3.3 Explore

How Is Temperature Related to Thermal Energy?

You may have been surprised by the results of the experiment in *Section 3.2.* You may have thought that since the temperature of the water in Beakers C and D was the same, they would have the same amount of thermal energy. But the experiment showed something different. It showed that temperature and thermal energy are different. Two substances at the same temperature can have different amounts of thermal energy. To understand how this is possible, you will need to know more about temperature and thermal energy.

temperature: how hot or cold a substance or object is; a measure of the average kinetic energy of the particles in a substance.

When a car sits in the Sun, its surface feels hot. What is happening to the molecules of matter to make the temperature of the car's surface rise?

What Are Temperature and Thermal Energy?

When scientists need to think about abstract ideas, they often use a model. You will do that now to imagine the relationship between temperature and thermal energy.

First, however, you will need to know just a little bit about temperature and thermal energy. You know that temperature has to do with how warm something feels. However, you do not know what happens to matter as it gets warmer. Matter is made of many, many small particles, too tiny to be seen. These particles are always moving. The more energy they have, the faster they move. When thermal energy in the form of heat is transferred from a warmer substance to a cooler substance, the particles in the cooler substance begin to move faster. The average energy of motion of the particles of the substance increases. Therefore, the temperature of the substance increases. The average energy of motion of particles in a substance is its kinetic energy. Therefore, **temperature** is the measure of the average kinetic energy of the particles of a substance. The thermal energy of the substance is the total energy of the substance. You can think of it as the sum of the kinetic energy of the particles.The thought experiment coming up will help you better understand this.

Stop and Think

1. Temperature is the average kinetic energy of the particles that make up a substance. Why do you think temperature would affect how much thermal energy a substance has?
2. Mass is the total amount of stuff in a substance, and thermal energy is the total energy of the particles in a substance. Why do you think mass would affect how much thermal energy a substance has?

When you discuss the answers as a class, notice any disagreements among your classmates. It is probably hard to agree on an answer. This is why a model will help.

A Thought Experiment

In this model, marbles are used to represent particles of matter. In matter, the particles are always moving. Some move more slowly, and some move more quickly. But they are always moving. In this model, the speed of each particle in a substance is represented by the speed of one marble as it rolls across the floor. Temperature is the average kinetic energy of all the particles. So, in this model, average kinetic energy represents temperature.

Finally, in this model, more marbles is a model for more mass. The more mass, the more thermal energy there is. So, in this model, total kinetic energy is used to represent thermal energy.

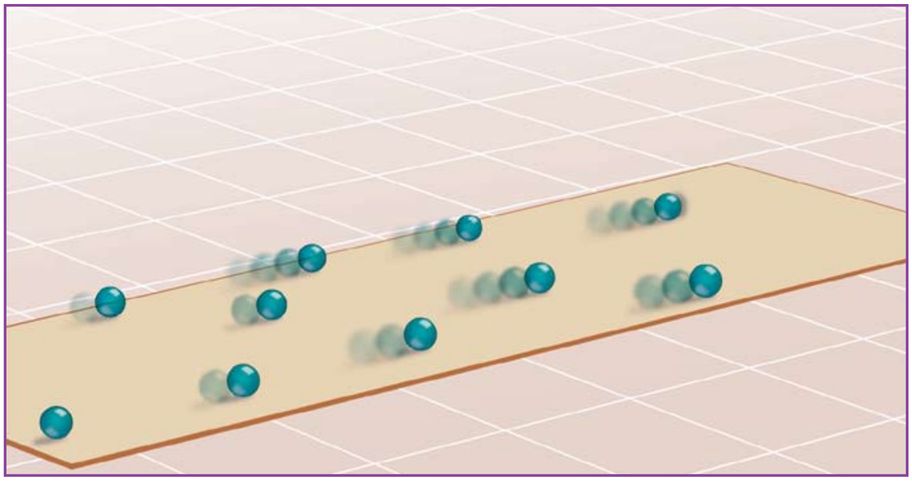
Think about these relationships, and follow the procedure to imagine how temperature and thermal energy are related.

