with a long stem inverted in a bowl of coloured water. This device was not very accurate or precise. The next technological development in the mid-1600s was the invention of sealed, alcohol-in-glass devices such as the common lab thermometer. Initially this thermometer had only fifty equal divisions but no zero reference point, so was not very useful for communicating actual temperatures. About 1725, the invention of the mercury-filled thermometer and the identification of two reproducible reference points (freezing point and boiling point of pure water) finally allowed different experimenters to measure temperatures with reasonable accuracy and reproducibility. These developments were essential for Charles to be able to conduct his experiments in the late 1700s.

More recently, advances in science and technology have produced a variety of electrical temperature sensors such as thermocouples (temperature-sensitive voltage of dissimilar metals) and thermistors (temperature-sensitive resistance). Thermocouples are best suited for high temperatures (such as ovens) and thermistors are best for lower temperatures (such as the digital home thermometers).

Figure 10
The exothermic combustion of propane provides the heat to warm the air in this hot-air balloon.

Practice

14. Butane is a gas that can be used in simple lighters.
(a) If 15 mL of butane gas at 0 °C is warmed to 25 °C, calculate its final volume.
(b) What assumptions did you make in your calculation?
(c) How does this calculation illustrate the need to use absolute temperatures?

15. An open, "empty" 2 L plastic pop container, which has an actual inside volume of 2.05 L, is removed from a refrigerator at 5 °C and allowed to warm up to 21 °C on a kitchen counter. What volume of air, measured at 21 °C, will leave the container as it warms?

16. Cooking pots have loose-fitting lids to allow air to escape while food is being heated. If a 1.5 L saucepan is heated from 22 °C to 100 °C, by what percentage will any gas in the pan increase in volume?

17. Jacques Charles became interested in temperature–volume relationships for gases because of his curiosity about hot-air balloon flight. Hot-air balloons are open containers that maintain the air inside at (very nearly) atmospheric pressure. Imagine that a modern balloon is being prepared for a flight when the air temperature is 20 °C. The propane burner (**Figure 10**) warms the air, causing it to expand by 20% (so every 1.00 L of air becomes 1.20 L). Calculate the final temperature, in degrees Celsius, of the air in the balloon.

18. A student decides to make a gas expansion thermometer by trapping some air (about 50–70 mL) inside an inverted 100 mL graduated cylinder, the open end of which is submerged in a beaker of water. The student reasons that she should be able to calculate the temperature of the surrounding air by measuring the volume of air inside the cylinder using the graduated scale on the cylinder walls.
(a) Draw a diagram of the apparatus and describe how it can function as a thermometer.
(b) Evaluate the design of this technology, using your knowledge of gas behaviour, and predict whether this design would provide accurate values. Suggest possible improvements.

BIOLOGY CONNECTION

Gas-Dependent Processes

There are many biological processes that depend on the properties of gases. You might come across some if you are taking a biology course.

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Learning Tip

Recall from previous work (Chapter 2, Section 2.4) that n represents the chemical amount of the gas, in moles.

The Combined Gas Law

One of the goals of science is the synthesis or putting together of different concepts. When Boyle's and Charles' laws are combined, the resulting **combined gas law** produces a relationship among the volume, temperature, and pressure of any fixed chemical amount of gas: ***the product of the pressure and volume of a gas sample is proportional to its absolute temperature in kelvin: $PV = kT$.***

Boyle's law: $PV =$ a constant (T and n are controlled variables.)

Charles' law: $\frac{V}{T} =$ a constant (P and n are controlled variables.)

If the product PV is constant at a fixed temperature, then $P\left(\frac{V}{T}\right)$ should also be a constant because V divided by a constant temperature is also constant. If the temperature changes, then Charles' law tells us that the ratio $\frac{V}{T}$ is constant at a fixed pressure. Therefore, multiplying a constant pressure by a constant ratio of volume to temperature certainly produces a number that is a constant. Using this reasoning (a mathematical method of joint variation), we can conclude that the product of the pressure and volume of a gas divided by its absolute temperature is a constant as long as the chemical amount of gas does not change:

$$\frac{PV}{T} = k$$

The relationship can be expressed in a convenient form for calculations involving changes in volume, temperature, or pressure for a particular gas sample:

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} \quad \text{(combined gas law)}$$

WWW WEB Activity

Simulation—The Combined Gas Law

This gas simulation program provides a visual representation of gas molecules and the effect of changing gas properties.

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The combined gas law is a useful starting point for all cases involving pressure, volume, and temperature, even if one of these variables is a constant (as in Boyle's and Charles' laws). A variable that is constant can easily be eliminated from the combined gas law equation, reducing it to an equation for either Boyle's or Charles' law as shown by Sample Problem 4.1.

SAMPLE problem 4.1

A steel cylinder with a fixed volume contains a gas at a pressure of 652 kPa and a temperature of 25 °C. If the cylinder is heated to 150 °C, use the combined gas law to calculate the new pressure.

Because the volume is constant, we can cancel V_1 and V_2 from the combined gas law equation because $V_1 = V_2$:

$$\frac{P_1 \cancel{V_1}}{T_1} = \frac{P_2 \cancel{V_2}}{T_2}$$

We can now solve for P_2 and then substitute the pressures and temperatures (after converting to kelvin):

$$T_1 = (25 + 273)\ \text{K} = 298\ \text{K}$$

$$T_2 = (150 + 273)\ \text{K} = 423\ \text{K}$$

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

$$= \frac{652\ \text{kPa} \times 423\ \cancel{\text{K}}}{298\ \cancel{\text{K}}}$$

$$= 925\ \text{kPa}$$

Alternatively, this can be expressed as a calculation of a new pressure directly related to the ratio of the temperatures and inversely related to the ratio of the volumes (which cancel to 1 in this case):

$$P_2 = P_1 \frac{T_2}{T_1} \frac{\cancel{V_1}}{\cancel{V_2}}$$

$$= 652\ \text{kPa} \times \frac{423\ \cancel{\text{K}}}{298\ \cancel{\text{K}}}$$

$$= 925\ \text{kPa}$$

If we assume that the steel walls are sufficiently strong, the gas will have a pressure of 925 kPa inside the cylinder.

DID YOU KNOW?

Gas Laws and Breathing

Breathing is something we all do. Experiments show that, on average, you inhale and exhale about 0.5 L of air, roughly 12 times per minute. How? Your lungs are like elastic balloons inside a flexible chest cavity. By activating muscles that raise your rib cage and lower your diaphragm, you increase the volume of your chest cavity (**Figure 11a**). Exhaling reverses this process (**Figure 11b**).

(a) Inhaling

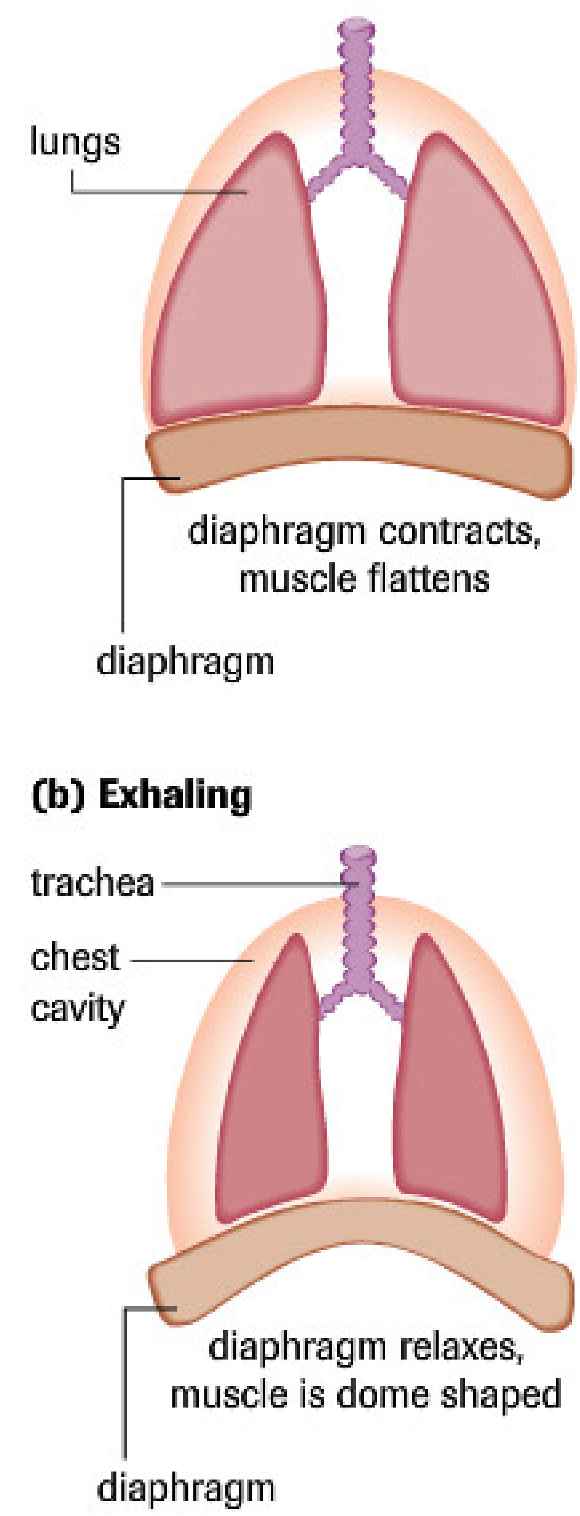

Figure 11
The diaphragm can be compared to a piston.

Figure 12
Various shapes and sizes of weather balloons are launched several times a day at more than 1000 sites in North America. (See Weather Forecasts, page 165.) Some of these weather balloons are reported as UFOs.

COMMUNICATION example 4

A balloon containing helium gas at 20 °C and a pressure of 100 kPa has a volume of 7.50 L (**Figure 12**). Calculate the volume of the balloon after it rises 10 km into the upper atmosphere, where the temperature is –36 °C and the outside air pressure is 28 kPa. Assume that no gas escapes and that the balloon is free to expand so that the gas pressure within it remains equal to the air pressure outside.

Solution

$T_1 = (20 + 273)\ \text{K} = 293\ \text{K}$

$T_2 = (-36 + 273)\ \text{K} = 237\ \text{K}$

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

$$V_2 = \frac{100\ \text{kPa} \times 7.50\ \text{L} \times 237\ \text{K}}{28\ \text{kPa} \times 293\ \text{K}}$$

$$= 22\ \text{L}$$

or

$$V_2 = 7.50\ \text{L} \times \frac{100\ \text{kPa}}{28\ \text{kPa}} \times \frac{237\ \text{K}}{293\ \text{K}}$$

$$= 22\ \text{L}$$

According to the combined gas law, the volume of the balloon in the upper atmosphere will be 22 L.

SUMMARY Gas Properties and Laws

STP: 0 °C and 101.325 kPa (exact values)
SATP: 25 °C and 100 kPa (exact values)
101.325 kPa = 1 atm = 760 mm Hg (exact values)
absolute zero = 0 K or –273.15 °C
T (K) = t (°C) + 273 (for calculation)

Boyle's law:	$P_1V_1 = P_2V_2$	(for constant temperature and chemical amount of gas)
Charles' law:	$\frac{V_1}{T_1} = \frac{V_2}{T_2}$	(for constant pressure and chemical amount of gas)
combined gas law:	$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$	(for constant chemical amount of gas)

WWW **WEB Activity**

Canadian Achievers—Malcolm King

Dr. Malcolm King switched from his training in polymer chemistry to a career searching for therapies for lung diseases. Now at the University of Alberta, Dr. King is drawing on his heritage as he researches the effectiveness of traditional Aboriginal remedies. What is Dr. King's theory on why so much of the world's research into lung function is concentrated in Canada? Why did he become interested in this field? What has King done to improve the health of Aboriginal Canadians?

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Practice

19. Express the combined gas law in your own words.

20. A large party balloon has a volume of 5.00 L at 20 °C and 100 kPa. Calculate the pressure for a volume of 6.00 L at 35 °C.

21. A cylinder of helium gas has a volume of 1.0 L. The gas in the cylinder exerts a pressure of 800 kPa at 30 °C. What volume would this gas occupy at SATP?

22. For any of the calculations in the previous questions, does the result depend on the identity of the gas? Explain briefly.

23. A 2.0 mL bubble of gas is released at the bottom of a lake where the pressure is 6.5 atm and the temperature is 10 °C. Predict the Celsius temperature of the gas bubble at the surface, where the pressure is 0.95 atm and the volume becomes 14.4 mL.

24. What assumption was made in all of the previous calculations?

25. Use Boyle's law to describe what happens during inhaling and exhaling (**Figure 11**).

26. Popcorn is a favourite snack food for many people (**Figure 13**). The corn kernel is heated, and some of the moisture inside the kernel vaporizes, starting a chain of events that leads to the tasty popped corn.

(a) If we assume a constant volume kernel (before popping), what happens to the pressure inside the kernel as the temperature increases? Justify your answer using appropriate mathematical equations or relationships.

(b) The pressure inside the kernel forces some superheated water and steam to penetrate into the starch granules, making them soft and gelatinous. When the hull of the kernel breaks at about 900 kPa, what happens to the volume of water vapour when the pressure quickly drops to about 100 kPa? Justify your answer using appropriate mathematical equations or relationships.

Figure 13
Popcorn was invented by Aboriginal peoples in North America long before the arrival of the Europeans. The popping method used very hot clay pots, which is a method similar to today's hot-air poppers.

Case Study

Compressed Gases

Not only are gases a major part of our lives, but compressed gases—that is, gases at pressures above atmospheric pressure—are particularly useful:

- The tires of vehicles contain pressurized air.
- Many people use gas barbecues with a pressurized propane fuel tank.
- Aerosol cans contain a propellant that carries the contents of the can out the nozzle; the propellant is a pressurized gas.
- Major surgery usually involves oxygen administered from a pressurized oxygen tank. It is often accompanied by an anesthetic, which may also be a pressurized gas, such as dinitrogen monoxide.

