Chapter 14

Thermal Energy and Heat

The BIG Idea

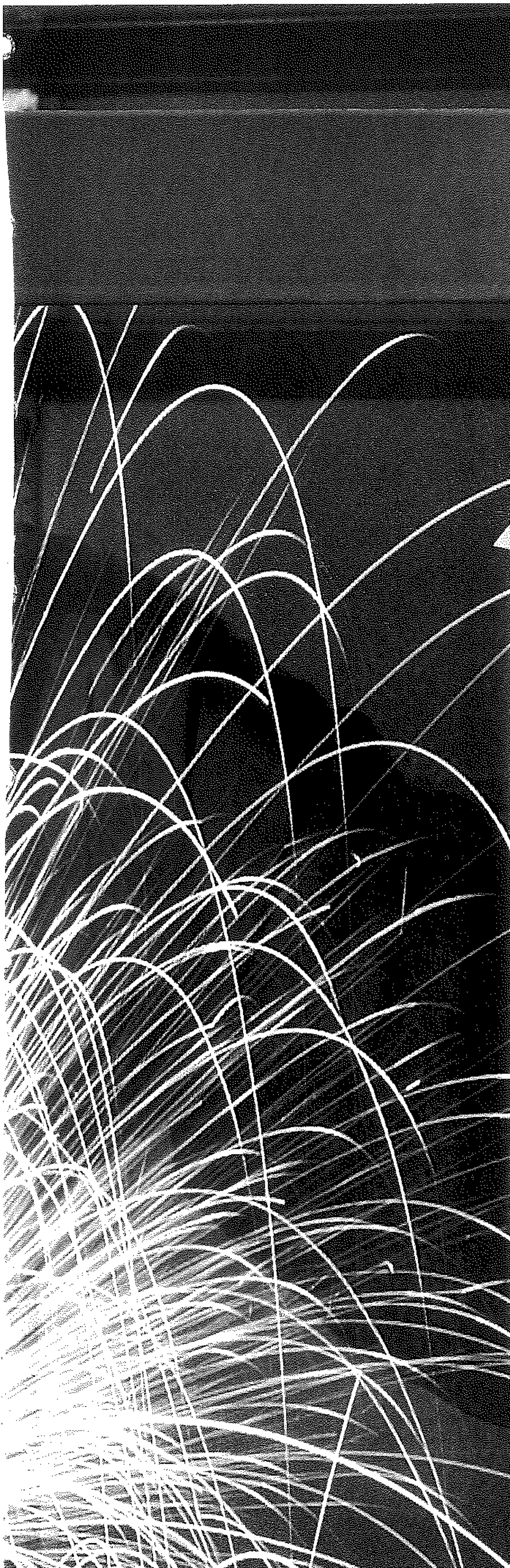
Transfer of Energy

How can heat be transferred from place to place?

Chapter Preview

1. **Temperature, Thermal Energy, and Heat**
   Discover How Cold Is the Water?
   Math Skills Converting Units
   Analyzing Data Specific Heat
   Technology Lab Build Your Own Thermometer
2. **The Transfer of Heat**
   Discover What Does It Mean to Heat Up?
   Try This Feel the Warmth
   Skills Activity Inferring
   Skills Lab Just Add Water
3. **Thermal Energy and States of Matter**
   Discover What Happens to Heated Metal?
   Skills Activity Observing
   At-Home Activity Frosty Balloons
4. **Uses of Heat**
   Discover What Happens at the Pump?
   Try This Shake It Up
   Active Art Four-Stroke Engine

Sparks fly as a welder melts metal with intense heat. ▶



Lab zone™ Chapter **Project**

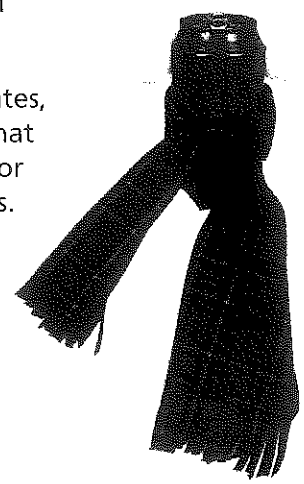
In Hot Water

In this chapter, you will find out what heat is and how it relates to thermal energy and temperature. As you read the chapter, you will use what you learn to construct a device that will insulate a container of hot water.

Your Goal To build a container for a 355-mL aluminum can that keeps water hot

Your container must

- minimize the loss of thermal energy from the hot water
- be built from materials approved by your teacher
- have insulation no thicker than 3 cm
- not use electricity or heating chemicals
- follow the safety guidelines in Appendix A



Plan It! With a group of classmates, brainstorm different materials that prevent heat loss. Write a plan for how you will test these materials. Include a list of the variables you will control when doing your tests. Perform your tests to determine the best insulating materials. Keep a log of your results. Then build and test the device.

Section 1

Temperature, Thermal Energy, and Heat

Reading Preview

Key Concepts

- What are the three common temperature scales?
- How is thermal energy related to temperature and heat?
- What does having a high specific heat mean?

Key Terms

- temperature
- Fahrenheit scale
- Celsius scale
- Kelvin scale
- absolute zero
- heat
- specific heat

Target Reading Skill

Comparing and Contrasting
As you read, compare and contrast temperature, thermal energy, and heat by completing a table like the one below.

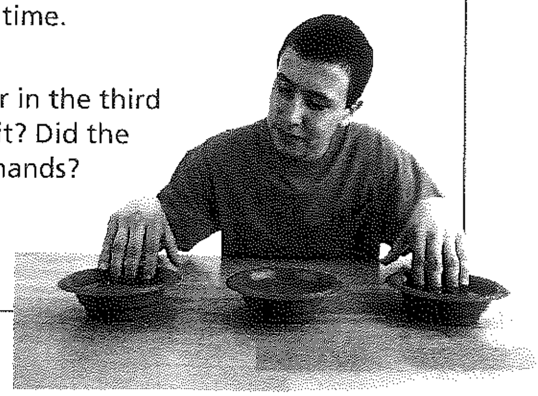
	Energy Measured	Units
Temp.	Average kinetic energy of particles	
Thermal energy		
Heat		

Lab zone Discover Activity

How Cold Is the Water?

1. Fill a plastic bowl with cold water, another with warm water, and a third with water at room temperature. Label each bowl and line them up.
2. Place your right hand in the cold water and your left hand in the warm water.
3. After about a minute, place both your hands in the third bowl at the same time.

Think It Over
Observing How did the water in the third bowl feel when you touched it? Did the water feel the same on both hands? If not, explain why.



The radio weather report says that today's high temperature will be 25 degrees. What should you wear? Do you need a coat to keep warm, or only shorts and a T-shirt? What you decide depends on what "25 degrees" means.

Temperature

You don't need a science book to tell you that the word *hot* means higher temperatures or the word *cold* means lower temperatures. When scientists think about high and low temperatures, however, they do not think about "hot" and "cold." Instead, they think about particles of matter in motion.

Recall that all matter is made up of tiny particles. These particles are always moving even if the matter they make up is stationary. Recall that the energy of motion is called kinetic energy. So all particles of matter have kinetic energy. The faster particles move, the more kinetic energy they have. **Temperature** is a measure of the average kinetic energy of the individual particles in matter.

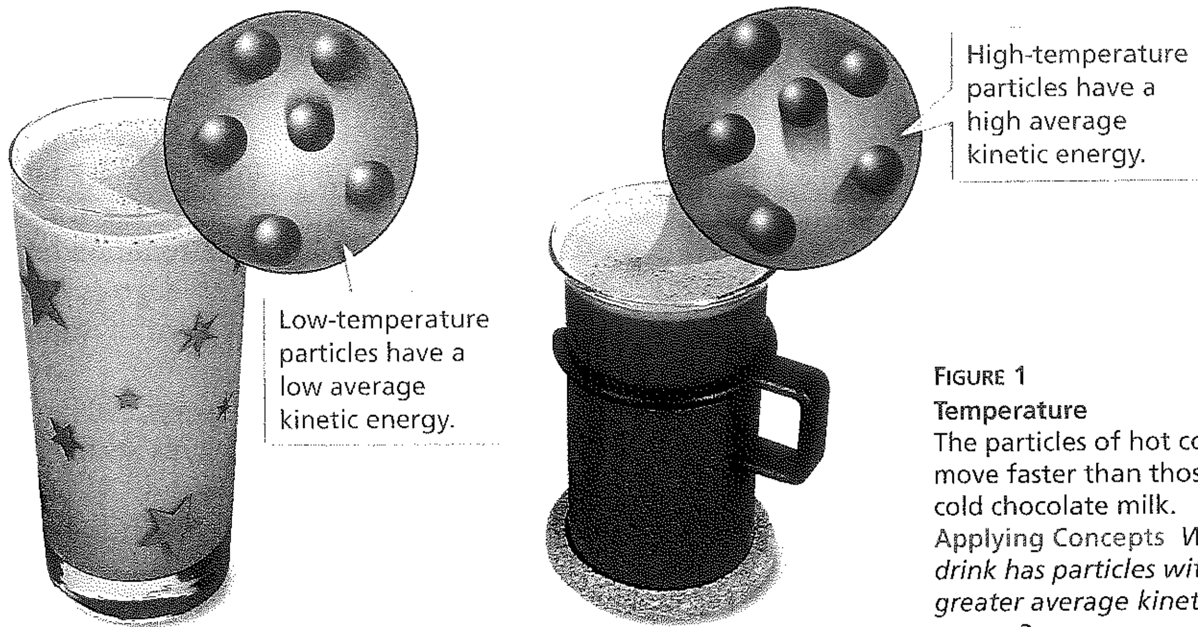


FIGURE 1
Temperature
The particles of hot cocoa move faster than those of cold chocolate milk.
Applying Concepts *Which drink has particles with greater average kinetic energy?*

In Figure 1, the hot cocoa has a higher temperature than the cold chocolate milk. The cocoa's particles are moving faster, so they have greater average kinetic energy. If the milk is heated, its particles will move faster, so their kinetic energy will increase. The temperature of the milk will rise.

Measuring Temperature To measure the temperature of the heated milk, you would probably use a thermometer like the one shown in Figure 2. A thermometer usually consists of a liquid such as alcohol sealed inside a narrow glass tube. When the tube is heated, the particles of the liquid speed up and spread out so the particles take up more space, or volume. You see the level of the liquid move up the tube. The reverse happens when the tube is cooled. The particles of the liquid slow down and move closer, taking up less volume. You see the level of the liquid move down in the tube.

A thermometer has numbers and units, or a scale, on it. When you read the scale on a thermometer, you read the temperature of the surrounding matter. Thermometers can have different scales. The temperature reading you see depends on the thermometer's scale.

Reading Checkpoint **What happens to the liquid particles inside a thermometer when it is heated?**

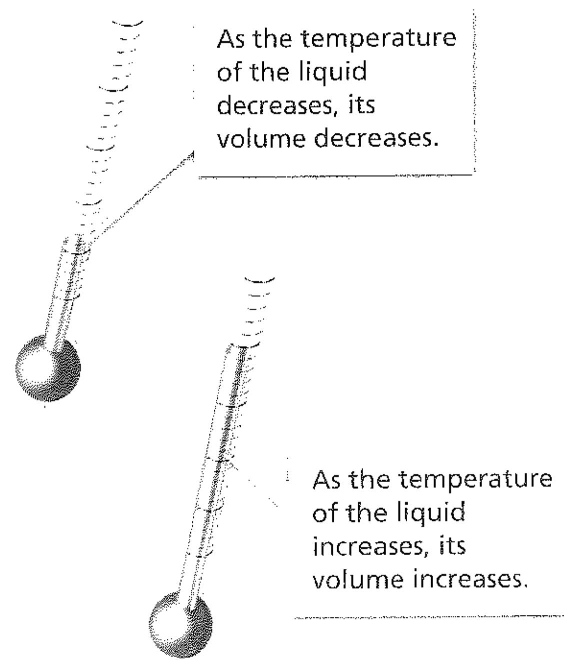


FIGURE 2
How a Thermometer Works
Temperature changes cause the level of the liquid inside a thermometer to rise and fall.

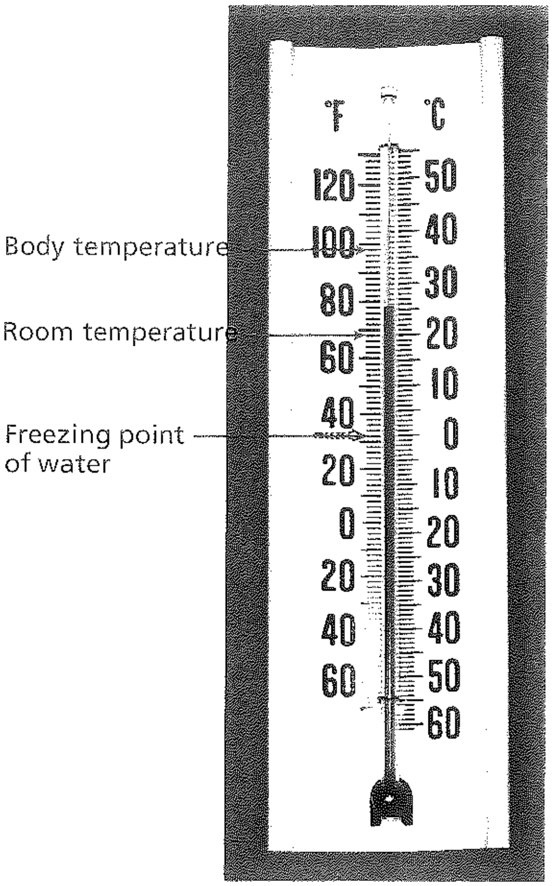


FIGURE 3
Temperature Scales
Many thermometers have both Celsius and Fahrenheit temperature scales.
Interpreting Photographs *What is the boiling point of water on the Celsius scale? On the Fahrenheit scale?*

Temperature Scales **The three common scales for measuring temperature are the Fahrenheit, Celsius, and Kelvin scales.** Each of these scales is divided into regular intervals.

The temperature scale you are probably most familiar with is the Fahrenheit scale. In the United States, the **Fahrenheit scale** is the most common temperature scale. The scale is divided into degrees Fahrenheit (°F). On this scale, the freezing point of water is 32°F and the boiling point is 212°F.

In nearly all other countries, however, the most common temperature scale is the **Celsius scale.** The Celsius scale is divided into degrees Celsius (°C), which are larger units than degrees Fahrenheit. On the Celsius scale, the freezing point of water is 0°C and the boiling point is 100°C.

The temperature scale commonly used in physical science is the **Kelvin scale.** Units on the Kelvin scale, called kelvins (K), are the same size as degrees on the Celsius scale. So, an increase of 1 K equals an increase of 1°C. The freezing point of water on the Kelvin scale is 273 K, and the boiling point is 373 K. The number 273 is special. Scientists have concluded from experiments that –273°C is the lowest temperature possible. No more thermal energy can be removed from matter at –273°C. Zero on the Kelvin scale represents –273°C and is called **absolute zero.**

Thermal Energy and Heat

Different objects at the same temperature can have different energies. To understand this, you need to know about thermal energy and about heat. You may be used to thinking about thermal energy as heat, but they are not the same thing. Temperature, thermal energy, and heat are closely related, but they are all different.

Thermal Energy You may recall that the total energy of all of the particles in an object is called thermal energy, or sometimes internal energy. The thermal energy of an object depends on the number of particles in the object, the temperature of the object, and the arrangement of the object's particles. You will learn about how the arrangement of particles affects thermal energy in Section 3.