Procedure

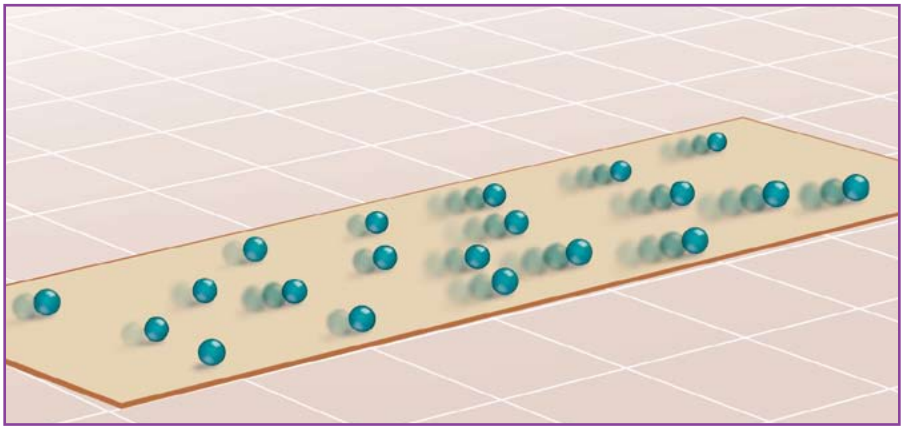
1. Make a copy of the table below to record your data.

Model of Marbles as Particles

Number of marbles (represents mass)	Kinetic energy of each marble (in energy units)	Average kinetic energy of marbles (represents temperature)	Total kinetic energy of marbles (represents thermal energy)
10 marbles	4, 4, 6, 5, 4, 7, 3, 4, 5, 4		
20 marbles	4, 4, 6, 5, 4, 7, 3, 4, 5, 4, 8, 4, 4, 7, 4, 7, 3, 2, 3, 4		



2. Begin by thinking about temperature. You will model that by averaging the kinetic energy of the marbles. Suppose that you have 10 identical marbles. They are all rolling across the floor at different speeds. The kinetic energy of each marble (in energy units) is given in the first row of the table. Calculate the average kinetic energy of the marbles. You can average the kinetic energy by dividing the sum of all the data values by 10. Record your data in the *Average Kinetic Energy of Marbles* column in the first row of the table.



3. Now imagine that instead of 10 marbles, you have 20 marbles. Again, the marbles are identical, and each marble is moving across the floor at a different speed. Calculate the average kinetic energy of the marbles. You can find the average by adding all the data values in the second row of the table and dividing by 20. Record your data in the *Average Kinetic Energy of Marbles* column in the second row of the table.

4. Now consider thermal energy. Thermal energy is a measure of the total energy in a substance or object. In this model then, thermal energy is the total energy of the marbles, or their total kinetic energy. Which set of marbles do you think has more total energy—the set of 10 marbles or the set of 20 marbles? Why?

5. Calculate the total kinetic energy of the marbles in each set in the table. Record your data in the *Total Kinetic Energy of Marbles* column of the table.

Analyze Your Data

1. How does the average kinetic energy data in the two sets of marbles compare?

2. How does the total kinetic energy data in the two sets of marbles compare?

3. Why does the set of 20 marbles moving across the floor represent more thermal energy than the set of 10 marbles, even though the average kinetic energy of both sets of marbles is the same?

4. How do you think the thermal energy of a set of 40 marbles would compare to the thermal energy of the 10-marble and 20-marble sets if they all have the same average kinetic energy?

5. Think back to the experiment in the previous section. Imagine that Row 1 of your marble data table represents the water in Beaker D (the one with 200 mL of warm water). Imagine that Row 2 of the table represents the water in Beaker C (the one with 400 mL of warm water). How is the marble model like the water in those beakers?

6. Use this model to develop a statement about why the water in Beaker C melted more ice than the water in Beaker D.

The body temperature of each polar bear is 37°C (98.6°F). Which polar bear in the picture do you think has more thermal energy?

thermometer: an instrument for measuring temperature.

degrees Celsius (°C): a unit of measurement for temperature, abbreviated as °C. At sea level, water freezes at 0°C and boils at 100°C.

degrees Fahrenheit (°F): a unit of measurement for temperature, abbreviated as °F. At sea level, water freezes at 32°F and boils at 212°F.

kelvin (K): a unit of measurement for temperature on the Kelvin scale.

