? At a steelworks, molten iron is heated to 1500° Celsius to remove impurities. It is most accurate to say that the molten iron contains a large amount of (i) temperature; (ii) heat; (iii) energy; (iv) two of these; (v) all three of these.

17 Temperature and Heat

Whether it's a sweltering summer day or a frozen midwinter night, your body needs to be kept at a nearly constant temperature. It has effective temperature-control mechanisms, but sometimes it needs help. On a hot day you wear less clothing to improve heat transfer from your body to the air and for better cooling by evaporation of perspiration. On a cold day you may sit by a roaring fire to absorb the energy that it radiates. The concepts in this chapter will help you understand the basic physics of keeping warm or cool.

The terms "temperature" and "heat" are often used interchangeably in everyday language. In physics, however, these two terms have very different meanings. In this chapter we'll define temperature in terms of how it's measured and see how temperature changes affect the dimensions of objects. We'll see that heat refers to energy transfer caused by temperature differences only and learn how to calculate and control such energy transfers.

Our emphasis in this chapter is on the concepts of temperature and heat as they relate to *macroscopic* objects such as cylinders of gas, ice cubes, and the human body. In Chapter 18 we'll look at these same concepts from a *microscopic* viewpoint in terms of the behavior of individual atoms and molecules. These two chapters lay the groundwork for the subject of **thermodynamics,** the study of energy transformations involving heat, mechanical work, and other aspects of energy and how these transformations relate to the properties of matter. Thermodynamics forms an indispensable part of the foundation of physics, chemistry, and the life sciences, and its applications turn up in such places as car engines, refrigerators, biochemical processes, and the structure of stars. We'll explore the key ideas of thermodynamics in Chapters 19 and 20.

LEARNING OUTCOMES

In this chapter, you'll learn...

- **17.1** The meaning of thermal equilibrium, and what thermometers really measure.
- **17.2** How different types of thermometers function.
- **17.3** The physics behind the absolute, or Kelvin, temperature scale.
- **17.4** How the dimensions of an object change as a result of a temperature change.
- **17.5** The meaning of heat, and how it differs from temperature.
- **17.6** How to do calculations that involve heat flow, temperature changes, and changes of phase.
- **17.7** How heat is transferred by conduction, convection, and radiation.

You'll need to review...

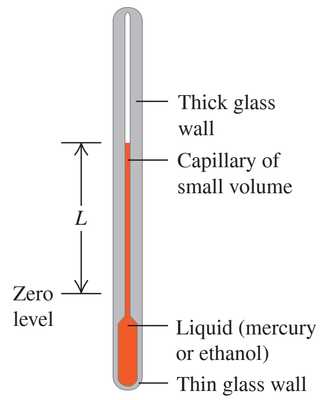
- **11.4** Stress and strain.
- **12.2** Measuring pressure.
- **14.4** Spring forces and interatomic forces.

17.1 TEMPERATURE AND THERMAL EQUILIBRIUM

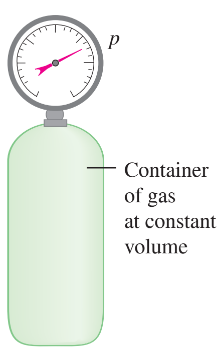
The concept of **temperature** is rooted in qualitative ideas based on our sense of touch. An object that feels "hot" usually has a higher temperature than a similar object that feels "cold." That's pretty vague, and the senses can be deceived. But many properties of matter that we can *measure*—including the length of a metal rod, steam pressure in a boiler, the ability of a wire to conduct an electric current, and the color of a very hot glowing object—depend on temperature.

Figure **17.1** Two devices for measuring temperature.

(a) Changes in temperature cause the liquid's volume to change.



(b) Changes in temperature cause the pressure of the gas to change.



Temperature is also related to the kinetic energies of the molecules of a material. In general this relationship is fairly complex, so it's not a good place to start in *defining* temperature. In Chapter 18 we'll look at the relationship between temperature and the energy of molecular motion for an ideal gas. However, we can define temperature and heat independently of any detailed molecular picture. In this section we'll develop a *macroscopic* definition of temperature.

To use temperature as a measure of hotness or coldness, we need to construct a temperature scale. To do this, we can use any measurable property of a system that varies with its "hotness" or "coldness." **Figure 17.1a** shows a familiar system that is used to measure temperature. When the system becomes hotter, the colored liquid (usually mercury or ethanol) expands and rises in the tube, and the value of L increases. Another simple system is a quantity of gas in a constant-volume container (Fig. 17.1b). The pressure p, measured by the gauge, increases or decreases as the gas becomes hotter or colder. A third example is the electrical resistance R of a conducting wire, which also varies when the wire becomes hotter or colder. Each of these properties gives us a number (L, p, or R) that varies with hotness and coldness, so each property can be used to make a **thermometer.**

To measure the temperature of an object, you place the thermometer in contact with the object. If you want to know the temperature of a cup of hot coffee, you stick the thermometer in the coffee; as the two interact, the thermometer becomes hotter and the coffee cools off a little. After the thermometer settles down to a steady value, you read the temperature. The system has reached an *equilibrium* condition, in which the interaction between the thermometer and the coffee causes no further change in the system. We call this a state of **thermal equilibrium.**

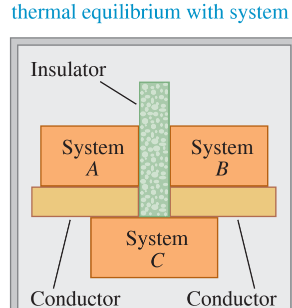
If two systems are separated by an insulating material or **insulator** such as wood, plastic foam, or fiberglass, they influence each other more slowly. Camping coolers are made with insulating materials to delay the cold food inside from warming up and attaining thermal equilibrium with the hot summer air outside. An *ideal insulator* is an idealized material that permits no interaction at all between the two systems. It prevents the systems from attaining thermal equilibrium if they aren't in thermal equilibrium at the start. Real insulators, like those in camping coolers, aren't ideal, so the contents of the cooler will warm up eventually. But an ideal insulator is nonetheless a useful idealization, like a massless rope or a frictionless incline.

The Zeroth Law of Thermodynamics

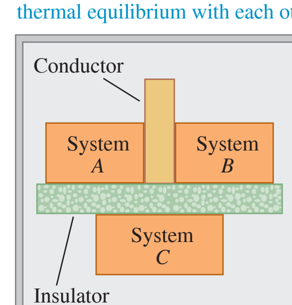
We can discover an important property of thermal equilibrium by considering three systems, A, B, and C, that initially are not in thermal equilibrium (**Fig. 17.2**). We surround them with an ideal insulating box so that they cannot interact with anything except each other. We separate systems A and B with an ideal insulating wall (the green slab in Fig. 17.2a), but we let system C interact with both systems A and B. We show this interaction in the figure by a yellow slab representing a thermal **conductor,** a material that *permits* thermal interactions through it. We wait until thermal equilibrium is attained; then A and B are each in thermal equilibrium with C. But are they in thermal equilibrium *with each other?*

Figure **17.2** The zeroth law of thermodynamics.

(a) If systems A and B are each in thermal equilibrium with system C ...



(b) ... then systems A and B are in thermal equilibrium with each other.



To find out, we separate system C from systems A and B with an ideal insulating wall (Fig. 17.2b), then replace the insulating wall between A and B with a *conducting* wall that lets A and B interact. What happens? Experiment shows that *nothing* happens; there are no additional changes to A or B. We can summarize this result as follows:

ZEROTH LAW OF THERMODYNAMICS If C is initially in thermal equilibrium with both A and B, then A and B are also in thermal equilibrium with each other.

(The importance of the zeroth law was recognized only after the first, second, and third laws of thermodynamics had been named. Since it is fundamental to all of them, the name "zeroth" seemed appropriate. We'll learn about the other laws of thermodynamics in Chapters 19 and 20.)

Now suppose system C is a thermometer, such as the liquid-in-tube system of Fig. 17.1a. In Fig. 17.2a the thermometer C is in contact with both A and B. In thermal equilibrium, when the thermometer reading reaches a stable value, the thermometer measures the temperature of both A and B; hence both A and B have the *same* temperature. Experiment shows that thermal equilibrium isn't affected by adding or removing insulators, so the reading of thermometer C wouldn't change if it were in contact only with A or only with B. We conclude:

CONDITION FOR THERMAL EQUILIBRIUM Two systems are in thermal equilibrium if and only if they have the same temperature.

This is what makes a thermometer useful; a thermometer actually measures *its own* temperature, but when a thermometer is in thermal equilibrium with another object, the temperatures must be equal. When the temperatures of two systems are different, they *cannot* be in thermal equilibrium.

TEST YOUR UNDERSTANDING OF SECTION 17.1 You put a thermometer in a pot of hot water and record the reading. What temperature have you recorded? (i) The temperature of the water; (ii) the temperature of the thermometer; (iii) an equal average of the temperatures of the water and thermometer; (iv) a weighted average of the temperatures of the water and thermometer, with more emphasis on the temperature of the water; (v) a weighted average of the water and thermometer, with more emphasis on the temperature of the thermometer.

ANSWER

(ii) A liquid-in-tube thermometer actually measures its own temperature. If the thermometer stays in the hot water long enough, it will come to thermal equilibrium with the water and its temperature will be the same as that of the water.

17.2 THERMOMETERS AND TEMPERATURE SCALES

To make the liquid-in-tube device shown in Fig. 17.1a into a useful thermometer, we need to mark a scale on the tube wall with numbers on it. Suppose we label the thermometer's liquid level at the freezing temperature of pure water "zero" and the level at the boiling temperature "100," and divide the distance between these two points into 100 equal intervals called *degrees*. The result is the **Celsius temperature scale** (formerly called the *centigrade* scale in English-speaking countries). The Celsius temperature for a state colder than freezing water is a negative number. The Celsius scale is used, both in everyday life and in science and industry, almost everywhere in the world.

Another common type of thermometer uses a *bimetallic strip,* made by bonding strips of two different metals together (**Fig. 17.3a**). When the temperature of the composite strip increases, one metal expands more than the other and the strip bends (Fig. 17.3b). This strip is usually formed into a spiral, with the outer end anchored to the thermometer case and the inner end attached to a pointer (Fig. 17.3c). The pointer rotates in response to temperature changes.

Figure 17.3 Use of a bimetallic strip as a thermometer.

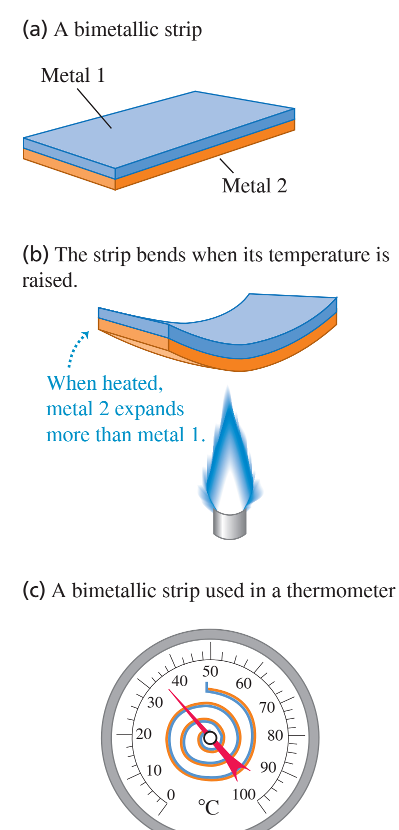


Figure **17.4** A temporal artery thermometer measures infrared radiation from the skin that overlies one of the important arteries in the head. Although the thermometer cover touches the skin, the infrared detector inside the cover does not.

In a *resistance thermometer* the changing electrical resistance of a coil of fine wire, a carbon cylinder, or a germanium crystal is measured. Resistance thermometers are usually more precise than most other types.

Some thermometers detect the amount of infrared radiation emitted by an object. (We'll see in Section 17.7 that *all* objects emit electromagnetic radiation, including infrared, as a consequence of their temperature.) One example is a *temporal artery thermometer* (**Fig. 17.4**). A nurse runs this over a patient's forehead in the vicinity of the temporal artery, and an infrared sensor in the thermometer measures the radiation from the skin. This device gives more accurate values of body temperature than do oral or ear thermometers.

In the **Fahrenheit temperature scale,** still used in the United States, the freezing temperature of water is 32°F and the boiling temperature is 212°F, both at standard atmospheric pressure. There are 180 degrees between freezing and boiling, compared to 100 on the Celsius scale, so one Fahrenheit degree represents only $\frac{100}{180}$, or $\frac{5}{9}$, as great a temperature change as one Celsius degree.

To convert temperatures from Celsius to Fahrenheit, note that a Celsius temperature T_C is the number of Celsius degrees above freezing; the number of Fahrenheit degrees above freezing is $\frac{9}{5}$ of this. But freezing on the Fahrenheit scale is at 32°F, so to obtain the actual Fahrenheit temperature T_F, multiply the Celsius value by $\frac{9}{5}$ and then add 32°. Symbolically,

$$\underset{\text{Fahrenheit temperature}}{T_F} = \tfrac{9}{5}\underset{\text{Celsius temperature}}{T_C} + 32^\circ \qquad (17.1)$$

To convert Fahrenheit to Celsius, solve this equation for T_C:

$$\underset{\text{Celsius temperature}}{T_C} = \tfrac{5}{9}\left(\underset{\text{Fahrenheit temperature}}{T_F} - 32^\circ\right) \qquad (17.2)$$

In words, subtract 32° to get the number of Fahrenheit degrees above freezing, and then multiply by $\frac{5}{9}$ to obtain the number of Celsius degrees above freezing—that is, the Celsius temperature.

We don't recommend memorizing Eqs. (17.1) and (17.2). Instead, understand the reasoning that led to them so that you can derive them on the spot when you need them, checking your reasoning with the relationship 100°C = 212°F.

It is useful to distinguish between an actual temperature and a temperature *interval* (a difference or change in temperature). An actual temperature of 20° is stated as 20°C (twenty degrees Celsius), and a temperature *interval* of 15° is 15 C° (fifteen Celsius degrees). A beaker of water heated from 20°C to 35°C undergoes a temperature change of 15 C°.

CAUTION **Converting temperature differences** Keep in mind that Eqs. (17.1) and (17.2) apply to *temperatures,* not *temperature differences.* To convert a temperature difference in Fahrenheit degrees (F°) to one in Celsius degrees (C°), simply multiply by $\frac{5}{9}$; to convert a temperature difference in C° to one in F°, multiply by $\frac{9}{5}$.

TEST YOUR UNDERSTANDING OF SECTION 17.2 Which of the following types of thermometers have to be in thermal equilibrium with the object being measured in order to give accurate readings? (i) A bimetallic strip; (ii) a resistance thermometer; (iii) a temporal artery thermometer; (iv) both (i) and (ii); (v) all of (i), (ii), and (iii).

ANSWER

(iv) Both a bimetallic strip and a resistance thermometer measure their own temperature. For this to be equal to the temperature of the object being measured, the thermometer and object must be in thermal equilibrium. A temporal artery thermometer detects the infrared radiation from a person's skin; the detector and skin need not be at the same temperature.

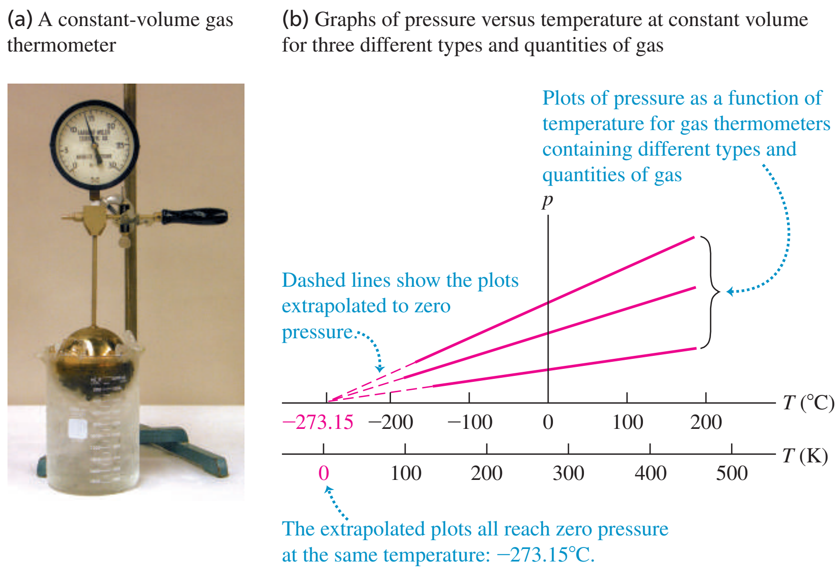


Figure **17.5** (a) Using a constant-volume gas thermometer to measure temperature. (b) The greater the amount of gas in the thermometer, the higher the graph of pressure p versus temperature T.

17.3 GAS THERMOMETERS AND THE KELVIN SCALE

When we calibrate two thermometers, such as a liquid-in-tube system and a resistance thermometer, so that they agree at 0°C and 100°C, they may not agree exactly at intermediate temperatures. Any temperature scale defined in this way always depends somewhat on the specific properties of the material used. Ideally, we would like to define a temperature scale that *doesn't* depend on the properties of a particular material. To establish a truly material-independent scale, we first need to develop some principles of thermodynamics. We'll return to this fundamental problem in Chapter 20. Here we'll discuss a thermometer that comes close to the ideal, the *constant-volume gas thermometer.*

The principle of a constant-volume gas thermometer is that the pressure of a gas at constant volume increases with temperature. We place a quantity of gas in a constant-volume container (**Fig. 17.5a**) and measure its pressure by one of the devices described in Section 12.2. To calibrate this thermometer, we measure the pressure at two temperatures, say 0°C and 100°C, plot these points on a graph, and draw a straight line between them. Then we can read from the graph the temperature corresponding to any other pressure. Figure 17.5b shows the results of three such experiments, each using a different type and quantity of gas.

By extrapolating this graph, we see that there is a hypothetical temperature, −273.15°C, at which the absolute pressure of the gas would become zero. This temperature turns out to be the *same* for many different gases (at least in the limit of very low gas density). We can't actually observe this zero-pressure condition. Gases liquefy and solidify at very low temperatures, and the proportionality of pressure to temperature no longer holds.

We use this extrapolated zero-pressure temperature as the basis for a temperature scale with its zero at this temperature. This is the **Kelvin temperature scale,** named for the British physicist Lord Kelvin (1824–1907). The units are the same size as those on the Celsius scale, but the zero is shifted so that $0\,\mathrm{K} = -273.15°\mathrm{C}$ and $273.15\,\mathrm{K} = 0°\mathrm{C}$ (Fig. 17.5b); that is,

$$\underbrace{T_K}_{\text{Kelvin temperature}} = \underbrace{T_C}_{\text{Celsius temperature}} + 273.15 \qquad (17.3)$$

A common room temperature, 20°C (= 68°F), is 20 + 273.15, or about 293 K.

CAUTION Never say "degrees kelvin" In SI nomenclature, the temperature mentioned above is read "293 kelvins," not "degrees kelvin" (**Fig. 17.6**). We capitalize Kelvin when it refers to the temperature scale; however, the *unit* of temperature is the *kelvin,* which is not capitalized (but is nonetheless abbreviated as a capital K).

BIO APPLICATION Mammalian Body Temperatures Most mammals maintain body temperatures in the range from 36°C to 40°C (309 K to 313 K). A high metabolic rate warms the animal from within, and insulation (such as fur and body fat) slows heat loss.

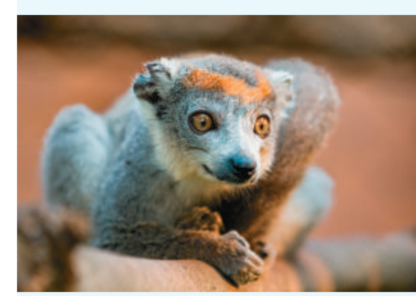
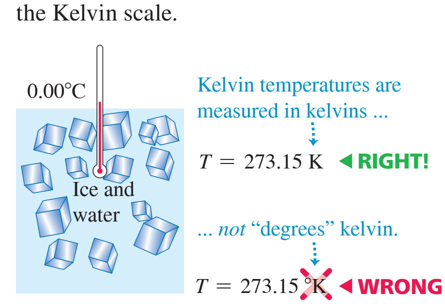


Figure **17.6** Correct and incorrect uses of the Kelvin scale.



EXAMPLE 17.1 Body temperature

You place a small piece of ice in your mouth. Eventually, the water all converts from ice at $T_1 = 32.00°\text{F}$ to body temperature, $T_2 = 98.60°\text{F}$. Express these temperatures in both Celsius degrees and kelvins, and find $\Delta T = T_2 - T_1$ in both cases.

IDENTIFY and SET UP Our target variables are stated above. We convert Fahrenheit temperatures to Celsius by using Eq. (17.2), and Celsius temperatures to Kelvin by using Eq. (17.3).

EXECUTE From Eq. (17.2), $T_1 = 0.00°\text{C}$ and $T_2 = 37.00°\text{C}$; then $\Delta T = T_2 - T_1 = 37.00\ \text{C}°$. To get the Kelvin temperatures, just add 273.15 to each Celsius temperature: $T_1 = 273.15\ \text{K}$ and $T_2 = 310.15\ \text{K}$. The temperature difference is $\Delta T = T_2 - T_1 = 37.00\ \text{K}$.

EVALUATE The Celsius and Kelvin scales have different zero points but the same size degrees. Therefore *any* temperature difference ΔT is the *same* on the Celsius and Kelvin scales. However, ΔT is *not* the same on the Fahrenheit scale; here, for example, $\Delta T = 66.60\ \text{F}°$.

KEYCONCEPT The Celsius and Kelvin scales have different zero points, but differences in temperature are the same in both scales: Increasing the temperature by 37.00 C° is the same as increasing it by 37.00 K.

The Kelvin Scale and Absolute Temperature

CAUTION Updating the Kelvin scale The definition of the Kelvin scale given here was accurate as of 2018. As of 2019, there is a new definition of this scale based on the definition of the joule and the value of the Boltzmann constant (which we'll introduce in Chapter 18). The change in definition has no effect, however, on the calculations in this textbook and calculations that you'll make.

The Celsius scale has two fixed points: the normal freezing and boiling temperatures of water. But we can define the Kelvin scale by using a gas thermometer with only a single reference temperature. Figure 17.5b shows that the pressure p in a gas thermometer is directly proportional to the Kelvin temperature. So we can define the ratio of any two Kelvin temperatures T_1 and T_2 as the ratio of the corresponding gas-thermometer pressures p_1 and p_2:

Definition of Kelvin scale: Ratio of two **temperatures in kelvins** ...

$$\frac{T_2}{T_1} = \frac{p_2}{p_1} \tag{17.4}$$

... equals ratio of corresponding **pressures** in **constant-volume gas thermometer**.

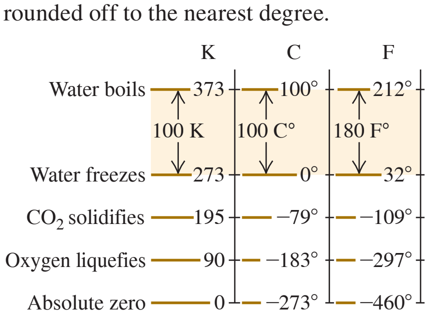
To complete the definition of T, we need only specify the Kelvin temperature of a single state. For reasons of precision and reproducibility, the state chosen is the *triple point* of water, the unique combination of temperature and pressure at which solid water (ice), liquid water, and water vapor can all coexist. It occurs at a temperature of 0.01°C and a water-vapor pressure of 610 Pa (about 0.006 atm). (This is the pressure of the *water,* not the gas pressure in the *thermometer.*) The triple-point temperature of water is *defined* to have the value $T_{\text{triple}} = 273.16\ \text{K}$, corresponding to 0.01°C. From Eq. (17.4), if p_{triple} is the pressure in a gas thermometer at temperature T_{triple} and p is the pressure at some other temperature T, then T is given on the Kelvin scale by

$$T = T_{\text{triple}}\frac{p}{p_{\text{triple}}} = (273.16\ \text{K})\frac{p}{p_{\text{triple}}} \tag{17.5}$$

Gas thermometers are impractical for everyday use. They are bulky and very slow to come to thermal equilibrium. They are used principally to establish high-precision standards and to calibrate other thermometers.

