Temperature, Heat, and Expansion

The pie cools—the air warms.

All matter—solid, liquid, and gas—is composed of continually jiggling atoms or molecules. Because of this random motion, the atoms and molecules in matter have kinetic energy. The average kinetic energy of these individual particles causes an effect we can sense—warmth. Whenever something becomes warmer, the kinetic energy of its atoms or molecules has increased.

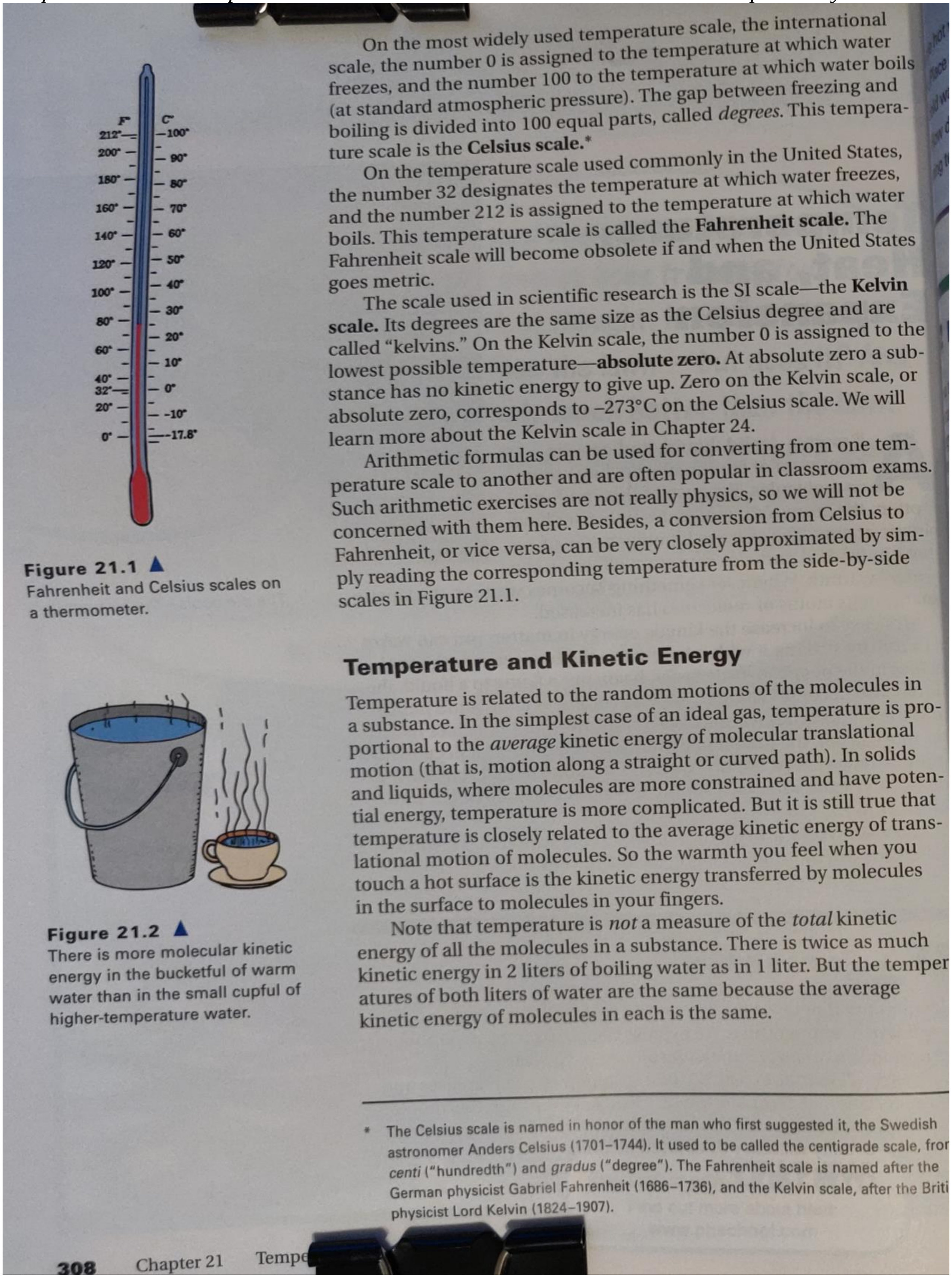
It's easy to increase the kinetic energy in matter. You can warm a penny by striking it with a hammer—the blow causes the molecules in the penny to jostle faster. If you put a flame to a liquid, the liquid also becomes warmer. Rapidly compress air in a tire pump and the air becomes warmer. When the atoms or molecules in matter move faster, the matter gets warmer. Its atoms or molecules have more kinetic energy. For brevity in this chapter, rather than saying *atoms and molecules*, we'll simply say molecules—by which we mean either.

So when you warm up by a fire on a cold winter night, you are increasing the molecular kinetic energy in your body.

21.1 Temperature

The quantity that tells how hot or cold something is compared with a standard is **temperature.** We express temperature by a number that corresponds to a degree mark on some chosen scale.

Nearly all matter expands when its temperature increases and contracts when its temperature decreases. A common thermometer measures temperature by showing the expansion and contraction of a liquid—usually mercury or colored alcohol—in a glass tube using a scale.



On the most widely used temperature scale, the international scale, the number 0 is assigned to the temperature at which water freezes, and the number 100 to the temperature at which water boils (at standard atmospheric pressure). The gap between freezing and boiling is divided into 100 equal parts, called *degrees.* This temperature scale is the **Celsius scale.***

On the temperature scale used commonly in the United States, the number 32 designates the temperature at which water freezes, and the number 212 is assigned to the temperature at which water boils. This temperature scale is called the **Fahrenheit scale.** The Fahrenheit scale will become obsolete if and when the United States goes metric.

The scale used in scientific research is the SI scale—the **Kelvin scale.** Its degrees are the same size as the Celsius degree and are called "kelvins." On the Kelvin scale, the number 0 is assigned to the lowest possible temperature—**absolute zero.** At absolute zero a substance has no kinetic energy to give up. Zero on the Kelvin scale, or absolute zero, corresponds to –273°C on the Celsius scale. We will learn more about the Kelvin scale in Chapter 24.

Arithmetic formulas can be used for converting from one temperature scale to another and are often popular in classroom exams. Such arithmetic exercises are not really physics, so we will not be concerned with them here. Besides, a conversion from Celsius to Fahrenheit, or vice versa, can be very closely approximated by simply reading the corresponding temperature from the side-by-side scales in Figure 21.1.

Figure 21.1 ▲
Fahrenheit and Celsius scales on a thermometer.

Temperature and Kinetic Energy

Temperature is related to the random motions of the molecules in a substance. In the simplest case of an ideal gas, temperature is proportional to the *average* kinetic energy of molecular translational motion (that is, motion along a straight or curved path). In solids and liquids, where molecules are more constrained and have potential energy, temperature is more complicated. But it is still true that temperature is closely related to the average kinetic energy of translational motion of molecules. So the warmth you feel when you touch a hot surface is the kinetic energy transferred by molecules in the surface to molecules in your fingers.

Note that temperature is *not* a measure of the *total* kinetic energy of all the molecules in a substance. There is twice as much kinetic energy in 2 liters of boiling water as in 1 liter. But the temperatures of both liters of water are the same because the average kinetic energy of molecules in each is the same.

Figure 21.2 ▲
There is more molecular kinetic energy in the bucketful of warm water than in the small cupful of higher-temperature water.

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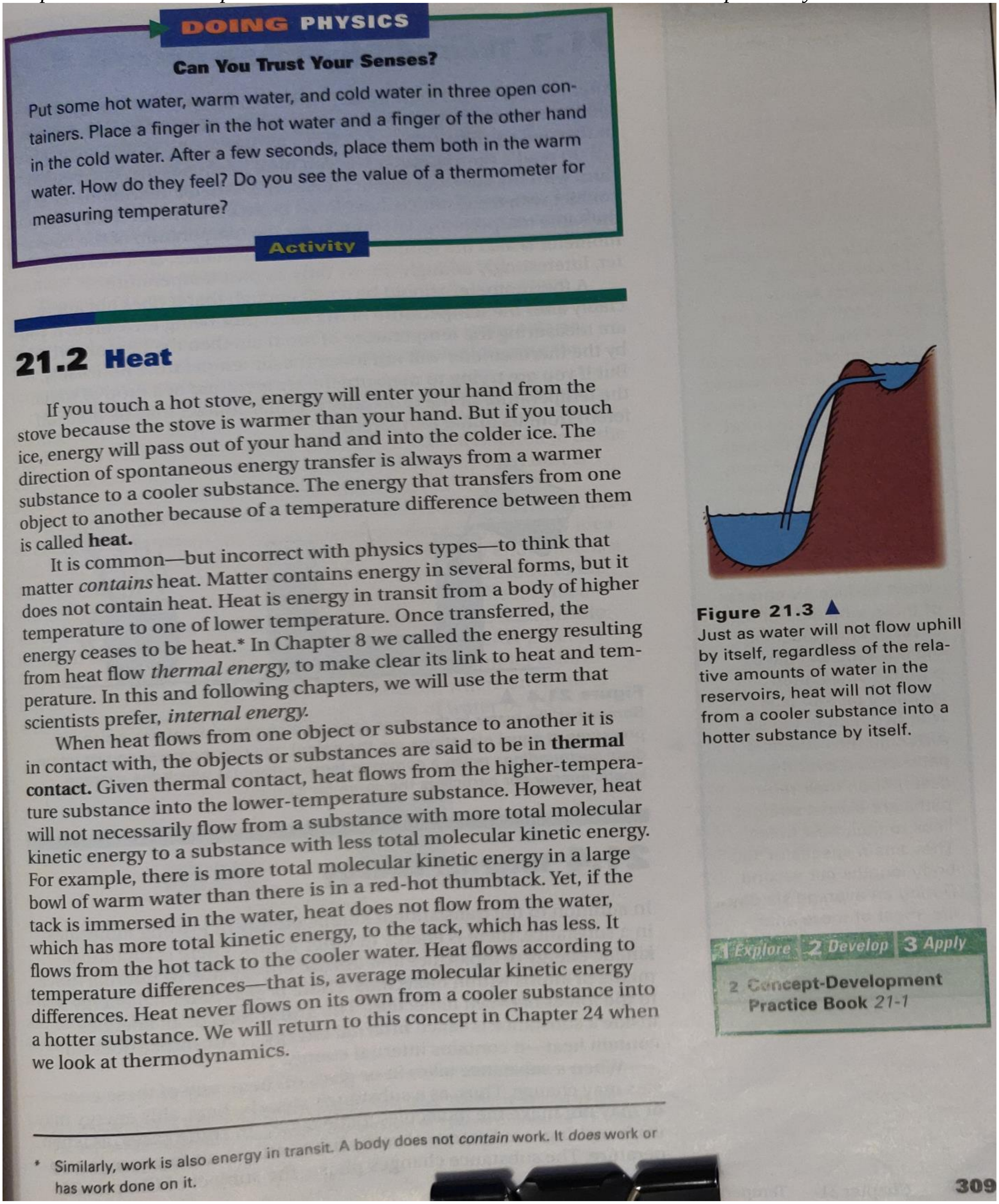
* The Celsius scale is named in honor of the man who first suggested it, the Swedish astronomer Anders Celsius (1701–1744). It used to be called the centigrade scale, fror *centi* ("hundredth") and *gradus* ("degree"). The Fahrenheit scale is named after the German physicist Gabriel Fahrenheit (1686–1736), and the Kelvin scale, after the Briti physicist Lord Kelvin (1824–1907).



DOING PHYSICS

Can You Trust Your Senses?

Put some hot water, warm water, and cold water in three open containers. Place a finger in the hot water and a finger of the other hand in the cold water. After a few seconds, place them both in the warm water. How do they feel? Do you see the value of a thermometer for measuring temperature?

Activity

21.2 Heat

If you touch a hot stove, energy will enter your hand from the stove because the stove is warmer than your hand. But if you touch ice, energy will pass out of your hand and into the colder ice. The direction of spontaneous energy transfer is always from a warmer substance to a cooler substance. The energy that transfers from one object to another because of a temperature difference between them is called **heat.**

It is common—but incorrect with physics types—to think that matter *contains* heat. Matter contains energy in several forms, but it does not contain heat. Heat is energy in transit from a body of higher temperature to one of lower temperature. Once transferred, the energy ceases to be heat.* In Chapter 8 we called the energy resulting from heat flow *thermal energy,* to make clear its link to heat and temperature. In this and following chapters, we will use the term that scientists prefer, *internal energy.*

When heat flows from one object or substance to another it is in contact with, the objects or substances are said to be in **thermal contact.** Given thermal contact, heat flows from the higher-temperature substance into the lower-temperature substance. However, heat will not necessarily flow from a substance with more total molecular kinetic energy to a substance with less total molecular kinetic energy. For example, there is more total molecular kinetic energy in a large bowl of warm water than there is in a red-hot thumbtack. Yet, if the tack is immersed in the water, heat does not flow from the water, which has more total kinetic energy, to the tack, which has less. It flows from the hot tack to the cooler water. Heat flows according to temperature differences—that is, average molecular kinetic energy differences. Heat never flows on its own from a cooler substance into a hotter substance. We will return to this concept in Chapter 24 when we look at thermodynamics.