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The more particles an object has at a given temperature, the more thermal energy it has. For example, a 1-liter pot of hot cocoa at 75°C has more thermal energy than a 0.2-liter mug of hot cocoa at 75°C because the pot contains more cocoa particles. On the other hand, the higher the temperature of an object, the more thermal energy the object has. Therefore, if two 1-liter pots of hot cocoa have different temperatures, the pot with the higher temperature has more thermal energy. In Section 3, you will learn about how thermal energies differ for solids, liquids, and gases.

Heat Thermal energy that is transferred from matter at a higher temperature to matter at a lower temperature is called **heat.** The scientific definition of heat is different from its everyday use. In a conversation, you might say that an object contains heat. However, objects contain thermal energy, not heat. Only when thermal energy is transferred is it called heat. **Heat is thermal energy moving from a warmer object to a cooler object.** For example, when you hold an ice cube in your hand, as shown in Figure 4, the ice cube melts because thermal energy is transferred from your hand to the ice cube.

Recall that work also involves the transfer of energy. Since work and heat are both energy transfers, they are both measured in the same unit—joules.

Reading Checkpoint **Why does an ice cube melt in your hand?**

Math Skills

Converting Units

To convert a Fahrenheit temperature to a Celsius temperature, use the following formula.

$$°C = \frac{5}{9}(°F - 32)$$

For example, if the temperature in your classroom is 68°F, what is the temperature in degrees Celsius?

$$°C = \frac{5}{9}(68 - 32)$$

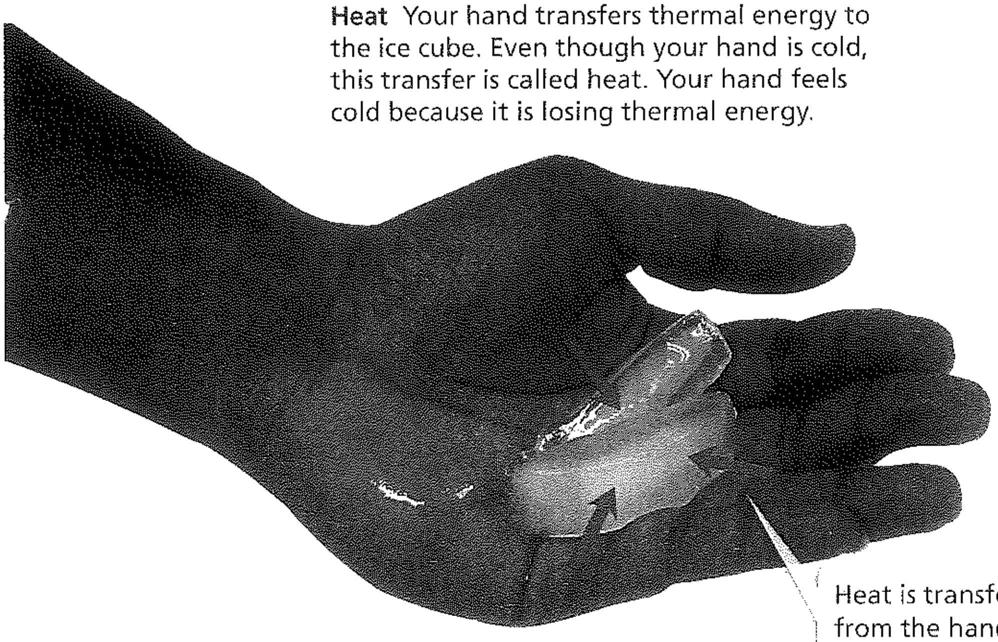
$$°C = \frac{5}{9} \times 36$$

$$°C = 20$$

The temperature of your classroom is 20°C.

Practice Problem While at the beach, you measure the ocean temperature as 77°F. What is the temperature of the ocean in degrees Celsius?

FIGURE 4
Heat Your hand transfers thermal energy to the ice cube. Even though your hand is cold, this transfer is called heat. Your hand feels cold because it is losing thermal energy.



Heat is transferred from the hand to the ice cubes.

FIGURE 5
Specific Heat of Sand and Water
The specific heat of water is greater than the specific heat of sand. On a sunny day the water feels cooler than the sand.

Specific Heat

Imagine running across hot sand toward the ocean. You run to the water's edge, but you don't go any farther—the water is too cold. How can the sand be so hot and the water so cold? After all, the sun heats both of them. The answer is that water requires more heat to raise its temperature than sand does.

When an object is heated, its temperature rises. But the temperature does not rise at the same rate for all objects. The amount of heat required to raise the temperature of an object depends on the object's chemical makeup. To change the temperature of different objects by the same amount, different amounts of heat are required.

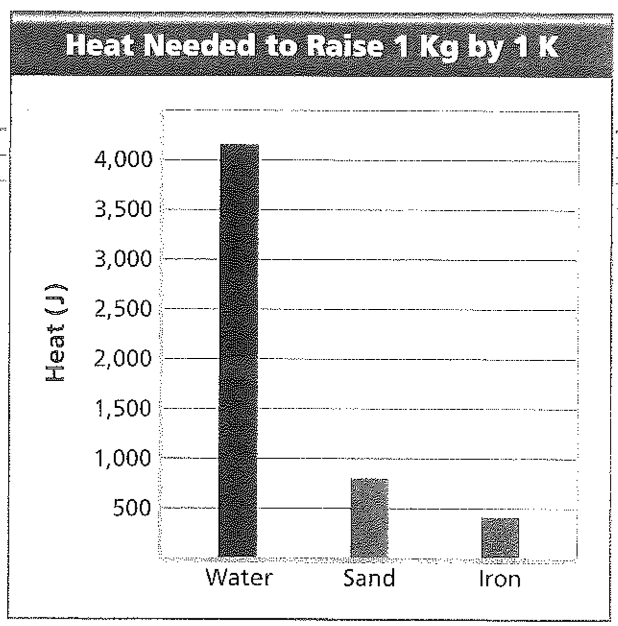
Scientists have defined a quantity to measure the relationship between heat and temperature change. The amount of energy required to raise the temperature of 1 kilogram of a material by 1 kelvin is called its **specific heat.** The unit of measure for specific heat is joules per kilogram-kelvin, or J/(kg·K).

Math Analyzing Data

Specific Heat

The specific heat of three different materials was measured. These data are shown in the graph.

1. Reading Graphs What three materials are compared in the graph?
2. Interpreting Data About how much heat is required to raise 1 kg of water by 1 K?
3. Drawing Conclusions According to the graph, which material requires more heat to raise its temperature by 1 K, iron or sand?



Look at the specific heats of the materials listed in Figure 6. Notice that the specific heat of water is quite high. One kilogram of water requires 4,180 joules of energy to raise its temperature 1 kelvin.

A material with a high specific heat can absorb a great deal of thermal energy without a great change in temperature. On the other hand, a material with a low specific heat would have a large temperature change after absorbing the same amount of thermal energy.

The energy gained or lost by a material is related to its mass, change in temperature, and specific heat. You can calculate thermal energy changes with the following formula.

Change in energy =
Mass × Specific heat × Change in temperature

How much heat is required to raise the temperature of 5 kilograms of water by 10 kelvins?

$$\text{Change in energy} = 5\text{ kg} \times 4{,}180\text{ J/(kg}\cdot\text{K)} \times 10\text{ K} = 209{,}000\text{ J}$$

You need to transfer 209,000 joules to the water to increase its temperature by 10 kelvins.

Reading Checkpoint **What formula allows you to determine an object's change in thermal energy?**

Specific Heat of Common Materials

Material	Specific Heat (J/(kg·K))
Aluminum	903
Copper	385
Glass	837
Ice	2,060
Iron	450
Sand	800
Silver	235
Water	4,180

FIGURE 6
This table lists the specific heats of several common materials.
Interpreting Tables *How much more energy is required to raise the temperature of 1 kg of iron by 1 K than to raise the temperature of 1 kg of copper by 1 K?*

Section 1 Assessment

Target Reading Skill Comparing and Contrasting Use the information in your table to help you answer Questions 1 and 2 below.

Reviewing Key Concepts

1. a. Identifying What is temperature?
   b. Describing How do thermometers measure temperature?
   c. Comparing and Contrasting How are the three temperature scales alike? How are they different?
2. a. Defining What is heat?
   b. Explaining What is the relationship between thermal energy and temperature? Between thermal energy and heat?
   c. Relating Cause and Effect What happens to the motion of an object's particles as the object's thermal energy increases? What happens to the temperature of the object?
3. a. Reviewing Why do some materials get hot more quickly than others?
   b. Calculating You stir your hot cocoa with a silver spoon that has a mass of 0.032 kg. The spoon's temperature increases from 20 K to 60 K. What is the change in the spoon's thermal energy? (*Hint:* Use the table in Figure 6 to find the specific heat of silver.)

Math Practice

4. Converting Units Convert 5.0°F to degrees Celsius.
5. Converting Units The surface temperature on the planet Venus can reach 860°F. Convert this temperature to degrees Celsius.

Lab zone **Technology Lab**

• Tech & Design •

Build Your Own Thermometer

Problem

Can you build a thermometer out of simple materials?

Design Skills

evaluating the design, measuring, making models

Materials

- bowl of hot water • bowl of ice water
- water of unknown temperature
- tap water • 500-mL beaker
- clear glass juice or soda bottle, 20–25 cm
- clear plastic straw, 18–20 cm • food coloring
- plastic dropper • cooking oil
- modeling clay
- metric ruler
- fine-point marker

Procedure

1. You can use simple materials to build a model of an alcohol thermometer. First, mix food coloring into a beaker of tap water. Then fill a glass bottle with the colored water.
2. Place a straw in the bottle. Use modeling clay to position the straw so that it extends at least 10 cm above the bottle mouth. Do not let the straw touch the bottom. The clay should completely seal off the bottle mouth. Make sure there is no air in the bottle.
3. Using a dropper, add colored water into the straw to a level 5 cm above the bottle. Place a drop of cooking oil in the straw to prevent evaporation.
4. Place your thermometer into a bowl of hot water. When the colored water reaches its highest level, place a mark on the straw.
5. Place your thermometer in the bowl of ice water. Place a mark on the straw when the water reaches its lowest level.
6. Create a scale for your model thermometer. Divide the distance between the two marks into 5-mm intervals. Starting with the lowest point, label the intervals on the straw 0, 1, 2, 3, and so on.
7. Measure the temperature of two unknown samples with your thermometer. Record both temperatures.

Analyze and Conclude

1. **Evaluating the Design** Do you think your model accurately represents an alcohol thermometer? How is it like a real thermometer? How is it different?
2. **Inferring** How can you use the concepts of matter and the kinetic energy of particles to explain the way your model works?
3. **Measuring** Approximately what Celsius temperatures do you think your model measures? Explain your estimate.
4. **Making Models** Examine the structure and materials used in your model. Propose a change that would improve the model. Explain your choice.

Communicate

Create a poster to show how an alcohol thermometer works. Explain how the Celsius and Fahrenheit scales compare. For example, does 0° have the same meaning on both scales? Use a diagram with labels and captions to communicate your ideas.

Section 2 The Transfer of Heat

Reading Preview

Key Concepts

- What are the three forms of heat transfer?
- In what direction does heat move?
- How are conductors and insulators different?

Key Terms

- conduction
- convection
- convection current
- radiation
- conductor
- insulator

Target Reading Skill

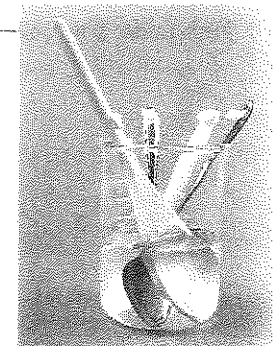
Identifying Main Ideas As you read the How Is Heat Transferred? section, write the main idea in a graphic organizer like the one below. Then write three supporting details that give examples of the main idea.

Main Idea

Heat can be transferred in three ways . . .

Detail	Detail	Detail

Lab zone Discover Activity



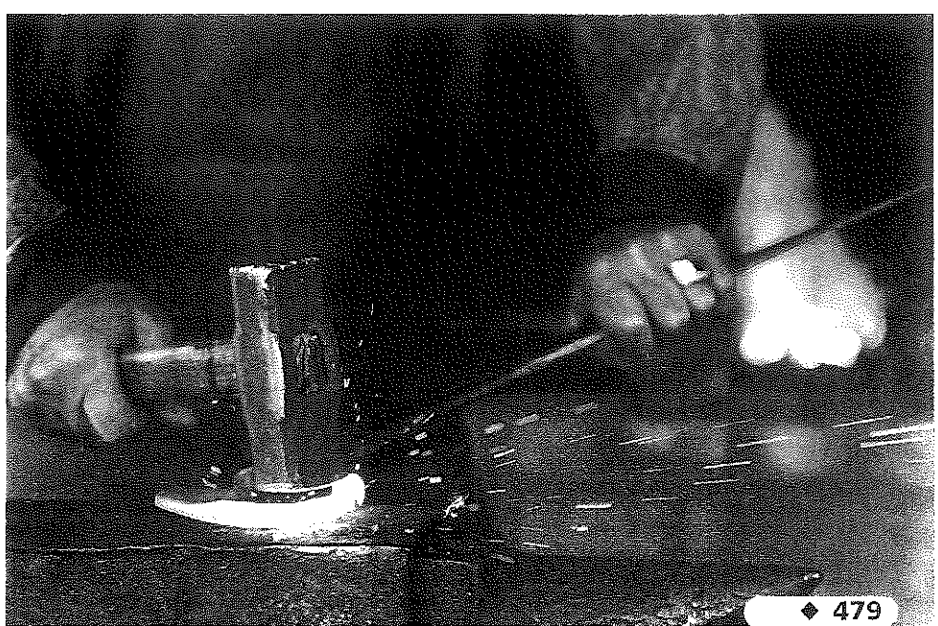
What Does It Mean to Heat Up?

1. Obtain several utensils made of different materials, such as silver, stainless steel, plastic, and wood.
2. Stand the utensils in a beaker so that they do not touch each other.
3. Press a small gob of frozen butter on the handle of each utensil. Make sure that when the utensils stand on end, the butter is at the same height on each one.
4. Pour hot water into the beaker until it is about 6 cm below the butter. Watch the butter on the utensils for several minutes. What happens?
5. Wash the utensils in soapy water when you finish.

Think It Over

Observing What happened to the butter? Did the same thing happen on every utensil? How can you account for your observations?

Blacksmithing is hot work. A piece of iron held in the fire of the forge becomes warmer and begins to glow. At the same time, the blacksmith feels hot air rising from the forge, and his face and arms begin to feel warmer. Each of these movements of energy is a transfer of heat.



A blacksmith at work ▶

How Is Heat Transferred?

There are three ways that heat can move. **Heat is transferred by conduction, convection, and radiation.** The blacksmith experiences all three.

Conduction In the process of **conduction,** heat is transferred from one particle of matter to another without the movement of the matter. Think of a metal spoon in a pot of water on an electric stove. The fast-moving particles in the hot electric coil collide with the slow-moving particles in the cool pot. The transfer of heat causes the pot's particles to move faster. Then the pot's particles collide with the water's particles, which in turn collide with the particles in the spoon. As the particles move faster, the metal spoon becomes hotter.

If you were to touch the spoon, heat would be transferred to your fingers. Too much heat transferred this way can cause a burn!

In Figure 7, heat from the fire is transferred to the stone beneath it. Then it is transferred from the stone to the metal tools. This transfer of heat from the fire to the tools is due to conduction.

Convection If you watch a pot of hot water on a stove, you will see the water moving. This movement transfers heat within the water. In **convection,** heat is transferred by the movement of currents within a fluid.

When the water at the bottom of the pot is heated, its particles move faster. The particles also move farther apart. As a result, the heated water becomes less dense. You may remember that a less dense fluid will float on top of a denser one. So the heated water rises. The surrounding, cooler water flows into its place. This flow creates a circular motion known as a **convection current.**

Convection currents can transfer heated air. As the air above the fire in Figure 7 is heated, it becomes less dense and rises up the chimney. When the warm air rises, cool air flows into its place.