Figure 17.7 shows the relationships among the three temperature scales we have discussed. The Kelvin scale is called an **absolute temperature scale,** and its zero point [$T = 0\ \text{K} = -273.15°\text{C}$, the temperature at which $p = 0$ in Eq. (17.5)] is called **absolute zero.** At absolute zero a system of molecules (such as a quantity of a gas, a liquid, or a solid) has its *minimum* possible total energy (kinetic plus potential); because of quantum effects, it is *not* correct to say that all molecular motion ceases at absolute zero. In Chapter 20 we'll define more completely what we mean by absolute zero through thermodynamic principles that we'll develop in the next several chapters.

Figure 17.7 Relationships among Kelvin (K), Celsius (C), and Fahrenheit (F) temperature scales. Temperatures have been rounded off to the nearest degree.



TEST YOUR UNDERSTANDING OF SECTION 17.3 Rank the following temperatures from highest to lowest: (i) 0.00°C; (ii) 0.00°F; (iii) 260.00 K; (iv) 77.00 K; (v) −180.00°C.

ANSWER **(i), (iii), (ii), (v), (iv)** To compare these temperatures, convert them all to the Kelvin scale. For (i), the Kelvin temperature is $T_K = T_C + 273.15 = 0.00 + 273.15 = 273.15\ \text{K}$; for (ii), $T_C = \frac{5}{9}(T_F - 32°) = \frac{5}{9}(0.00° - 32°) = -17.78°\text{C}$ and $T_K = T_C + 273.15 = -17.78 + 273.15 = 255.37\ \text{K}$; for (iii), $T_K = 260.00\ \text{K}$; for (iv), $T_K = 77.00\ \text{K}$; and for (v), $T_K = T_C + 273.15 = -180.00 + 273.15 = 93.15\ \text{K}$.

17.4 THERMAL EXPANSION

Most materials expand when their temperatures increase. Rising temperatures make the liquid expand in a liquid-in-tube thermometer (Fig. 17.1a) and bend bimetallic strips (Fig. 17.3b). A completely filled and tightly capped bottle of water cracks when it is heated, but you can loosen a metal jar lid by running hot water over it. These are all examples of *thermal expansion*.

Linear Expansion

Suppose a solid rod has a length L_0 at some initial temperature T_0. When the temperature changes by ΔT, the length changes by ΔL. Experiments show that if ΔT is not too large (say, less than 100 C° or so), ΔL is *directly proportional* to ΔT (**Fig. 17.8a**). If two rods made of the same material have the same temperature change, but one is twice as long as the other, then the *change* in its length is also twice as great. Therefore ΔL must also be proportional to L_0 (Fig. 17.8b). We may express these relationships in an equation:

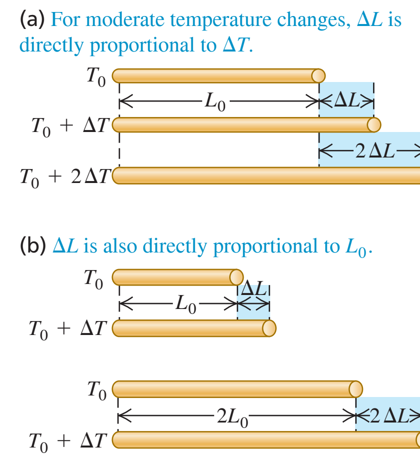


Figure 17.8 How the length of a rod changes with a change in temperature. (Length changes are exaggerated for clarity.)

Linear thermal expansion: Change in length, Original length, Temperature change, Coefficient of linear expansion

$$\Delta L = \alpha L_0 \Delta T \qquad (17.6)$$

The constant α, which has different values for different materials, is called the **coefficient of linear expansion.** The units of α are K^{-1} or $(C^\circ)^{-1}$. (Remember that a temperature interval is the same on the Kelvin and Celsius scales.) If an object has length L_0 at temperature T_0, then its length L at a temperature $T = T_0 + \Delta T$ is

$$L = L_0 + \Delta L = L_0 + \alpha L_0 \Delta T = L_0(1 + \alpha\,\Delta T) \qquad (17.7)$$

For many materials, every linear dimension changes according to Eq. (17.6) or (17.7). Thus L could be the thickness of a rod, the side length of a square sheet, or the diameter of a hole. Some materials, such as wood or single crystals, expand differently in different directions. We won't consider this complication.

We can understand thermal expansion qualitatively on a molecular basis. Picture the interatomic forces in a solid as springs, as in **Fig. 17.9a**. (We explored the analogy between spring forces and interatomic forces in Section 14.4.) Each atom vibrates about its equilibrium position. When the temperature increases, the energy and amplitude of the vibration also increase. The interatomic spring forces are not symmetrical about the equilibrium position; they usually behave like a spring that is easier to stretch than to compress. As a result, when the amplitude of vibration increases, the *average* distance between atoms also increases (Fig. 17.9b). As the atoms get farther apart, every dimension increases.

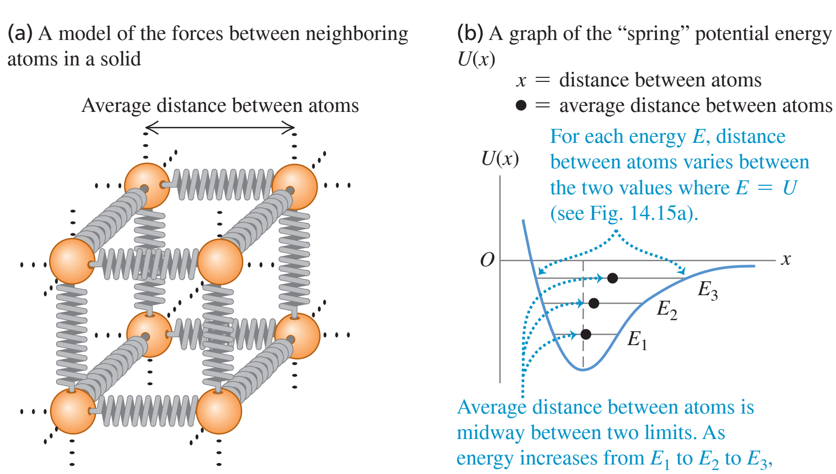


Figure 17.9 (a) We can model atoms in a solid as being held together by "springs" that are easier to stretch than to compress. (b) A graph of the "spring" potential energy $U(x)$ versus distance x between neighboring atoms is *not* symmetrical (compare Fig. 14.20b). As the energy increases and the atoms oscillate with greater amplitude, the average distance increases.

Figure 17.10 When an object undergoes thermal expansion, any holes in the object expand as well. (The expansion is exaggerated.)

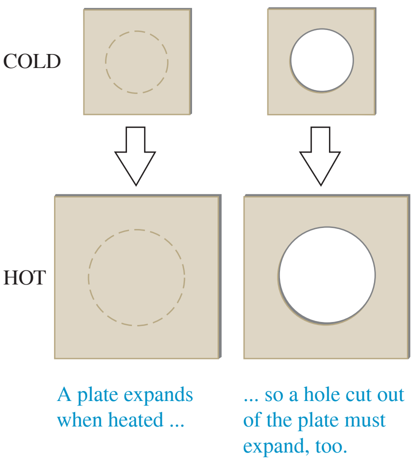
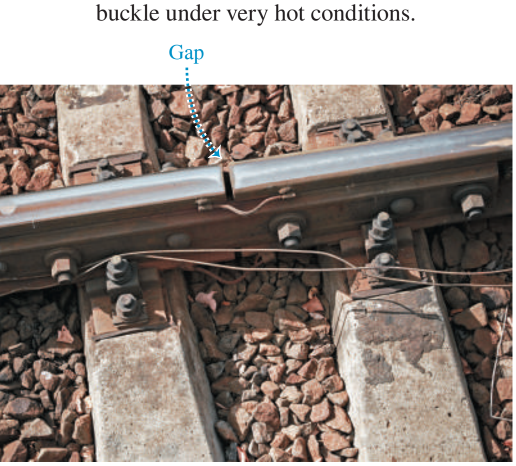


Figure 17.11 This railroad track has a gap between segments to allow for thermal expansion. (The "clickety-clack" sound familiar to railroad passengers comes from the wheels passing over such gaps.) On hot days, the segments expand and fill in the gap. If there were no gaps, the track could buckle under very hot conditions.



CAUTION **Heating an object with a hole** If a solid object has a hole in it, what happens to the size of the hole when the temperature of the object increases? A common misconception is that if the object expands, the hole will shrink because material expands into the hole. But, in fact, if the object expands, the hole will expand too (**Fig. 17.10**); *every* linear dimension of an object changes in the same way when the temperature changes. Think of the atoms in Fig. 17.9a as outlining a cubical hole. When the object expands, the atoms move apart and the hole increases in size. The only situation in which a "hole" will fill in due to thermal expansion is when two separate objects expand and close the gap between them (**Fig. 17.11**).

The direct proportionality in Eq. (17.6) is not exact; it is *approximately* correct only for sufficiently small temperature changes. For a given material, α varies somewhat with the initial temperature T_0 and the size of the temperature interval. We'll ignore this complication here, however. **Table 17.1** lists values of α for several materials. Within the precision of these values we don't need to worry whether T_0 is 0°C or 20°C or some other temperature. Typical values of α are very small; even for a temperature change of 100 C°, the fractional length change $\Delta L/L_0$ is only of the order of $\frac{1}{1000}$ for the metals in the table.

Volume Expansion

Increasing temperature usually causes increases in *volume* for both solids and liquids. Just as with linear expansion, experiments show that if the temperature change ΔT is less than 100 C° or so, the increase in volume ΔV is approximately proportional to both the temperature change ΔT and the initial volume V_0:

Volume thermal expansion: $$\Delta V = \beta V_0 \Delta T \qquad (17.8)$$

Change in volume (ΔV); Coefficient of volume expansion (β); Original volume (V_0); Temperature change (ΔT)

The constant β characterizes the volume expansion properties of a particular material; it is called the **coefficient of volume expansion.** The units of β are K^{-1} or $(C°)^{-1}$. As with linear expansion, β varies somewhat with temperature, and Eq. (17.8) is an approximate relationship that is valid only for small temperature changes. For many substances, β decreases at low temperatures. **Table 17.2** lists values of β for several materials near room temperature. Note that the values for liquids are generally much larger than those for solids.

For solid materials we can find a simple relationship between the volume expansion coefficient β and the linear expansion coefficient α. Consider a cube of material with side length L and volume $V = L^3$. At the initial temperature the values are L_0 and V_0. When the temperature increases by dT, the side length increases by dL and the volume increases by an amount dV:

$$dV = \frac{dV}{dL}dL = 3L^2\,dL$$

TABLE 17.1 Coefficients of Linear Expansion

Material	α [K^{-1} or $(C°)^{-1}$]
Aluminum	2.4×10^{-5}
Brass	2.0×10^{-5}
Copper	1.7×10^{-5}
Glass	$0.4–0.9 \times 10^{-5}$
Invar (nickel–iron alloy)	0.09×10^{-5}
Quartz (fused)	0.04×10^{-5}
Steel	1.2×10^{-5}

TABLE 17.2 Coefficients of Volume Expansion

Solids	β [K^{-1} or $(C°)^{-1}$]	Liquids	β [K^{-1} or $(C°)^{-1}$]
Aluminum	7.2×10^{-5}	Ethanol	75×10^{-5}
Brass	6.0×10^{-5}	Carbon disulfide	115×10^{-5}
Copper	5.1×10^{-5}	Glycerin	49×10^{-5}
Glass	$1.2–2.7 \times 10^{-5}$	Mercury	18×10^{-5}
Invar	0.27×10^{-5}		
Quartz (fused)	0.12×10^{-5}		
Steel	3.6×10^{-5}		

Now we replace L and V by the initial values L_0 and V_0. From Eq. (17.6), dL is

$$dL = \alpha L_0\, dT$$

Since $V_0 = L_0^3$, this means that dV can also be expressed as

$$dV = 3L_0^2 \alpha L_0\, dT = 3\alpha V_0\, dT$$

This is consistent with the infinitesimal form of Eq. (17.8), $dV = \beta V_0\, dT$, only if

$$\beta = 3\alpha \tag{17.9}$$

(Check this relationship for some of the materials listed in Tables 17.1 and 17.2.)

PROBLEM-SOLVING STRATEGY 17.1 Thermal Expansion

IDENTIFY *the relevant concepts:* Decide whether the problem involves changes in length (linear thermal expansion) or in volume (volume thermal expansion).

SET UP *the problem* using the following steps:

1. List the known and unknown quantities and identify the target variables.
2. Choose Eq. (17.6) for linear expansion and Eq. (17.8) for volume expansion.

EXECUTE *the solution* as follows:

1. Solve for the target variables. If you are given an initial temperature T_0 and must find a final temperature T corresponding to a given length or volume change, find ΔT and calculate $T = T_0 + \Delta T$. Remember that the size of a hole in a material varies with temperature just as any other linear dimension, and that the volume of a hole (such as the interior of a container) varies just as that of the corresponding solid shape.
2. Maintain unit consistency. Both L_0 and ΔL (or V_0 and ΔV) must have the same units. If you use a value of α or β in K^{-1} or $(C°)^{-1}$, then ΔT must be in either kelvins or Celsius degrees; from Example 17.1, the two scales are equivalent *for temperature differences.*

EVALUATE *your answer:* Check whether your results make sense.

EXAMPLE 17.2 Length change due to temperature change

WITH VARIATION PROBLEMS

A surveyor uses a steel measuring tape that is exactly 50.000 m long at a temperature of 20°C. The markings on the tape are calibrated for this temperature. (a) What is the length of the tape when the temperature is 35°C? (b) When it is 35°C, the surveyor uses the tape to measure a distance. The value that she reads off the tape is 35.794 m. What is the actual distance?

IDENTIFY and SET UP This problem concerns the linear expansion of a measuring tape. We are given the tape's initial length $L_0 = 50.000$ m at $T_0 = 20°C$. In part (a) we use Eq. (17.6) to find the change ΔL in the tape's length at $T = 35°C$, and use Eq. (17.7) to find L. (Table 17.1 gives the value of α for steel.) Since the tape expands, at 35°C the distance between two successive meter marks is greater than 1 m. Hence the actual distance in part (b) is *larger* than the distance read off the tape by a factor equal to the ratio of the tape's length L at 35°C to its length L_0 at 20°C.

EXECUTE (a) The temperature change is $\Delta T = T - T_0 = 15\ C° = 15$ K; from Eqs. (17.6) and (17.7),

$$\Delta L = \alpha L_0\, \Delta T = (1.2 \times 10^{-5}\,K^{-1})(50\,m)(15\,K)$$
$$= 9.0 \times 10^{-3}\,m = 9.0\,mm$$
$$L = L_0 + \Delta L = 50.000\,m + 0.009\,m = 50.009\,m$$

(b) Our result from part (a) shows that at 35°C, the slightly expanded tape reads a distance of 50.000 m when the true distance is 50.009 m. We can rewrite the algebra of part (a) as $L = L_0(1 + \alpha\,\Delta T)$; at 35°C, *any* true distance will be greater than the reading by the factor $50.009/50.000 = 1 + \alpha\,\Delta T = 1 + 1.8 \times 10^{-4}$. The true distance is therefore

$$(1 + 1.8 \times 10^{-4})(35.794\,m) = 35.800\,m$$

EVALUATE In part (a) we needed only two of the five significant figures of L_0 to compute ΔL to the same number of decimal places as L_0. Our result shows that metals expand very little under moderate temperature changes. However, even the small difference 0.009 m = 9 mm found in part (b) between the scale reading and the true distance can be important in precision work.

KEYCONCEPT A change in temperature causes the *length* of an object to change by an amount that is approximately proportional to the object's initial length and to the temperature change ΔT.

EXAMPLE 17.3 Volume change due to temperature change

WITH VARIATION PROBLEMS

A $200\ \text{cm}^3$ glass flask is filled to the brim with mercury at 20°C. How much mercury overflows when the temperature of the system is raised to 100°C? The coefficient of *linear* expansion of the glass is $0.40 \times 10^{-5}\ \text{K}^{-1}$.

IDENTIFY and SET UP This problem involves the volume expansion of the glass and of the mercury. The amount of overflow depends on the *difference* between the volume changes ΔV for these two materials, both given by Eq. (17.8). The mercury will overflow if its coefficient of volume expansion β (see Table 17.2) is greater than that of glass, which we find from Eq. (17.9) using the given value of α.

EXECUTE From Table 17.2, $\beta_{\text{Hg}} = 18 \times 10^{-5}\ \text{K}^{-1}$. That is indeed greater than $\beta_{\text{glass}} = 3\alpha_{\text{glass}} = 3(0.40 \times 10^{-5}\ \text{K}^{-1}) = 1.2 \times 10^{-5}\ \text{K}^{-1}$, from Eq. (17.9). The volume overflow is then

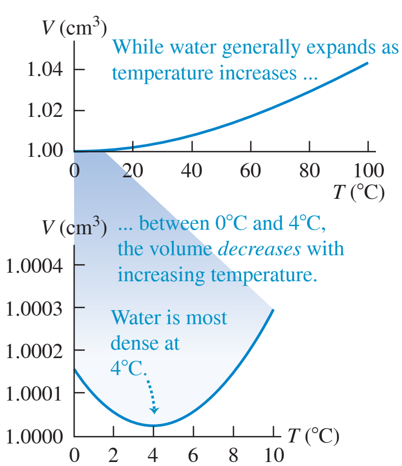
$$
\begin{aligned}
\Delta V_{\text{Hg}} - \Delta V_{\text{glass}} &= \beta_{\text{Hg}} V_0 \Delta T - \beta_{\text{glass}} V_0 \Delta T \\
&= V_0 \Delta T(\beta_{\text{Hg}} - \beta_{\text{glass}}) \\
&= (200\ \text{cm}^3)(80\ \text{C}°)(18 \times 10^{-5} - 1.2 \times 10^{-5}) = 2.7\ \text{cm}^3
\end{aligned}
$$

EVALUATE This is basically how a mercury-in-glass thermometer works; the column of mercury inside a sealed tube rises as T increases because mercury expands faster than glass.

As Tables 17.1 and 17.2 show, glass has smaller coefficients of expansion α and β than do most metals. This is why you can use hot water to loosen a metal lid on a glass jar; the metal expands more than the glass does.

KEYCONCEPT A change in temperature causes the *volume* of an object to change by an amount that is approximately proportional to the object's initial volume and to the temperature change ΔT.

Figure 17.12 The volume of 1 gram of water in the temperature range from 0°C to 100°C. By 100°C the volume has increased to $1.043\ \text{cm}^3$. If the coefficient of volume expansion were constant, the curve would be a straight line.



Thermal Expansion of Water

Water, in the temperature range from 0°C to 4°C, *decreases* in volume with increasing temperature. In this range its coefficient of volume expansion is *negative*. Above 4°C, water expands when heated (**Fig. 17.12**). Hence water has its greatest density at 4°C. Water also expands when it freezes, which is why ice humps up in the middle of the compartments in an ice-cube tray. By contrast, most materials contract when they freeze.

This anomalous behavior of water has an important effect on plant and animal life in lakes. A lake cools from the surface down; above 4°C, the cooled water at the surface flows to the bottom because of its greater density. But when the surface temperature drops below 4°C, the water near the surface is less dense than the warmer water below. Hence the downward flow ceases, and the water near the surface remains colder than that at the bottom. As the surface freezes, the ice floats because it is less dense than water. The water at the bottom remains at 4°C until nearly the entire lake is frozen. If water behaved like most substances, contracting continuously on cooling and freezing, lakes would freeze from the bottom up. Circulation due to density differences would continuously carry warmer water to the surface for efficient cooling, and lakes would freeze solid much more easily. This would destroy all plant and animal life that cannot withstand freezing. If water did not have its special properties, the evolution of life would have taken a very different course.

Thermal Stress

If we clamp the ends of a rod rigidly to prevent expansion or contraction and then change the temperature, **thermal stresses** develop. The rod would like to expand or contract, but the clamps won't let it. The resulting stresses may become large enough to strain the rod irreversibly or even break it. (Review the discussion of stress and strain in Section 11.4.)

Engineers must account for thermal stress when designing structures (see Fig. 17.11). Concrete highways and bridge decks usually have gaps between sections, filled with a flexible material or bridged by interlocking teeth (**Fig. 17.13**), to permit expansion and contraction of the concrete. Long steam pipes have expansion joints or U-shaped sections to prevent buckling or stretching with temperature changes. If one end of a steel bridge is rigidly fastened to its abutment, the other end usually rests on rollers.

Figure 17.13 Expansion joints on bridges are needed to accommodate changes in length that result from thermal expansion.

To calculate the thermal stress in a clamped rod, we compute the amount the rod *would* expand (or contract) if not held and then find the stress needed to compress (or stretch) it back to its original length. Suppose that a rod with length L_0 and cross-sectional area A is held at constant length while the temperature is reduced, causing a tensile stress. From Eq. (17.6), the fractional change in length if the rod were free to contract would be

$$\left(\frac{\Delta L}{L_0}\right)_{\text{thermal}} = \alpha\,\Delta T \tag{17.10}$$

Since the temperature decreases, both ΔL and ΔT are negative. The tension must increase by an amount F that is just enough to produce an equal and opposite fractional change in length $(\Delta L/L_0)_{\text{tension}}$. From the definition of Young's modulus, Eq. (11.10),

$$Y = \frac{F/A}{\Delta L/L_0} \quad \text{so} \quad \left(\frac{\Delta L}{L_0}\right)_{\text{tension}} = \frac{F}{AY} \tag{17.11}$$

If the length is to be constant, the *total* fractional change in length must be zero. From Eqs. (17.10) and (17.11), this means that

$$\left(\frac{\Delta L}{L_0}\right)_{\text{thermal}} + \left(\frac{\Delta L}{L_0}\right)_{\text{tension}} = \alpha\,\Delta T + \frac{F}{AY} = 0$$

Solve for the tensile stress F/A required to keep the rod's length constant:

Thermal stress:

$$\frac{F}{A} = -Y\alpha\,\Delta T \tag{17.12}$$

Force needed to keep length of rod constant

Cross-sectional area of rod

Young's modulus

Temperature change

Coefficient of linear expansion

For a decrease in temperature, ΔT is negative, so F and F/A are positive; this means that a *tensile* force and stress are needed to maintain the length. If ΔT is positive, F and F/A are negative, and the required force and stress are *compressive*.

If there are temperature differences within an object, nonuniform expansion or contraction will result and thermal stresses can be induced. You can break a glass bowl by pouring very hot water into it; the thermal stress between the hot and cold parts of the bowl exceeds the breaking stress of the glass, causing cracks. The same phenomenon makes ice cubes crack when dropped into warm water.

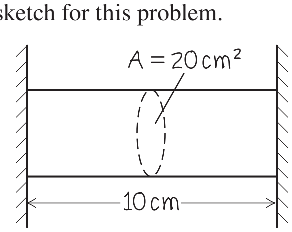
EXAMPLE 17.4 Thermal stress

WITH VARIATION PROBLEMS

An aluminum cylinder 10 cm long, with a cross-sectional area of 20 cm^2, is used as a spacer between two steel walls. At 17.2°C it just slips between the walls. Calculate the stress in the cylinder and the total force it exerts on each wall when it warms to 22.3°C, assuming that the walls are perfectly rigid and a constant distance apart.

IDENTIFY and SET UP See **Fig. 17.14**. The cylinder of given cross-sectional area A exerts force F on each wall; our target variables are the stress F/A and F itself. We use Eq. (17.12) to relate F/A to the temperature change ΔT, and from that calculate F. (The length of the cylinder is irrelevant.) We find Young's modulus Y_{Al} and the coefficient of linear expansion α_{Al} from Tables 11.1 and 17.1, respectively.

Figure **17.14** Our sketch for this problem.



EXECUTE We have $Y_{\text{Al}} = 7.0 \times 10^{10}$ Pa and $\alpha_{\text{Al}} = 2.4 \times 10^{-5}\ \text{K}^{-1}$, and $\Delta T = 22.3°\text{C} - 17.2°\text{C} = 5.1\ \text{C}° = 5.1$ K. From Eq. (17.12), the stress is

$$\begin{aligned}\frac{F}{A} &= -Y_{\text{Al}}\alpha_{\text{Al}}\Delta T \\ &= -(7.0 \times 10^{10}\ \text{Pa})(2.4 \times 10^{-5}\ \text{K}^{-1})(5.1\ \text{K}) \\ &= -8.6 \times 10^{6}\ \text{Pa} = -1200\ \text{lb/in.}^2\end{aligned}$$

The total force is the cross-sectional area times the stress:

$$\begin{aligned}F = A\left(\frac{F}{A}\right) &= (20 \times 10^{-4}\ \text{m}^2)(-8.6 \times 10^{6}\ \text{Pa}) \\ &= -1.7 \times 10^{4}\ \text{N} = -1.9\ \text{tons}\end{aligned}$$

EVALUATE The stress on the cylinder and the force it exerts on each wall are immense. Such thermal stresses must be accounted for in engineering.

