6

CHAPTER 6

Thermal Energy and Thermodynamics

WHAT'S THE difference between a cup of hot tea and a cup of cool tea? The answer involves molecular motion. In Jean's hot cup the molecules that constitute the tea are moving faster than those in the cooler cup. Matter in all forms is made up of constantly jiggling particles—namely, atoms and/or molecules. When they jiggle at a very slow rate, they form solids. When they jiggle faster, they slide over one another and we have a liquid. When the same particles move so fast that they disconnect and fly loose, we have a gas. When they move still faster, electrons can be torn loose from the atoms, forming a plasma. So whether a substance is a solid, a liquid, a gas, or a plasma depends on the motion of its particles. In this and the following chapter we will investigate the effects of particle motions. We call the energy that a body has by virtue of its energetic jostling of atoms and molecules **thermal energy.**

FIGURE 6.1
Can we trust our sense of hot and cold? Do both fingers feel the same temperature when they are dipped in the warm water? Try this and see (feel) for yourself.

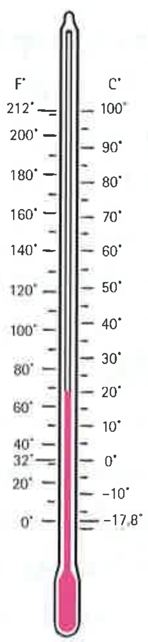

FIGURE 6.2
Fahrenheit and Celsius scales on a thermometer.

6.1 Temperature

EXPLAIN THIS What are two temperatures for ice water?

When you touch a hot stove, thermal energy enters your hand because the stove is warmer than your hand. When you touch a piece of ice, however, thermal energy passes out of your hand and into the colder ice. The quantity that indicates how warm or cold an object is relative to some standard is called **temperature.** We express the temperature of matter by a number that corresponds to the degree of hotness on some chosen scale. A common thermometer measures temperature by means of the expansion and contraction of a liquid, usually mercury or colored alcohol.

The most common temperature scale used worldwide is the Celsius scale, named in honor of the Swedish astronomer Anders Celsius (1701–1744), who first suggested the scale of 100 equal parts (*degrees*) between the freezing point and boiling point of water. The number 0 is assigned to the temperature at which water freezes, and the number 100 to the temperature at which water boils (at sea-level atmospheric pressure).

The most common temperature scale used in the United States is the Fahrenheit scale, named after its originator, the German physicist D. G. Fahrenheit (1686–1736). On this scale the number 32 is assigned to the temperature at which water freezes, and the number 212 is assigned to the temperature at which water boils. The Fahrenheit scale will become obsolete if and when the United States changes to the metric system.

Arithmetic formulas used for converting from one temperature scale to the other are common in classroom exams. Because such arithmetic exercises are not really physics, we won't be concerned with these conversions (perhaps important in a math class, but not here). Besides, the conversion between Celsius and Fahrenheit temperatures is closely approximated in the side-by-side scales of Figure 6.2.*

Temperature is proportional to the average translational kinetic energy per particle that makes up a substance. By *translational* we mean to-and-fro linear motion. For a gas, we refer to how fast the gas particles are bouncing back and forth; for a liquid, we refer to how fast they slide and jiggle past each other; and for a solid, we refer to how fast the particles move as they vibrate and jiggle in place. Note that temperature does *not* depend on how much of the substance you have. If you have a cup of hot water and then pour half of the water onto the floor, the water remaining in the cup hasn't changed its temperature. The water remaining in the cup contains half the thermal energy that the full cup of water contained, because there are only half as many water molecules in the cup as before. Temperature is a *per-particle property; thermal energy* is related to the sum total kinetic energy of all of the particles in your sample.** Twice as much hot water has twice the thermal energy, even though its temperature (the average KE per particle) is the same.

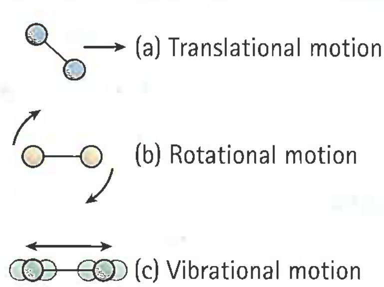

FIGURE 6.3
Particles in matter move in different ways. They move from one place to another, they rotate, and they vibrate to and fro. All these modes of motion, plus potential energy, contribute to the overall energy of a substance. Temperature, however, is defined by translational motion.

When we measure the temperature of something with a conventional thermometer, thermal energy flows between the thermometer and the object whose temperature we are measuring. When the object and the

VIDEO:
Low Temperature with Liquid Nitrogen

* Okay, if you really want to know, the formulas for temperature conversion are $C = \frac{5}{9}(F - 32)$ and $F = \frac{9}{5}C + 32$, where C is the Celsius temperature and F is the Fahrenheit temperature.
** Rather than the term *thermal energy,* physicists prefer the term *internal energy,* to emphasize that the energy is internal to a body.

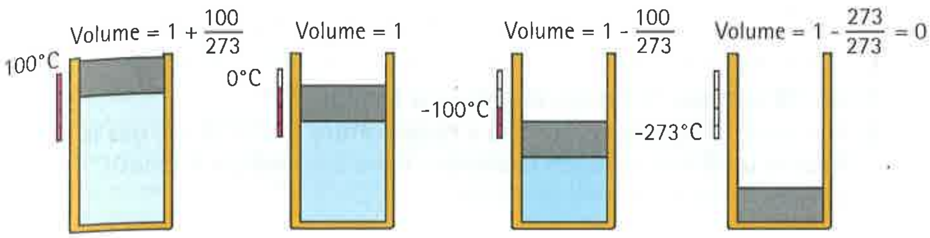

FIGURE 6.4
When pressure is held constant, the volume of a gas changes by $\frac{1}{273}$ of its volume at 0°C with each 1°C change in temperature. At 100°C, the volume is $\frac{100}{273}$ greater than it is at 0°C. When the temperature is reduced to −100°C, the volume is reduced by $\frac{100}{273}$. The rule breaks down near −273°C, where the volume does not really reach zero.

thermometer have the same average kinetic energy per particle, we say that they are in *thermal equilibrium.* When we measure something's temperature, we are really reading the temperature of the thermometer when it and the object have reached thermal equilibrium.

6.2 Absolute Zero

EXPLAIN THIS How cold is absolute zero?

As thermal motion increases, a solid object first melts and becomes a liquid. With more thermal motion it then vaporizes. As the temperature further increases, molecules break apart (dissociate) into atoms, and atoms lose some or all of their electrons, thereby forming a cloud of electrically charged particles—a *plasma.* Plasmas exist in stars, where the temperature is millions of degrees Celsius. Temperature has no upper limit.

