Section 1

States of Matter

Reading Preview

Key Concepts

- What are the characteristics of a solid?
- What are the characteristics of a liquid?
- What are the characteristics of a gas?

Key Terms

- solid • crystalline solid
- amorphous solid • liquid
- fluid • surface tension
- viscosity • gas

Target Reading Skill

Building Vocabulary A definition states the meaning of a word or phrase by telling about its most important feature or function. After you read the section, reread the paragraphs that contain definitions of Key Terms. Use all the information you have learned to write a definition of each Key Term in your own words.

Lab zone **Discover Activity**

What Are Solids, Liquids, and Gases?

1. Break an antacid tablet (fizzing type) into three or four pieces. Place them inside a large, uninflated balloon.
2. Fill a 1-liter plastic bottle about halfway with water. Stretch the mouth of the balloon over the top of the bottle, taking care to keep the tablet pieces inside the balloon.
3. Jiggle the balloon so that the pieces fall into the bottle. Observe what happens for about two minutes.
4. Remove the balloon and examine its contents.

Think It Over

Forming Operational Definitions Identify examples of the different states of matter—solids, liquids, and gases—that you observed in this activity. Define each of the three states in your own words.

It's a bitter cold January afternoon. You are practicing ice hockey moves on a frozen pond. Relaxing later, you close your eyes and recall the pond in July, when you and your friends jumped into the refreshing water on a scorching hot day. Was the water in July made of the same water you skated on this afternoon? Perhaps, but you're absolutely certain that solid water and liquid water do not look or feel the same. Just imagine trying to swim in an ice-covered pond in January or play hockey on liquid water in July!

FIGURE 1
A Wintry Solid
As a solid, water makes a great surface for ice hockey.
Observing *What useful property does the frozen water have here?*

Your everyday world is full of substances that can be classified as solids, liquids, or gases. (You will read about a less familiar form of matter, called plasma, elsewhere.) Solids, liquids, and gases may be elements, compounds, or mixtures. Gold is an element. Water is a compound you've seen as both a solid and a liquid. Air is a mixture of gases. Although it's easy to list examples of these three states of matter, defining them is more difficult. To define solids, liquids, and gases, you need to examine their properties. The familiar states of matter are defined not by what they are made of but mainly by whether or not they hold their volume and shape.

Solids

What would happen if you were to pick up a solid object, such as a pen or a comb, and move it from place to place around the room? What would you observe? Would the object ever change in size or shape as you moved it? Would a pen become larger if you put it in a bowl? Would a comb become flatter if you placed it on a tabletop? Of course not. A **solid** has a definite shape and a definite volume. If your pen has a cylindrical shape and a volume of 6 cubic centimeters, then it will keep that shape and volume in any position and in any container.

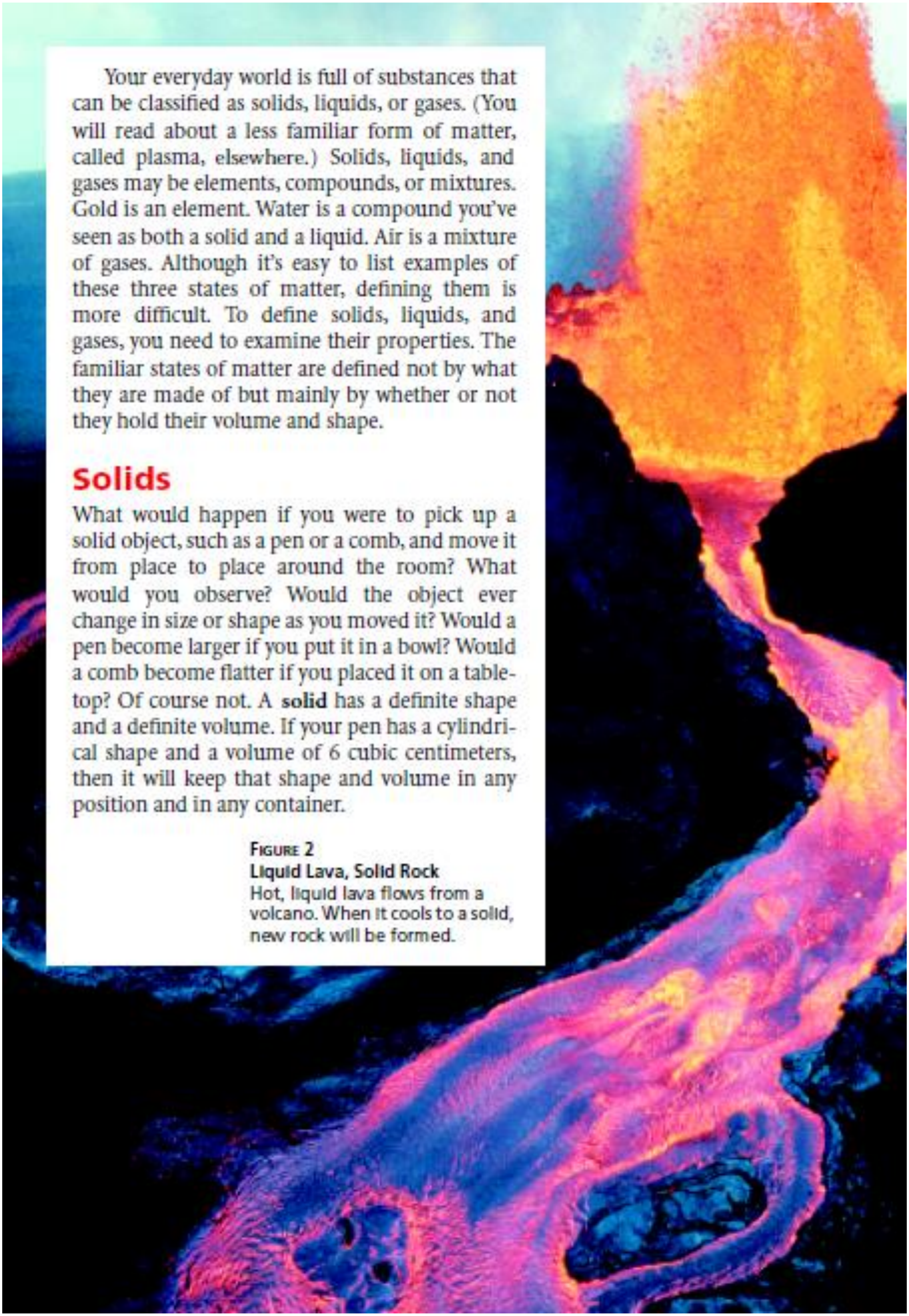


FIGURE 2
Liquid Lava, Solid Rock
Hot, liquid lava flows from a volcano. When it cools to a solid, new rock will be formed.

Figure 3
Behavior of Solid Particles
Particles of a solid vibrate back and forth but stay in place.