KEYCONCEPT To keep the length of an object constant when the temperature changes, forces must be applied to both of its ends. The required stress (force per unit area) is proportional to the temperature change.

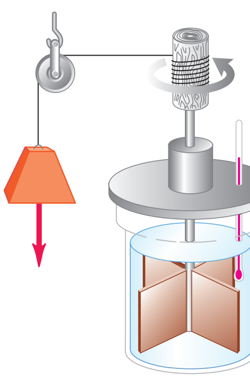
TEST YOUR UNDERSTANDING OF SECTION 17.4 In the bimetallic strip shown in Fig. 17.3a, metal 1 is copper. Which of the following materials could be used for metal 2? (There may be more than one correct answer). (i) Steel; (ii) brass; (iii) aluminum.

ANSWER

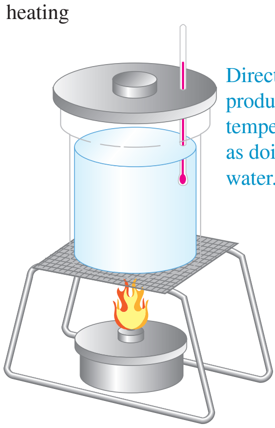
(ii) and (iii) Metal 2 must expand more than metal 1 when heated and so must have a larger coefficient of linear expansion α. From Table 17.1, brass and aluminum have larger values of α than copper, but steel does not.

Figure **17.15** The same temperature change of the same system may be accomplished by (a) doing work on it or (b) adding heat to it.

(a) Raising the temperature of water by doing work on it



(b) Raising the temperature of water by direct heating



17.5 QUANTITY OF HEAT

When you put a cold spoon into a cup of hot coffee, the spoon warms up and the coffee cools down as they approach thermal equilibrium. What causes these temperature changes is a transfer of *energy* from one substance to another. Energy transfer that takes place solely because of a temperature difference is called *heat flow* or *heat transfer,* and energy transferred in this way is called **heat.**

An understanding of the relationship between heat and other forms of energy emerged during the 18th and 19th centuries. Sir James Joule (1818–1889) studied how water can be warmed by vigorous stirring with a paddle wheel (**Fig. 17.15a**). The paddle wheel adds energy to the water by doing *work* on it, and Joule found that *the temperature rise is directly proportional to the amount of work done.* The same temperature change can also be caused by putting the water in contact with some hotter object (Fig. 17.15b); hence this interaction must also involve an energy exchange. We'll explore the relationship between heat and mechanical energy in Chapters 19 and 20.

CAUTION **Temperature vs. heat** It is absolutely essential for you to distinguish between *temperature* and *heat.* Temperature depends on the physical state of a material and is a quantitative description of its hotness or coldness. In physics the term "heat" always refers to energy in transit from one object or system to another because of a temperature difference, never to the amount of energy contained within a particular system. We can change the temperature of an object by adding heat to it or taking heat away, or by adding or subtracting energy in other ways, such as mechanical work (Fig. 17.15a). If we cut an object in half, each half has the same temperature as the whole; but to raise the temperature of each half by a given interval, we add *half* as much heat as for the whole.

We can define a *unit* of quantity of heat based on temperature changes of some specific material. The **calorie** (abbreviated cal) is *the amount of heat required to raise the temperature of 1 gram of water from 14.5°C to 15.5°C.* A food-value calorie is actually a kilocalorie (kcal), equal to 1000 cal. A corresponding unit of heat that uses Fahrenheit degrees and British units is the **British thermal unit,** or Btu. One Btu is the quantity of heat required to raise the temperature of 1 pound (weight) of water 1 F° from 63°F to 64°F.

Because heat is energy in transit, there must be a definite relationship between these units and the familiar mechanical energy units such as the joule (**Fig. 17.16**). Experiments similar in concept to Joule's have shown that

$$\begin{aligned} 1\ \text{cal} &= 4.186\ \text{J} \\ 1\ \text{kcal} &= 1000\ \text{cal} = 4186\ \text{J} \\ 1\ \text{Btu} &= 778\ \text{ft}\cdot\text{lb} = 252\ \text{cal} = 1055\ \text{J} \end{aligned}$$

Figure **17.16** The word "energy" is of Greek origin. This label on a can of Greek coffee shows that 100 milliliters of prepared coffee have an energy content ($\epsilon\nu\acute{\epsilon}\rho\gamma\epsilon\iota\alpha$) of 9.6 kilojoules or 2.3 kilocalories.

The calorie is not a fundamental SI unit. The International Committee on Weights and Measures recommends using the joule as the basic unit of energy in all forms, including heat. We'll follow that recommendation in this book.

Specific Heat

We use the symbol Q for quantity of heat. When it is associated with an infinitesimal temperature change dT, we call it dQ. The quantity of heat Q required to increase the temperature of a mass m of a certain material from T_1 to T_2 is found to be approximately proportional to the temperature change $\Delta T = T_2 - T_1$. It is also proportional to the mass m of material. When you're heating water to make tea, you need twice as much heat for two cups as for one if the temperature change is the same. The quantity of heat needed also depends on the nature of the material; raising the temperature of 1 kilogram of water by 1 C° requires 4190 J of heat, but only 910 J is needed to raise the temperature of 1 kilogram of aluminum by 1 C°.

Putting all these relationships together, we have

Heat required to change temperature of a certain mass

Mass of material

$$Q = mc\,\Delta T \tag{17.13}$$

Temperature change

Specific heat of material

The **specific heat** c has different values for different materials. For an infinitesimal temperature change dT and corresponding quantity of heat dQ,

$$dQ = mc\,dT \tag{17.14}$$

$$c = \frac{1}{m}\frac{dQ}{dT} \quad \text{(specific heat)} \tag{17.15}$$

In Eqs. (17.13), (17.14), and (17.15), when Q (or dQ) and ΔT (or dT) are positive, heat enters the object and its temperature increases. When they are negative, heat leaves the object and its temperature decreases.

CAUTION **The definition of heat** Remember that dQ does not represent a change in the amount of heat *contained* in an object. Heat is always energy *in transit* as a result of a temperature difference. There is no such thing as "the amount of heat in an object."

The specific heat of water is approximately

$$4190\ \text{J/kg}\cdot\text{K} \qquad 1\ \text{cal/g}\cdot\text{C}^\circ \qquad \text{or} \qquad 1\ \text{Btu/lb}\cdot\text{F}^\circ$$

The specific heat of a material always depends somewhat on the initial temperature and the temperature interval. **Figure 17.17** shows this dependence for water. In this chapter we'll usually ignore this small variation.

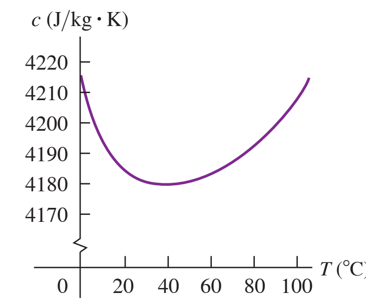


Figure 17.17 Specific heat of water as a function of temperature. The value of c varies by less than 1% between 0°C and 100°C.

EXAMPLE 17.5 Feed a cold, starve a fever

During a bout with the flu an 80 kg man ran a fever of 39.0°C (102.2°F) instead of the normal body temperature of 37.0°C (98.6°F). Assuming that the human body is mostly water, how much heat is required to raise his temperature by that amount?

IDENTIFY and SET UP This problem uses the relationship among heat (the target variable), mass, specific heat, and temperature change. We use Eq. (17.13) to determine the required heat Q, with $m = 80$ kg, $c = 4190$ J/kg · K (for water), and $\Delta T = 39.0°\text{C} - 37.0°\text{C} = 2.0\ \text{C}^\circ = 2.0$ K.

EXECUTE From Eq. (17.13),

$$Q = mc\,\Delta T = (80\ \text{kg})(4190\ \text{J/kg}\cdot\text{K})(2.0\ \text{K}) = 6.7 \times 10^5\ \text{J}$$

EVALUATE This corresponds to 160 kcal. In fact, the specific heat of the human body is about 3480 J/kg · K, 83% that of water, because protein, fat, and minerals have lower specific heats. Hence a more accurate answer is $Q = 5.6 \times 10^5$ J = 133 kcal. Either result shows us that were it not for the body's temperature-regulating systems, taking in energy in the form of food would produce measurable changes in body temperature. (The elevated temperature of a person with the flu results from the body's extra activity in response to infection.)

KEYCONCEPT To find the amount of heat required to change the temperature of a mass m of material by an amount ΔT, multiply m by ΔT and by the specific heat c of the material. Heat is positive when it flows into an object and negative when it flows out.

EXAMPLE 17.6 Overheating electronics

You are designing an electronic circuit element made of 23 mg of silicon. The electric current through it adds energy at the rate of 7.4 mW = 7.4×10^{-3} J/s. If your design doesn't allow any heat transfer out of the element, at what rate does its temperature increase? The specific heat of silicon is 705 J/kg · K.

IDENTIFY and SET UP The energy added to the circuit element gives rise to a temperature increase, just as if heat were flowing into the element at the rate $dQ/dt = 7.4 \times 10^{-3}$ J/s. Our target variable is the rate of temperature change dT/dt. We can use Eq. (17.14),which relates infinitesimal temperature changes dT to the corresponding heat dQ, to obtain an expression for dQ/dt in terms of dT/dt.

EXECUTE We divide both sides of Eq. (17.14) by dt and rearrange:

$$\frac{dT}{dt} = \frac{dQ/dt}{mc} = \frac{7.4 \times 10^{-3}\ \text{J/s}}{(23 \times 10^{-6}\ \text{kg})(705\ \text{J/kg}\cdot\text{K})} = 0.46\ \text{K/s}$$

EVALUATE At this rate of temperature rise (27 K/min), the circuit element would soon self-destruct. Heat transfer is an important design consideration in electronic circuit elements.

KEYCONCEPT Any energy flow (not just heat) into or out of a quantity of material can cause the temperature of the material to change. The rate of energy flow is equal to the mass times the specific heat of the material times the rate of temperature change.

Molar Heat Capacity

Sometimes it's more convenient to describe a quantity of substance in terms of the number of *moles* n rather than the *mass* m of material. Recall from your study of chemistry that a mole of any pure substance always contains the same number of molecules. (We'll discuss this point in more detail in Chapter 18.) The *molar mass* of any substance, denoted by M, is the mass per mole. (The quantity M is sometimes called *molecular weight,* but *molar mass* is preferable; the quantity depends on the mass of a molecule, not its weight.) For example, the molar mass of water is $18.0\ \text{g/mol} = 18.0 \times 10^{-3}\ \text{kg/mol}$; 1 mole of water has a mass of $18.0\ \text{g} = 0.0180\ \text{kg}$. The total mass m of material is equal to the mass per mole M times the number of moles n:

$$m = nM \tag{17.16}$$

Replacing the mass m in Eq. (17.13) by the product nM, we find

$$Q = nMc\,\Delta T \tag{17.17}$$

The product Mc is called the **molar heat capacity** (or *molar specific heat*) and is denoted by C (capitalized). With this notation we rewrite Eq. (17.17) as

Heat required to change temperature of a certain number of moles

$$Q = nC\,\Delta T \tag{17.18}$$

Number of moles of material

Temperature change

Molar heat capacity of material

Figure 17.18 Water has a much higher specific heat than the glass or metals used to make cookware. This helps explain why it takes several minutes to boil water on a stove, even though the pot or kettle reaches a high temperature very quickly.

Comparing to Eq. (17.15), we can express the molar heat capacity C (heat per mole per temperature change) in terms of the specific heat c (heat per mass per temperature change) and the molar mass M (mass per mole):

$$C = \frac{1}{n}\frac{dQ}{dT} = Mc \qquad \text{(molar heat capacity)} \tag{17.19}$$

For example, the molar heat capacity of water is

$$\begin{aligned} C = Mc &= (0.0180\ \text{kg/mol})(4190\ \text{J/kg}\cdot\text{K}) \\ &= 75.4\ \text{J/mol}\cdot\text{K} \end{aligned}$$

Table 17.3 gives values of specific heat and molar heat capacity for several substances. Note the remarkable large specific heat for water (**Fig. 17.18**).

CAUTION **The meaning of "heat capacity"** The term "heat capacity" is unfortunate because it gives the erroneous impression that an object *contains* a certain amount of heat. Remember, heat is energy in transit to or from an object, not the energy residing in the object.

Measurements of specific heats and molar heat capacities for solid materials are usually made at constant atmospheric pressure; the corresponding values are called the *specific heat* and *molar heat capacity at constant pressure,* denoted by c_p and C_p. For a gas it is usually easier to keep the substance in a container with constant *volume;* the corresponding values are called the *specific heat* and *molar heat capacity at constant volume,* denoted by c_V and C_V. For a given substance, C_V and C_p are different. If the system can expand while heat is added, there is additional energy exchange through the performance of *work* by the system on its surroundings. If the volume is constant, the system does no work. For gases the difference between C_p and C_V is substantial. We'll study heat capacities of gases in detail in Section 19.7.

TABLE 17.3 Approximate Specific Heats and Molar Heat Capacities (Constant Pressure)

Substance	Specific Heat, c (J/kg · K)	Molar Mass, M (kg/mol)	Molar Heat Capacity, C (J/mol · K)
Aluminum	910	0.0270	24.6
Beryllium	1970	0.00901	17.7
Copper	390	0.0635	24.8
Ethanol	2428	0.0461	111.9
Ethylene glycol	2386	0.0620	148.0
Ice (near 0°C)	2100	0.0180	37.8
Iron	470	0.0559	26.3
Lead	130	0.207	26.9
Marble ($CaCO_3$)	879	0.100	87.9
Mercury	138	0.201	27.7
Salt (NaCl)	879	0.0585	51.4
Silver	234	0.108	25.3
Water (liquid)	4190	0.0180	75.4

The last column of Table 17.3 shows something interesting. The molar heat capacities for most elemental solids are about the same: about 25 J/mol · K. This correlation, named the *rule of Dulong and Petit* (for its discoverers), forms the basis for a very important idea. The number of atoms in 1 mole is the same for all elemental substances. This means that on a *per atom* basis, about the same amount of heat is required to raise the temperature of each of these elements by a given amount, even though the *masses* of the atoms are very different. The heat required for a given temperature increase depends only on *how many* atoms the sample contains, not on the mass of an individual atom. We'll see the reason the rule of Dulong and Petit works so well when we study the molecular basis of heat capacities in greater detail in Chapter 18.

TEST YOUR UNDERSTANDING OF SECTION 17.5 You wish to raise the temperature of each of the following samples from 20°C to 21°C. Rank these in order of the amount of heat needed to do this, from highest to lowest. (i) 1 kilogram of mercury; (ii) 1 kilogram of ethanol; (iii) 1 mole of mercury; (iv) 1 mole of ethanol.

ANSWER

(ii), (i), (iv), (iii) For (i) and (ii), the relevant quantity is the specific heat c of the substance, which is the amount of heat required to raise the temperature of 1 *kilogram* of that substance by 1 K (1 C°). From Table 17.3, these values are (i) 138 J for mercury and (ii) 2428 J for ethanol. For (iii) and (iv) we need the molar heat capacity C, which is the amount of heat required to raise the temperature of 1 *mole* of that substance by 1 C°. Again from Table 17.3, these values are (iii) 27.7 J for mercury and (iv) 111.9 J for ethanol. (The ratio of molar heat capacities is different from the ratio of the specific heats because a mole of mercury and a mole of ethanol have different masses.)

17.6 CALORIMETRY AND PHASE CHANGES

Calorimetry means "measuring heat." We have discussed the energy transfer (heat) involved in temperature changes. Heat is also involved in *phase changes,* such as the melting of ice or boiling of water. Once we understand these additional heat relationships, we can analyze a variety of problems involving quantity of heat.

Phase Changes

We use the term **phase** to describe a specific state of matter, such as a solid, liquid, or gas. The compound H_2O exists in the *solid phase* as ice, in the *liquid phase* as water, and in the *gaseous phase* as steam. (These are also referred to as **states of matter:** the solid state, the liquid state, and the gaseous state.) A transition from one phase to another is called a **phase change** or *phase transition*. For any given pressure a phase change takes place at a definite temperature, usually accompanied by heat flowing in or out and a change of volume and density.

Figure 17.19 The surrounding air is at room temperature, but this ice–water mixture remains at 0°C until all of the ice has melted and the phase change is complete.

A familiar phase change is the melting of ice. When we add heat to ice at 0°C and normal atmospheric pressure, the temperature of the ice *does not* increase. Instead, some of it melts to form liquid water. If we add the heat slowly, to maintain the system very close to thermal equilibrium, the temperature remains at 0°C until all the ice is melted (**Fig. 17.19**). The effect of adding heat to this system is not to raise its temperature but to change its *phase* from solid to liquid.

To change 1 kg of ice at 0°C to 1 kg of liquid water at 0°C and normal atmospheric pressure requires 3.34×10^5 J of heat. The heat required per unit mass is called the **heat of fusion** (or sometimes *latent heat of fusion*), denoted by L_f. For water at normal atmospheric pressure the heat of fusion is

$$L_f = 3.34 \times 10^5 \text{ J/kg} = 79.6 \text{ cal/g} = 143 \text{ Btu/lb}$$

More generally, to melt a mass m of material that has a heat of fusion L_f requires a quantity of heat Q given by

$$Q = mL_f$$

This process is *reversible*. To freeze liquid water to ice at 0°C, we have to *remove* heat; the magnitude is the same, but in this case, Q is negative because heat is removed rather than added. To cover both possibilities and to include other kinds of phase changes, we write

Heat transfer in a phase change

$$Q = \pm mL \qquad (17.20)$$

Mass of material that changes phase
Latent heat for this phase change
+ if heat enters material, − if heat leaves

The plus sign (heat entering) is used when the material melts; the minus sign (heat leaving) is used when it freezes. The heat of fusion is different for different materials, and it also varies somewhat with pressure.

For any given material at any given pressure, the freezing temperature is the same as the melting temperature. At this unique temperature the liquid and solid phases can coexist in a condition called **phase equilibrium.**

We can go through this whole story again for *boiling* or *evaporation,* a phase transition between liquid and gaseous phases. The corresponding heat (per unit mass) is called the **heat of vaporization** L_v. At normal atmospheric pressure the heat of vaporization L_v for water is

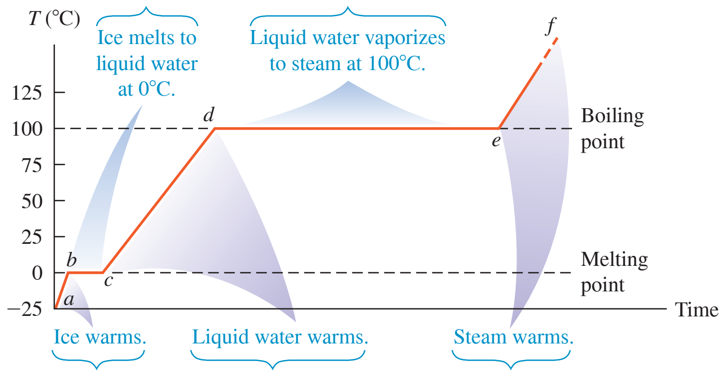
$$L_v = 2.256 \times 10^6 \text{ J/kg} = 539 \text{ cal/g} = 970 \text{ Btu/lb}$$

That is, it takes 2.256×10^6 J to change 1 kg of liquid water at 100°C to 1 kg of water vapor at 100°C. By comparison, to raise the temperature of 1 kg of water from 0°C to 100°C requires $Q = mc\,\Delta T = (1.00 \text{ kg})(4190 \text{ J/kg} \cdot \text{C°})(100 \text{ C°}) = 4.19 \times 10^5$ J, less than one-fifth as much heat as is required for vaporization at 100°C. This agrees with everyday kitchen experience; a pot of water may reach boiling temperature in a few minutes, but it takes a much longer time to completely evaporate all the water away.

Like melting, boiling is a reversible transition. When heat is removed from a gas at the boiling temperature, the gas returns to the liquid phase, or *condenses,* giving up to its surroundings the same quantity of heat (heat of vaporization) that was needed to vaporize it. At a given pressure the boiling and condensation temperatures are always the same; at this temperature the liquid and gaseous phases can coexist in phase equilibrium.

Figure **17.20** Graph of temperature versus time for a specimen of water initially in the solid phase (ice). Heat is added to the specimen at a constant rate. The temperature remains constant during each change of phase, provided that the pressure remains constant.

***Phase* of water changes.** During these periods, temperature stays constant and the phase change proceeds as heat is added: $Q = +mL$.



***Temperature* of water changes.** During these periods, temperature rises as heat is added: $Q = mc\Delta T$.

$a \rightarrow b$: Ice initially at −25°C is warmed to 0°C.
$b \rightarrow c$: Temperature remains at 0°C until all ice melts.
$c \rightarrow d$: Water is warmed from 0°C to 100°C.
$d \rightarrow e$: Temperature remains at 100°C until all water vaporizes.
$e \rightarrow f$: Steam is warmed to temperatures above 100°C.

Both L_v and the boiling temperature of a material depend on pressure. Water boils at a lower temperature (about 95°C) in Denver than in Pittsburgh because Denver is at higher elevation and the average atmospheric pressure is lower. The heat of vaporization is somewhat greater at this lower pressure, about 2.27×10^6 J/kg.

Figure 17.20 summarizes these ideas about phase changes. **Table 17.4** lists heats of fusion and vaporization for some materials and their melting and boiling temperatures at normal atmospheric pressure. Very few *elements* have melting temperatures in the vicinity of ordinary room temperatures; one of the few is the metal gallium, shown in **Fig. 17.21**.

Figure **17.21** The metal gallium, shown here melting in a person's hand, is one of the few elements that melt in the vicinity of room temperature. Its melting temperature is 29.8°C, and its heat of fusion is 8.04×10^4 J/kg.

TABLE 17.4 Heats of Fusion and Vaporization

	Normal Melting Point		Heat of Fusion, L_f	Normal Boiling Point		Heat of Vaporization, L_v
Substance	**K**	**°C**	**(J/kg)**	**K**	**°C**	**(J/kg)**
Helium	*	*	*	4.216	−268.93	20.9×10^3
Hydrogen	13.84	−259.31	58.6×10^3	20.26	−252.89	452×10^3
Nitrogen	63.18	−209.97	25.5×10^3	77.34	−195.8	201×10^3
Oxygen	54.36	−218.79	13.8×10^3	90.18	−183.0	213×10^3
Ethanol	159	−114	104.2×10^3	351	78	854×10^3
Mercury	234	−39	11.8×10^3	630	357	272×10^3
Water	273.15	0.00	334×10^3	373.15	100.00	2256×10^3
Sulfur	392	119	38.1×10^3	717.75	444.60	326×10^3
Lead	600.5	327.3	24.5×10^3	2023	1750	871×10^3
Antimony	903.65	630.50	165×10^3	1713	1440	561×10^3
Silver	1233.95	960.80	88.3×10^3	2466	2193	2336×10^3
Gold	1336.15	1063.00	64.5×10^3	2933	2660	1578×10^3
Copper	1356	1083	134×10^3	1460	1187	5069×10^3

*A pressure in excess of 25 atmospheres is required to make helium solidify. At 1 atmosphere pressure, helium remains a liquid down to absolute zero.

Figure 17.22 When this airplane flew into a cloud at a temperature just below freezing, the plane struck supercooled water droplets in the cloud that rapidly crystallized and formed ice on the plane's nose (shown here) and wings. Such in-flight icing can be extremely hazardous, which is why commercial airliners are equipped with devices to remove ice.

A substance can sometimes change directly from the solid to the gaseous phase. This process is called *sublimation,* and the solid is said to *sublime.* The corresponding heat is called the *heat of sublimation,* L_s. Liquid carbon dioxide cannot exist at a pressure lower than about 5×10^5 Pa (about 5 atm), and "dry ice" (solid carbon dioxide) sublimes at atmospheric pressure. Sublimation of water from frozen food causes freezer burn. The reverse process, a phase change from gas to solid, occurs when frost forms on cold objects such as refrigerator cooling coils.

Very pure water can be cooled several degrees below the freezing temperature without freezing; the resulting unstable state is described as *supercooled.* When a small ice crystal is dropped in or the water is agitated, it crystallizes within a second or less (**Fig. 17.22**). Supercooled water *vapor* condenses quickly into fog droplets when a disturbance, such as dust particles or ionizing radiation, is introduced. This principle is used in "seeding" clouds, which often contain supercooled water vapor, to cause condensation and rain.