Figure 21.3 ▲
Just as water will not flow uphill by itself, regardless of the relative amounts of water in the reservoirs, heat will not flow from a cooler substance into a hotter substance by itself.

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* Similarly, work is also energy in transit. A body does not *contain* work. It *does* work or has work done on it.

21.5 Measurement of Heat

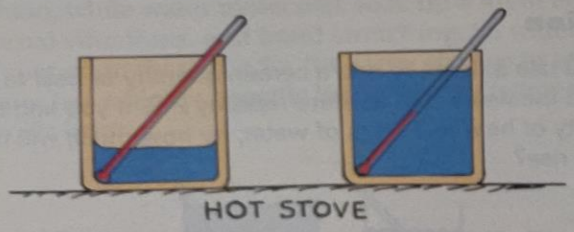
So we see that heat is energy transferred from one substance to another by a temperature difference. The amount of heat transferred can be determined by measuring the temperature change of a known mass of water that absorbs the heat.

When a substance absorbs heat, the resulting temperature change depends on more than just the mass of the substance. The quantity of heat that brings a cupful of soup to a boil might raise the temperature of a pot of soup by only a few degrees. To quantify heat, we must specify the *mass* and *kind* of substance affected.

The unit of heat is defined as the heat necessary to produce some standard, agreed-on temperature change for a specified mass of material. The most commonly used unit for heat is the **calorie.** The calorie is defined as the amount of heat required to raise the temperature of 1 gram of water by 1°C.

The **kilocalorie** is 1000 calories (the heat required to raise the temperature of 1 kilogram of water by 1°C). The heat unit used in rating foods is actually a kilocalorie, although it's often referred to as the calorie. To distinguish it from the smaller calorie, the food unit is sometimes called a Calorie (written with a capital C).

It is important to remember that the calorie and Calorie are units of energy. These names are historical carryovers from the early idea that heat was an invisible fluid called *caloric*. We now know heat is a form of energy. The United States is in a period of transition to the International System of Units (SI), where quantity of heat is measured in joules, the SI unit for all forms of energy. The relationship between calories and joules is that 1 calorie equals 4.184 J. In this book we'll learn about heat with the conceptually simpler calorie—but in the lab you may use the joule equivalent, where an input of 4.184 joules raises the temperature of 1 gram of water by 1°C.*



◄ **Figure 21.5**
Although the same quantity of heat is added to both containers, the temperature of the container with the smaller amount of water increases more.

The energy value in food is determined by burning the food and measuring the energy that is released as heat. Food and other fuels are rated by how much energy a certain mass of the fuel gives off as heat when burned.

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* Still another unit of heat is the British thermal unit (Btu). The Btu is defined as the quantity of heat required to change the temperature of 1 pound of water by 1°F. One Btu is equal to 1054 J.

Figure 21.6 ▲
To the weight watcher, the peanut contains 10 Calories; to the physicist, it releases 10 000 calories (or 41 840 joules) of energy when burned or digested.

Computational Example: Dimensional Analysis

A woman with an average diet consumes and expends about 2000 Calories per day. The energy used by her body is eventually given off as heat. How many joules per second does her body give off? Or, in other words, what is her average thermal power output?

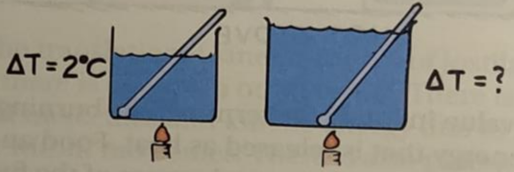
We find this by converting 2000 Calories per day to joules per second. We use the information that 1 Calorie = 4184 joules, 1 day = 24 hours, and 1 hour = 3600 seconds. The conversion is then set up as follows:

$$\frac{2000\ \cancel{\text{Cal}}}{1\ \cancel{\text{d}}} \times \frac{1\ \cancel{\text{d}}}{24\ \cancel{\text{h}}} \times \frac{1\ \cancel{\text{h}}}{3600\ \text{s}} \times \frac{4184\ \text{J}}{1\ \cancel{\text{Cal}}} = 96.8\ \text{J/s} = 96.8\ \text{W}$$

Notice that the original quantity (2000 Cal/d) is multiplied by a set of fractions in which the numerator equals the denominator. Since each fraction has the value 1, multiplying by it does not change the value of the original quantity. The rule for choosing which quantity to put in the numerator is that the units should cancel and reduce to those of the end result. (We call this technique "dimensional analysis.") So, on the average, the woman emits heat at the rate of 96.8 J/s, which is 96.8 watts. This is nearly the same as a glowing 100-W lamp! It's easy to see why a crowded room soon becomes warm! (Don't confuse the 96.8 watts given off by the woman with her internal temperature of 98.6°F. The closeness of the numerical values is a coincidence. A body's temperature and its rate of expending heat are entirely different from each other.)

Question

Suppose you use a flame to add a certain quantity of heat to 1 liter of water, and the water temperature rises by 2°C. If you add the same quantity of heat to 2 liters of water, by how much will its temperature rise?



Answer

Its temperature will rise by 1°C, because there are twice as many molecules in 2 liters of water and each molecule receives only half as much energy on average. So average kinetic energy, and temperature, increase by half as much.

21.6 Specific Heat Capacity

Almost everyone has noticed that some foods remain hot much longer than others. Boiled onions and moist squash on a hot dish, for example, are often too hot to eat while mashed potatoes may be just right. The filling of hot apple pie can burn your tongue while the crust will not, even when the pie has just been taken out of the oven. The aluminum covering on a frozen dinner can be peeled off with your bare fingers as soon as it is removed from the oven. (But be careful of the food beneath it!)

Different substances have different capacities for storing internal energy. If we heat a pot of water on a stove, we may find that it requires 15 minutes to raise it from room temperature to its boiling temperature. But if we were to put an equal mass of iron on the same flame, we would find that it would rise through the same temperature range in only about 2 minutes. For silver, the time would be less than a minute. We find that specific materials require specific quantities of heat to raise the temperature of a given mass of the material by a specified number of degrees.

Absorbed energy can affect substances in different ways. Absorbed energy that increases the translational speed of molecules is responsible for increases in temperature. Absorbed energy may also increase the rotation of molecules, increase the internal vibrations within molecules, or stretch intermolecular bonds and be stored as potential energy. These kinds of energy, however, are not measures of temperature. Temperature is a measure only of the kinetic energy of translational motion. Generally, only part of the energy absorbed by a substance raises its temperature.

Whereas 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. Iron atoms in the iron lattice primarily shake back and forth in translational fashion, while water molecules soak up a lot of energy in rotations, internal vibrations, and bond stretching. So water absorbs more heat per gram than iron for the same change in temperature. We say water has a higher **specific heat capacity** (sometimes simply called *specific heat*).

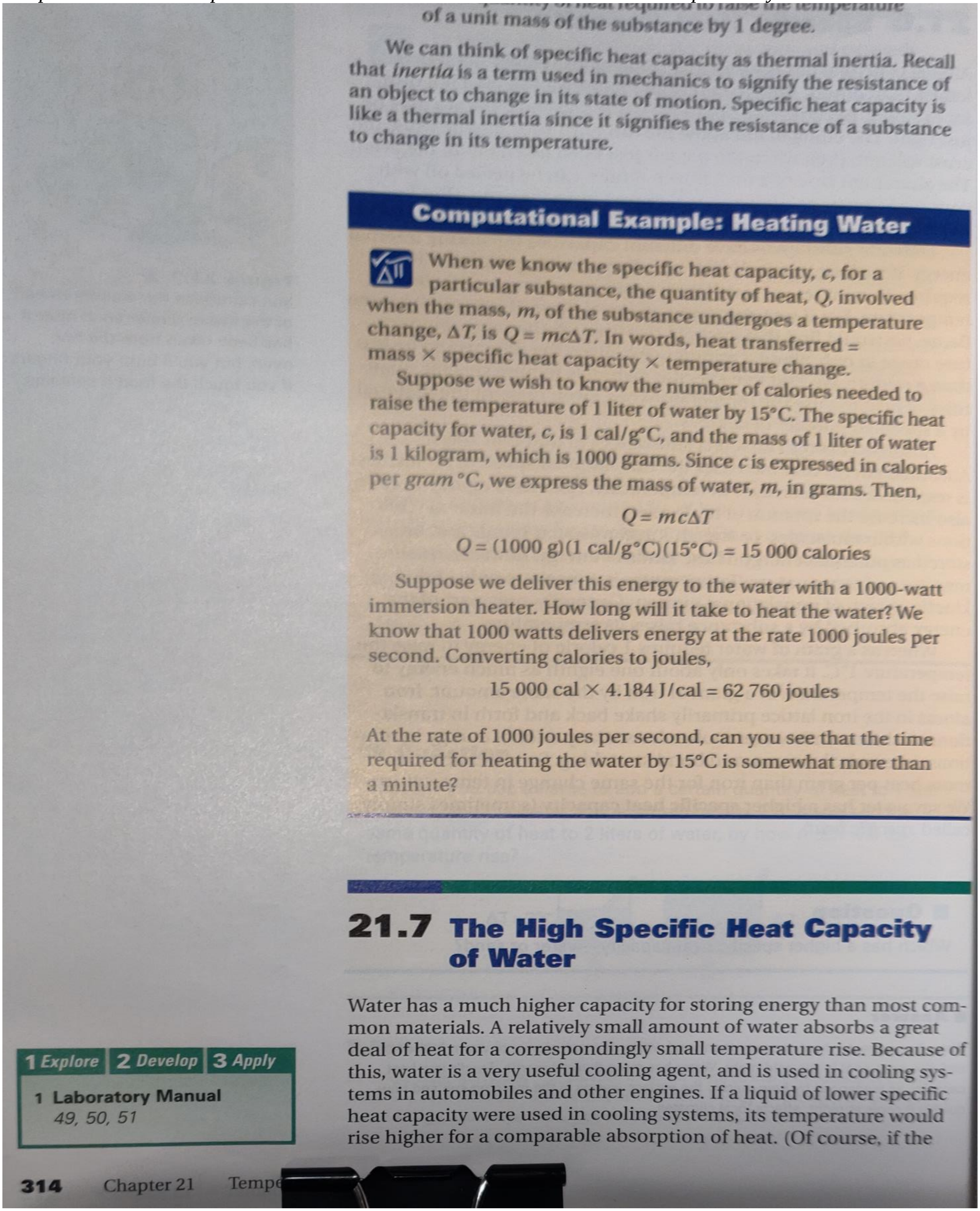
Figure 21.7 ▲
You can touch the aluminum pan of the frozen dinner soon after it has been taken from the hot oven, but you'll burn your fingers if you touch the food it contains.

■ Question

Which has a higher specific heat capacity—water or sand?

■ Answer

Water has a greater heat capacity than sand. Water is much slower to warm in the hot sun and slower to cool in the cold night. Water has more thermal inertia. Sand's low heat capacity, as evidenced by how quickly the surface warms in the morning sun and how quickly it cools at night, affects local climates.



of a unit mass of the substance by 1 degree.

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 change in its state of motion. Specific heat capacity is like a thermal inertia since it signifies the resistance of a substance to change in its temperature.

Computational Example: Heating Water

When we know the specific heat capacity, c, for a particular substance, the quantity of heat, Q, involved when the mass, m, of the substance undergoes a temperature change, ΔT, is $Q = mc\Delta T$. In words, heat transferred = mass × specific heat capacity × temperature change.

Suppose we wish to know the number of calories needed to raise the temperature of 1 liter of water by 15°C. The specific heat capacity for water, c, is 1 cal/g°C, and the mass of 1 liter of water is 1 kilogram, which is 1000 grams. Since c is expressed in calories per *gram* °C, we express the mass of water, m, in grams. Then,

$$Q = mc\Delta T$$

$$Q = (1000\text{ g})(1\text{ cal/g°C})(15\text{°C}) = 15\,000\text{ calories}$$

Suppose we deliver this energy to the water with a 1000-watt immersion heater. How long will it take to heat the water? We know that 1000 watts delivers energy at the rate 1000 joules per second. Converting calories to joules,

$$15\,000\text{ cal} \times 4.184\text{ J/cal} = 62\,760\text{ joules}$$

At the rate of 1000 joules per second, can you see that the time required for heating the water by 15°C is somewhat more than a minute?

21.7 The High Specific Heat Capacity of Water

Water has a much higher capacity for storing energy than most common materials. A relatively small amount of water absorbs a great deal of heat for a correspondingly small temperature rise. Because of this, water is a very useful cooling agent, and is used in cooling systems in automobiles and other engines. If a liquid of lower specific heat capacity were used in cooling systems, its temperature would rise higher for a comparable absorption of heat. (Of course, if the

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temperature of the liquid rises to the temperature of the engine, no further cooling will take place.) Water also takes longer to cool, a useful fact to your great-grandparents, who on cold winter nights likely used foot-warming hot-water bottles in their beds.

