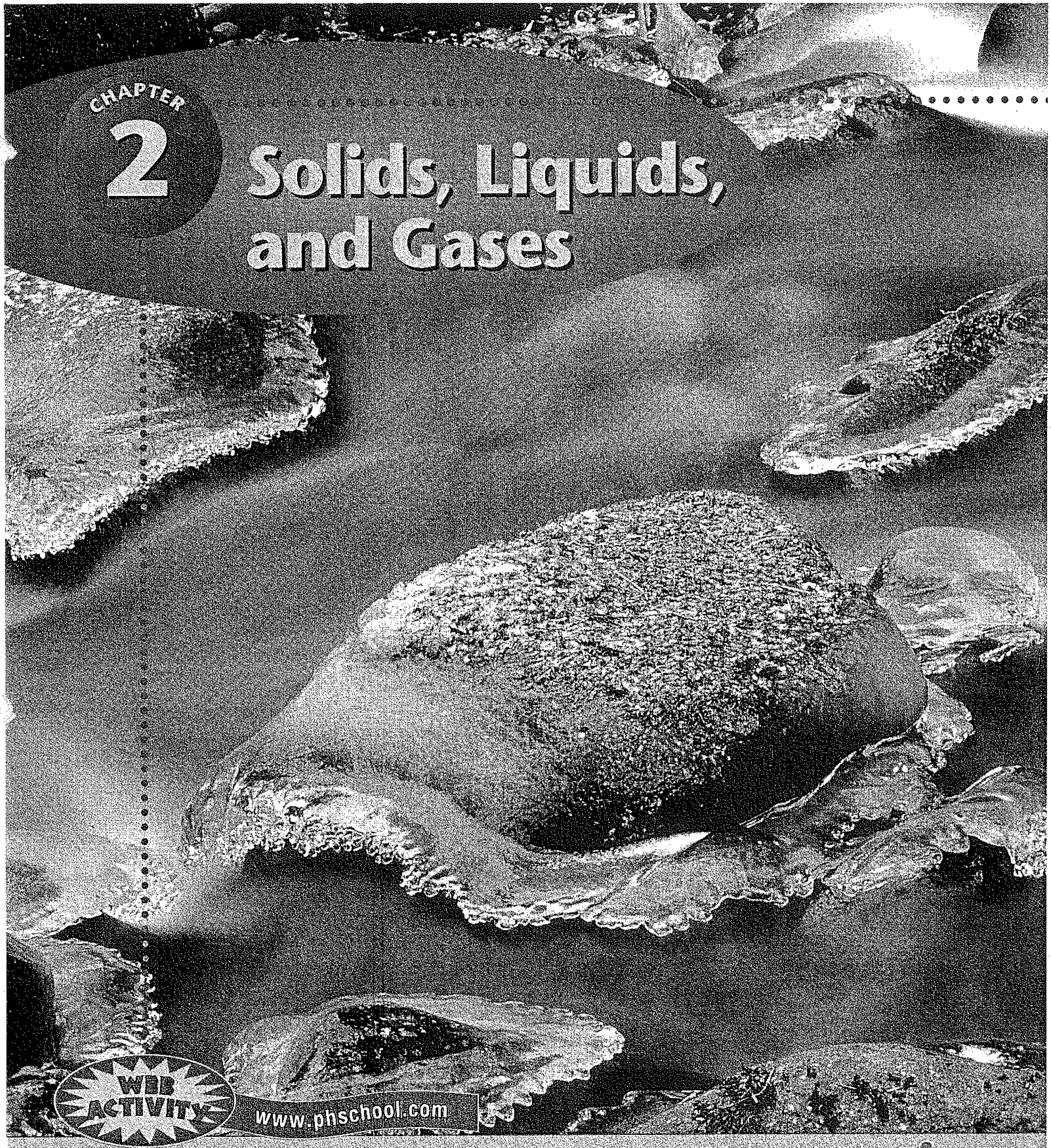
CHAPTER 2

Solids, Liquids, and Gases



SECTION 1 States of Matter

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SECTION 2 Gas Behavior

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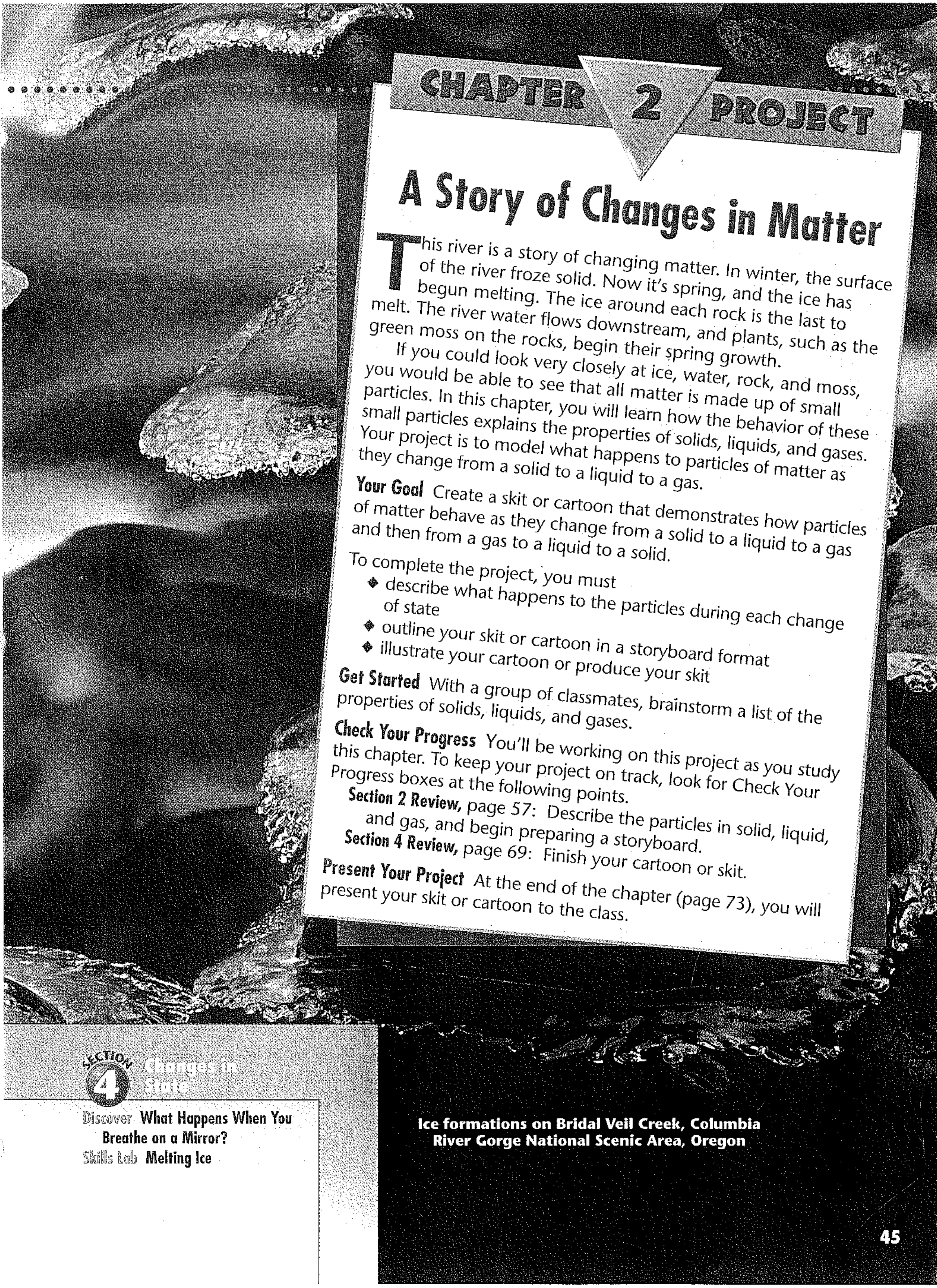


Ice formations on Bridal Veil Creek, Columbia River Gorge National Scenic Area, Oregon

CHAPTER 2 PROJECT

A Story of Changes in Matter

This river is a story of changing matter. In winter, the surface of the river froze solid. Now it's spring, and the ice has begun melting. The ice around each rock is the last to melt. The river water flows downstream, and plants, such as the green moss on the rocks, begin their spring growth.

If you could look very closely at ice, water, rock, and moss, you would be able to see that all matter is made up of small particles. In this chapter, you will learn how the behavior of these small particles explains the properties of solids, liquids, and gases. Your project is to model what happens to particles of matter as they change from a solid to a liquid to a gas.

Your Goal Create a skit or cartoon that demonstrates how particles of matter behave as they change from a solid to a liquid to a gas and then from a gas to a liquid to a solid.

To complete the project, you must

- describe what happens to the particles during each change of state
- outline your skit or cartoon in a storyboard format
- illustrate your cartoon or produce your skit

Get Started With a group of classmates, brainstorm a list of the properties of solids, liquids, and gases.

Check Your Progress You'll be working on this project as you study this chapter. To keep your project on track, look for Check Your Progress boxes at the following points.

Section 2 Review, page 57: Describe the particles in solid, liquid, and gas, and begin preparing a storyboard.

Section 4 Review, page 69: Finish your cartoon or skit.

Present Your Project At the end of the chapter (page 73), you will present your skit or cartoon to the class.

SECTION 4 **Changes in State**

Discover **What Happens When You Breathe on a Mirror?**

Skills Lab **Melting Ice**

Chapt. 2 – Physical Science

SECTION 1

States of Matter

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 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

Classifying 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.

GUIDE FOR READING

- ◆ **How are shape, volume, and particle motion useful in describing solids, liquids, and gases?**

Reading Tip **Before you read, list properties that you think characterize solids, liquids, and gases. Revise your list as you read.**

If you visit the annual Winter Carnival in St. Paul, Minnesota, you will see some unusual structures. To celebrate the cold winter weather, people carve huge sculptures out of ice. Over the years, the carnival has featured giant snow figures and ice palaces like the one shown here.

Even in Minnesota, anything made of snow and ice won't last beyond winter. When the temperature rises, snow figures and ice palaces melt into liquid water. And unlike frozen water, liquid water is a poor building material.

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

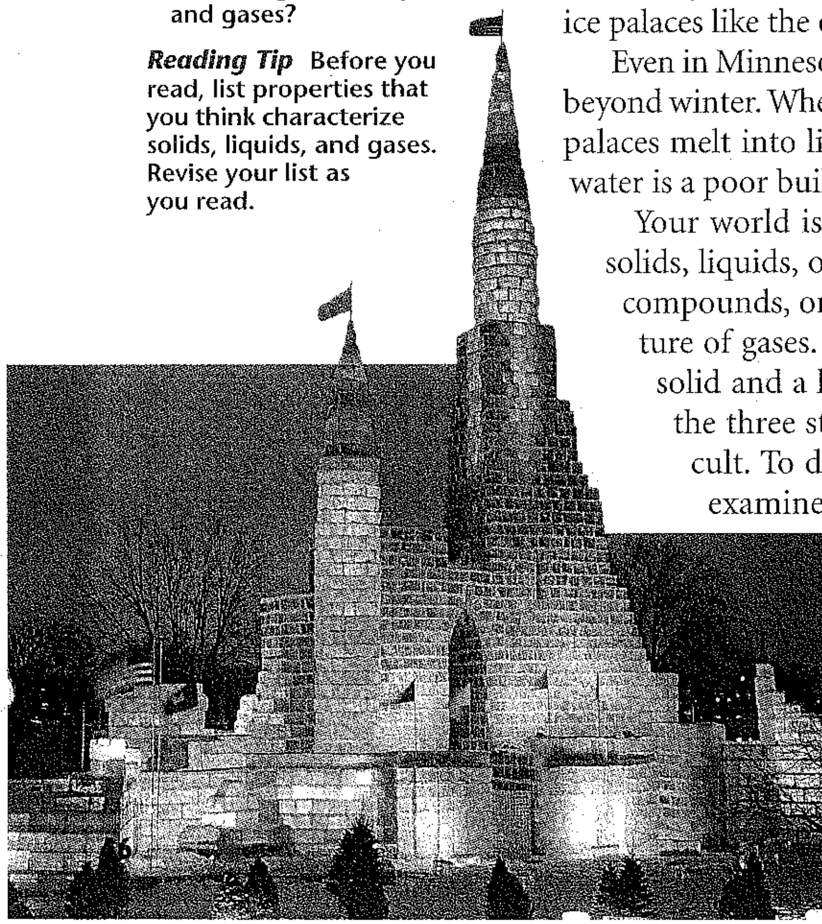


Figure 1 Each year ice palaces like this one delight visitors to the Winter Carnival in St. Paul, Minnesota.