Certain occupations require some work with pressurized gases. In the medical field, paramedics and doctors use oxygen tanks. Firefighters use compressed air tanks like those used by underwater divers. Some welders use oxyacetylene torches (**Figure 14**). This form of welding requires both a pressurized oxygen tank and a pressurized acetylene tank. Many scientists and their graduate students routinely use a pressurized gas for research because the gas is part of the reaction system or because it provides an inert (nonreactive) environment. Noble gases, such as argon, are also used to provide an inert environment in the computer chip industry, where oxygen would cause undesirable reactions.

Figure 14
The use of a controlled mixture of oxygen and acetylene provides the best combustion and very high temperatures necessary for cutting or welding metal.

The chemical safety hazards of some gases are similar to those of many other chemicals, which may be corrosive, toxic, flammable, dangerously reactive, or oxidizing agents. What makes compressed gases much more dangerous is the physical hazard of it becoming a "rocket": gas pressures can be as high as 15 MPa (about 150 atm). The hole in the tank, to which the valve stem and valve are connected, is the diameter of a pencil. If the gas is suddenly released through such a small opening, the very great pressure propels the tank, making it a formidable projectile. A damaged tank can go through a solid brick wall and cause considerable damage.

Professional and recreational underwater divers face risks associated with the use of a pressurized air tank or scuba (self-contained underwater breathing apparatus). The tank containing compressed air is attached to a regulator that releases the air at the same pressure as the underwater surroundings (**Figure 15**). The pressure underwater can be quite substantial. Breathing pressurized air is necessary to balance the internal and external pressures on the chest to allow divers to inflate their lungs. However, this creates problems if divers ascend to normal pressure too quickly or while holding their breath. According to Boyle's law, if the pressure is decreased, the volume of air increases. When the volume of air is contained in the lungs, the lungs would expand to accommodate the increased volume. This is very dangerous because the lungs could rupture. This is one reason why a person needs an understanding of gases and gas laws in order to obtain a scuba-diving licence and to dive safely.

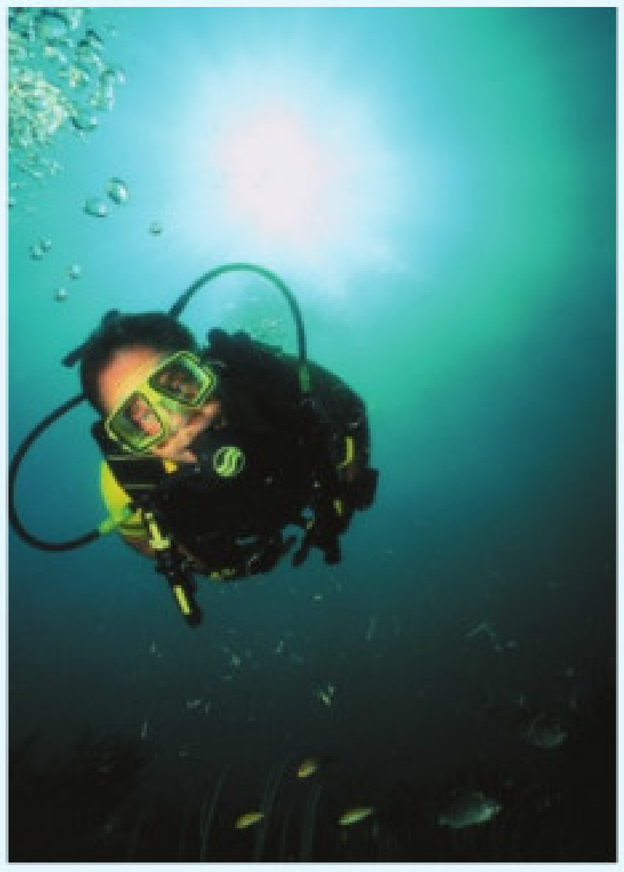

Figure 15
Every 10 m of depth adds about 1 atm (100 kPa) of pressure to the normal air pressure. At a depth of 20 m, the total pressure is about 300 kPa. In order to breathe, the air pressure must be about 300 kPa.

A European company recently developed an automobile powered by compressed gas. The Air Car (**Figure 16**) uses an electric pump to compress air into a tank. This compressed air, in turn, pumps the pistons to rotate the wheels and make the car move without the need for gasoline. The only exhaust that comes out of the tail pipe is cold air. The air pump that puts air into the tank plugs into an ordinary household outlet and takes four hours to refill. On a full tank of compressed air the vehicle can travel 80 km at a speed of 110 km/h, and farther at lower speeds. The manufacturer, Luxembourg-based Moteur Developpement International, describes the car as safe, nonpolluting, and inexpensive. Environmental scientists, however, are leery of the Air Car's claimed benefits. They point out that converting energy from electricity to compressed air is inefficient and uses more energy from the power plant than it delivers on the road. While there may not be any pollution from the car itself, the vehicle merely transfers the environmental burden to another place.

Figure 16
The Air Car is very quiet and produces no pollution during its operation.

Case Study Questions

1. Identify two consumer or commercial products that use or contain compressed air and two that involve other compressed gases.
2. Identify several careers that involve work with pressurized gases. How does knowledge of gas properties help the people in those careers?
3. Another problem of breathing air under pressure while scuba diving is that it forces more air to dissolve in the diver's bloodstream. Using gas laws and other information, describe why this can be dangerous to the diver. What can be done to prevent the problem or to solve the problem after it has been created?

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Extension

4. Helium has many uses (**Figure 17**) but one that is familiar to many people is its use in party balloons. Sometimes people inhale helium because it produces an unusual change in a person's voice. In a paragraph based on your Internet research, describe this effect as well as the dangers of inhaling helium.

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Figure 17
Modern airships are filled with the light noble gas, helium. Helium is also used in party balloons.

Section 4.1 Questions

1. Copy and complete **Table 6**. Show your work using appropriate conversion factors.

Table 6 Converting between Pressure Units

	Pressure (kPa)	Pressure (atm)	Pressure (mm Hg)
(a)		0.0875	
(b)	25.0		
(c)			842

2. Copy and complete **Table 7**.

Table 7 Converting between Celsius and Kelvin

	t (°C)	*T* (K)
(a)	25	
(b)	–35	
(c)		312
(d)		208

3. A syringe contains 50.0 mL of a gas at a pressure of 96.0 mm Hg. The end is sealed, and the plunger is pushed to compress the gas to 12.5 mL. What is the new pressure of the gas inside the syringe, assuming constant temperature?
4. Carbon dioxide produced by yeast in bread dough causes the dough to rise, even before it is baked (**Figure 18**). During baking, the carbon dioxide gas expands. Predict the final volume of 0.10 L of carbon dioxide in bread dough that is heated from 25 °C to 190 °C at a constant pressure.
5. An automobile tire has an internal volume of 27 L at 225 kPa and 18 °C.
   (a) What volume would the air inside the tire occupy if it escaped? (Atmospheric pressure at the time is 98 kPa and the temperature remains the same.)
   (b) How many times larger is the new volume compared with the original volume? How does this compare with the change in pressure?
6. In a cylinder of a diesel engine, 500 mL of air at 40.0 °C and 1.00 atm is powerfully compressed just before the diesel fuel is injected. The resulting pressure is 35.0 atm. If the final volume is 23.0 mL, what is the final temperature in the cylinder?
7. The gas laws described in this section involve the properties of volume, pressure, and temperature. Some of these variables have a direct relationship (as one increases, so does the other), and some have an inverse relationship (as one increases, the other decreases).
   (a) For each pair of the following variables, state whether the relationship is direct or inverse and sketch a graph:
      (i) pressure and volume at a constant temperature
      (ii) temperature and volume at a constant pressure
   (b) What other property of a gas must also be constant for all of the above?

Figure 18
The lightness of baked goods, such as bread and cakes, is a result of gas bubbles trapped in the dough or batter when it is heated. The leavening, or production of gas bubbles, can be due to vaporization of water, expansion of gases already in the dough or batter, or leavening agents such as yeast and baking powder. In contrast, bannock made by Aboriginal peoples does not require a leavening agent and is therefore easier to use when surviving on the land.

8. List the seven ways that empirical knowledge can be communicated. Where possible, provide a specific example from this section for each of these ways.
9. The air exhaled by a scuba diver (**Figure 15**) rises to the surface.
   (a) What happens to the bubbles as they rise? Describe your reasoning.
   (b) What assumptions did you make in your answer to (a)?
10. Why do aerosol cans have a warning not to incinerate the container?
11. Jet aircraft engines use energy from burning fuel to power the process of taking in cold air and releasing hot gases. Most of the intake air is nitrogen, which reacts only in negligible quantities. The expanding gas mixture escapes backward, and the reaction of this force drives the engine forward.
   (a) Assuming the $N_2(g)$ in the air is heated from –60 °C to 540 °C in the engine, express the volume increase as a ratio of final volume to initial volume, to a certainty of three significant digits.
   (b) Describe what other work the expanding gases in a jet engine must do, besides providing forward thrust. (*Hint:* An older term is "turbojet" engine.)

12. Read the following partial lab report. Complete the Prediction, Design (based on the apparatus shown in **Figure 19**), Analysis (of the Evidence in **Table 8**), and Evaluation (2, 3) portions of a lab report for this investigation. Include a graph in your Analysis.

Purpose

The purpose of this investigation is to test the combined gas law for the relationship between the pressure and the temperature of a gas.

Problem

What effect does the temperature of nitrogen gas have on the pressure it exerts?

Figure 19
This apparatus consists of a hollow metal sphere to which a pressure gauge is attached. Because the gas inside the sphere cannot expand, the relationship between temperature and pressure of a gas can be determined.

Table 8 Evidence: Variation of Pressure with Temperature

Temperature (°C)	Pressure (kPa)
0	100
20	106
40	115
60	123
80	129
100	135

13. Scientific laws are the most important type of empirical knowledge in science. Using an example from this section, write a brief summary describing how a scientific law becomes established.

14. The traditional or indigenous knowledge of the Aboriginal peoples is very important to their culture and survival. In a sentence or two, describe the characteristics of indigenous knowledge (IK). Why is this type of knowledge still important today? Identify some similarities and differences between indigenous knowledge and Western scientific knowledge.

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15. For a typical geyser (**Figure 20**), underground water seeps into a deep narrow shaft in the ground and is heated from below. Because of the depth, the pressure on the water is high, so the water at the bottom of the shaft boils at a much higher temperature than normal.
   (a) What happens to the volume of a 1.0 L bubble of water vapour at 130 °C and 3.05 atm when it reaches the surface, where the conditions are 100 °C and 1.01 atm?
   (b) Why is a narrow shaft necessary to produce the geyser effect?

Figure 20
Geysers are unusual and dramatic examples of geothermal energy used to heat water in a confined space.

16. Barometers, manometers, and Bourdon gauges all measure gas pressure. How are they similar and how are they different? How did the invention of these devices advance the science of gases? Working in a group, use the Internet to answer these questions and present your findings as a poster or multimedia presentation.

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Extension

17. Search the Internet for research reports on how close scientists have come to reaching absolute zero. What do the reports say about whether the kinetic energy of all entities is zero at absolute zero?

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18. Why is mercury used in most barometers, and not other liquids such as water, which is plentiful and nontoxic?

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Explaining the Properties of Gases 4.2

The early study of gases was strictly empirical. Boyle and Charles conducted their initial experiments that, after independent replication, led to the laws named in their honour. Boyle's and Charles' work occurred well before Dalton's atomic theory was published in 1803. The kinetic molecular theory (Chapter 2, Section 2.2) was developed by about 1860, thanks to the use of mathematical tools such as statistical analysis.

Before any law or theory is accepted by the scientific community, supporting evidence must be available. An acceptable theory must describe observations in terms of non-observable ideas, explain existing evidence, predict results of future experiments, and be as simple as possible in concept and application. The easiest thing for a theory to do is to explain existing evidence; the hardest thing is to successfully predict new evidence. Over the years the kinetic molecular theory (**Figure 1**) has been strongly supported by experimental evidence and is very useful in explaining the properties of gases. For the restricted theory presented in this textbook, we will limit predictions to qualitative properties and comparisons.

- The kinetic molecular theory explains why gases, unlike solids and liquids, are compressible. In a molecular solid, the distance between molecules is about the same size as the molecules themselves; in a liquid, it is generally slightly greater; and in a gas, the distance between molecules is about 20 to 30 times the size of the molecules. If most of the volume of a gas sample is empty space, it should be possible to force the molecules closer together.
- The kinetic molecular theory explains the concept of gas pressure. Pressure is considered to be the result of gas molecules colliding with objects—particularly the walls of a container. Based on this theory, the pressure exerted by a gas sample is the total force of these collisions distributed over an area of the container wall; in other words, force per unit area.
- The kinetic molecular theory explains Boyle's law. If the volume of a container is reduced, gas molecules will move a shorter distance before colliding with the walls of the container. The kinetic molecular theory suggests that they will collide with the walls more frequently, resulting in increased pressure on the container.
- The kinetic molecular theory explains Charles' law. An increase in temperature represents an increase in the average kinetic energy and therefore the average speed of the entities' motion. In a container in which the pressure can be kept constant (for example, in a cylinder with a piston or in a flexible-walled container such as a

DID YOU KNOW?

Analogy for States of Matter

To picture yourself as an entity in a solid, imagine yourself seated in a regular classroom. For a liquid, picture a school dance. For a gas, imagine yourself and three friends skating randomly in a large ice-hockey arena.

DID YOU KNOW?

Scientific versus Indigenous Knowledge

The usual development of scientific knowledge is from empirical to theoretical and an important goal is to explain natural substances and processes. In contrast, the indigenous knowledge of Aboriginal peoples is largely empirical and its goal is to use natural substances and processes to live in harmony with nature in order to survive on the land.