Radiation **Radiation** is the transfer of energy by electromagnetic waves. You can feel the radiation from a fire in a fireplace all the way across the room. Unlike conduction and convection, radiation does not require matter to transfer thermal energy. All of the sun's energy that reaches Earth travels through millions of kilometers of empty space.

Reading Checkpoint **How does radiation transfer thermal energy?**

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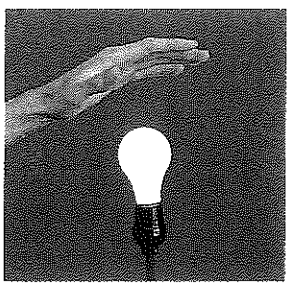
Lab zone **Try This Activity**

Feel the Warmth

How is heat transferred from a light bulb?



1. Turn on a lamp without the shade. Wait about a minute.
2. Hold the palm of your hand about 10 cm from the side of the bulb for about 15 seconds. **CAUTION:** *Do not touch the bulb. Remove your hand sooner if it gets too warm.*
3. Now hold the palm of your hand about 10 cm above the top of the bulb for about 15 seconds.

Drawing Conclusions
In which location did your hand feel warmer? Explain your observations in terms of heat transfer.

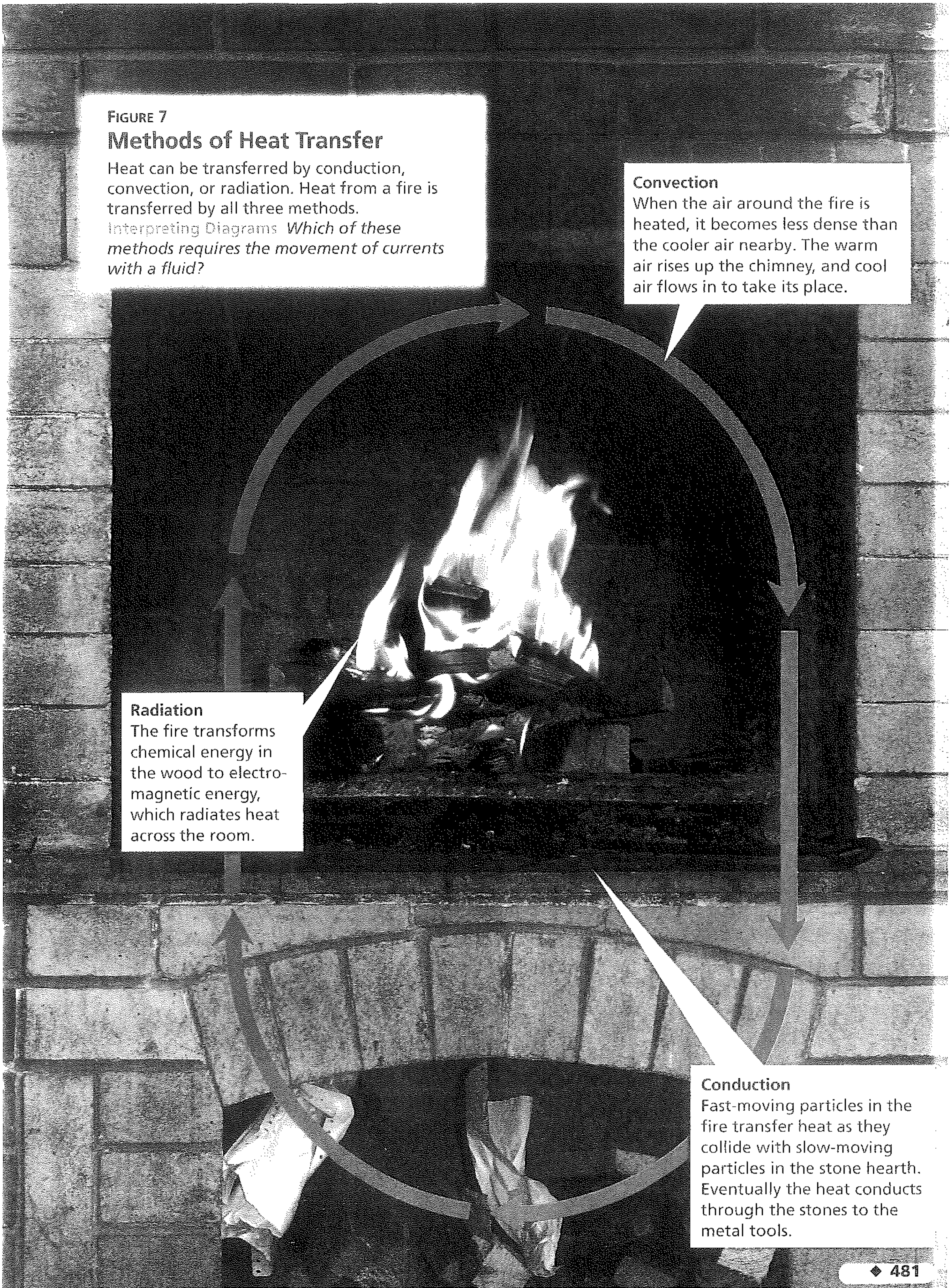


FIGURE 7
Methods of Heat Transfer
Heat can be transferred by conduction, convection, or radiation. Heat from a fire is transferred by all three methods.
Interpreting Diagrams *Which of these methods requires the movement of currents with a fluid?*

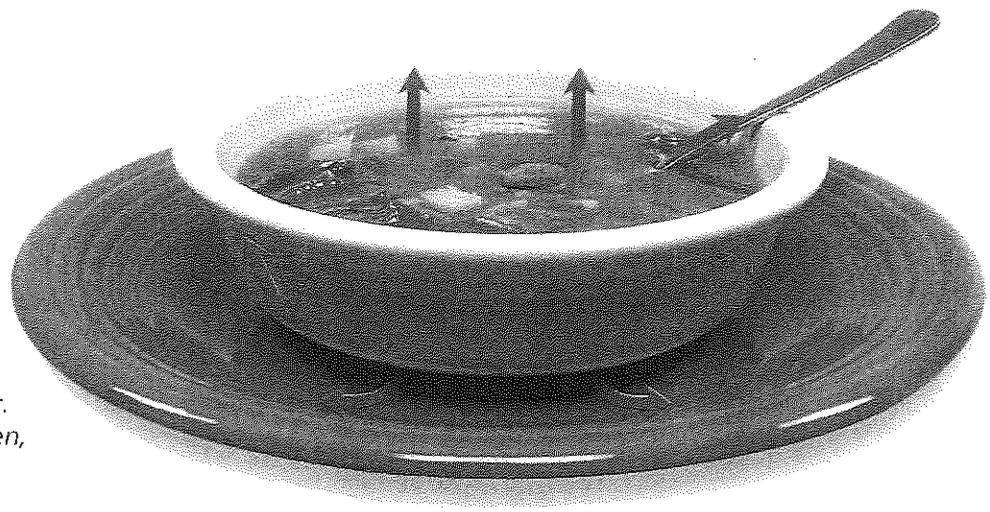


FIGURE 8
Heat Transfer From Food
The soup's heat is transferred to the bowl, the spoon, and the air.
Predicting *If the soup is not eaten, what will happen to its temperature?*

Heat Moves One Way

If two objects have different temperatures, heat will flow from the warmer object to the colder one. When heat flows into matter, the thermal energy of the matter increases. As the thermal energy increases, the temperature increases. At the same time, the temperature of the matter losing the heat decreases. Heat will flow from one object to the other until the two objects have the same temperature. You have probably seen this happen to your food. The bowl of hot soup shown in Figure 8, for example, cools to room temperature if you don't eat it quickly.

What happens when something becomes cold, such as when ice cream is made? The ingredients used to make it, such as milk and sugar, are not nearly as cold as the finished ice cream. In an ice cream maker, the ingredients are put into a metal can that is packed in ice. You might think that the ice transfers cold to the ingredients in the can. But this is not the case. There is no such thing as "coldness." Instead, the ingredients grow colder as thermal energy flows from them to the ice. Heat transfer occurs in only one direction.

Reading Checkpoint **Can heat flow from one object to a warmer object? Why or why not?**

Lab zone Skills Activity

Inferring

You pull some clothes out of the dryer as soon as they are dry. You grab your shirt without a problem, but when you pull out your jeans, you quickly drop them. The metal zipper is too hot to touch! What can you infer about which material in your jeans conducts thermal energy better? Explain.

Conductors and Insulators

Have you ever stepped from a rug to a tile floor on a cold morning? The tile floor feels colder than the rug. Yet if you measured their temperatures, they would be the same—room temperature. The difference between them has to do with how materials conduct heat. A material can be either a conductor or an insulator. **A conductor transfers thermal energy well. An insulator does not transfer thermal energy well.**

Conductors A material that conducts heat well is called a **conductor.** Metals such as silver and stainless steel are good conductors. A metal spoon conducts heat better than a wooden spoon. Some materials are good conductors because of the particles they contain and how those particles are arranged. A good conductor, such as a tile floor, feels cool to the touch because it easily transfers heat away from your skin.

Insulators A material that does not conduct heat well is called an **insulator.** Wood, wool, straw, and paper are good insulators. So are the gases in air. Clothes and blankets are insulators that slow the transfer of heat out of your body.

A well-insulated building is comfortable inside whether it is hot or cold outdoors. Insulation prevents heat from entering the building in hot weather and from escaping in cold weather. Much of the heat transfer in a building occurs through the windows. For this reason, insulating windows have two panes of glass with a thin space of air between them. The trapped air does not transfer heat well.

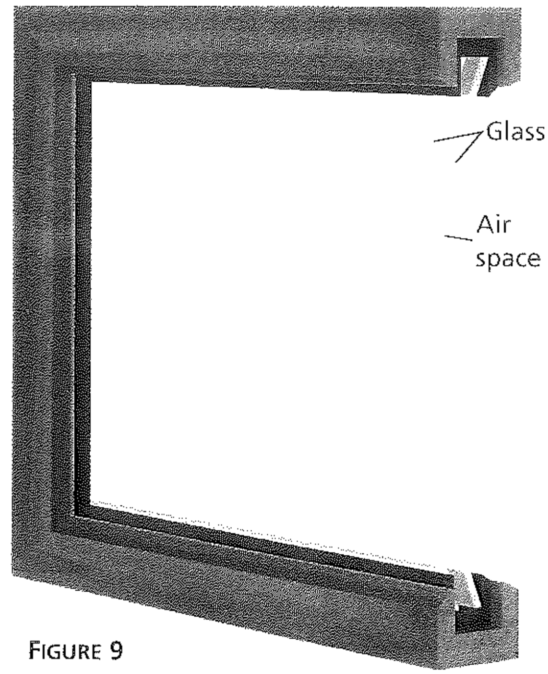


FIGURE 9
Insulating Windows
Air between the panes of this window acts as an insulator to slow the transfer of heat.

Reading Checkpoint **Is air better as an insulator or as a conductor?**

Section 2 Assessment

Target Reading Skill

Identifying Main Ideas Use your graphic organizer to help you answer Question 1 below.

Reviewing Key Concepts

1. a. Describing What are conduction, convection, and radiation?
   b. Classifying Identify each example of heat transfer as conduction, convection, or radiation: opening the windows in a hot room; a lizard basking in the sun; putting ice on a sprained ankle.
   c. Inferring How can heat be transferred across empty space?
2. a. Reviewing In what direction will heat flow between two objects with different temperatures?
   b. Applying Concepts How does a glass of lemonade become cold when you put ice in it?
3. a. Identifying What kind of substance conducts thermal energy well?
   b. Making Judgments Would a copper pipe work better as a conductor or an insulator? Why do you think so?
   c. Interpreting Diagrams Why are two panes of glass used in the window in Figure 9?

Writing in Science

Explanation Suppose you are camping on a mountain, and the air temperature is very cold. How would you keep warm? Would you build a fire or set up a tent? Write an explanation for each action you would take. Tell whether conduction, convection, or radiation is involved with each heat transfer.

Lab zone **Skills Lab**

Just Add Water

Problem

Can you build a calorimeter—a device that measures changes in thermal energy—and use it to determine how much thermal energy is transferred from hot water to cold water?

Skills Focus

observing, calculating, interpreting data

Materials

- hot tap water
- balance
- scissors
- pencil
- 4 plastic foam cups
- 2 thermometers or temperature probes
- beaker of water kept in an ice bath

Procedure

1. Predict how the amount of thermal energy lost by hot water will be related to the amount of thermal energy gained by cold water.
2. Copy the data table into your notebook.
3. Follow the instructions in the box to make two calorimeters. Find the mass of each empty calorimeter (including the cover) on a balance and record each mass in your data table.
4. From a beaker of water that has been sitting in an ice bath, add water (no ice cubes) to the cold-water calorimeter. Fill it about one-third full. Put the cover on, find the total mass, and record the mass in your data table.
5. Add hot tap water to the hot-water calorimeter. **CAUTION:** *Hot tap water can cause burns.* Fill the calorimeter about one-third full. Put the cover on, find the total mass, and record the mass in your data table.
6. Calculate the mass of the water in each calorimeter. Record the results in your data table.
7. Put thermometers through the holes in the covers of both calorimeters. Wait a minute or two and then record the temperatures. If you are using temperature probes, see your teacher for instructions.

Making a Calorimeter

A. Label a plastic foam cup with the letter *C*, which stands for cold water.

B. Cut 2 to 3 cm from the top of a second plastic foam cup. Invert the second cup inside the first. Label the cover with a *C* also. The cup and cover are your cold-water calorimeter.

C. Using a pencil, poke a hole in the cover large enough for a thermometer to fit into snugly.

D. Repeat Steps A, B, and C with two other plastic foam cups. This time, label both cup and cover with an *H*. This is your hot-water calorimeter.

Data Table

Calorimeter	Mass of Empty Cup (g)	Mass of Cup and Water (g)	Mass of Water (g)	Starting Temp. (°C)	Final Temp. (°C)	Change in Temp. (°C)
Cold Water						
Hot Water						

8. Remove both thermometers and covers. Pour the water from the cold-water calorimeter into the hot-water calorimeter. Put the cover back on the hot-water calorimeter, and insert a thermometer. Record the final temperature as the final temperature for both calorimeters.

Analyze and Conclude

1. Observing What is the temperature change of the cold water? Record your answer in the data table.
2. Observing What is the temperature change of the hot water? Record your answer in the data table.
3. Calculating Calculate the amount of thermal energy that enters the cold water by using the formula for the transfer of thermal energy. The specific heat of water is 4.18 J/(g·K).
   Thermal energy transferred =
   4.18 J/(g·K) × Mass of cold water × Temperature change of cold water
   Remember that a change of 1°C is equal to a change of 1 K.
4. Calculating Now use the same formula to calculate the amount of thermal energy leaving the hot water.
5. Calculating What unit should you use for your results for Questions 3 and 4?
6. Interpreting Data Was your prediction from Step 1 confirmed? How do you know?
7. Communicating What sources of error might have affected your results? Write a paragraph explaining how the lab could be redesigned in order to reduce the errors.

Design an Experiment

How would your results be affected if you started with much more hot water than cold? If you used more cold water than hot? Make a prediction. Then design a procedure to test your prediction. *Obtain your teacher's permission before carrying out your investigation.*

Section 3

Integrating Chemistry

Thermal Energy and States of Matter

Reading Preview

Key Concepts

- What are three states of matter?
- What causes matter to change state?
- What happens to a substance as its thermal energy increases?