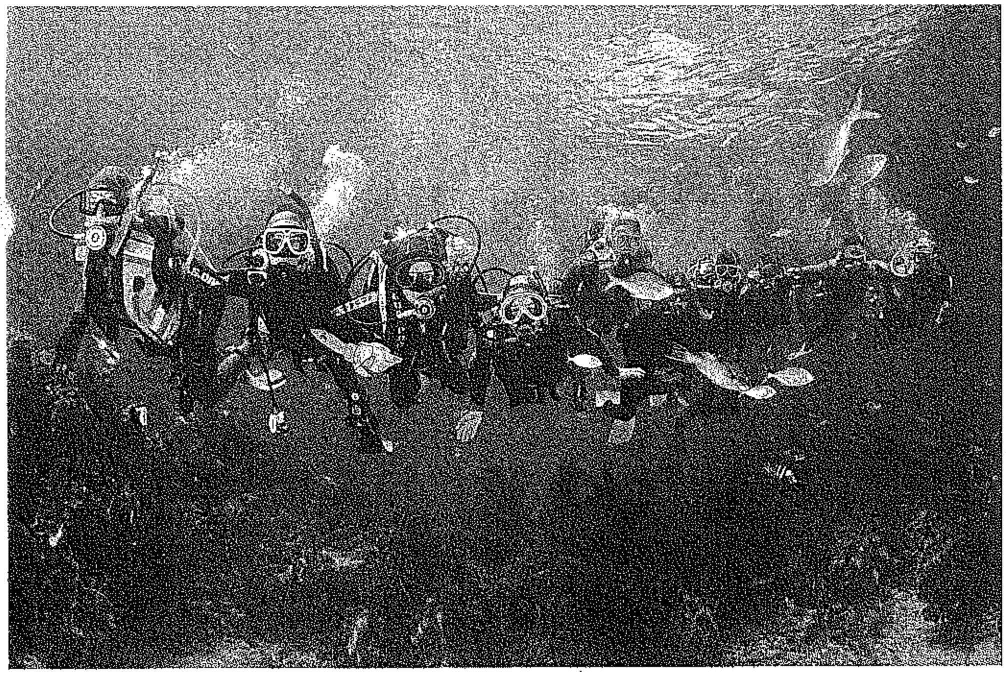


Figure 2 In the tanks on their backs these scuba divers carry air to breathe. ***Classifying*** *Find an example of each state of matter in this photograph.*

Solids

What 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 its size or shape as you moved it? Would a pen become larger if you put it in a bowl? Would a comb become flatter when you place it on a tabletop? Of course not. A **solid** has a definite volume and a definite shape. If your pen has a volume of 6 cm^3 and a cylindrical shape, then it will keep that volume and shape in any position and in any container.

Particles in a Solid The particles that make up a solid are packed very closely together, as shown in Figure 3A. In addition, each particle is tightly fixed in one position. This makes it hard to separate them. **Because the particles in a solid are packed tightly together and stay in fixed positions, a solid has a definite shape and volume.**

Are the particles in a solid completely motionless? No, not really. The particles vibrate, meaning they move back and forth slightly. This motion is similar to a person running in place. Or, you can think of the particles in a solid as something like a group of balls connected by tight springs. Like the balls in Figure 3B, the particles that make up a solid stay in about the same position. However, the individual pieces are still able to vibrate back and forth in their places.

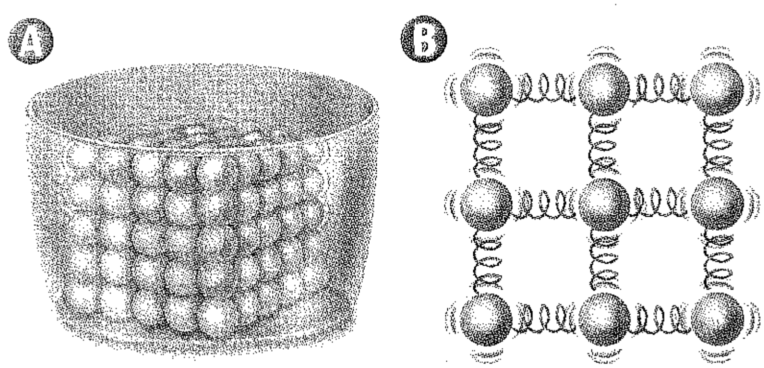


Figure 3 The balls represent the particles in a solid. **A.** A solid keeps its own shape. It doesn't take the shape of a container. **B.** The particles vibrate back and forth within the solid.

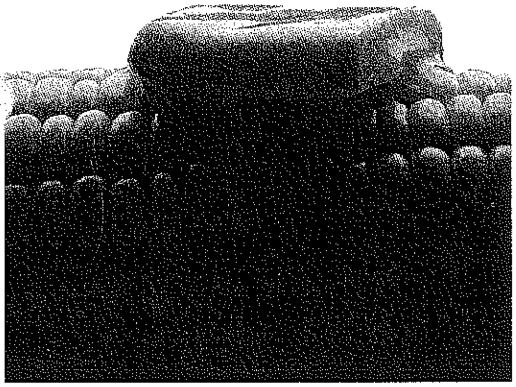


Figure 4 When you heat an amorphous solid such as this butter, it softens before it melts.

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, sand, and snow are examples of crystalline solids. When a crystalline solid such as snow is heated, it melts at a distinct temperature called its **melting point.**

In other solids the particles are not arranged in a regular pattern. These solids are called **amorphous solids** (uh MAWR fus). Plastics, rubber, and glass are amorphous solids. Unlike a crystalline solid, an amorphous solid does not have a distinct melting point. Instead, when it is heated it becomes softer and softer as its temperature rises. You have probably noticed this property in plastic items that have been out in the sun on a hot day. The plastic gradually melts. In fact, the word *plastic* means "able to be molded into many shapes."

☑ *Checkpoint How do crystalline and amorphous solids differ?*

Liquids

Unlike a solid, a **liquid** has no shape of its own. Instead, a liquid takes on the shape of its container. Without a container, a liquid spreads into a wide, shallow puddle.

However, liquids are like solids in that they do not easily compress or expand. If you tried to gently squeeze a water-filled plastic bag, for example, the water might change its shape, but its volume would not decrease or increase.

What if you have 100 mL of water in a container? If you pour it into another container that has a different shape, the water still fills 100 mL. It has the same volume no matter what shape its container has.

Figure 5 Although a liquid's volume does not change, it takes the shape of whatever container you pour it into. ***Comparing and Contrasting*** *How do the particles of a liquid differ from the particles of a solid?*

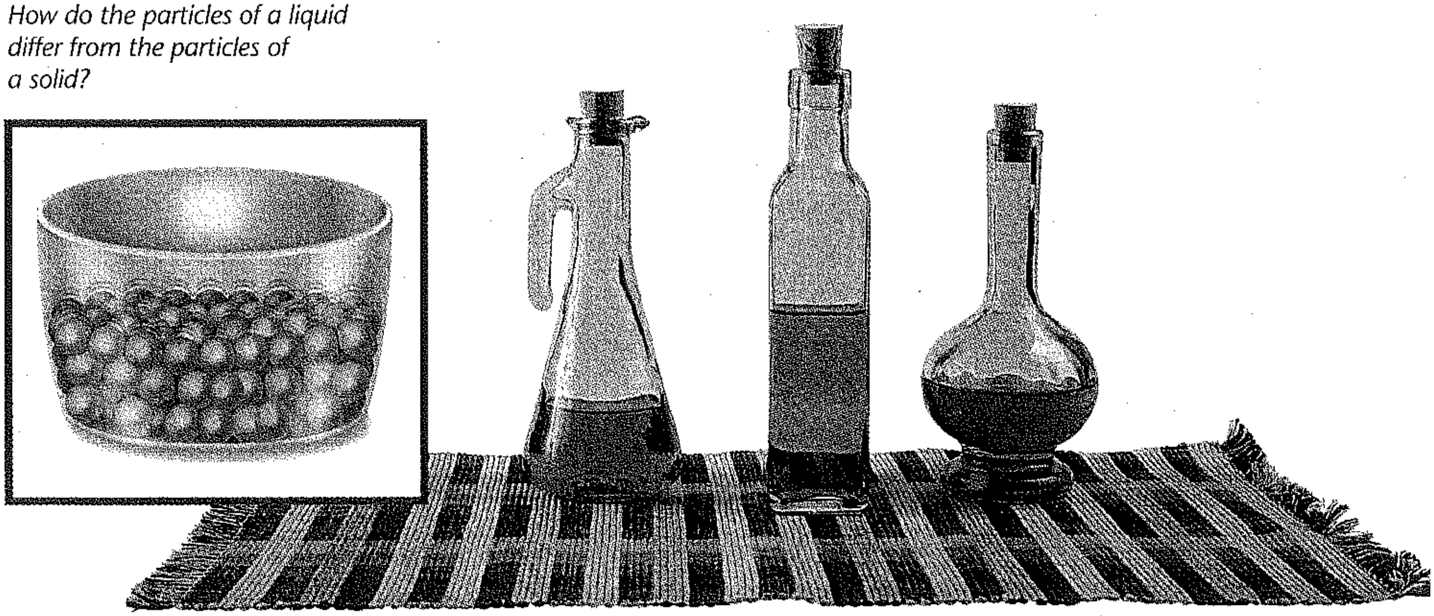


Figure 6 You can think of the particles of a liquid as somewhat like the people in this train station. They remain near one another but move from place to place.

Particles in a Liquid 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. **Because its particles are free to move, a liquid has no definite shape. However, it does have a definite volume.** You can compare a liquid to the rush-hour crowd at a train station. Like particles in a liquid, the people in the crowd move around the platform that contains them, but they stay in close contact with one another.

Viscosity Because particles in a liquid are free to move around one another, a liquid can flow from place to place. Some liquids flow more easily than others. The resistance of a liquid to flowing is called **viscosity** (vis KAHS uh tee). Liquids with high viscosity flow slowly. Cold molasses is an example of a liquid with a particularly high viscosity. Liquids with low viscosity flow quickly. Water, rubbing alcohol, and vinegar have relatively low viscosities.

INTEGRATING EARTH SCIENCE The viscosity of lava that erupts from a volcano helps classify the type of volcanic eruption. A volcano erupts quietly if it has thin, runny lava—that is, lava with low viscosity. High-viscosity lava, which is thick and sticky, is typical of a volcano that erupts explosively.

Gases

Unlike solids and liquids, a **gas** can change volume very easily. If you put a gas in a sealed container, the gas particles will spread apart or squeeze together to fill that container. The volume and shape of a gas is the volume and shape of its container. To illustrate this principle, take a deep breath. Your chest expands. Can you feel the air coming through your nose and mouth? Air is a mixture of

TRY THIS

As Thick as Honey

ACTIVITY

Here's how 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 liquid has a greater viscosity? What evidence leads you to this conclusion?