A liquid can sometimes be *superheated* above its normal boiling temperature. Any small disturbance such as agitation causes local boiling with bubble formation.

Steam heating systems for buildings use a boiling–condensing process to transfer heat from the furnace to the radiators. Each kilogram of water that is turned to steam in the boiler absorbs over 2×10^6 J (the heat of vaporization L_v of water) from the boiler and gives it up when it condenses in the radiators. Boiling–condensing processes are also used in refrigerators, air conditioners, and heat pumps. We'll discuss these systems in Chapter 20.

The temperature-control mechanisms of many warm-blooded animals make use of heat of vaporization, removing heat from the body by using it to evaporate water from the tongue (panting) or from the skin (sweating). Such *evaporative cooling* enables humans to maintain normal body temperature in hot, dry desert climates where the air temperature may reach 55°C (about 130°F). The skin temperature may be as much as 30°C cooler than the surrounding air. Under these conditions a normal person may perspire several liters per day, and this lost water must be replaced. Evaporative cooling also explains why you feel cold when you first step out of a swimming pool (**Fig. 17.23**).

Figure 17.23 The water may be warm and it may be a hot day, but these children will feel cold when they first step out of the swimming pool. That's because as water evaporates from their skin, it removes the heat of vaporization from their bodies. To stay warm, they will need to dry off immediately.

Evaporative cooling is also used to condense and recirculate "used" steam in coal-fired or nuclear-powered electric-generating plants. That's what goes on in the large, tapered concrete towers that you see at such plants.

Chemical reactions such as combustion are analogous to phase changes in that they involve definite quantities of heat. Complete combustion of 1 gram of gasoline produces about 46,000 J or about 11,000 cal, so the **heat of combustion** L_c of gasoline is

$$L_c = 46{,}000 \text{ J/g} = 4.6 \times 10^7 \text{ J/kg}$$

Energy values of foods are defined similarly. When we say that a gram of peanut butter "contains 6 calories," we mean that 6 kcal of heat (6000 cal or 25,000 J) is released when the carbon and hydrogen atoms in the peanut butter react with oxygen (with the help of enzymes) and are completely converted to CO_2 and H_2O. Not all of this energy is directly useful for mechanical work. We'll study the *efficiency* of energy utilization in Chapter 20.

Heat Calculations

Let's look at some examples of calorimetry calculations (calculations with heat). The basic principle is very simple: When heat flow occurs between two objects that are isolated from their surroundings, the amount of heat lost by one object must equal the amount gained by the other. Heat is energy in transit, so this principle is really just conservation of energy. Calorimetry, dealing entirely with one conserved quantity, is in many ways the simplest of all physical theories!

PROBLEM-SOLVING STRATEGY 17.2 Calorimetry Problems

IDENTIFY *the relevant concepts:* When heat flow occurs between two or more objects that are isolated from their surroundings, the *algebraic sum* of the quantities of heat transferred to all the objects is zero. We take a quantity of heat *added* to an object as *positive* and a quantity *leaving* an object as *negative*.

SET UP *the problem* using the following steps:

1. Identify the objects that exchange heat.
2. Each object may undergo a temperature change only, a phase change at constant temperature, or both. Use Eq. (17.13) for the heat transferred in a temperature change and Eq. (17.20) for the heat transferred in a phase change.
3. Consult Table 17.3 for values of specific heat or molar heat capacity and Table 17.4 for heats of fusion or vaporization.
4. List the known and unknown quantities and identify the target variables.

EXECUTE *the solution* as follows:

1. Use Eq. (17.13) and/or Eq. (17.20) and the energy-conservation relationship $\sum Q = 0$ to solve for the target variables. Ensure that you use the correct algebraic signs for Q and ΔT terms, and that you correctly write $\Delta T = T_{\text{final}} - T_{\text{initial}}$ and not the reverse.
2. If a phase change occurs, you may not know in advance whether all, or only part, of the material undergoes a phase change. Make a reasonable guess; if that leads to an unreasonable result (such as a final temperature higher or lower than any initial temperature), the guess was wrong. Try again!

EVALUATE *your answer:* Double-check your calculations, and ensure that the results are physically sensible.

EXAMPLE 17.7 A temperature change with no phase change

WITH VARIATION PROBLEMS

A camper pours 0.300 kg of coffee, initially in a pot at 70.0°C, into a 0.120 kg aluminum cup initially at 20.0°C. What is the equilibrium temperature? Assume that coffee has the same specific heat as water and that no heat is exchanged with the surroundings.

IDENTIFY and SET UP The target variable is the common final temperature T of the cup and coffee. No phase changes occur, so we need only Eq. (17.13). With subscripts C for coffee, W for water, and Al for aluminum, we have $T_{0C} = 70.0°\text{C}$ and $T_{0Al} = 20.0°\text{C}$; Table 17.3 gives $c_W = 4190\ \text{J/kg}\cdot\text{K}$ and $c_{Al} = 910\ \text{J/kg}\cdot\text{K}$.

EXECUTE The (negative) heat gained by the coffee is $Q_C = m_C c_W \Delta T_C$. The (positive) heat gained by the cup is $Q_{Al} = m_{Al} c_{Al} \Delta T_{Al}$. We set $Q_C + Q_{Al} = 0$ (see Problem-Solving Strategy 17.2) and substitute $\Delta T_C = T - T_{0C}$ and $\Delta T_{Al} = T - T_{0Al}$:

$$Q_C + Q_{Al} = m_C c_W \Delta T_C + m_{Al} c_{Al} \Delta T_{Al} = 0$$

$$m_C c_W (T - T_{0C}) + m_{Al} c_{Al} (T - T_{0Al}) = 0$$

Then we solve this expression for the final temperature T. A little algebra gives

$$T = \frac{m_C c_W T_{0C} + m_{Al} c_{Al} T_{0Al}}{m_C c_W + m_{Al} c_{Al}} = 66.0°\text{C}$$

EVALUATE The final temperature is much closer to the initial temperature of the coffee than to that of the cup; water has a much higher specific heat than aluminum, and we have more than twice as much mass of water. We can also find the quantities of heat by substituting the value $T = 66.0°\text{C}$ back into the original equations. We find $Q_C = -5.0 \times 10^3$ J and $Q_{Al} = +5.0 \times 10^3$ J. As expected, Q_C is negative: The coffee loses heat to the cup.

KEYCONCEPT In a calorimetry problem in which two objects at different temperatures interact by exchanging heat, energy is conserved: The sum of the heat flows (one positive, one negative) into the two objects is zero. The heat flow stops when the two objects reach the same temperature.

EXAMPLE 17.8 Changes in both temperature and phase

WITH VARIATION PROBLEMS

A glass contains 0.25 kg of Omni-Cola (mostly water) initially at 25°C. How much ice, initially at −20°C, must you add to obtain a final temperature of 0°C with all the ice melted? Ignore the heat capacity of the glass.

IDENTIFY and SET UP The Omni-Cola and ice exchange heat. The cola undergoes a temperature change; the ice undergoes both a temperature change and a phase change from solid to liquid. We use subscripts C for cola, I for ice, and W for water. The target variable is the mass of ice, m_I. We use Eq. (17.13) to obtain an expression for the amount of heat involved in cooling the drink to $T = 0°\text{C}$ and warming the ice to $T = 0°\text{C}$, and Eq. (17.20) to obtain an expression for the heat required to melt the ice at 0°C. We have $T_{0C} = 25°\text{C}$ and $T_{0I} = -20°\text{C}$, Table 17.3 gives $c_W = 4190\ \text{J/kg}\cdot\text{K}$ and $c_I = 2100\ \text{J/kg}\cdot\text{K}$, and Table 17.4 gives $L_f = 3.34 \times 10^5$ J/kg.

EXECUTE From Eq. (17.13), the (negative) heat gained by the Omni-Cola is $Q_C = m_C c_W \Delta T_C$. The (positive) heat gained by the ice in warming is $Q_I = m_I c_I \Delta T_I$. The (positive) heat required to melt the ice is $Q_2 = m_I L_f$. We set $Q_C + Q_I + Q_2 = 0$, insert $\Delta T_C = T - T_{0C}$ and $\Delta T_I = T - T_{0I}$, and solve for m_I:

$$m_C c_W \Delta T_C + m_I c_I \Delta T_I + m_I L_f = 0$$

$$m_C c_W (T - T_{0C}) + m_I c_I (T - T_{0I}) + m_I L_f = 0$$

$$m_I [c_I (T - T_{0I}) + L_f] = -m_C c_W (T - T_{0C})$$

$$m_I = m_C \frac{c_W (T_{0C} - T)}{c_I (T - T_{0I}) + L_f}$$

Substituting numerical values, we find that $m_I = 0.070\ \text{kg} = 70$ g.

EVALUATE Three or four medium-size ice cubes would make about 70 g, which seems reasonable given the 250 g of Omni-Cola to be cooled.

KEYCONCEPT When heat flows between two objects and one or both of them change phase, your calculations must include the heat required to cause the phase change. This depends on the object's mass and material and on which phase change occurs.

EXAMPLE 17.9 What's cooking?

WITH VARIATION PROBLEMS

A hot copper pot of mass 2.0 kg (including its copper lid) is at a temperature of 150°C. You pour 0.10 kg of cool water at 25°C into the pot, then quickly replace the lid so no steam can escape. Find the final temperature of the pot and its contents, and determine the phase of the water (liquid, gas, or a mixture). Assume that no heat is lost to the surroundings.

IDENTIFY and SET UP The water and the pot exchange heat. Three outcomes are possible: (1) No water boils, and the final temperature T is less than 100°C; (2) some water boils, giving a mixture of water and steam at 100°C; or (3) all the water boils, giving 0.10 kg of steam at 100°C or greater. We use Eq. (17.13) for the heat transferred in a temperature change and Eq. (17.20) for the heat transferred in a phase change.

EXECUTE First consider case (1), which parallels Example 17.8 exactly. The equation that states that the heat flow into the water equals the heat flow out of the pot is

$$Q_{\mathrm{W}} + Q_{\mathrm{Cu}} = m_{\mathrm{W}} c_{\mathrm{W}} (T - T_{0\mathrm{W}}) + m_{\mathrm{Cu}} c_{\mathrm{Cu}} (T - T_{0\mathrm{Cu}}) = 0$$

Here we use subscripts W for water and Cu for copper, with $m_{\mathrm{W}} = 0.10$ kg, $m_{\mathrm{Cu}} = 2.0$ kg, $T_{0\mathrm{W}} = 25°\mathrm{C}$, and $T_{0\mathrm{Cu}} = 150°\mathrm{C}$. From Table 17.3, $c_{\mathrm{W}} = 4190\ \mathrm{J/kg \cdot K}$ and $c_{\mathrm{Cu}} = 390\ \mathrm{J/kg \cdot K}$. Solving for the final temperature T and substituting these values, we get

$$T = \frac{m_{\mathrm{W}} c_{\mathrm{W}} T_{0\mathrm{W}} + m_{\mathrm{Cu}} c_{\mathrm{Cu}} T_{0\mathrm{Cu}}}{m_{\mathrm{W}} c_{\mathrm{W}} + m_{\mathrm{Cu}} c_{\mathrm{Cu}}} = 106°\mathrm{C}$$

But this is above the boiling point of water, which contradicts our assumption that no water boils! So at least some of the water boils.

So consider case (2), in which the final temperature is $T = 100°\mathrm{C}$ and some unknown fraction x of the water boils, where (if this case is correct) x is greater than zero and less than or equal to 1. The (positive) amount of heat needed to vaporize this water is $x m_{\mathrm{W}} L_{\mathrm{v}}$. The energy-conservation condition $Q_{\mathrm{W}} + Q_{\mathrm{Cu}} = 0$ is then

$$m_{\mathrm{W}} c_{\mathrm{W}} (100°\mathrm{C} - T_{0\mathrm{W}}) + x m_{\mathrm{W}} L_{\mathrm{v}} + m_{\mathrm{Cu}} c_{\mathrm{Cu}} (100°\mathrm{C} - T_{0\mathrm{Cu}}) = 0$$

We solve for the target variable x:

$$x = \frac{-m_{\mathrm{Cu}} c_{\mathrm{Cu}} (100°\mathrm{C} - T_{0\mathrm{Cu}}) - m_{\mathrm{W}} c_{\mathrm{W}} (100°\mathrm{C} - T_{0\mathrm{W}})}{m_{\mathrm{W}} L_{\mathrm{v}}}$$

With $L_{\mathrm{v}} = 2.256 \times 10^6$ J from Table 17.4, this yields $x = 0.034$. We conclude that the final temperature of the water and copper is 100°C and that $0.034(0.10\ \mathrm{kg}) = 0.0034\ \mathrm{kg} = 3.4$ g of the water is converted to steam at 100°C.

EVALUATE Had x turned out to be greater than 1, case (3) would have held; all the water would have vaporized, and the final temperature would have been greater than 100°C. Can you show that this would have been the case if we had originally poured less than 15 g of 25°C water into the pot?

KEYCONCEPT In many calorimetry problems you won't know whether or not a phase change occurs. To find out, try working the problem three ways (assuming no phase change, assuming part of the object changes phase, and assuming all of it changes phase). The way that leads to a sensible result is the correct one.

EXAMPLE 17.10 Combustion, temperature change, and phase change

In a particular camp stove, only 30% of the energy released in burning gasoline goes to heating the water in a pot on the stove. How much gasoline must we burn to heat 1.00 L (1.00 kg) of water from 20°C to 100°C and boil away 0.25 kg of it?

IDENTIFY and SET UP All of the water undergoes a temperature change and part of it undergoes a phase change, from liquid to gas. We determine the heat required to cause both of these changes, and then use the 30% combustion efficiency to determine the amount of gasoline that must be burned (the target variable). We use Eqs. (17.13) and (17.20) and the idea of heat of combustion.

EXECUTE To raise the temperature of the water from 20°C to 100°C requires

$$Q_1 = mc\,\Delta T = (1.00\ \mathrm{kg})(4190\ \mathrm{J/kg \cdot K})(80\ \mathrm{K}) = 3.35 \times 10^5\ \mathrm{J}$$

To boil 0.25 kg of water at 100°C requires

$$Q_2 = mL_{\mathrm{v}} = (0.25\ \mathrm{kg})(2.256 \times 10^6\ \mathrm{J/kg}) = 5.64 \times 10^5\ \mathrm{J}$$

The total energy needed is $Q_1 + Q_2 = 8.99 \times 10^5$ J. This is $30\% = 0.30$ of the total heat of combustion, which is therefore $(8.99 \times 10^5\ \mathrm{J})/0.30 = 3.00 \times 10^6$ J. As we mentioned earlier, the combustion of 1 g of gasoline releases 46,000 J, so the mass of gasoline required is $(3.00 \times 10^6\ \mathrm{J})/(46{,}000\ \mathrm{J/g}) = 65$ g, or a volume of about 0.09 L of gasoline.

EVALUATE This result suggests the tremendous amount of energy released in burning even a small quantity of gasoline. Another 123 g of gasoline would be required to boil away the remaining water; can you prove this?

KEYCONCEPT To find the amount of heat released when a quantity of substance undergoes combustion, multiply the mass that combusts by the heat of combustion of the substance.

TEST YOUR UNDERSTANDING OF SECTION 17.6 You take a block of ice at 0°C and add heat to it at a steady rate. It takes a time t to completely convert the block of ice to steam at 100°C. What do you have at time $t/2$? (i) All ice at 0°C; (ii) a mixture of ice and water at 0°C; (iii) water at a temperature between 0°C and 100°C; (iv) a mixture of water and steam at 100°C.

ANSWER

(iv) In time t the system goes from point b to point e in Fig. 17.20. According to this figure, at time $t/2$ (halfway along the horizontal axis from b to e), the system is at 100°C and is still boiling; that is, it is a mixture of liquid and gas. This says that most of the heat added goes into boiling the water.

17.7 MECHANISMS OF HEAT TRANSFER

We have talked about *conductors* and *insulators,* materials that permit or prevent heat transfer between objects. Now let's look in more detail at *rates* of energy transfer. In the kitchen you use a metal or glass pot for good heat transfer from the stove to whatever you're cooking, but your refrigerator is insulated with a material that *prevents* heat from flowing into the food inside the refrigerator. How do we describe the difference between these two materials?

The three mechanisms of heat transfer are conduction, convection, and radiation. *Conduction* occurs within an object or between two objects in contact. *Convection* depends on motion of mass from one region of space to another. *Radiation* is heat transfer by electromagnetic radiation, such as sunshine, with no need for matter to be present in the space between objects.

Conduction

If you hold one end of a copper rod and place the other end in a flame, the end you are holding gets hotter and hotter, even though it is not in direct contact with the flame. Heat reaches the cooler end by **conduction** through the material. The atoms in the hotter regions have more kinetic energy, on the average, than their cooler neighbors. They jostle their neighbors, giving them some of their energy. The neighbors jostle *their* neighbors, and so on through the material. The atoms don't move from one region of material to another, but their energy does.

Most metals also conduct heat by another, more effective mechanism. Within the metal, some electrons can leave their parent atoms and wander through the metal. These "free" electrons can rapidly carry energy from hotter to cooler regions of the metal, so metals are generally good conductors of heat. A metal rod at 20°C feels colder than a piece of wood at 20°C because heat can flow more easily from your hand into the metal. The presence of "free" electrons also causes most metals to be good electrical conductors.

In conduction, the direction of heat flow is always from higher to lower temperature. **Figure 17.24a** shows a rod of conducting material with cross-sectional area A and length L. The left end of the rod is kept at a temperature T_H and the right end at a lower temperature T_C, so heat flows from left to right. The sides of the rod are covered by an ideal insulator, so no heat transfer occurs at the sides.

When a quantity of heat dQ is transferred through the rod in a time dt, the rate of heat flow is dQ/dt. We call this rate the **heat current,** denoted by H. That is, $H = dQ/dt$. Experiments show that the heat current is proportional to the cross-sectional area A of the rod (Fig. 17.24b) and to the temperature difference $(T_H - T_C)$ and is inversely proportional to the rod length L (Fig. 17.24c):

Rate of heat flow · Temperatures of hot and cold ends of rod

Heat current in conduction

$$H = \frac{dQ}{dt} = kA\frac{T_H - T_C}{L} \qquad (17.21)$$

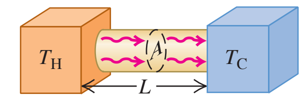
Length of rod · Thermal conductivity of rod material · Cross-sectional area of rod

The quantity $(T_H - T_C)/L$ is the temperature difference *per unit length;* it is called the magnitude of the **temperature gradient.** The numerical value of the **thermal conductivity** k depends on the material of the rod. Materials with large k are good conductors of heat; materials with small k are poor conductors, or insulators. Equation (17.21) also gives the heat current through a slab or through *any* homogeneous object with uniform cross section A perpendicular to the direction of flow; L is the length of the heat-flow path.

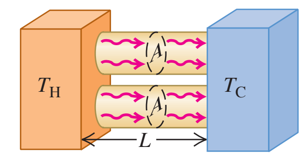
The units of heat current H are units of energy per time, or power; the SI unit of heat current is the watt $(1\ \text{W} = 1\ \text{J/s})$. We can find the units of k by solving Eq. (17.21) for k; you can show that the SI units are $\text{W/m}\cdot\text{K}$. **Table 17.5** gives some numerical values of k.

Figure **17.24** Steady-state heat flow due to conduction in a uniform rod.

(a) Heat current H



(b) Doubling the cross-sectional area of the conductor doubles the heat current (H is proportional to A).



(c) Doubling the length of the conductor halves the heat current (H is inversely proportional to L).

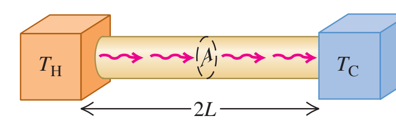


TABLE 17.5 Thermal Conductivities

Substance	k (W/m · K)
Metals	
Aluminum	205.0
Brass	109.0
Copper	385.0
Lead	34.7
Mercury	8.3
Silver	406.0
Steel	50.2
Solids (representative values)	
Brick, insulating	0.15
Brick, red	0.6
Concrete	0.8
Cork	0.04
Felt	0.04
Fiberglass	0.04
Glass	0.8
Ice	1.6
Rock wool	0.04
Styrofoam	0.027
Wood	0.12–0.04
Gases	
Air	0.024
Argon	0.016
Helium	0.14
Hydrogen	0.14
Oxygen	0.023

BIO APPLICATION Fur Versus Blubber The fur of an arctic fox is a good thermal insulator because it traps air, which has a low thermal conductivity k. (The value $k = 0.04\ \mathrm{W/m \cdot K}$ for fur is higher than for air, $k = 0.024\ \mathrm{W/m \cdot K}$, because fur also includes solid hairs.) The layer of fat beneath a bowhead whale's skin, called blubber, has six times the thermal conductivity of fur ($k = 0.24\ \mathrm{W/m \cdot K}$). So a 6 cm thickness of blubber ($L = 6$ cm) is required to give the same insulation as 1 cm of fur.

The thermal conductivity of "dead" (nonmoving) air is very small. A wool sweater keeps you warm because it traps air between the fibers. Many insulating materials such as Styrofoam and fiberglass are mostly dead air.

If the temperature varies in a nonuniform way along the length of the conducting rod, we introduce a coordinate x along the length and generalize the temperature gradient to be dT/dx. The corresponding generalization of Eq. (17.21) is

$$H = \frac{dQ}{dt} = -kA\frac{dT}{dx} \tag{17.22}$$

The negative sign indicates that heat flows in the direction of *decreasing* temperature. If temperature increases with increasing x, then $dT/dx > 0$ and $H < 0$; the negative value of H in this case means that heat flows in the negative x-direction, from high to low temperature.

For thermal insulation in buildings, engineers use the concept of **thermal resistance,** denoted by R. The thermal resistance R of a slab of material with area A is defined so that the heat current H through the slab is

$$H = \frac{A(T_\mathrm{H} - T_\mathrm{C})}{R} \tag{17.23}$$

where T_H and T_C are the temperatures on the two sides of the slab. Comparing this with Eq. (17.21), we see that R is given by

$$R = \frac{L}{k} \tag{17.24}$$

where L is the thickness of the slab. The SI unit of R is $1\ \mathrm{m^2 \cdot K/W}$. In the units used for commercial insulating materials in the United States, H is expressed in Btu/h, A is in $\mathrm{ft^2}$, and $T_\mathrm{H} - T_\mathrm{C}$ in F°. ($1\ \mathrm{Btu/h} = 0.293\ \mathrm{W}$.) The units of R are then $\mathrm{ft^2 \cdot F^\circ \cdot h/Btu}$, though values of R are usually quoted without units; a 6-inch-thick layer of fiberglass has an R value of 19 (that is, $R = 19\ \mathrm{ft^2 \cdot F^\circ \cdot h/Btu}$), a 2-inch-thick slab of polyurethane foam has an R value of 12, and so on. Doubling the thickness doubles the R value. Common practice in new construction in severe northern climates is to specify R values of around 30 for exterior walls and ceilings. When the insulating material is in layers, such as a plastered wall, fiberglass insulation, and wood exterior siding, the R values are additive. Do you see why?

PROBLEM-SOLVING STRATEGY 17.3 Heat Conduction

IDENTIFY *the relevant concepts:* Heat conduction occurs whenever two objects at different temperatures are placed in contact.

SET UP *the problem* using the following steps:

1. Identify the direction of heat flow (from hot to cold). In Eq. (17.21), L is measured along this direction, and A is an area perpendicular to this direction. You can often approximate an irregular-shaped container with uniform wall thickness as a flat slab with the same thickness and total wall area.
2. List the known and unknown quantities and identify the target variable.

EXECUTE *the solution* as follows:

1. If heat flows through a single object, use Eq. (17.21) to solve for the target variable.
2. If the heat flows through two different materials in succession (in *series*), the temperature T at the interface between them is intermediate between T_H and T_C, so that the temperature differences across the two materials are $(T_\mathrm{H} - T)$ and $(T - T_\mathrm{C})$. In steady-state heat flow, the same heat must pass through both materials, so the heat current H must be the *same* in both materials.
3. If heat flows through two or more *parallel* paths, then the total heat current H is the sum of the currents $H_1, H_2, \ldots$ for the separate paths. An example is heat flow from inside a room to outside, both through the glass in a window and through the surrounding wall. In parallel heat flow the temperature difference is the same for each path, but L, A, and k may be different for each path.
4. Be consistent with units. If k is expressed in $\mathrm{W/m \cdot K}$, for example, use distances in meters, heat in joules, and T in kelvins.

