Figure 9
A tall pendulum clock is also called a "grandfather clock."

7. Among automobile manufacturers, Volvo has one of the highest safety standards, aided by extensive research into developing safety systems. In one test of the ability of a Volvo sedan to absorb energy in a front-end collision, a stunt driver drives the car off the edge of a cliff, allowing the car to crash straight into the ground below. Assuming the speed of the car was 12 m/s at the top of the 5.4-m cliff, apply the law of conservation of energy to determine the car's impact speed. (Notice that the car's mass is not given. Can you explain why?)

Making Connections

8. A pendulum clock (**Figure 9**) requires a periodic energy input to keep working. Relate the operation of this clock to the law of conservation of energy. If possible, inspect one and describe how the input energy is achieved.

Reflecting

9. One name of the toy suggested in the chapter opener activity is the "switchback." Why is this a good name?

4.5 Thermal Energy and Heat

thermal energy: the total kinetic energy and potential energy of the atoms or molecules of a substance

temperature: a measure of the average kinetic energy of the atoms or molecules of a substance

We are surrounded by the use and effects of heat and thermal energy — thermostats control furnaces, large bodies of water help moderate the climate of certain regions, winds are generated by the uneven heating of Earth's surface and atmosphere, and the weather influences the clothes we wear. Furthermore, much of the energy we consume is eventually transformed into thermal energy. Thus, thermal energy and heat play a significant role in our lives.

Thermal energy and heat are not exactly the same, and temperature is different from both of them. **Thermal energy** is the total kinetic energy and potential energy (caused by electric forces) of the atoms or molecules of a substance. It depends on the mass, temperature, nature, and state of the substance. As stated earlier, heat is the transfer of energy from a hot body to a colder one. **Temperature** is a measure of the average kinetic energy of the atoms or molecules of a substance, which increases if the motion of the particles increases.

Consider, for example, 100 g of water at 50°C and 500 g of water at 50°C. The samples have the same temperature, but the bigger 500-g sample contains more thermal energy. If these samples were mixed, no heat would transfer between them because they are at the same temperature (**Figure 1(a)**).

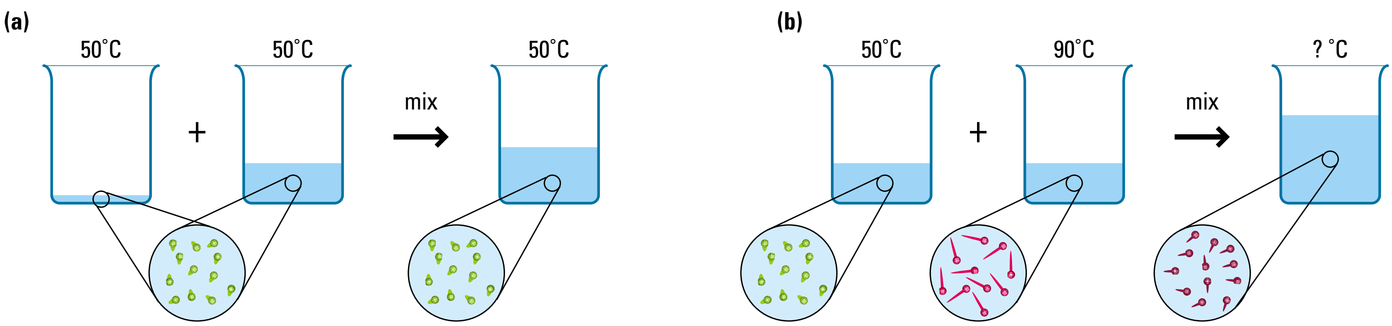

Figure 1
Comparing thermal energy, heat, and temperature
(a) When the average kinetic energy in one sample is the same as in the other, the temperatures are the same and no heat would flow if the samples are mixed.
(b) When the samples are of the same mass, the one with the higher temperature has both higher average kinetic energy and higher thermal energy.

