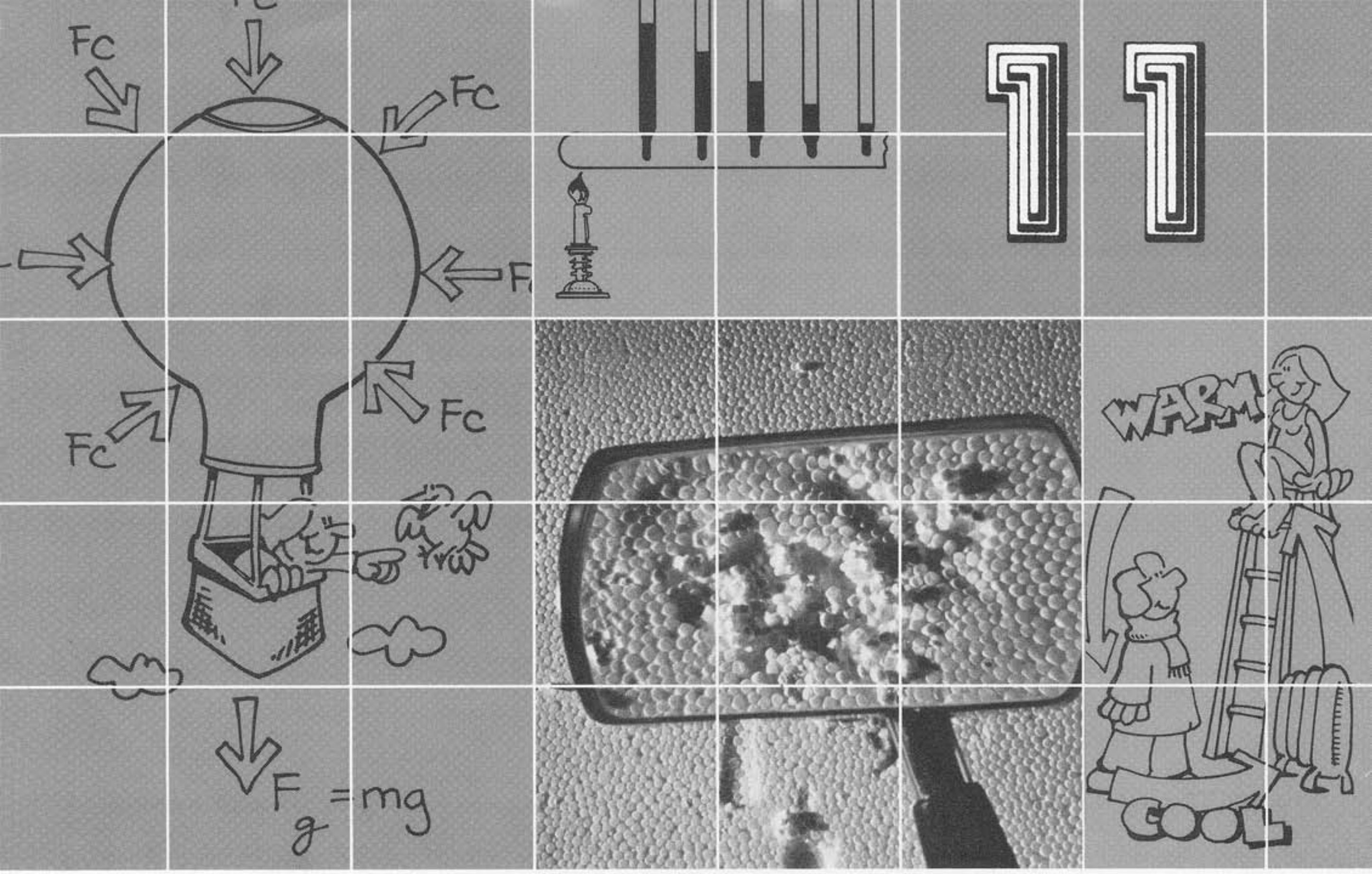


How Thermal Energy Is Transferred

Insulating your home can decrease your home heating costs. So can storm windows. But, using a fireplace can increase your heating costs by as much as 20% (not including the price of the wood!).

Comments like these occur frequently in advice we are given on decreasing the amount of fuel needed to heat or cool a home. In winter we try to keep thermal energy inside. During the summer we try to keep it outside. To evaluate the advice we are given, including surprising bits of advice like not using a fireplace in winter, we must understand the processes by which thermal energy is transferred from one place to another.