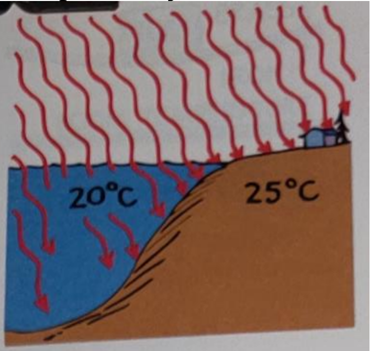

Figure 21.8 ▲
Water has a high specific heat and is transparent, so it takes more energy to heat up than land does. Why would its transparency be a factor?

This property of water to resist changes in temperature improves the climate in many places. The next time you are looking at a world globe, notice the high latitude of Europe. If water did not have a high heat capacity, the countries of Europe would be as cold as the northeastern regions of Canada, for both Europe and Canada get about the same amount of the sun's energy per square kilometer. The Atlantic current known as the Gulf Stream brings warm water northeast from the Caribbean. It holds much of its internal energy long enough to reach the North Atlantic off the coast of Europe, where it then cools. The energy released (one calorie per degree for each gram of water that cools) is carried by the westerly winds over the European continent.

Similarly, the climates differ on the east and west coasts of North America. The winds in the latitudes of North America are westerly. On the west coast, air moves from the Pacific Ocean to the land. Because of water's high heat capacity, ocean temperature does not vary much from summer to winter. The water is warmer than the air in the winter, and cooler than the air in the summer. In winter, the water warms the air that moves over it and warms the western coastal regions of North America. In summer, the water cools the air and the western coastal regions are cooled. On the east coast, air moves from the land to the Atlantic Ocean. Land, with a lower specific heat capacity, gets hot in summer but cools rapidly in winter. As a result of water's high heat capacity and the wind directions, the west coast city of San Francisco is warmer in the winter and cooler in the summer than the east coast city of Washington, D.C., which is at about the same latitude.

The central interior of a large continent usually experiences extremes of temperature. For example, the high summer and low winter temperatures common in Manitoba and the Dakotas 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 are!

21.8 Thermal Expansion

When the temperature of a substance is increased, its molecules jiggle faster and normally tend to move farther apart. This results in an *expansion* of the substance. With few exceptions, all forms of matter—solids, liquids, and gases—expand when they are heated and contract when they are cooled. For comparable pressures and comparable changes in temperature, gases generally expand or contract much more than liquids, and liquids expand or contract more than solids.*

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* This rule is valid if the solid, liquid, and gas expand against constant pressure. A gas in a container can be prevented from expanding, but then its pressure is not constant.

If concrete sidewalks and highway paving were laid down in one continuous piece, cracks would appear due to the expansion and contraction brought about by the difference between summer and winter temperatures. To prevent this, the surface is laid in small sections, each one being separated from the next by a small gap that is filled in with a substance such as tar. On a hot summer day, expansion often squeezes this material out of the joints.

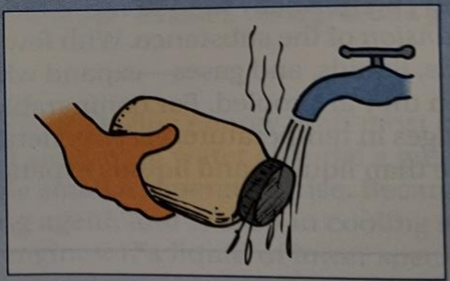
The *expansion* of materials must be allowed for in the construction of structures and devices of all kinds. A dentist uses filling material that has the same rate of expansion as teeth. The aluminum pistons of an automobile engine are enough smaller in diameter than the steel cylinders to allow for the much greater expansion rate of aluminum. A civil engineer uses steel of the same expansion rate as concrete for reinforcing concrete. Long steel bridges often have one end fixed while the other rests on rockers that allow for expansion. The roadway itself is segmented with tongue-and-groove-type gaps called expansion joints (Figure 21.9).

Figure 21.9 ▲
This gap is called an *expansion joint,* and allows the bridge to expand and contract.

DOING PHYSICS

Brains Over Brawn

The next time you find it difficult to unscrew a metal lid from a jar, let thermal expansion assist you. Heat the metal lid by placing it in a stream of hot water, or momentarily placing it on a hot stove. The metal lid will expand more than the glass. Presto! Can you see why a slight twist then opens the jar? Can you explain why this works? What's the physics here?



Activity

Different materials expand at different rates. In a **bimetallic strip**, two strips of different metals, say one of brass and the other of iron, are welded or riveted together (Figure 21.10). When the strip is heated, the difference in the amounts of expansion of brass and iron shows up easily. One side of the double strip becomes longer than the other, causing the strip to bend into a curve. On the other hand, when the strip is cooled, it bends in the opposite direction, because the metal that expands the most also contracts the most. The movement of the strip may be used to turn a pointer, regulate a valve, or operate a switch.

A **thermostat** is a practical application of a bimetallic strip (Figure 21.11). The back-and-forth bending of the bimetallic coil opens and closes an electric circuit. When the room becomes too cold, the coil bends toward the brass side, and in so doing it closes an electric switch that turns on the heat. When the room becomes too warm, the coil bends toward the iron side, which opens the switch and turns off the heating unit. Refrigerators are equipped with special thermostats to prevent them from becoming too hot or too cold. Bimetallic strips are used in oven thermometers, electric toasters, automatic chokes on carburetors, and other devices.

The amount of expansion of a substance depends on its change in temperature. If one part of a piece of glass is heated or cooled more rapidly than adjacent parts, the expansion or contraction that results may break the glass. This is especially true for thick glass. Heat-resistant glass is specially formulated to expand very little with increasing temperature.

Liquids expand appreciably with increases in temperature. When the gasoline tank of a car is filled at a gas station and the car is then parked for a while, the gasoline often overflows the tank. This occurs as the cold gasoline from the underground storage tanks warms up as it sits in the car's tank. As the gasoline warms, it expands and overflows the gas tank. Similarly, an automobile radiator filled to the brim with cold water overflows when heated.

In most cases, the expansion of liquids is greater than the expansion of solids. The gasoline overflowing a car's tank on a hot day is evidence for this. Similarly, a pot filled to the brim with water soon overflows when heated. Also, mercury rises in a thermometer when heated because the liquid mercury expands more than the glass.

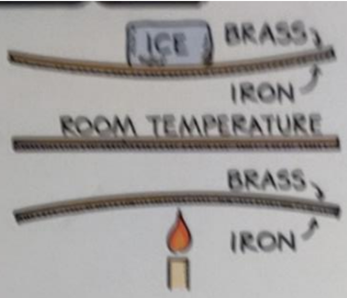


Figure 21.10 ▲
A bimetallic strip. Brass expands (or contracts) more when heated (or cooled) than does iron, so the strip bends as shown.

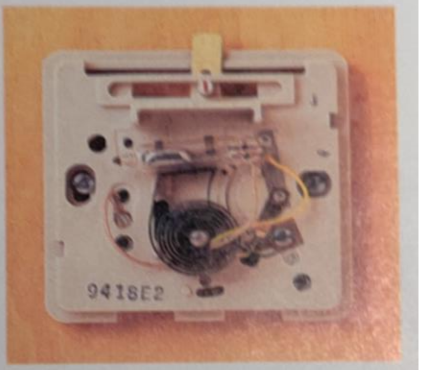


Figure 21.11 ▲
A thermostat. When the bimetallic coil expands, the mercury rolls away from the electrical contacts and breaks the circuit. When the coil contracts, the mercury rolls against the contacts and completes the electric circuit.

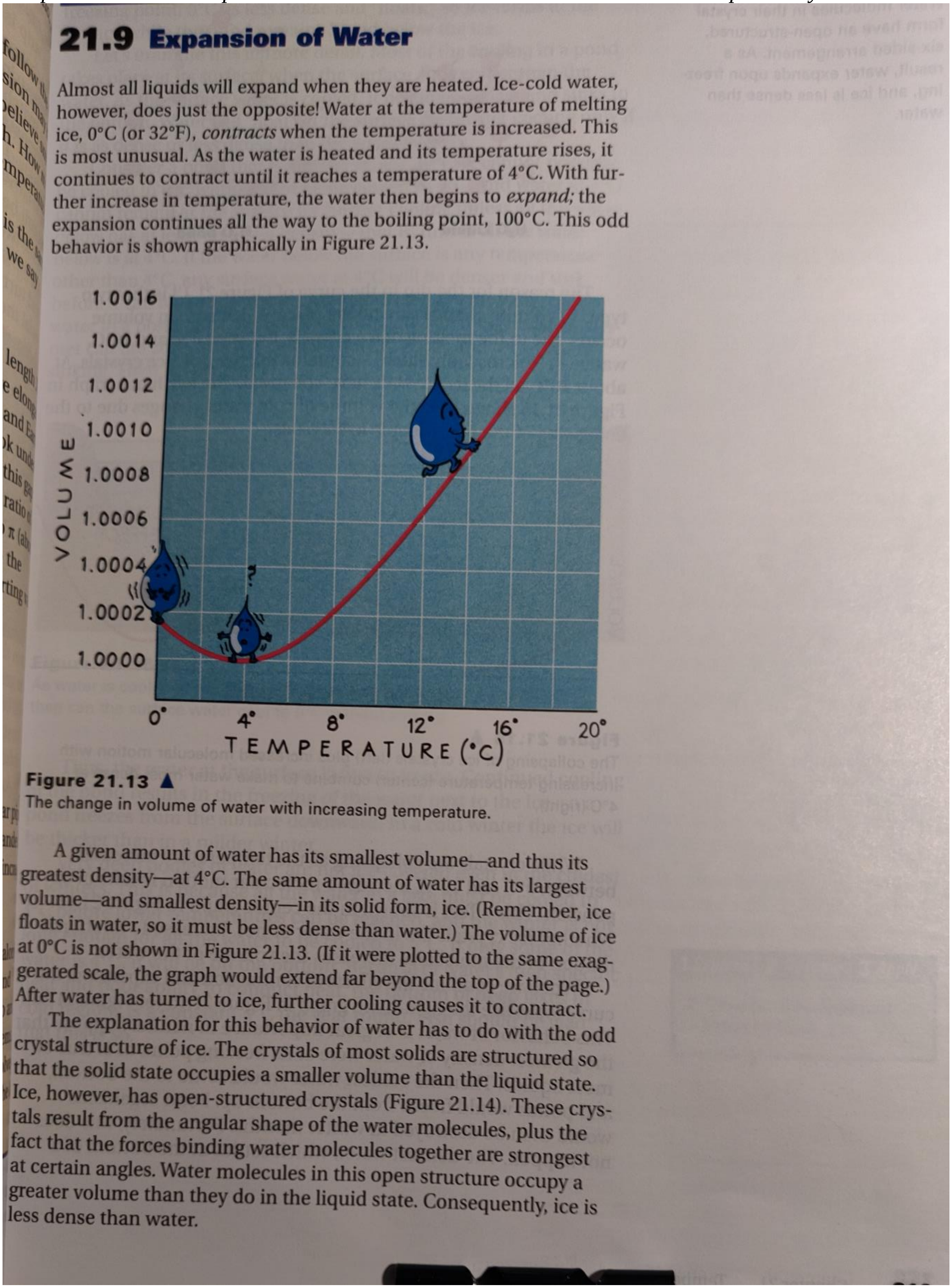
Figure 21.12 ▲
Place a dented Ping-Pong ball in boiling water, and you'll remove the dent. Why?

■ Question

Why is it advisable to allow telephone lines to sag when stringing them between poles in summer?

■ Answer

Telephone lines are longer in summer, when they are warmer, and shorter in winter, when they are cooler. They therefore sag more on hot summer days than in winter. If the telephone lines are not strung with enough sag in summer, they might contract too much and snap during the winter.



21.9 Expansion of Water

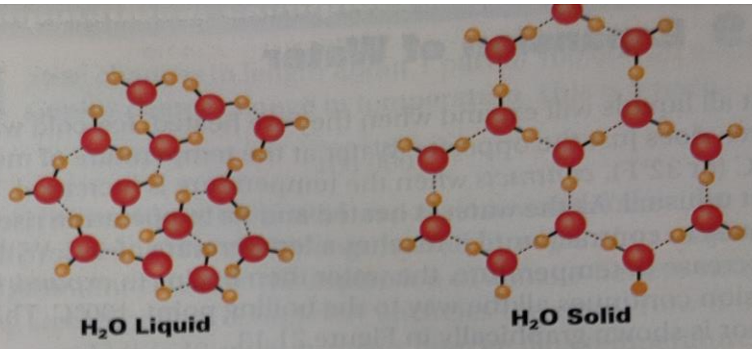
Almost all liquids will expand when they are heated. Ice-cold water, however, does just the opposite! Water at the temperature of melting ice, 0°C (or 32°F), *contracts* when the temperature is increased. This is most unusual. As the water is heated and its temperature rises, it continues to contract until it reaches a temperature of 4°C. With further increase in temperature, the water then begins to *expand;* the expansion continues all the way to the boiling point, 100°C. This odd behavior is shown graphically in Figure 21.13.