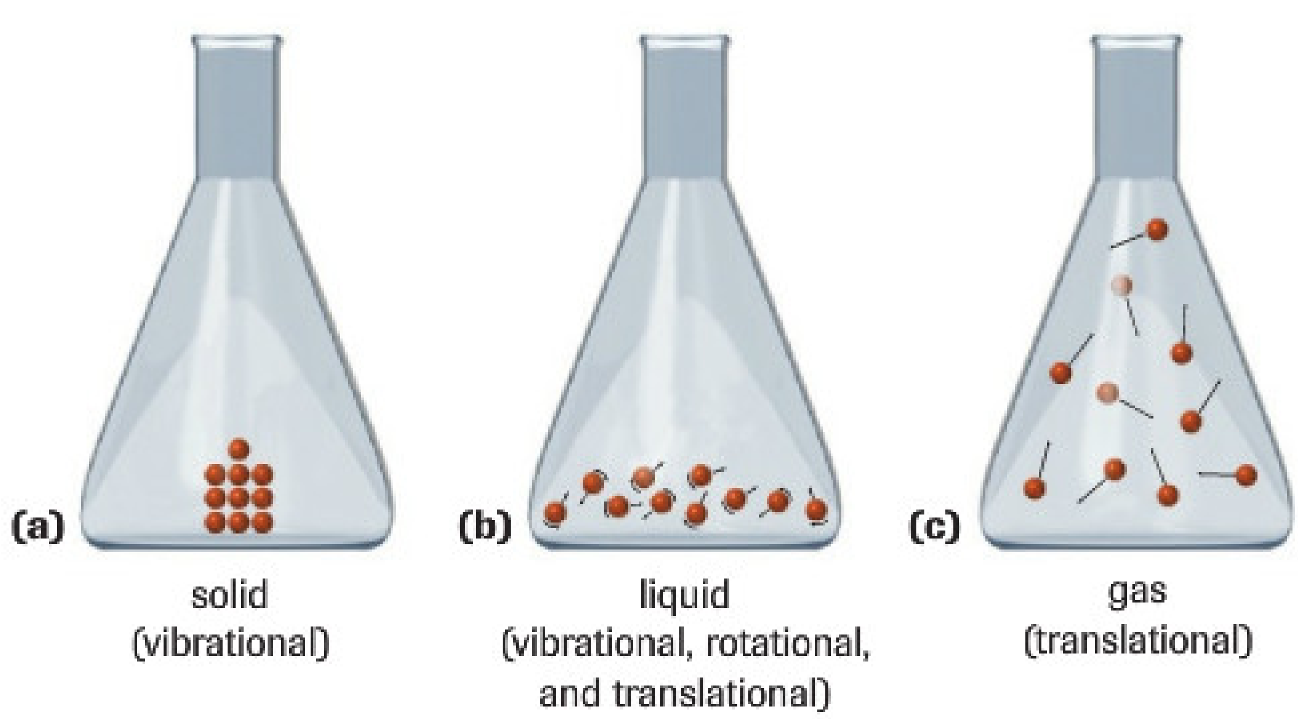

Figure 1
According to the kinetic molecular theory, the motion of molecules is different in solids, liquids, and gases.
(a) Entities in solids have primarily vibrational motion.
(b) Entities in liquids have vibrational, rotational, and some translational motion.
(c) The most important form of motion in gases is translational.

weather balloon), faster-moving molecules will collide more frequently with the container walls. They will also collide with more force, causing the walls to move outward. Thus, the volume of a gas sample increases with increasing temperature.

Practice

1. Use the kinetic molecular theory to explain the following observed properties of gases.
   (a) Gas pressure increases when the volume of the gas is kept constant and the temperature increases.
   (b) Gas pressure increases when the temperature is kept constant and the volume of the gas decreases.
   (c) Gases mix much more quickly than do liquids.
   (d) Oil, not air, is used in hydraulic systems.
   (e) At SATP, the average speed of air (oxygen and nitrogen) molecules is about 450 m/s, which is approximately the speed of a bullet fired from a rifle. Nevertheless, it takes several minutes for the odour of a perfume to diffuse throughout a room.
2. Describe at least three examples that show how kinetic molecular theory provides an explanation for natural or technological products or processes.
3. For a theory, such as the kinetic molecular theory, to become acceptable to the scientific community it must have satisfied some criteria. List four characteristics of an accepted scientific theory.

Figure 2
Elizabeth ("Elsie") MacGill, (1905–1980)

WWW WEB Activity

Canadian Achievers—Elizabeth MacGill

Elsie MacGill had a distinguished career in aeronautics—the science and technology of objects moving through the air. In her lifetime, she accomplished many "firsts" for women.

1. Identify some of these accomplishments.
2. List some gas properties that are important in aeronautics.

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Explaining the Law of Combining Volumes

The kinetic molecular theory explains many physical properties of gases. But what about their chemical properties? In other words, what happens during chemical reactions? Many chemical reactions involve gases as reactants and/or products.

In 1809, Joseph Gay-Lussac, a French scientist and a colleague of Jacques Charles, measured the relative volumes of gases involved in chemical reactions. For example, when he combined hydrogen and chlorine gases at the same temperature and pressure, he noticed that every one litre of hydrogen gas, $H_2(g)$, reacted with one litre of chlorine gas, $Cl_2(g)$, to produce two litres of hydrogen chloride gas, HCl(g).

	hydrogen	+	chlorine	→	hydrogen chloride
	1.0 L		1.0 L		2.0 L
ratio	1		1		2

His observations of several gas reactions led, after independent replication, to the **law of combining volumes**, which states that ***when measured at the same temperature and pressure, volumes of gaseous reactants and products of chemical reactions are always in simple ratios of whole numbers.*** This law is also known as Gay-Lussac's law of combining volumes. Not all reactants and products need be gases, but the law deals only with the gases consumed or produced. An example of this is the simple decomposition of liquid water, in which the volumes of hydrogen gas and oxygen gas produced are always in the ratio of 2:1 (**Figure 3**).

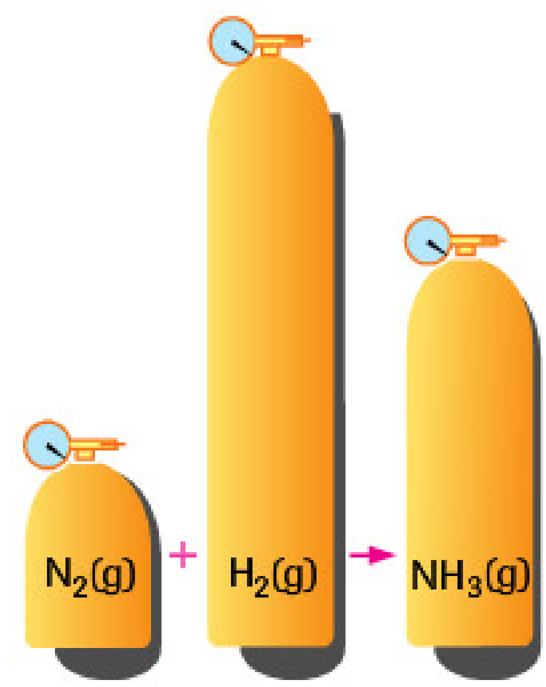
Two years after this law was formulated, Amedeo Avogadro proposed an explanation in terms of numbers of molecules. Unfortunately, Avogadro's idea was largely ignored for about half a century. When Gay-Lussac published his work about combining volumes, Avogadro was intrigued by the fact that reacting volumes of gases were in whole-number ratios, just like the coefficients in a balanced equation. Suggesting an explanation for the relationship between the volume ratios and coefficient ratios, Avogadro proposed that ***equal volumes of gases at the same temperature and pressure contain equal numbers of molecules,*** a statement that is now best called **Avogadro's theory.** Avogadro's initial idea was a hypothesis. Although it is still sometimes referred to as a hypothesis, the idea is firmly established. Therefore, Avogadro's idea now has the status of a theory.

This theoretical concept explains the law of combining volumes. For example, if a reaction occurs between two volumes of one gas and one volume of another gas at the same temperature and pressure, the theory says that two molecules of the first gas react with one molecule of the second gas. Another example is the reaction of nitrogen and hydrogen, in which ammonia is produced (**Figure 4**).

When all gases are at the same temperature and pressure, the law of combining volumes provides an efficient way of predicting the volumes of gases involved in a chemical reaction. As explained by Avogadro's theory, the mole ratios provided by the balanced equation are also the volume ratios. For example,

coefficients	$2\ C_4H_{10}(g)$ +	$13\ O_2(g)$	→	$8\ CO_2(g)$ +	$10\ H_2O(g)$
chemical amounts	2 mol	13 mol		8 mol	10 mol
volumes	2 L	13 L		8 L	10 L
example	4 mL	26 mL		16 mL	20 mL

Figure 3
Water decomposes to hydrogen and oxygen gases in a 2:1 volume ratio.



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

coefficients	1		3		2
mole ratio	1	:	3	:	2
volume ratio	1	:	3	:	2

Figure 4
One volume of nitrogen reacts with three volumes of hydrogen, producing two volumes of ammonia.

SAMPLE problem 4.2

Use the law of combining volumes to predict the volume of oxygen required for the complete combustion of 120 mL of butane gas from a lighter.

The first step is to write the balanced chemical equation, including what you are given and what you need to find:

$$2\ C_4H_{10}(g) + 13\ O_2(g) \rightarrow 8\ CO_2(g) + 10\ H_2O(g)$$

120 mL $\qquad$ V

From this chemical equation you can see that 13 mol of oxygen is required for every 2 mol of butane. Therefore, the volume of oxygen has to be greater than 120 mL by a factor of $\frac{13}{2}$:

$$V_{O_2} = 120\ \text{mL} \times \frac{13}{2}$$
$$= 780\ \text{mL}$$

To make sure that the ratio is used in the correct order, you could include the chemical formula with each quantity as shown below:

$$V_{O_2} = 120\ \cancel{\text{mL}\ C_4H_{10}} \times \frac{13\ \text{mL}\ O_2}{2\ \cancel{\text{mL}\ C_4H_{10}}} = 780\ \text{mL}\ O_2$$

Note the cancellation of the units and chemical formulas.

Learning Tip

This equivalence between the chemical amounts (coefficients) and the volumes only works for gases, and only if they are at the same temperature and pressure.

COMMUNICATION example

A catalytic converter in the exhaust system of a car uses oxygen (from the air) to convert carbon monoxide to carbon dioxide, which is released through the tailpipe. If we assume the same temperature and pressure, what volume of oxygen is required to react with 125 L of carbon monoxide produced during a 100 km trip?

Solution

$$2\,CO(g) + O_2(g) \rightarrow 2\,CO_2(g)$$

125 L　　V

$$V_{O_2} = 125\ L \times \frac{1}{2} = 62.5\ L$$

or

$$V_{O_2} = 125\ \cancel{L\,CO} \times \frac{1\ L\ O_2}{2\ \cancel{L\,CO}} = 62.5\ L\ O_2$$

According to the law of combining volumes, 62.5 L of oxygen is required.

Practice

4. Gay-Lussac was the first to notice and publish evidence of simple volume ratios of reacting gases.
   (a) State the law that was created from this evidence.
   (b) State the theory that can be used to explain this law.
   (c) Compare the characteristics of scientific laws and theories.
5. Gas barbecues burn propane using oxygen from the air. If 5.00 L of propane is burned, predict the volume of oxygen, at the same temperature and pressure, required for complete combustion.
6. In modern automobile catalytic converters, nitrogen monoxide (a pollutant) reacts with hydrogen to produce nitrogen and water vapour (part of the exhaust). The catalytic converter of a car meeting current emission standards removes about 1.2 L of nitrogen monoxide at SATP for every kilometre of driving. What volume of nitrogen gas is formed from 1.2 L of nitrogen monoxide at the same temperature and pressure?
7. Ammonia is produced from its elements in huge quantities at many facilities in Alberta.
   (a) Predict the volume of hydrogen (from natural gas) that is required to produce 1.0 ML of ammonia.
   (b) State the important assumption that must be made in this calculation.

CAREER CONNECTION

Meteorologist

Meteorologists use advanced knowledge of the physical and chemical properties of gases to study the atmosphere and how it interacts with the rest of the planet and everything on it. Meteorologists can work as weather forecasters or they can consult and provide specific analyses or weather warnings to governments and businesses.

Find out more about the possibilities of being a meteorologist, the work of meteorologists, and the training required.

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WWW WEB Activity

Web Quest—"Designer Air" for Tires

Most tires contain plain old air, but one of the latest trends is to fill car tires with pure nitrogen to increase safety and decrease gas consumption. This Web Quest lets you find out more about using pure nitrogen in tires. Your consulting group will be hired to make recommendations about this trend and answer this question: How is pure nitrogen gas different from air, and would those differences change how your vehicle performs?

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Case Study

Weather Forecasts

Meteorology is the study of the atmosphere and weather forecasting. This study is a good example of collecting information with various technologies, and then using this information to explain and predict events.

In Canada, human weather watchers and automated meteorological stations take readings to determine atmospheric pressure, temperature, humidity, wind, type and extent of cloud cover, and precipitation (rain, snow, and hail). Helium weather balloons are also used to collect data. Some weather balloons may go as high as 30 km, where the air pressure is 1.2 kPa and the air temperature is -47 °C. The designers of these balloons must therefore know about gas properties. Satellites take pictures of cloud development that indicate wind patterns, as well as snow and ice cover.

All the data, collected from these different sources, are then transmitted via a communications network to the computers at a regional weather office. Meteorologists use sophisticated computer models to study and simulate weather changes based on vast quantities of data collected around the world.

In Canada, the supercomputer at the Canadian Meteorological Centre in Montreal generates forecasts of atmospheric conditions that are used to develop regional predictions. The meteorologists at about 14 weather offices across Canada adapt these forecasts for the general public and the aviation, agricultural, energy, forestry, and shipping sectors. Every day, Environment Canada issues about 1300 public weather predictions for more than 200 geographic areas, and about 1000 aviation forecasts for 175 airports. The primary responsibility of Environment Canada is to warn Canadians about severe weather conditions that could threaten lives and property.

Weather maps summarize predictions for that day's weather, based on the conditions observed the previous day. These maps typically show the predicted temperatures for selected cities, warm fronts and cold fronts, and areas of precipitation. You have probably seen weather reports citing high- and low-pressure systems (**Figure 5**). Lows are associated with overcast skies and precipitation, while highs generally bring clear skies. The interaction between high- and low-pressure systems drives active weather.