In contrast, a definite limit exists at the lower end of the temperature scale. Gases expand when heated, and they contract when cooled. Nineteenth-century experiments found something quite amazing. They found that if one starts out with a gas, any gas, at 0°C while pressure is held constant, the volume changes by $\frac{1}{273}$ of the original volume for each degree Celsius change in temperature. When a gas was cooled from 0°C to −10°C, its volume decreased by $\frac{10}{273}$ and it contracted to $\frac{263}{273}$ of its original volume. If a gas at 0°C could be cooled down by 273°C, it would apparently contract $\frac{273}{273}$ volumes and be reduced to zero volume. Clearly, we cannot have a substance with zero volume.

Experimenters got similar results for pressure. Starting at 0°C, the pressure of a gas held in a container of fixed volume decreased by $\frac{1}{273}$ of the original pressure for each Celsius degree its temperature was lowered. If it were cooled to 273°C below zero, it would apparently have no pressure at all. In practice, every gas converts to a liquid before becoming this cold. Nevertheless, these decreases by $\frac{1}{273}$ increments suggested the idea of a lowest temperature: −273°C. That's the lower limit of temperature, **absolute zero.** At this temperature, molecules have lost all available kinetic energy.* No more energy can be removed from a substance at absolute zero. It can't get any colder.

The absolute temperature scale is called the *Kelvin scale,* named after the famous British mathematician and physicist William Thomson, First Baron Kelvin. Absolute zero is 0 K (short for "0 kelvin"; note that the word *degrees* is not used with Kelvin temperatures).** There are no negative numbers on the Kelvin scale. Its temperature divisions are identical to the divisions on the Celsius scale. Thus, the melting point of ice is 273 K, and the boiling point of water is 373 K.

* Even at absolute zero, molecules still possess a small amount of kinetic energy, called the *zero-point energy.* Helium, for example, has enough motion at absolute zero to prevent it from freezing. The explanation for this involves quantum theory.

** When Thomson became a baron he took his title from the Kelvin River, which ran through his estate. In 1968 the term *degrees Kelvin* (°K) was officially changed to simply *kelvins* (lowercase k), which is abbreviated K (capital K). The precise value of absolute zero (0 K) is −273.15°C.

Absolute zero isn't the coldest you can get. It's the coldest you can hope to approach.

fyi

- Thermal contact is not required with infrared thermometers that show digital temperature readings by measuring the infrared radiation emitted by all bodies.

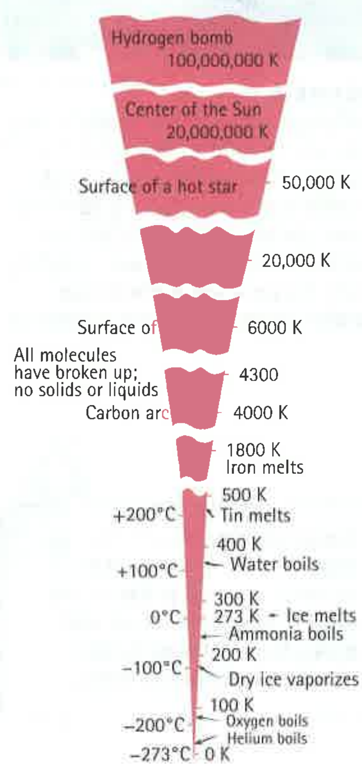

FIGURE 6.5
Some absolute temperatures.

SCREENCAST: Heat and Temperature

CHECKPOINT

1. **Which is larger: a Celsius degree or a kelvin?**
2. **A sample of hydrogen gas has a temperature of 0°C. If the gas is heated until its hydrogen molecules have doubled their kinetic energy, what is its temperature?**

Were these your answers?

1. Neither. They are equal.
2. The 0°C gas has an absolute temperature of 273 K. Twice as much kinetic energy means that it has twice the absolute temperature, or two times 273 K. This would be 546 K, or 273°C.

Just as dark is the absence of light, cold is the absence of thermal energy.

6.3 Heat

EXPLAIN THIS Why do we say that no substances contain heat?

When you place a warm object and a cool object in close proximity, thermal energy transfers in a direction from the warmer object to the cooler object. A physicist defines **heat** as the thermal energy transferred from one thing to another due to a temperature difference.

According to this definition, matter contains *thermal energy*—not heat. Once thermal energy has been transferred to an object or substance, it ceases to be heat. Again, for emphasis: a substance does not contain heat—it contains thermal energy. Heat is thermal energy in transit.

For substances in thermal contact, thermal energy flows from the higher-temperature substance into the lower-temperature substance until thermal equilibrium is reached. This does not mean that thermal energy necessarily flows from a substance with more thermal energy into one with less thermal energy. For example, a bowl of warm water contains more thermal energy than does a red-hot thumbtack. If the tack is placed into the water, thermal energy doesn't flow from the warm water to the tack. Instead, it flows from the hot tack to the cooler water. Thermal energy never flows unassisted from a low-temperature substance into a higher-temperature one.

FIGURE 6.6
The temperature of the sparks is very high, about 2000°C. That's a lot of energy per molecule of spark. But because there are relatively few molecules per spark, the total amount of thermal energy in the sparks is safely small. Temperature is one thing; transfer of thermal energy is another.

CHECKPOINT

1. **You apply a flame to 1 L of water for a certain time and its temperature rises by 2°C. If you apply the same flame for the same time to 2 L of water, by how much does its temperature rise?**
2. **If a fast marble hits a random scatter of slow marbles, does the fast marble usually speed up or slow down? Which lose(s) kinetic energy and which gain(s) kinetic energy: the initially fast-moving marble or the initially slow ones? How do these questions relate to the direction of heat flow?**

Were these your answers?

1. Its temperature rises by only 1°C, because 2 L of water contains twice as many molecules, and each molecule receives only half as much energy on the average. So the average kinetic energy, and thus the temperature, increases by half as much.

Temperature is measured in degrees. Heat is measured in joules (or calories). In the U.S. we speak of low-calorie foods and drinks. Most of the world speaks of low-joule foods and drinks.

2. A fast-moving marble slows when it hits slower-moving marbles. It gives up some of its kinetic energy to the slower ones. Likewise with heat. Molecules with more kinetic energy that make contact with slower molecules give some of their excess kinetic energy to the slower ones. The direction of heat flow is from hot to cold. For both the marbles and the molecules, however, the total energy of the system before and after contact is the same.

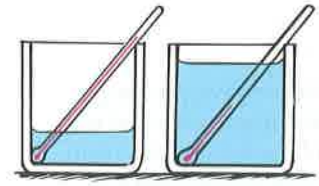

FIGURE 6.7
The pot on the left contains 1 L of water. The pot on the right contains 3 L of water. Although both pots absorb the same quantity of heat, the temperature increases three times as much in the pot with the smaller amount of water.