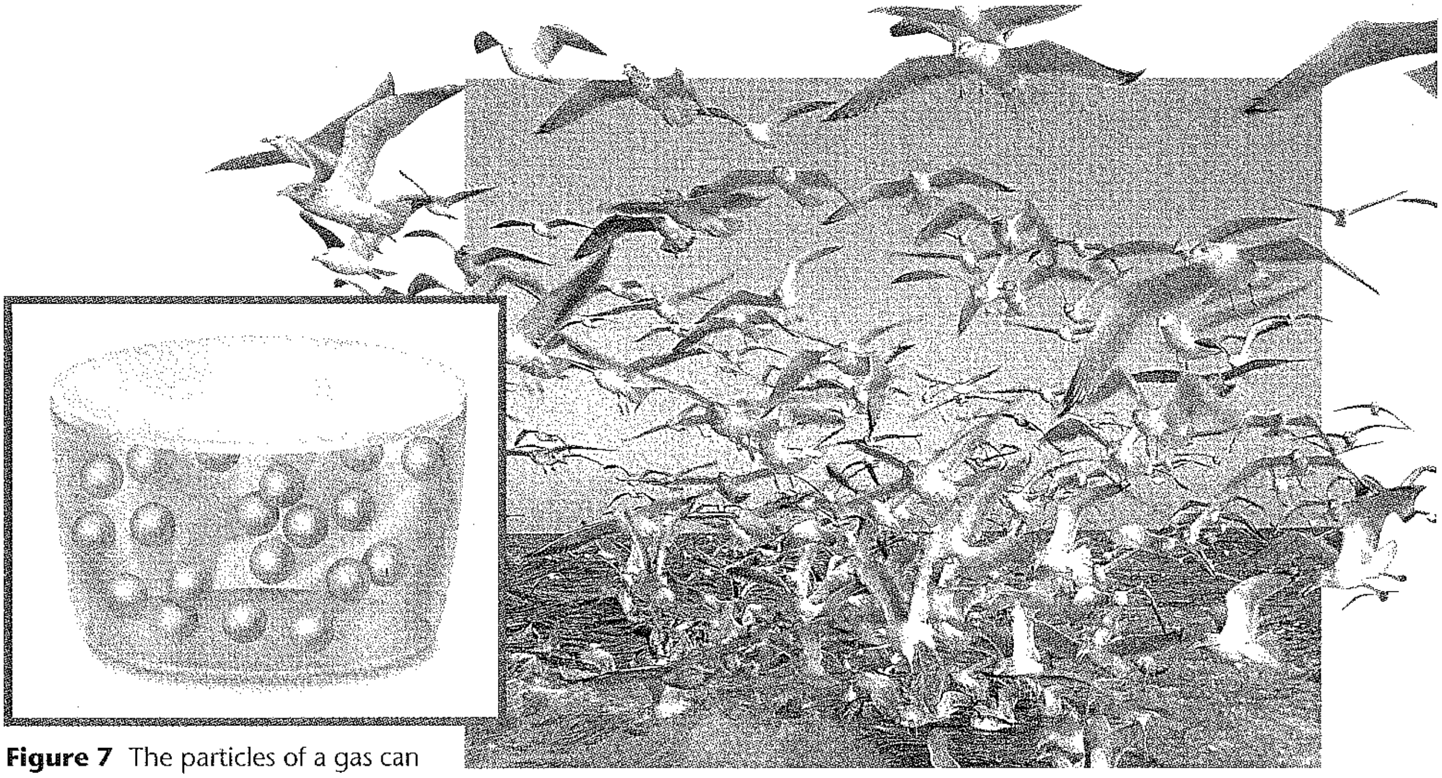


Figure 7 The particles of a gas can be squeezed into a small volume. If allowed to, they will spread out without limit, somewhat like this flock of gulls.

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 changes shape and volume. When you breathe out, the changes happen in reverse. If you hold your hand in front of your mouth, you can feel the air move around and past your fingers.

If you could see the individual particles that make up a gas, you would see tiny particles flying at high speeds in all directions. **Gas particles spread apart, filling all the space available to them. Thus, a gas has neither definite shape nor volume.** You can compare a gas to the flock of gulls shown in Figure 7. Like gas particles, these gulls fly very quickly in different directions. They can spread out to "fill" any available space.

Section 1 Review

1. Describe how particles in a solid are arranged.
2. How does the movement of particles in a liquid help to explain the shape and volume of liquids?
3. Use what you know about the particles in a gas to explain why a gas has no definite shape and no definite volume.
4. **Thinking Critically Relating Cause and Effect** Glass is an amorphous solid. How can you use that information to help explain why a glassblower can bend and shape a piece of glass that has been heated?

Science at Home

What Gives? Show your family how liquids and gases differ. Completely fill the bulb and cylinder of a turkey baster with water. Hold it over the sink. While you seal the end with your finger, have a family member squeeze the bulb. Now let the water out of the turkey baster. Again, seal the end with your finger and have a family member squeeze the bulb. Was there a difference? Use what you know about liquids and gases to explain the observations.

SECTION 2 Gas Behavior

DISCOVER ACTIVITY

How Can Air Keep Chalk From Breaking?

1. Standing on a chair or table, 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?

Every Thanksgiving, the people of New York City gather to watch a big parade. Maybe you have seen this parade on television, or even in person. The parade is famous for its large, floating balloons, like the one shown on this page. The balloons float because they are filled with helium, a gas that is less dense than air.

If you were in charge of a parade balloon, you would be faced with many different questions. How large is the balloon? How much helium should you put inside the balloon? Does the balloon behave differently in warm weather than in cold weather? To answer these questions and others like them, you would need to understand the properties of gases.

GUIDE FOR READING

- **How are the volume, temperature, and pressure of a gas related?**

Reading Tip **Before you read, change each heading into a question. Write a brief answer to each question as you read.**

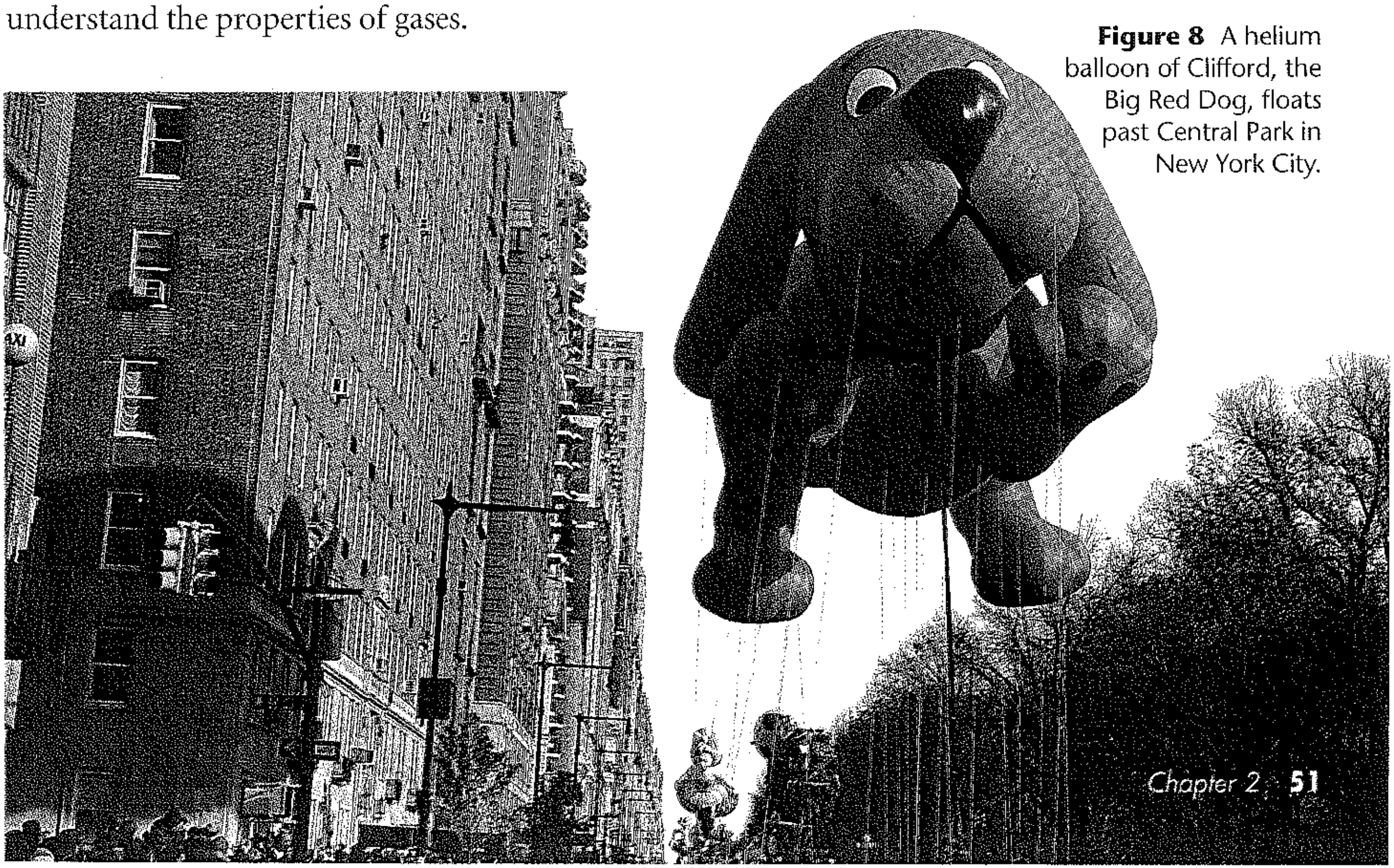


Figure 8 A helium balloon of Clifford, the Big Red Dog, floats past Central Park in New York City.

Figure 9 The helium gas in this tank is kept under high pressure within the volume set by the thick steel walls. *Predicting What happens to the helium atoms as they move into the balloons?*

Measuring Gases

How much helium is in the tank in Figure 9? You may think that measuring the volume of the tank will give you an answer. But gases easily squeeze together or spread out. To fill the tank, helium was compressed, or pressed together tightly. When the helium is used, it fills a total volume of inflated balloons much greater than the volume of the tank. The actual volume you get, however, depends on the temperature and air pressure that day. So what exactly do measurements of volume, pressure, and temperature mean?

Volume You know volume is the amount of space that matter fills. Volume is measured in cubic centimeters, milliliters, liters, and other units. Because gases 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 should be familiar with matter at different temperatures. But what exactly does temperature measure? Recall that in any substance—solid, liquid, or gas—the particles are constantly moving. **Temperature** is a measure of the average energy of 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 20°C, which is about room temperature, the particles in a typical gas travel about 500 meters per second!

Sharpen your Skills

Developing Hypotheses

ACTIVITY

1. Pour soapy water into a large pan. Add a little glycerin, if available.
2. Bend the ends of a wire or long pipe cleaner into a circle.
3. Dip the wire circle into the soapy water and then blow into the wire shape to make several bubbles. Observe the bubbles that you produce.
4. What factors seem to change the volume of the soap bubbles? How could you test your hypothesis?

Pressure Because gas particles are moving, they constantly collide with one another. They also collide with the walls of their container. As a result, the gas exerts an outward push 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 kilopascals (kPa).

INTEGRATING PHYSICS

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

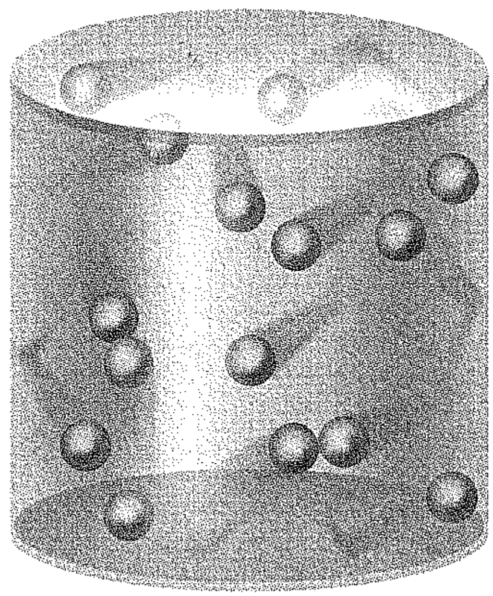


Figure 10 The gas particles are in constant motion, colliding with each other and with the walls of their container.