Next, consider 500 g of water at 50°C and 500 g of water at 90°C. The warmer sample has more thermal energy because the motion—in other words, the average kinetic energy—of the molecules is greater at a higher temperature. If the two samples were mixed, heat would transfer from the 90°C sample to the 50°C sample (**Figure 1(b)**).

Practice

Understanding Concepts

1. Explain the difference between the thermal energy and the temperature of a metal coin.
2. A parent places a baby bottle containing 150 mL of milk at 7°C into a pot containing 550 mL of water at 85°C.
   (a) Compare the average kinetic energy of the milk molecules and that of the water molecules.
   (b) Compare the thermal energy of the milk and the water.
   (c) Will the heat stop transferring from the water to the milk at some stage? Explain your answer.

Reflecting

3. Word association often helps in understanding science terminology. To relate thermal energy to various contexts, list as many words as you can that start with the prefix *therm* or *thermo*. Make a list of terms and their meanings for reference.

Methods of Heat Transfer

The definition of heat suggests that energy is transferred from a warmer body to a cooler body. This transfer occurs in three possible ways, which you have studied in previous science classes. These ways are conduction, convection, and radiation.

The skill of bending metal into different shapes, shown in **Figure 2(a)**, relies on heat transfer. The process of heat transferring through a material by the collision of atoms is called **conduction**. A metal rod is composed of billions of vibrating atoms and electrons. When one end of the rod is heated, the atoms there gain kinetic energy and vibrate more quickly. They collide with adjacent atoms, also causing them to vibrate more quickly. This action continues along the rod from the hotter end toward the colder end, as illustrated in **Figure 2(b)**. Conduction occurs best in metals, which have electrons that move much more freely than in other substances. (Metals are good electrical conductors for the same reason.) Conduction occurs much less in solids such as concrete, brick, and glass, and only slightly in liquids and gases.

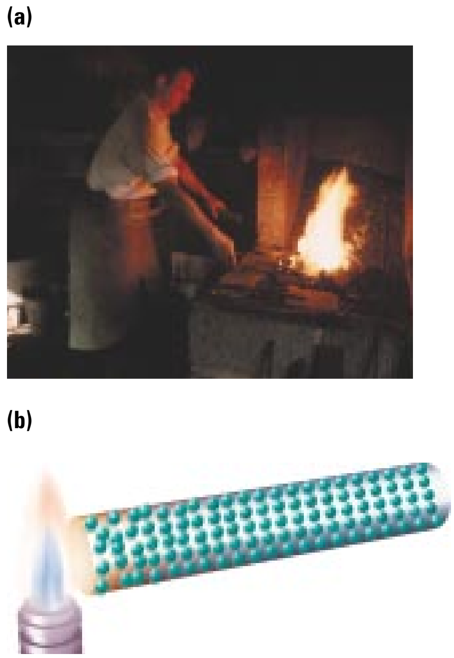

Figure 2
Conduction
(a) The metal rod must be hot before it can be bent into the desired shape. Heat from the fire is transferred through the metal by conduction.
(b) Heat conduction occurs by the collision of atoms.

conduction: the process of transferring heat through a material by the collision of atoms

convection: the process of transferring heat by a circulating path of fluid particles

The process of transferring heat by a circulating path of fluid particles is called **convection**. The circulating path is called a *convection current*. The particles of the fluid actually move, carrying energy with them. Consider, for example, a room in which an electric heater (without a fan) is located along one wall (**Figure 3**). The air particles near the heater gain t hermal energy and move faster. As they collide more, they move farther apart. As they spread out, the heated air becomes less dense than the surrounding cooler air. The warmer air then rises and is replaced with the denser, cooler air. A convection current forms and distributes energy throughout the room.