Figure 21.13 ▲
The change in volume of water with increasing temperature.

A given amount of water has its smallest volume—and thus its greatest density—at 4°C. The same amount of water has its largest volume—and smallest density—in its solid form, ice. (Remember, ice floats in water, so it must be less dense than water.) The volume of ice at 0°C is not shown in Figure 21.13. (If it were plotted to the same exaggerated scale, the graph would extend far beyond the top of the page.) After water has turned to ice, further cooling causes it to contract.

The explanation for this behavior of water has to do with the odd crystal structure of ice. The crystals of most solids are structured so that the solid state occupies a smaller volume than the liquid state. Ice, however, has open-structured crystals (Figure 21.14). These crystals result from the angular shape of the water molecules, plus the fact that the forces binding water molecules together are strongest at certain angles. Water molecules in this open structure occupy a greater volume than they do in the liquid state. Consequently, ice is less dense than water.

Figure 21.14 ▶
Water molecules in their crystal form have an open-structured, six-sided arrangement. As a result, water expands upon freezing, and ice is less dense than water.



The reason for the dip in the curve of Figure 21.13 is that two types of volume changes are taking place. A decrease in volume occurs due to the melting of ice crystals. Between 0°C and 10°C, water—a "microscopic slush"—contains microscopic ice crystals. At about 10°C all the ice crystals have collapsed. The left-hand graph in Figure 21.15 shows how the volume of cold water changes due to the collapsing of the microscopic ice crystals.

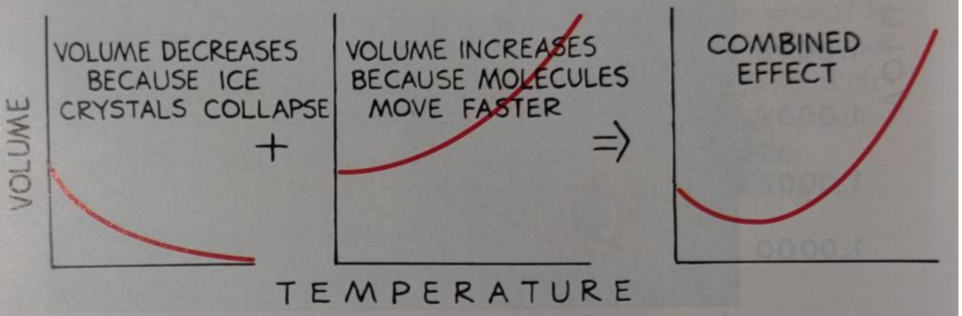


Figure 21.15 ▲
The collapsing of ice crystals (left) plus increased molecular motion with increasing temperature (center) combine to make water most dense at 4°C (right).

While crystals are collapsing as the temperature increases between 0°C and 10°C, increased molecular motion results in expansion. This effect is shown in the center graph in Figure 21.15. Whether ice crystals are in the water or not, increased vibrational motion of the molecules increases the volume of the water.

When we combine the effects of contraction and expansion, the curve looks like the right-hand graph in Figure 21.15 (or Figure 21.13). This behavior of water is of great importance in nature. Suppose that the greatest density of water were at its freezing point, as is true of most liquids. Then the coldest water would settle to the bottom, and ponds would freeze from the bottom up. Pond organisms would then be destroyed in winter months. Fortunately, this does not happen. The densest water, which settles at the bottom of a pond, is 4 degrees above the freezing temperature. Water at the freezing point, 0°C, is less dense and "floats," so ice forms at the surface while the pond remains liquid below the ice.

Let's examine this in more detail. Most of the cooling in a pond takes place at its surface, when the surface air is colder than the water. As the surface water is cooled, it becomes denser and sinks to the bottom. Water will "float" at the surface for further cooling only if it is as dense or less dense than the water below.

Consider a pond that is initially at, say, 10°C. It cannot possibly be cooled to 0°C without first being cooled to 4°C. And water at 4°C cannot remain at the surface for further cooling unless all the water below has at least an equal density—that is, unless all the water below is at 4°C. If the water below the surface is any temperature other than 4°C, any surface water at 4°C will be denser and sink before it can be further cooled. So before any ice can form, all the water in a pond must be cooled to 4°C. Only when this condition is met can the surface water be cooled to 3°, 2°, 1°, and 0°C without sinking. Then ice can form.

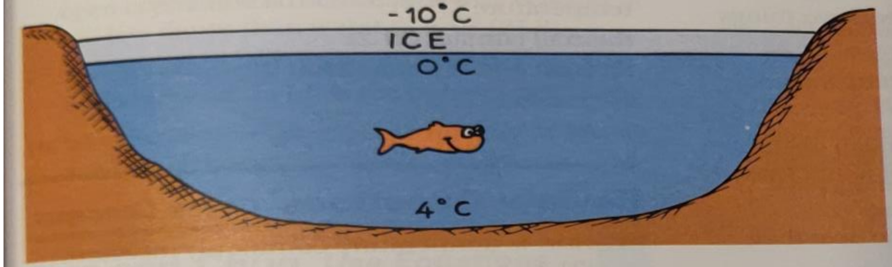
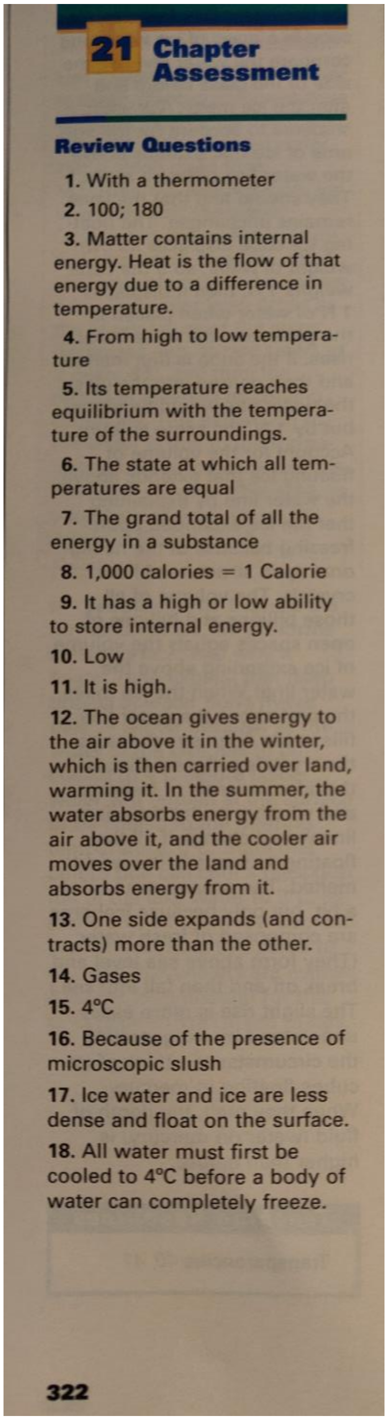


Figure 21.16 ▲
As water is cooled at the surface, it sinks until the entire lake is 4°C. Only then can the surface water cool to 0°C without sinking.

Thus, the water at the surface is first to freeze. Continued cooling of the pond results in the freezing of the water next to the ice, so a pond freezes from the surface downward. In a cold winter the ice will be thicker than in a milder winter.

Very deep bodies of water are not ice-covered even in the coldest of winters. This is because all the water in a lake must be cooled to 4°C before lower temperatures can be reached, and the winter is not long enough for all the water to be cooled to 4°C. If only some of the water is 4°C, it will lie on the bottom. Because of water's high specific heat and poor ability to conduct heat, the bottom of deep lakes in cold regions is a constant 4°C the year round. Fish should be glad that this is so.



21 Chapter Assessment

Review Questions

1. With a thermometer

2. 100; 180

3. Matter contains internal energy. Heat is the flow of that energy due to a difference in temperature.

4. From high to low temperature

5. Its temperature reaches equilibrium with the temperature of the surroundings.

6. The state at which all temperatures are equal

7. The grand total of all the energy in a substance

8. 1,000 calories = 1 Calorie

9. It has a high or low ability to store internal energy.

10. Low

11. It is high.

12. The ocean gives energy to the air above it in the winter, which is then carried over land, warming it. In the summer, the water absorbs energy from the air above it, and the cooler air moves over the land and absorbs energy from it.

13. One side expands (and contracts) more than the other.

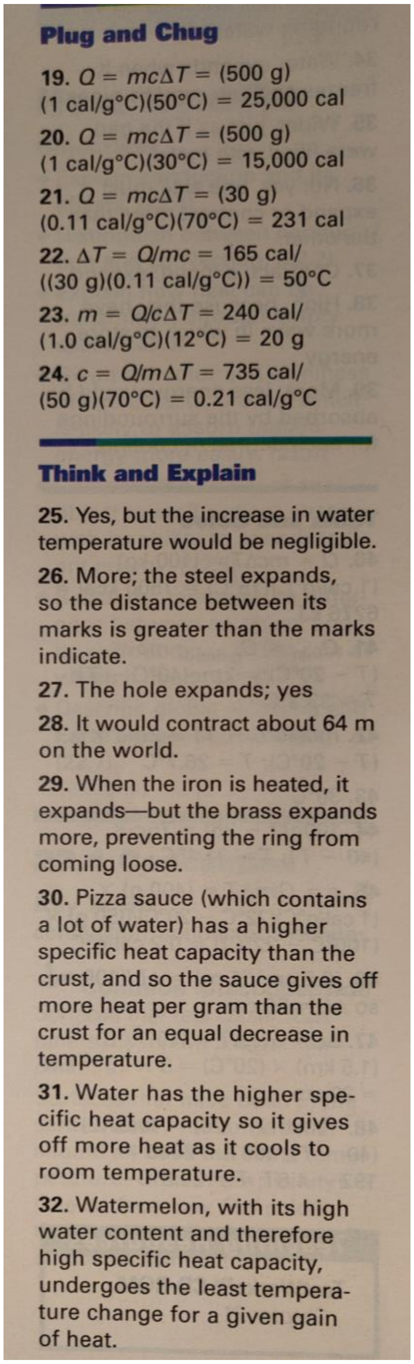
14. Gases

15. 4°C

16. Because of the presence of microscopic slush

17. Ice water and ice are less dense and float on the surface.

18. All water must first be cooled to 4°C before a body of water can completely freeze.



Plug and Chug

19. $Q = mc\Delta T = (500\text{ g})(1\text{ cal/g°C})(50°\text{C}) = 25{,}000\text{ cal}$

20. $Q = mc\Delta T = (500\text{ g})(1\text{ cal/g°C})(30°\text{C}) = 15{,}000\text{ cal}$

21. $Q = mc\Delta T = (30\text{ g})(0.11\text{ cal/g°C})(70°\text{C}) = 231\text{ cal}$

22. $\Delta T = Q/mc = 165\text{ cal}/((30\text{ g})(0.11\text{ cal/g°C})) = 50°\text{C}$

23. $m = Q/c\Delta T = 240\text{ cal}/(1.0\text{ cal/g°C})(12°\text{C}) = 20\text{ g}$

24. $c = Q/m\Delta T = 735\text{ cal}/(50\text{ g})(70°\text{C}) = 0.21\text{ cal/g°C}$

Think and Explain

25. Yes, but the increase in water temperature would be negligible.

26. More; the steel expands, so the distance between its marks is greater than the marks indicate.

27. The hole expands; yes

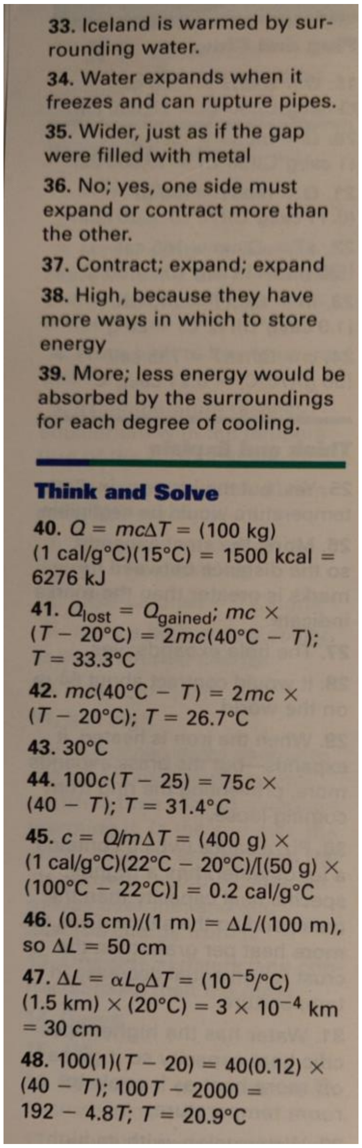
28. It would contract about 64 m on the world.

29. When the iron is heated, it expands—but the brass expands more, preventing the ring from coming loose.

30. Pizza sauce (which contains a lot of water) has a higher specific heat capacity than the crust, and so the sauce gives off more heat per gram than the crust for an equal decrease in temperature.