The firmness of an object inflated with a gas, such as a soccer ball, comes from the pressure of the gas. If the gas (in this case, air) leaks out of the ball, the pressure decreases and the ball becomes softer. But why does an inflated ball leak when punctured? A gas flows from an area of high pressure to an area of low pressure. The air inside the ball is at a higher pressure than the air outside. Gas particles inside the ball hit the hole more often than gas particles outside the hole. Because more inside particles hit the hole, they have a better chance of getting out of the ball. Thus, many more particles go out than in. The pressure inside drops until it is equal to the pressure outside.

☑ *Checkpoint* *What are three properties of a gas that you can measure?*

Relating Pressure and Volume

Pressure is also related to the volume of a container. For example, imagine that you are operating 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?

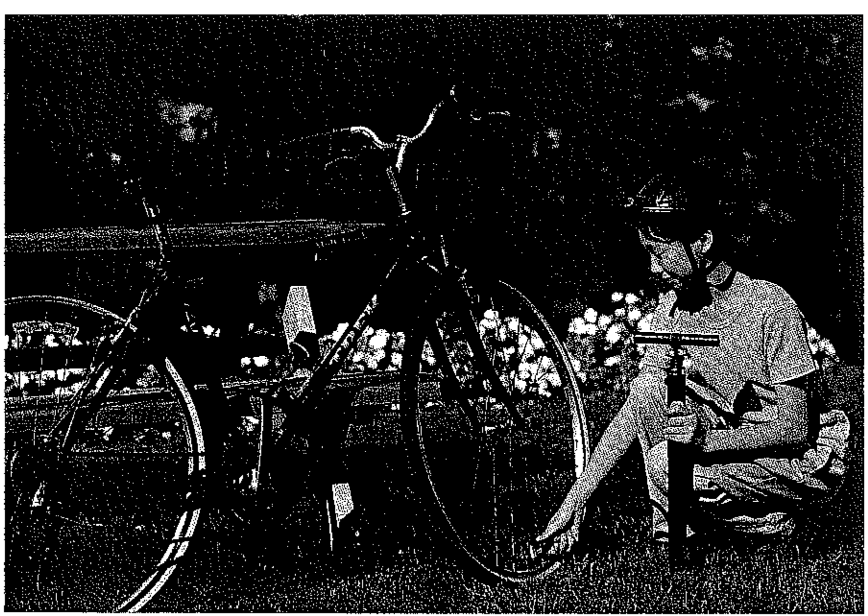


Figure 11 What will happen when this bicyclist operates the pump she is attaching? She will decrease the volume of air in the cylinder and increase its pressure. As a result, air will be forced into the bicycle tire and the tire will inflate.

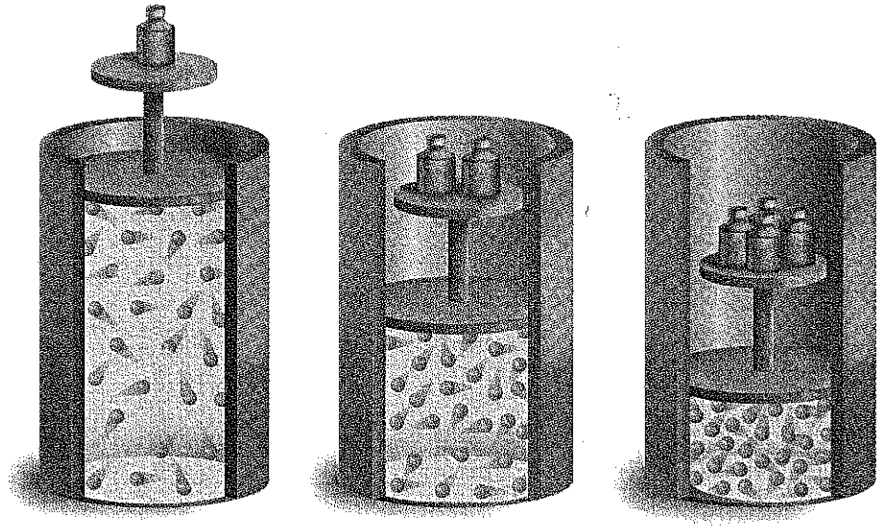


Figure 12 As weights are added on top, the same number of particles occupies a smaller volume. The pressure of the gas increases. This relationship is called Boyle's law.

The answer to this question comes from experiments with gases done by the English scientist Robert Boyle. In the 1600s, Boyle measured the volumes of gases at different pressures as he experimented with ways to improve air pumps. He saw that gases behave in a predictable way. **Boyle found that when the pressure of a gas is increased at constant temperature, the volume of the gas decreases. When the pressure is decreased, the volume increases.** This relationship between the pressure and volume of a gas is named **Boyle's law.**

INTEGRATING EARTH SCIENCE Boyle's law plays an important role in research done with some high-altitude balloons. These balloons are made from lightweight plastic. They are filled with only a small fraction of the helium they could hold. Why is that? As a balloon rises through the atmosphere, the air pressure around it decreases steadily. As the air pressure decreases, the helium inside the balloon expands, stretching the balloon to a greater and greater volume. 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. For example, if you squeeze an inflated balloon, you are decreasing its volume. You should be able to feel the increased pressure of the gas inside it. The bicycle pump described earlier is a similar case. As you push on the plunger, the volume of air inside the pump gets smaller and the pressure increases.

☑ *Checkpoint* *What is Boyle's law?*

Relating Pressure and Temperature

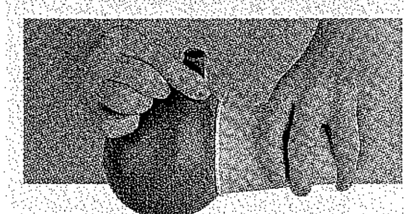
If you pour a bucketfull of sand onto your skin, it will not hurt at all. But suppose you are caught in a sandstorm. Because the sand grains are flying very fast, they will hurt a great deal! The faster the grains are traveling, the harder they will hit your skin.

TRY THIS

Balloon Test

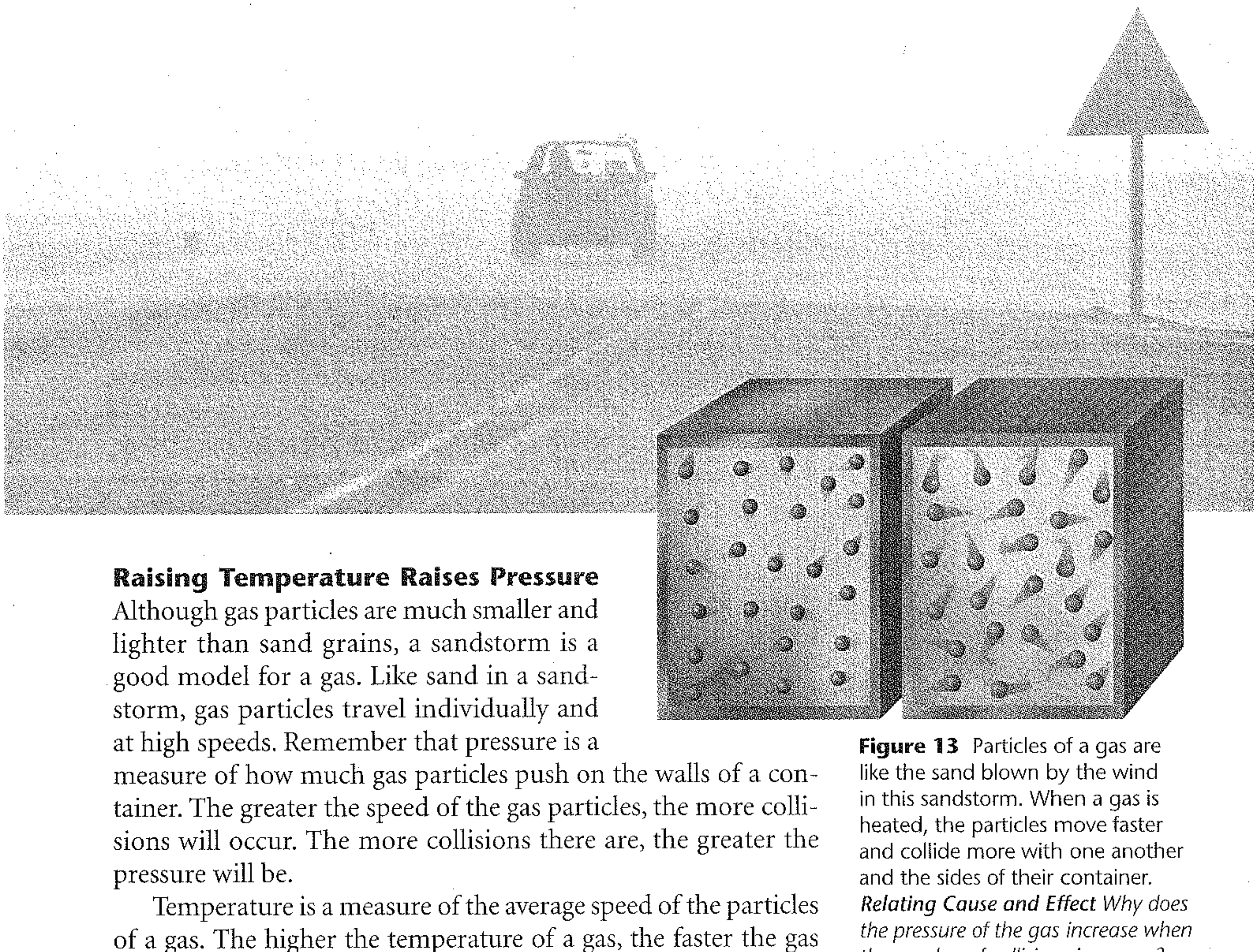
ACTIVITY

What happens when you change the volume of a gas?



1. Hold the open end of a paper cup on the side of a partly inflated balloon.
2. Inflate the balloon until it presses against the cup and then let go of the cup. What happens?

Developing Hypotheses Use what you know about pressure and volume to write a hypothesis that explains the behavior of the cup after you let it go. How could you test your hypothesis?



Raising Temperature Raises Pressure

Although gas particles are much smaller and lighter than sand grains, a sandstorm is a good model for a gas. Like sand in a sandstorm, gas particles travel individually and at high speeds. Remember that pressure is a measure of how much gas particles push on the walls of a container. The greater the speed of the gas particles, the more collisions will occur. The more collisions there are, the greater the pressure will be.

Figure 13 Particles of a gas are like the sand blown by the wind in this sandstorm. When a gas is heated, the particles move faster and collide more with one another and the sides of their container. ***Relating Cause and Effect*** *Why does the pressure of the gas increase when the number of collisions increases?*

Temperature is a measure of the average speed of the particles of a gas. The higher the temperature of a gas, the faster the gas 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.** A constant volume means a closed, rigid container.

Pressure and Temperature in Action Have you ever looked at the tires of an 18-wheel truck? Because these 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 get very hot. As the temperature increases, so does the pressure of the air inside the tire. If the pressure becomes higher than the tire can hold, the tire will burst apart. For this reason, truck drivers need to monitor and adjust tire pressure on long trips.

Relating Volume and Temperature

If the temperature of the gas in a balloon is increased, its volume will change. Will the volume increase or decrease? If you answered "increase," you are right. Gases increase in volume when the temperature increases. On the other hand, as the temperature decreases, the gas volume decreases. People in charge of the large balloons used for parades need to understand the effect that temperature has on volume so that the balloons can be inflated properly.