EVALUATE *your answer:* Are the results physically reasonable?

EXAMPLE 17.11 Conduction into a picnic cooler

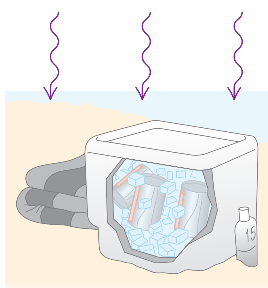
WITH VARIATION PROBLEMS

A Styrofoam cooler (**Fig. 17.25a**) has total wall area (including the lid) of $0.80\ \text{m}^2$ and wall thickness 2.0 cm. It is filled with ice, water, and cans of Omni-Cola, all at 0°C. What is the rate of heat flow into the cooler if the temperature of the outside wall is 30°C? How much ice melts in 3 hours?

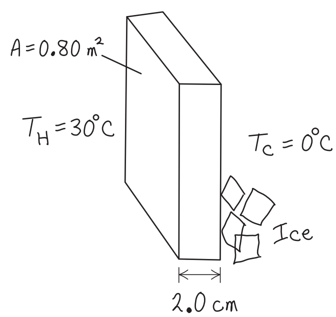
IDENTIFY and SET UP The target variables are the heat current H and the mass m of ice melted. We use Eq. (17.21) to determine H and Eq. (17.20) to determine m.

Figure **17.25** Conduction of heat across the walls of a Styrofoam cooler.

(a) A cooler at the beach



(b) Our sketch for this problem



EXECUTE We assume that the total heat flow is the same as it would be through a flat Styrofoam slab of area $0.80\ \text{m}^2$ and thickness $2.0\ \text{cm} = 0.020\ \text{m}$ (Fig. 17.25b). We find k from Table 17.5. From Eq. (17.21),

$$H = kA\frac{T_H - T_C}{L} = (0.027\ \text{W/m}\cdot\text{K})(0.80\ \text{m}^2)\frac{30°\text{C} - 0°\text{C}}{0.020\ \text{m}}$$
$$= 32.4\ \text{W} = 32.4\ \text{J/s}$$

The total heat flow is $Q = Ht$, with $t = 3\ \text{h} = 10{,}800\ \text{s}$. From Table 17.4, the heat of fusion of ice is $L_f = 3.34 \times 10^5\ \text{J/kg}$, so from Eq. (17.20) the mass of ice that melts is

$$m = \frac{Q}{L_f} = \frac{(32.4\ \text{J/s})(10{,}800\ \text{s})}{3.34 \times 10^5\ \text{J/kg}} = 1.0\ \text{kg}$$

EVALUATE The low heat current is a result of the low thermal conductivity of Styrofoam.

KEYCONCEPT If a temperature difference is maintained between the two sides of an object of thickness L and cross-sectional area A, there will be a steady heat current due to conduction from the high-temperature side to the low-temperature side. This conduction heat current is proportional to the temperature difference and to the ratio A/L.

EXAMPLE 17.12 Conduction through two bars I

WITH VARIATION PROBLEMS

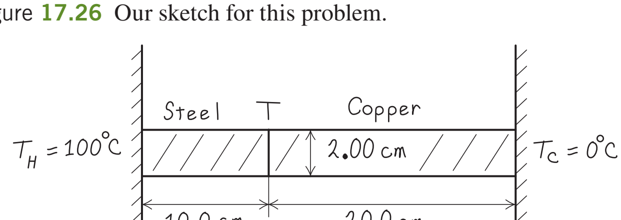
A steel bar 10.0 cm long is welded end to end to a copper bar 20.0 cm long. Each bar has a square cross section, 2.00 cm on a side. The free end of the steel bar is kept at 100°C by placing it in contact with steam, and the free end of the copper bar is kept at 0°C by placing it in contact with ice. Both bars are perfectly insulated on their sides. Find the steady-state temperature at the junction of the two bars and the total rate of heat flow through the bars.

IDENTIFY and SET UP **Figure 17.26** shows the situation. The heat currents in these end-to-end bars must be the same (see Problem-Solving Strategy 17.3). We are given "hot" and "cold" temperatures $T_H = 100°\text{C}$ and $T_C = 0°\text{C}$. With subscripts S for steel and Cu for copper, we write Eq. (17.21) separately for the heat currents H_S and H_{Cu} and set the resulting expressions equal to each other.

EXECUTE Setting $H_S = H_{Cu}$, we have from Eq. (17.21)

$$H_S = k_S A\frac{T_H - T}{L_S} = H_{Cu} = k_{Cu}A\frac{T - T_C}{L_{Cu}}$$

Figure **17.26** Our sketch for this problem.



We divide out the equal cross-sectional areas A and solve for T:

$$T = \frac{\dfrac{k_S}{L_S}T_H + \dfrac{k_{Cu}}{L_{Cu}}T_C}{\left(\dfrac{k_S}{L_S} + \dfrac{k_{Cu}}{L_{Cu}}\right)}$$

Substituting $L_S = 10.0\ \text{cm}$ and $L_{Cu} = 20.0\ \text{cm}$, the given values of T_H and T_C, and the values of k_S and k_{Cu} from Table 17.5, we find $T = 20.7°\text{C}$.

We can find the total heat current by substituting this value of T into either the expression for H_S or the one for H_{Cu}:

$$H_S = (50.2\ \text{W/m}\cdot\text{K})(0.0200\ \text{m})^2\frac{100°\text{C} - 20.7°\text{C}}{0.100\ \text{m}}$$
$$= 15.9\ \text{W}$$

$$H_{Cu} = (385\ \text{W/m}\cdot\text{K})(0.0200\ \text{m})^2\frac{20.7°\text{C}}{0.200\ \text{m}} = 15.9\ \text{W}$$

EVALUATE Even though the steel bar is shorter, the temperature drop across it is much greater (from 100°C to 20.7°C) than across the copper bar (from 20.7°C to 0°C). That's because steel is a much poorer conductor than copper.

KEYCONCEPT When there is a steady heat flow by conduction through two materials in succession, the heat current is the same in both materials: No energy is lost in going from one material to the next.

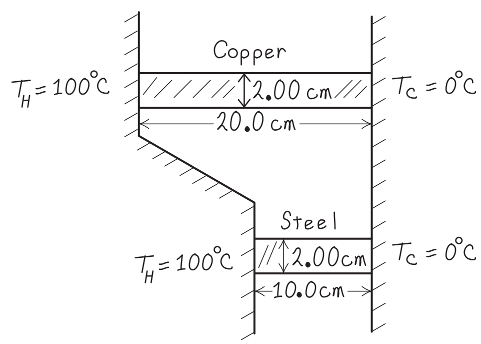
EXAMPLE 17.13 Conduction through two bars II

WITH VARIATION PROBLEMS

Suppose the two bars of Example 17.12 are separated. One end of each bar is kept at 100°C and the other end of each bar is kept at 0°C. What is the *total* heat current in the two bars?

IDENTIFY and SET UP **Figure 17.27** shows the situation. For each bar, $T_H - T_C = 100°C - 0°C = 100\ K$. The total heat current is the sum of the currents in the two bars, $H_S + H_{Cu}$.

Figure 17.27 Our sketch for this problem.



EXECUTE We write the heat currents for the two rods individually, and then add them to get the total heat current:

$$H = H_S + H_{Cu} = k_S A \frac{T_H - T_C}{L_S} + k_{Cu} A \frac{T_H - T_C}{L_{Cu}}$$

$$= (50.2\ W/m \cdot K)(0.0200\ m)^2 \frac{100\ K}{0.100\ m}$$

$$+ (385\ W/m \cdot K)(0.0200\ m)^2 \frac{100\ K}{0.200\ m}$$

$$= 20.1\ W + 77.0\ W = 97.1\ W$$

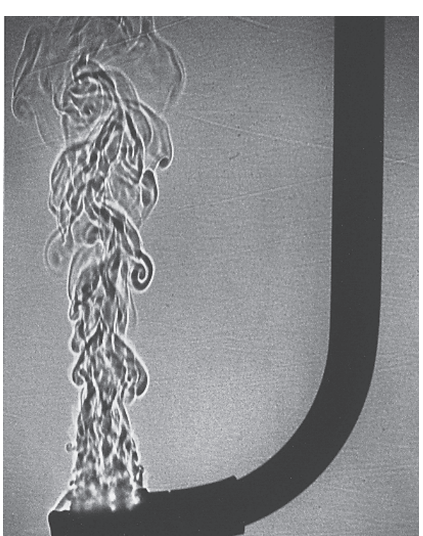
EVALUATE The heat flow in the copper bar is much greater than that in the steel bar, even though it is longer, because the thermal conductivity of copper is much larger. The total heat flow is greater than in Example 17.12 because the total cross section for heat flow is greater and because the full 100 K temperature difference appears across each bar.

KEYCONCEPT Even if two different objects have the same constant temperature difference between their ends, the heat current H through the two objects can be different. The value of H depends on the dimensions of the object and the thermal conductivity of the material of the object.

Convection

Convection is the transfer of heat by mass motion of a fluid from one region of space to another. Familiar examples include hot-air and hot-water home heating systems, the cooling system of an automobile engine, and the flow of blood in the body. If the fluid is circulated by a blower or pump, the process is called *forced convection;* if the flow is caused by differences in density due to thermal expansion, such as hot air rising, the process is called *free convection* (**Fig. 17.28**).

Figure 17.28 A heating element in the tip of this submerged tube warms the surrounding water, producing a complex pattern of free convection.



Free convection in the atmosphere plays a dominant role in determining the daily weather, and convection in the oceans is an important global heat-transfer mechanism. On a smaller scale, soaring hawks and glider pilots make use of thermal updrafts from the warm earth. The most important mechanism for heat transfer within the human body (needed to maintain nearly constant temperature in various environments) is *forced* convection of blood, with the heart as the pump.

Convective heat transfer is a very complex process, and there is no simple equation to describe it. Here are a few experimental facts:

1. The heat current due to convection is directly proportional to the surface area. That's why radiators and cooling fins, which use convection to transfer heat, have large surface areas.

2. The viscosity of fluids slows natural convection near a stationary surface. For air, this gives rise to a surface film that on a vertical surface typically has about the same insulating value as 1.3 cm of plywood (R value = 0.7). Forced convection decreases the thickness of this film, increasing the rate of heat transfer. This is the reason for the "wind-chill factor"; you get cold faster in a cold wind than in still air with the same temperature.

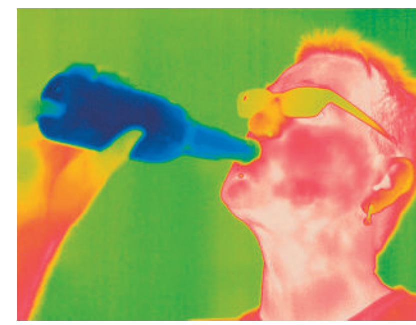
3. The heat current due to free convection is found to be approximately proportional to the $\frac{5}{4}$ power of the temperature difference between the surface and the main body of fluid.

Radiation

Radiation is the transfer of heat by electromagnetic waves such as visible light, infrared, and ultraviolet radiation. Everyone has felt the warmth of the sun's radiation and the intense heat from a charcoal grill or the glowing coals in a fireplace. Most of the heat from these very hot objects reaches you not by conduction or convection in the intervening air but by *radiation*. This heat transfer would occur even if there were nothing but vacuum between you and the source of heat.

Every object, even at ordinary temperatures, emits energy in the form of electromagnetic radiation. Around 20°C, nearly all the energy is carried by infrared waves with wavelengths much longer than those of visible light (see Fig. 17.4 and **Fig. 17.29**). As the temperature rises, the wavelengths shift to shorter values. At 800°C, an object emits enough visible radiation to appear "red-hot," although even at this temperature most of the energy is carried by infrared waves. At 3000°C, the temperature of an incandescent lamp filament, the radiation contains enough visible light that the object appears "white-hot."

Figure **17.29** This false-color infrared photograph reveals radiation emitted by various parts of the man's body. The strongest emission (colored red) comes from the warmest areas, while there is very little emission from the bottle of cold beverage.



The rate of energy radiation from a surface is proportional to the surface area A and to the fourth power of the absolute (Kelvin) temperature T. The rate also depends on the nature of the surface; we describe this dependence by a quantity e called **emissivity.** A dimensionless number between 0 and 1, e is the ratio of the rate of radiation from a particular surface to the rate of radiation from an equal area of an ideal radiating surface at the same temperature. Emissivity also depends somewhat on temperature. Thus we can to nine significant figures, its express the heat current $H = dQ/dt$ due to radiation from a surface as

$$\underbrace{H}_{\text{Heat current in radiation}} = \overbrace{A}^{\text{Area of emitting surface}}\overbrace{e}^{\text{Emissivity of surface}}\underbrace{\sigma}_{\text{Stefan–Boltzmann constant}}\underbrace{T^4}_{\text{Absolute temperature of surface}} \qquad (17.25)$$

This relationship is called the **Stefan–Boltzmann law** in honor of its late-19th-century discoverers. The **Stefan–Boltzmann constant** σ (Greek sigma) is a fundamental constant; to nine significant figures, its numerical value is

$$\sigma = 5.67037442 \times 10^{-8}\ \text{W/m}^2 \cdot \text{K}^4$$

You should check unit consistency in Eq. (17.25). Emissivity (e) is often larger for dark surfaces than for light ones. The emissivity of a smooth copper surface is about 0.3, but e for a dull black surface can be close to unity.

EXAMPLE 17.14 Heat transfer by radiation

WITH VARIATION PROBLEMS

A thin, square steel plate, 10 cm on a side, is heated in a blacksmith's forge to 800°C. If the emissivity is 0.60, what is the total rate of radiation of energy from the plate?

IDENTIFY and SET UP The target variable is H, the rate of emission of energy from the plate's two surfaces. We use Eq. (17.25) to calculate H.

EXECUTE The total surface area is $2(0.10\ \text{m})^2 = 0.020\ \text{m}^2$, and $T = 800°\text{C} = 1073\ \text{K}$. Then Eq. (17.25) gives

$$\begin{aligned} H &= Ae\sigma T^4 \\ &= (0.020\ \text{m}^2)(0.60)(5.67 \times 10^{-8}\ \text{W/m}^2 \cdot \text{K}^4)(1073\ \text{K})^4 = 900\ \text{W} \end{aligned}$$

EVALUATE The nearby blacksmith will easily feel the heat radiated from this plate.

KEYCONCEPT All objects emit energy in the form of electromagnetic radiation due to their temperature. The heat current of this radiation is proportional to the object's surface area, to the emissivity of its surface, and to the fourth power of the object's Kelvin temperature.

Radiation and Absorption

While an object at absolute temperature T is radiating, its surroundings at temperature T_s are also radiating, and the object *absorbs* some of this radiation. If it is in thermal equilibrium with its surroundings, $T = T_s$ and the rates of radiation and absorption must be equal. For this to be true, the rate of absorption must be given in general by $H = Ae\sigma T_s^4$.

Then the *net* rate of radiation from an object at temperature T with surroundings at temperature T_s is $Ae\sigma T^4 - Ae\sigma T_s^4$, or

$$\underbrace{H_{\text{net}}}_{\text{Net heat current in radiation}} = \overbrace{A}^{\text{Area of emitting surface}}\overbrace{e}^{\text{Emissivity of surface}}\underbrace{\sigma}_{\text{Stefan–Boltzmann constant}}(\underbrace{T^4 - T_s^4}_{\text{Absolute temperatures of surface }(T)\text{ and surroundings }(T_s)}) \qquad (17.26)$$

In Eq. (17.26) a positive value of H means a net heat flow *out of* the object. This will be the case if $T > T_s$.

EXAMPLE 17.15 Radiation from the human body

WITH VARIATION PROBLEMS

What is the total rate of radiation of energy from a human body with surface area $1.20\ \text{m}^2$ and surface temperature $30°\text{C} = 303\ \text{K}$? If the surroundings are at a temperature of 20°C, what is the *net* rate of radiative heat loss from the body? The emissivity of the human body is very close to unity, irrespective of skin pigmentation.

IDENTIFY and SET UP We must consider both the radiation that the body emits and the radiation that it absorbs from its surroundings. Equation (17.25) gives the rate of radiation of energy from the body, and Eq. (17.26) gives the net rate of heat loss.

EXECUTE Taking $e = 1$ in Eq. (17.25), we find that the body radiates at a rate

$$\begin{aligned} H &= Ae\sigma T^4 \\ &= (1.20\ \text{m}^2)(1)(5.67 \times 10^{-8}\ \text{W/m}^2 \cdot \text{K}^4)(303\ \text{K})^4 = 574\ \text{W} \end{aligned}$$

This loss is partly offset by absorption of radiation, which depends on the temperature of the surroundings. From Eq. (17.26), the *net* rate of radiative energy transfer is

$$\begin{aligned} H_{\text{net}} &= Ae\sigma(T^4 - T_s^4) \\ &= (1.20\ \text{m}^2)(1)(5.67 \times 10^{-8}\ \text{W/m}^2 \cdot \text{K}^4)[(303\ \text{K})^4 - (293\ \text{K})^4] \\ &= 72\ \text{W} \end{aligned}$$

EVALUATE The value of H_{net} is positive because the body is losing heat to its colder surroundings.

KEYCONCEPT An object at Kelvin temperature T emits electromagnetic radiation but also absorbs radiation from its surroundings at Kelvin temperature T_s. The *net* heat current is proportional to the object's surface area, to the emissivity of its surface, and to the difference between T^4 and T_s^4.

Applications of Radiation

Heat transfer by radiation is important in some surprising places. A premature baby in an incubator can be cooled dangerously by radiation if the walls of the incubator happen to be cold, even when the *air* in the incubator is warm. Some incubators regulate the air temperature by measuring the baby's skin temperature.

An object that is a good absorber must also be a good emitter. An ideal radiator, with emissivity $e = 1$, is also an ideal absorber, absorbing *all* of the radiation that strikes it. Such an ideal surface is called an ideal black body or simply a **blackbody.** Conversely, an ideal *reflector,* which absorbs *no* radiation at all, is also a very ineffective radiator.

This is the reason for the silver coatings on vacuum ("Thermos") bottles, invented by Sir James Dewar (1842–1923). A vacuum bottle has double glass walls. The air is pumped out of the spaces between the walls; this eliminates nearly all heat transfer by conduction and convection. The silver coating on the walls reflects most of the radiation from the contents back into the container, and the wall itself is a very poor emitter. Thus a vacuum bottle can keep coffee or soup hot for several hours. The Dewar flask, used to store very cold liquefied gases, is exactly the same in principle.

Radiation, Climate, and Climate Change

Our planet constantly absorbs radiation coming from the sun. In thermal equilibrium, the rate at which our planet absorbs solar radiation must equal the rate at which it emits radiation into space. The presence of an atmosphere on our planet has a significant effect on this equilibrium.

Most of the radiation emitted by the sun (which has a surface temperature of 5800 K) is in the visible part of the spectrum, to which our atmosphere is transparent. But the average surface temperature of the earth is only 287 K (14°C). Hence most of the radiation that our planet emits into space is infrared radiation, just like the radiation from the person shown in

Fig. 17.29. However, our atmosphere is *not* completely transparent to infrared radiation. This is because our atmosphere contains carbon dioxide (CO_2), which is its fourth most abundant constituent (after nitrogen, oxygen, and argon). Molecules of CO_2 in the atmosphere *absorb* some of the infrared radiation coming upward from the surface. They then re-radiate the absorbed energy, but some of the re-radiated energy is directed back down toward the surface instead of escaping into space. In order to maintain thermal equilibrium, the earth's surface must compensate for this by increasing its temperature T and hence its total rate of radiating energy (which is proportional to T^4). This phenomenon, called the **greenhouse effect,** makes our planet's surface temperature about 33°C higher than it would be if there were no atmospheric CO_2. If CO_2 were absent, the earth's average surface temperature would be below the freezing point of water, and life as we know it would be impossible.

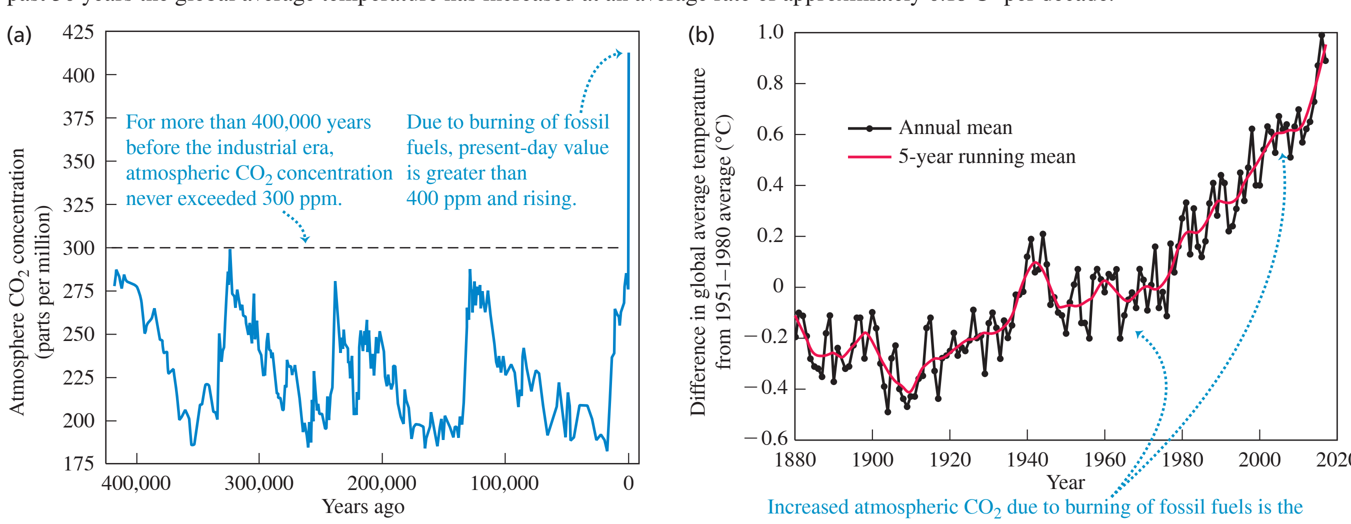
While atmospheric CO_2 has benefits, too much of it can have extremely negative consequences. Measurements of air trapped in ancient Antarctic ice show that over the past 650,000 years CO_2 has constituted less than 300 parts per million of our atmosphere. Since the beginning of the industrial age, however, the burning of fossil fuels such as coal and petroleum has elevated the atmospheric CO_2 concentration to unprecedented levels (**Fig. 17.30a**). As a consequence, since the 1950s the global average surface temperature has increased by 0.9°C and the earth has experienced the hottest years ever recorded (Fig. 17.30b). If we continue to consume fossil fuels at the same rate, by 2050 the atmospheric CO_2 concentration will reach 600 parts per million, well off the scale of Fig. 17.30a. The resulting temperature increase will have dramatic effects on global climate. In polar regions massive quantities of ice will melt and run from solid land to the sea, thus raising ocean levels worldwide and threatening the homes and lives of hundreds of millions of people who live near the coast. Coping with these threats is one of the greatest challenges facing 21st-century civilization.

TEST YOUR UNDERSTANDING OF SECTION 17.7 A room has one wall made of concrete, one wall made of copper, and one wall made of steel. All of the walls are the same size and at the same temperature of 20°C. Which wall feels coldest to the touch? (i) The concrete wall; (ii) the copper wall; (iii) the steel wall; (iv) all three walls feel equally cold.

ANSWER

(ii) When you touch one of the walls, heat flows from your hand to the lower-temperature wall. The more rapidly heat flows from your hand, the colder you'll feel. Equation (17.21) shows that the rate of heat flow is proportional to the thermal conductivity k. From Table 17.5, copper has a much higher thermal conductivity ($385.0\ \mathrm{W/m \cdot K}$) than steel ($50.2\ \mathrm{W/m \cdot K}$) or concrete ($0.8\ \mathrm{W/m \cdot K}$), and so the copper wall feels the coldest.

Figure **17.30** (a) Due to humans burning fossil fuels, the concentration of carbon dioxide in the atmosphere is now more than 33% greater than in the pre-industrial era. (b) Due to the increased CO_2 concentration, during the past 50 years the global average temperature has increased at an average rate of approximately 0.18 C° per decade.



CHAPTER 17 SUMMARY

Temperature and temperature scales: Two objects in thermal equilibrium must have the same temperature. A conducting material between two objects permits them to interact and come to thermal equilibrium; an insulating material impedes this interaction.