Particles in a Solid The particles that make up a solid are packed very closely together. In addition, each particle is tightly fixed in one position. **This fixed, closely packed arrangement of particles causes a solid to have a definite shape and volume.**

Are the particles in a solid completely motionless? No, not really. The particles vibrate, meaning that they move back and forth slightly. This motion is similar to a group of people running in place. The particles that make up a solid stay in about the same position, but they vibrate in place.

Types of Solids In many solids, the particles form a regular, repeating pattern. These patterns create crystals. Solids that are made up of crystals are called **crystalline solids** (KRIS tuh lin). Salt, sugar, and snow are examples of crystalline solids. When a crystalline solid is heated, it melts at a specific temperature.

In **amorphous solids** (uh MAWR fus), the particles are not arranged in a regular pattern. Plastics, rubber, and glass are amorphous solids. Unlike a crystalline solid, an amorphous solid does not melt at a distinct temperature. Instead, it may become softer and softer or change into other substances.

Reading Checkpoint How do crystalline and amorphous solids differ?

Figure 4
Types of Solids
Solids are either crystalline or amorphous.

◀ Quartz is a crystalline solid. Its particles are arranged in a regular pattern.

◀ Butter is an amorphous solid. Its particles are not arranged in a regular pattern.

Liquids

A **liquid** has a definite volume but no shape of its own. Without a container, a liquid spreads into a wide, shallow puddle. Like a solid, however, a liquid does have a constant volume. If you gently tried to squeeze a water-filled plastic bag, for example, the water might change shape, but its volume would not decrease or increase. Suppose that you have 100 milliliters of milk in a pitcher. If you pour it into a tall glass, you still have 100 milliliters. The milk has the same volume no matter what shape its container has.

Particles in a Liquid In general, the particles in a liquid are packed almost as closely as in a solid. However, the particles in a liquid move around one another freely. You can compare this movement to the way you might move a group of marbles around in your hand. In this comparison, the solid marbles serve as models for the particles of a liquid. The marbles slide around one another but stay in contact. **Because its particles are free to move, a liquid has no definite shape. However, it does have a definite volume.** These freely moving particles allow a liquid to flow from place to place. For this reason, a liquid is also called a **fluid,** meaning "a substance that flows."

FIGURE 5
Equivalent Volumes
A liquid takes the shape of its container but its volume does not change.

FIGURE 6
Behavior of Liquid Particles
Particles in a liquid are packed close together but move freely, allowing liquids to flow.
Comparing and Contrasting *How are liquids and solids alike? How do they differ?*

FIGURE 7
Surface Tension
Water beads up on a leaf due to attractions between the water molecules. Surface tension in water is strong enough to support the weight of an insect.

Lab zone **Try This Activity**

As Thick as Honey

You can compare the viscosity of two liquids.

1. Place on a table a clear plastic jar almost filled with honey and another clear plastic jar almost filled with vegetable oil. Make sure that the tops of both jars are tightly closed.
2. Turn the jars upside down at the same time. Observe what happens.
3. Turn the two jars right-side up and again watch what happens.

Drawing Conclusions Which fluid has a greater viscosity? What evidence leads you to this conclusion?

Properties of Liquids One characteristic property of liquids is surface tension. **Surface tension** is the result of an inward pull among the molecules of a liquid that brings the molecules on the surface closer together. Perhaps you have noticed that water forms droplets and can bead up on many surfaces, such as the leaf shown in Figure 7. That's because water molecules attract one another strongly. These attractions cause molecules at the water's surface to be pulled slightly toward the water molecules beneath the surface.

Due to surface tension, the surface of water can act like a sort of skin. For example, a sewing needle floats when you place it gently on the surface of a glass of water, but it quickly sinks if you push it below the surface. Surface tension enables the water strider in Figure 7 to "walk" on the calm surface of a pond.

Another property of liquids is **viscosity** (vis KAHS uh tee)—a liquid's resistance to flowing. A liquid's viscosity depends on the size and shape of its particles and the attractions between the particles. Some liquids flow more easily than others. Liquids with high viscosity flow slowly. Honey is an example of a liquid with a particularly high viscosity. Liquids with low viscosity flow quickly. Water and vinegar have relatively low viscosities.

Reading Checkpoint **What property of liquids causes water to form droplets?**

Gases

Like a liquid, a gas is a fluid. Unlike a liquid, however, a **gas** can change volume very easily. If you put a gas in a closed container, the gas particles will either spread apart or be squeezed together as they fill that container. Take a deep breath. Your chest expands, and your lungs fill with air. Air is a mixture of gases that acts as one gas. When you breathe in, air moves from your mouth to your windpipe to your lungs. In each place, the air has a different shape. When you breathe out, the changes happen in reverse.

What about the volume of the air? If you could see the particles that make up a gas, you would see them moving in all directions. The particles are no longer limited by the space in your body, so they move throughout the room. **As they move, gas particles spread apart, filling all the space available. Thus, a gas has neither definite shape nor definite volume.** You will read more about the behavior of gases in Section 3.

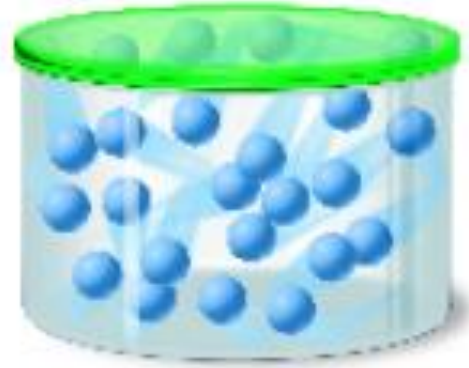


FIGURE 8
Modeling Gas Particles
The particles of a gas can be squeezed into a small volume.
Predicting *What will happen if the container lid is removed?*

Reading Checkpoint **How does breathing demonstrate that gases are fluids?**

Section 1 Assessment

Target Reading Skill

Building Vocabulary Use your definitions to help answer the questions below.

Reviewing Key Concepts

1. a. **Listing** What are the general characteristics of solids?
   b. **Comparing and Contrasting** How do crystalline solids differ from amorphous solids?
   c. **Drawing Conclusions** A glass blower can bend and shape a piece of glass that has been heated. Is glass a crystalline or an amorphous solid? Explain.
2. a. **Describing** How may liquids be described in terms of shape and volume?
   b. **Explaining** How do the positions and movements of particles in a liquid help to explain the shape and volume of the liquid?
   c. **Relating Cause and Effect** Explain why a sewing needle can float on the surface of water in a glass.
3. a. **Reviewing** What determines the shape and volume of a gas inside a container?
   b. **Applying Concepts** Use what you know about the particles in a gas to explain why a gas has no definite shape and no definite volume.

Lab zone At-Home Activity

Squeezing Liquids and Gases Show your family how liquids and gases differ. Fill the bulb and cylinder of a turkey baster with water. Seal the end with your finger and hold it over the sink. Have a family member squeeze the bulb. Now empty the turkey baster. Again, seal the end with your finger and have a family member squeeze the bulb. Did the person notice any difference? Use what you know about liquids and gases to explain your observations.