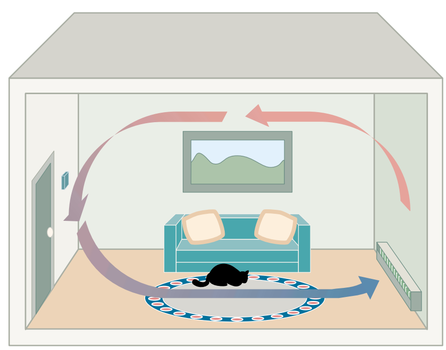

Figure 3
A convection current is set up in a room with an electric heater along one wall.

Both conduction and convection involve particles. However, heat can also transfer through a vacuum, a space with no particles. Evidence of this occurs as energy from the Sun reaches us after travelling through empty space. Thus, there

radiation: the process in which energy is transferred by means of electromagnetic waves

is a third method of heat transfer, one that requires no particles. **Radiation** is the process in which energy is transferred by means of electromagnetic waves. Examples of these waves are visible light, microwaves, radio waves, radar, X rays, and infrared rays. Infrared rays are also called heat radiation because the dominant form of radiation emitted from objects at everyday temperatures is infrared radiation. (See the drawing of the electromagnetic spectrum in section 9.1.)

Heat emitted from an object in the form of infrared rays can be detected by an infrared photograph called a *thermograph*. For example, a cancerous tumour is slightly warmer than its surroundings, so it is detected as a shaded region in a thermograph. Some new cars are equipped with infrared detectors that allow drivers to "see" objects such as a deer or a jogger about four times as far away as the headlights of their cars allow. Another example is shown in **Figure 4**.

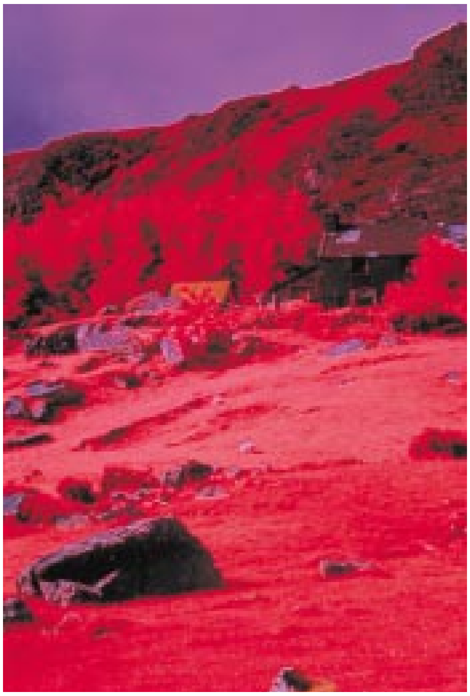

Figure 4
This is an infrared photograph of a farm house in Ireland. The darkest colours indicate the highest temperature.

Practice

Understanding Concepts

4. Explain the following:
   (a) Curling irons and clothes irons have plastic handles.
   (b) High-quality cooking pots are often made with copper bottoms.
   (c) Inserting a metal skewer into a potato will decrease the amount of time required to bake the potato in an oven.
   (d) Smoke in a fireplace rises up the chimney.
5. Discuss whether this statement is true or false: In heat conduction, energy is transferred but the particles themselves are not transferred.
6. If air were a good conductor, you would feel cool even on a day when the air temperature is 25°C. Explain why.
7. Would it be better to place an electric room heater near the floor or the ceiling of a room? Explain your answer.
8. What happens to the density of a substance when it is heated?
9. Why is heat radiation vastly different from conduction and convection?

Calculating Heat Transfer

The transfer of heat from one body to another causes either a temperature change, or a change of state, or both. Here we will consider temperature changes.