The Celsius and Fahrenheit temperature scales are based on the freezing ($0°C = 32°F$) and boiling ($100°C = 212°F$) temperatures of water. One Celsius degree equals $\frac{9}{5}$ Fahrenheit degrees. (See Example 17.1.)

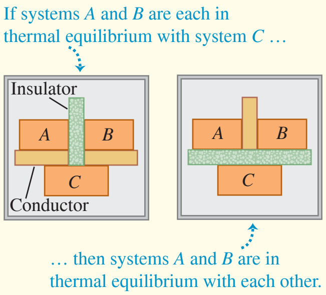
The Kelvin scale has its zero at the extrapolated zero-pressure temperature for a gas thermometer, $-273.15°C = 0$ K. In the gas-thermometer scale, the ratio of two temperatures T_1 and T_2 is defined to be equal to the ratio of the two corresponding gas-thermometer pressures p_1 and p_2.

$$T_F = \tfrac{9}{5}T_C + 32° \qquad (17.1)$$

$$T_C = \tfrac{5}{9}(T_F - 32°) \qquad (17.2)$$

$$T_K = T_C + 273.15 \qquad (17.3)$$

$$\frac{T_2}{T_1} = \frac{p_2}{p_1} \qquad (17.4)$$



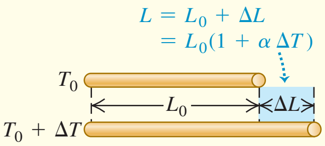
Thermal expansion and thermal stress: A temperature change ΔT causes a change in any linear dimension L_0 of a solid object. The change ΔL is approximately proportional to L_0 and ΔT. Similarly, a temperature change causes a change ΔV in the volume V_0 of any solid or liquid; ΔV is approximately proportional to V_0 and ΔT. The quantities α and β are the coefficients of linear expansion and volume expansion, respectively. For solids, $\beta = 3\alpha$. (See Examples 17.2 and 17.3.)

When a material is cooled or heated and held so it cannot contract or expand, it is under a tensile stress F/A. (See Example 17.4.)

$$\Delta L = \alpha L_0 \, \Delta T \qquad (17.6)$$

$$\Delta V = \beta V_0 \, \Delta T \qquad (17.8)$$

$$\frac{F}{A} = -Y\alpha \, \Delta T \qquad (17.12)$$



Heat, phase changes, and calorimetry: Heat is energy in transit from one object to another as a result of a temperature difference. Equations (17.13) and (17.18) give the quantity of heat Q required to cause a temperature change ΔT in a quantity of material with mass m and specific heat c (alternatively, with number of moles n and molar heat capacity $C = Mc$, where M is the molar mass and $m = nM$). When heat is added to an object, Q is positive; when it is removed, Q is negative. (See Examples 17.5 and 17.6.)

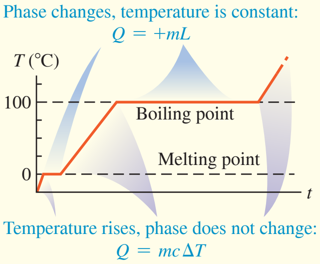
To change a mass m of a material to a different phase at the same temperature (such as liquid to vapor), a quantity of heat given by Eq. (17.20) must be added or subtracted. Here L is the heat of fusion, vaporization, or sublimation.

In an isolated system whose parts interact by heat exchange, the algebraic sum of the Q's for all parts of the system must be zero. (See Examples 17.7–17.10.)

$$Q = mc \, \Delta T \qquad (17.13)$$

$$Q = nC \, \Delta T \qquad (17.18)$$

$$Q = \pm mL \qquad (17.20)$$



Conduction, convection, and radiation: Conduction is the transfer of heat within materials without bulk motion of the materials. The heat current H depends on the area A through which the heat flows, the length L of the heat-flow path, the temperature difference $(T_H - T_C)$, and the thermal conductivity k of the material. (See Examples 17.11–17.13.)

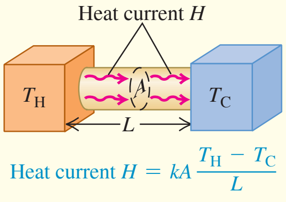
Convection is a complex heat-transfer process that involves mass motion from one region to another.

Radiation is energy transfer through electromagnetic radiation. The radiation heat current H depends on the surface area A, the emissivity e of the surface (a pure number between 0 and 1), and the Kelvin temperature T. Here σ is the Stefan–Boltzmann constant. The *net* radiation heat current H_{net} from an object at temperature T to its surroundings at temperature T_s depends on both T and T_s. (See Examples 17.14 and 17.15.)

$$H = \frac{dQ}{dt} = kA\frac{T_H - T_C}{L} \qquad (17.21)$$

$$H = Ae\sigma T^4 \qquad (17.25)$$

$$H_{net} = Ae\sigma(T^4 - T_s^4) \qquad (17.26)$$



Chapter 17 Media Assets

GUIDED PRACTICE

For assigned homework and other learning materials, go to Mastering Physics.

KEY EXAMPLE VARIATION PROBLEMS

Be sure to review EXAMPLES 17.2, 17.3, and 17.4 (Section 17.4) before attempting these problems.

VP17.4.1 A metal rod is 0.500 m in length at a temperature of 15.0°C. When you raise its temperature to 37.0°C, its length increases by 0.220 mm. (a) What is the coefficient of linear expansion of the metal? (b) If a second rod of the same metal has length 0.300 m at 25.0°C, how will its length change if the temperature drops to −20.0°C?

VP17.4.2 A copper mug that can hold 250 cm^3 of liquid is filled to the brim with ethanol at 20.0°C. If you lower the temperature of the mug and ethanol to −50.0°C, what is the maximum additional volume of ethanol you can add to the mug without spilling any? (See Table 17.2. Ethanol remains a liquid at temperatures down to −114°C.)

VP17.4.3 A cylindrical brass rod is 10.0 cm in length and 0.500 cm in radius at 25.0°C. How much force do you have to apply to each end of the rod to maintain its length when the temperature is decreased to 13.0°C? Are the required forces tensile or compressive? (See Table 17.1. Brass has Young's modulus 9.0×10^{10} Pa.)

VP17.4.4 A rod made of metal A is attached end to end to another rod made of metal B, making a combined rod of overall length L. The coefficients of linear expansion of metals A and B are α_A and α_B, respectively, and $\alpha_B > \alpha_A$. When the temperature of the combined rod is increased by ΔT, the overall length increases by ΔL. What was the initial length of the rod of metal A?

Be sure to review EXAMPLES 17.7, 17.8, and 17.9 (Section 17.6) before attempting these problems.

VP17.9.1 You place a piece of aluminum at 250.0°C in 5.00 kg of liquid water at 20.0°C. None of the water boils, and the final temperature of the water and aluminum is 22.0°C. What is the mass of the piece of aluminum? Assume no heat is exchanged with the container that holds the water. (See Table 17.3.)

VP17.9.2 You place an ice cube of mass 7.50×10^{-3} kg and temperature 0.00°C on top of a copper cube of mass 0.460 kg. All of the ice melts, and the final equilibrium temperature of the two substances is 0.00°C. What was the initial temperature of the copper cube? Assume no heat is exchanged with the surroundings. (See Tables 17.3 and 17.4.)

VP17.9.3 You have 1.60 kg of liquid ethanol at 28.0°C that you wish to cool. What mass of ice at initial temperature −5.00°C should you add to the ethanol so that all of the ice melts and the resulting ethanol–water mixture has temperature 10.0°C? Assume no heat is exchanged with the container that holds the ethanol. (See Tables 17.3 and 17.4.)

VP17.19.4 You put a silver ingot of mass 1.25 kg and initial temperature 315°C in contact with 0.250 kg of ice at initial temperature −8.00°C. Assume no heat is exchanged with the surroundings. (a) What is the final equilibrium temperature? (b) What fraction of the ice melts? (See Tables 17.3 and 17.4.)

Be sure to review EXAMPLES 17.11, 17.12, 17.13, 17.14, and 17.15 (Section 17.7) before attempting these problems.

VP17.15.1 A square pane of glass 0.500 m on a side is 6.00 mm thick. When the temperatures on the two sides of the glass are 25.0°C and −10.0°C, the heat current due to conduction through the glass is 1.10×10^3 W. (a) What is the thermal conductivity of the glass? (b) If the thickness of the glass is increased to 9.00 mm, what will be the heat current?

VP17.15.2 A brass rod and a lead rod, each 0.250 m long and each with cross-sectional area 2.00×10^{-4} m^2, are joined end to end to make a composite rod of overall length 0.500 m. The free end of the brass rod is maintained at a high temperature, and the free end of the lead rod is maintained at a low temperature. The temperature at the junction of the two rods is 185°C, and the heat current due to conduction through the composite rod is 6.00 W. What are the temperatures of (a) the free end of the brass rod and (b) the free end of the lead rod? (See Table 17.5.)

VP17.15.3 The emissivity of the surface of a star is approximately 1. The star Sirius A emits electromagnetic radiation at a rate of 9.7×10^{27} W and has a surface temperature of 9940 K. What is the radius of Sirius in meters and as a multiple of the sun's radius (6.96×10^8 m)?

VP17.15.4 A building in the desert is made of concrete blocks (emissivity 0.91) and has an exposed surface area of 525 m^2. If the building is maintained at 20.0°C but the temperature on a hot desert night is 35.0°C, what is the net rate at which the building absorbs energy by radiation?

BRIDGING PROBLEM Steady-State Heat Flow: Radiation and Conduction

One end of a solid cylindrical copper rod 0.200 m long and 0.0250 m in radius is inserted into a large block of solid hydrogen at its melting temperature, 13.84 K. The other end is blackened and exposed to thermal radiation from surrounding walls at 500.0 K. (Some telescopes in space employ a similar setup. A solid refrigerant keeps the telescope very cold—required for proper operation—even though it is exposed to direct sunlight.) The sides of the rod are insulated, so no energy is lost or gained except at the ends of the rod. (a) When equilibrium is reached, what is the temperature of the blackened end? The thermal conductivity of copper at temperatures near 20 K is 1670 W/m · K. (b) At what rate (in kg/h) does the solid hydrogen melt?

SOLUTION GUIDE

IDENTIFY and SET UP

1. Draw a sketch of the situation, showing all relevant dimensions.
2. List the known and unknown quantities, and identify the target variables.
3. In order for the rod to be in equilibrium, how must the radiation heat current from the walls into the blackened end of the rod compare to the conduction heat current from this end to the other end and into the solid hydrogen? Use your answers to select the appropriate equations for part (a).
4. How does the heat current from the rod into the hydrogen determine the rate at which the hydrogen melts? (*Hint:* See Table 17.4.) Use your answer to select the appropriate equations for part (b).

EXECUTE

5. Solve for the temperature of the blackened end of the rod. (*Hint:* Since copper is an excellent conductor of heat at low temperature, you can assume that the temperature of the blackened end is only slightly higher than 13.84 K.)
6. Use your result from step 5 to find the rate at which the hydrogen melts.

EVALUATE

7. Is your result from step 5 consistent with the hint in that step?
8. How would your results from steps 5 and 6 be affected if the rod had twice the radius?

PROBLEMS

•, ••, •••: Difficulty levels. **CP**: Cumulative problems incorporating material from earlier chapters. **CALC**: Problems requiring calculus. **DATA**: Problems involving real data, scientific evidence, experimental design, and/or statistical reasoning. **BIO**: Biosciences problems.

DISCUSSION QUESTIONS

Q17.1 Explain why it would not make sense to use a full-size glass thermometer to measure the temperature of a thimbleful of hot water.

Q17.2 If you heat the air inside a rigid, sealed container until its Kelvin temperature doubles, the air pressure in the container will also double. Is the same thing true if you double the Celsius temperature of the air in the container? Explain.

Q17.3 Many automobile engines have cast-iron cylinders and aluminum pistons. What kinds of problems could occur if the engine gets too hot? (The coefficient of volume expansion of cast iron is approximately the same as that of steel.)

Q17.4 Why do frozen water pipes burst? Would a mercury thermometer break if the temperature went below the freezing temperature of mercury? Why or why not?

Q17.5 Two objects made of the same material have the same external dimensions and appearance, but one is solid and the other is hollow. When their temperature is increased, is the overall volume expansion the same or different? Why?

Q17.6 Why is it sometimes possible to loosen caps on screw-top bottles by dipping the capped bottle briefly into hot water?

Q17.7 The inside of an oven is at a temperature of 200°C (392°F). You can put your hand in the oven without injury as long as you don't touch anything. But since the air inside the oven is also at 200°C, why isn't your hand burned just the same?

Q17.8 A newspaper article about the weather states that "the temperature of an object measures how much heat the object contains." Is this description correct? Why or why not?

Q17.9 A student asserts that a suitable unit for specific heat is $1\ \text{m}^2/\text{s}^2 \cdot \text{C}°$. Is she correct? Why or why not?

Q17.10 In some household air conditioners used in dry climates, air is cooled by blowing it through a water-soaked filter, evaporating some of the water. How does this cool the air? Would such a system work well in a high-humidity climate? Why or why not?

Q17.11 The units of specific heat c are $\text{J/kg} \cdot \text{K}$, but the units of heat of fusion L_f or heat of vaporization L_v are simply J/kg. Why do the units of L_f and L_v not include a factor of $(\text{K})^{-1}$ to account for a temperature change?

Q17.12 Why is a hot, humid day in the tropics generally more uncomfortable for human beings than a hot, dry day in the desert?

Q17.13 A piece of aluminum foil used to wrap a potato for baking in a hot oven can usually be handled safely within a few seconds after the potato is removed from the oven. The same is not true of the potato, however! Give two reasons for this difference.

Q17.14 Desert travelers sometimes keep water in a canvas bag. Some water seeps through the bag and evaporates. How does this cool the water inside the bag?

Q17.15 When you first step out of the shower, you feel cold. But as soon as you are dry you feel warmer, even though the room temperature does not change. Why?

Q17.16 The climate of regions adjacent to large bodies of water (like the Pacific and Atlantic coasts) usually features a narrower range of temperature than the climate of regions far from large bodies of water (like the prairies). Why?

Q17.17 When water is placed in ice-cube trays in a freezer, why doesn't the water freeze all at once when the temperature has reached 0°C? In fact, the water freezes first in a layer adjacent to the sides of the tray. Why?

Q17.18 Before giving you an injection, a physician swabs your arm with isopropyl alcohol at room temperature. Why does this make your arm feel cold? (*Hint:* The reason is *not* the fear of the injection! The boiling point of isopropyl alcohol is 82.4°C.)

Q17.19 A cold block of metal feels colder than a block of wood at the same temperature. Why? A *hot* block of metal feels hotter than a block of wood at the same temperature. Again, why? Is there any temperature at which the two blocks feel equally hot or cold? What temperature is this?

Q17.20 A person pours a cup of hot coffee, intending to drink it five minutes later. To keep the coffee as hot as possible, should she put cream in it now or wait until just before she drinks it? Explain.

Q17.21 When a freshly baked apple pie has just been removed from the oven, the crust and filling are both at the same temperature. Yet if you sample the pie, the filling will burn your tongue but the crust will not. Why is there a difference? (*Hint:* The filling is moist while the crust is dry.)

Q17.22 Old-time kitchen lore suggests that things cook better (evenly and without burning) in heavy cast-iron pots. What desirable characteristics do such pots have?

Q17.23 In coastal regions in the winter, the temperature over the land is generally colder than the temperature over the nearby ocean; in the summer, the reverse is usually true. Explain. (*Hint:* The specific heat of soil is only 0.2–0.8 times as great as that of water.)

Q17.24 It is well known that a potato bakes faster if a large nail is stuck through it. Why? Does an aluminum nail work better than a steel one? Why or why not? (*Note:* Don't try this in a microwave oven!) There is also a gadget on the market to hasten the roasting of meat; it consists of a hollow metal tube containing a wick and some water. This is claimed to work much better than a solid metal rod. How does it work?

Q17.25 Glider pilots in the Midwest know that thermal updrafts are likely to occur in the vicinity of freshly plowed fields. Why?

Q17.26 Some folks claim that ice cubes freeze faster if the trays are filled with hot water, because hot water cools off faster than cold water. What do you think?

Q17.27 We're lucky that the earth isn't in thermal equilibrium with the sun (which has a surface temperature of 5800 K). But why aren't the two objects in thermal equilibrium?

Q17.28 When energy shortages occur, magazine articles sometimes urge us to keep our homes at a constant temperature day and night to conserve fuel. They argue that when we turn down the heat at night, the walls, ceilings, and other areas cool off and must be reheated in the morning. So if we keep the temperature constant, these parts of the house will not cool off and will not have to be reheated. Does this argument make sense? Would we really save energy by following this advice?

EXERCISES

Section 17.2 Thermometers and Temperature Scales

17.1 • Convert the following Celsius temperatures to Fahrenheit: (a) −62.8°C, the lowest temperature ever recorded in North America (February 3, 1947, Snag, Yukon); (b) 56.7°C, the highest temperature ever recorded in the United States (July 10, 1913, Death Valley, California); (c) 31.1°C, the world's highest average annual temperature (Lugh Ferrandi, Somalia).

17.2 • **BIO** **Temperatures in Biomedicine.** (a) **Normal body temperature.** The average normal body temperature measured in the mouth is 310 K. What would Celsius and Fahrenheit thermometers read for this temperature? (b) **Elevated body temperature.** During very vigorous exercise, the body's temperature can go as high as 40°C. What would Kelvin and Fahrenheit thermometers read for this temperature? (c) **Temperature difference in the body.** The surface temperature of the body is normally about 7 C° lower than the internal temperature. Express this temperature difference in kelvins and in Fahrenheit degrees. (d) **Blood storage.** Blood stored at 4.0°C lasts safely for about 3 weeks, whereas blood stored at −160°C lasts for 5 years. Express both temperatures on the Fahrenheit and Kelvin scales. (e) **Heat stroke.** If the body's temperature is above 105°F for a prolonged period, heat stroke can result. Express this temperature on the Celsius and Kelvin scales.

17.3 • (a) On January 22, 1943, the temperature in Spearfish, South Dakota, rose from −4.0°F to 45.0°F in just 2 minutes. What was the temperature change in Celsius degrees? (b) The temperature in Browning, Montana, was 44.0°F on January 23, 1916. The next day the temperature plummeted to −56°F. What was the temperature change in Celsius degrees?

Section 17.3 Gas Thermometers and the Kelvin Scale

17.4 • Derive an equation that gives T_K as a function of T_F to the nearest hundredth of a degree. Solve the equation and thereby obtain an equation for T_F as a function of T_K.

17.5 •• You put a bottle of soft drink in a refrigerator and leave it until its temperature has dropped 10.0 K. What is its temperature change in (a) F° and (b) C°?

17.6 • (a) Calculate the one temperature at which Fahrenheit and Celsius thermometers agree with each other. (b) Calculate the one temperature at which Fahrenheit and Kelvin thermometers agree with each other.

17.7 • The pressure of a gas at the triple point of water is 1.35 atm. If its volume remains unchanged, what will its pressure be at the temperature at which CO_2 solidifies?

17.8 • Convert the following Kelvin temperatures to the Celsius and Fahrenheit scales: (a) the midday temperature at the surface of the moon (400 K); (b) the temperature at the tops of the clouds in the atmosphere of Saturn (95 K); (c) the temperature at the center of the sun $(1.55 \times 10^7\ \mathrm{K})$.

17.9 •• **A Constant-Volume Gas Thermometer.** An experimenter using a gas thermometer found the pressure at the triple point of water (0.01°C) to be 4.80×10^4 Pa and the pressure at the normal boiling point (100°C) to be 6.50×10^4 Pa. (a) Assuming that the pressure varies linearly with temperature, use these two data points to find the Celsius temperature at which the gas pressure would be zero (that is, find the Celsius temperature of absolute zero). (b) Does the gas in this thermometer obey Eq. (17.4) precisely? If that equation were precisely obeyed and the pressure at 100°C were 6.50×10^4 Pa, what pressure would the experimenter have measured at 0.01°C? (As we'll learn in Section 18.1, Eq. (17.4) is accurate only for gases at very low density.)

17.10 •• A constant-volume gas thermometer registers an absolute pressure corresponding to 325 mm of mercury when in contact with water at the triple point. What pressure does it read when in contact with water at the normal boiling point?

Section 17.4 Thermal Expansion

17.11 • The Humber Bridge in England has the world's longest single span, 1410 m. Calculate the change in length of the steel deck of the span when the temperature increases from −5.0°C to 18.0°C.

17.12 • One of the tallest buildings in the world is the Taipei 101 in Taiwan, at a height of 1671 feet. Assume that this height was measured on a cool spring day when the temperature was 15.5°C. You could use the building as a sort of giant thermometer on a hot summer day by carefully measuring its height. Suppose you do this and discover that the Taipei 101 is 0.471 foot taller than its official height. What is the temperature, assuming that the building is in thermal equilibrium with the air and that its entire frame is made of steel?

17.13 • A U.S. penny has a diameter of 1.9000 cm at 20.0°C. The coin is made of a metal alloy (mostly zinc) for which the coefficient of linear expansion is $2.6 \times 10^{-5}\ \mathrm{K}^{-1}$. What would its diameter be on a hot day in Death Valley (48.0°C)? On a cold night in the mountains of Greenland (−53°C)?

17.14 • **Ensuring a Tight Fit.** Aluminum rivets used in airplane construction are made slightly larger than the rivet holes and cooled by "dry ice" (solid CO_2) before being driven. If the diameter of a hole is 4.500 mm, what should be the diameter of a rivet at 23.0°C if its diameter is to equal that of the hole when the rivet is cooled to −78.0°C, the temperature of dry ice? Assume that the expansion coefficient remains constant at the value given in Table 17.1.

17.15 •• A copper cylinder is initially at 20.0°C. At what temperature will its volume be 0.150% larger than it is at 20.0°C?

17.16 •• A geodesic dome constructed with an aluminum framework is a nearly perfect hemisphere; its diameter measures 55.0 m on a winter day at a temperature of −15°C. How much more interior space does the dome have in the summer, when the temperature is 35°C?

17.17 •• A glass flask whose volume is 1000.00 cm^3 at 0.0°C is completely filled with mercury at this temperature. When flask and mercury are warmed to 55.0°C, 8.95 cm^3 of mercury overflow. If the coefficient of volume expansion of mercury is $18.0 \times 10^{-5}\ \mathrm{K}^{-1}$, compute the coefficient of volume expansion of the glass.

17.18 •• A steel tank is completely filled with 1.90 m^3 of ethanol when both the tank and the ethanol are at 32.0°C. When the tank and its contents have cooled to 18.0°C, what additional volume of ethanol can be put into the tank?

17.19 •• A machinist bores a hole of diameter 1.35 cm in a steel plate that is at 25.0°C. What is the cross-sectional area of the hole (a) at 25.0°C and (b) when the temperature of the plate is increased to 175°C? Assume that the coefficient of linear expansion remains constant over this temperature range.

17.20 • Consider a flat metal plate with width w and length l, so its area is $A = lw$. The metal has coefficient of linear expansion α. Derive an expression, in terms of α, that gives the change ΔA in area for a change ΔT in temperature.

17.21 •• Steel train rails are laid in 12.0-m-long segments placed end to end. The rails are laid on a winter day when their temperature is −9.0°C. (a) How much space must be left between adjacent rails if they are just to touch on a summer day when their temperature is 33.0°C? (b) If the rails are originally laid in contact, what is the stress in them on a summer day when their temperature is 33.0°C?

17.22 •• A brass rod is 185 cm long and 1.60 cm in diameter. What force must be applied to each end of the rod to prevent it from contracting when it is cooled from 120.0°C to 10.0°C?

17.23 • The increase in length of an aluminum rod is twice the increase in length of an Invar rod with only a third of the temperature increase. Find the ratio of the lengths of the two rods.

Section 17.5 Quantity of Heat

17.24 • In an effort to stay awake for an all-night study session, a student makes a cup of coffee by first placing a 200 W electric immersion heater in 0.320 kg of water. (a) How much heat must be added to the water to raise its temperature from 20.0°C to 80.0°C? (b) How much time is required? Assume that all of the heater's power goes into heating the water.

17.25 •• An aluminum tea kettle with mass 1.10 kg and containing 1.80 kg of water is placed on a stove. If no heat is lost to the surroundings, how much heat must be added to raise the temperature from 20.0°C to 85.0°C?