Section 2

Changes of State

Reading Preview

Key Concepts

- What happens to a substance during changes between solid and liquid?
- What happens to a substance during changes between liquid and gas?
- What happens to a substance during changes between solid and gas?

Key Terms

- melting
- melting point
- freezing
- vaporization
- evaporation
- boiling
- boiling point
- condensation
- sublimation

Target Reading Skill

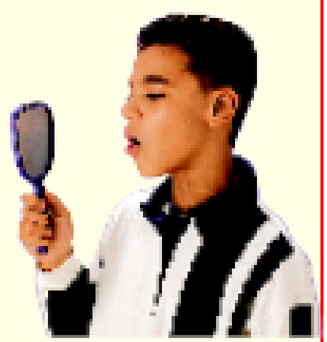
Outlining As you read, make an outline about changes of state. Use the red headings for the main ideas and the blue headings for the supporting ideas.

Changes in State

I. Changes Between Solid and Liquid
  A. Melting
  B.
II. Changes Between Liquid and Gas

Lab zone Discover Activity

What Happens When You Breathe on a Mirror?



1. Obtain a hand mirror. Clean it with a dry cloth. Describe the mirror's surface.
2. Hold the mirror about 15 cm away from your face. Try to breathe against the mirror's surface.
3. Reduce the distance until breathing on the mirror produces a visible change. Record what you observe.

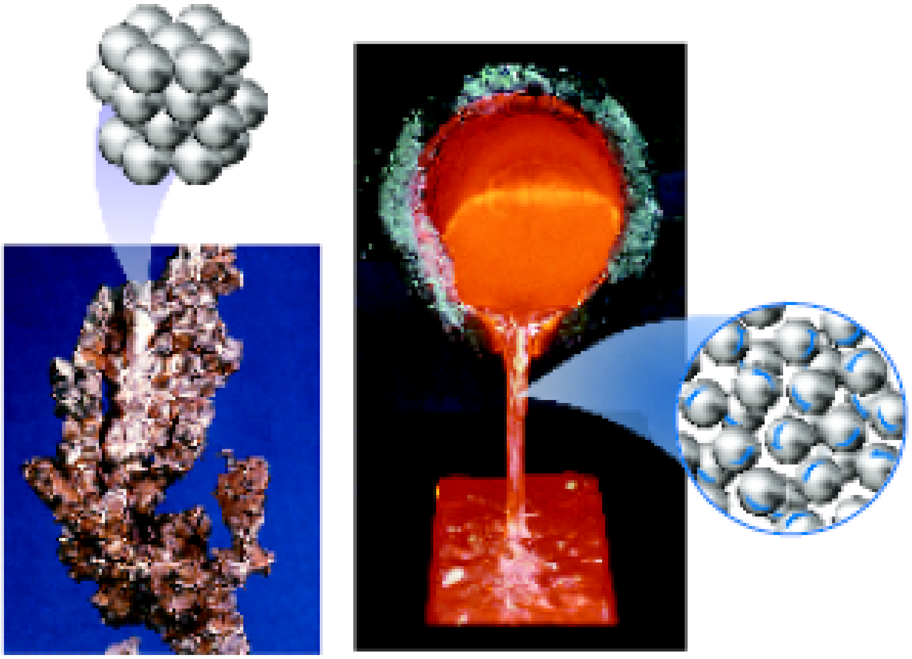
Think It Over

Developing Hypotheses What did you observe when you breathed on the mirror held close to your mouth? How can you explain that observation? Why did you get different results when the mirror was at greater distances from your face?

Picture an ice cream cone on a hot summer day. The ice cream quickly starts to drip onto your hand. You're not surprised. You know that ice cream melts if it's not kept cold. But why does the ice cream melt?

Particles of a substance at a warmer temperature have more thermal energy than particles of that same substance at a cooler temperature. Remember from earlier that thermal energy always flows as heat from a warmer substance to a cooler substance. So, when you take ice cream outside on a hot summer day, it absorbs thermal energy from the air and your hand. The added energy changes the ice cream from a solid to a liquid.

Increased thermal energy turns an ice cream cone into a gooey mess! ▶



Solid silver

Liquid silver

FIGURE 9
Solid to Liquid
In solid silver, atoms are in a regular, cubic pattern. Atoms in liquid (molten) silver have no regular arrangement.
Applying Concepts *How can a jewelry maker take advantage of changes in the state of silver?*

Changes Between Solid and Liquid

How does the physical state of a substance relate to its thermal energy? Particles of a liquid have more thermal energy than particles of the same substance in solid form. As a gas, the particles of this same substance have even more thermal energy. A substance changes state when its thermal energy increases or decreases sufficiently. A change from solid to liquid involves an increase in thermal energy. As you can guess, a change from liquid to solid is just the opposite: It involves a decrease in thermal energy.

Melting The change in state from a solid to a liquid is called **melting.** In most pure substances, melting occurs at a specific temperature, called the **melting point.** Because melting point is a characteristic property of a substance, chemists often compare melting points when trying to identify an unknown material. The melting point of pure water, for example, is 0°C.

What happens to the particles of a substance as it melts? Think of an ice cube taken from the freezer. The energy to melt the ice comes mostly from the air in the room. At first, the added thermal energy makes the water molecules vibrate faster, raising their temperature. **At its melting point, the particles of a solid substance are vibrating so fast that they break free from their fixed positions.** At 0°C, the temperature of the ice stops increasing. Any added energy continues to change the arrangement of the water molecules from ice crystals into liquid water. The ice melts.