Kelvin scale: a temperature scale where absolute zero theoretically indicates that no thermal energy is present; 0 K = –273°C.

What Is Temperature?

The thought experiment on the preceding pages related thermal energy and temperature. Most people think about temperature as how hot something feels. When you touch an object to feel its temperature, you are actually feeling the impacts of particles in that object. The faster the particles move when they hit your hand, the hotter the object feels.

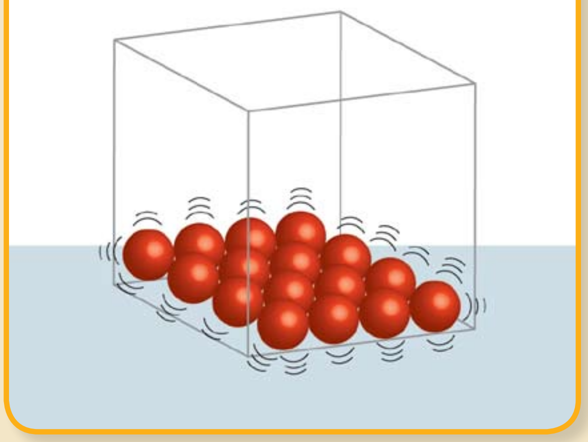
The speed of each particle in a substance depends on how much energy that particle has. Think of the people in a gym. Some people have lots of energy, and they are moving fast. Some are tired and have a low energy level. They are moving more slowly. Everyone is moving, so everyone in the gym has at least some energy. If many people in the gym are moving around quickly, the gym feels more energetic. If most people are moving more slowly, the gym feels less energetic. It is similar with the atoms and molecules that make up substances.

When a particle of a substance has less kinetic energy, it moves more slowly. When a particle has more kinetic energy, it moves faster. The particles in a substance are moving at many speeds. When more of the particles are moving fast, the substance has a higher temperature and feels warmer. When more of the particles are moving slowly, the substance has a lower temperature and feels cooler.

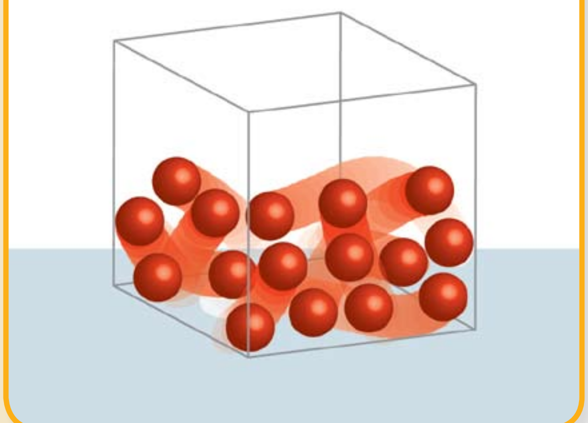
Temperature, then, is the average kinetic energy of the particles making up the substance. Some materials are made up of more than one substance, and their temperature is related to the average kinetic energy of all the different kinds of particles in the material. Temperature is measured using a **thermometer**. The most common units of temperature are **degrees Celsius (°C)** and **degrees Fahrenheit (°F)**. Scientists also use another unit, a **kelvin (K)**, to measure temperature. The **Kelvin scale** is a temperature scale where absolute zero is the temperature at which there theoretically is no thermal energy present. That is, theoretically, no particles are moving. Absolute zero is equal to approximately –273°C.

Temperature is an important factor that determines whether a substance is a solid, liquid, or gas. In a solid, the average speed of the particles is slow. The particles are close together and simply vibrate in place. As temperature rises, the average speed of the particles increases. At some point, the particles have enough kinetic energy that they begin to slide past one another while they are moving. The solid has become a liquid. As temperature rises even higher, the average speed of the particles increases even more. At some point, the fast-moving particles have so much energy that they literally bounce off the walls. They bounce around and fill all of the space in whatever container encloses them. The liquid has become a gas. The process of changing from solid to liquid to gas is endothermic. It requires heat. This process can be reversed. If a gas is cooled, the temperature drops, the particles slow down, and at some point, they form a liquid. Cooling further, the molecules slow even more, and the liquid becomes a solid. During the process of changing from gas to liquid to solid, the substance gives off heat. Cooling is an exothermic process.