Charles's Law In the late 1700s, a French scientist named Jacques Charles examined the relationship between the temperature and volume of a gas kept at a constant pressure. He measured the volume of a gas at various temperatures in a container whose volume could change. **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.** Remember that at higher temperatures, gas particles move faster. As a result, they collide more often with the walls around them. As long as the volume of the container can change, the total push of the collisions results in the gas taking up more space. The volume of the gas increases.

Charles's Law in Action You can see the effects of Charles's law demonstrated with a simple party balloon. Look at Figure 15 on the next page. The photograph on the left shows a balloon in a beaker of water, resting on a tub of ice. A smaller beaker of water keeps the balloon submerged in the larger beaker. In the photograph on the right, the beakers have been

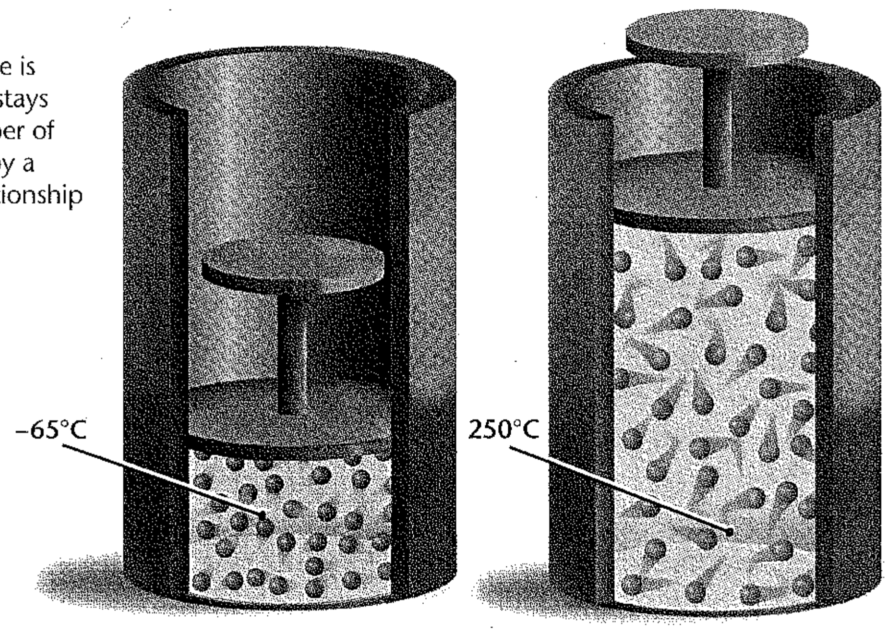
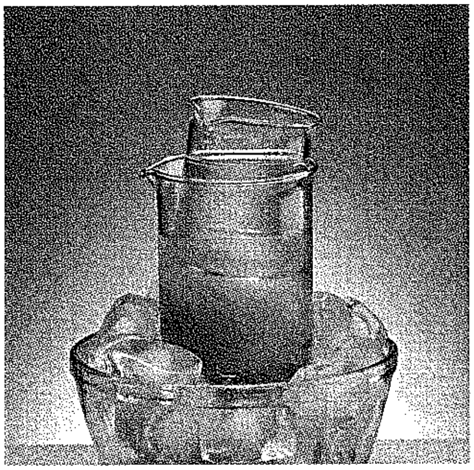
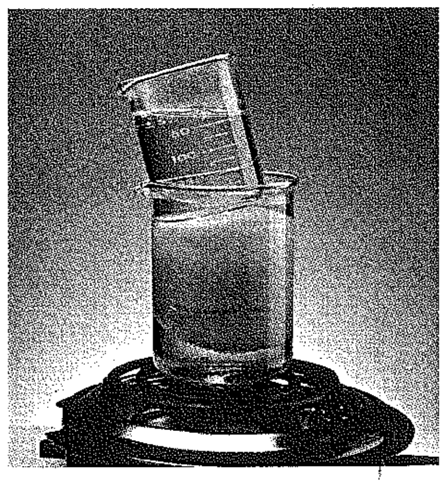


Figure 14 If temperature is increased while pressure stays constant, the same number of particles of gas will occupy a greater volume. This relationship is called Charles's law.

transferred to a hot plate and heated. When you compare the photos, you should notice a change. The balloon on the right is larger. This difference is the result of an increase in the volume of the air as it is heated.

In this example, pressure remains more or less constant because the expanding air is in a flexible container. But what would happen if the balloon reached its limit in size? When the balloon can no longer expand, the continued increase in temperature would cause an increase in pressure. Eventually the pressure would break the balloon.

Boyle, Charles, and others often described the behavior of gases by focusing on only two variables 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, must consider these combined effects.

Figure 15 Observe what happens to the volume of the balloon when it is heated. *Predicting How might the balloon on the right change if it were allowed to cool down?*

Section 2 Review

1. Describe the relationship between the pressure and the volume of a gas.
2. If you change the temperature of a gas but keep the volume the same, how does the pressure change?
3. What is Charles's law?
4. **Thinking Critically Applying Concepts** Suppose it is the night before Thanksgiving, and you are in charge of inflating a balloon for the Thanksgiving Day parade. You just learned that the temperature will rise 15°C by the time the parade starts. How will this information affect the way you inflate your balloon?

Check Your Progress

CHAPTER PROJECT

With the members of your group, write a description of how particles behave in each of the three states of matter. Next, think of different ways to model each state, using drawings and words. Decide if you want to demonstrate a change of state as cartoon pictures or by acting out the motion of particles in a skit. (*Hint:* Prepare a storyboard. A storyboard is a series of simple drawings and captions that outline the action of a story.)

Section 3 Graphing Gas Behavior

DISCOVER ACTIVITY

What Does a Graph of Pressure and Temperature Show?

Temperature (°C)	Pressure (kPa)
0	8
5	11
10	14
15	17
20	20
25	23

1. In an experiment, the temperature was varied for a constant volume of gas. Gas pressure was measured after each 5°C change. You now need to graph the data in this table.
2. Show temperature on the horizontal axis with a scale from 0°C to 25°C. Show pressure on the vertical axis with a scale equally spaced from 0 kPa to 25 kPa.
3. For each pair of measurements, draw a point on the graph.
4. Draw a line to connect the points.

Think It Over

Graphing Use the graph to describe the relationship between the pressure and temperature of a gas.

GUIDE FOR READING

- **What do graphs for Charles's law and Boyle's law look like?**

Reading Tip **As you read about the experiments in this section, refer to the graphs in Figures 19 and 21.**

The population of a town is increasing. The schools are becoming more crowded, and the people need to decide whether to build more schools. Newspapers illustrate their articles about the problem with graphs.

How could a graph help tell this story? **Graphs** are diagrams that tell how two variables, or factors, are related. Graphs show how changes in one variable result in changes in a second variable. You can use graphs to make predictions. For example, according to the graph in Figure 16, the town might have a population of 32,000 in 2020. That assumes, of course, that population continues to grow by the same amount. In this section, you will learn how to interpret graphs that relate properties of gases.

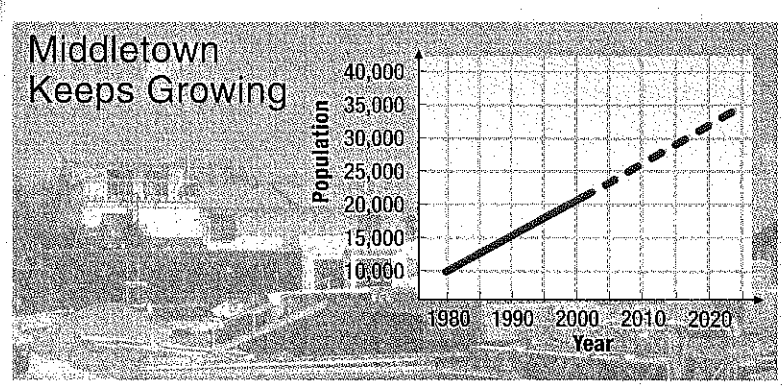
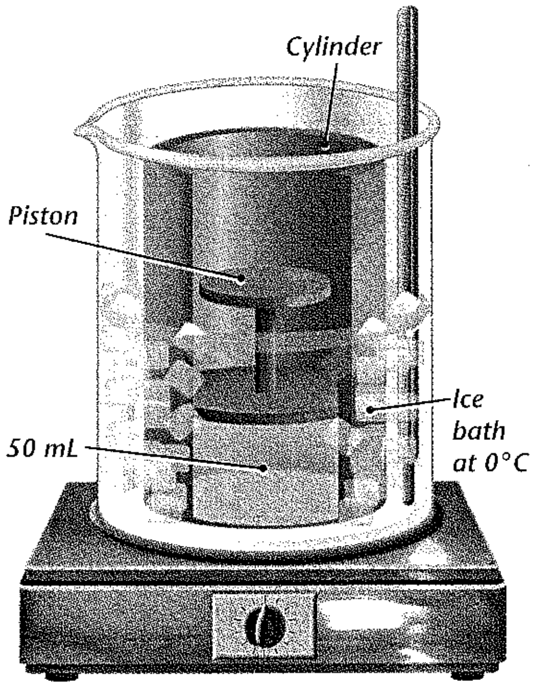


Figure 16 This graph shows that population in the town is growing steadily. The dashed line predicts what the population would be if the current growth rate continues.



Temperature (°C)	Temperature (K)	Volume (mL)
0	273	50
10	283	52
20	293	54
30	303	56
40	313	58
50	323	60
60	333	62
70	343	63
80	353	66
90	363	67
100	373	69

Figure 17 As the temperature of the water bath increases, the gas inside the cylinder is warmed by the water. The data from the experiment are recorded in the table. Celsius temperature measurements are converted to kelvins by adding 273 to each value.

Temperature and Volume

Recall from Section 2 that Charles's law relates the temperature and volume of a gas kept at a constant pressure. You can examine this relationship by doing an experiment in which you change the temperature of a gas and measure its volume. Then you can graph the data you have recorded and look for a relationship.

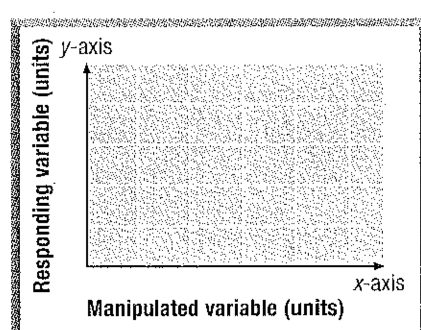
Collecting Data As you can see from the cutaway view in Figure 17, the gas in the experiment is in a cylinder that has a movable piston. The piston moves up and down freely, which allows the gas to change volume and keep the same pressure. To control the temperature, the cylinder is placed in a water bath.

The experiment begins with an ice-water bath at 0°C, and the gas volume at 50 mL. Then the water bath is slowly heated. Very gradually, the temperature increases from 0°C to 100°C. Each time the temperature increases by 10°C, the volume of the gas in the cylinder is recorded.

You'll notice a second set of temperatures listed in the table in Figure 17. Scientists often work with gas temperatures in units called kelvins. To convert from Celsius degrees to kelvins, you add 273. The kelvin temperatures will be used to graph the data.