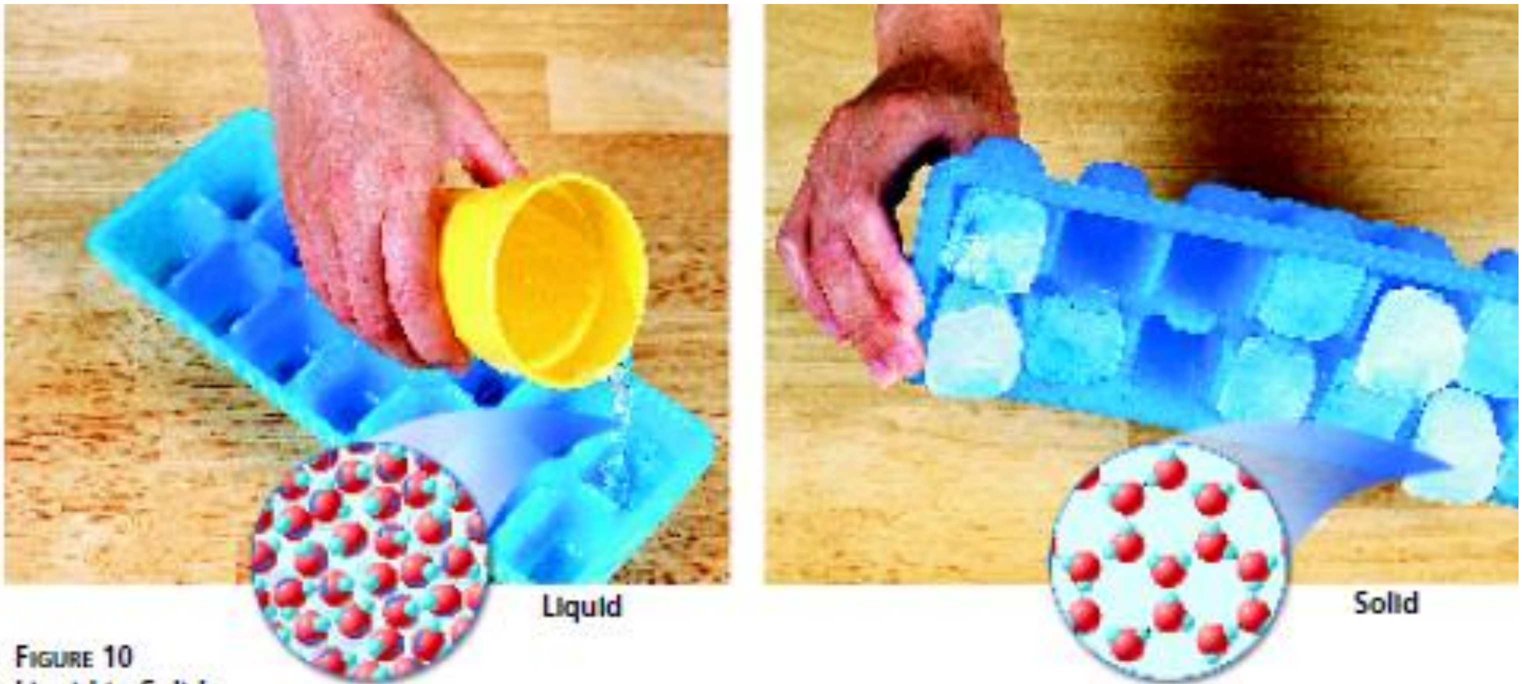


FIGURE 10
Liquid to Solid
Just a few hours in a freezer will change liquid water into a solid.

Freezing The change of state from liquid to solid is called **freezing.** It is just the reverse of melting. **At its freezing temperature, the particles of a liquid are moving so slowly that they begin to form regular patterns.**

When you put liquid water into a freezer, for example, the water loses energy to the cold air in the freezer. The water molecules move more and more slowly as they lose energy. Over time, the water becomes solid ice. When water begins to freeze, its temperature remains at 0°C until freezing is complete. The freezing point of water, 0°C, is the same as its melting point.

Reading Checkpoint What happens to the particles of a liquid as they lose more and more energy?

Changes Between Liquid and Gas

Have you ever wondered how clouds form, or why rain falls from clouds? And why do puddles dry up after a rain shower? To answer these questions, you need to look at what happens when changes occur between the liquid and gas states.

The change from a liquid to a gas is called **vaporization** (vay puhr ih ZAY shun). **Vaporization takes place when the particles in a liquid gain enough energy to form a gas.** There are two main types of vaporization—evaporation and boiling.

Evaporation Vaporization that takes place only on the surface of a liquid is called **evaporation** (ee vap uh RAY shun). A shrinking puddle is an example. Water in the puddle gains energy from the ground, the air, or the sun. The added energy enables some of the water molecules on the surface of the puddle to escape into the air, or evaporate.

Lab zone Try This Activity

Keeping Cool

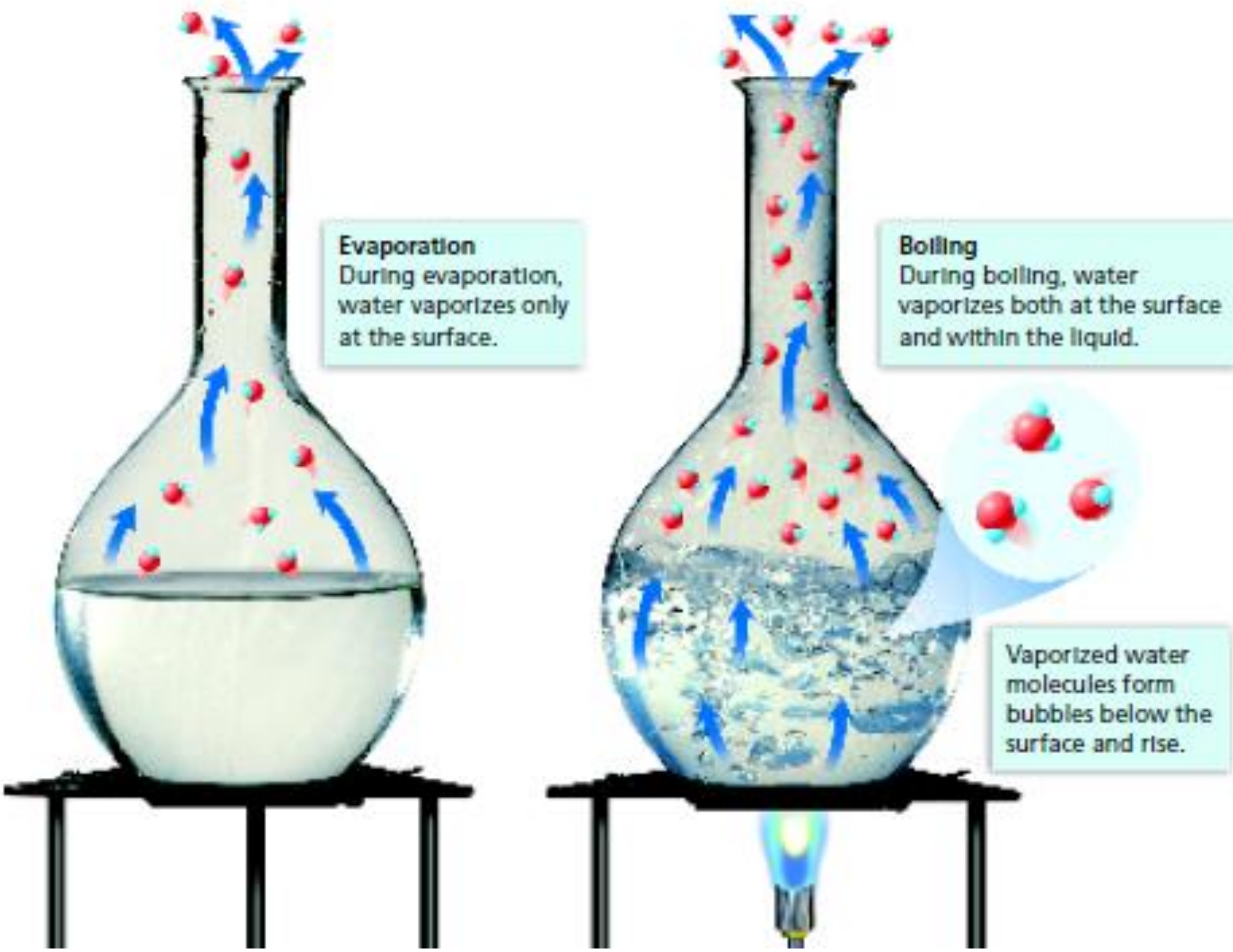
1. Wrap the bulbs of two alcohol thermometers with equal amounts of gauze.
2. Lay the thermometers on a paper towel on a table.
3. Use a medicine dropper to put 10 drops of water on the gauze surrounding the bulb of one thermometer.
4. Using rubbing alcohol rather than water, repeat step 3 with the second thermometer.
5. Read the temperatures on the two thermometers for several minutes.