6.4 Quantity of Heat

EXPLAIN THIS Which is the largest: 1 calorie, 1 Calorie, or 1 joule?

Heat, like work, is energy in transit and is measured in joules. In the U.S. heat has traditionally been measured in calories, another measure of thermal energy. In science courses, the joule is usually preferred. It takes 4.19 J (or equivalently, 1 calorie) of heat to change the temperature of 1 g of water by 1°C.*

The energy ratings of foods and fuels are determined from the energy released when they are burned. (Metabolism is really "burning" at a slow rate.) A common heat unit for labeling food is the kilocalorie (kcal), which is 1000 calories (cal), the heat needed to change the temperature of 1 kg of water by 1°C. To differentiate this unit and the smaller calorie, the food unit is usually called a *Calorie,* with a capital C. So 1 Calorie is really 1000 calories.

What we've learned thus far about heat and thermal energy is summed up in the *laws of thermodynamics.* The word **thermodynamics** stems from Greek words meaning "movement of heat."

FIGURE 6.8
In science lab, 1 calorie = 4.19 joules. In the kitchen, 1 Calorie = 1000 calories = 4190 joules, as Chef Manuel Hewitt attests. A potato provides slightly more than twice as many Calories of energy per gram as a carrot.

CHECKPOINT
Which raises the temperature of water more: adding 4.19 J or 1 calorie?

Was this your answer?
They have the same effect. This is like asking which is longer: a 1.61-km-long track or a 1-mi-long track. They're the same length, just expressed in different units.

6.5 The Laws of Thermodynamics

EXPLAIN THIS How does thermodynamics relate to the conservation of energy?

When thermal energy transfers as heat, the energy lost in one place is gained in another in accord with conservation of energy. When the law of energy conservation is applied to thermal systems, we call it the **first law of thermodynamics.** We state it generally in the following form:

When heat enters or leaves a system, the system gains or loses an amount of energy equal to the amount of heat transferred.

SCREENCAST: Thermodynamics

* So 1 calorie = 4.19 J. Another common unit of heat is the British thermal unit (Btu). The Btu is defined as the amount of heat required to change the temperature of 1 lb of water by 1°F. One Btu is equal to 1054 J.

fyi

- The only weight-loss plan endorsed by the first law of thermodynamics: Burn more calories than you consume and you will lose weight—guaranteed.

FIGURE 6.9
When you push down on the piston, you do work on the air inside. What happens to its temperature?

Whatever the system—be it a steam engine, Earth's atmosphere, or the body of a living creature—heat added to it can have two effects. It can increase the system's thermal energy, or it can enable the system to do work on its surroundings (or both). This leads to the following statement of the first law of thermodynamics:

Heat added = increase in the system's energy
+ external work done by the system

Suppose that you put an air-filled, rigid, airtight can on a hot plate and add a certain amount of thermal energy to the can. **Warning:** *Do not actually do this.* Because the can has a fixed volume, the walls of the can don't move, so no work is done. All of the heat going into the can increases the thermal energy of the enclosed air, so its temperature rises. Now suppose instead that the can is a flexible container that can expand. The heated air does work as the sides of the can expand, exerting a force for some distance on the surrounding atmosphere. Because some of the added heat goes into doing work, less of the added heat goes into increasing the thermal energy of the enclosed air. Can you see that the temperature of the enclosed air rises less when it does work than when it doesn't do work? The first law of thermodynamics makes good sense.*

The **second law of thermodynamics** restates what we've learned about the direction of heat flow:

Heat never spontaneously flows from a cold substance to a hot substance.

When heat flow is spontaneous—that is, without the assistance of external work—the direction of flow is always from hot to cold. In winter, heat flows from inside a warm home to the cold air outside. In summer, heat flows from the hot air outside into the home's cooler interior. Heat can be made to flow the other way *only* when work is done on the system or by adding energy from another source. This occurs with heat pumps that move heat from cooler outside air into a home's warmer interior, or with air conditioners that remove heat from a home's cool interior to the warmer air outside. Without external effort, the direction of heat flow is always from hot to cold. The second law, like the first, makes logical sense.**

The **third law of thermodynamics** restates what we've learned about the lowest limit of temperature:

No system can reach absolute zero.

As investigators attempt to reach this lowest temperature, it becomes more difficult to get closer to it. In 2010, after nine years of work, a team in Finland recorded a record low of one-billionth of a kelvin (1 nanokelvin), tantalizingly close to the unattainable 0 K.

fyi

- Work can also be done when one gas expands into another. A useful concept for analyzing such situations is called **enthalpy.** Enthalpy is the change in the thermal energy of a system plus the product of its pressure and volume. You are likely to encounter enthalpy in future studies of chemistry or biology.

* The laws of thermodynamics were the rage back in the 1800s. At that time, horses and buggies were yielding to steam-driven locomotives. There is the story of the engineer who explained the operation of a steam engine to a peasant. The engineer cited in detail the operation of the steam cycle, how expanding steam drives a piston that in turn rotates the wheels. After some thought, the peasant asked, "Yes, I understand all that. But where's the horse?" This story illustrates how difficult it is to abandon our way of thinking about the world when a newer method comes along to replace established ways. Are we different today?

** There is also a *zeroth law of thermodynamics,* which states that if systems *A* and *B* are each in thermal equilibrium with system *C*, then *A* and *B* are in thermal equilibrium with each other. The importance of this law was recognized only after the first, second, and third laws had been named, hence the name "zeroth" seemed appropriate.

6.6 Entropy

EXPLAIN THIS Why does the smell of cookies baking in an oven soon fill the room?

The first law of thermodynamics states that energy can be neither created nor destroyed. It speaks of the *quantity* of energy. The second law speaks of the *quality* of energy, as energy becomes more diffuse and ultimately degenerates into waste.

With this broader perspective, the second law can be stated another way:

In natural processes, high-quality energy tends to transform into lower-quality energy—order tends to disorder.

Processes in which disorder returns to order without external help don't occur in nature. Interestingly, time is given a direction via this thermodynamic rule. Time's arrow always points from order to disorder.*

The idea of ordered energy tending to disordered energy is embodied in the concept of *entropy*.** **Entropy** is the measure of how energy spreads to disorder in a system. When disorder increases, entropy increases. The molecules of an automobile's exhaust, for example, cannot spontaneously recombine to form more highly organized gasoline molecules. Warm air that spreads throughout a room when the oven door is open cannot spontaneously return to the oven. Whenever a physical system is allowed to spread its energy freely, it always does so in a manner such that entropy increases, while the energy of the system available for doing work decreases.†

FIGURE 6.10
Entropy.