Graphing the Results A graph consists of a grid set up by two lines—one horizontal and one vertical. Each line, or axis, is divided into equal units. The horizontal, or *x*-, axis shows the manipulated variable, in this case, temperature. The vertical,

Figure 18 The horizontal, or *x*-, axis and the vertical, or *y*-, axis are the "backbone" of a graph. ***Interpreting Diagrams*** *Which variable is placed on the x-axis?*



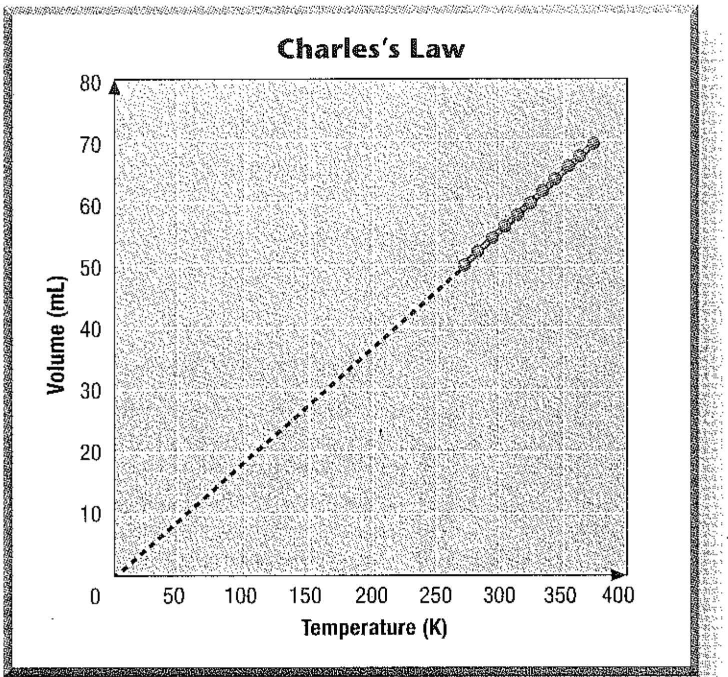


Figure 19 This graph of the data from Figure 17 shows the linear relationship between temperature and volume known as Charles's law. The dotted line predicts how the graph would look if the gas could be cooled to lower temperatures.

or *y*-, axis shows the responding variable, in this case, volume. Each axis is labeled with the name of the variable, the units of measurement, and a range of values.

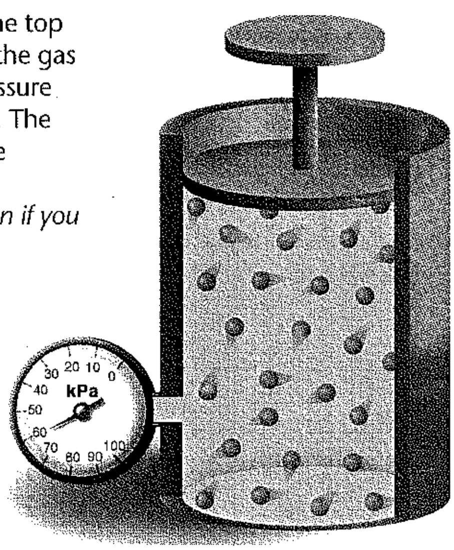
Look at the graph in Figure 19. It appears as if the line would continue downward if data could be collected for lower temperatures. Such a line would pass through the point (0, 0). When a graph of two variables is a straight line passing through the (0, 0) point, the relationship is linear and the variables are said to be **directly proportional** to each other. **The graph of Charles's law shows that the volume of a gas is directly proportional to its kelvin temperature under constant pressure.**

☑ *Checkpoint On which axis of a graph do you show the responding variable?*

Pressure and Volume

You can perform another experiment to show how pressure and volume are related when temperature is kept constant. Recall that the relationship between pressure and volume is called Boyle's law.

Figure 20 By pushing on the top of the piston, you compress the gas and thereby increase the pressure of the gas inside the cylinder. The data from the experiment are recorded in the table.
Predicting What would happen if you pulled up on the piston?



Volume (mL)	Pressure (kPa)
100	60
90	67
80	75
70	86
60	100

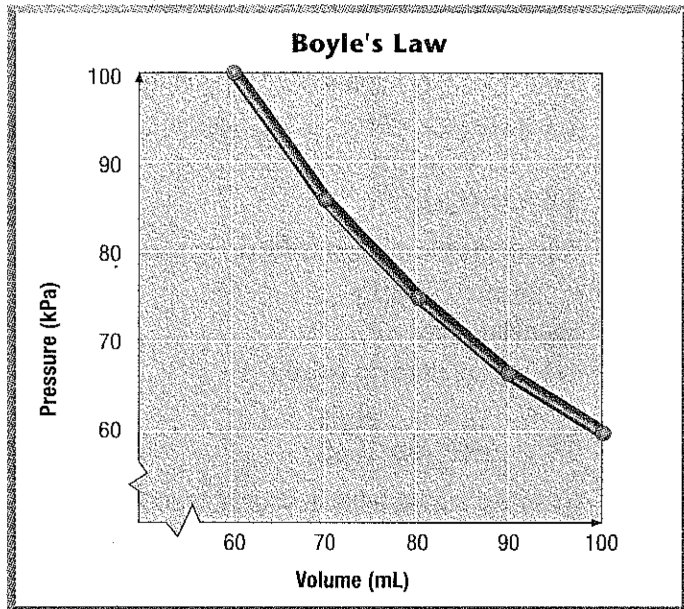
Collecting Data The gas in this experiment is also contained in a cylinder with a movable piston. In this case, however, a pressure gauge indicates the pressure of the gas inside.

The experiment begins with the volume of the gas at 100 mL. The pressure of the gas is 60 kilopascals. Next, the piston is slowly pushed into the cylinder, compressing the gas, or shrinking its volume. The pressure of the gas is recorded after each 10-mL change in volume.

Graphing the Results To observe the relationship of the pressure and volume of a gas, it helps to display the data in another graph. In the pressure-volume experiment, the manipulated variable is volume. Volume is shown on the scale of the horizontal axis from 60 mL to 100 mL. The responding variable is pressure. Pressure is shown on the scale of the vertical axis from 60 kPa to 100 kPa.

As you can see in Figure 21, the points lie on a curve. Notice that the curve slopes downward from left to right. Also notice that the curve is steep close to the vertical axis and becomes less steep close to the horizontal axis. When a graph of two measurements forms this kind of curve, the relationship is nonlinear and the measurements are said to **vary inversely** with each other. **The graph for Boyle's law shows that the pressure of a gas varies inversely with its volume at constant temperature.** In other words, the pressure of a gas decreases as its volume increases.

Figure 21 This graph of the data from Figure 20 shows the nonlinear relationship between pressure and volume known as Boyle's law. (The broken lines between 0 and 60 show gaps in the scales.)



Section 3 Review

1. Describe a graph of Charles's law.
2. Describe a graph of Boyle's law.
3. How can you tell the difference between a graph in which one variable is directly proportional to another and a graph in which two variables vary inversely?
4. **Thinking Critically Interpreting Graphs** Suppose the temperature of the gas in the experiment illustrated in Figure 17 was increased to 400 K (127°C). Use Figure 19 to predict the new volume of the gas.

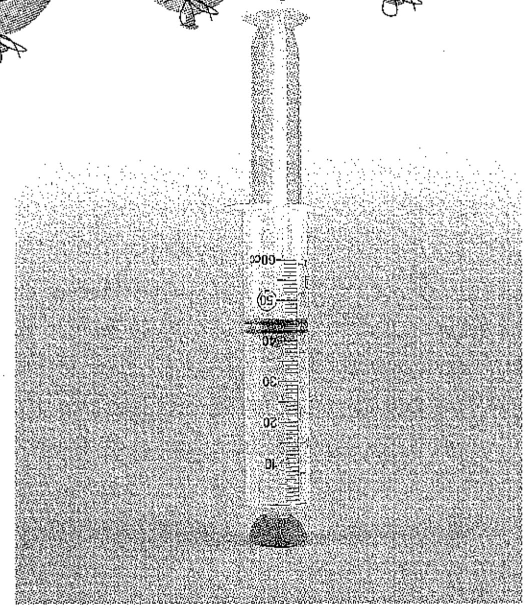
Science at Home

News Data Look for graphs in your newspaper or in news magazines. Point out to members of your family which variable is the manipulated variable and which is the responding variable for each graph. Then compare any line graphs you have found to the graphs in this section. Which of your graphs show two variables that are directly proportional to each other? Do any show variables that vary inversely?

Skills Lab

Drawing Conclusions

It's a Gas



You can use a syringe as a model of an air pump. In this lab, you will determine how the pressure you exert on a syringe is related to the volume of the air inside it.

Problem

How does the volume of a gas change as the pressure you exert on it increases?

Materials

strong plastic syringe (with no needle), at least 35 cm^3 capacity
modeling clay
4 books of uniform weight

Procedure

1. Make a data table in your notebook like the one below.
2. Lift the plunger of the syringe as high as it will move without going off scale. The volume inside the syringe will then be as large as possible.
3. Seal the small opening of the syringe with a piece of clay. The seal must be airtight.
4. Hold the syringe upright with the clay end on the table. With the help of a partner, place a single book on top of the plunger. Balance the book carefully so it does not fall.
5. Read the volume indicated by the plunger and record it in your data table.
6. Predict what will happen as more books are placed on the syringe.
7. Place another book on top of the first book. Read the new volume and record it in your data table.

DATA TABLE

Adding Books		Removing Books	
Number of Books	Volume (cm^3)	Number of Books	Volume (cm^3)
0		4	
1		3	
2		2	
3		1	
4		0	

8. One by one, place each of the remaining books on top of the plunger. After you add each book, record the volume of the syringe in your data table.
9. Predict what will happen as books are removed from the plunger one by one.
10. Remove the books one at a time. After you remove each book, again record the volume of the syringe in your data table.

Analyze and Conclude

1. Make a line graph of the data obtained from Steps 5, 7, and 8. Show volume in cubic centimeters (cm^3) on the vertical axis and number of books on the horizontal axis. Title this Graph 1.
2. Make a second line graph of the data obtained from Step 10. Title this Graph 2.
3. Did the results you obtained support your predictions in Steps 6 and 9? Explain.
4. Describe the shape of Graph 1. What does the graph tell you about the relationship between the volume and pressure of a gas?
5. Compare Graph 2 with Graph 1. How can you explain any differences in the two graphs?
6. **Think About It** Did the volume change between the addition of the first and second book? Did it change by the same amount between the addition of the second book and third book? Between the third and fourth book? What is happening to the gas particles in air that could explain this behavior?

Design an Experiment

How could you use ice and warm water to show how the temperature and volume of a gas are related? Design an experiment to test the effect of changing the temperature of a gas. With your teacher's approval, conduct this experiment.

SECTION 4 Changes in State

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?

GUIDE FOR READING

- When thermal energy is transferred, in what direction does it flow?
- How does the energy of a substance change when it changes state?

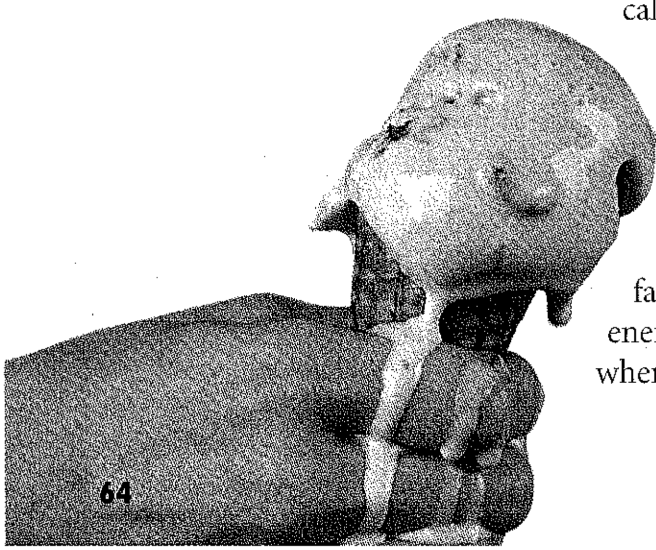
Reading Tip As you read, make an outline that includes the headings and main ideas of the section.

Think of what happens to 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.

Energy and Changes in State

Under different conditions, a substance may be at different temperatures. At a warmer temperature, the particles of the substance have a higher average energy of motion than at a cooler temperature. The energy that the particles of a substance have is called **thermal energy.** The amount of thermal energy in a substance depends partly on its temperature and the way its particles are arranged.

Thermal energy is transferred from one substance to another as heat. **Thermal energy always flows from a warmer substance to a cooler substance.** When heat flows into a substance, its particles gain energy and move faster. When heat flows from a substance, its particles lose energy and move more slowly. So thermal energy is involved when a substance changes state.