Interpreting Data Which liquid evaporates faster? Explain your answer.

Boiling Another kind of vaporization is called boiling. **Boiling** occurs when a liquid changes to a gas below its surface as well as at the surface. You see the results of this process when the boiling liquid bubbles. The temperature at which a liquid boils is called its **boiling point.** As with melting points, chemists use boiling points to help identify an unknown substance.

Boiling Point and Air Pressure The boiling point of a substance depends on the pressure of the air above it. The lower the pressure, the less energy needed for the particles of the liquid to escape into the air. In places close to sea level, the boiling point of water is 100°C. In the mountains, however, air pressure is lower and so is water's boiling point. In Denver, Colorado, where the elevation is 1,600 meters above sea level, water boils at 95°C.

FIGURE 11
Evaporation and Boiling
Liquids can vaporize in two ways.
Interpreting Diagrams *How do these processes differ?*



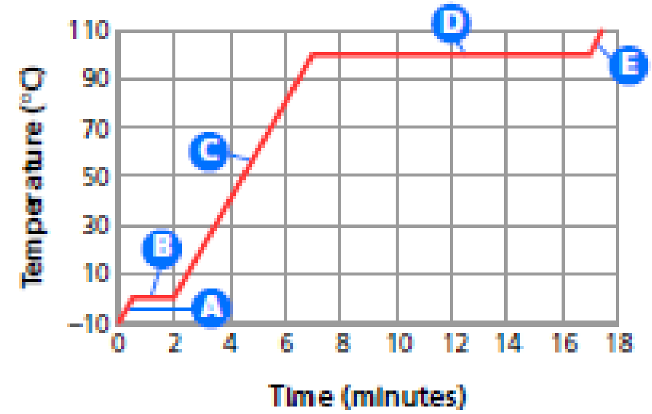
Math Analyzing Data

Temperature and Changes of State

A beaker of ice at –10°C was slowly heated to 110°C. The changes in the temperature of the water over time were recorded. The data were plotted on the graph shown here.

1. **Reading Graphs** What two variables are plotted on the graph?
2. **Reading Graphs** What is happening to the temperature of the water during segment C of the graph?
3. **Interpreting Data** What does the temperature value for segment B represent? For segment D?
4. **Drawing Conclusions** What change of state is occurring during segment B of the graph? During segment D?

Changes of State for Water



5. **Inferring** In which segment, A or E, do the water molecules have more thermal energy? Explain your reasoning.

Figure 12
Condensation of Water
Water vapor from a hot shower contacts the cool surface of a bathroom mirror and condenses into a liquid.

Condensation The opposite of vaporization is called **condensation.** One way you can observe condensation is by breathing onto a mirror. When warm water vapor in your breath reaches the cooler surface of the mirror, the water vapor condenses into liquid droplets. **Condensation occurs when particles in a gas lose enough thermal energy to form a liquid.** For example, clouds typically form when water vapor in the atmosphere condenses into liquid droplets. When the droplets get heavy enough, they fall to the ground as rain.

You cannot see water vapor. Water vapor is a colorless gas that is impossible to see. The steam you see above a kettle of boiling water is not water vapor, and neither are clouds or fog. What you see in those cases are tiny droplets of liquid water suspended in air.

Reading Checkpoint How do clouds typically form?

Changes Between Solid and Gas

If you live where the winters are cold, you may have noticed that snow seems to disappear even when the temperature stays well below freezing. This change is the result of sublimation. **Sublimation** occurs when the surface particles of a solid gain enough energy that they form a gas. **During sublimation, particles of a solid do not pass through the liquid state as they form a gas.**

One example of sublimation occurs with dry ice. Dry ice is the common name for solid carbon dioxide. At ordinary atmospheric pressures, carbon dioxide cannot exist as a liquid. So instead of melting, solid carbon dioxide changes directly into a gas. As it changes state, the carbon dioxide absorbs thermal energy. This property helps keep materials near dry ice cold and dry. For this reason, using dry ice is a way to keep temperature low when a refrigerator is not available. When dry ice becomes a gas, it cools water vapor in the nearby air. The water vapor then condenses into a liquid, forming fog around the dry ice.

Reading Checkpoint **What physical state is skipped during the sublimation of a substance?**

FIGURE 13
Dry Ice
When solid carbon dioxide, called "dry ice," sublimates, it changes directly into a gas. Predicting *If you allowed the dry ice to stand at room temperature for several hours, what would be left in the glass dish? Explain.*

Section 2 Assessment

Target Reading Skill Outlining Use the information in your outline about changes of state to help you answer the questions below.

Reviewing Key Concepts

1. a. Reviewing What happens to the particles of a solid as it becomes a liquid?
   b. Applying Concepts How does the thermal energy of solid water change as it melts?
   c. Making Judgments You are stranded in a blizzard. You need water to drink, and you're trying to stay warm. Should you melt snow and then drink it, or just eat snow? Explain.
2. a. Describing What is vaporization?
   b. Comparing and Contrasting Name the two types of vaporization. Tell how they are similar and how they differ.
   c. Relating Cause and Effect Why does the evaporation of sweat cool your body on a warm day?
3. a. Identifying What process occurs as pieces of dry ice gradually get smaller?
   b. Interpreting Photos What is the fog you see in the air around the dry ice in Figure 13? Why does the fog form?

Writing in Science

Using Analogies Write a short essay in which you create an analogy to describe particle motion. Compare the movements and positions of people dancing with the motions of water molecules in liquid water and in water vapor.

Section 3

Gas Behavior

Reading Preview

Key Concepts

- What types of measurements are useful when working with gases?
- How are the volume, temperature, and pressure of a gas related?

Key Terms

- pressure
- Boyle's law
- Charles's law

Target Reading Skill

Asking Questions Before you read, preview the red headings. In a graphic organizer like the one below, ask a *what* or *how* question for each heading. As you read, write the answers to your questions.

Gases

Question	Answer
What measure-ments are useful in studying gases?	Measurements useful in studying gases include . . .

Lab zone Discover Activity

How Can Air Keep Chalk From Breaking?