In a solid, the particles remain close together and simply vibrate in place.



In a liquid, the particles have enough kinetic energy to slide fluidly past one another.



What Is Thermal Energy?

In your experiment in the preceding section, you observed that some of the ice in the bags melted and became a liquid. Ice is the solid form of water. The particles that make up ice are molecules of water. The water molecules in ice move slowly, so slowly that they merely vibrate in place. When the ice bags were put into the beakers, thermal energy from the water transferred to the ice. The thermal energy caused the molecules in the ice to move faster. Soon, the molecules moved around too quickly to stay in place as a solid. They began to separate from the solid ice and changed into a liquid.

Because thermal energy from the water in the beaker transferred to the bag of ice, the water in the beaker now had less thermal energy. The molecules in the water moved more slowly because they had less energy available. As a result, the temperature of the water dropped.

From this, you might suppose that thermal energy, like temperature, is related to kinetic energy. If you think that, you are right. The thermal energy in a substance is the total kinetic energy of all the particles in the substance. If you warm a substance or object, as each particle speeds up, the average speed of the particles (temperature) increases, and so does the total speed (kinetic energy) of the particles (thermal energy).

You use thermal energy to cook your breakfast.

If you think about thermal energy as the total kinetic energy of all the particles of a substance or object, then you can probably figure out why the mass of a substance affects its thermal energy. When a substance or object has more mass, it has more particles. This is why you found a difference in the amount of thermal energy in different amounts of water that were at the same temperature. Although the particles in both beakers were moving with the same kinetic energy, there are more particles in 400 mL of water than in 200 mL of water. At the same temperature, 400 mL of water has more thermal energy than 200 mL of water.

The relationship between thermal energy and kinetic energy is the reason that similar factors affect how much thermal or kinetic energy an object or substance has. Remember, from *Learning Set 2,* that the two factors that determine the amount of kinetic energy in an object are its speed and mass. The same factors determine the amount of thermal energy in an object or substance: the speed particles are moving and how many particles there are (mass).

This all means that temperature and thermal energy are related, but they are not the same thing. Temperature, the average kinetic energy of particles, tells you how warm something is. Thermal energy, the total kinetic energy of the particles, tells you the extent to which a substance or object can transfer heat or make something else warmer. If an object's temperature increases, its thermal energy increases also.

However, because thermal energy depends on both temperature and mass, two objects at the same temperature do not necessarily have the same thermal energy.

Temperature and thermal energy are related in another important way. Temperature determines the direction in which thermal energy naturally flows—from warmer objects (higher temperature) to cooler objects (lower temperature). When a warmer object is in contact with a cooler object, the particles at the boundary collide. In each collision, kinetic energy is transferred from one particle to another. In collisions, the faster particles of the warmer object tend to lose some speed, and the slower particles in the cooler object tend to gain some speed. As a result, the warmer object becomes cooler, and the cooler object becomes warmer.

Joules

Scientists measure energy and work in units called **joules**. A joule is the amount of work required to lift a 100-g mass a distance of about 1 m. The unit is named after James Prescott Joule, who was a nineteenth century English physicist. He studied the relationship between heat, work, and energy. A joule is abbreviated as "J."

All types of energy can be measured in joules. Part of Joule's research was studying the relationship between thermal energy and work. Different types of energy are related by the amount of work they can do. The amount of work required to lift a 100-g mass to a height of 1 m is about the same as the thermal energy required to raise the temperature of 1 g of air by 1°C. By calculating energy amounts in joules, scientists can compare different types of energy and keep track of the amount of energy present as it is transformed from one type to another.

joule: a unit of measurement for energy, abbreviated as J; the amount of work required to lift a 100-g mass a distance of about 1 m.

Joule used a device similar to this one to measure the mechanical equivalent of heat.