Different substances require different amounts of energy to increase the temperature of a given mass of the substance. This occurs because different substances have different capacities to hold heat. For example, water holds heat better than steel. Therefore, water is said to have a higher specific heat capacity than steel. The word "specific" indicates that we are considering an equal mass of each substance. In SI units, the mass is 1.0 kg. Thus, **specific heat capacity** (c) is a measure of the amount of energy needed to raise the temperature of 1.0 kg of a substance by 1.0°C. It is measured in joules per kilogram degree Celsius, J/(kg•°C).

specific heat capacity: (c) a measure of the amount of energy needed to raise the temperature of 1.0 kg of a substance by 1.0°C

The English scientist James Prescott Joule performed original investigations to determine the specific heat capacities of various substances. He discovered, for instance, that 4.18×10^3 J of energy is required to raise the temperature of 1.0 kg of water by 1.0°C:

$$c_w = 4.18 \times 10^3 \frac{\text{J}}{\text{kg•°C}} \quad \text{where } c_w \text{ is the specific heat capacity of water}$$

This value also means that 1.0 kg of water releases 4.18×10^3 J of energy when its temperature drops by 1.0°C.

The quantity of heat gained or lost by a body, Q, is directly proportional to the mass, m, of the body, its specific heat capacity, c, and the change in the body's temperature, Δt. The equation relating these factors is

$$Q = mc\Delta t$$

Sample Problem 1

How much heat is needed to raise the temperature of 2.2 kg of water from 20°C to the boiling point? (Assume two significant digits.)

Solution

$m = 2.2\ \text{kg}$

$c = 4.18 \times 10^3\ \dfrac{\text{J}}{\text{kg}\bullet{}^\circ\text{C}}$

$\Delta t = 100^\circ\text{C} - 20^\circ\text{C} = 80^\circ\text{C}$

$Q = \ ?$

$$\begin{aligned} Q &= mc\Delta t \\ &= (2.2\ \text{kg})\left(4.18 \times 10^3\ \frac{\text{J}}{\text{kg}\bullet{}^\circ\text{C}}\right)(80^\circ\text{C}) \\ Q &= 7.4 \times 10^5\ \text{J} \end{aligned}$$

The heat required is 7.4×10^5 J, or 0.74 MJ.

The specific heat capacities of different substances are shown in **Table 1**.

Table 1 Specific Heat Capacities of Common Substances

Substance	Specific heat capacity (J/(kg•°C))	Substance	Specific heat capacity (J/(kg•°C))
glass	8.4×10^2	water	4.18×10^3
iron	4.5×10^2	alcohol	2.5×10^3
brass	3.8×10^2	ice	2.1×10^3
silver	2.4×10^2	steam	2.1×10^3
lead	1.3×10^2	aluminum	9.2×10^2

When heat is transferred from one body to another, it normally flows from the hotter body to the colder one. The amount of heat transferred obeys the **principle of heat exchange**, which is stated as follows:

principle of heat exchange: When heat is transferred from one body to another, the amount of heat lost by the hot body equals the amount of heat gained by the cold body.

Principle of Heat Exchange

When heat is transferred from one body to another, the amount of heat lost by the hot body equals the amount of heat gained by the cold body.

Since this is another version of the law of conservation of energy, it can be written using the following equations:

$$Q_{\text{lost}} + Q_{\text{gained}} = 0$$

or

$$\underbrace{m_1 c_1 \Delta t_1}_{\text{heat lost}} + \underbrace{m_2 c_2 \Delta t_2}_{\text{heat gained}} = 0$$

Sample Problem 2

A 200-g piece of iron at 350°C is submerged in 300 g of water at 10°C to be cooled quickly. Determine the final temperature of the iron and the water. (Assume two significant digits.)

Solution

$m_i = 0.20$ kg

$m_w = 0.30$ kg

$c_i = 4.5 \times 10^2 \frac{\text{J}}{\text{kg•°C}}$

$c_w = 4.18 \times 10^3 \frac{\text{J}}{\text{kg•°C}}$

Let the final temperature be t_f.