31. Water has the higher specific heat capacity so it gives off more heat as it cools to room temperature.

32. Watermelon, with its high water content and therefore high specific heat capacity, undergoes the least temperature change for a given gain of heat.



33. Iceland is warmed by surrounding water.

34. Water expands when it freezes and can rupture pipes.

35. Wider, just as if the gap were filled with metal

36. No; yes, one side must expand or contract more than the other.

37. Contract; expand; expand

38. High, because they have more ways in which to store energy

39. More; less energy would be absorbed by the surroundings for each degree of cooling.

Think and Solve

40. $Q = mc\Delta T = (100\text{ kg})(1\text{ cal/g°C})(15°\text{C}) = 1500\text{ kcal} = 6276\text{ kJ}$

41. $Q_{\text{lost}} = Q_{\text{gained}}$; $mc \times (T - 20°\text{C}) = 2mc(40°\text{C} - T)$; $T = 33.3°\text{C}$

42. $mc(40°\text{C} - T) = 2mc \times (T - 20°\text{C})$; $T = 26.7°\text{C}$

43. 30°C

44. $100c(T - 25) = 75c \times (40 - T)$; $T = 31.4°C$

45. $c = Q/m\Delta T = (400\text{ g}) \times (1\text{ cal/g°C})(22°\text{C} - 20°\text{C})/[(50\text{ g}) \times (100°\text{C} - 22°\text{C})] = 0.2\text{ cal/g°C}$

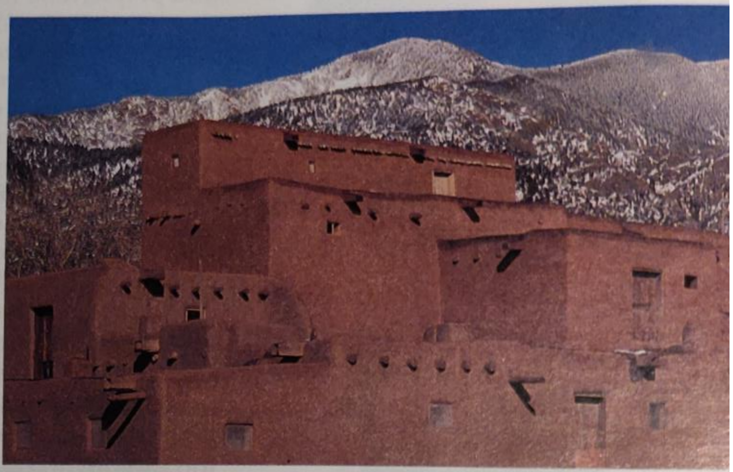
46. $(0.5\text{ cm})/(1\text{ m}) = \Delta L/(100\text{ m})$, so $\Delta L = 50\text{ cm}$

47. $\Delta L = \alpha L_0 \Delta T = (10^{-5}/°\text{C})(1.5\text{ km}) \times (20°\text{C}) = 3 \times 10^{-4}\text{ km} = 30\text{ cm}$

48. $100(1)(T - 20) = 40(0.12) \times (40 - T)$; $100T - 2000 = 192 - 4.8T$; $T = 20.9°\text{C}$

Chapter 22

Heat Transfer


Thick adobe walls slow heat transfer.

The spontaneous transfer of heat is always from warmer objects to cooler objects. If several objects near one another have different temperatures, then those that are warm become cooler and those that are cool become warmer, until all have a common temperature. This equalization of temperatures is brought about in three ways: by *conduction*, by *convection*, and by *radiation*.

22.1 Conduction

If you hold one end of an iron rod in a flame, before long the rod will become too hot to hold. Heat has transferred through the metal by **conduction.** Conduction of heat can take place within materials and between different materials that are in direct contact. Materials that conduct heat well are known as heat **conductors.** Metals are the best conductors. Among the common metals, silver is the most conductive, followed by copper, aluminum, and iron.

Conduction is explained by collisions between atoms or molecules, and the actions of loosely bound electrons. In the iron rod, the flame causes the atoms at the heated end to vibrate more rapidly. These atoms vibrate against neighboring atoms, which in turn do the same. More important, free electrons that can drift through the metal are made to jostle and transfer energy by colliding with atoms and other free electrons within the rod.

Materials composed of atoms with "loose" outer electrons are good conductors of heat (and electricity also). Because metals have the "loosest" outer electrons, they are the best conductors of heat and electricity.

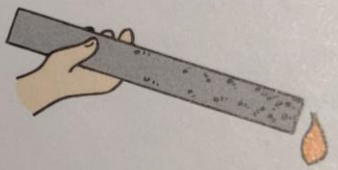


Figure 22.1 ▲
Heat from the flame causes atoms and free electrons in the end of the metal to move faster and jostle against others, which in turn do the same and increase the energy of vibrating atoms down the length of the rod.

Touch a piece of metal and a piece of wood in your immediate vicinity. Which one *feels* colder? Which is *really* colder? Your answers should be different. If the materials are in the same vicinity, they

Figure 22.2 ▲
The tile floor feels cold to the bare feet, while the carpet at the same temperature feels warm. This is because tile is a better conductor than carpet.

Figure 22.3 ▲
A "warm" blanket does not provide you with heat; it simply slows the transfer of your body heat to the surroundings.

should have the same temperature, room temperature. Thus neither is really colder. Yet, the metal *feels* colder because it is a better conductor; heat easily moves out of your warmer hand into the cooler metal. Wood, on the other hand, is a poor conductor. Little heat moves out of your hand into the wood, so your hand does not sense that it is touching something cooler. Wood, wool, straw, paper, cork, and polystyrene (Styrofoam) are all poor heat conductors. Instead, they are called good **insulators** because they delay the transfer of heat. A poor conductor is a good insulator.

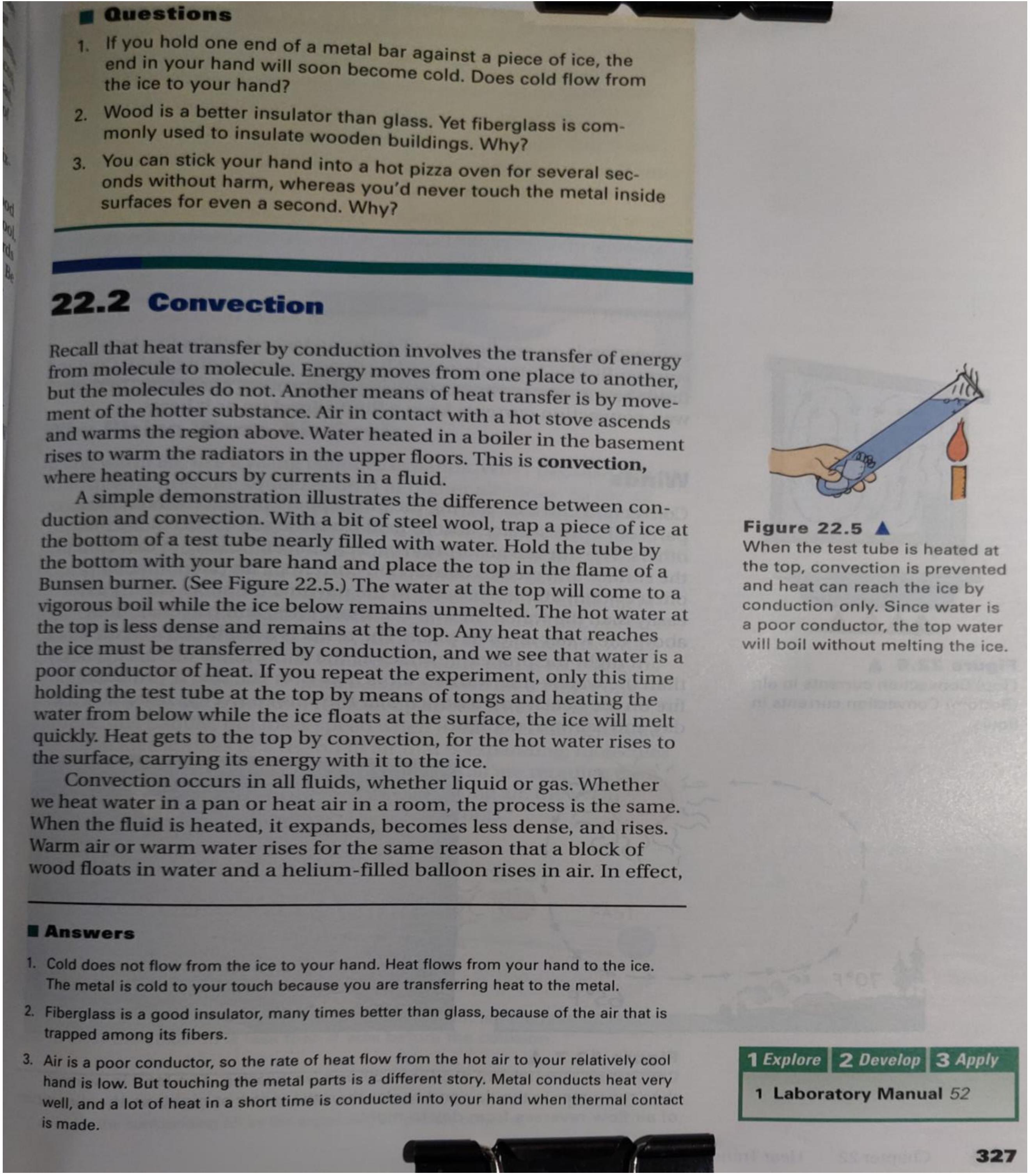
Liquids and gases, in general, are good insulators. Air is a mixture of gases and conducts heat very poorly—air is a very good insulator. Porous materials having many small air spaces are good insulators. The good insulating properties of materials such as wool, fur, and feathers are largely due to the air spaces they contain. Birds vary their insulation by fluffing their feathers to create air spaces. Be glad that air is a poor conductor, for if it were not, you'd feel quite chilly on a 25°C (77°F) day!

Snowflakes imprison a lot of air in their crystals and are good insulators. Snow slows the escape of heat from Earth's surface, shields Eskimo dwellings from the cold, and provides protection from the cold to animals on cold winter nights. Snow, like any blanket, is not a source of heat; it simply prevents any heat from escaping too rapidly.

Heat is energy and is tangible. Cold is not; cold is simply the absence of heat. Strictly speaking, there is no "cold" that passes through a conductor or an insulator. Only heat is transferred. We don't insulate a home to keep the cold out; we insulate to keep the heat in. If the home becomes colder, it is because heat flows out.

It is important to note that no insulator can totally prevent heat from getting through it. An insulator just reduces the rate at which heat penetrates. Even the best-insulated warm homes in winter will gradually cool. Insulation delays heat transfer.

Figure 22.4 ▲
Snow lasts longest on the roof of a well-insulated house. Thus, the snow patterns reveal the conduction, or lack of conduction, of heat through the roof. Can you see how the insulation of these houses varies?



Questions

1. If you hold one end of a metal bar against a piece of ice, the end in your hand will soon become cold. Does cold flow from the ice to your hand?
2. Wood is a better insulator than glass. Yet fiberglass is commonly used to insulate wooden buildings. Why?
3. You can stick your hand into a hot pizza oven for several seconds without harm, whereas you'd never touch the metal inside surfaces for even a second. Why?

22.2 Convection

Recall that heat transfer by conduction involves the transfer of energy from molecule to molecule. Energy moves from one place to another, but the molecules do not. Another means of heat transfer is by movement of the hotter substance. Air in contact with a hot stove ascends and warms the region above. Water heated in a boiler in the basement rises to warm the radiators in the upper floors. This is **convection,** where heating occurs by currents in a fluid.

A simple demonstration illustrates the difference between conduction and convection. With a bit of steel wool, trap a piece of ice at the bottom of a test tube nearly filled with water. Hold the tube by the bottom with your bare hand and place the top in the flame of a Bunsen burner. (See Figure 22.5.) The water at the top will come to a vigorous boil while the ice below remains unmelted. The hot water at the top is less dense and remains at the top. Any heat that reaches the ice must be transferred by conduction, and we see that water is a poor conductor of heat. If you repeat the experiment, only this time holding the test tube at the top by means of tongs and heating the water from below while the ice floats at the surface, the ice will melt quickly. Heat gets to the top by convection, for the hot water rises to the surface, carrying its energy with it to the ice.

Convection occurs in all fluids, whether liquid or gas. Whether we heat water in a pan or heat air in a room, the process is the same. When the fluid is heated, it expands, becomes less dense, and rises. Warm air or warm water rises for the same reason that a block of wood floats in water and a helium-filled balloon rises in air. In effect,

Figure 22.5 ▲
When the test tube is heated at the top, convection is prevented and heat can reach the ice by conduction only. Since water is a poor conductor, the top water will boil without melting the ice.

Answers

1. Cold does not flow from the ice to your hand. Heat flows from your hand to the ice. The metal is cold to your touch because you are transferring heat to the metal.
2. Fiberglass is a good insulator, many times better than glass, because of the air that is trapped among its fibers.
3. Air is a poor conductor, so the rate of heat flow from the hot air to your relatively cool hand is low. But touching the metal parts is a different story. Metal conducts heat very well, and a lot of heat in a short time is conducted into your hand when thermal contact is made.