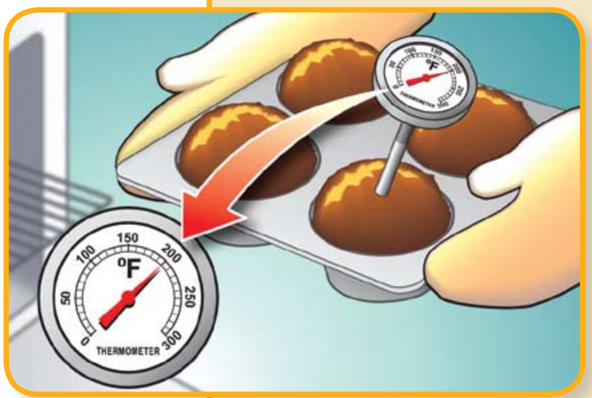
Reflect

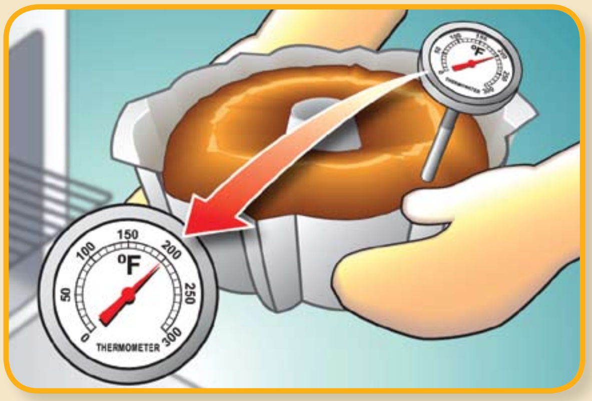
1. How is kinetic energy related to thermal energy?
2. How is temperature related to thermal energy?
3. List two real-world examples of thermal energy from one substance being used to increase the temperature of another substance. What do you think affects how fast the second substance heats up?
4. List two real-world examples of substances or objects cooling. What do you think happens to their thermal energy as they cool?
5. Do you think thermal energy is a kind of kinetic energy or a kind of potential energy? Why?

Conference

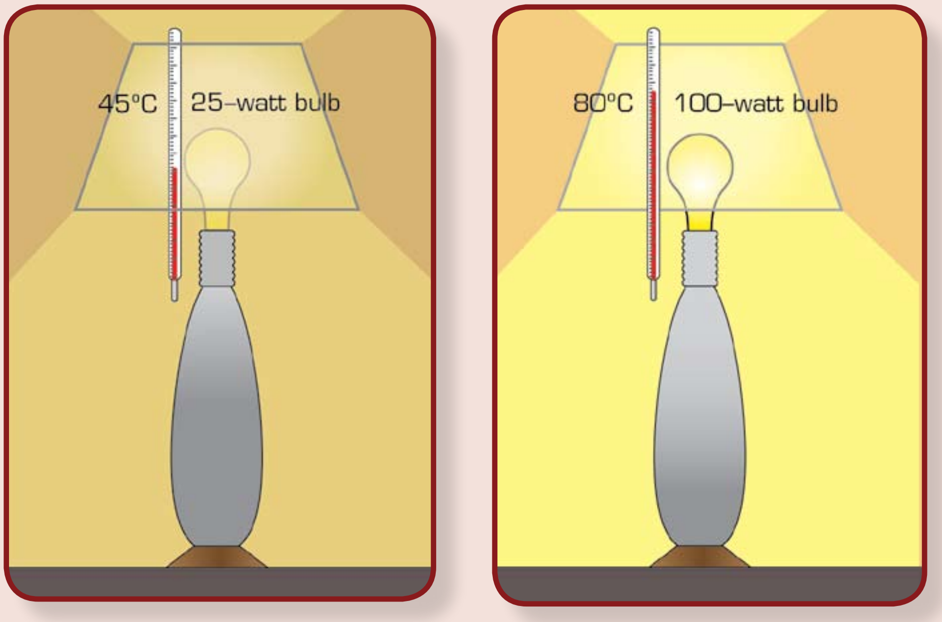
You will now have a chance to apply what you learned about temperature and thermal energy. Your group will be assigned one of the pairs of objects on these pages. Your job will be to decide which of the objects in your pair has more thermal energy and why.