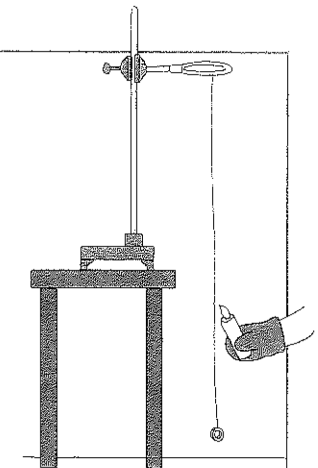
Key Terms

- state
- change of state
- melting
- freezing
- evaporation
- boiling
- condensation
- thermal expansion

Target Reading Skill

Building Vocabulary Using a word in a sentence helps you think about how best to explain the word. After you read the section, reread the paragraphs that contain definitions of Key Terms. Use all the information you have learned to write a meaningful sentence for each Key Term.

Lab zone Discover Activity



What Happens to Heated Metal?

1. Wrap one end of a one-meter-long metal wire around a clamp on a ring stand.
2. Tie the other end through several washers. Adjust the clamp so that the washers swing freely, but nearly touch the floor.
3. Light a candle. Hold the candle with an oven mitt, and heat the wire. **CAUTION:** *Be careful near the flame, and avoid dripping hot wax on yourself.* Predict how heat from the candle will affect the wire.
4. With your hand in the oven mitt, swing the wire. Observe any changes in the motion of the washers.
5. Blow out the candle and allow the wire to cool. After several minutes, swing the wire again and observe its motion.

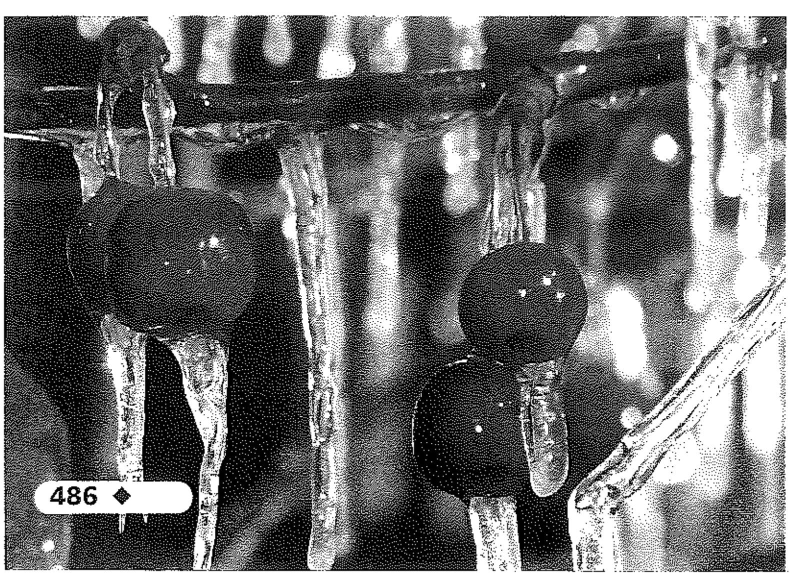
Think It Over

Inferring Based on your observations, what can you conclude about the effect of heating a solid?

Throughout the day, the temperature at a cherry farm drops steadily. The anxious farmer awaits the updated weather forecast. The news is not good. The temperature is expected to fall even further during the night. Low temperatures could wipe out the entire crop. He considers picking the crop early, but the cherries are not yet ripe.

Instead, the farmer tells his workers to haul in hoses and spray the cherry trees with water. As the temperature drops, the water begins to freeze. The ice keeps the cherries warm!

How can ice possibly keep anything warm? The answer has to do with how thermal energy is transferred as water becomes ice.



◀ Cherries at 0°C sprayed with water

States of Matter

What happens when you hold an ice cube in your hand? It melts. The solid and the liquid are both the same material—water. Water can exist in three different **states**, or forms. **In fact, most matter on Earth can exist in three states—solid, liquid, and gas.** Although the chemical composition of matter remains the same, the arrangement of the particles that make up the matter differs from one state to another.

Solids The particles that make up a solid are packed together in relatively fixed positions. Particles of a solid cannot move out of their positions. They can only vibrate back and forth. This is why solids retain a fixed shape and volume. Because the shape and volume of the plastic helmets shown in Figure 10 do not change, the plastic is a solid.

Liquids The particles that make up a liquid are close together, but they are not held together as tightly as those of a solid. Because liquid particles can move around, liquids don't have a definite shape. But liquids do have a definite volume. In Figure 10, notice how the river water changes shape.

Gases In gases, the particles are moving so fast that they don't even stay close together. Gases expand to fill all the space available. They don't have a fixed shape or volume. Because air is a gas, it can expand to fill the raft in Figure 10 and also take the raft's shape.

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FIGURE 10
Three States of Matter
The plastic helmets, the water in the river, and the air that fills the raft are examples of three states of matter—solid, liquid, and gas. Classifying *Which state of matter is represented by the plastic oars?*

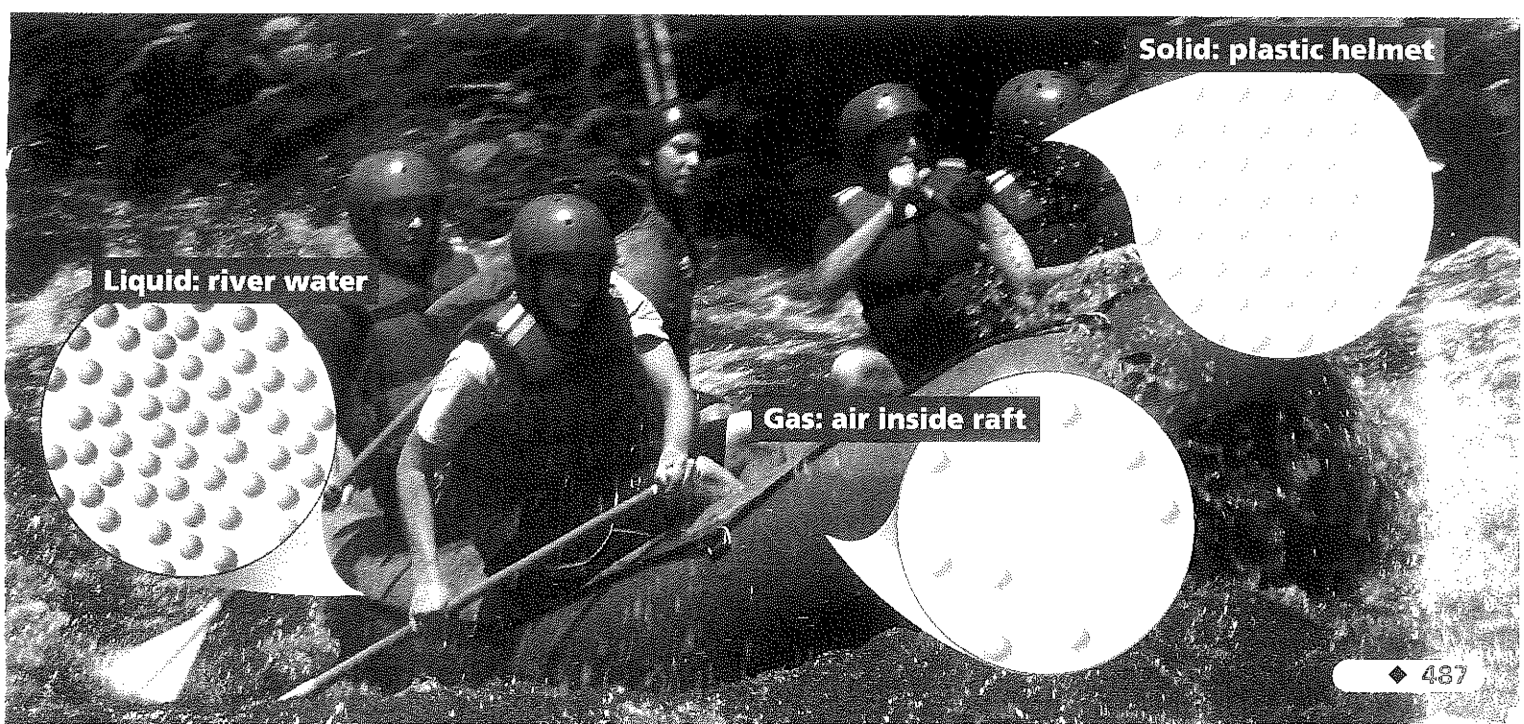


FIGURE 11
Melted Chocolate
Though normally a solid at room temperature, this chocolate has absorbed enough thermal energy to become a liquid.

Changes of State

The physical change from one state of matter to another is called a **change of state.** The state of matter depends on the amount of thermal energy it has. The more thermal energy matter has, the faster its particles move. Since a gas has more thermal energy than a liquid, the particles of a gas move faster than the particles of the same matter in the liquid state.

Matter can change from one state to another when thermal energy is absorbed or released. The graph in Figure 12 shows that as thermal energy increases, matter changes from a solid to a liquid and then to a gas. A gas changes to a liquid and then to a solid as thermal energy is removed from it.

The flat regions of the graph show conditions under which thermal energy is changing but temperature remains the same. Under these conditions, matter is changing from one state to another. During a change of state, the addition or loss of thermal energy changes the arrangement of the particles. However, the average kinetic energy of those particles does not change. Since temperature is a measure of average kinetic energy, temperature does not change as the state of matter changes.

Solid–Liquid Changes of State The change of state from a solid to a liquid is called **melting.** Melting occurs when a solid absorbs thermal energy. As the thermal energy of the solid increases, the structure of its particles breaks down. The particles become freer to move around. The temperature at which a solid changes to a liquid is called the melting point.

The change of state from a liquid to a solid is called **freezing.** Freezing occurs when matter releases thermal energy. The temperature at which matter changes from a liquid to a solid is called its freezing point.

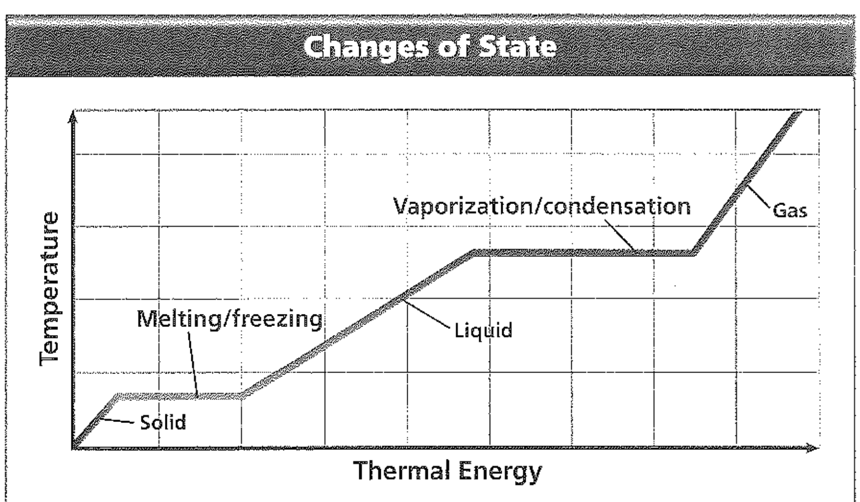


FIGURE 12
During a change in state, the thermal energy of matter increases while its temperature remains the same.

For a given type of matter, the freezing point and melting point are the same. The difference between the two is whether the matter is gaining or releasing thermal energy. The farmer had his workers spray the orange trees with water because the freezing water releases thermal energy into the oranges.

Liquid–Gas Changes of State The process by which matter changes from the liquid to the gas state is called vaporization. During this process, particles in a liquid absorb thermal energy and move faster. Eventually they move fast enough to escape the liquid as gas particles. If vaporization takes place at the surface of a liquid, it is called **evaporation.** At higher temperatures, vaporization can occur below the surface of a liquid as well. This process is called **boiling.** When a liquid boils, gas bubbles that form within the liquid rise to the surface. The temperature at which a liquid boils is called its boiling point.

When a gas loses a certain amount of thermal energy, it will change into a liquid. A change from the gas state to the liquid state is called **condensation.** You have probably seen beads of water appear on the outside of a cold drinking glass. This occurs because water vapor that is present in the air loses thermal energy when it comes in contact with the cold glass.

Reading Checkpoint **What change of state occurs in evaporation?**

Lab zone **Skills Activity**

Observing

Put a teakettle on a stove or a lab burner and bring the water to a boil. Look carefully at the white vapor coming out of the spout. **CAUTION:** *Steam and boiling water can cause serious burns.* In what state of matter is the white vapor that you see? What is present, but not visible, in the small space between the white vapor and the spout?

FIGURE 13
Condensation
Under certain weather conditions, water vapor in the air can condense into fog.
Applying Concepts *As it condenses, does water absorb or release thermal energy?*

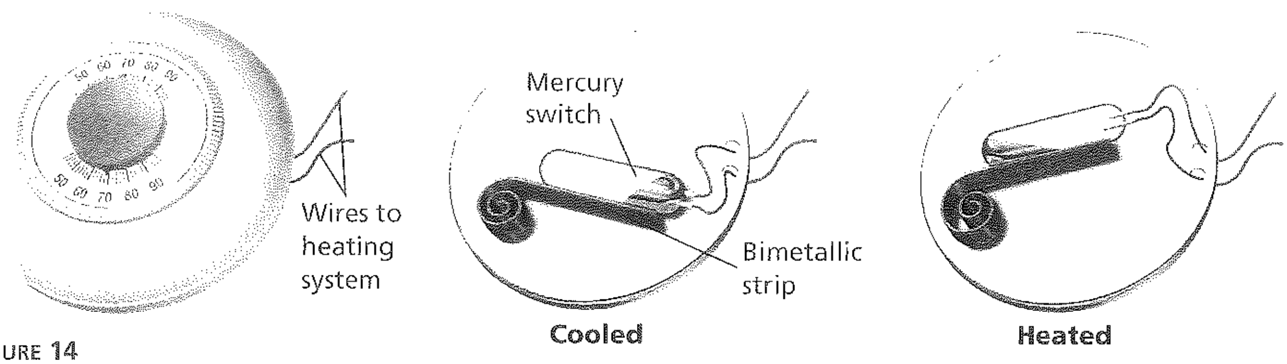


FIGURE 14
Thermostat
A bimetallic strip controls many thermostats. When it cools, the strip curls up and lowers the switch, allowing mercury to flow over the wires. When the strip warms up, it uncurls and raises the switch.

Thermal Expansion

Have you ever loosened a tight jar lid by holding it under a stream of hot water? This works because the metal lid expands a little. Do you know why? **As the thermal energy of matter increases, its particles spread out and the substance expands.** With a few exceptions, this is true for all matter, even when the matter is not changing state. The expanding of matter when it is heated is known as **thermal expansion.**

When matter is cooled, thermal energy is released. The motion of the particles slows down and the particles move closer together. In nearly all cases, as matter is cooled, it contracts, or decreases in volume.

Heat-regulating devices called thermostats use thermal expansion to work. Many thermostats contain bimetallic strips, which are strips of two different metals joined together. Different metals expand at different rates. When the bimetallic strip is heated, one side expands more than the other. This causes the strip to uncurl. The movement of the strip operates a switch, which can turn a heating system on or off.

Section 3 Assessment

Target Reading Skill Building Vocabulary Use your sentences to help answer the questions.

Reviewing Key Concepts

1. a. Identifying Name three states of matter.
   b. Comparing and Contrasting How are the three states of matter different from each other? How are they the same?
2. a. Reviewing What causes a change in state?
   b. Describing Why does the temperature of matter remain the same while the matter changes state?
   c. Relating Cause and Effect What causes a solid to melt?
3. a. Defining How can a liquid expand without changing state?
   b. Applying Concepts Why should you poke holes in a potato before baking it?
   c. Interpreting Diagrams How does a thermostat make use of thermal expansion?