However, when work is input to a system, as in living organisms, the entropy of the system can decrease. All living things, from bacteria to trees to human beings, extract energy from their surroundings and use this energy to increase their own organization. The process of extracting energy (for instance, breaking down a highly organized food molecule into smaller molecules) increases entropy elsewhere, so life forms plus their waste products have a net increase in entropy. Energy must be transformed within the living system to support life. When it is not, the organism soon dies and tends toward disorder.

The laws of thermodynamics can be stated this way: You can't win (because you can't get any more energy out of a system than you put into it), you can't break even (because you can't get as much useful energy out as you put in), and you can't get out of the game (entropy in the universe is always increasing).

6.7 Specific Heat Capacity

EXPLAIN THIS Why does a hot frying pan cool faster than equally hot water?

While eating, you've likely noticed that some foods remain hotter much longer than others. Whereas the filling of hot apple pie can burn your tongue, the crust does not, even when the pie has just been removed from the oven. Or a piece of toast may be comfortably eaten a few seconds after

* In the previous century when movies were new, audiences were amazed to see a train come to a stop inches away from a heroine tied to the tracks. This was filmed by starting with the train at rest, inches away from the heroine, and then moving *backward*, gaining speed. When the film was reversed, the train was seen to move *toward* the heroine. (Next time, watch closely for the telltale smoke that *enters* the smokestack.)

** Entropy can be expressed mathematically. The increase in entropy ΔS of a thermodynamic system is equal to the amount of heat added to the system ΔQ divided by the Kelvin temperature T at which the heat is added: $\Delta S = \Delta Q/T$.

† Interestingly enough, the American writer Ralph Waldo Emerson, who lived during the time when the second law of thermodynamics was the new science topic of the day, philosophically speculated that not everything becomes more disordered with time and cited the example of human thought. Ideas about the nature of things grow increasingly refined and better organized as they pass through the minds of succeeding generations. Human thought is evolving toward more order.

FIGURING PHYSICAL SCIENCE

Problem Solving

If the specific heat capacity c is known for a substance, then the heat transferred = specific heat capacity × mass × change in temperature. This can be expressed by the formula

$$Q = cm\Delta T$$

where Q is the quantity of heat, c is the specific heat capacity of the substance, m is the mass, and ΔT is the corresponding change in temperature of the substance. When mass m is in grams, using the specific heat capacity of water as 1.0 cal/g·°C gives Q in calories.

SAMPLE PROBLEM 1

What would be the final temperature of a mixture of 50 g of 20°C water and 50 g of 40°C water?

Solution:

The heat gained by the cooler water equals the heat lost by the warmer water. Because the masses of water are the same, the final temperature is midway, 30°C. So we'll end up with 100 g of 30°C water.

SAMPLE PROBLEM 2

Consider mixing 100 g of 25°C water with 75 g of 40°C water. Show that the final temperature of the mixture is 31.4°C.

Solution:

Here we have different masses of water that are mixed together. We equate the heat gained by the cool water to the heat lost by the warm water. We can express this equation formally, then let the expressed terms lead to a solution:

Heat gained by cool water = heat lost by warm water

$$cm_1\Delta T_1 = cm_2\Delta T_2$$

ΔT_1 doesn't equal ΔT_2 as in Sample Problem 1 because of different masses of water. Some thinking shows that ΔT_1 is the final temperature T minus 25°C, because T will be greater than 25°C. ΔT_2 is 40°C minus T, because T will be less than 40°C. Then,

$$c(100\text{ g})(T - 25) = c(75\text{ g})(40 - T)$$
$$100T - 2500 = 3000 - 75T$$
$$T = 31.4°\text{C}$$

SAMPLE PROBLEM 3

Radioactive decay in Earth's interior provides enough energy to keep the interior hot, generate magma, and provide warmth to natural hot springs. This is due to the average release of about 0.03 J/kg each year. Show that the time it takes for a chunk of thermally insulated rock to increase 500°C in temperature (assuming that the specific heat of the rock sample is 800 J/kg·°C) is 13.3 million years.

Solution:

Here we switch to rock, but the same concept applies. And we switch to specific heat capacity expressed in joules per kilogram per degree Celsius. No particular mass is specified, so we'll work with quantity of heat/mass (for our answer should be the same for a small chunk of rock or a huge chunk).

From $Q = cm\Delta T$ we divide by m and get $Q/m = c\Delta T$ = (800 J/kg·°C) × (500°C) = 400,000 J/kg. The time required is (400,000 J/kg) ÷ (0.03 J/kg·yr) = 13.3 million years. Small wonder it remains hot down there!

FIGURE 6.11
The filling of hot apple pie may be too hot to eat, even though the crust is not.

coming from the hot toaster, whereas you must wait several minutes before eating soup that has the same high temperature.

Different substances have different thermal capacities for storing energy. If we heat a pot of water on a stove, we might find that it requires 15 minutes to rise from room temperature to its boiling temperature. But an equal mass of iron on the same stove would rise through the same temperature range in only about 2 minutes. For silver, the time would be less than a minute. Equal masses of different materials require different quantities of heat to change their temperatures by a specified number of degrees.*

As mentioned earlier, a gram of water requires 1 calorie of energy to raise the temperature 1°C. It takes only about one-eighth as much energy to raise the temperature of a gram of iron by the same amount. Water absorbs more heat than iron for the same change in temperature. We say water has a higher **specific heat capacity** (sometimes simply called *specific heat*):

> **The specific heat capacity of any substance is defined as the quantity of heat required to change the temperature of a unit mass of the substance by 1°C.**

* In the case of silver and iron, silver atoms are about twice as massive as iron atoms. A given mass of silver contains only about half as many atoms as an equal mass of iron, so only about half the heat is needed to raise the temperature of the silver. Hence, the specific heat of silver is about half that of iron.

We can think of specific heat capacity as thermal inertia. Recall that *inertia* is a term used in mechanics to signify the resistance of an object to a change in its state of motion. Specific heat capacity is like thermal inertia because it signifies the resistance of a substance to a change in temperature.

The High Specific Heat Capacity of Water

Water has a much higher capacity for storing thermal energy than almost any other substance. The reason for water's high specific heat capacity involves the various ways that energy can be absorbed. Energy absorbed by any substance increases the jiggling motion of molecules, which raises the temperature. Or absorbed energy may increase the amount of internal vibration or rotation within the molecules, which adds to the stored energy but does not raise the temperature. Usually absorption of energy involves a combination of both. When we compare water molecules with atoms in a metal, we find many more ways for water molecules to absorb energy without increasing translational kinetic energy. So water has a much higher specific heat capacity than metals—and most other common materials.

SCREENCAST: Specific Heat

CHECKPOINT

1. **Which has a higher specific heat capacity: water or sand? In other words, which takes longer to warm in sunlight (or longer to cool at night)?**
2. **Why does a piece of watermelon stay cool for a longer time than sandwiches do when both are removed from a picnic cooler on a hot day?**

Were these your answers?