Long before modern weather analysis and prediction, Aboriginal Canadians were able to anticipate the local weather. People living on the land were keen observers of natural phenomena, such as wind direction and cloud patterns, and could predict weather changes based on this traditional knowledge. For example, sun-dogs (bright spots usually occurring in pairs on either side of the Sun) signalled a drastic change in the weather. On the western Prairies, a bow-shaped cloud formation bordering an expanse of clear sky indicated that a Chinook wind was coming. Air rushing out of caves warned of a fast-moving low-pressure system bringing stormy weather. The reaction of animals to oncoming weather was also important forecast information.

Case Study Questions

1. Use the gas laws to describe how a fast-moving low-pressure system could cause air to rush out of a cave.
2. State some examples of observations used by Aboriginal peoples to predict weather changes.
3. Historically, measurements of pressure, temperature, and relative humidity were made using a mercury barometer, thermometer, and sling psychrometer (wet/dry bulb thermometer) respectively. How has the technology used to measure these three important atmospheric variables changed? Briefly describe each modern example, including the type of sensor and typical precision values.

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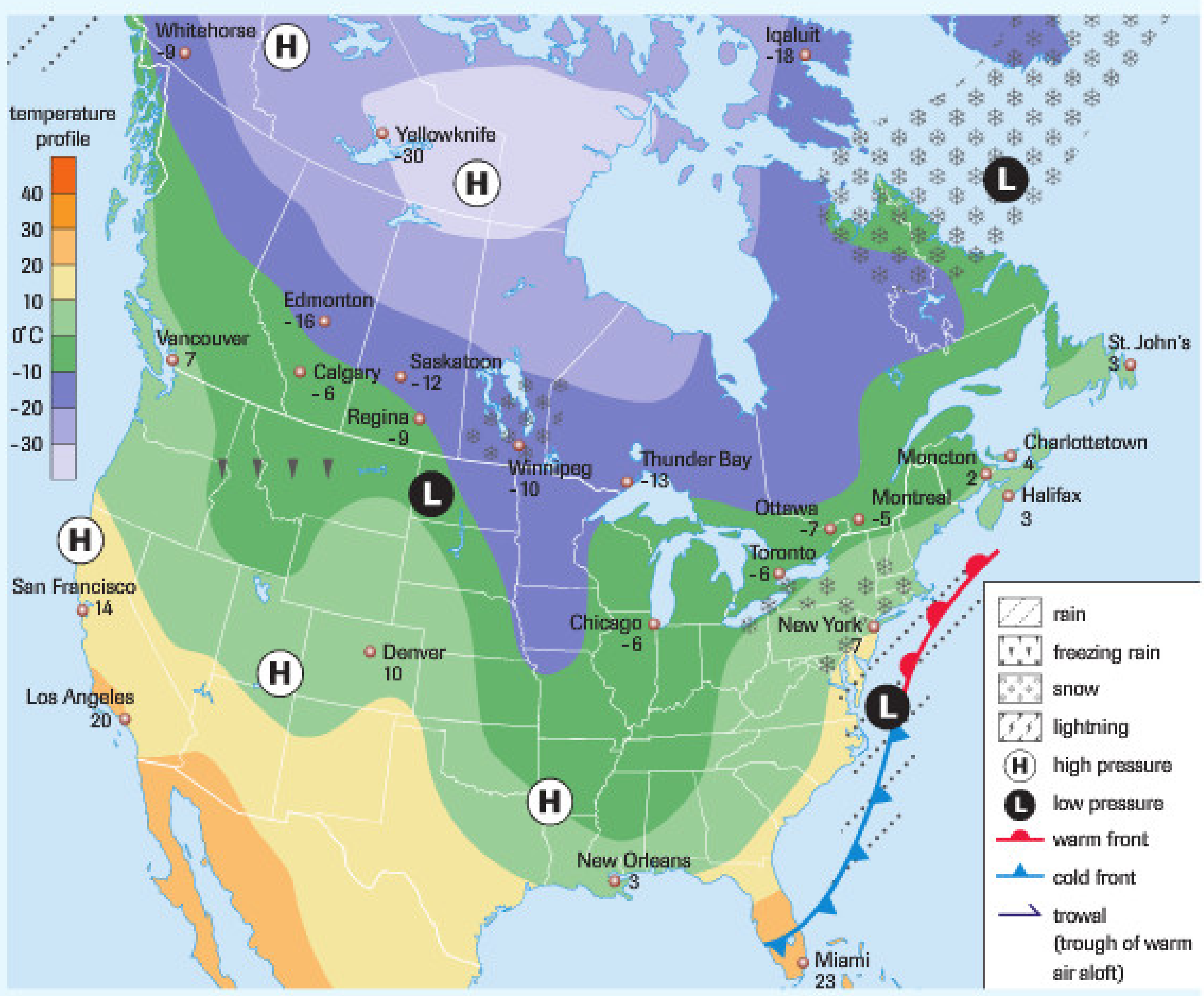

Figure 5
Other than temperature, the most commonly used gas property in weather reports is pressure, often referred to as "highs" and "lows."

Section 4.2 Questions

1. Use the kinetic molecular theory to explain in words or diagrams each of the following observations.
   (a) A drop of food colouring is carefully added to a glass of water. After sitting without stirring for a short period of time, the colour is evenly distributed throughout the water.
   (b) At the same pressure, cooler air has a higher density than warmer air.
   (c) A layer of pure zinc is deposited onto the surface of a piece of copper. After heating briefly in a flame, a brass (solid solution) layer forms on the surface.
2. In the development of the gas laws in the previous section, it was necessary to always keep the chemical amount of the gas constant. Suppose a container with a fixed volume contains a certain chemical amount of gas. If the chemical amount of gas is doubled and the temperature kept constant, predict the change in pressure. Justify your prediction using the kinetic molecular theory.
3. (a) State the law of combining volumes.
   (b) Using the formation reaction for nitrogen dioxide gas as an example, predict the ratio of combining volumes.
   (c) Explain your prediction using simple molecular model diagrams.
4. Some sulfur compounds are undesirable components of much of Alberta's fossil fuels. For example, sour natural gas contains hydrogen sulfide in varying proportions. In some cases, hydrogen sulfide is burned in gas flares often seen around Alberta. In other cases, the pure sulfur is extracted from the gas as a useful byproduct (**Figure 6**).

Figure 6
Pure elemental sulfur is a useful byproduct of the natural gas processing industry. Here at the Shell Waterton gas plant near Pincher Creek, Alberta, pure sulfur extracted from the sour gas is stored in blocks before being marketed to the fertilizer, pharmaceutical, and manufacturing industries. Sulfur is one of the world's most common elements.

   (a) One technology for removing hydrogen sulfide from sour natural gas involves converting part of the hydrogen sulfide to sulfur dioxide by burning in air. Predict the volume of oxygen required to burn 124 kL of hydrogen sulfide measured at the same temperature and pressure.
   (b) The remaining hydrogen sulfide then reacts with the sulfur dioxide as shown in the reaction equation below. Calculate the volume of sulfur dioxide a chemical engineer would predict to react completely with 248 kL of hydrogen sulfide. The gases are measured at 350 °C and 250 kPa.

   $$16\ H_2S(g) + 8\ SO_2(g) \rightarrow 3\ S_8(s) + 16\ H_2O(g)$$

5. The production of nitric acid is important to the fertilizer and explosives industries. Chemical engineers routinely use gas laws to design and control processes such as the Ostwald process.
   (a) The production of nitric acid by the Ostwald process begins with the combustion of ammonia:

   $$4\ NH_3(g) + 5\ O_2(g) \rightarrow 4\ NO(g) + 6\ H_2O(g)$$

   Predict the volume of oxygen required to react with 100 L of ammonia as well as the volumes of nitrogen oxide and water vapour produced. All gases are measured at 800 °C and 200 kPa.
   (b) In another step of the Ostwald process, nitrogen monoxide reacts with oxygen to form nitrogen dioxide. Predict the volume of oxygen at 800 °C and 200 kPa required to produce 750 L of nitrogen dioxide at the same temperature and pressure.
   (c) Nitric acid is produced by reacting nitrogen dioxide with water:

   $$3\ NO_2(g) + H_2O(l) \rightarrow 2\ HNO_3(aq) + NO(g)$$

   Predict the volume of nitrogen monoxide produced by the reaction of 100 L of nitrogen dioxide with excess water. Both gases are measured at the same temperature and pressure as in (b).
   (d) A high-nitrogen fertilizer is made by reacting ammonia gas with nitric acid to produce aqueous ammonium nitrate. Can the law of combining volumes be used to predict the volume of ammonia gas required to react with 100 L of nitric acid? Justify your answer.
6. Science provides the theoretical basis for interpreting and explaining natural and technological products and processes. Provide two natural and two technological examples that can be explained using the kinetic molecular theory. Give a brief explanation for each example.

Extension

7. Explanations from scientific theories are judged on their ability to explain empirical knowledge in a logical, consistent, and simple fashion. How well does Avogadro's theory fit these criteria? Consider and evaluate whether this theory makes sense (is logical) and agrees with other theories (is consistent).

Molar Volume of Gases 4.3

The evolution of scientific knowledge often involves integrating two or more concepts. An example of this is the combination of Boyle's and Charles' laws to create the combined gas law. Avogadro's idea and the mole concept (Chapter 2) can also be combined. According to Avogadro's theory, equal volumes of any gases at the same temperature and pressure contain an equal number of entities (usually molecules). The mole concept indicates that a mole is a specific number of entities—Avogadro's number of entities. Therefore, for all gases at a specific temperature and pressure, there must be a certain volume—the molar volume—that contains one mole of entities. **Molar volume** is the volume that one mole of a gas occupies at a specified temperature and pressure. Logically, molar volume should be the same for all gases at the same temperature and pressure. For scientific work, the most useful temperature and pressure conditions are either SATP or STP. It has been determined empirically that the molar volume of a gas at SATP is approximately 24.8 L/mol. The molar volume of a gas at STP is approximately 22.4 L/mol (**Figure 1**). Molar volume is often given the symbol V_m.

Figure 1
At STP, one mole of gas has a volume of 22.4 L, which is approximately the volume of 11 "empty" 2 L pop bottles.

Knowing the molar volume of gases allows scientists to work with easily measured volumes of gases when specific chemical amounts of gases are needed. Measuring the volume of a gas is much more convenient than measuring its mass. Imagine trapping a gas in a container and trying to measure its mass on a balance—and then making corrections for the buoyant force of the surrounding air. Also, working with gas volumes is more precise because the process involves measuring relatively large volumes rather than relatively small masses. Molar volume can be used as a conversion factor to convert chemical amount to volume, as shown in the following example.

COMMUNICATION example 1

Calculate the volume occupied by 0.024 mol of carbon dioxide gas at SATP.

Solution

$$V_{CO_2} = 0.024\ \cancel{mol} \times \frac{24.8\ L}{1\ \cancel{mol}}$$

$$= 0.60\ L$$

Using molar volume at SATP, the gas will occupy 0.60 L.

Notice how the units cancel in the example above. A molar volume can also be used to convert from a volume to a chemical amount. In this case, the molar volume ratio must be inverted to allow for the correct cancellation of units.

Learning Tip

In SI symbols, the relationship of chemical amount (n), volume (V), and molar volume (V_m) is expressed as

$$n = \frac{V}{V_m} \quad \text{or} \quad V = nV_m$$

COMMUNICATION example 2

What chemical amount of oxygen is available for a combustion reaction in a volume of 5.6 L at STP?

Solution

$$n_{O_2} = 5.6\ \cancel{L} \times \frac{1\ mol}{22.4\ \cancel{L}}$$

$$= 0.25\ mol$$

Using molar volume at STP, 0.25 mol of oxygen is available.

Gases such as oxygen and nitrogen are often liquefied for storage and transportation, and then allowed to vaporize for use in a technological application. Helium is stored and transported as a compressed gas. Both liquefied and compressed gases are sold by mass. Molar volume and molar mass can be combined to calculate the volume of gas that is available from a known mass of a substance.

Figure 2
Helium-filled balloons are popular items for parties and store promotions.

SAMPLE problem 4.3

Helium-filled balloons (**Figure 2**), often used for party decorations, are less dense than air, so they stay aloft and will rise unless tied down by a string. What volume does 3.50 g of helium gas occupy at SATP?

To answer this question, we first need to convert the mass into the chemical amount:

$$n_{He} = 3.50\ \cancel{g} \times \frac{1\ mol}{4.00\ \cancel{g}}$$
$$= 0.875\ mol$$

Now we can convert this chemical amount into a volume at SATP, using the molar volume:

$$V_{He} = 0.875\ \cancel{mol} \times \frac{24.8\ L}{1\ \cancel{mol}}$$
$$= 21.7\ L$$

Once these two steps are clearly understood, they can be combined into a single calculation, as shown below. Notice how you can plan your use of the conversion factors by planning the cancellation of the units. All units except the final unit cancel.

$$V_{He} = 3.50\ \cancel{g} \times \frac{1\ \cancel{mol}}{4.00\ \cancel{g}} \times \frac{24.8\ L}{1\ \cancel{mol}}$$
$$= 21.7\ L$$

COMMUNICATION example 3

A propane tank for a barbecue contains liquefied propane. If the tank mass drops by 9.1 kg after a month's use, what volume of propane gas at SATP was used for cooking?

Solution

$$V_{C_3H_8} = 9.1\ k\cancel{g} \times \frac{1\ \cancel{mol}}{44.11\ \cancel{g}} \times \frac{24.8\ L}{1\ \cancel{mol}}$$
$$= 5.2\ kL$$

Using molar volume at SATP, 5.2 kL of gas was used.