Lab zone At-Home Activity

Frosty Balloons Blow up two balloons so that they are the same size. Have a family member use a measuring tape to measure the circumference of the balloons. Place one of the balloons in the freezer for 15 to 20 minutes. Then measure both balloons again. Explain how changes in thermal energy cause the change in size.

Section 4

Uses of Heat

Reading Preview

Key Concepts

- How do heat engines use thermal energy?
- How do refrigerators keep things cold?

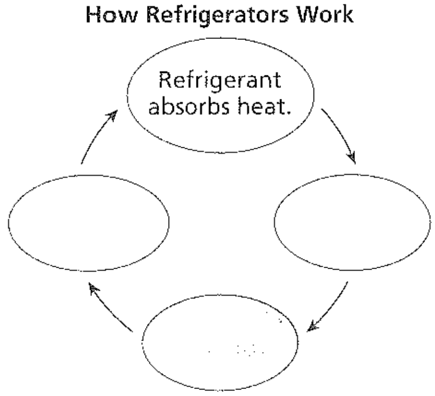
Key Terms

- heat engine
- external combustion engine
- internal combustion engine
- refrigerant

Target Reading Skill

Sequencing A sequence is the order in which the steps in a process occur. As you read, make a cycle diagram that shows how refrigerators work. Write each phase of the cooling system's cycle in a separate circle.

How Refrigerators Work



Lab zone Discover Activity

What Happens at the Pump?

1. Obtain a bicycle pump and a deflated basketball or soccer ball.
2. Feel the pump with your hand. Note whether it feels cool or warm to the touch.
3. Use the pump to inflate the ball to the recommended pressure.
4. As soon as you stop pumping, feel the pump again. Observe any changes in temperature.

Think It Over

Developing Hypotheses Propose an explanation for any changes that you observed.

For more than 100 years, the steam locomotive was a symbol of power and speed. It first came into use in the 1830s, and was soon hauling hundreds of tons of freight faster than a horse could gallop. Today, many trains are pulled by diesel locomotives that are far more efficient than steam locomotives.

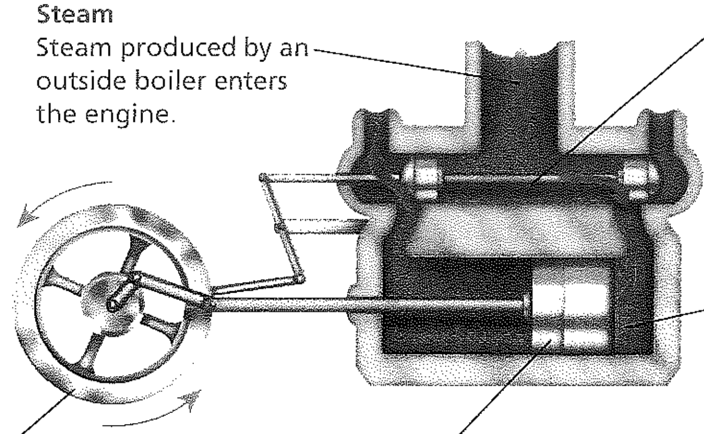
Heat Engines

To power a coal-burning steam locomotive, coal is shoveled into a roaring fire. Heat is then transferred from the fire to water in the boiler. But how can heat move a train?

The thermal energy of the coal fire must be transformed to the mechanical energy, or energy of motion, of the moving train. You already know about the reverse process, the transformation of mechanical energy to thermal energy. It happens when you rub your hands together to make them warm.

The transformation of thermal energy to mechanical energy requires a device called a **heat engine.** Heat engines usually make use of combustion. You may recall that combustion is the process of burning a fuel, such as coal or gasoline. During combustion, chemical energy that is stored in fuel is transformed to thermal energy. **Heat engines transform thermal energy to mechanical energy.** Heat engines are classified according to whether combustion takes place outside the engine or inside the engine.

FIGURE 15
External Combustion Engine
In a steam-powered external combustion engine, expanding steam pushes a piston back and forth inside a cylinder. The steam's thermal energy is transformed to mechanical energy.



External Combustion Engines Engines that burn fuel outside the engine in a boiler are called **external combustion engines.** A steam engine, like the one shown in Figure 15, is an example of an external combustion engine. The combustion of wood, coal, or oil heats water in a boiler. As its thermal energy increases, the liquid water turns to water vapor, or steam. The steam is then passed through a sliding valve into the engine, where it pushes against a metal plunger called a piston. Work is done on the piston as it moves back and forth in a tube called a cylinder. The piston's motion turns a flywheel.

Internal Combustion Engines Engines that burn fuel in cylinders inside the engine are called **internal combustion engines.** Diesel and gasoline engines, which power most automobiles, are internal combustion engines. A piston inside a cylinder moves up and down, turning a crankshaft. The motion of the crankshaft is transferred to the wheels of the car.

Each up or down movement by a piston is called a stroke. Most diesel and gasoline engines are four-stroke engines, as shown in Figure 16. Automobile engines usually have four, six, or eight cylinders. The four-stroke process occurs in each cylinder, and is repeated many times each second.

Reading Checkpoint **How many cylinders do automobiles usually have?**

Lab zone Try This Activity

Shake It Up
How does work relate to temperature?
1. Place a handful of dry sand in a metal container that has a cover.
2. Measure the temperature of the sand with a thermometer.
3. Cover the can and shake it vigorously for a minute or two.
4. Predict any change in the temperature of the sand. Was your prediction correct?

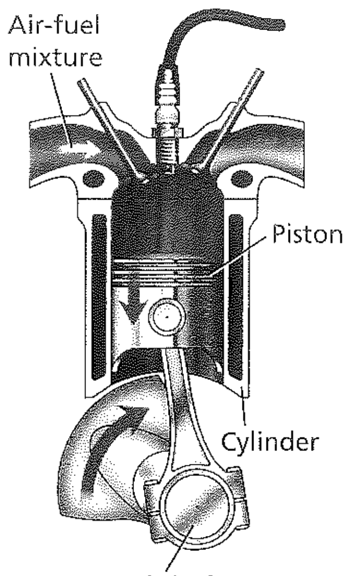
Classifying Identify any energy transformations and use them to explain your observations.

FIGURE 16

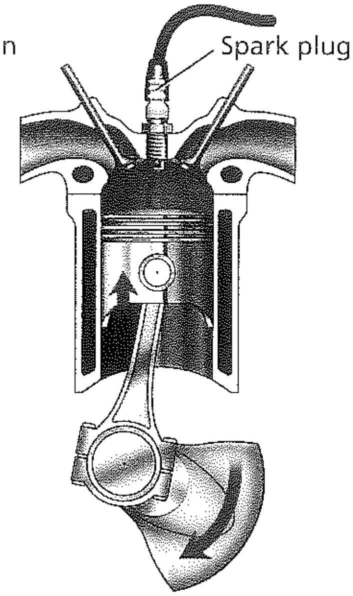
Four-Stroke Engine

Most automobiles use four-stroke engines. These four strokes occur repeatedly in each of the engine's cylinders.

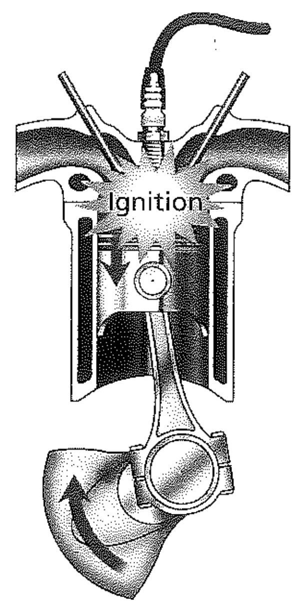
Interpreting Diagrams *During which stroke is thermal energy transformed to mechanical energy?*



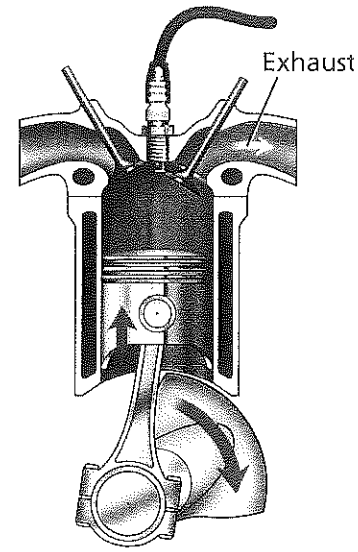
1 Intake Stroke
A mixture of fuel and air is drawn into the cylinder as the piston moves down.



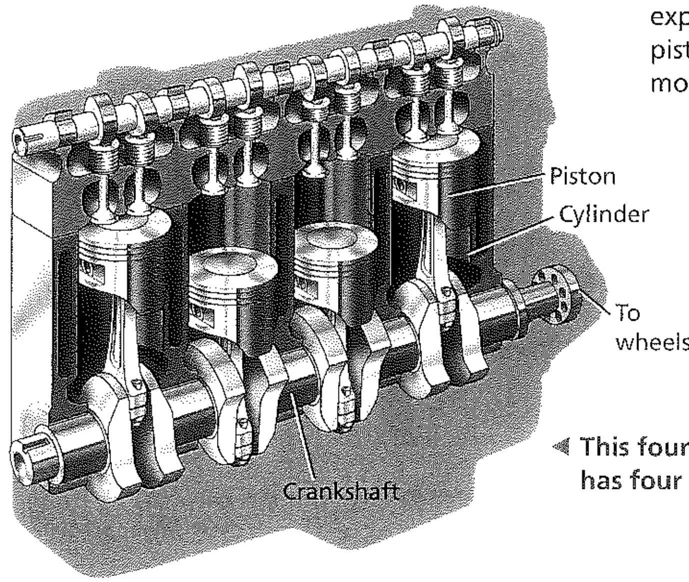
2 Compression Stroke
The mixture is compressed into a smaller space as the piston moves back up.



3 Power Stroke
A spark plug ignites the mixture. The heated gas expands and pushes the piston down. The piston moves the crankshaft.



4 Exhaust Stroke
The piston moves back up, pushing the heated gas out. This makes room for new fuel and air, so that the cycle can be repeated.



◀ **This four-stroke engine has four cylinders.**

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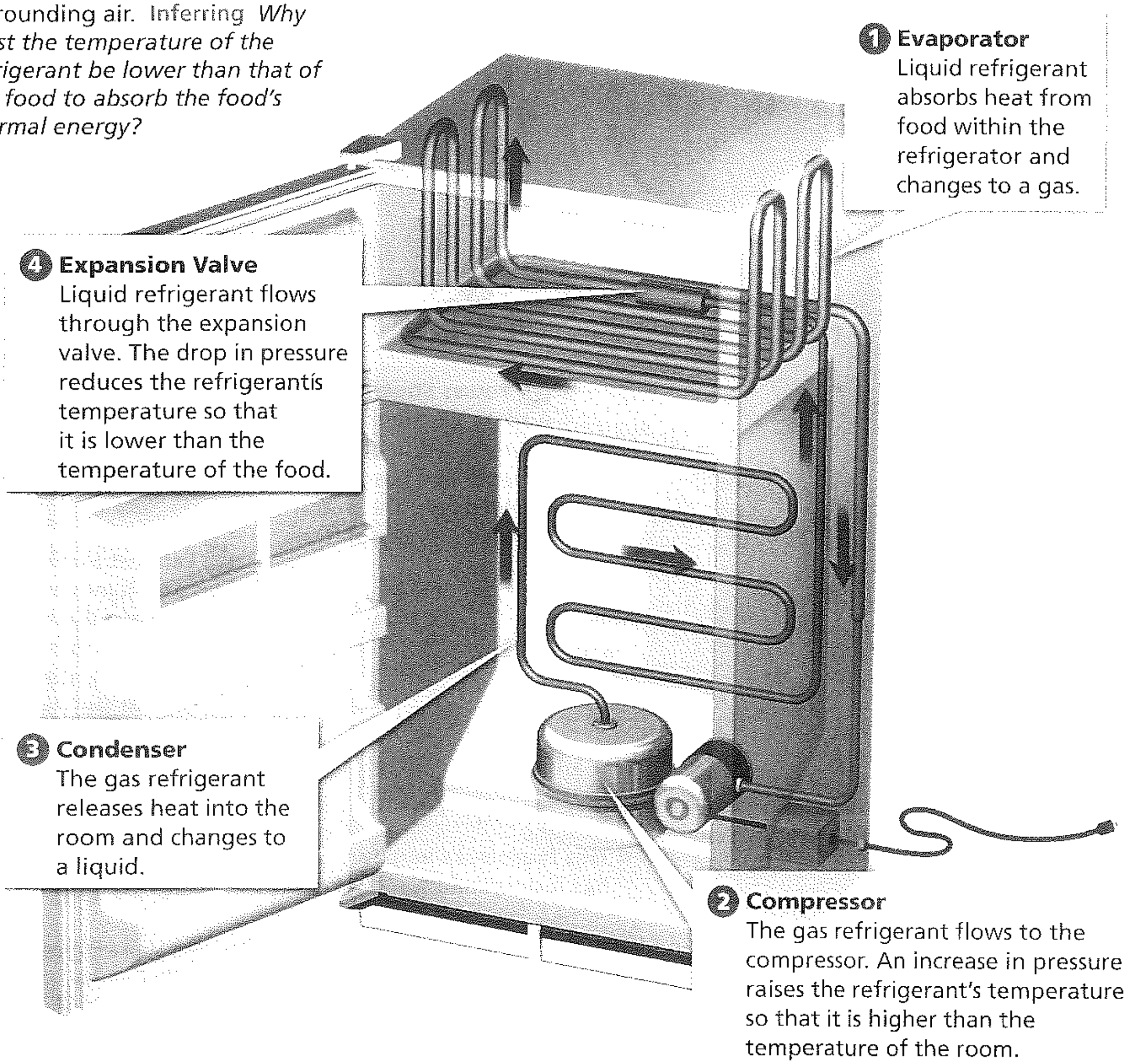
Cooling Systems

The transfer of heat can sometimes be used to keep things cool. Are you surprised? After all, heat naturally flows from a warm area to a cold area—not the other way around. But some devices, such as refrigerators, can transfer heat from cold areas to warm areas.

Refrigerators A refrigerator is cold inside. So where does the heat in the warm air rising from the back of a refrigerator come from? You may be surprised to learn that part of the heat actually comes from food in the refrigerator! **A refrigerator is a device that transfers thermal energy from inside the refrigerator to the room outside.** In doing so, the refrigerator transfers thermal energy from a cool area to a warm area.

FIGURE 17
Refrigerator
Inside a refrigerator, refrigerant moves through a system of pipes, transferring thermal energy from inside the refrigerator to the surrounding air. Inferring *Why must the temperature of the refrigerant be lower than that of the food to absorb the food's thermal energy?*



A substance called a **refrigerant** absorbs and releases heat in a refrigerator. As shown in Figure 17, the refrigerant moves through a closed system of pipes. These pipes run along the back of the refrigerator and inside where food is stored. The coiled pipes inside make up the evaporator. As the refrigerant enters the evaporator, it is a liquid. Because it is colder than the food, it absorbs the thermal energy of the food. The food's thermal energy raises the refrigerant's temperature, causing it to evaporate. Then, the gas refrigerant enters an electric pump called a compressor. The compressor increases the refrigerant's pressure, further raising its temperature.

From the compressor, the gas refrigerant flows to the coiled pipes at the back of the refrigerator that make up the condenser. When it enters the condenser, the refrigerant is warmer than the air in the room. It releases heat into the air and its temperature drops, causing the refrigerant to condense. The pressure of the liquid refrigerant is decreased as it flows into a narrow opening called an expansion valve. The decreased pressure lowers the refrigerant's temperature further. The refrigerant recycles as it flows back to the evaporator.

Air Conditioners The air conditioners used in homes, schools, and cars cool air in the same way that a refrigerator cools food. Refrigerant in a system of pipes changes from a liquid to a gas and back again to transfer heat. Unlike a refrigerator, however, an air conditioner absorbs heat from the air inside a room or car and transfers it to the outdoors.