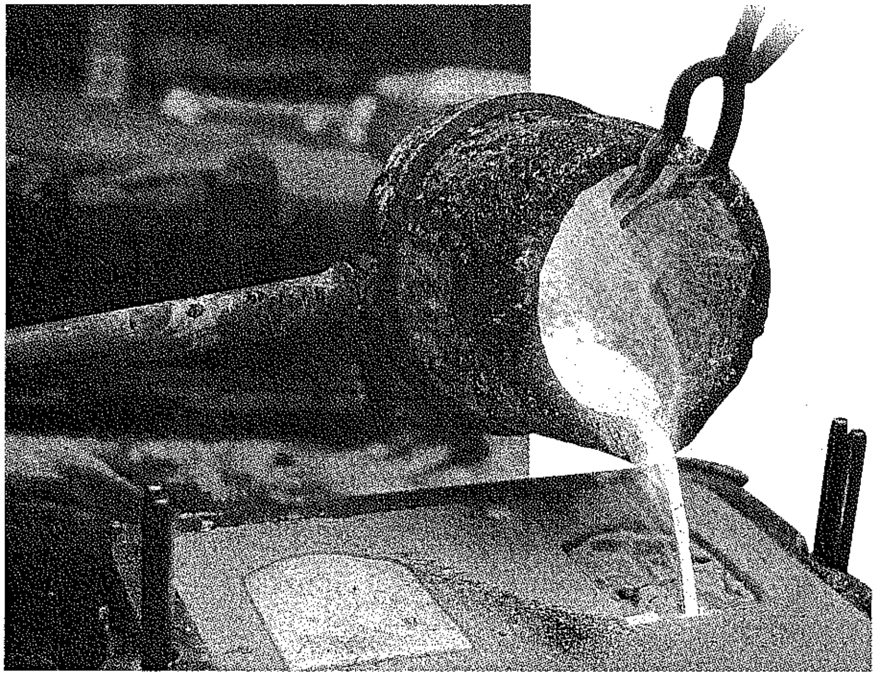


Figure 22 A jeweler melts silver before pouring it into a mold. ***Predicting*** *What happens to the silver particles as the melted silver cools down?*

You saw that the arrangement and motion of the particles of a substance determine whether the substance is a solid, a liquid, or a gas. The particles of a solid have the least thermal energy. They simply vibrate in a fixed position. The particles of a liquid have more thermal energy. They move around one another freely, although they remain close to one another and are confined to a definite volume. The particles of a gas have the most thermal energy. They are separated from one another and move around in all directions at high speeds. **A substance changes state when its thermal energy increases or decreases by a sufficient amount.**

Changes Between Liquid and Solid

Each specific substance changes states at temperatures that are typical for that substance. But the overall pattern for the way substances change state is the same.

Melting The change in state from a solid to a liquid is **melting.** In Section 1, you saw that a crystalline solid melts at a specific temperature, called the melting point. The melting point of a substance depends on how strongly its particles attract one another.

Think of an ice cube taken from the freezer. The energy to melt comes from the air in the room. At first, the added thermal energy makes the water molecules vibrate faster, raising their temperature. At 0°C, the water molecules are vibrating so fast that they break free from their positions in ice crystals. For a time, the temperature of the ice stops increasing. Instead, the added energy changes the arrangement of the water molecules from ice crystals into liquid water. This is the process you observe as melting.

☑ *Checkpoint* *What happens to the particles of a solid as it gains more and more thermal energy?*

Social Studies CONNECTION

In the United States, home refrigerators became common in the 1920s. Before then, people used ice to keep food cold. Blocks of ice were cut from frozen lakes and stored in "ice houses." Many people earned their livings by supplying ice to homes and businesses.

In Your Journal

Imagine that it's about 1920.Your family is in the ice business. You have just heard about a new product called a refrigerator. Write a letter describing how this new product will change your life.

Figure 23 In this photo taken in New England about 1890, you can see the pond ice was cut into large blocks. The blocks were stored in the icehouse.

Freezing Now suppose you put the liquid water from the melted ice cube into a freezer. After a while, the water will freeze back into ice. **Freezing** is the change of state from liquid to solid—just the reverse of melting.

When you put liquid water into the freezer, the water loses energy to the cold air in the freezer. At first, the water molecules move more slowly. When the temperature reaches 0°C, the molecules are moving so slowly that they form regular patterns. These patterns are the crystals that form ice. When water freezes, the temperature stays at 0°C until freezing is complete. (This is the same temperature at which ice melts.)

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 the ways that water changes between the liquid and gas states.

Vaporization The change from liquid water into water vapor is an example of **vaporization** (vay puhr ih ZAY shuhn). Vaporization occurs when a liquid gains enough energy to become a gas. There are two main types of vaporization.

The first kind, called **evaporation** (ee vap uh RAY shun), takes place only on the surface of a liquid. A drying puddle is an example. The water in the puddle gains energy from the ground, the air, or the sun. The energy enables the molecules on the surface of the puddle to escape into the air. Evaporation also occurs when you sweat. Sweat evaporates as it gains thermal energy from your skin, cooling you down on a hot day or when you exercise.

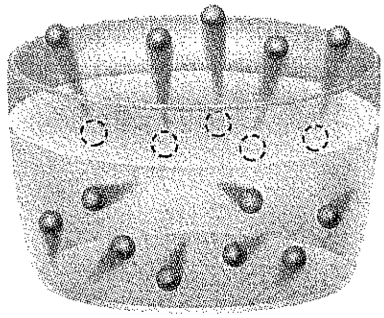


Figure 24 During evaporation, particles leave the surface of a liquid.

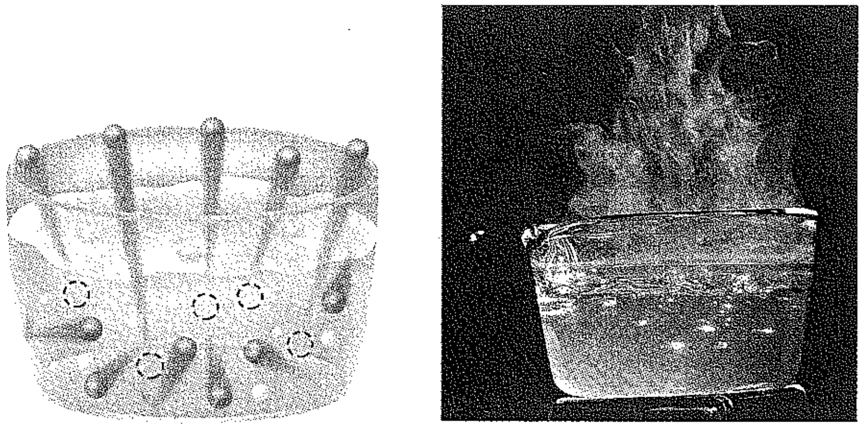


Figure 25 During boiling, groups of particles form bubbles of gas at many locations throughout the liquid. These bubbles rise to the surface, where the particles escape. ***Applying Concepts*** *What happens to the boiling point of water when the air pressure increases?*

The second kind of vaporization, called **boiling,** takes place inside a liquid as well as at the surface. Each liquid boils at a specific temperature called its **boiling point.** Like the melting point of a solid, the boiling point of a liquid depends on how strongly the particles of the substance are attracted to one another.

Boiling Point and Air Pressure The boiling point of a sub-

INTEGRATING EARTH SCIENCE

stance depends on the pressure of the air above a liquid. The lower the air pressure above the liquid, the less energy that liquid molecules need to escape into the air. As you go up in elevation, air pressure decreases. At the air pressure 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 the boiling point of water.

The city of Denver, Colorado, is 1,600 meters above sea level for example. At this elevation, the boiling point of water is 95°C. When a recipe calls for boiling water, cooks in Denver have to be careful. Food doesn't cook as quickly at 95°C as it does at 100°C.

Condensation The opposite of vaporization is called condensation. **Condensation** occurs when gas particles lose enough thermal energy to become a liquid. 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 can observe condensation 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. The droplets then evaporate into water vapor again.

Remember that when you observe steam from boiling water, clouds, or mist, you are not seeing water vapor, a gas that's impossible to see. What you see in those cases are tiny droplets of liquid water suspended in air.

☑ ***Checkpoint*** *How are vaporization and condensation related?*

Changes Between Solid and Gas

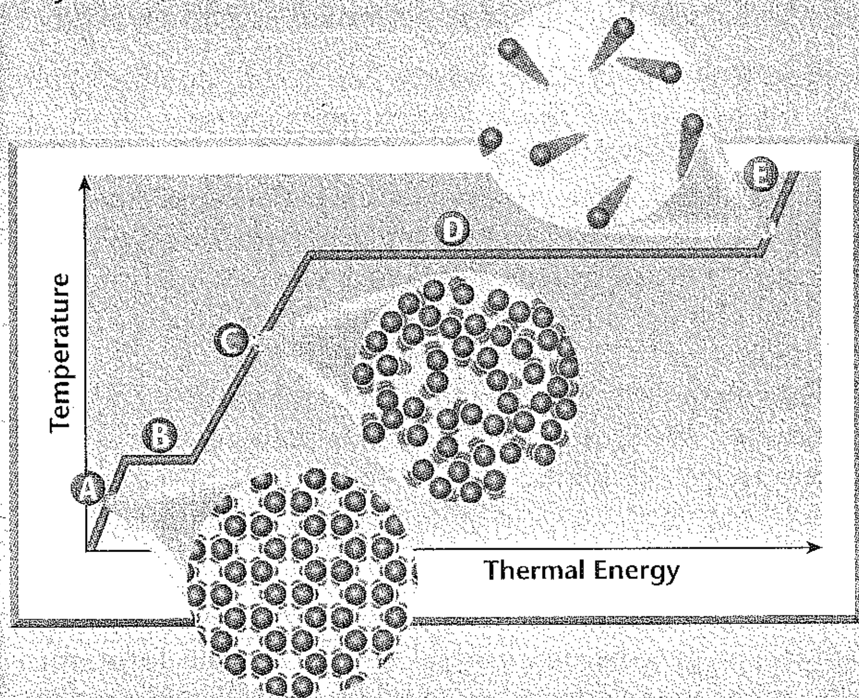
If you live where the winters are cold, you may have noticed that snow seems to disappear even when the temperature stays well below freezing. This happens because of sublimation. **Sublimation** occurs when the surface particles of a solid gain enough energy to become a gas. Particles do not pass through the liquid state at all. Some solids, such as naphthalene (moth balls), sublime more easily than others, such as table salt.

EXPLORING *Changes of State*

What changes occur as you slowly heat a beaker of ice from –10°C to 110°C?

A ***Solid***
Below 0°C, water exists in its solid state—ice. Although the water molecules in ice crystals stay in fixed positions, they do vibrate. As the molecules are heated, they vibrate faster and the temperature rises.

B ***Melting***
When more energy is added to ice at 0°C, the molecules overcome the forces that keep them in ice crystals. The ice melts or turns to liquid water. As ice melts, the molecules rearrange but do not move faster. Thus, the temperature of the ice stays at 0°C.



C ***Liquid***
Water must be liquid before its temperature can rise above 0°C. As liquid water is heated, the molecules move faster and the temperature rises again.

D ***Vaporization***
When more energy is added to liquid water at 100°C, molecules escape the liquid state and become a gas. This process is called vaporization. When water boils, the molecules overcome the forces that hold them together as liquids, but they do not move faster. Thus, the temperature stays at 100°C.

E ***Gas***
Water must be in its gas state—called water vapor—before its temperature can rise above 100°C. As water vapor is heated, the molecules move faster and the temperature rises again.