$\Delta t_i = t_f - 350°\text{C}$

$\Delta t_w = t_f - 10°\text{C}$

$$m_i c_i \Delta t_i + m_w c_w \Delta t_w = 0$$

iron water

$$(0.20 \text{ kg})\left(4.5 \times 10^2 \frac{\text{J}}{\text{kg•°C}}\right)(t_f - 350°\text{C}) + (0.30 \text{ kg})\left(4.18 \times 10^3 \frac{\text{J}}{\text{kg•°C}}\right)(t_f - 10°\text{C}) = 0$$

$$90 t_f - 3.15 \times 10^4 °\text{C} + 1.25 \times 10^3 t_f - 1.25 \times 10^4 °\text{C} = 0$$

$$1.34 \times 10^3 t_f = 4.40 \times 10^4 °\text{C}$$

$$t_f = 33°\text{C}$$

The final temperature of the iron and water is 33°C.

Practice

Understanding Concepts

10. Calculate the amount of heat needed to raise the temperature of the following:
    (a) 8.4 kg of water by 6.0°C
    (b) 2.1 kg of alcohol by 32°C
11. Determine the heat lost when
    (a) 3.7 kg of water cools from 31°C to 24°C
    (b) a 540-g piece of silver cools from 78°C to 14°C
12. Rearrange the equation $Q = mc\Delta t$ to obtain an equation for
    (a) c (b) m (c) Δt
13. An electric immersion heater delivers 0.050 MJ of energy to 5.0 kg of a liquid, changing its temperature from 32°C to 42°C. Find the specific heat capacity of the liquid.
14. Determine how much brass can be heated from 20°C to 32°C using 1.0 MJ of energy.
15. A 2.5-kg pane of glass, initially at 41°C, loses 4.2×10^4 J of heat. What is the new temperature of the glass?
16. A 120-g mug at 21°C is filled with 210 g of coffee at 91°C. Assuming all of the heat lost by the coffee is transferred to the mug, what is the final temperature of the coffee? The specific heat capacity of the mug is 7.8×10^2 J/(kg•°C).

Answers

10. (a) 2.1×10^5 J
    (b) 1.7×10^5 J
11. (a) 1.1×10^5 J
    (b) 8.3×10^3 J
13. 1.0×10^3 J/(kg•°C)
14. 2.2×10^2 kg
15. 21°C
16. 84°C

SUMMARY Thermal Energy and Heat

- It is important to distinguish between thermal energy, heat, and temperature.
- Heat transfer can occur by means of conduction, convection, and radiation.
- The quantity of heat, Q, transferred to an object of mass m and specific heat capacity c in raising its temperature by Δt is found using the equation $Q = mc\Delta t$.

Section 4.5 Questions

Understanding Concepts

1. Distinguish between heat and thermal energy.
2. One morning you walk barefoot across a rug onto a tiled floor. The rug and the floor are at the same temperature, yet the tiled floor feels much colder. Explain why.
3. What is the most likely method of heat transfer through
   (a) a metal? (b) a vacuum? (c) a liquid?
4. Water from a tap at 11°C sits in a watering can where it eventually reaches 21°C.
   (a) Where did the energy that warms up the water come from?
   (b) Determine the mass of the water sample if it has absorbed 21 kJ of energy during the temperature change.
5. Hang gliders and birds of prey ride convection currents called thermals. Describe the conditions that cause thermals.
6. Calculate the heat transferred in each case.
   (a) The temperature of a 6.4-kg piece of lead changes from 12°C to 39°C.
   (b) A 2.4-kg chunk of ice cools from −13°C to −19°C.

Applying Inquiry Skills

7. Describe how you would set up a demonstration to show
   (a) convection in water
   (b) convection in air
   (c) conduction in a solid
8. In an experiment to determine the specific heat capacity of a metal sample, a student quickly transfers a 0.70-kg bar of metal M from boiling water into 0.45 kg of water at 16°C. The highest temperature reached by the metal and water together is 28°C.
   (a) Determine the specific heat capacity of metal M.
   (b) What is the possible identity of metal M?
   (c) Describe sources of error in this type of experiment.

Making Connections

9. Police discovered a car that slid off the road and down a cliff. Research to find how a forensic scientist could use infrared photography to determine approximately how long ago the mishap occurred. Follow the links for Nelson Physics 11, 4.5.

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