SUMMARY Molar Volumes

molar volume: the volume that one mole of a gas occupies at a specified temperature and pressure

$V_m = 22.4$ L/mol at STP $\qquad V_m = 24.8$ L/mol at SATP

Section 4.3 Questions

1. Describe the concept of molar volume in your own words.
2. Justify the fact that molar volume requires a specified temperature and pressure.
3. Relate the molar volume at SATP to some familiar volume.
4. Describe the similarities and differences between calculations of chemical amounts using molar masses and molar volumes.
5. Weather balloons filled with hydrogen gas are occasionally reported as UFOs. They can reach altitudes of about 40 km. What volume does 7.50 mol of hydrogen gas in a weather balloon occupy at SATP?
6. Sulfur dioxide gas is emitted from marshes, volcanoes, and refineries that process crude oil and natural gas. Calculate the chemical amount of sulfur dioxide contained in 50 mL at SATP.
7. Neon gas under low pressure and high voltage emits the red light that glows in advertising signs (**Figure 3**). Determine the volume occupied by 2.25 mol of neon gas at STP before the gas is added to neon tubes in a sign.

Figure 3
When an electric current is passed through a glass tube containing the noble gas neon, the gas glows a characteristic red colour.

8. Oxygen is released by plants during photosynthesis and is used by plants and animals during respiration. Predict the chemical amount of oxygen present in 20.0 L of air at STP. Assume that air is 20% oxygen by volume.
9. One gram of baking powder produces about 0.13 g of carbon dioxide. Predict the volume occupied by 0.13 g of carbon dioxide gas at SATP.
10. Volatile liquids vaporize rapidly from opened containers or spills. Some vapours, such as those from gasoline, contribute to the formation of smog. Calculate the volume at STP occupied by vapours from 50.0 g of spilled gasoline (assume complete vaporization of octane, $C_8H_{18}(l)$).
11. Millions of tonnes of nitrogen dioxide is dumped into the atmosphere each year by automobiles. This is a major cause of smog formation. Calculate the volume of 1.00 t (1.00 Mg) of nitrogen dioxide at SATP.
12. Water vapour plays an important role in the weather patterns on Earth. What mass of water must vaporize to produce 1.00 L of water vapour at SATP?
13. Natural gas (assume pure methane) reacts with oxygen in the air to heat most homes in Alberta. Predict the mass of oxygen gas required to react completely with 1.00 L of methane, with all gases measured at SATP.
14. Carbon dioxide is commonly used in fire extinguishers.
    (a) Determine the density (in grams per litre) of carbon dioxide at SATP (to a certainty of two significant digits).
    (b) If the density of air at SATP is 1.2 g/L, use this value and your answer to (a) to suggest one reason for the use of carbon dioxide as a fire-extinguishing agent.
    (c) State another important characteristic of carbon dioxide that makes it suitable for use in a fire extinguisher.

Extension

15. When performing calculations, we assume in this textbook that all gases behave exactly the same. You can make your own judgment on how valid this assumption is by considering the empirical values for molar volumes of selected gases (**Table 1**).

Table 1 Molar Volumes of Five Gases

Gas	Molar volume (L/mol at STP)
O_2	22.397
N_2	22.402
CO_2	22.260
H_2	22.433
NH_3	22.097

    (a) Which gas has a molar volume that differs the most from the given (rounded) value of 22.4 L/mol?
    (b) Using your knowledge of molecular properties, suggest a reason why this gas is different from the rest.

4.4 The Ideal Gas Law

Up to this point in your study of gases you have studied various laws and generalizations such as Boyle's law, Charles' law, the law of combining volumes, and molar volumes. All of these empirical properties are assumed to apply perfectly to all gases; in other words, all gases behave like an ideal gas. An **ideal gas** is a hypothetical gas that obeys all the gas laws perfectly under all conditions; that is, it does not condense into a liquid when cooled, and graphs of its volume and temperature and of pressure and temperature are perfectly straight lines (see **Figure 7** in Section 4.1).

The kinetic molecular theory (KMT) provides a good explanation of gas pressure, temperature, and the gas laws for an ideal gas. What about for real gases? **Table 1** shows the comparison between ideal and real gases in terms of the kinetic molecular theory.

DID YOU KNOW?

Ideal Concepts

The discovery that the gas laws are not perfect should come as no surprise. No scientific knowledge can perfectly describe or explain natural phenomena (the real world). Scientific knowledge is always an ideal simplification. Some scientists claim that science is *reductionist* and only works by viewing the world as something much simpler than it really is. Other scientists respond that, although this may be true, the continuing challenge in science is to get closer and closer to the truth—whatever that might be. Science in this sense is open-ended—there are many discoveries yet to be made. Some scientists are beginning to appreciate Aboriginal concepts of interconnectedness and finding relevant applications in science.

Table 1 Comparison of Ideal and Real Gases

KMT assumption for ideal gases	Interpretation for real gases
Gas molecules are very far apart compared to their size. In other words, the molecules' size is negligible.	For high pressures, the molecules are forced much closer together and their size becomes significant. In other words, the empty space available is less than the size of the container.
Gas molecules are in constant, random, straight-line motion because no forces exist between them.	As the temperature decreases, the molecules slow down. At some point, the intermolecular attractions may cause the molecules to stick together and the gas becomes a liquid.
Gas molecules undergo perfectly elastic collisions in which no energy is lost and collisions (and rebounds) occur very quickly (**Figure 1(a)**).	Molecules of a real gas are more like "soft" spheres (**Figure 1(b)**). Shape change during collision and rebound makes this process occur a little more slowly. This means that the pressure of the gas is actually a little less than ideal.

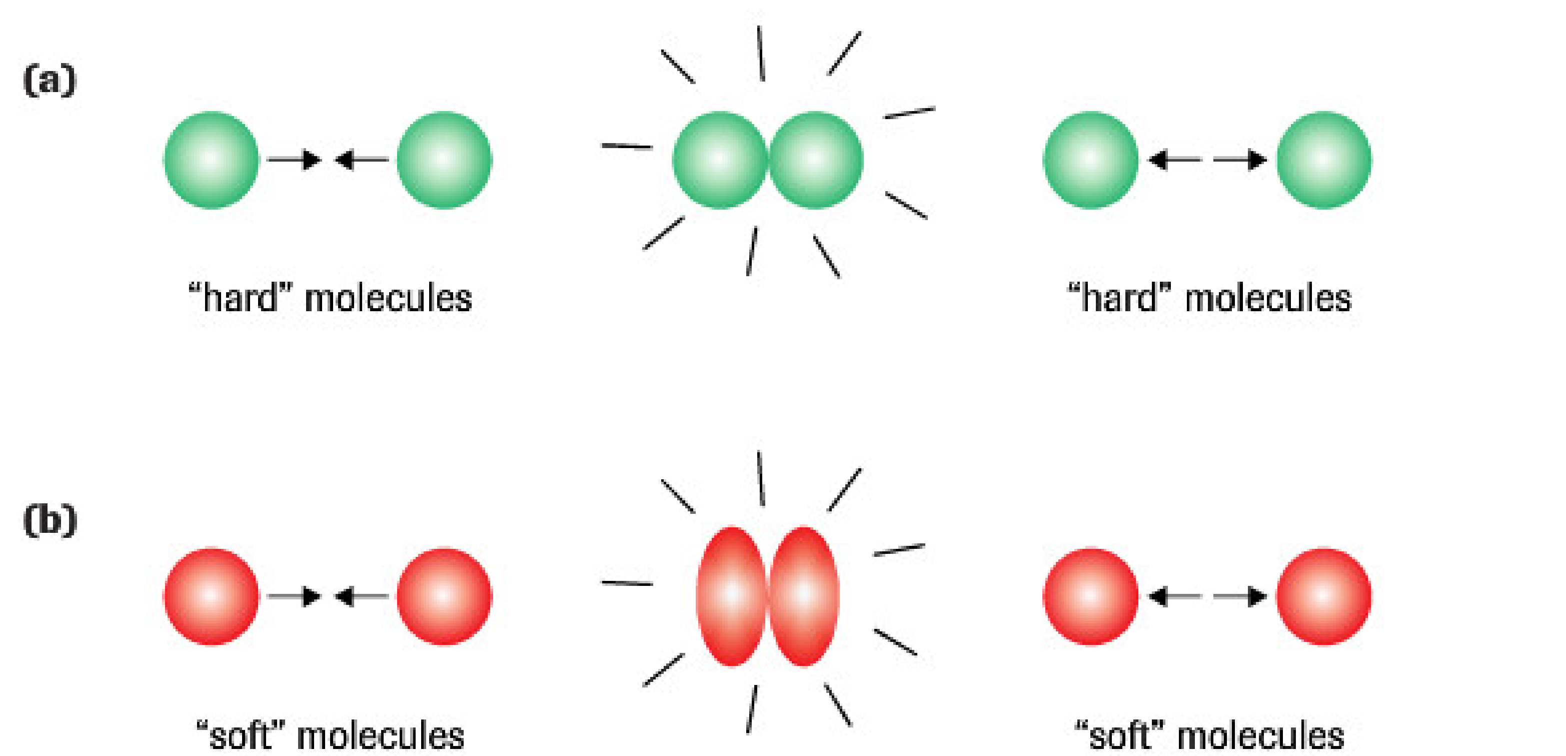

Figure 1
(a) In an ideal gas, the molecules collide like perfectly hard spheres and rebound very quickly after collision.
(b) In a real gas, the molecules are "soft" (can be deformed) and intermolecular attractions are important. The process of collision takes a slightly longer time, as a result.

There is considerable evidence to suggest that, for relatively low pressures and high temperatures such as STP and SATP conditions, real gases behave very nearly like ideal gases. It is only when the pressures become very large (>1 MPa) and the temperatures become very low (approaching the condensation point of the gas) that any differences between real and ideal become significant. In this textbook, all gases are dealt with as if they are ideal.

A single, ideal-gas equation describes the interrelationship of pressure, temperature, volume, and chemical amount of matter—the four variables that define a gaseous system.

- According to Boyle's law, the volume of a gas is inversely proportional to the pressure: $V \propto \frac{1}{P}$.
- According to Charles' law, the volume of a gas is directly proportional to the absolute temperature: $V \propto T$.
- According to Avogadro's theory, the volume of a gas is directly proportional to the chemical amount of matter: $V \propto n$.

Combining these three statements produces the following relationship:

$$V \propto \frac{1}{P} \times T \times n$$

Another way of stating this is:

$$V = (\text{a constant, } R) \times \frac{1}{P} \times T \times n$$

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

$$\boldsymbol{PV = nRT} \quad \textbf{(ideal gas law)}$$

Synthesis is a goal of science. This equation is another example in which several concepts are combined (synthesized) into one broader concept. Scientists call this concept the **ideal gas law**. The constant, R, is known as the **universal gas constant**. The value for the universal gas constant can be obtained by substituting STP (or SATP) conditions for one mole of an ideal gas into the ideal gas law and solving for R. Using more certain values for STP and the molar volume at STP,

$$R = \frac{PV}{nT}$$

$$= \frac{101.325 \text{ kPa} \times 22.414 \text{ L}}{1.000 \text{ mol} \times 273.15 \text{ K}}$$

$$= \frac{8.314 \text{ kPa}{\bullet}\text{L}}{\text{mol}{\bullet}\text{K}}$$

The value of the universal gas constant depends on the units chosen to measure volume, pressure, and temperature.

If any three of the four variables in the ideal gas law are known, the fourth can be calculated by means of the ideal gas law equation. Often, however, the mass of a gas, rather than the chemical amount, is the known quantity. In this case, a two-step calculation is required.

DID YOU KNOW?

van der Waals Forces

In 1873, Johannes van der Waals hypothesized the existence of attraction between gas molecules to explain deviations from the ideal gas law. The general forces of attraction, called van der Waals forces, include London forces and dipole–dipole forces.

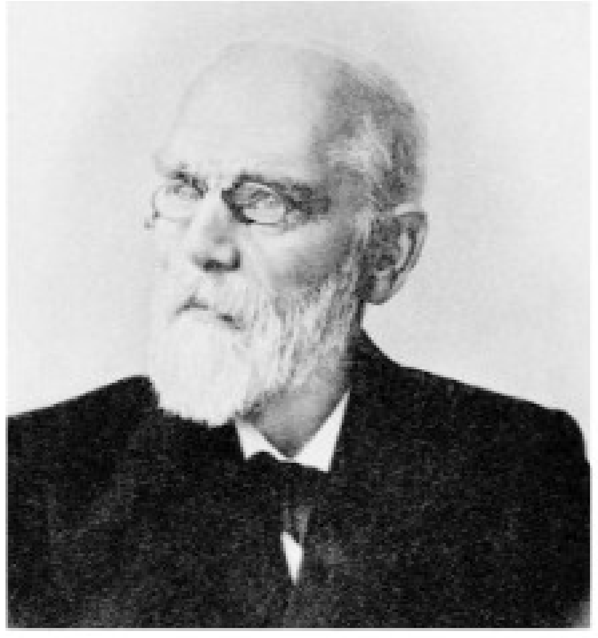

Figure 2
Johannes van der Waals (1937–1923)

WWW WEB Activity

Simulation—The Ideal Gas Law

In this simulation you can choose from a variety of different gases. By manipulating one variable—pressure, mass, or temperature—you can create graphs and observe mathematical relationships between any of these variables and volume. You can also use the values obtained to test the ideal gas law.

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SAMPLE problem 4.4

A common use of the ideal gas law is to predict volumes or masses of gases under specified conditions of temperature and pressure. For example, predict the volume occupied by 0.78 g of hydrogen at 22 °C and 125 kPa.

To use the ideal gas law, you first need to convert the mass into the chemical amount of hydrogen.

$$n_{H_2} = 0.78 \text{ g} \times \frac{1 \text{ mol}}{2.02 \text{ g}} = 0.39 \text{ mol}$$

Retain the unrounded value in your calculator for the calculation.
Now you can use the ideal gas law to determine the volume of hydrogen at the conditions specified.

$$PV = nRT$$

$$V_{H_2} = \frac{nRT}{P}$$

$$= \frac{0.39 \text{ mol} \times 8.314 \text{ kPa•L} \times 295 \text{ K}}{125 \text{ kPa} \times 1 \text{ mol•K}} = 7.6 \text{ L}$$

$$\text{or} \quad V_{H_2} = 0.78 \text{ g} \times \frac{1 \text{ mol}}{2.02 \text{ g}} \times \frac{8.314 \text{ kPa•L}}{1 \text{ mol•K}} \times \frac{295 \text{ K}}{125 \text{ kPa}} = 7.6 \text{ L}$$

Notice how the units cancel. This is a good check of your calculation.