In the last chapter we described the changes that occur when thermal energy is transferred from one object to another without worrying about how the transfer actually occurs. In this chapter we look at the three transfer processes—convection, conduction, and radiation-absorption. *Convection* describes the transfer of thermal energy in liquids and gases. *Conduction* describes the transfer process that occurs predominantly in solids. *Radiation-absorption* is the process by which thermal energy is transferred through empty space. Home heating and cooling involve all three processes.

CONVECTION

One method of transferring thermal energy is to heat a substance and then allow the substance to move, carrying the thermal energy with it to a new location. This mechanism is called *convection*. Smoke from a fire, steam from a tea kettle, and hot exhaust fumes from automobiles all carry thermal energy from a source and disperse it throughout the surrounding air. This process, the primary mechanism by which thermal energy is transferred in liquids and gases, relies upon two characteristics of gases and liquids. The first is that they flow, carrying thermal energy with them. The second characteristic is that warmed gases and liquids rise in their cooler surroundings. Before looking at the transfer of thermal energy itself, we need to understand why warmed fluids rise.

Warmed Fluids Rise

One way to analyze the process by which warmed fluids rise is to apply Newton's laws. A hot-air balloon accelerates upward when the air inside the balloon is warmer than the surrounding air. According to Newton's second law, a net force must act upward on the balloon. To see how this net upward force arises, we must identify all forces acting on the balloon. Two forces act: a gravitational force due to the earth-balloon interaction and a contact force

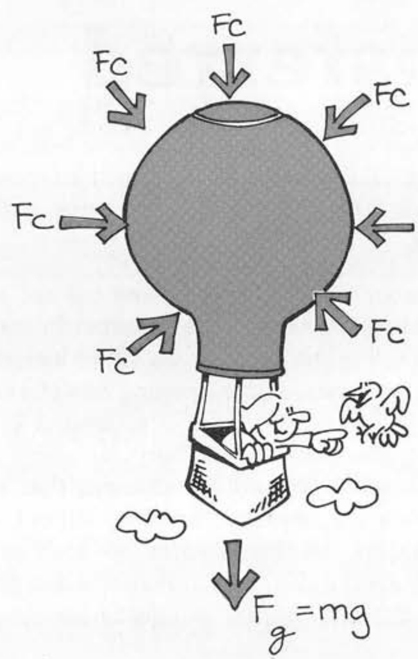


Figure 11-1
The interaction between the balloon and air leads to forces that act on the balloon in all directions.

arising from the interaction between the surrounding air and the balloon. The gravitational force acts downward. The contact force acts in all directions, as shown in Figure 11-1. On a still day, the horizontal forces cancel. Since the balloon rises, we know that the vertical forces do not cancel. The surrounding air must push the balloon up more than gravity pulls it down.

It may seem strange to you that the air below the balloon pushes upward. A model that helps us visualize this is illustrated in Figure 11-2. We can imagine that the atmosphere consists of a series of layers. Because of its weight, each layer presses down on the layers below it. To keep the upper layers from collapsing into a thin layer at the earth's surface, the lower layers must exert upward forces to balance gravity. These forces are exerted through collisions between molecules in two adjacent layers. Called **buoyant forces,** these forces are just large enough for each layer to support the layers above it. Force X is equal to the weight of layer A; force Y is equal to the weight of layers A and B; force Z is equal to the weight of layers A, B, and C; and so forth.

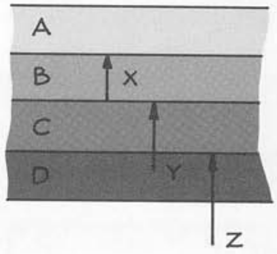


Figure 11-2
Each layer in the atmosphere must exert enough force upward to support the layers of air above it.