1. Water has the higher specific heat capacity. In the same sunlight, the temperature of water increases more slowly than the temperature of sand. And water cools more slowly at night. (Walking or running barefoot across scorching sand in daytime is a different experience from doing the same in the evening!) The low specific heat capacity of sand and soil, as evidenced by how quickly they warm in the morning Sun and how quickly they cool at night, affects local climates.
2. Water in the melon has more "thermal inertia" than sandwich ingredients, and it resists changes in temperature much more. This thermal inertia is specific heat capacity.

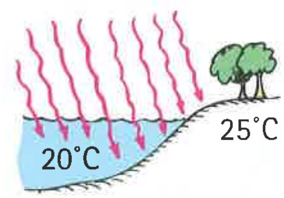

FIGURE 6.12
Because water has a high specific heat capacity and is transparent, it takes more energy to warm the water than to warm the land. Solar energy striking the land is concentrated at the surface, but energy striking the water extends beneath the surface and so is "diluted."

Water's high specific heat capacity affects the world's climate. Look at a globe and notice the high latitude of Europe. Water's high specific heat capacity helps keep Europe's climate appreciably milder than regions of the same latitude in northeastern regions of Canada. Both Europe and Canada receive about the same amount of sunlight per square kilometer. Fortunately for Europeans, the Atlantic Ocean current known as the Gulf Stream carries warm water northeast from the Caribbean Sea, retaining much of its thermal energy long enough to reach the North Atlantic Ocean off the coast of Europe. There the water releases 4.19 J of energy for each gram of water that cools by 1°C. The released energy is carried by westerly winds over the European continent.

Water is useful in the cooling systems of automobiles and other engines because it absorbs a great quantity of heat for small increases in temperature. Water also takes longer to cool.

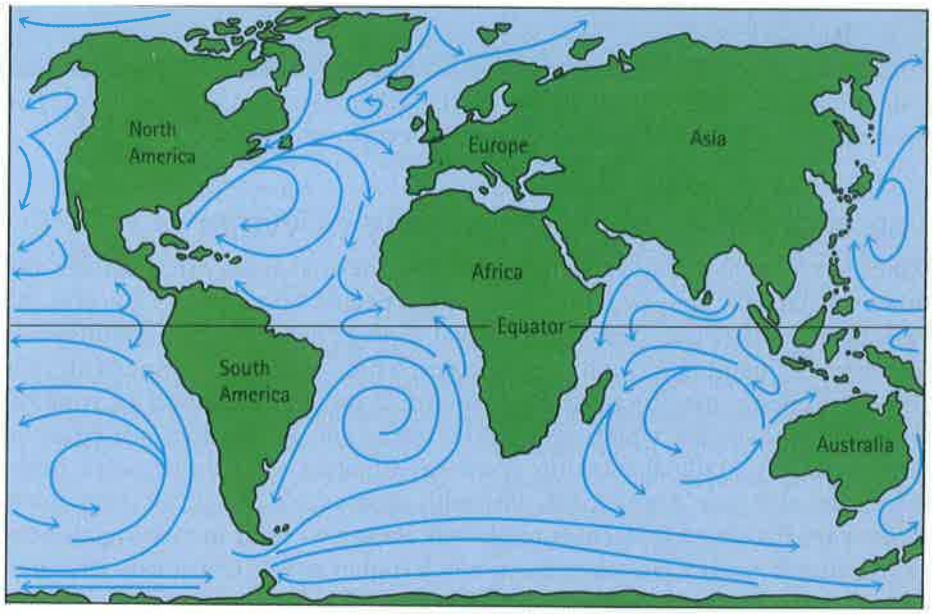

FIGURE 6.13
Many ocean currents, shown in blue, distribute heat from the warmer equatorial regions to the colder polar regions.

A similar effect occurs in the United States. The winds in North America are mostly westerly. On the West Coast, air moves from the Pacific Ocean to the land. In winter months, the ocean water is warmer than the air. Air blows over the warm water and then moves over the coastal regions. This produces a warm climate. In summer, the opposite occurs. Air blowing over the water carries cooler air to the coastal regions. The East Coast benefits less from the moderating effects of water because the direction of air is from the land to the Atlantic Ocean. Land, with a lower specific heat capacity, gets hot in the summer but cools rapidly in the winter.

Islands and peninsulas do not have the temperature extremes that are common in interior regions of a continent. The high summer and low winter temperatures common in Manitoba and the Dakotas, for example, are largely due to the absence of large bodies of water. Europeans, islanders, and people living near ocean air currents should be glad that water has such a high specific heat capacity. San Franciscans certainly are!

CHECKPOINT

Bermuda is close to North Carolina, but, unlike North Carolina, it has a tropical climate year-round. Why?

Was this your answer?
Bermuda is an island. The surrounding water warms it when it might otherwise be too cold, and cools it when it might otherwise be too warm.

6.8 Thermal Expansion

EXPLAIN THIS Why do telephone lines sag more in the summer?

SCREENCAST: Thermal Expansion

As the temperature of a substance increases, its molecules jiggle faster and move farther apart. The result is *thermal expansion*. Most substances expand when heated and contract when cooled. Sometimes the changes aren't noticeable, and sometimes they are. Telephone wires are longer and sag more on a hot summer day than in winter. Railroad tracks that were laid on cold winter days expand and may even buckle in the hot summer (Figure 6.14). Metal lids on glass fruit jars can often be loosened by heating them under hot water. If one part of a piece of glass is heated or cooled more rapidly than adjacent parts, the resulting expansion or contraction may break the glass. This is especially true of thick glass. Pyrex glass is an exception because it is specially formulated to expand very little with increasing temperature.

Thermal expansion must be taken into account in structures and devices of all kinds. A civil engineer uses reinforcing steel with the same expansion rate as concrete. A long steel bridge usually has one end anchored while the other rests on rockers (Figure 6.15). Notice also that many bridges have tongue-and-groove gaps called *expansion joints* (Figure 6.16). Similarly, concrete roadways and sidewalks are intersected by gaps, which are sometimes filled with tar, so that the concrete can expand freely in summer and contract in winter.

FIGURE 6.14
Thermal expansion. Extreme heat on a July day caused the buckling of these railroad tracks.

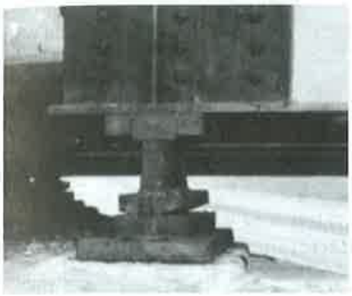

FIGURE 6.15
One end of the bridge rides on rockers to allow for thermal expansion. The other end (not shown) is anchored.