COMMUNICATION example

What mass of argon gas (**Figure 3**) should be introduced into an evacuated 0.88 L tube to produce a pressure of 90 kPa at 30 °C?

Solution

$$PV = nRT$$

$$n_{Ar} = \frac{PV}{RT}$$

$$= \frac{90 \text{ kPa} \times 0.88 \text{ L•mol•K}}{8.314 \text{ kPa•L} \times 303 \text{ K}} = 0.031 \text{ mol}$$

$$m_{Ar} = 0.31 \text{ mol} \times \frac{39.95 \text{ g}}{1 \text{ mol}} = 1.3 \text{ g}$$

$$\text{or } m_{Ar} = 0.88 \text{ L} \times \frac{1 \text{ mol•K}}{8.314 \text{ kPa•L}} \times \frac{90 \text{ kPa}}{303 \text{ K}} \times \frac{39.95 \text{ g}}{1 \text{ mol}} = 1.3 \text{ g}$$

According to the ideal gas law, 1.3 g of argon should be used.

Figure 3
Argon has many practical uses, such as in welding, surgical lasers, and light bulbs. Argon and other noble gases are also used to produce "neon art." Argon produces a lavender colour when subjected to a high voltage. What colour does neon produce?

Practice

1. In your own words, state the three assumptions of the kinetic molecular theory for ideal gases.
2. List the previously known concepts that have been synthesized into the ideal gas law.
3. Determine the pressure in a 50 L compressed air cylinder containing 30 mol of air at a temperature of 40 °C.

4. Predict the chemical amount of methane gas present in a sample that has a volume of 500 mL at 35.0 °C and 210 kPa.
5. What volume does 50 kg of oxygen gas occupy at a pressure of 150 kPa and a temperature of 125 °C?

SUMMARY Properties of an Ideal Gas

Empirical
- V–T and P–T graphs are straight lines
- gas does not condense to a liquid when cooled
- $PV = nRT$

Theoretical
- volume (size) of molecules is negligible
- there are no forces of attraction between molecules
- collisions are elastic (no energy is lost)

EXTENSION

Collecting Gases Over Water

Extend your understanding of the gas laws with a refinement of Investigation 4.3.

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LAB EXERCISE 4.B

Evaluating an Experimental Design

Report Checklist

- ○ Purpose
- ○ Problem
- ○ Hypothesis
- ● Prediction
- ○ Design
- ○ Materials
- ○ Procedure
- ○ Evidence
- ● Analysis
- ● Evaluation (2, 1, 3)

A good test of the design of an experiment is to use it to find the value of a well-known constant. In the Evaluation, determine the percent difference in Part 2 and evaluate the Design in Part 1.

Purpose
The purpose of this experiment is to evaluate the Design by determining the value of the universal gas constant.

Problem
What is the value of the universal gas constant, R?

Design
A measured mass of oxygen gas is collected by water displacement, and the volume, temperature, and pressure of the gas are measured.

Evidence
$m = 1.27$ g $V = 1.00$ L
$P = 99.0$ kPa $t = 21$ °C

INVESTIGATION 4.3 *Introduction*

Using the Ideal Gas Law

Report Checklist

- ○ Purpose
- ○ Problem
- ○ Hypothesis
- ○ Prediction
- ○ Design
- ○ Materials
- ○ Procedure
- ● Evidence
- ● Analysis
- ● Evaluation (1, 3)

The molar mass of a compound is an important characteristic that, in some cases, can help to identify a substance. Molar masses of known compounds are obtained using accepted atomic molar masses from the periodic table.

Purpose
The purpose of this investigation is to use the ideal gas law to determine an important characteristic of an unknown substance.

Problem
What is the molar mass of an unknown gas?

Design
A sample of gas is collected in a graduated cylinder by downward displacement of water. The volume, temperature, and pressure of the gas are measured, along with the change in mass of the original container.

To perform this investigation, turn to page 179.

Section 4.4 Questions

1. Using the kinetic molecular theory, describe the three main ways that an ideal gas differs from a real gas.
2. Under what conditions does a real gas most resemble an ideal gas? Explain, using the kinetic molecular theory and intermolecular forces.
3. When sweetgrass is burned or a leaf of fresh sage is rubbed between your hands, the fragrance is immediately obvious. Write a theoretical explanation for these observations.
4. Unlike an ideal gas, a real gas condenses to a liquid when the temperature is low enough. What does this indicate about the interaction between the molecules and why the gas is real versus ideal?
5. When an air bag is activated in a collision, sodium azide rapidly decomposes to produce nitrogen gas. Chemical engineers carefully choose the quantity of sodium azide to produce the required chemical amount of nitrogen gas. Use the ideal gas law to predict the chemical amount of nitrogen gas required to fill a 60 L air bag at a pressure of 233 kPa and a temperature of 25 °C.
6. At what temperature does 10.5 g of ammonia gas exert a pressure of 85.0 kPa in a 30.0 L container?
7. Use the ideal gas law to determine three ways to reduce the volume of gas in the shock absorber (cylinder and piston) of an automobile.
8. Use the ideal gas law and the molar volume at STP to calculate a value for the universal gas constant using units of atmospheres (atm) instead of kilopascals (kPa).
9. A 1.49 g sample of a pure gas occupies a volume of 981 mL at 42.0 °C and 117 kPa.
   (a) Determine the molar mass of the compound.
   (b) If the chemical formula is known to be XH_3, identify the element "X."
10. What is the volume of an ideal gas at STP and at SATP? What is the main reason that these values differ? Justify your answer with suitable calculations.
11. The density of a gas is the mass per unit volume of the gas in units of, for example, grams per litre. By finding the mass of one litre (assume 1.00 L) of gas, you can then calculate the density of the gas. Knowledge of the densities of gases compared with the density of air (at 1.2 g/L) can save your life.
    (a) What is the density of carbon monoxide gas at 20 °C and 98 kPa in a home?
    (b) Using your answer to (a), where should a carbon monoxide detector be located, close to the floor or close to the ceiling?
    (c) If potentially lethal carbon dioxide comes from a fire and carbon monoxide comes from a furnace, what other variable might affect the densities of these gases released within a home?
    (d) What is the density of propane, $C_3H_8(g)$, at 22 °C and 96.7 kPa?
    (e) If the density of air at 20 °C is 1.2 g/L, what happens to propane gas that may leak from a propane cylinder in a basement or from the tank of an automobile in an underground parkade? Why is this a problem?
12. A hot-air balloon rises up through the air because the density of the air inside the balloon is less than the density of the outside air. Using the ideal gas law, describe how this occurs.
13. Skiing in the back country can be very dangerous because of the possibility of being buried alive in an avalanche. Some enterprising people have come up with an avalanche air bag (**Figure 4**) to save lives. How does it work? Describe, in steps, how you would calculate how much nitrogen gas is required in the canister.

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Figure 4
This avalanche air bag system is normally contained in a lightweight backpack while skiing. It only inflates when the skier is caught in an avalanche and pulls the emergency cord.

Extension

14. Alberta produces about 80% of the natural gas produced in Canada and exports about three quarters of its production, mostly to the United States. Scientists and engineers are developing the technology to obtain maximum benefit from this natural resource. Their work requires that they understand the science of gases.
    (a) Natural gas, from gas wells drilled into pockets of gas far underground, is a mixture of gases. List the main gases present.
    (b) Which non-hydrocarbon impurities are removed first?
    (c) Which hydrocarbon gases are typically found along with methane? Why is it important to understand real and ideal gases in order to remove these gases?
    (d) What are NGLs? List some important products made from NGLs.

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INVESTIGATION 4.1

Pressure and Volume of a Gas

This investigation is a replication of a famous experiment first done by Robert Boyle in 1662. Write your Design using the information given, and remember to include a plan and identify the variables. Include a graph and a word statement describing the relationship as part of your Analysis.

Report Checklist

- ○ Purpose
- ○ Problem
- ○ Hypothesis
- ○ Prediction
- ● Design
- ○ Materials
- ○ Procedure
- ● Evidence
- ● Analysis
- ○ Evaluation

Purpose
The purpose of this investigation is to create a general relationship between the pressure and volume of a gas.

Problem
What effect does increasing the pressure have on the volume of a gas?

Materials
eye protection
Boyle's law apparatus or 35 mL plastic syringe
large rubber stopper or support block
cork borer
5 textbooks or equal masses (1 kg)

Procedure
1. Pull out the syringe plunger so that 30 mL of air is inside the cylinder.
2. If a syringe cap is not provided, bore a small hole in the rubber stopper deep enough so that the tip of the syringe fits tightly inside the stopper. Make sure that the tip of the syringe does not leak.
3. Hold the syringe barrel vertical, and measure the initial volume of air in the syringe.
4. While holding the syringe securely, carefully place one textbook or mass on the end of the plunger (**Figure 1**). (Your partner should balance the mass and be prepared to catch it if it starts to tilt.)
5. Record the mass placed on the syringe and the new volume of air.
6. Repeat steps 4 and 5 for a total of 4 or 5 books or masses.

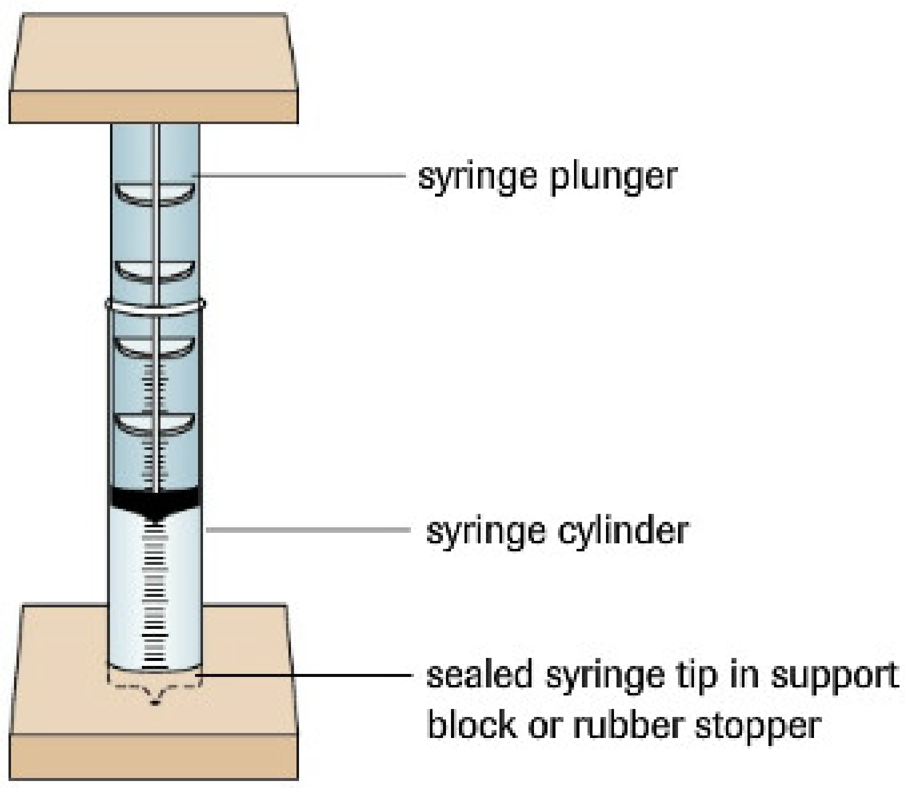

Figure 1
Setup of apparatus for Investigation 4.1

INVESTIGATION 4.2

Report Checklist

- ○ Purpose
- ○ Problem
- ○ Hypothesis
- ○ Prediction
- ○ Design
- ○ Materials
- ○ Procedure
- ● Evidence
- ● Analysis
- ● Evaluation (1, 3)

Temperature and Volume of a Gas

This investigation, like Investigation 4.1, is a controlled experiment in which all variables are kept constant except the two variables being investigated, in this case temperature and volume. Include a graph and a word statement describing the relationship as part of your Analysis. In your Evaluation, pay particular attention to the sources of experimental uncertainties.

Purpose

The purpose of this investigation is to create a general relationship between the temperature and volume of a gas.

Problem

What effect does increasing the temperature have on the volume of a gas?

Design

A volume of air is sealed inside a syringe, which is then placed in a water bath. As the temperature of the air is manipulated, the volume of air inside the syringe is measured as the responding variable. Two controlled variables are the chemical amount of gas inside the syringe and the pressure of the gas.

Materials

lab apron
eye protection
plastic syringe (35–60 mL)
cap or stopper for the syringe tip
burette clamp
thermometer or temperature probe and clamp
600 mL beaker
ring stand
hot plate
stirring rod
boiling stones or chips

Heat the water slowly, and make sure that the tested gas in the syringe does not eject the plunger. Wear eye protection.

Procedure

1. Set the syringe plunger to about 15–20 mL of air.
2. Seal the tip of the syringe with a cap or stopper.
3. Set up the ring stand with the 600 mL beaker on the hot plate (**Figure 2**).
4. Use the burette clamp to hold the syringe as far as possible into the beaker without touching the sides or bottom.
5. Clamp the thermometer or probe so that the bulb is close to, but not touching, the syringe.
6. Add water at room temperature to about 1 cm from the top of the beaker. Drop in a few boiling stones.
7. After a few minutes, record the temperature and volume of air. (See Appendix F.3 for a note on precision when reading a thermometer.)
8. Turn on the hot plate. Heat the water slowly, stirring occasionally.
9. Record the gas volume and temperature about every 10 °C until about 90 °C. (It may be necessary to tap or twist the plunger occasionally to make sure that it is not stuck.)