We can use this model to explain why objects rise, sink, or remain stationary in air. If we draw an imaginary line around any part of the atmosphere (Figure 11-3), the section enclosed by the line is in equilibrium. The weight of the enclosed air and the air above this section is balanced by the buoyant forces exerted by the layers of air below it. Now replace this section of the atmosphere with a filled balloon. If the balloon and its contents weigh the same as the air they replace, the balloon remains stationary. If they weigh more, the buoyant forces exerted by the lower layers are not large enough to support them, and the balloon sinks. If they weigh less, the buoyant forces are

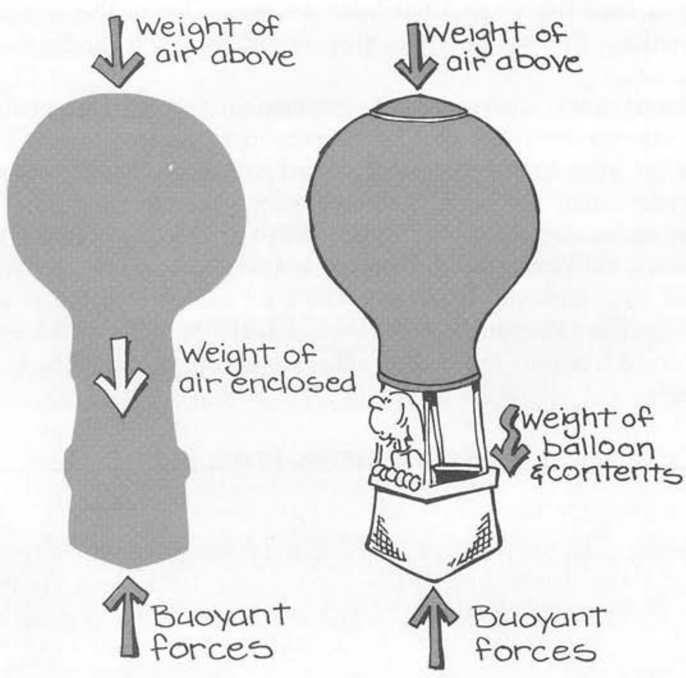


Figure 11-3
The balloon replaces one section of the atmosphere. If it weighs the same as the air that it replaces, the balloon remains stationary. If it weighs more, the balloon sinks. If it weighs less, the balloon rises.

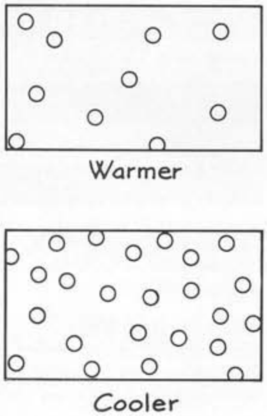


Figure 11-4
A given volume of gas contains more molecules if it is cool than if it is warm.

larger than their combined weight, and the balloon rises. The weight of the balloon and its contents, compared to the weight of the air they replace, determines whether the balloon rises, sinks, or remains stationary. The same argument applies to any volume of fluid placed in another fluid. Its motion depends on its weight compared to the weight of the fluid it replaces.

This model can be used to explain the fact that warmer air rises when placed in cooler surroundings. If we compare equal volumes of cool and warm air at the same pressure, the cooler air always weighs more. As the molecules of a gas gain thermal energy, they start moving farther apart. As shown in Figure 11-4, a given volume of gas contains more molecules if it is cool than if it is warm and therefore weighs more. Hot-air balloons rise because the hot air inside the balloon weighs considerably less than the cooler air it replaces. Consequently, if we introduce a sample of warmed air into the atmosphere, it will rise. Similarly, a sample of air that is cooler than its surroundings will sink. The motion of warmer or cooler samples within a fluid provides a mechanism by which thermal energy can be transferred throughout the fluid.