1. Stand on a chair and drop a piece of chalk onto a hard floor. Observe what happens to the chalk.
2. Wrap a second piece of chalk in wax paper or plastic food wrap. Drop the chalk from the same height used in Step 1. Observe the results.
3. Wrap a third piece of chalk in plastic bubble wrap. Drop the chalk from the same height used in Step 1. Observe the results.

Think It Over

Inferring Compare the results from Steps 1, 2, and 3. What properties of the air in the bubble wrap accounted for the results in Step 3?

How do you prepare a hot-air balloon for a morning ride? First, you inflate the balloon, using powerful air fans. Then you heat the air inside with propane gas burners. But the balloon and its cargo won't begin to rise until the warmer air inside is less dense than the air outside the balloon. How does this change occur? How can you keep the balloon floating safely through the atmosphere? How can you make it descend when you are ready to land? To answer these and other questions, you would need to understand the relationships between the temperature, pressure, and volume of a gas.

Before a flight, a hot-air balloon is filled with air. ▶

Measuring Gases

How much helium is in the tank in Figure 14? If you don't know the mass of the helium, you may think that measuring the volume of the tank will give you an answer. But gases easily contract or expand. To fill the tank, helium was compressed—or pressed together tightly—to decrease its volume. When you use the helium to fill balloons, it fills a total volume of inflated balloons much greater than the volume of the tank. The actual volume of helium you get, however, depends on the temperature and air pressure that day. **When working with a gas, it is helpful to know its volume, temperature, and pressure.** So what exactly do these measurements mean?

Volume From Chapter 1, you know that volume is the amount of space that matter fills. Volume is measured in cubic centimeters (cm^3), milliliters (mL), liters (L), and other units. Because gas particles move and fill the space available, the volume of a gas is the same as the volume of its container.

Temperature Hot soup, warm hands, cool breezes—you are familiar with matter at different temperatures. But what does temperature tell you? Recall that the particles within any substance are constantly moving. Temperature is a measure of the average energy of random motion of the particles of a substance. The faster the particles are moving, the greater their energy and the higher the temperature. You might think of a thermometer as a speedometer for molecules.

Even at ordinary temperatures, the average speed of particles in a gas is very fast. At room temperature, or about 20°C, the particles in a typical gas travel about 500 meters per second—more than twice the cruising speed of a jet plane!

FIGURE 14
How Much Helium?
A helium tank the height of this girl can fill over 500 balloons!
Interpreting Photos *How is the helium in the tank different from the helium in the balloons?*

Pressure Gas particles constantly collide with one another and with the walls of their container. As a result, the gas pushes on the walls of the container. The **pressure** of the gas is the force of its outward push divided by the area of the walls of the container. Pressure is measured in units of pascals (Pa) or kilopascals (kPa). (1 kPa = 1,000 Pa.)

$$\text{Pressure} = \frac{\text{Force}}{\text{Area}}$$

The firmness of a gas-filled object comes from the pressure of the gas. For example, the air inside a fully pumped basketball has a higher pressure than the air outside. This higher pressure is due to a greater concentration of gas particles inside the ball than in the surrounding air. (Concentration is the number of particles in a given unit of volume.)

When air leaks out of a basketball, the pressure decreases and the ball becomes softer. Why does a ball leak even when it has a tiny hole? The higher pressure inside the ball results in gas particles hitting the inner surface of the ball more often. Therefore, gas particles inside the ball reach the hole and escape more often than gas particles outside the ball reach the hole and enter. Thus, many more particles go out than in. The pressure inside drops until it is equal to the pressure outside.

Reading Checkpoint What units are used to measure pressure?

Math Skills

Using Formulas

Pressure can be calculated using the formula below. Force is measured in newtons (N). If area is measured in square meters (m^2), pressure is expressed in pascals (Pa).

$$\text{Pressure} = \frac{\text{Force}}{\text{Area}}$$

For example, a machine exerts a force of 252 N on a piston having an area of 0.430 m^2. What is the pressure on the piston in Pa?

$$\text{Pressure} = \frac{252\ \text{N}}{0.430\ \text{m}^2}$$
$$= 586\ \text{Pa}$$

Practice Problem A trash compactor exerts a force of 5,600 N over an area of 0.342 m^2. What pressure does the compactor exert in Pa?

FIGURE 15
A Change in Pressure
A punctured basketball deflates as the gas particles begin to escape.

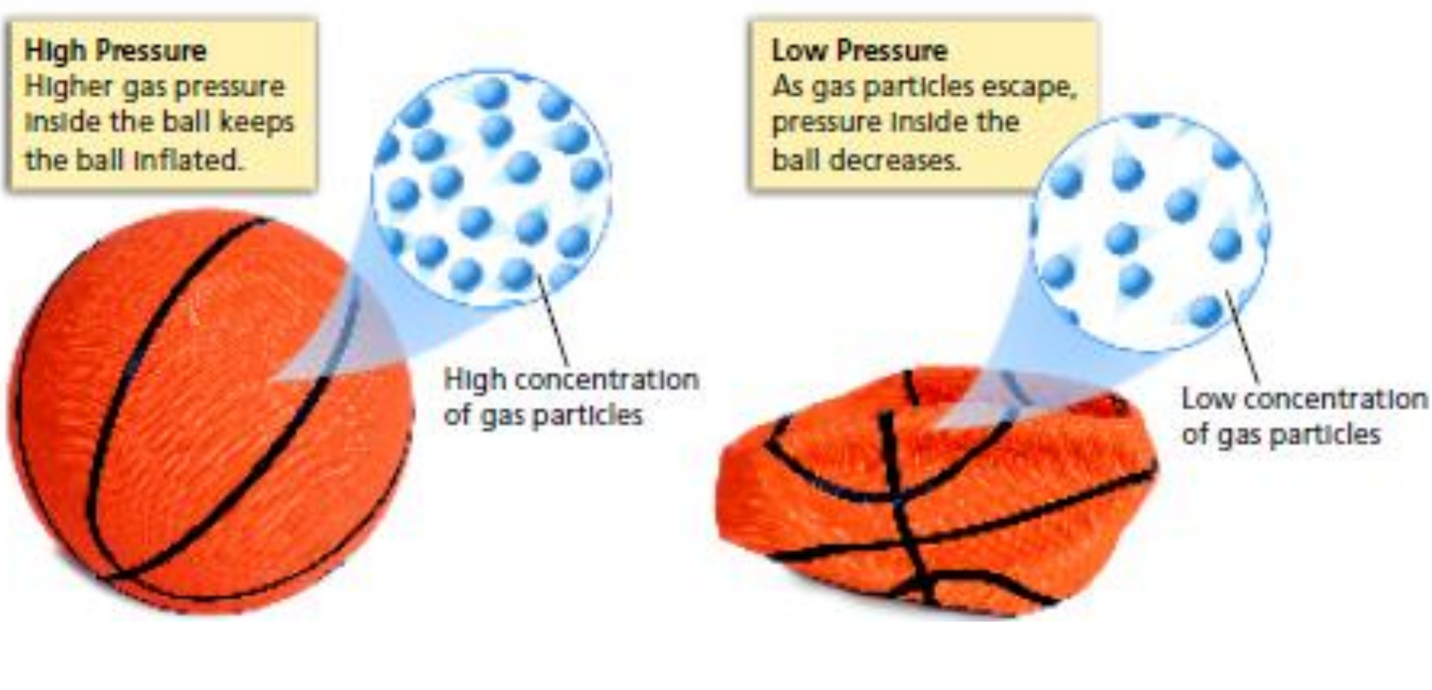


Figure 16
Inflating a Tire
A bicycle pump makes use of the relationship between the volume and pressure of a gas.