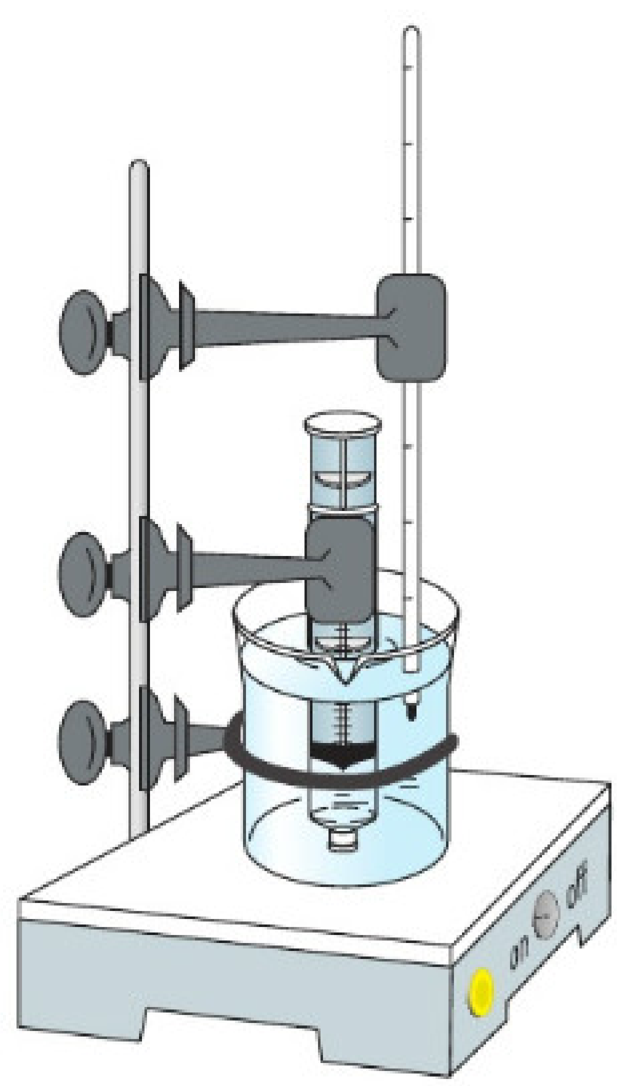

Figure 2
Setup of apparatus for Investigation 4.2

INVESTIGATION 4.3

Using the Ideal Gas Law

The molar mass of a pure substance is an important characteristic that, in some cases, can help to identify the substance. Molar masses of known compounds are obtained using accepted atomic molar masses from the periodic table.

Report Checklist

- ○ Purpose
- ○ Problem
- ○ Hypothesis
- ○ Prediction
- ○ Design
- ○ Materials
- ○ Procedure
- ● Evidence
- ● Analysis
- ● Evaluation (1, 3)

Purpose

The purpose of this investigation is to use the ideal gas law to determine an important characteristic of an unknown substance.

Problem

What is the molar mass of an unknown gas?

Design

A sample of gas is collected in a graduated cylinder by downward displacement of water (**Figure 3**). The volume, temperature, and pressure of the gas are measured, along with the change in mass of the original container.

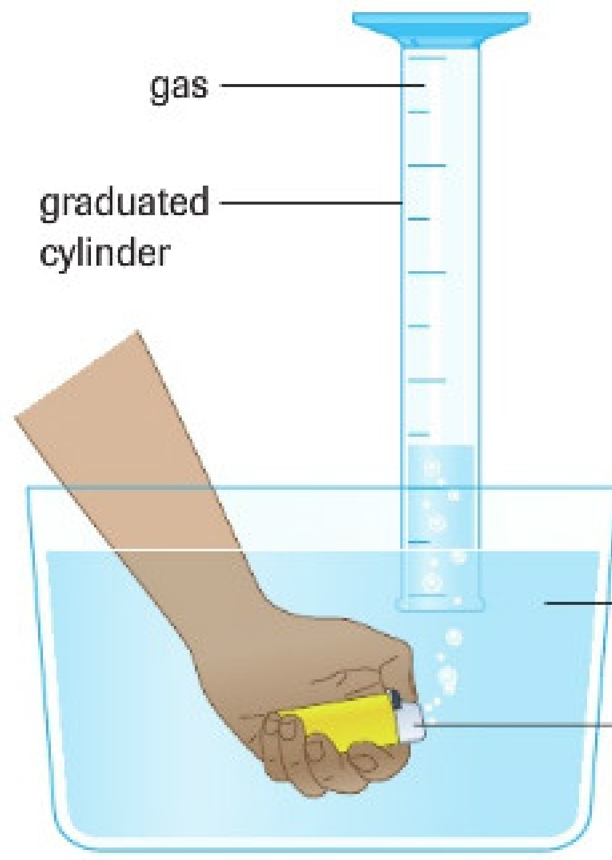

Figure 3
The gas can be collected by downward displacement of water.

Materials

lab apron
eye protection
lighter (with flint removed) or cylinder of unknown gas, with tubing
plastic bucket (approx. 4 L)
500 mL graduated cylinder or 600 mL graduated beaker
balance
thermometer or temperature probe
barometer

The gas used may be flammable. Work in a well-ventilated area. Keep away from sparks and flames.

Procedure

1. Determine the initial mass of the lighter or gas canister.
2. Pour water into the bucket until it is two-thirds full. Completely fill the graduated cylinder with water and invert it in the bucket (**Figure 3**). Ensure that no air has been trapped in the cylinder.
3. Hold the lighter or tubing from the gas canister in the water and under the cylinder. Release the gas until you have collected 400 to 500 mL of gas. Make sure that all the bubbles enter the cylinder.
4. Equalize the pressures inside and outside the cylinder by adjusting the position of the cylinder until the water levels inside and outside the cylinder are the same.
5. Read the measurement on the cylinder, and record the volume of gas collected.
6. Record the ambient (room) temperature and pressure.
7. Dry the lighter or gas canister (if necessary), and determine its final mass.
8. Release the gas from the cylinder in a fume hood or outdoors.

Outcomes

Knowledge

- express atmospheric pressure in a variety of ways, including units of mm Hg, atm, and kPa (4.1)
- convert between the Celsius and absolute (kelvin) temperature scales (4.1, 4.4)
- describe and compare the behaviour of real and ideal gases in terms of kinetic molecular theory (4.2, 4.4)
- explain the law of combining volumes (4.2)
- illustrate how Boyle's, Charles', and combined gas laws are related to the ideal gas law (4.4)
- perform calculations based on the ideal gas law under STP, SATP, and other conditions (4.4)

STS

- identify and use a scientific problem-solving model (all sections)
- state that the goal of science is knowledge about the natural world (all sections)

Skills

- initiating and planning: state hypotheses and make predictions related to the pressure, temperature, and volume of a gas (4.1, 4.4); describe procedures for safe use and disposal of laboratory materials (4.1, 4.4)
- performing and recording: perform laboratory and simulated experiments to illustrate the gas laws, identifying and controlling variables (4.1, 4.4); use thermometers, balances, and other measuring devices to collect data on gases (4.1, 4.4); use research tools to collect information about real and ideal gases and applications of gases (all sections); perform an investigation to determine the molar mass from gaseous volume (4.4)
- analyzing and interpreting: draw and interpret graphs of experimental evidence that relate pressure and temperature to gas volume (4.1); identify the limitations of measurement (4.1, 4.4); identify a gas based on an analysis of experimental evidence (4.4)
- communication and teamwork: use appropriate SI notation and certainty in significant digits (all sections); work collaboratively and communicate effectively (all sections)

Key Terms

4.1

pressure

atmospheric pressure

STP

SATP

Boyle's law

absolute zero

absolute temperature scale

Charles' law

combined gas law

4.2

law of combining volumes

Avogadro's theory

4.3

molar volume

4.4

ideal gas

ideal gas law

universal gas constant

Key Equations

Boyle's law: $P_1V_1 = P_2V_2$ (4.1)

Charles' law: $\frac{V_1}{T_1} = \frac{V_2}{T_2}$ (4.1)

Combined gas law: $\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$ (4.1)

$T\,(\text{K}) = t\,(°\text{C}) + 273$ (4.1)

Ideas gas law: $PV = nRT$ (4.4)

MAKE a summary

1. Prepare a concept map for this topic. One suggested organization is:
   1st level: Gas
   2nd level: empirical, theoretical
   3rd level: qualitative properties; quantitative properties (with graph sketches); real and ideal gases (with an explanation); law of combining volumes (with an explanation)
   additional levels: (complete details)
2. Revisit your answers to the Starting Points questions at the beginnng of this chapter. How would you answer the questions differently now? Why?

Go To

Go to myNelson.com

The following components are available on the Nelson Web site. Follow the links for *Nelson Chemistry Alberta 20–30*.

- an interactive Self Quiz for Chapter 4
- additional Diploma Exam-style Review questions
- Illustrated Glossary
- additional IB-related material

There is more information on the Web site wherever you see the Go icon in this chapter.

EXTENSION

CBC radio ONE QUIRKS & QUARKS

Kettle Call

Why does the noise in a kettle increase in volume until just before the boiling point and then go silent for a brief time? Dr. Ron Kydd, from the University of Calgary, suggests that collapsing bubbles may be the cause.

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Many of these questions are in the style of the Diploma Exam. You will find guidance for writing Diploma Exams in Appendix H. Exam study tips and test-taking suggestions are on the Nelson Web site. Science Directing Words used in Diploma Exams are in bold type.

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DO NOT WRITE IN THIS TEXTBOOK.

Part 1

1. Which one of the following is **not** a physical property of a gas?
A. is incompressible
B. flows easily
C. assumes the shape of the container
D. assumes the volume of the container

Use this information to answer questions 2 and 3.

Atmospheric pressure is an important variable for describing and explaining weather patterns and for predicting future weather. At sea level, the average atmospheric pressure is about 101 kPa.

2. Atmospheric pressure is defined as
A. the weight of air
B. the force exerted by air on all objects
C. the force per unit area exerted by air on all objects
D. the height of a column of mercury in a long, narrow tube

3. Average atmospheric pressure at sea level is approximately equal to
A. 0.1 Pa
B. 1 atm
C. 76 mm Hg
D. 101 atm

4. NR Based on many measurements, the normal body temperature of a human is about 37 °C. This corresponds to an absolute temperature of _______ K.

5. NR A bicycle pump contains 250 mL of air at a pressure of 102 kPa. If the pump is closed and the pressure increases to 210 kPa, the new volume becomes _______ mL.

6. NR A party balloon containing 3.5 L of air is taken from inside a house at 22 °C to the outdoors where the temperature is −15 °C. The new volume of the balloon is _______ L.

7. Under what conditions is a real gas most similar to an ideal gas?
A. low temperature and low pressure
B. low temperature and high pressure
C. high temperature and high pressure
D. high temperature and low pressure

8. According to the kinetic molecular theory, an ideal gas has all of the following characteristics *except*
A. molecules of zero or insignificant size
B. molecules that attract each other
C. molecules that move randomly
D. molecules that are widely separated

Use this information to answer questions 9 to 11.

The empirical study of gases provided a number of laws that formed the basis for important developments in chemistry such as atomic theory and the mole concept.

Statements

1. The volume of a gas varies inversely with the pressure on the gas.
2. Volumes of reacting gases are always in simple, whole number ratios.
3. The volume of a gas varies directly with the absolute temperature of the gas.
4. The volume of a gas varies directly with the absolute temperature and inversely with the pressure.

9. NR The statements that correspond to Boyle's law, Charles' law, the combined gas law, and the law of combining volumes are, respectively, __, __, __, and __.

10. Which statements require that the temperature be a controlled variable?
A. 1, 2, 3, and 4
B. 1, 3, and 4 only
C. 1 and 2 only
D. 3 and 4 only

11. Identify the statement that is best explained by Avogadro's theory.
A. 1
B. 2
C. 3
D. 4

12. NR A Chinook is a warm, dry winter wind that causes a rapid change in the weather in southern Alberta. The final volume of a cubic metre (1.00 kL) of air at −23 °C and 102 kPa when the conditions change to 12 °C and 96 kPa is predicted to be ________ kL.

Use this information to answer questions 13 to 15.

Disastrous explosions have resulted from the unsafe storage and handling of the fertilizer, ammonium nitrate, which can decompose rapidly according to the following unbalanced chemical equation.

$$\_\_ NH_4NO_3(s) \rightarrow \_\_ N_2(g) + \_\_ H_2O(g) + \_\_ O_2(g)$$

13. NR The simplest, whole-number coefficients to balance this chemical equation are, in order, __, __, __, and __.

14. According to Avogadro's theory, the ratio of the coefficients of the gaseous products represents the relative quantities of

A. molecules
B. masses
C. volumes
D. pressures

15. NR If 49.6 L of water vapour is produced, the volume of oxygen gas produced at the same temperature and pressure is _____ L.

16. Argon gas is an inert gas that moves other gases through a research or industrial system. The volume occupied by 4.2 kg of argon gas at SATP is

A. 4.2 L
B. 1.3 kL
C. 2.4 kL
D. 2.6 kL

17. Large quantities of chlorine gas are produced from salt to make bleach and treat water. The chemical amount of chlorine in 170 L of gas at 35 °C and 400 kPa is

A. 13.3 mol
B. 26.6 mol
C. 37.6 mol
D. 234 mol

Part 2

18. Convert each of the following temperatures into absolute temperatures in kelvin.

(a) freezing point of water
(b) 21 °C (room temperature)
(c) absolute zero

19. Convert the following gas pressures to units of pascals:

(a) A bike tire is pumped up to a pressure of 4.00 atm.
(b) During manufacture, light bulbs are filled with argon to a pressure of 763 mm Hg.
(c) Ammonia is produced in a reaction vessel at a pressure of 450 atm.

20. Convert each of the following gas volumes into a chemical amount.

(a) 5.1 L of carbon monoxide gas at SATP
(b) 20.7 mL of fluorine gas at STP

21. Calculate the volume at SATP, of each of the following chemical amounts of gas.

(a) 500 mol of hydrogen (most common element in the universe)
(b) 56 kmol of hydrogen sulfide (a toxin found in sour natural gas)

22. State each of the following laws in a sentence beginning "The volume of a gas sample ..."

(a) Boyle's law
(b) Charles' law
(c) the ideal gas law

23. **Compare** a law and a theory. Use Charles' law and the kinetic molecular theory to support your answer.