✓ Reading Checkpoint **How are air conditioners and refrigerators similar?**

Section 4 Assessment

Target Reading Skill Sequencing Refer to your cycle diagram about cooling systems as you answer Question 2.

Reviewing Key Concepts

1. a. Describing What does a heat engine do?
   b. Comparing and Contrasting How are internal combustion engines different from external combustion engines? How are they similar?
   c. Making Generalizations Why do you think modern cars use internal rather than external combustion engines?
2. a. Identifying What changes of state occur in the refrigerant of a refrigerator?
   b. Explaining Where do the changes of state occur?
   c. Predicting If the compressor in a refrigerator stopped working, how would its failure affect the heat transfer cycle?

Writing in Science

Cause-and-Effect Paragraph The invention of the heat engine and refrigerator both had a great impact on society. Write about how daily life might be different if either system had not been invented.

Chapter 14 Study Guide

The BIG Idea **Transfer of Energy** Heat can be transferred by conduction, convection, or radiation.

1 Temperature, Thermal Energy, and Heat

Key Concepts

- The three common scales for measuring temperature are the Fahrenheit, Celsius, and Kelvin scales.
- Heat is thermal energy moving from a warmer object to a cooler object.
- A material with a high specific heat can absorb a great deal of thermal energy without a great change in temperature.
- Change in energy = Mass × Specific heat × Change in temperature

Key Terms

temperature
Fahrenheit scale
Celsius scale
Kelvin scale
absolute zero
heat
specific heat

2 The Transfer of Heat

Key Concepts

- Heat is transferred by conduction, convection, and radiation.
- If two objects have different temperatures, heat will flow from the warmer object to the colder one.
- A conductor transfers thermal energy well. An insulator does not transfer thermal energy well.

Key Terms

conduction
convection
convection current
radiation
conductor
insulator

3 Thermal Energy and States of Matter

Key Concepts

- Most matter on Earth can exist in three states—solid, liquid, and gas.
- Matter can change from one state to another when thermal energy is absorbed or released.
- As the thermal energy of matter increases, its particles spread out and the substance expands.

Key Terms

state
change of state
melting
freezing
evaporation
boiling
condensation
thermal expansion

4 Uses of Heat

Key Concepts

- Heat engines transform thermal energy to mechanical energy.
- A refrigerator is a device that transfers thermal energy from inside the refrigerator to the room outside.

Key Terms

heat engine
external combustion engine
internal combustion engine
refrigerant

Review and Assessment

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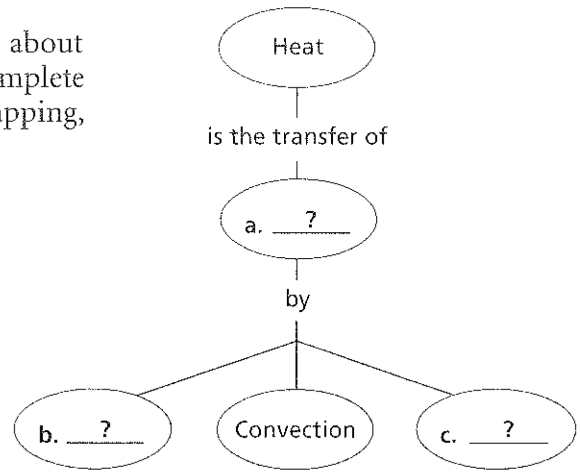
Organizing Information

Concept Mapping Copy the concept map about heat onto a separate sheet of paper. Then complete it and add a title. (For more on Concept Mapping, see the Skills Handbook.)



Reviewing Key Terms

Choose the letter of the best answer.

1. A measure of the average kinetic energy of the particles of an object is its
   a. heat.
   b. temperature.
   c. specific heat.
   d. thermal energy.
2. If you want to know the amount of heat needed to raise the temperature of 2 kg of steel by 10°C, you need to know steel's
   a. temperature. b. thermal energy.
   c. state. d. specific heat.
3. The process by which heat moves from one particle of matter to another without the movement of matter itself is called
   a. convection.
   b. conduction.
   c. radiation.
   d. thermal expansion.
4. Vaporization that occurs below the surface of a liquid is called
   a. evaporation. b. melting.
   c. boiling. d. freezing.
5. The process of burning a fuel is called
   a. combustion.
   b. thermal expansion.
   c. radiation.
   d. boiling.

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

6. A temperature reading of zero on the Celsius scale is equal to absolute zero.
7. A convection current is the circular motion of a fluid caused by the rising of heated fluid.
8. An insulator conducts heat well.
9. When a substance is freezing, the thermal energy of the substance decreases.
10. In an external combustion engine, the fuel is burned inside the engine.

Writing in Science

Proposed Solution You have been asked to design a bridge for an area that is quite hot in the summer and cold in the winter. Propose a design plan for the bridge. Include in your plan how expansion joints will help the bridge react in hot and cold temperatures.

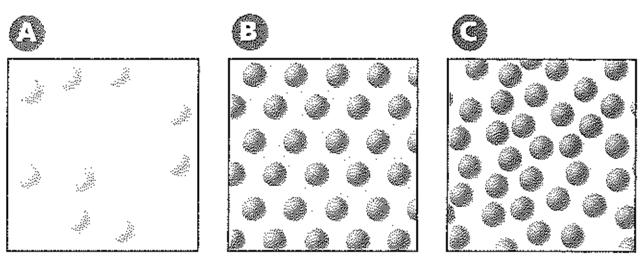
Review and Assessment

Checking Concepts

11. What happens to the particles of a solid as the thermal energy of the solid increases?
12. During a summer night, the air temperature drops by 10°C. Will the temperature of the water in a nearby lake change by the same amount? Explain why or why not.
13. When you heat a pot of water on the stove, a convection current is formed. Explain how this happens.
14. How can you add thermal energy to a substance without increasing its temperature?
15. When molten steel becomes solid, is energy absorbed or released by the steel? Explain.
16. Describe how a thermostat controls the temperature in a building.

Thinking Critically

17. Relating Cause and Effect Why is the air pressure in a car's tires different before and after the car has been driven for an hour?
18. Applying Concepts When they are hung, telephone lines are allowed to sag. Can you think of a reason why?
19. Interpreting Diagrams The three illustrations below represent the molecules in three different materials. Which is a solid? A liquid? A gas?



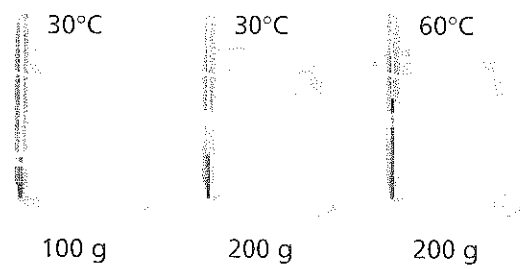
20. Developing Hypotheses A refrigerator is running in a small room. The refrigerator door is open, but the room does not grow any cooler. Use the law of conservation of energy to explain why the temperature does not drop.

Math Practice

21. Converting Units A recipe says to preheat your oven to 275°F. What is this temperature in degrees Celsius?
22. Converting Units The temperature in a greenhouse is 86°F. Convert this temperature to degrees Celsius.

Applying Skills

Use the illustration of three containers of water to answer Questions 23–25.



23. Interpreting Data Compare the average motion of the molecules in the three containers. Explain your answer.
24. Drawing Conclusions Compare the total amount of thermal energy in the three containers. Explain your answer.
25. Calculating Which container would need the least amount of thermal energy to raise its temperature by 1 K? The specific heat of water is 4,180 J/(kg·K).

Lab zone Chapter Project

Performance Assessment Talk with your classmates about their container designs. When you've had a chance to look them over, predict the final water temperature for each container. Record the starting temperature for each one, including your own. Record the final temperatures at the end of each demonstration. Which insulating materials seemed to work the best? Describe how you could improve your container, based on what you learned.

Standardized Test Prep

Test-Taking Tip

Using Formulas

For some questions, you will need to use a formula to find the correct answer. It is important to know which formula to use. Look for key words in the question to help you decide which formula will help you answer the question. Then substitute the values provided to make your calculations.

Sample Question

The specific heat of iron is 450 J/(kg·K). How much heat must be transferred to 15 kg of iron to raise its temperature by 4.0 K?

A 450 J
B 2,700 J
C 5,400 J
D 27,000 J

Answer

The question deals with the amount of heat needed to change the temperature of a material. The specific heat of that material, iron, is provided. You need to use the formula for calculating thermal energy changes.

Change in energy = Mass × Specific heat × Change in temperature

Change in energy = 15 kg × 450 J/(kg·K) × 4.0 K
Change in energy = 27,000 J

The correct answer is **D.**

Choose the letter of the best answer.

1. When cold, dry air passes over a much warmer body of water, a type of fog called sea smoke is produced. Which process explains why this occurs?
   A melting
   B condensation
   C boiling
   D freezing

2. The table below shows the specific heat of four metals. If 1,540 J of heat is transferred to 4 kg of each metal, which metal will increase in temperature by 1 K?

Specific Heat of Metals

Metal	Specific Heat (J/(kg·K))
Silver	235
Iron	450
Copper	385
Aluminum	903

   F Silver
   G Copper
   H Iron
   J Aluminum

3. A student wants to measure the temperature at which several different liquids freeze. In the student's experiment, temperature is the
   A hypothesis.
   B responding variable.
   C manipulated variable.
   D operational definition.

4. Two solid metal blocks are placed in a container. If there is a transfer of heat between the blocks, then they must have different
   F boiling points.
   G melting points.
   H specific heats.
   J temperatures.

5. A thermometer measures
   A temperature.
   B thermal energy.
   C heat.
   D specific heat.

Constructed Response

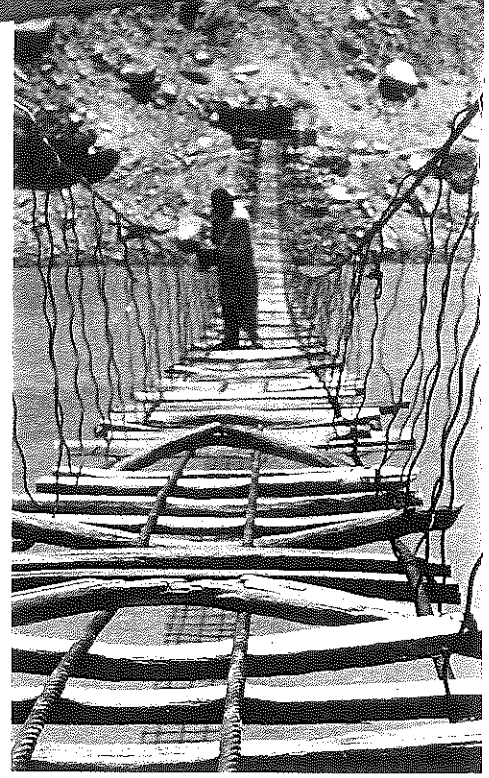
6. Explain how heat is transferred by conduction, convection, and radiation. Give an example of each.

Interdisciplinary
Exploration

Bridges—From Vines to Steel

Have you ever

- balanced on a branch or log to cross a brook?
- jumped from rock to rock in a streambed?
- swung on a vine or rope over a river?



Vine Footbridge
Crossing Hunza River in northern Pakistan

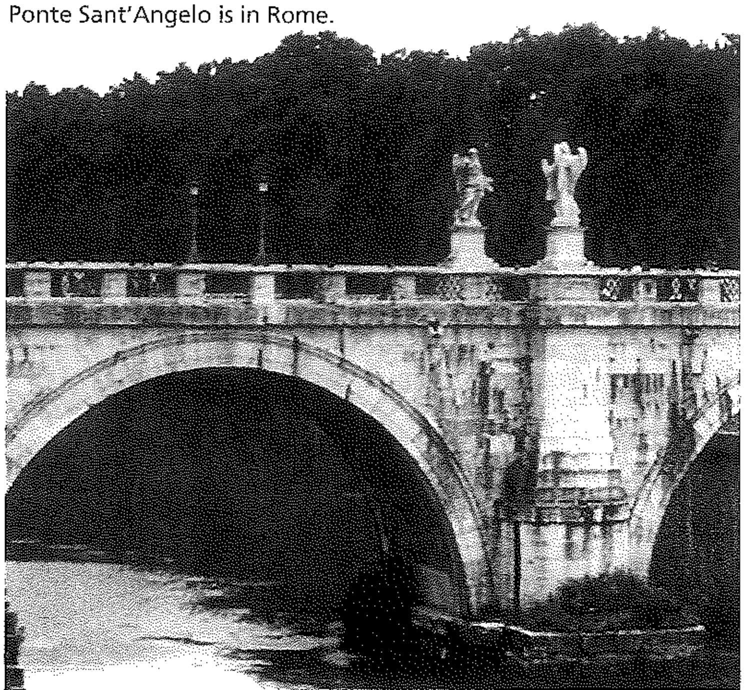
Then you have used the same ways that early people used to get over obstacles. Fallen trees, twisted vines, and natural stones formed the first bridges.

Bridges provide easy ways of getting over difficult obstacles. For thousands of years, bridges have also served as forts for defense, scenes of great battles, and homes for shops and churches. They have also been sites of mystery, love, and intrigue. They span history—linking cities, nations, and empires and encouraging trade and travel.

But bridges have not always been as elaborate as they are today. The earliest ones were made of materials that were free and plentiful. In deep forests, people used beams made from small trees. In tropical regions where vegetation was thick, people wove together vines and grasses, then hung them to make walkways over rivers and gorges.

No matter what the structures or materials, bridges reflect the people who built them. The ancient civilizations of China, Egypt, Greece, and Rome all designed strong, graceful bridges to connect and control their empires.

Roman Arch Bridge
Ponte Sant'Angelo is in Rome.



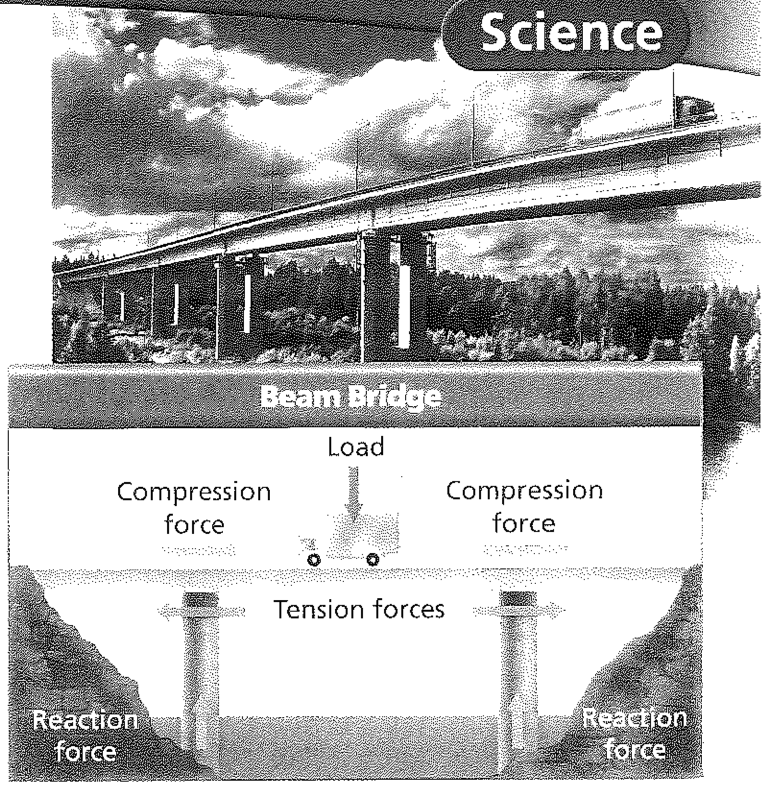
The Balance of Forces

What keeps a bridge from falling down? How does it support its own weight and the weight of people and traffic on it? Builders found the answers by considering the various forces that act on a bridge.