1 Explore **2 Develop** **3 Apply**
1 Laboratory Manual *52*

DOING PHYSICS

Watching Convection

After bringing a beaker full of water to a boil, drop a small amount of dark dye or food coloring into the water. You'll see that it disperses very rapidly. Watch the flow of the dye carefully. Can you see that it follows the convection flow? Light a match and then blow it out. Hold the match still and observe the smoke trail. In what direction does the smoke travel? Is the smoke's trail an example of convection? Explain. Where else can you see the paths of convection? How about in the air over a hot stove?

Activity

convection is an application of Archimedes' principle, for the warmer fluid is buoyed upward by denser surrounding fluid. Cooler fluid then moves to the bottom, and the process continues. In this way, convection currents keep a fluid stirred up as it heats.

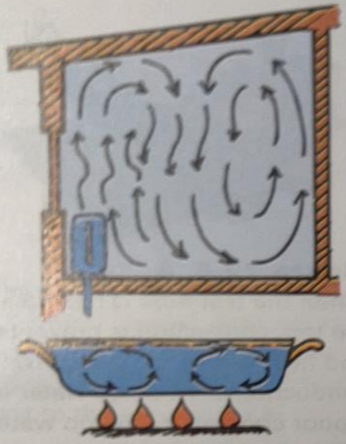


Figure 22.6 ▲
(Top) Convection currents in air. (Bottom) Convection currents in liquid.

Winds

Convection currents stirring the atmosphere produce winds. Some parts of Earth's surface absorb heat from the sun more readily than others. The uneven absorption causes uneven heating of the air near the surface and creates convection currents. This phenomenon is often evident at the seashore. In the daytime the shore warms more easily than the water. Air over the shore rises, and cooler air from above the water takes its place. The result is a sea breeze (Figure 22.7).

At night the process reverses as the shore cools off more quickly than the water—the warmer air is now over the sea. If you build a fire on the beach you'll notice that the smoke sweeps inward in the day and seaward at night.

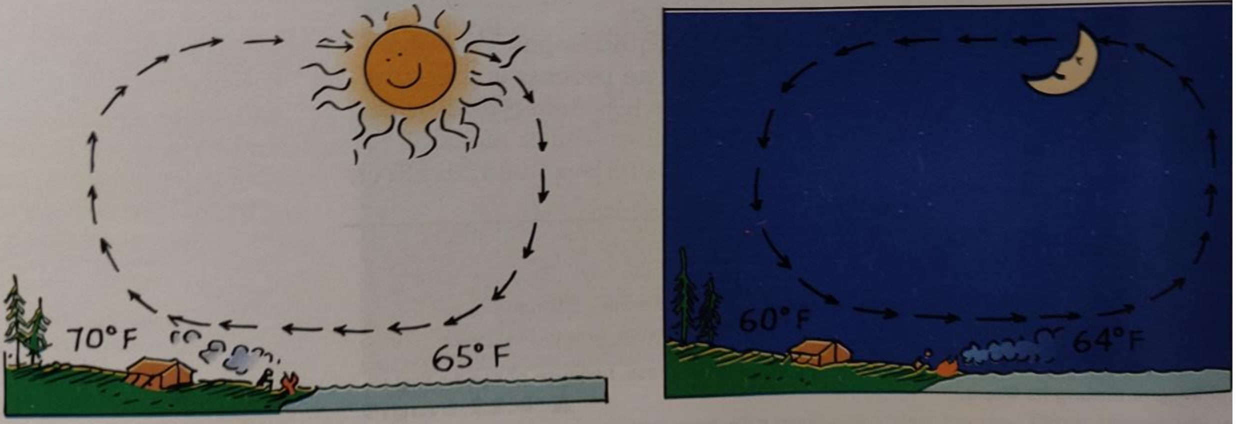


Figure 22.7 ▲
Convection currents are produced by uneven heating. The land is warmer than the water in the day and cooler than the water at night, so the direction of air flow reverses from day to night.

DOING PHYSICS

Cool Hand

With your mouth open wide, blow on your hand. Notice that your breath is warm. Now pucker your lips to make a small opening with your mouth and blow on your hand again. Does the temperature of the air on your hand feel the same? In which case does your exhaled breath expand more—when blowing with your mouth open wide or when blowing with your lips puckered? When did the air on your hand feel cooler? Why?

Activity

Why Rising Warm Air Cools

Rising warm air, like a rising balloon, expands. Why? Because less atmospheric pressure squeezes on it at higher altitudes. As the air expands, it cools—just the opposite of what happens when air is compressed. If you've ever compressed air with a tire pump, you probably noticed that the air and pump became quite hot. The opposite happens when air expands. Expanding air cools.

We can understand the cooling of expanding air by thinking of molecules of air as tiny balls bouncing against one another. Speed is picked up by a ball when it is hit by another that approaches with a greater speed. But when a ball collides with one that is receding, its rebound speed is reduced (Figure 22.8). Likewise for a Ping-Pong ball moving toward a paddle; it picks up speed when it hits an approaching paddle, but loses speed when it hits a receding paddle. The same idea applies to a region of air that is expanding; molecules collide, on the average, with more molecules that are receding than are approaching (Figure 22.9). Thus, in expanding air, the average speed of the molecules decreases and the air cools.*

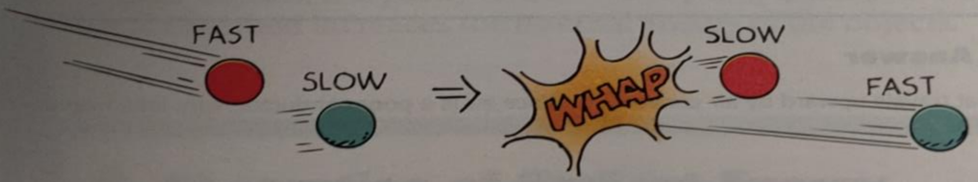


Figure 22.8 ▲
When a molecule collides with a target molecule that is receding, its rebound speed after the collision is less than it was before the collision.

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[*] Where does the energy go in this case? We will see in Chapter 24 that it goes into work done on the surrounding air as the expanding air pushes outward.

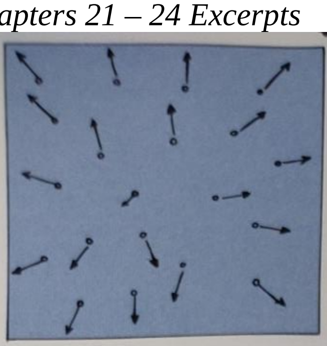


Figure 22.9 ▲ Molecules in a region of expanding air collide more often with receding molecules than with approaching ones. Their rebound speeds therefore tend to decrease and, as a result, the expanding air cools.

Question

You can hold your fingers beside the candle flame without harm, but not above the flame. Why?

22.3 Radiation

Heat from the sun is able to pass through the atmosphere and warm Earth's surface. This heat does not pass through the atmosphere by conduction, for air is one of the poorest conductors. Nor does it pass through by convection, for convection begins only after Earth is warmed. We also know that neither convection nor conduction is possible in the empty space between our atmosphere and the sun. The sun's heat is transmitted by another process—**radiation.***

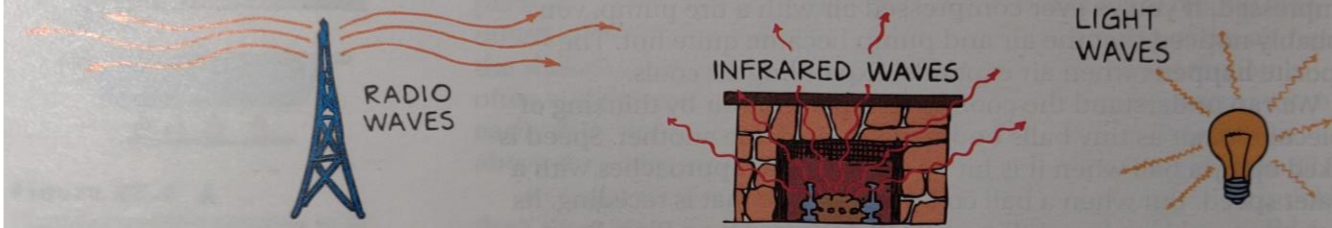


Figure 22.10 ▲ Types of radiant energy (electromagnetic waves).

Any energy, including heat, that is transmitted by radiation is called **radiant energy.** Radiant energy is in the form of *electromagnetic waves.* It includes radio waves, microwaves, infrared radiation, visible light, ultraviolet radiation, X-rays, and gamma rays. These types of radiant energy are listed in order of wavelength, from longest to shortest.**

Answer

Heat travels upward by air convection. Since air is a poor conductor, very little heat travels sideways.

---

* The word *radiation* has more than one meaning. Do not confuse heat radiation with radioactive radiation, which is given off by the nuclei of radioactive atoms such as uranium and radium.

** Infrared (below-the-red) radiation has longer wavelengths than those of visible light. The longest visible wavelengths are for red light, and the shortest are for violet light. Ultraviolet (beyond-the-violet) radiation has shorter wavelengths. (More on wavelength in Chapter 25, and electromagnetic waves in Chapters 27 and 37.)

DOING PHYSICS

Blocking Infrared Radiation

Sit close to a fire in a fireplace and feel the heat on your closed eyelids. The heat you feel is from infrared radiation, for most of the air that is heated goes up the chimney. Your eyelids are very sensitive to infrared rays. Now slip a pair of glasses over your eyes and your eyes cool—instant relief. Why? The glass or plastic lenses transmit the visible waves, allowing you to see the fire, but they absorb the infrared waves, thus blocking the heat from the fire.

Activity

All objects continually emit radiant energy in a mixture of wavelengths. Objects at low temperatures emit long waves, just as long, lazy waves are produced when you shake a rope with little energy (Figure 22.11, top). Higher-temperature objects emit waves of shorter wavelengths. Objects of everyday temperatures emit waves mostly in the long-wavelength end of the infrared region, which is between radio and light waves. Shorter-wavelength infrared waves absorbed by our skin produce the sensation of heat. Thus, when we speak of heat radiation, we are speaking of infrared radiation.

If an object is hot enough, some of the radiant energy it emits is in the range of visible light. At a temperature of about 500°C an object begins to emit the longest waves we can see, red light. Higher temperatures produce a yellowish light. At about 1200°C all the different waves to which the eye is sensitive are emitted and we see an object as "white hot."

Common sources that give the sensation of heat are the burning embers in a fireplace, a lamp filament, and the sun. All of these emit both infrared radiation and visible light. When this radiant energy falls on other objects, it is partly reflected and partly absorbed. The part that is absorbed increases the internal energy of the objects.

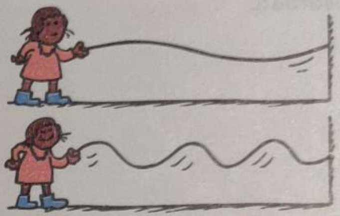
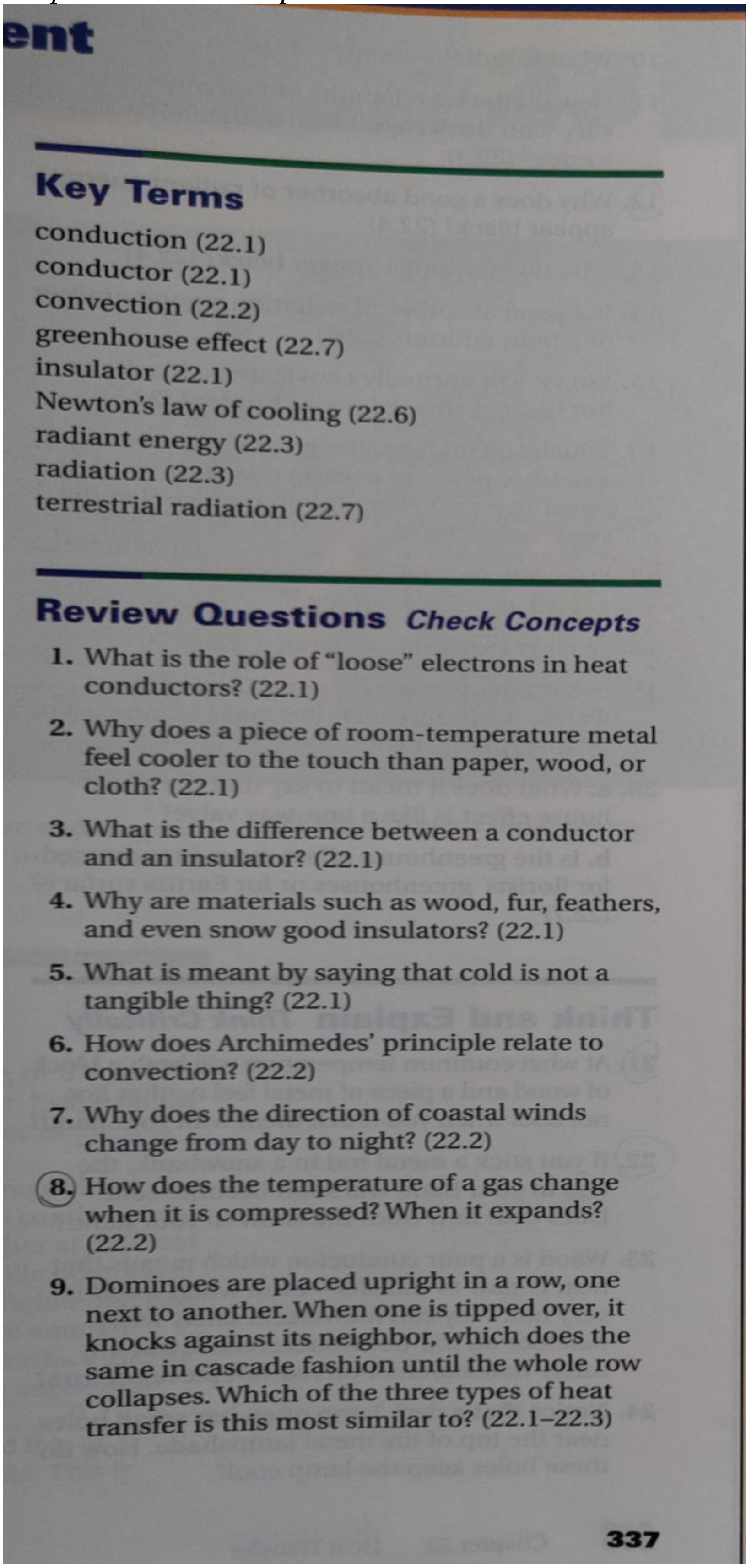


Figure 22.11 ▲
Shorter wavelengths are produced when the rope is shaken more rapidly.