a) Pair 1:

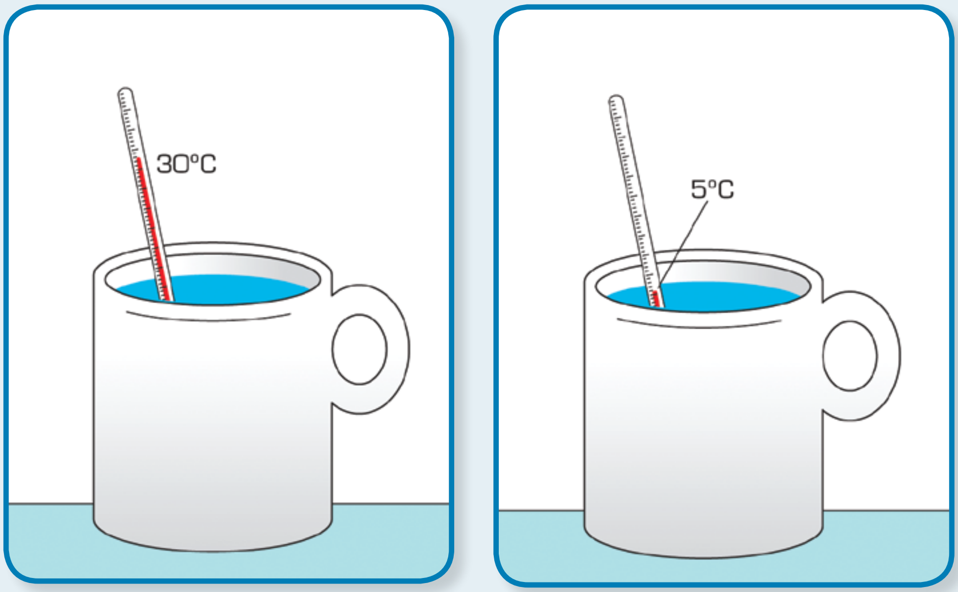




b) Pair 2:



c) Pair 3:



d) Pair 4:

Begin by describing what you know about the type of matter in the objects you were assigned. Then think about the number of particles in the two objects. With your group, write a description of the two objects, and describe the amount of thermal energy in each in terms of the number of particles and the temperature. Then answer these questions.

- If you put ice cubes in or next to each of your objects, which would melt the ice cubes more quickly? Why?
- Which object has more thermal energy? What evidence did you use to determine that?

Communicate

Share Your Ideas

Share your group's observations, reasoning, and conclusions with the class. As a class, prepare a chart like the one on the next page that lists the pairs of objects. Also, discuss the evidence used to determine which object has more thermal energy. Note any similarities or differences in the evidence used.

Thermal Energy Table		
Objects	**More thermal energy**	**Less thermal energy**
Pair 1		
Pair 2		
Pair 3		
Pair 4		

Then, as a class, take on a different challenge. You should have four objects in the *More Thermal Energy* column. Try to place these four objects in order of decreasing thermal energy, with the object with the most thermal energy on top. While doing this, consider the following questions:

- What evidence can you use to compare the thermal energy contained in objects made of different materials?
- Is it possible to compare the thermal energy of a cake with that of a light bulb? Why or why not?
- What additional information might you need in order to compare the thermal energy of objects made of different materials?

What's the Point?

Temperature is related to but not the same as thermal energy. Thermal energy and temperature both depend on the kinetic energy of the particles in a substance. The particles in a substance are moving at many different speeds. Particles moving at a slower speed have less kinetic energy. Particles moving at a faster speed have more kinetic energy. Temperature is a measure of the average kinetic energy of all the particles making up a substance. Temperature does not depend upon the mass of an object.

The thermal energy of a substance is a measure of the total kinetic energy of its particles. Therefore, the total number of particles contained in an object, or its mass, is a factor that determines how much thermal energy an object has. Thermal energy also depends on temperature: the higher the temperature of an object, the greater its kinetic energy. Thermal energy flows naturally from objects at a higher temperature to objects at a lower temperature. Energy is measured in units called joules.