Pressure and Volume

Suppose you are using a bicycle pump. By pressing down on the plunger, you force the gas inside the pump through the rubber tube and out the nozzle into the tire. What will happen if you close the nozzle and then push down on the plunger?

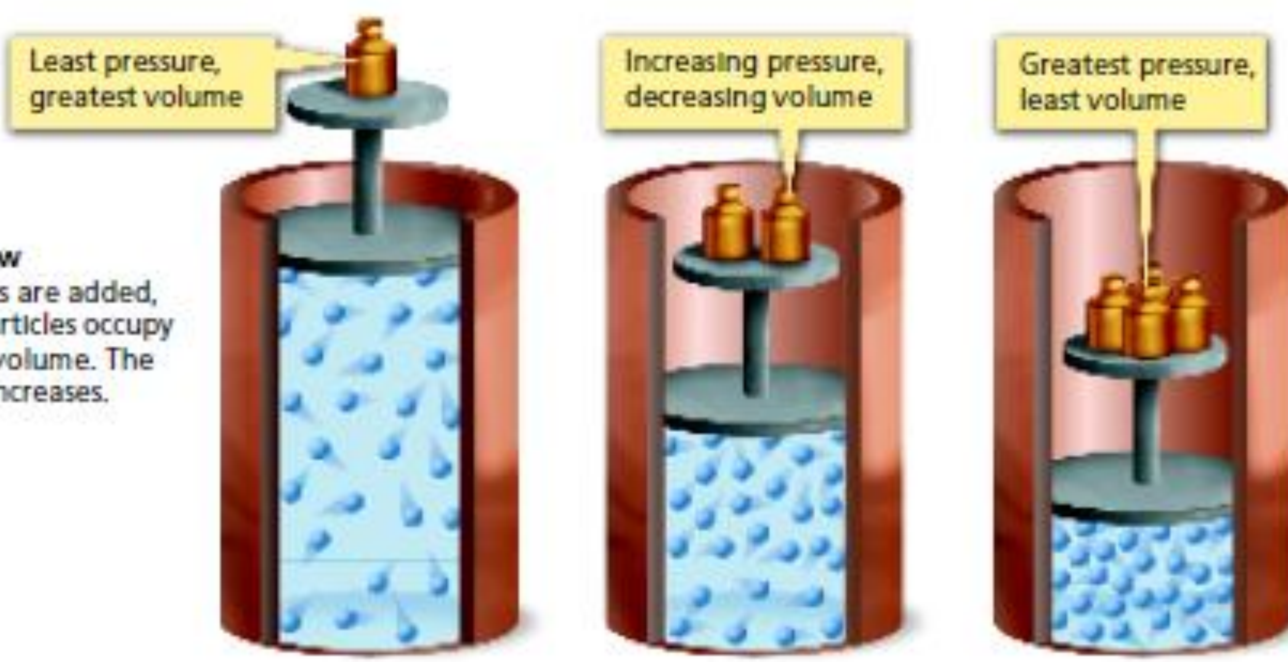
Boyle's Law The answer to this question comes from experiments done by the scientist Robert Boyle in an effort to improve air pumps. In the 1600s, Boyle measured the volumes of gases at different pressures. **Boyle found that when the pressure of a gas at constant temperature is increased, the volume of the gas decreases. When the pressure is decreased, the volume increases.** This relationship between the pressure and the volume of a gas is called **Boyle's law.**

Boyle's Law in Action Boyle's law plays a role in research using high-altitude balloons. Researchers fill the balloons with only a small fraction of the helium gas that the balloons can hold. As a balloon rises through the atmosphere, the air pressure around it decreases and the balloon expands. If the balloon were fully filled at takeoff, it would burst before it got very high.

Boyle's law also applies to situations in which the *volume* of a gas is changed. Then the *pressure* changes in the opposite way. A bicycle pump works this way. As you push on the plunger, the volume of air inside the pump cylinder gets smaller and the pressure increases, forcing air into the tire.

Reading Checkpoint **What could cause a helium balloon to burst as it rises in the atmosphere?**

Figure 17
Boyle's Law
As weights are added, the gas particles occupy a smaller volume. The pressure increases.



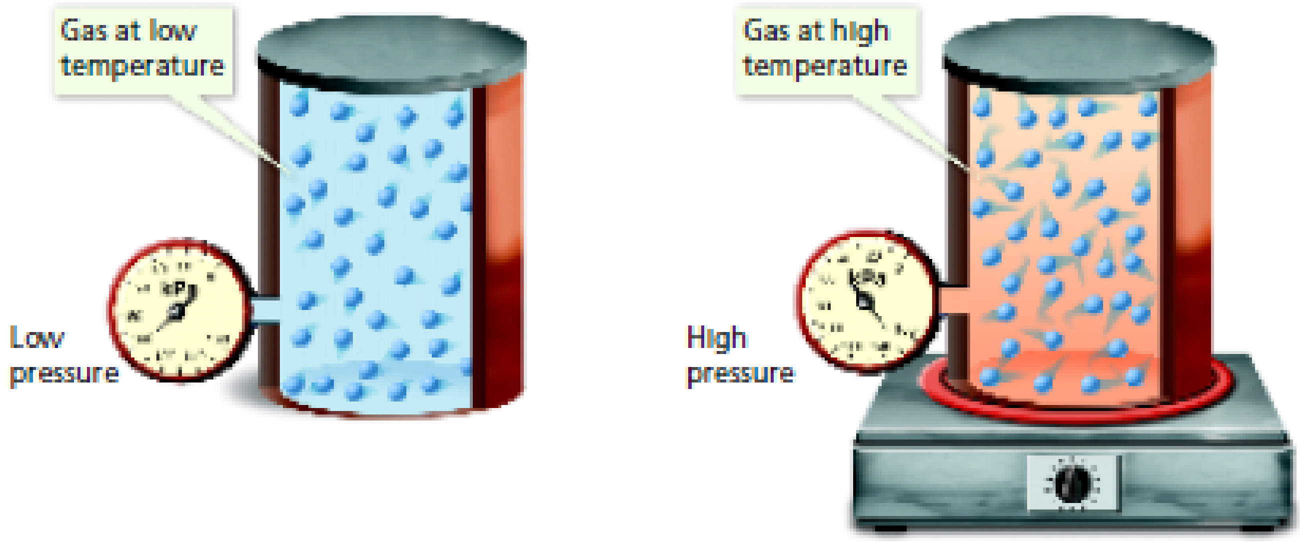


FIGURE 18
Gas Pressure and Temperature
When a gas is heated, the particles move faster and collide more with each other and with the walls of their container. The pressure of the gas increases.