17.26 • BIO **Heat Loss During Breathing.** In very cold weather a significant mechanism for heat loss by the human body is energy expended in warming the air taken into the lungs with each breath. (a) On a cold winter day when the temperature is $-20°C$, what amount of heat is needed to warm to body temperature ($37°C$) the 0.50 L of air exchanged with each breath? Assume that the specific heat of air is $1020\ J/kg \cdot K$ and that 1.0 L of air has mass 1.3×10^{-3} kg. (b) How much heat is lost per hour if the respiration rate is 20 breaths per minute?

17.27 • BIO While running, a 70 kg student generates thermal energy at a rate of 1200 W. For the runner to maintain a constant body temperature of 37°C, this energy must be removed by perspiration or other mechanisms. If these mechanisms failed and the energy could not flow out of the student's body, for what amount of time could a student run before irreversible body damage occurred? (*Note:* Protein structures in the body are irreversibly damaged if body temperature rises to 44°C or higher. The specific heat of a typical human body is $3480\ J/kg \cdot K$, slightly less than that of water. The difference is due to the presence of protein, fat, and minerals, which have lower specific heats.)

17.28 •• **On-Demand Water Heaters.** Conventional hot-water heaters consist of a tank of water maintained at a fixed temperature. The hot water is to be used when needed. The drawbacks are that energy is wasted because the tank loses heat when it is not in use and that you can run out of hot water if you use too much. Some utility companies are encouraging the use of *on-demand* water heaters (also known as *flash heaters*), which consist of heating units to heat the water as you use it. No water tank is involved, so no heat is wasted. A typical household shower flow rate is 2.5 gal/min (9.46 L/min) with the tap water being heated from 50°F (10°C) to 120°F (49°C) by the on-demand heater. What rate of heat input (either electrical or from gas) is required to operate such a unit, assuming that all the heat goes into the water?

17.29 • You are given a sample of metal and asked to determine its specific heat. You weigh the sample and find that its weight is 28.4 N. You carefully add 1.25×10^4 J of heat energy to the sample and find that its temperature rises 18.0 C°. What is the sample's specific heat?

17.30 • CP A 25,000 kg subway train initially traveling at 15.5 m/s slows to a stop in a station and then stays there long enough for its brakes to cool. The station's dimensions are 65.0 m long by 20.0 m wide by 12.0 m high. Assuming all the work done by the brakes in stopping the train is transferred as heat uniformly to all the air in the station, by how much does the air temperature in the station rise? Take the density of the air to be $1.20\ kg/m^3$ and its specific heat to be $1020\ J/kg \cdot K$.

17.31 • CP While painting the top of an antenna 225 m in height, a worker accidentally lets a 1.00 L water bottle fall from his lunchbox. The bottle lands in some bushes at ground level and does not break. If a quantity of heat equal to the magnitude of the change in mechanical energy of the water goes into the water, what is its increase in temperature?

17.32 • CP A nail driven into a board increases in temperature. If we assume that 60% of the kinetic energy delivered by a 1.80 kg hammer with a speed of 7.80 m/s is transformed into heat that flows into the nail and does not flow out, what is the temperature increase of an 8.00 g aluminum nail after it is struck ten times?

17.33 •• CP A 15.0 g bullet traveling horizontally at 865 m/s passes through a tank containing 13.5 kg of water and emerges with a speed of 534 m/s. What is the maximum temperature increase that the water could have as a result of this event?

Section 17.6 Calorimetry and Phase Changes

17.34 • You have 750 g of water at 10.0°C in a large insulated beaker. How much boiling water at 100.0°C must you add to this beaker so that the final temperature of the mixture will be 75°C?

17.35 •• A 500.0 g chunk of an unknown metal, which has been in boiling water for several minutes, is quickly dropped into an insulating Styrofoam beaker containing 1.00 kg of water at room temperature (20.0°C). After waiting and gently stirring for 5.00 minutes, you observe that the water's temperature has reached a constant value of 22.0°C. (a) Assuming that the Styrofoam absorbs a negligibly small amount of heat and that no heat was lost to the surroundings, what is the specific heat of the metal? (b) Which is more useful for storing thermal energy: this metal or an equal weight of water? Explain. (c) If the heat absorbed by the Styrofoam actually is not negligible, how would the specific heat you calculated in part (a) be in error? Would it be too large, too small, or still correct? Explain.

17.36 • BIO **Treatment for a Stroke.** One suggested treatment for a person who has suffered a stroke is immersion in an ice-water bath at 0°C to lower the body temperature, which prevents damage to the brain. In one set of tests, patients were cooled until their internal temperature reached 32.0°C. To treat a 70.0 kg patient, what is the minimum amount of ice (at 0°C) you need in the bath so that its temperature remains at 0°C? The specific heat of the human body is $3480\ J/kg \cdot C°$, and recall that normal body temperature is 37.0°C.

17.37 •• A blacksmith cools a 1.20 kg chunk of iron, initially at 650.0°C, by trickling 15.0°C water over it. All of the water boils away, and the iron ends up at 120.0°C. How much water did the blacksmith trickle over the iron?

17.38 •• A copper calorimeter can with mass 0.100 kg contains 0.160 kg of water and 0.0180 kg of ice in thermal equilibrium at atmospheric pressure. If 0.750 kg of lead at 255°C is dropped into the calorimeter can, what is the final temperature? Assume that no heat is lost to the surroundings.

17.39 •• A copper pot with a mass of 0.500 kg contains 0.170 kg of water, and both are at 20.0°C. A 0.250 kg block of iron at 85.0°C is dropped into the pot. Find the final temperature of the system, assuming no heat loss to the surroundings.

17.40 • In a container of negligible mass, 0.200 kg of ice at an initial temperature of $-40.0°C$ is mixed with a mass m of water that has an initial temperature of 80.0°C. No heat is lost to the surroundings. If the final temperature of the system is 28.0°C, what is the mass m of the water that was initially at 80.0°C?

17.41 • A 6.00 kg piece of solid copper metal at an initial temperature T is placed with 2.00 kg of ice that is initially at $-20.0°C$. The ice is in an insulated container of negligible mass and no heat is exchanged with the surroundings. After thermal equilibrium is reached, there is 1.20 kg of ice and 0.80 kg of liquid water. What was the initial temperature of the piece of copper?

17.42 •• An ice-cube tray of negligible mass contains 0.290 kg of water at 18.0°C. How much heat must be removed to cool the water to 0.00°C and freeze it? Express your answer in joules, calories, and Btu.

17.43 • How much heat is required to convert 18.0 g of ice at $-10.0°C$ to steam at 100.0°C? Express your answer in joules, calories, and Btu.

17.44 •• An open container holds 0.550 kg of ice at $-15.0°C$. The mass of the container can be ignored. Heat is supplied to the container at the constant rate of 800.0 J/min for 500.0 min. (a) After how many minutes does the ice *start* to melt? (b) After how many minutes, from the time when the heating is first started, does the temperature begin to rise above 0.0°C? (c) Plot a curve showing the temperature as a function of the elapsed time.

17.45 • CP What must the initial speed of a lead bullet be at 25.0°C so that the heat developed when it is brought to rest will be just sufficient to melt it? Assume that all the initial mechanical energy of the bullet is converted to heat and that no heat flows from the bullet to its surroundings. (Typical rifles have muzzle speeds that exceed the speed of sound in air, which is 347 m/s at 25.0°C.)

17.46 •• BIO Steam Burns Versus Water Burns. What is the amount of heat input to your skin when it receives the heat released (a) by 25.0 g of steam initially at 100.0°C, when it is cooled to skin temperature (34.0°C)? (b) By 25.0 g of water initially at 100.0°C, when it is cooled to 34.0°C? (c) What does this tell you about the relative severity of burns from steam versus burns from hot water?

17.47 • BIO "The Ship of the Desert." Camels require very little water because they are able to tolerate relatively large changes in their body temperature. While humans keep their body temperatures constant to within one or two Celsius degrees, a dehydrated camel permits its body temperature to drop to 34.0°C overnight and rise to 40.0°C during the day. To see how effective this mechanism is for saving water, calculate how many liters of water a 400 kg camel would have to drink if it attempted to keep its body temperature at a constant 34.0°C by evaporation of sweat during the day (12 hours) instead of letting it rise to 40.0°C. (*Note:* The specific heat of a camel or other mammal is about the same as that of a typical human, 3480 J/kg · K. The heat of vaporization of water at 34°C is 2.42×10^6 J/kg.)

17.48 • BIO Evaporation of sweat is an important mechanism for temperature control in some warm-blooded animals. (a) What mass of water must evaporate from the skin of a 70.0 kg man to cool his body 1.00 C°? The heat of vaporization of water at body temperature (37°C) is 2.42×10^6 J/kg. The specific heat of a typical human body is 3480 J/kg · K (see Exercise 17.27). (b) What volume of water must the man drink to replenish the evaporated water? Compare to the volume of a soft-drink can (355 cm^3).

17.49 •• CP An asteroid with a diameter of 10 km and a mass of 2.60×10^{15} kg impacts the earth at a speed of 32.0 km/s, landing in the Pacific Ocean. If 1.00% of the asteroid's kinetic energy goes to boiling the ocean water (assume an initial water temperature of 10.0°C), what mass of water will be boiled away by the collision? (For comparison, the mass of water contained in Lake Superior is about 2×10^{15} kg.)

17.50 • A laboratory technician drops a 0.0850 kg sample of unknown solid material, at 100.0°C, into a calorimeter. The calorimeter can, initially at 19.0°C, is made of 0.150 kg of copper and contains 0.200 kg of water. The final temperature of the calorimeter can and contents is 26.1°C. Compute the specific heat of the sample.

17.51 •• An insulated beaker with negligible mass contains 0.250 kg of water at 75.0°C. How many kilograms of ice at −20.0°C must be dropped into the water to make the final temperature of the system 40.0°C?

17.52 • A 4.00 kg silver ingot is taken from a furnace at 750.0°C and placed on a large block of ice at 0.0°C. Assuming that all the heat given up by the silver is used to melt the ice, how much ice is melted?

17.53 •• A plastic cup of negligible mass contains 0.280 kg of an unknown liquid at a temperature of 30.0°C. A 0.0270 kg mass of ice at a temperature of 0.0°C is added to the liquid, and when thermal equilibrium is reached the temperature of the combined substances is 14.0°C. Assuming no heat is exchanged with the surroundings, what is the specific heat capacity of the unknown liquid?

Section 17.7 Mechanisms of Heat Transfer

17.54 •• Two rods, one made of brass and the other made of copper, are joined end to end. The length of the brass section is 0.300 m and the length of the copper section is 0.800 m. Each segment has cross-sectional area 0.00500 m^2. The free end of the brass segment is in boiling water and the free end of the copper segment is in an ice–water mixture, in both cases under normal atmospheric pressure. The sides of the rods are insulated so there is no heat loss to the surroundings. (a) What is the temperature of the point where the brass and copper segments are joined? (b) What mass of ice is melted in 5.00 min by the heat conducted by the composite rod?

17.55 •• A copper bar is welded end to end to a bar of an unknown metal. The two bars have the same lengths and cross-sectional areas. The free end of the copper bar is maintained at a temperature T_H that can be varied. The free end of the unknown metal is kept at 0.0°C. To measure the thermal conductivity of the unknown metal, you measure the temperature T at the junction between the two bars for several values of T_H. You plot your data as T versus T_H, both in kelvins, and find that your data are well fit by a straight line that has slope 0.710. What do your measurements give for the value of the thermal conductivity of the unknown metal?

17.56 •• One end of an insulated metal rod is maintained at 100.0°C, and the other end is maintained at 0.00°C by an ice–water mixture. The rod is 60.0 cm long and has a cross-sectional area of 1.25 cm^2. The heat conducted by the rod melts 8.50 g of ice in 10.0 min. Find the thermal conductivity k of the metal.

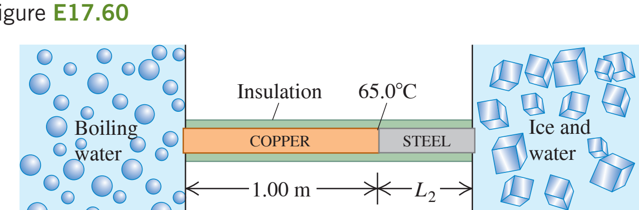
17.57 •• A carpenter builds an exterior house wall with a layer of wood 3.0 cm thick on the outside and a layer of Styrofoam insulation 2.2 cm thick on the inside wall surface. The wood has $k = 0.080$ W/m · K, and the Styrofoam has $k = 0.027$ W/m · K. The interior surface temperature is 19.0°C, and the exterior surface temperature is −10.0°C. (a) What is the temperature at the plane where the wood meets the Styrofoam? (b) What is the rate of heat flow per square meter through this wall?

17.58 • An electric kitchen range has a total wall area of 1.40 m^2 and is insulated with a layer of fiberglass 4.00 cm thick. The inside surface of the fiberglass has a temperature of 175°C, and its outside surface is at 35.0°C. The fiberglass has a thermal conductivity of 0.040 W/m · K. (a) What is the heat current through the insulation, assuming it may be treated as a flat slab with an area of 1.40 m^2? (b) What electric-power input to the heating element is required to maintain this temperature?

17.59 • Air has a very low thermal conductivity. This explains why we feel comfortable wearing short sleeves in a 20°C environment even though our body temperature is 37°C. Material objects feel cooler to our immediate touch than the air, owing to relatively high thermal conductivities. (a) Touch a few surfaces in a room-temperature environment and rank them in order of which feel the coolest to which feel the warmest. Objects that feel cooler have larger thermal conductivities. Consider a wood surface, a metallic surface, and a glass surface, and rank these in order from coolest to warmest. (b) How does your ranking compare to the thermal conductivities listed in Table 17.5?

17.60 • A long rod, insulated to prevent heat loss along its sides, is in perfect thermal contact with boiling water (at atmospheric pressure) at one end and with an ice–water mixture at the other (**Fig. E17.60**). The rod consists of a 1.00 m section of copper (one end in boiling water) joined end to end to a length L_2 of steel (one end in the ice–water mixture). Both sections of the rod have cross-sectional areas of 4.00 cm^2. The temperature of the copper–steel junction is 65.0°C after a steady state has been set up. (a) How much heat per second flows from the boiling water to the ice–water mixture? (b) What is the length L_2 of the steel section?

Figure **E17.60**



17.61 • A pot with a steel bottom 8.50 mm thick rests on a hot stove. The area of the bottom of the pot is 0.150 m^2. The water inside the pot is at 100.0°C, and 0.390 kg are evaporated every 3.00 min. Find the temperature of the lower surface of the pot, which is in contact with the stove.

17.62 •• You are asked to design a cylindrical steel rod 50.0 cm long, with a circular cross section, that will conduct 190.0 J/s from a furnace at 400.0°C to a container of boiling water under 1 atmosphere. What must the rod's diameter be?

17.63 •• A picture window has dimensions of $1.40 \text{ m} \times 2.50 \text{ m}$ and is made of glass 5.20 mm thick. On a winter day, the temperature of the outside surface of the glass is −20.0°C, while the temperature of the inside surface is a comfortable 19.5°C. (a) At what rate is heat being lost through the window by conduction? (b) At what rate would heat be lost through the window if you covered it with a 0.750-mm-thick layer of paper (thermal conductivity $0.0500 \text{ W/m} \cdot \text{K}$)?

17.64 • What is the rate of energy radiation per unit area of a blackbody at (a) 273 K and (b) 2730 K?

17.65 • **Size of a Light-Bulb Filament.** The operating temperature of a tungsten filament in an incandescent light bulb is 2450 K, and its emissivity is 0.350. Find the surface area of the filament of a 150 W bulb if all the electrical energy consumed by the bulb is radiated by the filament as electromagnetic waves. (Only a fraction of the radiation appears as visible light.)

17.66 •• The emissivity of tungsten is 0.350. A tungsten sphere with radius 1.50 cm is suspended within a large evacuated enclosure whose walls are at 290.0 K. What power input is required to maintain the sphere at 3000.0 K if heat conduction along the supports is ignored?

17.67 • **The Sizes of Stars.** The hot glowing surfaces of stars emit energy in the form of electromagnetic radiation. It is a good approximation to assume $e = 1$ for these surfaces. Find the radii of the following stars (assumed to be spherical): (a) Rigel, the bright blue star in the constellation Orion, which radiates energy at a rate of 2.7×10^{32} W and has surface temperature 11,000 K; (b) Procyon B (visible only using a telescope), which radiates energy at a rate of 2.1×10^{23} W and has surface temperature 10,000 K. (c) Compare your answers to the radius of the earth, the radius of the sun, and the distance between the earth and the sun. (Rigel is an example of a *supergiant* star, and Procyon B is an example of a *white dwarf* star.)

PROBLEMS

17.68 •• Figure 17.12 shows that the graph of the volume of 1 gram of liquid water can be closely approximated by a parabola in the temperature range between 0°C and 10°C. (a) Show that the equation of this parabola has the form $V = A + B(T_C - 4.0°\text{C})^2$ and find the values of the constants A and B. (b) Define the temperature-dependent quantity $\beta(T_C)$ in terms of the equation $dV = \beta(T_C)\, V\, dT$. Use the result of part (a) to find the value of $\beta(T_C)$ for $T_C = 1.0°\text{C}, 4.0°\text{C}, 7.0°\text{C}$, and $10.0°\text{C}$. Your results show that β is not constant in this temperature range but is approximately constant above 7.0°C.

17.69 •• **CP** A Foucault pendulum consists of a brass sphere with a diameter of 35.0 cm suspended from a steel cable 10.5 m long (both measurements made at 20.0°C). Due to a design oversight, the swinging sphere clears the floor by a distance of only 2.00 mm when the temperature is 20.0°C. At what temperature will the sphere begin to brush the floor?

17.70 •• A steel wire has density 7800 kg/m^3 and mass 2.50 g. It is stretched between two rigid supports separated by 0.400 m. (a) When the temperature of the wire is 20.0°C, the frequency of the fundamental standing wave for the wire is 440 Hz. What is the tension in the wire? (b) What is the temperature of the wire if its fundamental standing wave has frequency 460 Hz? For steel the coefficient of linear expansion is $1.2 \times 10^{-5} \text{ K}^{-1}$ and Young's modulus is 20×10^{10} Pa.

17.71 •• An unknown liquid has density ρ and coefficient of volume expansion β. A quantity of heat Q is added to a volume V of the liquid, and the volume of the liquid increases by an amount ΔV. There is no phase change. In terms of these quantities, what is the specific heat capacity c of the liquid?

17.72 •• **CP** A small fused quartz sphere swings back and forth as a simple pendulum on the lower end of a long copper wire that is attached to the ceiling at its upper end. The amplitude of swing is small. When the wire has a temperature of 20.0°C, its length is 3.00 m. What is the percentage change in the period of the motion if the temperature of the wire is increased to 220°C? (*Hint:* Use the power series expansion for $(1 + x)^n$ in Appendix B.)

17.73 ••• You propose a new temperature scale with temperatures given in °M. You define 0.0°M to be the normal melting point of mercury and 100.0°M to be the normal boiling point of mercury. (a) What is the normal boiling point of water in °M? (b) A temperature change of 10.0 M° corresponds to how many C°?

17.74 • **CP CALC** A 250 kg weight is hanging from the ceiling by a thin copper wire. In its fundamental mode, this wire vibrates at the frequency of concert A (440 Hz). You then increase the temperature of the wire by 40 C°. (a) By how much will the fundamental frequency change? Will it increase or decrease? (b) By what percentage will the speed of a wave on the wire change? (c) By what percentage will the wavelength of the fundamental standing wave change? Will it increase or decrease?

17.75 ••• You are making pesto for your pasta and have a cylindrical measuring cup 10.0 cm high made of ordinary glass $[\beta = 2.7 \times 10^{-5}\ (\text{C}°)^{-1}]$ that is filled with olive oil $[\beta = 6.8 \times 10^{-4}\ (\text{C}°)^{-1}]$ to a height of 3.00 mm below the top of the cup. Initially, the cup and oil are at room temperature (22.0°C). You get a phone call and forget about the olive oil, which you inadvertently leave on the hot stove. The cup and oil heat up slowly and have a common temperature. At what temperature will the olive oil start to spill out of the cup?

17.76 •• A surveyor's 30.0 m steel tape is correct at 20.0°C. The distance between two points, as measured by this tape on a day when its temperature is 5.00°C, is 25.970 m. What is the true distance between the points?

17.77 •• A metal rod that is 30.0 cm long expands by 0.0650 cm when its temperature is raised from 0.0°C to 100.0°C. A rod of a different metal and of the same length expands by 0.0350 cm for the same rise in temperature. A third rod, also 30.0 cm long, is made up of pieces of each of the above metals placed end to end and expands 0.0580 cm between 0.0°C and 100.0°C. Find the length of each portion of the composite rod.

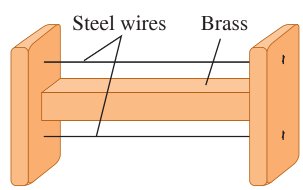
17.78 •• A copper sphere with density 8900 kg/m^3, radius 5.00 cm, and emissivity $e = 1.00$ sits on an insulated stand. The initial temperature of the sphere is 300 K. The surroundings are very cold, so the rate of absorption of heat by the sphere can be neglected. (a) How long does it take the sphere to cool by 1.00 K due to its radiation of heat energy? Neglect the change in heat current as the temperature decreases. (b) To assess the accuracy of the approximation used in part (a), what is the fractional change in the heat current H when the temperature changes from 300 K to 299 K?

17.79 ••• (a) Equation (17.12) gives the stress required to keep the length L of a rod constant as its temperature T changes. Show that if L is permitted to change by an amount ΔL when T changes by ΔT, the stress is

$$\frac{F}{A} = Y\left(\frac{\Delta L}{L_0} - \alpha\,\Delta T\right)$$

where F is the tension on the rod, L_0 is the original length of the rod, A its cross-sectional area, α its coefficient of linear expansion, and Y its Young's modulus. (b) A heavy brass bar has projections at its ends (**Fig. P17.79**). Two fine steel wires, fastened between the projections, are just taut (zero tension) when the whole system is at 20°C. What is the tensile stress in the steel wires when the temperature of the system is raised to 140°C? Make any simplifying assumptions you think are justified, but state them.

Figure **P17.79**



17.80 •• CP A metal wire, with density ρ and Young's modulus Y, is stretched between rigid supports. At temperature T, the speed of a transverse wave is found to be v_1. When the temperature is increased to $T + \Delta T$, the speed decreases to $v_2 < v_1$. Determine the coefficient of linear expansion of the wire.

17.81 •• A steel ring with a 2.5000 in. inside diameter at 20.0°C is to be warmed and slipped over a brass shaft with a 2.5020 in. outside diameter at 20.0°C. (a) To what temperature should the ring be warmed? (b) If the ring and the shaft together are cooled by some means such as liquid air, at what temperature will the ring just slip off the shaft?

17.82 • BIO Doughnuts: Breakfast of Champions! A typical doughnut contains 2.0 g of protein, 17.0 g of carbohydrates, and 7.0 g of fat. Average food energy values are 4.0 kcal/g for protein and carbohydrates and 9.0 kcal/g for fat. (a) During heavy exercise, an average person uses energy at a rate of 510 kcal/h. How long would you have to exercise to "work off" one doughnut? (b) If the energy in the doughnut could somehow be converted into the kinetic energy of your body as a whole, how fast could you move after eating the doughnut? Take your mass to be 60 kg, and express your answer in m/s and in km/h.

17.83 •• There is 0.050 kg of an unknown liquid in a plastic container of negligible mass. The liquid has a temperature of 90.0°C. To measure the specific heat capacity of the unknown liquid, you add a mass m_w of water that has a temperature of 0.0°C to the liquid and measure the final temperature T after the system has reached thermal equilibrium. You repeat this measurement for several values of m_w, with the initial temperature of the unknown liquid always equal to 90.0°C. The plastic container is insulated, so no heat is exchanged with the surroundings. You plot your data as m_w versus T^{-1}, the inverse of the final temperature T. Your data points lie close to a straight line that has slope 2.15 kg·C°. What does this result give for the value of the specific heat capacity of the unknown liquid?

17.84 •• You cool a 100.0 g slug of red-hot iron (temperature 745°C) by dropping it into an insulated cup of negligible mass containing 85.0 g of water at 20.0°C. Assuming no heat exchange with the surroundings, (a) what is the final temperature of the water and (b) what is the final mass of the iron and the remaining water?