Figure 26 shows a common example of sublimation, the change in dry ice. "Dry ice" is the common name for solid carbon dioxide (CO_2). At ordinary air pressures, carbon dioxide cannot exist as a liquid. So instead of melting, solid carbon dioxide changes directly into a gas. As it changes state, it absorbs thermal energy, so it keeps materials near it cold and dry. For this reason, it's an excellent way to keep temperatures low when a refrigerator is not available. Recall that you cannot see the gas that dry ice forms. The fog around it results when water vapor from the nearby air cools and forms tiny droplets.

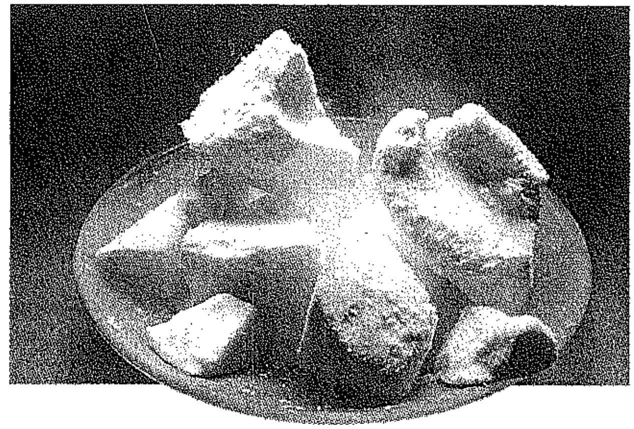


Figure 26 Dry ice is solid carbon dioxide. It changes directly to gaseous carbon dioxide in the process of sublimation. The energy absorbed in this change of state cools the water vapor in the air, creating fog. ***Inferring*** *Describe what happens to the carbon dioxide particles during sublimation.*

Identifying Substances Through Changes of State

Chemists sometimes face the problem of identifying unknown materials. In Chapter 1, you learned that the combination of properties a substance has can be used to identify it. To make such identification possible, chemists have built up a data bank of information about the properties of substances. As a result, comparing melting points and boiling points can be important steps in identifying an unknown material.

Suppose, for example, that chemists are trying to identify three clear, colorless liquids. One is water, another is chloroform (once used to cause sleep during surgery), and a third is ethanol (a type of alcohol). You already know the melting and boiling points of water. Chloroform melts at –64°C and boils at 61°C. Ethanol melts at –117°C and boils at 79°C. You can thus see how testing for these properties would help researchers identify them.

Section 4 Review

1. If an object at 50°C is placed in ice water, how will the object's temperature change? Explain.
2. What is happening to the particles of a liquid as it changes into a gas?
3. What's the main difference between boiling and evaporation?
4. Explain what happens to dry ice when it is left standing at room temperature.
5. **Thinking Critically Applying Concepts** If you are stranded in a blizzard and are trying to stay warm, why should you melt snow and then drink it instead of just eating snow?

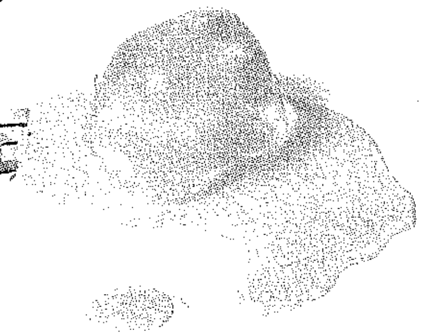
Check Your Progress CHAPTER PROJECT

Use the information you learned in this section to revise your storyboard, if necessary. Then if you are creating a cartoon, draw the cartoon and write the captions. If you are presenting a skit, write a script and stage directions. Rehearse the skit with the members of your group.

Skills Lab

Measuring

Melting Ice



In this experiment, you will measure the temperature of melting ice.

Problem

How does the temperature of the surroundings affect the rate at which ice melts?

Materials

stopwatch or timer
thermometer or temperature probe
2 plastic cups, about 200 mL each
2 stirring rods, preferably plastic
ice cubes, about 2 cm on each side
warm water, about 40°C–45°C
water at room temperature, about 20°C–25°C

Procedure

1. Read Steps 1–8. Based on your own experience, predict which ice cube will melt faster.
2. In your notebook, make a data table like the one below.
3. Fill a cup halfway with warm water (about 40°C to 45°C). Fill a second cup to the same depth with water at room temperature.
4. Record the exact temperature of the water in each cup. If you are using a temperature probe, see your teacher for instructions.
5. Obtain two ice cubes that are as close to the same size as possible.
6. Place one ice cube in each cup. Begin timing with a stopwatch. Gently stir each cup with a stirring rod until the ice has completely melted.
7. Observe both ice cubes carefully. At the moment one of the ice cubes is completely melted, record the time and the temperature of the water in the cup.
8. Wait for the second ice cube to melt. Record its melting time and the water temperature.

Analyze and Conclude

1. Was your prediction in Step 1 supported by the results of the experiment? Explain why or why not.
2. In which cup did the water temperature change the most? Explain this result.
3. When the ice melted, its molecules gained enough energy to overcome the forces holding them together as solid ice. What is the source of that energy?
4. **Think About It** How well could you time the exact moment that each ice cube completely melted? How might errors in measurements affect your conclusions?

Design an Experiment

When a lake freezes in winter, only the top turns to ice. Design an experiment to model the melting of a frozen lake during the spring. With your teacher's approval, carry out your experiment. Be prepared to share your results with the class.

DATA TABLE

	Beginning Temperature (°C)	Time to Melt (s)	Final Temperature (°C)
Cup 1			
Cup 2			

CHAPTER 2 STUDY GUIDE

Section 1 States of Matter

Key Ideas

- Solids have a definite shape and volume because the particles in a solid are packed tightly together and stay in fixed positions.
- Particles in a liquid move freely around one another. A liquid has no definite shape, but it does have a definite volume.
- The particles of a gas spread apart to fill all the space available to them. Thus, a gas has neither definite shape nor definite volume.

Key Terms

solid
crystalline solid
melting point
amorphous solid
liquid
viscosity
gas

Section 2 Gas Behavior

Key Ideas

- At constant temperature, when the volume of a gas decreases, its pressure increases.
- In a rigid container, raising the temperature of a gas increases its pressure.
- In a flexible container, raising the temperature of a gas increases its volume.

Key Terms

temperature
pressure
Charles's law
Boyle's law

Section 3 Graphing Gas Behavior

INTEGRATING MATHEMATICS

Key Ideas

- A graph shows that the volume of a gas and its kelvin temperature are directly proportional at constant pressure.
- A graph shows that the volume of a gas at constant temperature varies inversely with its pressure.

Key Terms

graph
directly proportional
vary inversely

Section 4 Changes in State

Key Ideas

- The particles of a substance gain thermal energy as the temperature increases.
- Changes of state can occur when a substance gains or loses thermal energy.

Key Terms

thermal energy
melting
freezing
vaporization
evaporation
boiling
boiling point
condensation
sublimation

Organizing Information

Compare/Contrast Table Copy the compare/contrast table about the states of matter onto a separate sheet of paper. Then complete it and add a title. (For more on compare/contrast tables, see the Skills Handbook.)

State of Matter	Shape	Volume	Example (at room temperature)
a. ?	Definite	b. ?	Diamond
Liquid	c. ?	Definite	d. ?
Gas	e. ?	Not definite	f. ?

Reviewing Content

For more review of key concepts, see the Interactive Student Tutorial CD-ROM.

Multiple Choice

Choose the letter of the answer that best completes each statement.

1. A substance whose particles are close together but move freely around one another is a(n)
   a. crystalline solid. b. liquid.
   c. gas. d. amorphous solid.
2. Unlike solids and liquids, a gas will
   a. keep its volume in different containers.
   b. keep its shape in different containers.
   c. expand to fill the space available to it.
   d. have its volume decrease when the temperature rises.
3. Boyle's law states that the volume of a gas increases when its
   a. pressure increases.
   b. pressure decreases.
   c. temperature falls.
   d. temperature rises.
4. The vertical axis of a graph shows the
   a. responding variable.
   b. manipulated variable.
   c. constant factors.
   d. same variable as the x-axis.
5. When a liquid freezes, its particles
   a. move more rapidly.
   b. escape from its surface more quickly.
   c. vibrate faster.
   d. slow down and form patterns.

True or False

If the statement is true, write true. If it is false, change the underlined word or words to make it a true statement.

6. Rubber and glass become softer and softer over a wide range of temperatures. They are examples of crystalline solids.
7. The energy from the movement of particles is measured by the temperature of a substance.
8. If a gas is contained in a rigid container, raising its temperature will increase its volume.
9. Charles's law states that the volume of a gas varies inversely with its temperature.
10. The boiling point of a liquid is lower at sea level than on a mountain.

Checking Concepts

11. Describe the motion of particles in a solid.
12. Compare and contrast liquids with high and low viscosities.
13. How is the temperature of a substance related to the energy of movement of the particles in the substance?
14. What happens to the gas particles when the air in an inflated ball leaks out?
15. What happens during condensation?
16. What happens to water molecules when water is heated from 90°C to 110°C?
17. Compare the processes of melting and freezing.
18. **Writing to Learn** Imagine you are Robert Boyle or Jacques Charles at the time you described the law that came to be known by your name. Tell the story of your experiments and results as you think Boyle or Charles would if either one could talk to the students in your class today. Write down exactly what you would say.

Thinking Critically

19. **Relating Cause and Effect** Explain why placing a dented table tennis ball in boiling water is one way to remove a dent in the ball. Assume it has no holes.
20. **Comparing and Contrasting** Using diagrams, show the gas particles in an air mattress before you lie down on it and while you are lying on it.
21. **Applying Concepts** Describe what happens when an ice cube and solid carbon dioxide are each placed in a warm room. Why do you think the solid carbon dioxide is called "dry ice"?
22. **Inferring** When snow on the ground undergoes sublimation, where does the necessary energy come from?

Applying Skills

After each 10°C change in temperature, the mass of a compound dissolved in 100 mL of water was measured. Use this data to answer Questions 23–25.

Temperature (°C)	Mass of Compound Dissolved (g)
0	37
10	47
20	56
30	66
40	75

23. Graphing Graph the data for mass dissolved at each temperature. Label the horizontal axis from 0°C to 60°C and the vertical axis from 0 grams to 100 grams.

24. Interpreting Data What does the graph show about the effect of temperature on the amount of the compound that will dissolve in water?

25. Predicting Assume the amount of the compound dissolved continues to increase as the water is heated. Predict how many grams dissolve at 50°C.

Performance Assessment

CHAPTER PROJECT

Present Your Project If you prepared a cartoon, read the captions to the class and discuss the illustrations. If you prepared a skit, perform the skit in front of the class. After you finish your presentation, invite the class to ask questions about your project. Be prepared to share the decisions you made in creating your presentation.

Reflect and Record In your journal, describe the strengths and weaknesses of the way you modeled changes of state. How successful was your model? How well did your classmates understand your cartoon or skit? Describe what you learned from observing the projects of your classmates.

Test Preparation

Use these questions to prepare for standardized tests.

Read the information below. Then answer Questions 26–29.

A scientist measured the pressure of a sample of a gas at various volumes. The temperature of the gas was kept constant. The data are shown below.

Volume (cm^3)	Pressure (kPa)
15	222
21	159
31	108
50	67

26. At which volume was the pressure the highest?
a. 15 cm^3 **b.** 21 cm^3
c. 31 cm^3 **d.** 50 cm^3

27. If a measurement was taken when the volume was 25 cm^3, the pressure would be
a. about 25 kPa. **b.** about 70 kPa.
c. about 130 kPa. **d.** about 240 kPa.

28. What will happen to the pressure if the volume is increased to 75 cm^3?
a. The pressure will increase.
b. The pressure will decrease.
c. The pressure will remain the same.
d. There is no way to predict the pressure.

29. If you were to construct a graph with volume on the horizontal axis and pressure on the vertical axis, what would your graph look like?
a. a straight line slanting up from left to right
b. a curve slanting down from left to right
c. a straight horizontal line
d. a U-shaped line