24. Avogadro's idea is sometimes called a principle, a hypothesis, a law, or a theory. Is Avogadro's idea empirical or theoretical? **Explain** your answer.

25. **Describe** and **compare** the behaviour of real and ideal gases in terms of the kinetic molecular theory and intermolecular forces at

(a) low temperature and high pressure
(b) high temperature and low pressure

26. Pressurized hydrogen gas is used to fuel some prototype automobiles. **Determine** the new volume of a 28.8 L sample of hydrogen for which the pressure is increased from 100 kPa to 350 kPa? State the assumptions that you need to make in order to answer this question.

27. A student buys a 4.0 L party balloon in a store where the inside temperature is 23 °C. Outside, the balloon shrinks to 3.5 L. **Predict** the outside temperature in Celsius.

28. In an industrial process, bromine is produced by reacting chlorine with bromide ions in seawater. **Determine** what chemical amount of bromine is present in an 18.8 L sample of bromine gas at 60 kPa and 140 °C.

29. A 5.00 L balloon contains helium at SATP at ground level. **Predict** the balloon's volume when it floats to an altitude where the temperature is −15 °C and the atmospheric pressure is 91.5 kPa.

30. Before Boyle's and Charles' initial hypotheses became laws, their experiments had to be replicated by other scientists. For each of Boyle's and Charles' experiments, write a Problem statement in terms of variables and write a general Design including the identification of manipulated, responding, and important controlled variables.

31. Improper automobile tire inflation is one of the leading DE causes of tire failure. Manufacturers recommend that tire pressure be checked once a month. The recommended tire pressure for a particular vehicle is printed on a sticker (**Figure 1**) that is often attached to the driver-side door jamb or in the glove compartment. You should never use the pressure printed on the outside of the tire. This pressure is the maximum tire pressure from the tire manufacturer and is not the pressure recommended for a particular vehicle.

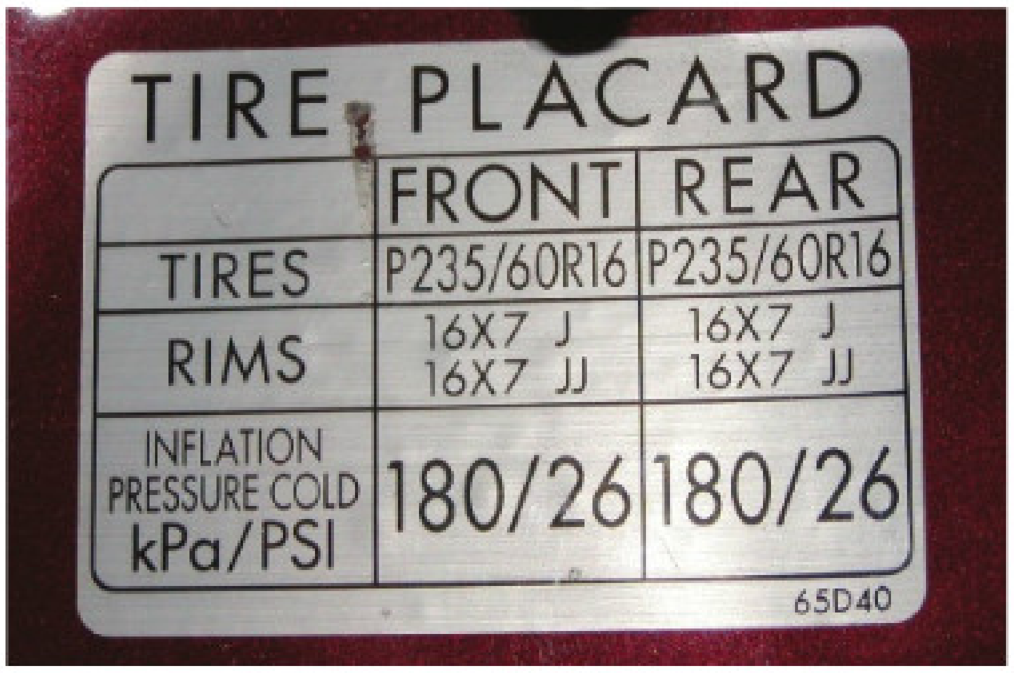

Figure 1
An example of a tire pressure sticker found on a vehicle

(a) Convert the recommended cold tire pressure (Figure 1) from units of kilopascals to atmospheres.
(b) Assuming a "cold" temperature of 15 °C and a constant volume, **predict** the tire pressure if the temperature is 40 °C.
(c) **Explain** your answer to (b) using the kinetic molecular theory.
(d) Manufacturers recommend that tire pressure be checked when the tires are cold (i.e., not driven for several hours). Suggest a problem that may occur if the tire pressure is adjusted to the recommended value when the tires are very hot after driving for a long time.

32. A particular glass container can hold an internal pressure of only 195 kPa before breaking. The container is filled with a gas at 19.5 °C and 96.7 kPa and then heated. **Predict** the temperature at which the container will break.

33. Electrical power plants commonly use steam to drive DE turbines, producing mechanical energy from the pressure of the steam. The rotating turbine is connected to a generator that produces electricity. Steam enters a turbine at a high temperature and pressure and exits, still a gas, at a lower temperature and pressure.
(a) **Determine** the final pressure of steam that is converted from 10.0 kL at 600 kPa and 150 °C to 18.0 kL at 110 °C.
(b) **Determine** the mass of steam that has gone through the turbine.

34. On summer afternoons, warm air masses often rise rapidly DE through the atmosphere, creating cumulus clouds or, sometimes, cumulonimbus (thunderstorm) clouds (**Figure 2**). Use the kinetic molecular theory to **explain** this rising of the warm air mass.

Figure 2
Cumulus clouds

35. During the production of nitric acid, ammonia reacts with DE oxygen to produce nitrogen monoxide:

$$4\ NH_3(g) + 5\ O_2(g) \rightarrow 4\ NO(g) + 6\ H_2O(g)$$

(a) Calculate the volumes of ammonia and oxygen required to produce 1.00 L of nitrogen monoxide. All gases are measured at the same temperature and pressure.
(b) Use Avogadro's theory to **explain** the relationship used to calculate the volumes in (a).

36. Yeast cells in bread dough convert glucose into either DE carbon dioxide and water or carbon dioxide and ethanol, as shown in the following chemical equations:

$$C_6H_{12}O_6(aq) + 6\ O_2(g) \rightarrow 6\ CO_2(g) + 6\ H_2O(l)$$

$$C_6H_{12}O_6(aq) \rightarrow 2\ CO_2(g) + 2\ C_2H_5OH(l)$$

(a) Use the law of combining volumes to **predict** the volume of carbon dioxide produced when 50 mL of oxygen gas reacts with excess glucose.
(b) For equal chemical amounts of glucose reacted, which of the two reactions will produce the greater degree of leavening (rising due to gas formation)? **Justify** your answer.

37. Suppose that you were trapped in a room in which there was a slow natural gas leak (assume pure methane). In order to breathe as little natural gas as possible, should you be near the ceiling or the floor? Use the molar volume at SATP to calculate the densities of methane and nitrogen to **justify** your answer.

38. One of the most common uses of carbon dioxide gas is carbonating beverages, such as soft drinks.
   (a) Squeezing a plastic bottle increases the pressure inside the bottle. What is the new volume of a 300 mL sample of carbon dioxide gas when the pressure doubles?
   (b) A carbonated drink contains pressurized carbon dioxide gas above the liquid. In addition to the usual factors such as temperature and pressure that affect the volume of a gas, what other variable is important?
   (c) **Explain** why a can of carbonated pop sometimes overflows when opened.

39. An investigation was conducted to determine the relationship between the pressure and solubility of nitrogen in water.

DE

Purpose
The purpose of this investigation is to create a possible relationship between two variables.

Problem
What effect does the pressure of nitrogen gas have on its solubility in water at a fixed temperature?

Evidence

Table 1 Solubility of Nitrogen Gas in Water at 25 °C

Pressure (kPa)	Solubility (mmol/L)
50	0.33
100	0.67
150	1.04
200	1.35
250	1.61
300	1.98

   (a) Complete the Analysis, including a graph.
   (b) From the graph, **infer** the chemical amount of nitrogen gas that could dissolve at 225 kPa in 5.00 L of blood (assume mostly water) in a scuba diver.
   (c) Calculate the volume of nitrogen gas that would come out of 5.00 L of solution at 100 kPa if the diver had been submerged at 300 kPa and surfaced too quickly.
   (d) **Describe** briefly how knowledge of gas properties is important for scuba diving.

40. Hydrochlorofluorocarbons (HCFCs) are being used to replace chlorofluorocarbons (CFCs) because HCFCs are believed to do less damage to the ozone layer. The purpose of the following investigation is to use molar mass to identify an HCFC gas. Complete the Analysis section of the following report.

Purpose
The purpose of this investigation is to use gas concepts in a chemical analysis.

Problem
Is the HCFC sample tested $CHF_2Cl(g)$, $C_2H_3FCl_2(g)$, or $C_2H_3F_2Cl(g)$?

Design
A sample of an HCFC from a canister of the compressed gas is collected in a graduated cylinder by the downward displacement of water (**Figure 3**). The volume, temperature, and pressure of the gas are measured, along with the change in mass of the gas canister. Assume that the HCFC is not soluble in water.

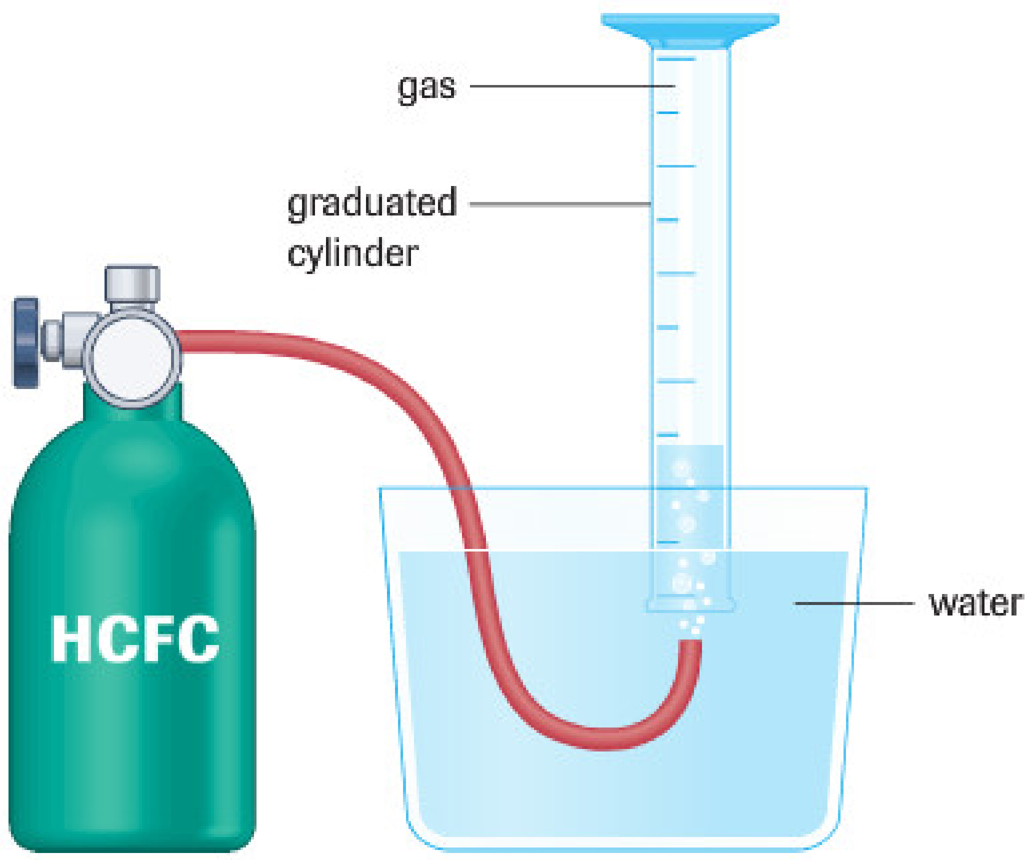

Figure 3
Collection of a known mass of HCFC

Evidence
initial mass of canister = 457.64 g
atmospheric pressure = 100.1 kPa
final mass of canister = 454.26 g
ambient temperature = 22.0 °C
volume = 840 mL

41. **Design** an experiment to test one of the gas laws. Assume that you have only everyday materials available to you, such as a pump, a pressure gauge, a balloon, a pail, hot and cold water, a measuring cup, a tape measure, and an outdoor alcohol thermometer. Complete the following categories: Problem, Prediction, Design, Materials (including sketch of the apparatus), Procedure, and outline the steps required for the Analysis.

42. A temperature inversion is a weather pattern that can trap polluted air near ground level. **Describe** the circumstances and the process by which the polluted air becomes trapped.

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43. Review the focusing questions on page 142. Using the knowledge you have gained from this unit, briefly **outline** a response to each of these questions.

Extension

44. Research how gases are used in both medical anaesthetics and undersea exploration. Choose one application for each, and prepare a two-paragraph description of this application.

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45. There are many examples in science where new ideas are immediately rejected (without any of the usual testing) because they do not fit within the existing theories and beliefs of the scientific community. One example is the explanation of gas pressure by Daniel Bernoulli in 1738—about sixty years before Dalton's atomic theory and over a hundred years before emergence of the kinetic molecular theory. **Summarize** Bernoulli's hypothesis. Why was this idea not widely accepted? What does this example illustrate about the nature of science?

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46. The Bermuda Triangle has claimed many boats and planes (**Figure 4**). One hypothesis is that large volumes of natural gas released from the ocean floor may cause the boats to sink and the planes to drop.
    (a) **Explain** why boats might sink.
    (b) **Explain** why planes might drop.
    (c) Use the Internet to research the Bermuda Triangle. Which explanation for the losses seems most reasonable to you? Defend your choice in a brief report.

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Figure 4
The Bermuda Triangle