FIGURE 6.16
This gap in the roadway of a bridge is called an expansion joint; it allows the bridge to expand and contract.

Thermal expansion accounts for the creaky noises often heard in the attics of old houses on cold nights.

The fact that different substances expand at different rates is nicely illustrated with a bimetallic strip (Figure 6.17). This device is made of two strips of different metals welded together, one of brass and the other of iron. When heated, the greater expansion of the brass bends the strip. This bending may be used to turn a pointer, regulate a valve, or close a switch.

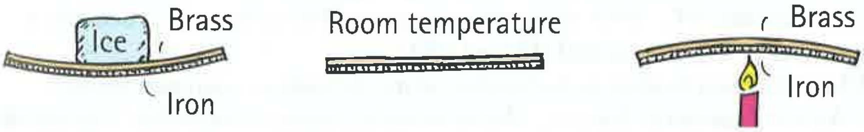

FIGURE 6.17
A bimetallic strip. Brass expands more when heated than iron does, and it contracts more when cooled. Because of this behavior, the strip bends as shown.

A practical application of a bimetallic strip wrapped into a coil is the thermostat (Figure 6.18). When a room becomes too cold, the coil bends toward the brass side and activates an electrical switch that turns on the heater. When the room gets too warm, the coil bends toward the iron side, which breaks the electrical circuit and turns off the heater. Although bimetallic strips nicely illustrate practical physics, electronic sensors now replace them in thermostats and many other thermal devices.

With increases in temperature, liquids expand more than solids. We notice this when gasoline overflows from a car's tank on a hot day. If the tank and its contents expanded at the same rate, no overflow would occur. This is why a gas tank being filled shouldn't be "topped off," especially on a hot day.

VIDEO:
How a Thermostat Works

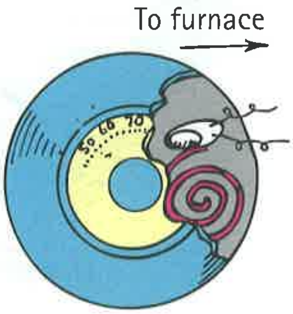

FIGURE 6.18
A pre-electronic thermostat. When the bimetallic coil expands, the drop of liquid mercury rolls away from the electrical contacts and breaks the electrical circuit. When the coil contracts, the mercury rolls against the contacts and completes the circuit.

SCREENCAST: Thermal Expansion of Water

6.9 Expansion of Water

EXPLAIN THIS Why does ice float?

Water, like most other substances, expands when heated. But interestingly, it *doesn't* expand in the temperature range between 0°C and 4°C. Something quite fascinating happens in this range.

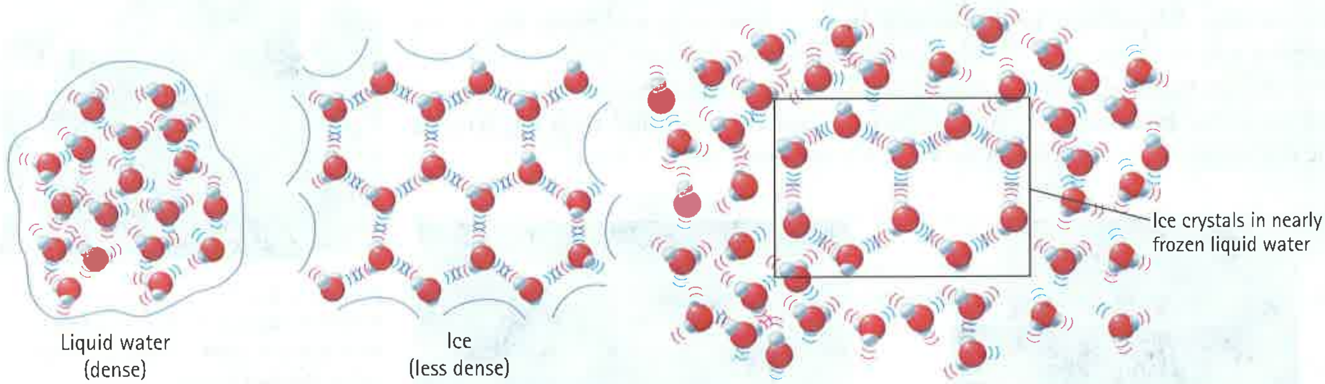

FIGURE 6.19
(Left) Water molecules in a liquid are closer together than water molecules in frozen ice (center) because of the open crystalline structure of ice. At temperatures close to 0°C (right) ice crystals in water increase the volume, decreasing water's density.

FIGURE 6.20
The six-sided structure of a snowflake is a result of the six-sided ice crystals that make it up. The crystals are made when water vapor in a cloud condenses directly to the solid form. Most snowflakes are not as symmetrical as this one.

Ice has a crystalline structure, with open-structured crystals. Water molecules in this open structure have more space between them than they do in the liquid phase (Figure 6.19). This means that ice is less dense than water. When ice melts, not all the open-structured crystals collapse. Some remain in the ice-water mixture, making up a microscopic slush that slightly "bloats" the water—increases its volume slightly. This results in ice water being less dense than slightly warmer water. As the temperature of water is increased from 0°C, more of the ice crystals collapse. The melting of these ice crystals further decreases the volume of the water. Two opposite processes occur for the water at the same time—contraction and expansion. Volume decreases as ice crystals collapse, while volume increases due to greater molecular motion. The collapsing effect dominates until the temperature reaches 4°C. After that, expansion overrides contraction because most of the ice crystals have melted (Figure 6.21).

When ice water freezes to become solid ice, its volume increases quite noticeably. As solid ice cools further, like most substances, it contracts. The density of ice at any temperature is much lower than the density of water, which is why ice floats on water. This behavior of water is very important in nature. If water were most dense at 0°C, it would settle to the bottom of a pond or lake and freeze there instead of at the surface.

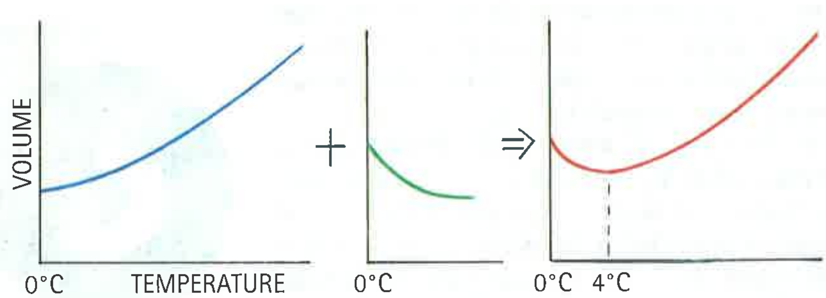

FIGURE 6.21
The blue curve indicates the normal expansion of water with increasing temperature. The green curve indicates the contraction of ice crystals in ice water as they melt with increasing temperature. The red curve shows the result of both processes.