17.85 •• CALC Debye's T^3 Law. At very low temperatures the molar heat capacity of rock salt varies with temperature according to Debye's T^3 law:

$$C = k\frac{T^3}{\theta^3}$$

where $k = 1940\ \text{J/mol}\cdot\text{K}$ and $\theta = 281\ \text{K}$. (a) How much heat is required to raise the temperature of 1.50 mol of rock salt from 10.0 K to 40.0 K? (*Hint:* Use Eq. (17.18) in the form $dQ = nC\,dT$ and integrate.) (b) What is the average molar heat capacity in this range? (c) What is the true molar heat capacity at 40.0 K?

17.86 •• The heat one feels when sitting near the fire in a fireplace or at a campfire is due almost entirely to thermal radiation. (a) Estimate the diameter and length of an average campfire log. (b) Compute the surface area of such a log. (c) Use the Stefan–Boltzmann law to determine the power emitted by thermal radiation by such a log when it burns at a typical temperature of 700°C in a surrounding air temperature of 20.0°C. The emissivity of a burning log is close to unity.

17.87 • Hot Air in a Physics Lecture. (a) A typical student listening attentively to a physics lecture has a heat output of 100 W. How much heat energy does a class of 140 physics students release into a lecture hall over the course of a 50 min lecture? (b) Assume that all the heat energy in part (a) is transferred to the 3200 m^3 of air in the room. The air has specific heat 1020 J/kg·K and density 1.20 kg/m^3. If none of the heat escapes and the air conditioning system is off, how much will the temperature of the air in the room rise during the 50 min lecture? (c) If the class is taking an exam, the heat output per student rises to 280 W. What is the temperature rise during 50 min in this case?

17.88 ••• CALC The molar heat capacity of a certain substance varies with temperature according to the empirical equation

$$C = 29.5\ \text{J/mol}\cdot\text{K} + (8.20 \times 10^{-3}\ \text{J/mol}\cdot\text{K}^2)T$$

How much heat is necessary to change the temperature of 3.00 mol of this substance from 27°C to 227°C? (*Hint:* Use Eq. (17.18) in the form $dQ = nC\,dT$ and integrate.)

17.89 •• BIO Bicycling on a Warm Day. If the air temperature is the same as the temperature of your skin (about 30°C), your body cannot get rid of heat by transferring it to the air. In that case, it gets rid of the heat by evaporating water (sweat). During bicycling, a typical 70 kg person's body produces energy at a rate of about 500 W due to metabolism, 80% of which is converted to heat. (a) How many kilograms of water must the person's body evaporate in an hour to get rid of this heat? The heat of vaporization of water at body temperature is 2.42×10^6 J/kg. (b) The evaporated water must, of course, be replenished, or the person will dehydrate. How many 750 mL bottles of water must the bicyclist drink per hour to replenish the lost water? (Recall that the mass of a liter of water is 1.0 kg.)

17.90 •• BIO Overheating. (a) By how much would the body temperature of the bicyclist in Problem 17.89 increase in an hour if he were unable to get rid of the excess heat? (b) Is this temperature increase large enough to be serious? To find out, how high a fever would it be equivalent to, in °F? (Recall that the normal internal body temperature is 98.6°F and the specific heat of the body is 3480 J/kg·C°.)

17.91 • BIO A Thermodynamic Process in an Insect. The African bombardier beetle (*Stenaptinus insignis*) can emit a jet of defensive spray from the movable tip of its abdomen (**Fig. P17.91**). The beetle's body has reservoirs containing two chemicals; when the beetle is disturbed, these chemicals combine in a reaction chamber, producing a compound that is warmed from 20°C to 100°C by the heat of reaction. The high pressure produced allows the compound to be sprayed out at speeds up to 19 m/s (68 km/h), scaring away predators of all kinds. (The beetle shown in Fig. P17.91 is 2 cm long.) Calculate the heat of reaction of the two chemicals (in J/kg). Assume that the specific heat of the chemicals and of the spray is the same as that of water, 4.19×10^3 J/kg·K, and that the initial temperature of the chemicals is 20°C.

Figure **P17.91**

17.92 ••• **CP** A industrious explorer of the polar regions has devised a contraption for melting ice. It consists of a sealed 10 L cylindrical tank with a porous grate separating the top half from the bottom half. The bottom half includes a paddle wheel attached to an axle that passes outside the cylinder, where it is attached by a gearbox and pulley system to a stationary bicycle. Pedaling the bicycle rotates the paddle wheel inside the cylinder. The tank includes 6.00 L of water and 3.00 kg of ice at 0.0°C. The water fills the bottom chamber, where it may be agitated by the paddle wheel, and partially fills the upper chamber, which also includes the ice. The bicycle is pedaled with an average torque of 25.0 N · m at a rate of 30.0 revolutions per minute. The system is 70% efficient. (a) For what length of time must the explorer pedal the bicycle to melt all the ice? (b) How much longer must he pedal to raise the temperature of the water to 10.5°C?

17.93 •• You have 1.50 kg of water at 28.0°C in an insulated container of negligible mass. You add 0.600 kg of ice that is initially at −22.0°C. Assume that no heat exchanges with the surroundings. (a) After thermal equilibrium has been reached, has all of the ice melted? (b) If all of the ice has melted, what is the final temperature of the water in the container? If some ice remains, what is the final temperature of the water in the container, and how much ice remains?

17.94 •• A thirsty nurse cools a 2.00 L bottle of a soft drink (mostly water) by pouring it into a large aluminum mug of mass 0.257 kg and adding 0.120 kg of ice initially at −15.0°C. If the soft drink and mug are initially at 20.0°C, what is the final temperature of the system, assuming that no heat is lost?

17.95 ••• A copper calorimeter can with mass 0.446 kg contains 0.0950 kg of ice. The system is initially at 0.0°C. (a) If 0.0350 kg of steam at 100.0°C and 1.00 atm pressure is added to the can, what is the final temperature of the calorimeter can and its contents? (b) At the final temperature, how many kilograms are there of ice, how many of liquid water, and how many of steam?

17.96 • A Styrofoam bucket of negligible mass contains 1.75 kg of water and 0.450 kg of ice. More ice, from a refrigerator at −15.0°C, is added to the mixture in the bucket, and when thermal equilibrium has been reached, the total mass of ice in the bucket is 0.884 kg. Assuming no heat exchange with the surroundings, what mass of ice was added?

17.97 ••• In a container of negligible mass, 0.0400 kg of steam at 100°C and atmospheric pressure is added to 0.200 kg of water at 50.0°C. (a) If no heat is lost to the surroundings, what is the final temperature of the system? (b) At the final temperature, how many kilograms are there of steam and how many of liquid water?

17.98 •• **BIO** **Mammal Insulation.** Animals in cold climates often depend on *two* layers of insulation: a layer of body fat (of thermal conductivity 0.20 W/m · K) surrounded by a layer of air trapped inside fur or down. We can model a black bear (*Ursus americanus*) as a sphere 1.5 m in diameter having a layer of fat 4.0 cm thick. (Actually, the thickness varies with the season, but we are interested in hibernation, when the fat layer is thickest.) In studies of bear hibernation, it was found that the outer surface layer of the fur is at 2.7°C during hibernation, while the inner surface of the fat layer is at 31.0°C. (a) What is the temperature at the fat–inner fur boundary so that the bear loses heat at a rate of 50.0 W? (b) How thick should the air layer (contained within the fur) be?

17.99 •• **Effect of a Window in a Door.** A carpenter builds a solid wood door with dimensions 2.00 m × 0.95 m × 5.0 cm. Its thermal conductivity is $k = 0.120$ W/m · K. The air films on the inner and outer surfaces of the door have the same combined thermal resistance as an additional 1.8 cm thickness of solid wood. The inside air temperature is 20.0°C, and the outside air temperature is −8.0°C. (a) What is the rate of heat flow through the door? (b) By what factor is the heat flow increased if a window 0.500 m on a side is inserted in the door? The glass is 0.450 cm thick, and the glass has a thermal conductivity of 0.80 W/m · K. The air films on the two sides of the glass have a total thermal resistance that is the same as an additional 12.0 cm of glass.

17.100 ••• **CP** At 0°C, a cylindrical metal bar with radius r and mass M is slid snugly into a circular hole in a large, horizontal, rigid slab of thickness d. For this metal, Young's modulus is Y and the coefficient of linear expansion is α. A light but strong hook is attached to the underside of the metal bar; this apparatus is used as part of a hoist in a shipping yard. The coefficient of static friction between the bar and the slab is μ_s. At a temperature T above 0°C, the hook is attached to a large container and the slab is raised. What is the largest mass the container can have without the metal bar slipping out of the slab as the container is slowly lifted? The slab undergoes negligible thermal expansion.

17.101 •• Compute the ratio of the rate of heat loss through a single-pane window with area 0.15 m^2 to that for a double-pane window with the same area. The glass of a single pane is 4.2 mm thick, and the air space between the two panes of the double-pane window is 7.0 mm thick. The glass has thermal conductivity 0.80 W/m · K. The air films on the room and outdoor surfaces of either window have a combined thermal resistance of 0.15 $m^2 \cdot$ K/W.

17.102 • Rods of copper, brass, and steel—each with cross-sectional area of 2.00 cm^2—are welded together to form a Y-shaped figure. The free end of the copper rod is maintained at 100.0°C, and the free ends of the brass and steel rods at 0.0°C. Assume that there is no heat loss from the surfaces of the rods. The lengths of the rods are: copper, 13.0 cm; brass, 18.0 cm; steel, 24.0 cm. What is (a) the temperature of the junction point; (b) the heat current in each of the three rods?

17.103 •• **BIO** **Jogging in the Heat of the Day.** You have probably seen people jogging in extremely hot weather. There are good reasons not to do this! When jogging strenuously, an average runner of mass 68 kg and surface area 1.85 m^2 produces energy at a rate of up to 1300 W, 80% of which is converted to heat. The jogger radiates heat but actually absorbs more from the hot air than he radiates away. At such high levels of activity, the skin's temperature can be elevated to around 33°C instead of the usual 30°C. (Ignore conduction, which would bring even more heat into his body.) The only way for the body to get rid of this extra heat is by evaporating water (sweating). (a) How much heat per second is produced just by the act of jogging? (b) How much *net* heat per second does the runner gain just from radiation if the air temperature is 40.0°C (104°F)? (Remember: He radiates out, but the environment radiates back in.) (c) What is the *total* amount of excess heat this runner's body must get rid of per second? (d) How much water must his body evaporate every minute due to his activity? The heat of vaporization of water at body temperature is 2.42×10^6 J/kg. (e) How many 750 mL bottles of water must he drink after (or preferably before!) jogging for a half hour? Recall that a liter of water has a mass of 1.0 kg.

17.104 ••• **BIO** **Basal Metabolic Rate.** The *basal metabolic rate* is the rate at which energy is produced in the body when a person is at rest. A 75 kg (165 lb) person of height 1.83 m (6 ft) has a body surface area of approximately 2.0 m^2. (a) What is the net amount of heat this person could radiate per second into a room at 18°C (about 65°F) if his skin's surface temperature is 30°C? (At such temperatures, nearly all the heat is infrared radiation, for which the body's emissivity is 1.0, regardless of the amount of pigment.) (b) Normally, 80% of the energy produced by metabolism goes into heat, while the rest goes into things like pumping blood and repairing cells. Also normally, a person at rest can get rid of this excess heat just through radiation. Use your answer to part (a) to find this person's basal metabolic rate.

17.105 ••• CALC **Time Needed for a Lake to Freeze Over.** (a) When the air temperature is below 0°C, the water at the surface of a lake freezes to form an ice sheet. Why doesn't freezing occur throughout the entire volume of the lake? (b) Show that the thickness of the ice sheet formed on the surface of a lake is proportional to the square root of the time if the heat of fusion of the water freezing on the underside of the ice sheet is conducted through the sheet. (c) Assuming that the upper surface of the ice sheet is at −10°C and the bottom surface is at 0°C, calculate the time it will take to form an ice sheet 25 cm thick. (d) If the lake in part (c) is uniformly 40 m deep, how long would it take to freeze all the water in the lake? Is this likely to occur?

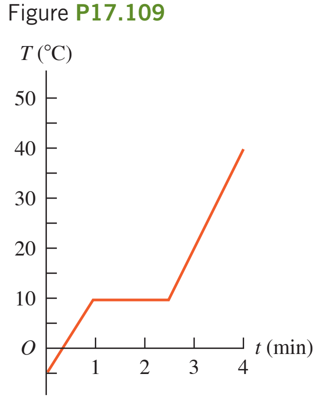
17.106 • The rate at which radiant energy from the sun reaches the earth's upper atmosphere is about $1.50\ \mathrm{kW/m^2}$. The distance from the earth to the sun is 1.50×10^{11} m, and the radius of the sun is 6.96×10^{8} m. (a) What is the rate of radiation of energy per unit area from the sun's surface? (b) If the sun radiates as an ideal blackbody, what is the temperature of its surface?

17.107 ••• **A Thermos for Liquid Helium.** A physicist uses a cylindrical metal can 0.250 m high and 0.090 m in diameter to store liquid helium at 4.22 K; at that temperature the heat of vaporization of helium is 2.09×10^{4} J/kg. Completely surrounding the metal can are walls maintained at the temperature of liquid nitrogen, 77.3 K, with vacuum between the can and walls. How much liquid helium boils away per hour? The emissivity of the metal can is 0.200. The only heat transfer between the metal can and the surrounding walls is by radiation.

17.108 •• A metal sphere with radius 3.20 cm is suspended in a large metal box with interior walls that are maintained at 30.0°C. A small electric heater is embedded in the sphere. Heat energy must be supplied to the sphere at the rate of 0.660 J/s to maintain the sphere at a constant temperature of 41.0°C. (a) What is the emissivity of the metal sphere? (b) What power input to the sphere is required to maintain it at 82.0°C? What is the ratio of the power required for 82.0°C to the power required for 41.0°C? How does this ratio compare with 2^4? Explain.

17.109 •• DATA As a physicist, you put heat into a 500.0 g solid sample at the rate of 10.0 kJ/min while recording its temperature as a function of time. You plot your data as shown in **Fig. P17.109**. (a) What is the latent heat of fusion for this solid? (b) What are the specific heats of the liquid and solid states of this material?

Figure P17.109



17.110 ••• DATA At a chemical plant where you are an engineer, a tank contains an unknown liquid. You must determine the liquid's specific heat capacity. You put 0.500 kg of the liquid into an insulated metal cup of mass 0.200 kg. Initially the liquid and cup are at 20.0°C. You add 0.500 kg of water that has a temperature of 80.0°C. After thermal equilibrium has been reached, the final temperature of the two liquids and the cup is 58.1°C. You then empty the cup and repeat the experiment with the same initial temperatures, but this time with 1.00 kg of the unknown liquid. The final temperature is 49.3°C. Assume that the specific heat capacities are constant over the temperature range of the experiment and that no heat is lost to the surroundings. Calculate the specific heat capacity of the liquid and of the metal from which the cup is made.

17.111 •• DATA As a mechanical engineer, you are given two uniform metal bars A and B, made from different metals, to determine their thermal conductivities. You measure both bars to have length 40.0 cm and uniform cross-sectional area $2.50\ \mathrm{cm^2}$. You place one end of bar A in thermal contact with a very large vat of boiling water at 100.0°C and the other end in thermal contact with an ice–water mixture at 0.0°C. To prevent heat loss along the bar's sides, you wrap insulation around the bar. You weigh the amount of ice initially as 300 g. After 45.0 min, you weigh the ice again; 191 g of ice remains. The ice–water mixture is in an insulated container, so the only heat entering or leaving it is the heat conducted by the metal bar.

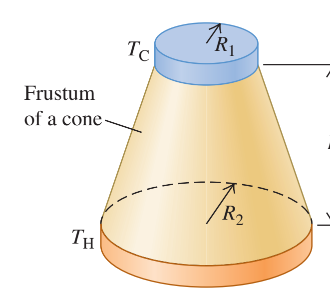
You are confident that your data will allow you to calculate the thermal conductivity k_A of bar A. But this measurement was tedious—you don't want to repeat it for bar B. Instead, you glue the bars together end to end, with adhesive that has very large thermal conductivity, to make a composite bar 80.0 m long. You place the free end of A in thermal contact with the boiling water and the free end of B in thermal contact with the ice–water mixture. The composite bar is thermally insulated. Hours later, you notice that ice remains in the ice–water mixture. Measuring the temperature at the junction of the two bars, you find that it is 62.4°C. After 10 min you repeat that measurement and get the same temperature, with ice remaining in the ice–water mixture. From your data, calculate the thermal conductivities of bar A and of bar B.

CHALLENGE PROBLEMS

17.112 • At a remote arctic research base, liquid water is obtained by melting ice in a propane-fueled conversion tank. Propane has a heat of combustion of 25.6 MJ/L, and 30% of the released energy supplies heat to the tank. Liquid water at 0°C is drawn off the tank at a rate of 500 mL/min, while a corresponding amount of ice at 0°C is continually inserted into the tank from a hopper. How long will an 18 L tank of propane fuel this operation?

17.113 ••• CALC A frustum of a cone (**Fig. P17.113**) has smaller radius R_1, larger radius R_2, and length L and is made from a material with thermal conductivity k. Derive an expression for the conductive heat current through the frustum when the side with radius R_1 is kept at temperature T_H and the side with radius R_2 is kept at temperature T_C. [*Hint:* Parameterize the axis of the frustum using coordinate x. Use Eq. (17.21) for the heat current H through a differential slice of the frustum with length dx, area $A = \pi r^2$ (where r is a function of x), and temperature difference dT. Separate variables and integrate on dT and dx.]

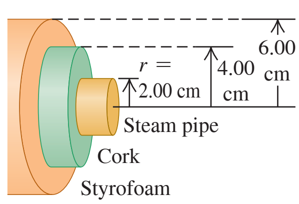
Figure P17.113



17.114 ••• BIO **A Walk in the Sun.** Consider a poor lost soul walking at 5 km/h on a hot day in the desert, wearing only a bathing suit. This person's skin temperature tends to rise due to four mechanisms: (i) energy is generated by metabolic reactions in the body at a rate of 280 W, and almost all of this energy is converted to heat that flows to the skin; (ii) heat is delivered to the skin by convection from the outside air at a rate equal to $k'A_{skin}(T_{air} - T_{skin})$, where k' is $54\ \mathrm{J/h \cdot C° \cdot m^2}$, the exposed skin area A_{skin} is $1.5\ \mathrm{m^2}$, the air temperature T_{air} is 47°C, and the skin temperature T_{skin} is 36°C; (iii) the skin absorbs radiant energy from the sun at a rate of $1400\ \mathrm{W/m^2}$; (iv) the skin absorbs radiant energy from the environment, which has temperature 47°C. (a) Calculate the net rate (in watts) at which the person's skin is heated by all four of these mechanisms. Assume that the emissivity of the skin is $e = 1$ and that the skin temperature is initially 36°C. Which mechanism is the most important? (b) At what rate (in L/h) must perspiration evaporate from this person's skin to maintain a constant skin temperature? (The heat of vaporization of water at 36°C is 2.42×10^{6} J/kg.) (c) Suppose the person is protected by light-colored clothing ($e \approx 0$) and only $0.45\ \mathrm{m^2}$ of skin is exposed. What rate of perspiration is required now? Discuss the usefulness of the traditional clothing worn by desert peoples.

17.115 ••• A hollow cylinder has length L, inner radius a, and outer radius b, and the temperatures at the inner and outer surfaces are T_2 and T_1. (The cylinder could represent an insulated hot-water pipe.) The thermal conductivity of the material of which the cylinder is made is k. Derive an equation for (a) the total heat current through the walls of the cylinder; (b) the temperature variation inside the cylinder walls. (c) Show that the equation for the total heat current reduces to Eq. (17.21) for linear heat flow when the cylinder wall is very thin. (d) A steam pipe with a radius of 2.00 cm, carrying steam at 140°C, is surrounded by a cylindrical jacket with inner and outer radii 2.00 cm and 4.00 cm and made of a type of cork with thermal conductivity 4.00×10^{-2} W/m · K. This in turn is surrounded by a cylindrical jacket made of a brand of Styrofoam with thermal conductivity 2.70×10^{-2} W/m · K and having inner and outer radii 4.00 cm and 6.00 cm (**Fig. P17.115**). The outer surface of the Styrofoam has a temperature of 15°C. What is the temperature at a radius of 4.00 cm, where the two insulating layers meet? (e) What is the total rate of transfer of heat out of a 2.00 m length of pipe?

Figure **P17.115**



MCAT-STYLE PASSAGE PROBLEMS

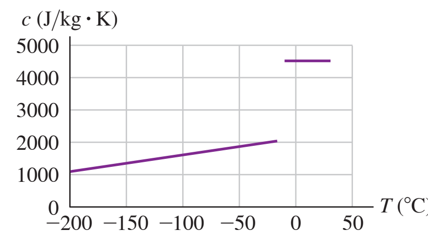
BIO Preserving Cells at Cold Temperatures. In cryopreservation, biological materials are cooled to a very low temperature to slow down chemical reactions that might damage the cells or tissues. It is important to prevent the materials from forming ice crystals during freezing. One method for preventing ice formation is to place the material in a protective solution called a *cryoprotectant*. Stated values of the thermal properties of one cryoprotectant are listed here:

Melting point	−20°C
Latent heat of fusion	2.80×10^5 J/kg
Specific heat (liquid)	4.5×10^3 J/kg · K
Specific heat (solid)	2.0×10^3 J/kg · K
Thermal conductivity (liquid)	1.2 W/m · K
Thermal conductivity (solid)	2.5 W/m · K

17.116 You place 35 g of this cryoprotectant at 22°C in contact with a cold plate that is maintained at the boiling temperature of liquid nitrogen (77 K). The cryoprotectant is thermally insulated from everything but the cold plate. Use the values in the table to determine how much heat will be transferred from the cryoprotectant as it reaches thermal equilibrium with the cold plate. (a) 1.5×10^4 J; (b) 2.9×10^4 J; (c) 3.4×10^4 J; (d) 4.4×10^4 J.

17.117 Careful measurements show that the specific heat of the solid phase depends on temperature (**Fig. P17.117**). How will the actual time needed for this cryoprotectant to come to equilibrium with the cold plate compare with the time predicted by using the values in the table? Assume that all values other than the specific heat (solid) are correct. The actual time (a) will be shorter; (b) will be longer; (c) will be the same; (d) depends on the density of the cryoprotectant.

Figure **P17.117**



17.118 In another experiment, you place a layer of this cryoprotectant between one 10 cm × 10 cm cold plate maintained at −40°C and a second cold plate of the same size maintained at liquid nitrogen's boiling temperature (77 K). Then you measure the rate of heat transfer. Another lab wants to repeat the experiment but uses cold plates that are 20 cm × 20 cm, with one at −40°C and the other at 77 K. How thick does the layer of cryoprotectant have to be so that the rate of heat transfer by conduction is the same as that when you use the smaller plates? (a) One-quarter the thickness; (b) half the thickness; (c) twice the thickness; (d) four times the thickness.

17.119 To measure the specific heat in the liquid phase of a newly developed cryoprotectant, you place a sample of the new cryoprotectant in contact with a cold plate until the solution's temperature drops from room temperature to its freezing point. Then you measure the heat transferred to the cold plate. If the system isn't sufficiently isolated from its room-temperature surroundings, what will be the effect on the measurement of the specific heat? (a) The measured specific heat will be greater than the actual specific heat; (b) the measured specific heat will be less than the actual specific heat; (c) there will be no effect because the thermal conductivity of the cryoprotectant is so low; (d) there will be no effect on the specific heat, but the temperature of the freezing point will change.

ANSWERS

Chapter Opening Question ?

(iii) The molten iron contains a large amount of energy. An object *has* a temperature but does not *contain* temperature. By "heat" we mean energy that is in transit from one object to another as a result of temperature difference between the objects. Objects do not *contain* heat.

Key Example VARIATION Problems

VP17.4.1 (a) $2.00 \times 10^{-5}\ \mathrm{K}^{-1}$ (b) length decreases by 0.270 mm

VP17.4.2 12 cm^3

VP17.4.3 1.7×10^3 N; tensile

VP17.4.4 $\dfrac{1}{\alpha_B - \alpha_A}\left(\alpha_B L - \dfrac{\Delta L}{\Delta T}\right)$

VP17.9.1 0.20 kg

VP17.9.2 14.0°C

VP17.9.3 0.181 kg

VP17.9.4 (a) 3.31°C (b) all of it

VP17.15.1 (a) 0.754 W/m · K (b) 733 W

VP17.15.2 (a) 254°C (b) −31°C

VP17.15.3 1.2×10^9 m; 1.7 times the sun's radius

VP17.15.4 4.4×10^4 W

Bridging Problem

(a) 14.26 K (b) 0.427 kg/h