Figure 22.12 ▲
Most of the heat from a fireplace goes up the chimney by convection. The heat that warms us comes to us by radiation.

22.4 Absorption of Radiant Energy

Absorption and reflection are opposite processes. Therefore, a good absorber of radiant energy reflects very little radiant energy, including the range of radiant energy we call light. So a good absorber appears dark. A perfect absorber reflects no radiant energy and appears perfectly black. The pupil of the eye, for example, allows



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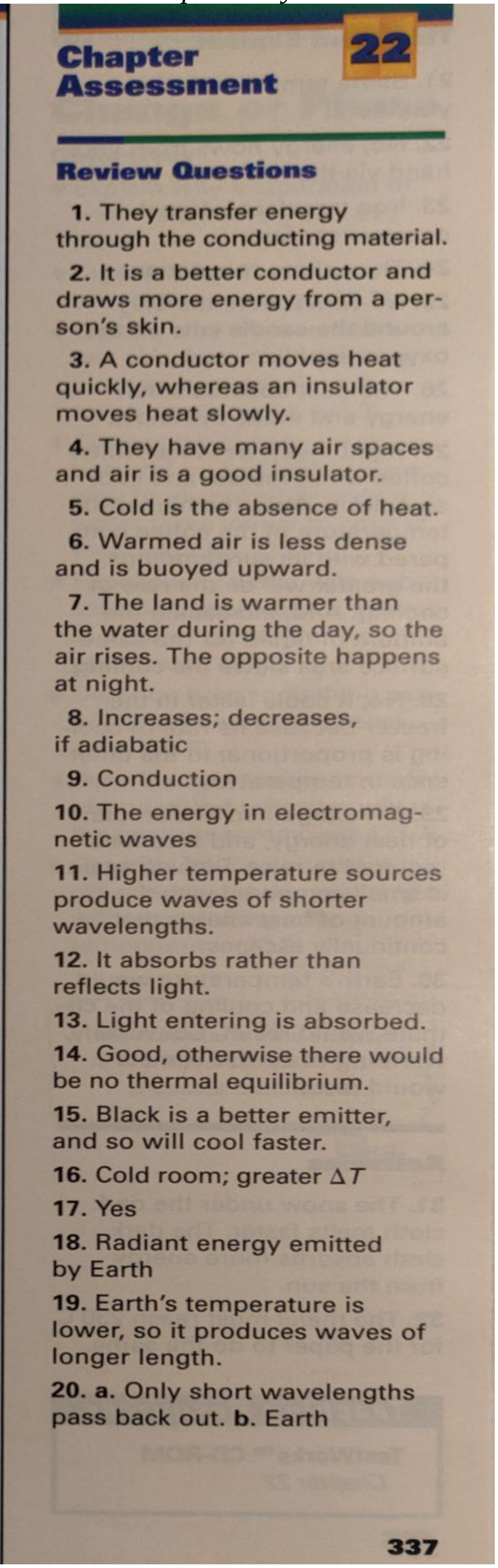
Key Terms

conduction (22.1)
conductor (22.1)
convection (22.2)
greenhouse effect (22.7)
insulator (22.1)
Newton's law of cooling (22.6)
radiant energy (22.3)
radiation (22.3)
terrestrial radiation (22.7)

Review Questions *Check Concepts*

1. What is the role of "loose" electrons in heat conductors? (22.1)
2. Why does a piece of room-temperature metal feel cooler to the touch than paper, wood, or cloth? (22.1)
3. What is the difference between a conductor and an insulator? (22.1)
4. Why are materials such as wood, fur, feathers, and even snow good insulators? (22.1)
5. What is meant by saying that cold is not a tangible thing? (22.1)
6. How does Archimedes' principle relate to convection? (22.2)
7. Why does the direction of coastal winds change from day to night? (22.2)
8. How does the temperature of a gas change when it is compressed? When it expands? (22.2)
9. Dominoes are placed upright in a row, one next to another. When one is tipped over, it knocks against its neighbor, which does the same in cascade fashion until the whole row collapses. Which of the three types of heat transfer is this most similar to? (22.1–22.3)



Chapter Assessment 22

Review Questions

1. They transfer energy through the conducting material.

2. It is a better conductor and draws more energy from a person's skin.

3. A conductor moves heat quickly, whereas an insulator moves heat slowly.

4. They have many air spaces and air is a good insulator.

5. Cold is the absence of heat.

6. Warmed air is less dense and is buoyed upward.

7. The land is warmer than the water during the day, so the air rises. The opposite happens at night.

8. Increases; decreases, if adiabatic

9. Conduction

10. The energy in electromagnetic waves

11. Higher temperature sources produce waves of shorter wavelengths.

12. It absorbs rather than reflects light.

13. Light entering is absorbed.

14. Good, otherwise there would be no thermal equilibrium.

15. Black is a better emitter, and so will cool faster.

16. Cold room; greater ΔT

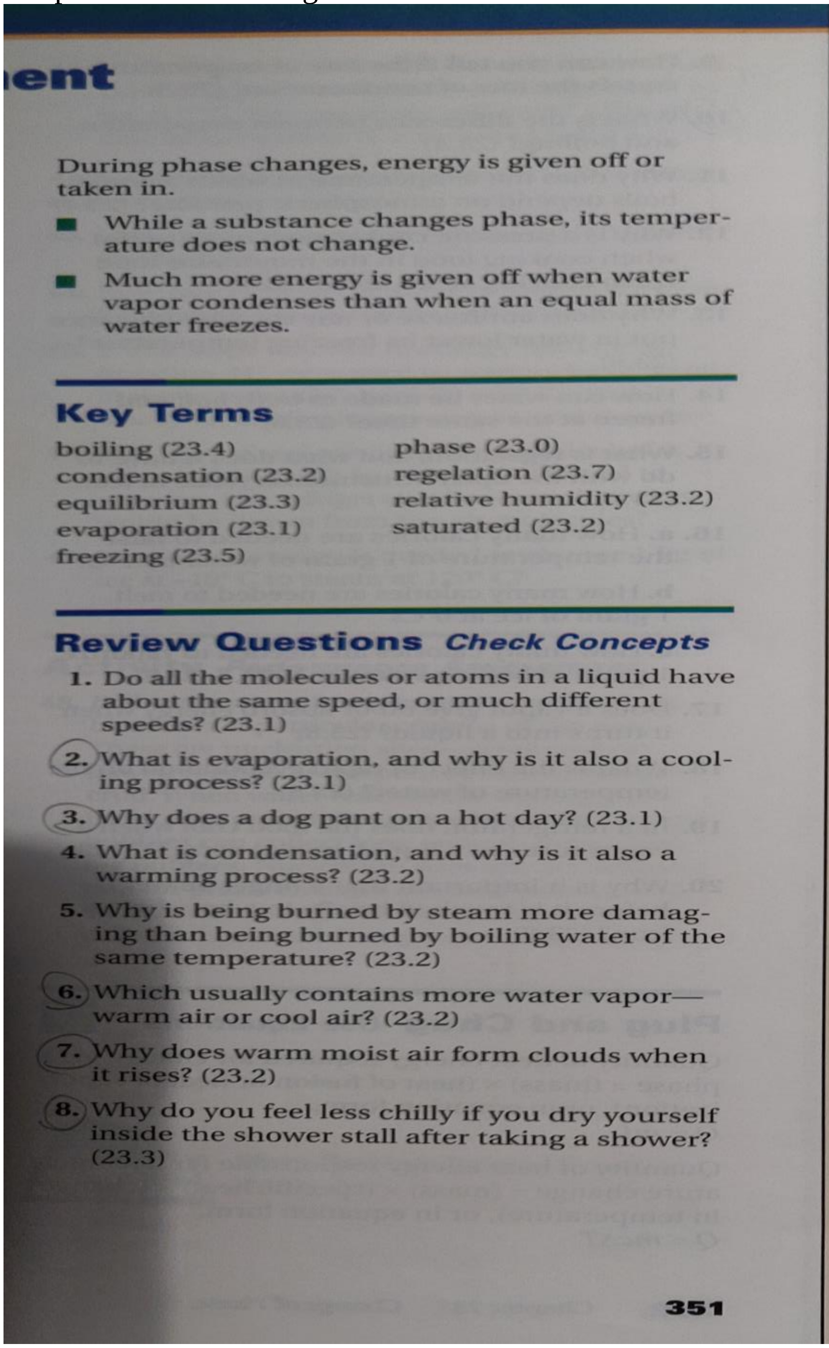
17. Yes

18. Radiant energy emitted by Earth

19. Earth's temperature is lower, so it produces waves of longer length.

20. a. Only short wavelengths pass back out. **b.** Earth

Chapter 23 Phase Changes



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During phase changes, energy is given off or taken in.

- While a substance changes phase, its temperature does not change.
- Much more energy is given off when water vapor condenses than when an equal mass of water freezes.

Key Terms

boiling (23.4)	phase (23.0)
condensation (23.2)	regelation (23.7)
equilibrium (23.3)	relative humidity (23.2)
evaporation (23.1)	saturated (23.2)
freezing (23.5)	

Review Questions *Check Concepts*

1. Do all the molecules or atoms in a liquid have about the same speed, or much different speeds? (23.1)
2. What is evaporation, and why is it also a cooling process? (23.1)
3. Why does a dog pant on a hot day? (23.1)
4. What is condensation, and why is it also a warming process? (23.2)
5. Why is being burned by steam more damaging than being burned by boiling water of the same temperature? (23.2)
6. Which usually contains more water vapor—warm air or cool air? (23.2)
7. Why does warm moist air form clouds when it rises? (23.2)
8. Why do you feel less chilly if you dry yourself inside the shower stall after taking a shower? (23.3)

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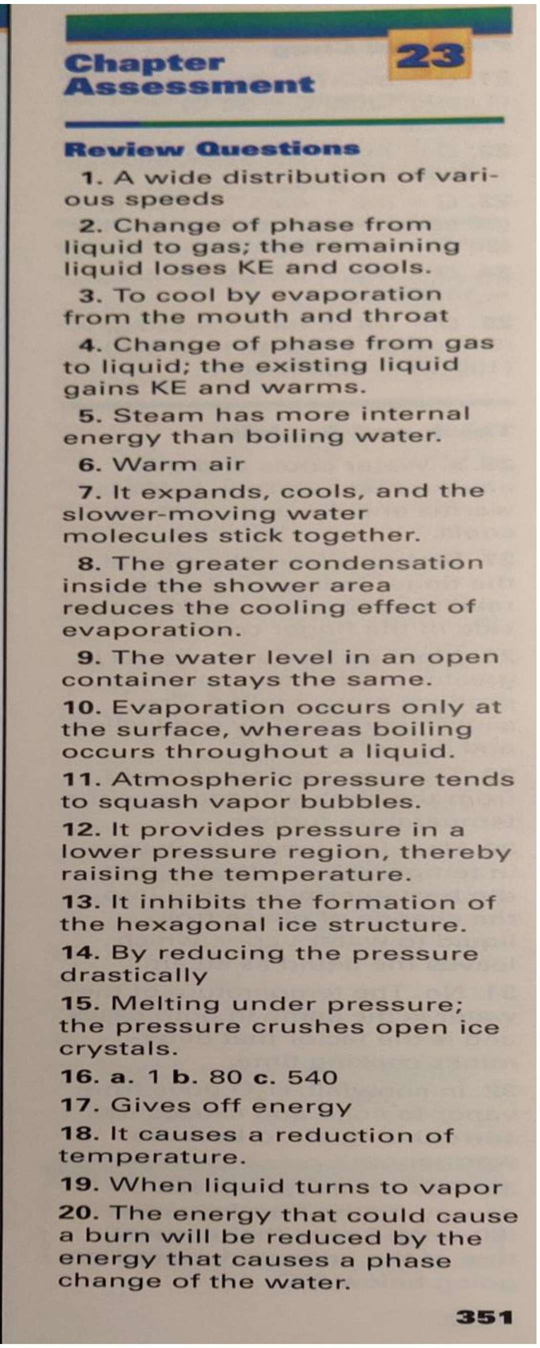