The weight of the bridge and the traffic on it are called the *load.* When a heavy truck crosses a beam bridge, the weight of the load forces the beam to curve downward. This creates tension forces that stretch the bottom of the beam. At the same time, the load also creates compression forces at the top of the beam.

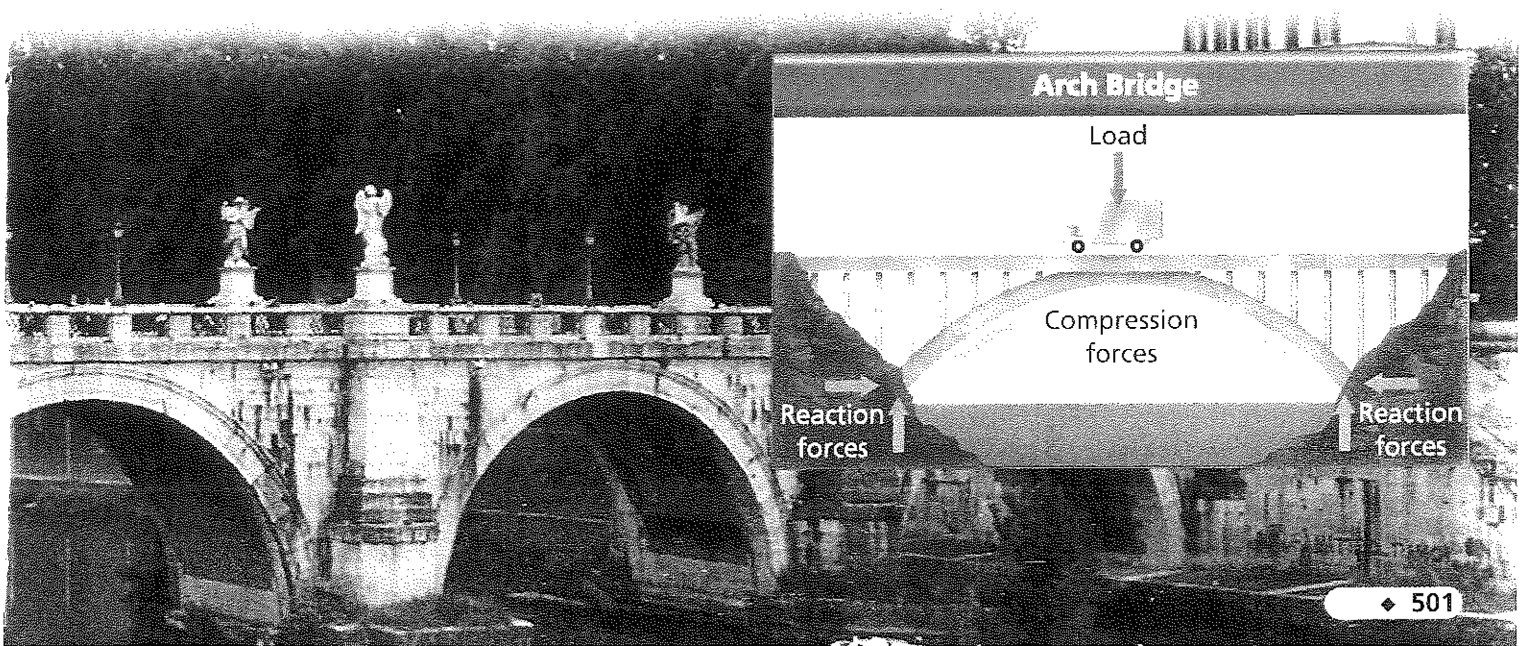
Since the bridge doesn't collapse under the load, there must be upward forces to balance the downward forces. In simple beam bridges, builders anchor the beam to the ground or to end supports called abutments. To cross longer spans or distances, they construct piers under the middle span. Piers and abutments are structures that act as upward forces—reaction forces.

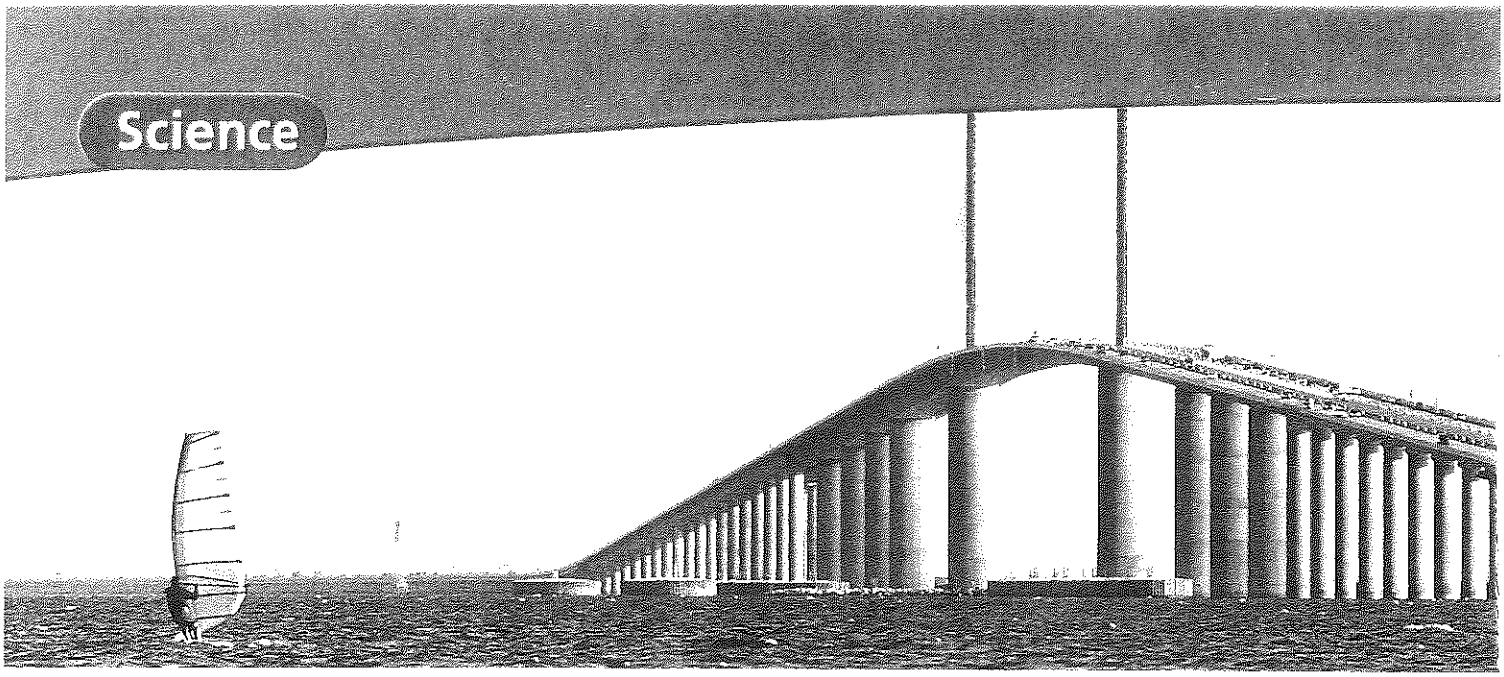
Another type of bridge, the arch bridge, supports its load by compression. A heavy load on a stone arch bridge squeezes or pushes the stones together, creating compression throughout the structure. Weight on the arch bridge pushes down to the ends of the arch. The side walls and abutments act as reaction forces.



Beam Bridge
A beam bridge spans the Saima channel in Scandinavia (top).

Early engineers discovered that arch bridges made of stone could span wider distances than simple beam bridges. Arch bridges are also stronger and more durable. Although the Romans were not the first to build arch bridges, they perfected the form in their massive, elegant structures. Early Roman arch bridges were built without mortar, or "glue." The arch held together because the stones were skillfully shaped to work in compression. After nearly 2,000 years, some of these Roman arch bridges are still standing.





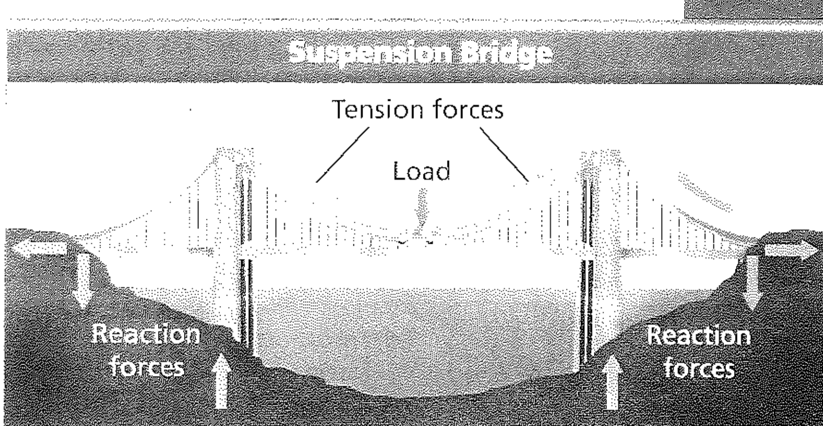
The Structure of Modern Bridges

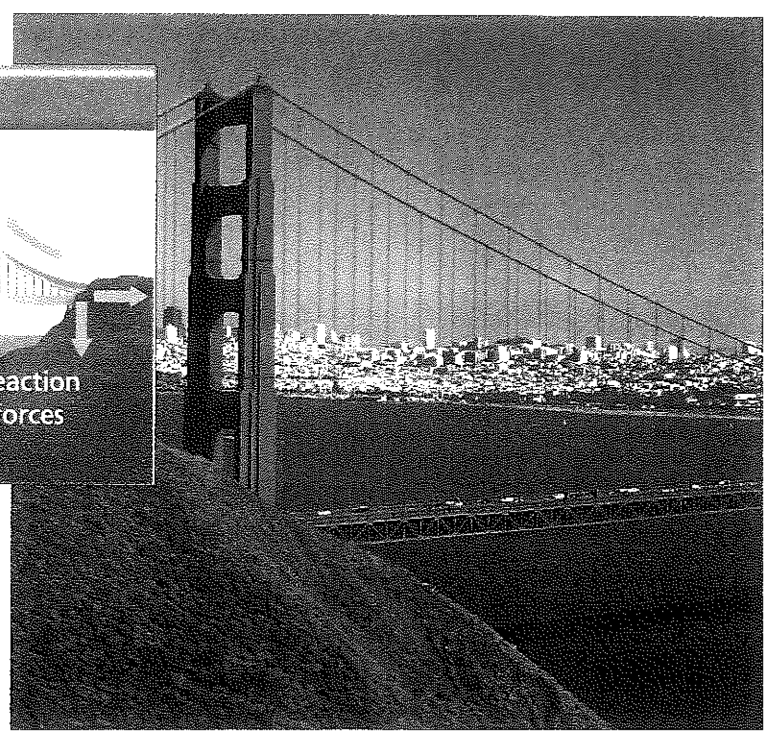
By the 1800s in the United States, bridge builders began to use cast iron instead of stone and wood. By the late 1800s, they were using steel, which was strong and relatively lightweight. The use of new building materials was not the only change. Engineers began designing different types of bridges as well. They found that they could build longer, larger bridges by using a suspension structure.

Suspension bridges are modern versions of long, narrow, woven bridges found in tropical regions. These simple, woven suspension bridges can span long distances. Crossing one of these natural structures is like walking a tightrope. The weight of people and animals traveling over the bridge pushes down on the ropes, stretching them and creating tension forces.

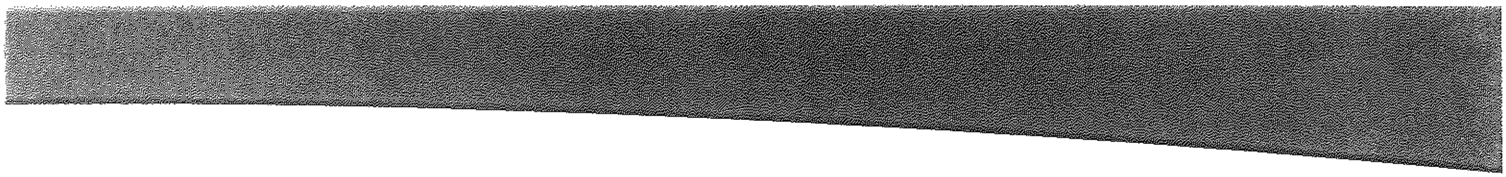
Modern suspension bridges follow the same principles of tension as do woven bridges. A suspension bridge is strong in tension. In suspension bridges, parallel cables are stretched the entire length of the bridge—over giant towers. The cables are anchored at each end of the bridge. The roadway hangs from the cables, attached by wire suspenders. The weight of the bridge and the load on it act to pull apart or stretch the cables. This pulling apart creates tension forces.

The towers of a suspension bridge act as supports for the bridge cables. The abutments that anchor the cables exert reaction forces as well. So forces in balance keep a suspension bridge from collapsing.

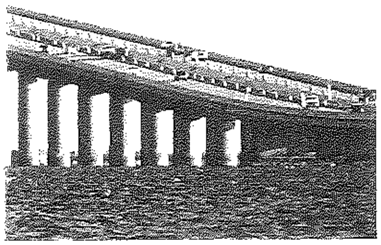




Suspension Bridge
The Golden Gate Bridge in California



Cable-Stayed Bridge
The Sunshine Skyway Bridge spans a broad section of Tampa Bay in Florida. The cables, attached to the center of the roadway, enable travelers to have a clear view.



When the Brooklyn Bridge opened in New York City in1883, it was the longest suspension bridge in the world. The Golden Gate Bridge in San Francisco, which was opened in 1937, was another great engineering feat.

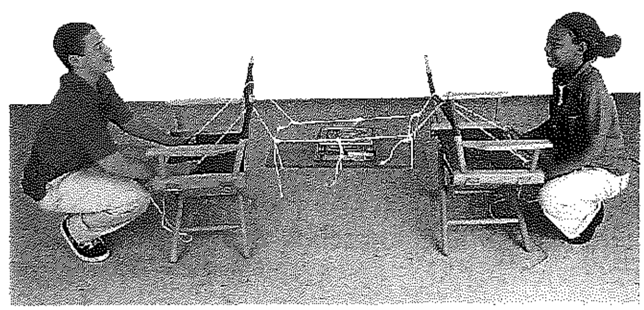
Recently, engineers have developed a new bridge design called the cable-stayed bridge. It looks similar to a suspension bridge because both are built with towers and cables. But the two bridges are quite different. The cables on the cable-stayed bridge attach to the towers, so the towers bear the weight of the bridge and the load on it. In contrast, the cables on a suspension bridge ride over the towers and anchor at the abutments. So on a suspension bridge, both the towers and abutments bear the load.

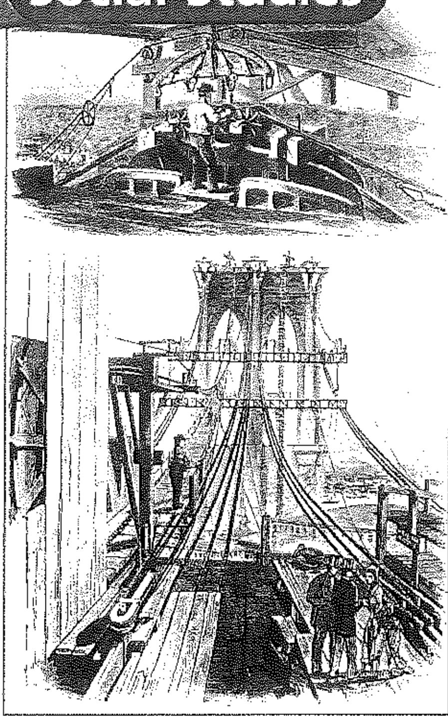
Science Activity

Work in groups to make a suspension bridge, using two chairs, a wooden plank, rope, and some books.