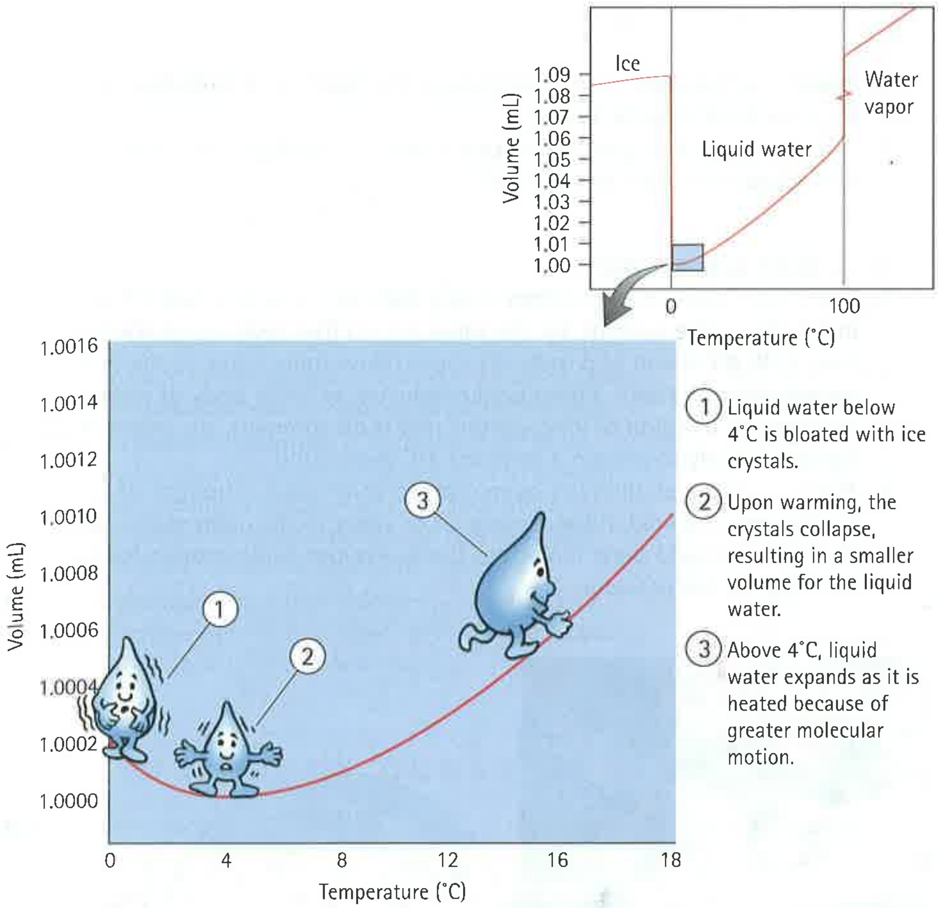

FIGURE 6.22
Between 0°C and 4°C, the volume of liquid water decreases as temperature increases. Above 4°C, thermal expansion exceeds contraction and volume increases as temperature increases.

A pond freezes from the surface downward. In a cold winter the ice is thicker than in a mild winter. Water at the bottom of an ice-covered pond is 4°C, which is relatively warm for organisms that live there. Interestingly, very deep bodies of water are not ice-covered even in the coldest of winters. This is because all the water must be cooled to 4°C before lower temperatures can be reached. For deep water, the winter is not long enough to reduce an entire pond to 4°C. Any 4°C water lies at the bottom. Because of water's high specific heat capacity and poor ability to conduct heat, the bottom of deep bodies of water in cold regions remains at a constant 4°C year round. Fish should be glad that this is so.

Because water is most dense at 4°C, colder water rises and freezes on the surface. This means that fish remain in relative warmth!

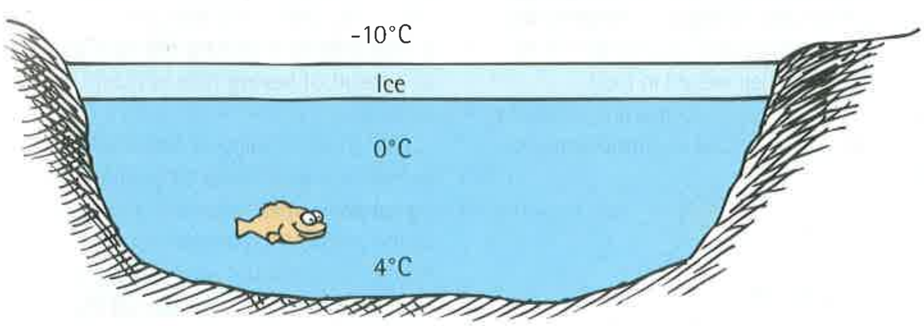

FIGURE 6.23
As water cools, it sinks until the entire pond is at 4°C. Then, as water at the surface cools further, it floats on top and can freeze. Once ice is formed, temperatures lower than 4°C can extend down into the pond.

6.9 Expansion of Water

28. When the temperature of ice-cold water is increased slightly, does it undergo a net expansion or a net contraction?
29. What is the reason for ice being less dense than water?
30. At what temperature do the combined effects of contraction and expansion produce the smallest volume of water?

ACTIVITIES (HANDS-ON APPLICATION)

31. How much energy is in a nut? Burn it and find out. The heat from the flame is energy released when carbon and hydrogen in the nut combine with oxygen in the air (oxidation reactions) to produce CO_2 and H_2O. Pierce a nut (pecan or walnut halves work best) with a bent paper clip that holds the nut above the table surface. Above this, secure a can of water so that you can measure its temperature change when the nut burns. Use about 10^3 cm (10 mL) of water and a Celsius thermometer. As soon as you ignite the nut with a match, place the can of water above it, and record the increase in water temperature once the flame burns out. The number of calories released by the burning nut can be calculated by the formula $Q = cm\Delta T$, where c is the water's specific heat (1 cal/g·°C), m is the mass of water, and ΔT is the change in temperature. The energy in food is expressed in terms of the Calorie, which is 1000 of the calories you'll measure. So to find the number of Calories, divide your result by 1000. (See Think and Solve Exercise 36.)
32. Write a letter to your grandparents describing how you're learning to see connections in nature that have eluded you until now, and how you're learning to distinguish between related ideas. Use temperature and heat as examples.