Chapter Assessment 23

Review Questions

1. A wide distribution of various speeds

2. Change of phase from liquid to gas; the remaining liquid loses KE and cools.

3. To cool by evaporation from the mouth and throat

4. Change of phase from gas to liquid; the existing liquid gains KE and warms.

5. Steam has more internal energy than boiling water.

6. Warm air

7. It expands, cools, and the slower-moving water molecules stick together.

8. The greater condensation inside the shower area reduces the cooling effect of evaporation.

9. The water level in an open container stays the same.

10. Evaporation occurs only at the surface, whereas boiling occurs throughout a liquid.

11. Atmospheric pressure tends to squash vapor bubbles.

12. It provides pressure in a lower pressure region, thereby raising the temperature.

13. It inhibits the formation of the hexagonal ice structure.

14. By reducing the pressure drastically

15. Melting under pressure; the pressure crushes open ice crystals.

16. **a.** 1 **b.** 80 **c.** 540

17. Gives off energy

18. It causes a reduction of temperature.

19. When liquid turns to vapor

20. The energy that could cause a burn will be reduced by the energy that causes a phase change of the water.

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Figure 24.3 ▲
Do work on the pump by pressing down on the piston and you compress the air inside. Adiabatic compression—the air is warmed.

24.3 Adiabatic Processes

The process of compression or expansion of a gas so that no heat enters or leaves a system is said to be **adiabatic** (Greek for "impassible"). Adiabatic changes of volume can be achieved by performing the process rapidly so that heat has little time to enter or leave (as with a bicycle pump), or by thermally insulating a system from its surroundings (with Styrofoam, for example).

A common example of a near adiabatic process is the compression and expansion of gases in the cylinders of an automobile engine (Figure 24.4). Compression and expansion occur in only a few hundredths of a second, too short a time for appreciable heat energy to leave the combustion chamber. For very high compressions, like those in a diesel engine, the temperatures achieved are high enough to ignite a fuel mixture without the use of a spark plug. Diesel engines have no spark plugs.

So when work is done on a gas by adiabatically compressing it, the gas gains internal energy and becomes warmer. When a gas adiabatically expands, it does work on its surroundings and gives up internal energy, and thus becomes cooler. Recall the activity in Chapter 22 of blowing on your hand with puckered lips so your breath expands as it leaves your mouth (repeated here in Figure 24.5). Your breath is considerably cooler than when blown from your wide-open mouth without expanding.

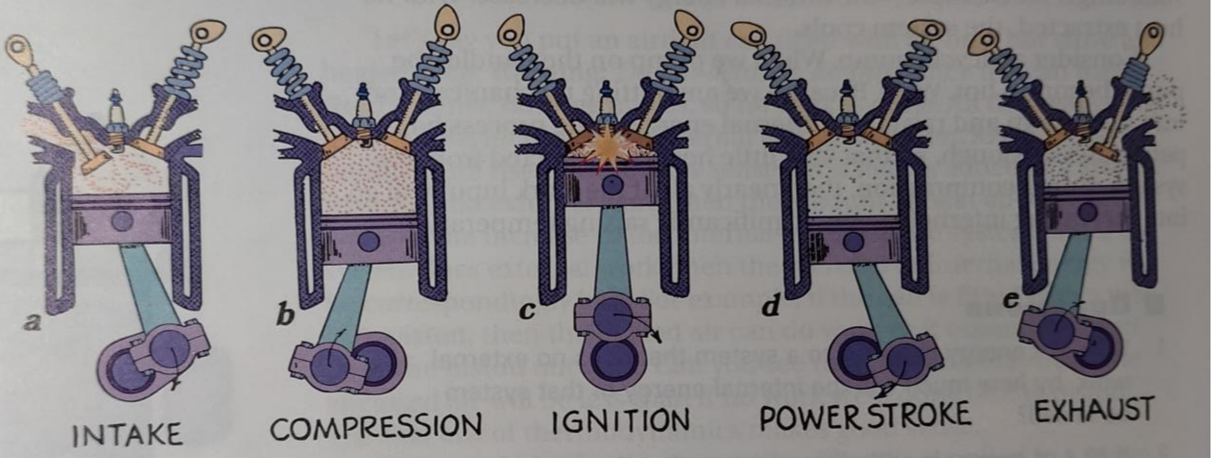

Figure 24.4 ▲
One cycle of a four-stroke internal combustion engine. (a) A fuel-air mixture fills the cylinder as the piston moves down. (b) The piston moves up and compresses the mixture—adiabatically, since no heat transfer occurs. (c) The spark plug fires, ignites the mixture, and raises its temperature. (d) Adiabatic expansion pushes the piston downward—the power stroke. (e) The burned gases are pushed out the exhaust valve, and the cycle repeats.

Air temperature may be changed by adding or subtracting heat, by changing the pressure of the air, or by both. Heat may be added by solar radiation, by long-wave Earth radiation, by moisture condensation, or by contact with the warm ground. Heat may be subtracted by radiation to space, by evaporation of rain falling through dry air, or by contact with cold surfaces.

There are many atmospheric processes, usually involving time scales of a day or less, in which the amount of heat added or subtracted is very small—small enough that the process is nearly adiabatic. We then have the adiabatic form of the first law:

Change in air temperature ~ pressure change

Adiabatic processes in the atmosphere occur in large masses of air that have dimensions on the order of kilometers. We'll call these large masses of air *blobs*. Due to their large size, mixing of different temperatures or pressures of air occurs only at their edges and doesn't appreciably alter the overall composition of the blobs. A blob behaves as if it were enclosed in a giant, tissue-light garment bag. As a blob of air flows up the side of a mountain, its pressure lessens, allowing it to expand and cool. The reduced pressure results in reduced temperature. Measurements show that the temperature of a blob of dry air drops by 10°C for each 1-kilometer increase in altitude (or for a decrease in pressure due to a 1-kilometer increase in altitude). So dry air cools 10°C for each kilometer it rises (Figure 24.6). Air flowing over tall mountains or rising in thunderstorms or cyclones may change elevation by several kilometers. So if a blob of dry air at ground level with a comfortable temperature of 25°C rose to 6 kilometers, its temperature would be a frigid –35°C. On the other hand, if air at a typical temperature of –20°C at an altitude of 6 kilometers descended to the ground, its temperature would be a roasting 40°C.

A dramatic example of this adiabatic warming is the *chinook*—a wind that blows down from the Rocky Mountains across the Great Plains. Cold air moving down the slopes of the mountains is compressed by the atmosphere into a smaller volume and is appreciably

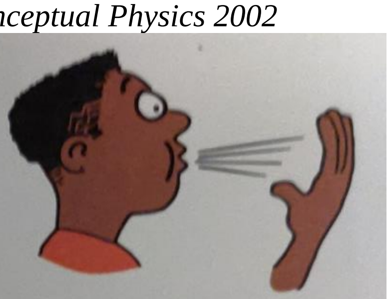

Figure 24.5 ▲ Blow warm air onto your hand from your wide-open mouth. Now reduce the opening between your lips so the air expands as you blow. Adiabatic expansion—the air is cooled.

Questions

1. If a blob of air initially at 0°C expands adiabatically while flowing upward alongside a mountain a vertical distance of 1 km, what will its temperature be? When it has risen 5 km?
2. Imagine a giant dry-cleaner's garment bag full of air at a temperature of –10°C floating like a balloon with a string hanging from it 6 km above the ground. If you were able to yank it suddenly to the ground, what would its approximate temperature be?

Answers

1. At 1-km elevation, its temperature will be –10°C; at 5 km, –50°C.
2. If it were pulled down so quickly that heat conduction was negligible, it would be adiabatically compressed by the atmosphere and its temperature would rise to a piping hot 50°C (122°F), just as compressed air gets hot in a bicycle pump.

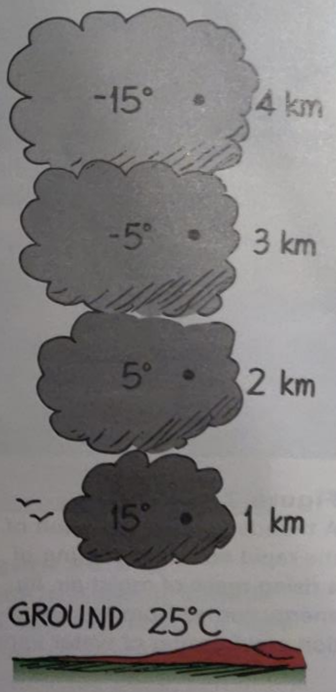

Figure 24.6 ▲ The temperature of a blob of dry air that expands adiabatically changes by about 10°C for each kilometer of elevation.

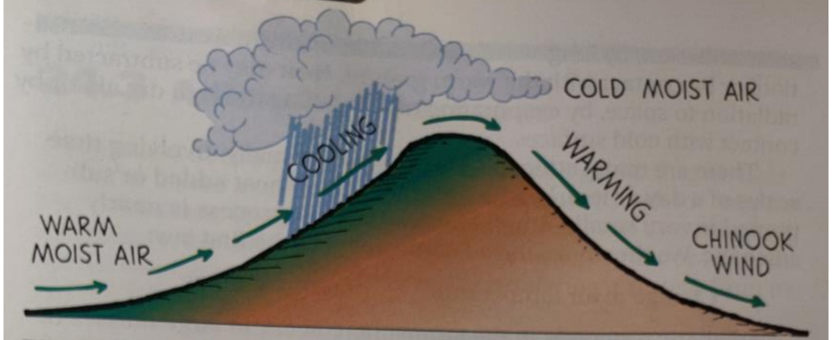

Figure 24.7 ▲
Chinooks, warm dry winds, occur when high-altitude air descends and is adiabatically warmed.

warmed. In this way communities in the paths of chinooks experience relatively warm weather in midwinter. The effect of expansion or compression on gases is quite impressive.*

24.4 Second Law of Thermodynamics

If we place a hot brick next to a cold brick, the hot brick will cool as heat flows to the cold brick. The cold brick will warm and the hot brick will cool until both bricks arrive at a common temperature: thermal equilibrium. No energy will be destroyed, in accord with the first law of thermodynamics. But pretend the hot brick takes heat from the cold brick and becomes hotter. Would this violate the first law of thermodynamics? Not if the cold brick becomes correspondingly colder so that the total energy of both bricks remains the same. This would not violate the first law, but it would violate the second law of thermodynamics. The second law tells us the direction of heat flow in natural processes. The **second law of thermodynamics** can be stated in many ways, but most simply it is this:

> Heat will never of itself flow from a cold object to a hot object.

Heat flows one way, downhill from hot to cold. In winter, heat flows from inside a warm heated home to the cold air outside. In summer, heat flows from the hot air outside into the cooler interior. The direction of heat flow is from hot to cold. Heat can be made to flow the other way, but only by imposing external effort—as occurs

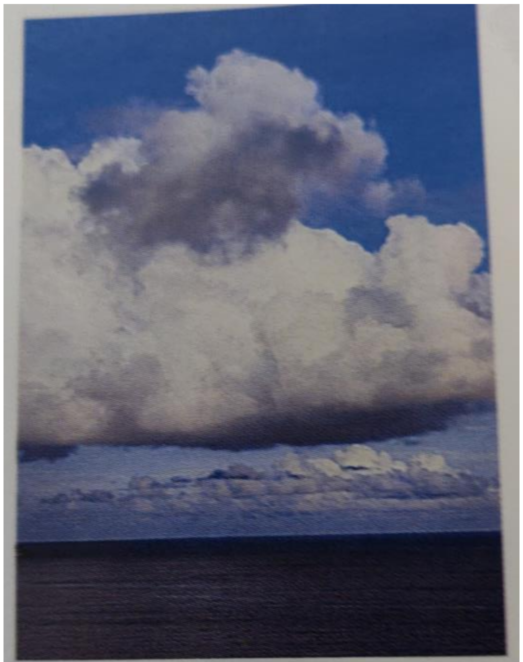

Figure 24.8 ▲
A thunderhead is the result of the rapid adiabatic cooling of a rising mass of moist air. Its energy comes from condensation and freezing of water vapor.

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* Interestingly enough, when you're flying at high altitudes where outside air temperature is typically −35°C, you're quite comfortable in your warm cabin—but not because The process of compressing outside air to near sea-level cabin pressure