Pressure and Temperature

If you dropped a few grains of sand onto your hand, you would hardly feel them. But what if you were caught in a sandstorm? Ouch! The sand grains fly around very fast, and they would sting if they hit you. The faster the grains travel, the harder they hit your skin.

Although gas particles are much smaller than sand grains, a sandstorm is a good model for gas behavior. Like grains of sand in a sandstorm, gas particles travel individually and at high speeds (but randomly). The faster the gas particles move, the more frequently they collide with the walls of their container and the greater the force of the collisions.

Increasing Temperature Raises Pressure Recall from Section 2 that the higher the temperature of a substance, the faster its particles are moving. Now you can state a relationship between temperature and pressure. **When the temperature of a gas at constant volume is increased, the pressure of the gas increases. When the temperature is decreased, the pressure of the gas decreases.** (*Constant volume* means that the gas is in a closed, rigid container.)

Pressure and Temperature in Action Have you ever looked at the tires of an 18-wheel truck? Because the tires need to support a lot of weight, they are large, heavy, and stiff. The inside volume of these tires doesn't vary much. On long trips, especially in the summer, a truck's tires can become very hot. As the temperature increases, so does the pressure of the air inside the tire. If the pressure becomes greater than the tire can hold, the tire will burst. For this reason, truck drivers need to monitor and adjust tire pressure on long trips.

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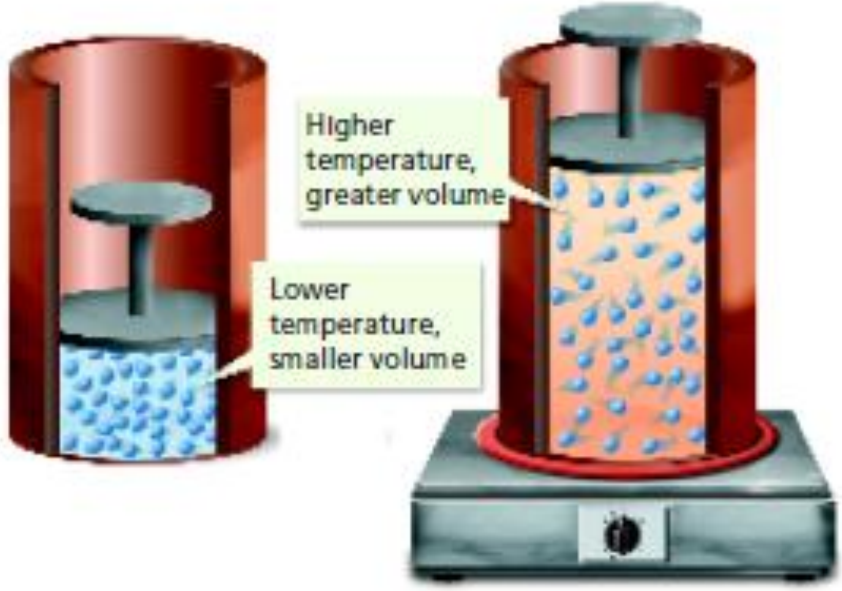
FIGURE 19
Charles's Law
Changing the temperature of a gas at constant pressure changes its volume in a similar way.
Inferring *What happens to the gas particles in the balloon as the gas is warmed?*



▲ A gas-filled balloon is at room temperature.

▲ The balloon is lowered into liquid nitrogen at –196°C.

▲ The balloon shrinks as gas volume decreases.

Volume and Temperature

In the late 1700s, French scientist Jacques Charles helped start a new sport. He and others took to the skies in the first hydrogen balloons. Charles's interest in balloon rides led him to discover how gas temperature and volume are related.

Charles's Law Jacques Charles examined the relationship between the temperature and volume of a gas that is kept at a constant pressure. He measured the volume of a gas at various temperatures in a container that could change volume. (A changeable volume allows the pressure to remain constant.) **Charles found that when the temperature of a gas is increased at constant pressure, its volume increases. When the temperature of a gas is decreased at constant pressure, its volume decreases.** This principle is called **Charles's law.**

Charles's Law in Action In Figure 19, you can see the effects of Charles's law demonstrated with a simple party balloon. Time-lapse photos show a balloon as it is slowly lowered into liquid nitrogen at nearly −200°C, then removed. The changes to the balloon's volume result from changes in the temperature of the air inside the balloon. The pressure remains more or less constant because the air is in a flexible container.

▲ When removed from the nitrogen, the gas warms and the balloon expands.

▲ The balloon is at room temperature again.

Now think again about a hot-air balloon. Heating causes the air inside the balloon to expand. Some of the warm air leaves through the bottom opening of the balloon, keeping the pressure constant. But now, the air inside is less dense than the air outside the balloon, so the balloon begins to rise. If the pilot allows the air in the balloon to cool, the reverse happens. The air in the balloon contracts, and more air enters through the opening. The density of the air inside increases, and the balloon starts downward.

Boyle, Charles, and others often described the behavior of gases by focusing on only two factors that vary at a time. In everyday life, however, gases can show the effects of changes in pressure, temperature, and volume all at once. People who work with gases, such as tire manufacturers and balloonists, must consider these combined effects.

Reading Checkpoint **What factor is kept unchanged when demonstrating Charles's law?**

FIGURE 20
Hot-Air Balloon
Balloonists often use a propane burner to heat the air in a balloon.

Section 3 Assessment

Target Reading Skill **Asking Questions** Use the answers to the questions you wrote about the headings to help you answer the questions below.

Reviewing Key Concepts

1. a. **Defining** How is gas pressure defined?
   b. **Describing** Describe how the motions of gas particles are related to the pressure exerted by the gas.
   c. **Relating Cause and Effect** Why does pumping more air into a basketball increase the pressure inside the ball?
2. a. **Reviewing** How does Boyle's law describe the relationship between gas pressure and volume?
   b. **Explaining** Explain why increasing the temperature of a gas in a closed, rigid container causes the pressure in the container to increase.
   c. **Applying Concepts** Suppose it is the night before a big parade, and you are in charge of inflating the parade balloons. You just learned that the temperature will rise 15°C between early morning and the time the parade starts. How will this information affect the way you inflate the balloons?

Math Practice

3. **Using Formulas** Suppose the atmosphere exerts a force of 124,500 N on a kitchen table with an area of 1.5m^2. What is the pressure in pascals of the atmosphere on the table?