PLUG AND CHUG (FORMULA FAMILIARIZATION)

$$Q = cmT$$

33. Use the formula above to show that it takes 3000 cal to raise the temperature of 300 g of water from 20°C to 30°C. For the specific heat capacity c, use (1 cal/g·°C).
34. Use the same formula to show that it takes 12,570 joules to raise the temperature of the same mass (0.30 kg) of water through the same temperature interval. For the specific heat capacity c, use 4,190 J/kg·°C.
35. Show that 3000 cal = 12,570 J, the same quantity of thermal energy in different units.

THINK AND SOLVE (MATHEMATICAL APPLICATION)

The quantity of heat Q released or absorbed from a substance of specific heat c (which can be expressed in units of cal/g·°C or J/kg·°C) and mass m (in units of g or kg, undergoing a change in temperature ΔT is $Q = cm\Delta T$.

36. Will Maynez burns a 0.6-g peanut beneath 50 g of water, which increases in temperature from 22°C to 50°C. (The specific heat capacity of water is 1.0 cal/g·°C.) (a) Assuming 40% efficiency, show that the peanut's food value is 3500 calories. (b) Then show how the food value in calories per gram is 5.8 kcal/g (or 5.8 Cal/g).

37. Consider a 6.0-g steel nail 8.0 cm long and a hammer that exerts an average force of 600 N on the nail when it is being driven into a piece of wood. The nail becomes warmer. Show that the increase in the nail's temperature is 17.8°C. (Assume that the specific heat capacity of steel is 450 J/kg·°C.)
38. If you wish to warm 50 kg of water by 20°C for your bath, show that the amount of heat needed is 1000 kcal (1000 Cal). Then show that this rounds off to be about 4200 kJ.
39. The specific heat capacity of steel is 450 J/kg·°C. Show that the amount of heat needed to raise the temperature of a 10-kg piece of steel from 0°C to 100°C is 450,000 J. How does this compare with the heat needed to raise the temperature of the same mass of water through the same temperature difference? (For water, c = 4190 J/kg·°C.)
40. In the lab, you submerge 100 g of 40°C nails in 200 g of 20°C water. (The specific heat of iron is 0.12 cal/g·°C.) Equate the heat gained by the water to the heat lost by the nails, and show that the final temperature of the water is about 21°C.

To solve the problems that follow, you will need knowledge of the average coefficient of linear expansion, α, which differs for different materials. We define α to be the change in length (L) per unit length—or the fractional change in length—for a temperature change of 1 °C. That is, $\alpha = \Delta L/L$ per °C. For aluminum, $\alpha = 24 \times 10^{-6}$/°C, and for steel, $\alpha = 11 \times 10^{-6}$/°C. The change in length ΔL of a material is given by $\Delta L = L\alpha\Delta T$.

41. Consider a 1-m bar that expands 0.6 cm when heated. Show that when similarly heated, a 100-m bar of the same material becomes 100.6 m long.
42. Suppose that the 1.3-km main span of steel for the Golden Gate Bridge had no expansion joints. Show that for an increase in temperature of 20°C, the bridge would be nearly 0.3 m longer.
43. Imagine people breathing on the length of a 40,000-km steel pipe that forms a ring to fit snugly entirely around the circumference of Earth so as to raise its temperature by 1°C. The pipe gets longer—and is no longer snug. How high does it then stand above ground level? Show that the answer is an astounding 70 m higher! (To simplify, consider only the expansion of its radial distance from the center of Earth, and apply the geometry formula that relates circumference C and radius r—that is, $C = 2\pi r$)

THINK AND RANK (ANALYSIS)

44. Rank, from greatest to least, the magnitudes of these units of thermal energy: (a) 1 calorie. (b) 1 Calorie. (c) 1 joule.
45. Three blocks of metal at the same temperature are placed on a hot stove. Their specific heat capacities are given, after their identities, in the list that follows. Rank these blocks of metal, from greatest to least, in terms of how quickly they warm up: (a) Steel, 450 J/kg·°C. (b) Aluminum, 910 J/kg·°C. (c) Copper, 390 J/kg·°C.
46. How much the lengths of various substances change with temperature changes is given by their coefficients of linear expansion, α. The greater the value of α, the greater the change in length for a given change in temperature. Three kinds of metal wires are stretched between distant telephone poles. Rank these wires, from greatest to least, in terms of how much they will sag on a hot summer day: (a) Copper, $\alpha = 17 \times 10^{-6}$/°C. (b) Aluminum, $\alpha = 24 \times 10^{-6}$/°C. (c) Steel, $\alpha = 11 \times 10^{-6}$/°C.
47. The precise volume of 200 grams of water in a beaker depends on the temperature of the water. Rank the following temperatures from greatest volume of 200 grams of water to least volume of 200 grams of water: (a) 0°C. (b) 4°C. (c) 10°C.

EXERCISES (SYNTHESIS)

6.1 Temperature

48. A friend says that molecules in a mixture of gases in thermal equilibrium have the same average *kinetic energy*. Do you agree or disagree? Defend your answer.
49. A friend says that molecules in a mixture of gases in thermal equilibrium have the same average *speed*. Do you agree or disagree? Defend your answer.
50. A friend tells you that the surface temperature of a particular star is 50,000 degrees. You're not sure whether your friend meant Celsius degrees or kelvins. How much difference is involved in this ambiguity?
51. Why would you expect the molecules in a gas to have a variety of speeds?
52. Consider two glasses, one filled with water and the other half full, both at the same temperature. In which glass are the water molecules moving faster? In which is there greater thermal energy? In which will more heat be required to increase the temperature by 1°C?
53. Which is greater: an increase in temperature of 1°C or an increase of 1°F?
54. Which contains the greater amount of thermal energy: an iceberg or a cup of hot coffee? Defend your answer.

6.2 Absolute Zero

55. On which temperature scale does the average kinetic energy of molecules double when the temperature doubles?
56. What will be the temperature of a 0°C steel block if its thermal energy is doubled?
57. What will be the temperature of 0°C helium gas if its thermal energy is halved?

6.3 Heat

58. What name is given to "thermal energy in transit"?
59. Instead of saying a red-hot horseshoe contains heat, it is correct to say a red-hot horseshoe contains what?
60. What is the general direction of the flow of thermal energy? What is the name of that flow?

6.4 Quantity of Heat

61. Which of these involves the most thermal energy: 1 calorie, 1 Calorie, or 1 joule?
62. Which of these involves the least thermal energy: 1 calorie, 1 Calorie, or 1 joule?
63. Which raises the temperature of water more: the addition of 1 calorie or of 1 joule?

6.5 The Laws of Thermodynamics

64. If 100 joules of heat is added to a system that does no external work, by how much is the thermal energy of the system raised?
65. If 100 joules of heat is added to a system that does 40 joules of external work, by how much is the thermal energy of the system raised?
66. Which law of thermodynamics tells us what is most probable in nature?
67. Which law of thermodynamics involves absolute zero?