- Place two chairs back-to-back and stretch 2 ropes over the backs of the chairs. Hold the ropes at both ends.
- Tie three pieces of rope to the longer ropes. Place the plank through the loops.
- With a partner, hold the ropes tightly at each end. Load books on top of the plank to see how much it will hold.

Why is it important to anchor the ropes tightly at each end?





Brooklyn Bridge
This bridge connects Brooklyn and Manhattan (above).
It took 14 years for workers to complete the bridge (left).

Against All Odds

When John Roebling was hired in 1868 to build the Brooklyn Bridge, he was already a skilled suspension bridge engineer. He had been working on plans for the bridge since 1855.

But before bridge construction even began in 1869, John Roebling died in a construction accident. Fortunately, he had worked out his bridge design to the last detail. His son, Colonel Washington Roebling, who was also a skilled engineer, dedicated himself to carrying out his father's plans.

The construction dragged on for 14 years and cost nearly 30 lives. Colonel Roebling himself became so disabled that he was forced to direct construction from his home. Using a telescope, Colonel Roebling followed every detail. His remarkable, energetic wife, Emily Warren Roebling, learned enough engineering principles to deliver and explain his orders to the workers.

As soon as the giant towers were up, workers unrolled the steel wire back and forth across the towers to weave the cables. The next step was to twist the wires together. But the workmen were terrified of hanging so high on the bridge and refused to work.

Finally, Frank Farrington, the chief mechanic, crossed the river on a small chair dangling from a wheel that ran across an overhead line. Farrington completed his journey to the roar of the crowd. Somewhat reassured, the builders returned to work. But it took two more years to string the cables. The bridge was one of the greatest engineering achievements of its time.

In the end, the Brooklyn Bridge project succeeded only because of the determination and sacrifices of the Roebling family. It became the model for hundreds of other suspension bridges.

Social Studies Activity

How do you think the Brooklyn Bridge changed the lives of New Yorkers? In groups, research the history of another famous bridge. Present your findings to your class along with drawings and photos. Find out

- when and why the bridge was built
- what type of bridge it is
- what effects the bridge has on people's lives—on trade, travel, and population
- how landforms affected the bridge building
- about events connected to the bridge

Bridge Opens Amid Fanfare

May 25, 1883—Thousands of people gathered yesterday for a ceremony to celebrate the opening of the Brooklyn Bridge. This amazing bridge, which connects Manhattan to Brooklyn, has been over twenty years in the making.

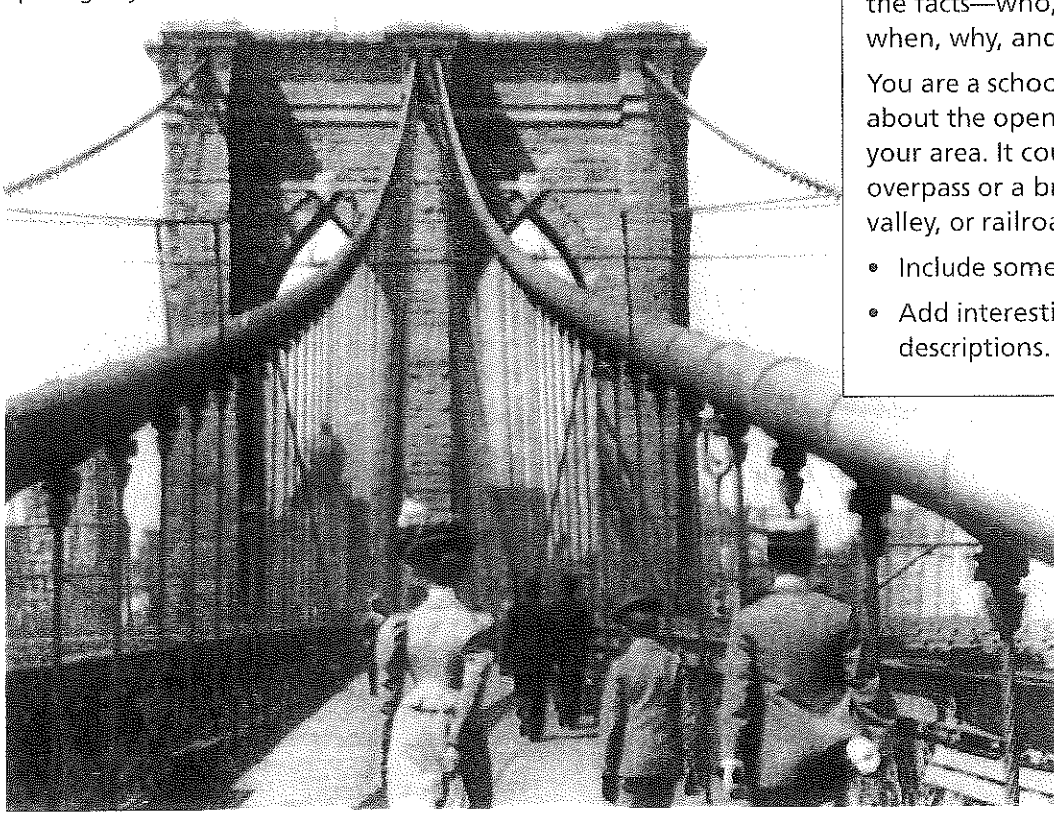
The crowds were so thick that many of the ceremony's ticket-holders had trouble reaching the bridge. Eager spectators filled the streets and sidewalks on either side. People gathered on rooftops and filled nearby windows. Some watched from ferryboats going back and forth across the river. One group even climbed a nearby telegraph pole. Hundreds of New York City police officers were on the job, keeping order.

The ceremonies began with music by the Twenty-third Regiment Band. Several New York politicians and dignitaries gave speeches praising the bridge's construction as an amazing feat of engineering.

The engineer-in-chief of the project, J.A. Roebling, lived nearby, and watched the event and celebration through a telescope, from the comfort of home. He later received honors when a procession marched to his residence. The closing ceremony began at eight o'clock in the evening, when hundreds of rockets began illuminating the sky. The whole river sparkled, reflecting the light from the spectacular show.

The Brooklyn Bridge is worth all the fanfare it has received. It is the largest suspension bridge in the world. The weight of the bridge is 14,080 tons. It is estimated that the added weight of vehicles and pedestrians traveling on the bridge will be about 3,100 tons. Therefore, the bridge can sustain an astonishing total weight of 17,780 tons.

Brooklyn Bridge
People walked across the bridge on opening day.



Language Arts Activity

A reporter's goal is to inform and entertain the reader. Using a catchy opening line draws interest. Then the reader wants to know the facts—who, what, where, when, why, and how (5 W's and H).

You are a school reporter. Write about the opening of a bridge in your area. It could be a highway overpass or a bridge over water, a valley, or railroad tracks.

- Include some of the 5 W's and H.
- Add interesting details and descriptions.

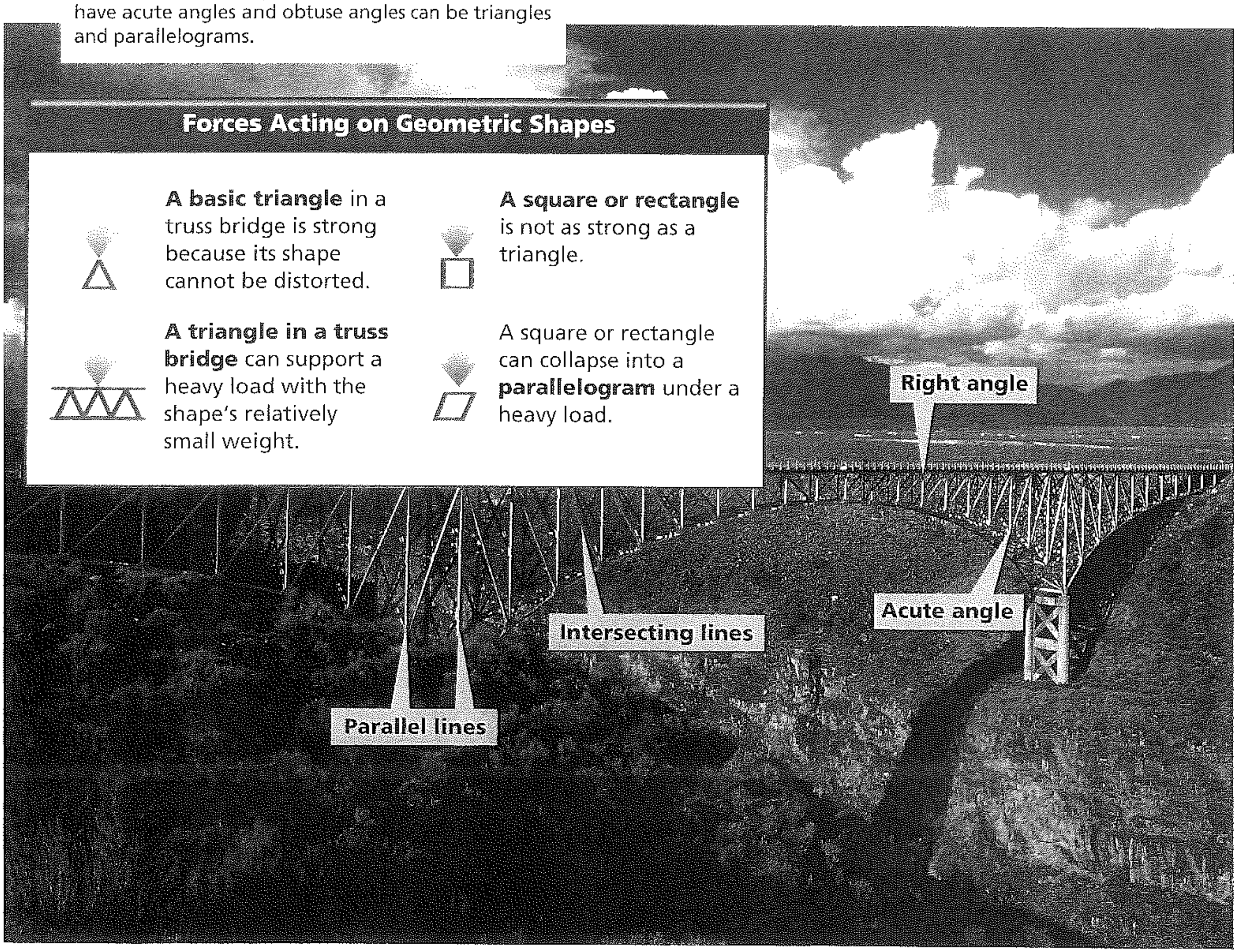
Mathematics

Bridge Geometry

As railroad traffic increased in the late 1800s, truss bridges became popular. Designed with thin vertical and diagonal supports to add strength, truss bridges were actually reinforced beam bridge structures. Many of the early wood truss bridges couldn't support the trains that rumbled over them. Cast iron and steel trusses soon replaced wood trusses.

Using basic triangular structures, engineers went to work on more scientific truss bridge designs. The accuracy of the design is crucial to handling the stress from heavy train loads and constant vibrations. As in all bridge structures, each steel piece has to be measured and fitted accurately—including widths, lengths, angles, and points of intersection and attachment.

Geometric Angles and Figures
Engineers use various geometric figures in drawing bridge plans. Figures that have right angles are squares, rectangles, and right triangles. Figures that have acute angles and obtuse angles can be triangles and parallelograms.



Forces Acting on Geometric Shapes

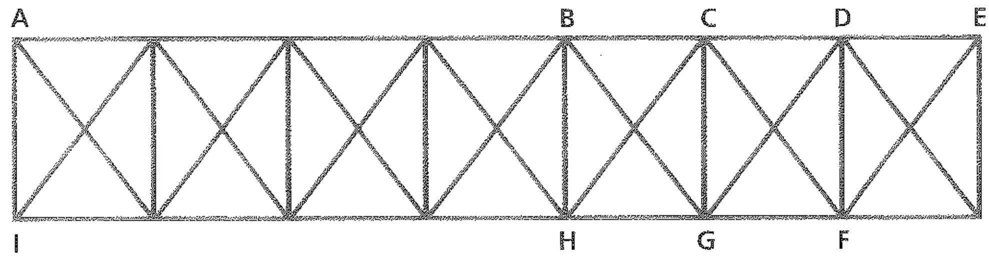
A basic triangle in a truss bridge is strong because its shape cannot be distorted.

A square or rectangle is not as strong as a triangle.

A triangle in a truss bridge can support a heavy load with the shape's relatively small weight.

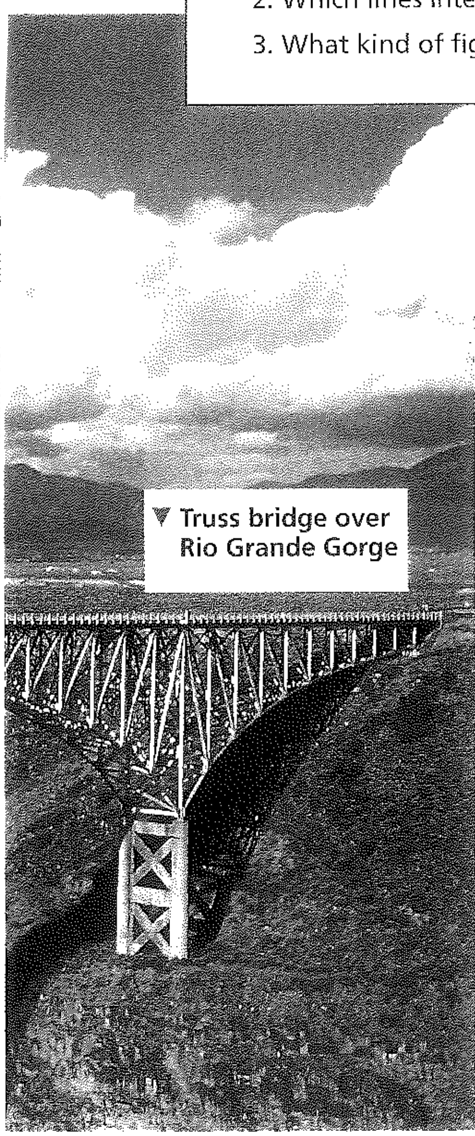
A square or rectangle can collapse into a **parallelogram** under a heavy load.

Math Activity



The chief building engineer has asked you to draw up exact plans for a new truss bridge. How well will you do as an assistant? Review the captions and labels on the previous page. Then answer these questions:

1. Which lines are parallel?
2. Which lines intersect?
3. What kind of figure is formed by *ABHI*?
4. What kind of figure is formed by *HCF*?
5. What kind of angle is *BGF*—obtuse or right?
6. What kind of angle is *CHG*?
7. What kind of triangle is *BHG*? What makes it this kind of triangle?
8. Why is a triangle stronger than a square?



▼ **Truss bridge over Rio Grande Gorge**

Tie It Together

Work in small groups to build a model of a bridge out of a box of spaghetti and a roll of masking tape. Meet as a group to choose the type of bridge you will build. Each bridge should be strong enough to hold a brick. You can build

- a beam bridge
- a truss bridge
- an arch bridge
- a suspension bridge (This one is challenging.)

After drawing a sketch of the bridge design, assign jobs for each team member. Then

- decide how long the bridge span will be
- measure and cut the materials
- build the roadway first for beam, truss, and suspension bridges
- build the arch first in an arch bridge

When your bridge is complete, display it in the classroom. Test the strength of each bridge by placing a brick on the roadway. Discuss the difference in bridge structures. Determine which bridge design is the strongest.