Warm Air Rising Leads to Convection

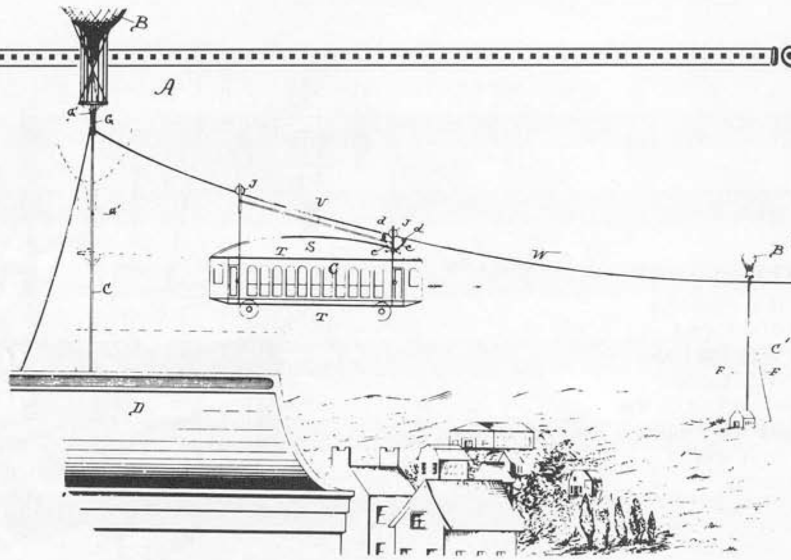
Because warmed air rises, it can transfer thermal energy from an energy source to other locations. **Convection** is the process of transferring thermal energy by the movement of warmer gases or liquids in cooler surroundings. A candle, for example, transfers thermal energy to the air surrounding its flame. The heated air next to the flame weighs less than the cooler air surrounding it, so it rises. As the heated air moves upward, it is replaced by cooler air. This cooler air is then heated by the candle flame, rises, and is again replaced by cooler air. The process continues as long as the candle burns and cooler air is available to replace the air that has been warmed. Due to the upward motion of the warmed air, thermal energy is transferred from the candle flame to the surrounding air.

In a closed room, this rising and replacement process eventually leads to the closed cycle shown in Figure 11-5. Typically, a radiator acts as the energy source. The air near the radiator is warmed and rises. As it moves upward, this air interacts with the walls, with the people in the room, and with the furniture. Its molecules collide with molecules in the walls, people, and furniture. With each collision, thermal energy is transferred from the warmer air to the cooler surroundings. Gradually, the air cools, sinks, and is eventually drawn back to the radiator. The process repeats itself. Thermal energy has been transferred from the radiator to other objects in the room by the process of convection.

Figure 11-5
The air near the radiator is warmed and rises. After losing some of its energy to the rest of the room, this cooler air sinks and is drawn back over the radiator where it is heated once again.

SELF-CHECK 11A

Convection can occur in liquids as well as in gases. Draw the circulation of water that is established when an ice cube floats at the surface, as shown in Figure 11-6.



FLOATING FROM TOWN TO TOWN

San Francisco's cable cars convert gravitational potential energy into kinetic energy. But, how can the people of the flatlands take advantage of this readily available form of energy? Andrew J. Morrison figured it out when he designed an aerial railroad that used the idea of hot air rising. The air in two balloons (*B* and *B'*) are heated so that they weigh less than an equal volume of surrounding air. Thus, they feel a net upward force and move upward. To keep the balloons from floating away, they are held by cables (*C* and *C'*). Connected between the two balloons is a third cable, (*W*), from which a railroad passenger car (*T*) is suspended. Balloon *B* is kept on a longer string than balloon *B'* so the car starts at *B* with greater gravitational potential energy than it would have at *B'*. It is all downhill, so the car and its passengers roll to their destination. To come back they need only pull in balloon *B* and let balloon *B'* float higher in the air. Mr. Morrison was apparently concerned about the downward force that the railroad car would exert on the cable. To decrease this force he added an upward force on the car. The roof area (*S*) is a compartment that can be filled with warmed air. The upward force on this gas will decrease the net force applied on the cable. We can only wonder if Mr. Morrison thought about how the force on this gas would affect the travel time of the car.

Convection in Fireplaces

A fireplace behaves in the same way as a candle or a radiator. It is an energy source that can heat the surrounding air, establishing convection. Unfortunately, the process of convection works to our disadvantage at the hearth.

Like a radiator, a fire in the fireplace warms the air near it. This warmed air weighs less than an equal volume of cooler air, and it rises. Unlike the air warmed by a radiator, however, the air warmed by a fireplace contains poisonous gases that must be exhausted outside the house. A chimney is open at the roof, and the warmed air goes out the chimney rather than being recycled back into the room. Warm air going out the chimney does not do much to keep a cold body warm!

If that were the whole story, a fireplace would be neither advantageous nor disadvantageous—a nice, though useless, ornament. But it is worse than that. Air must be drawn from the room to replace the air exhausted up the

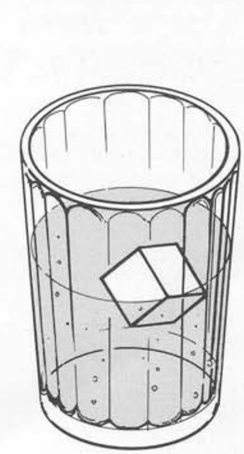


Figure 11-6

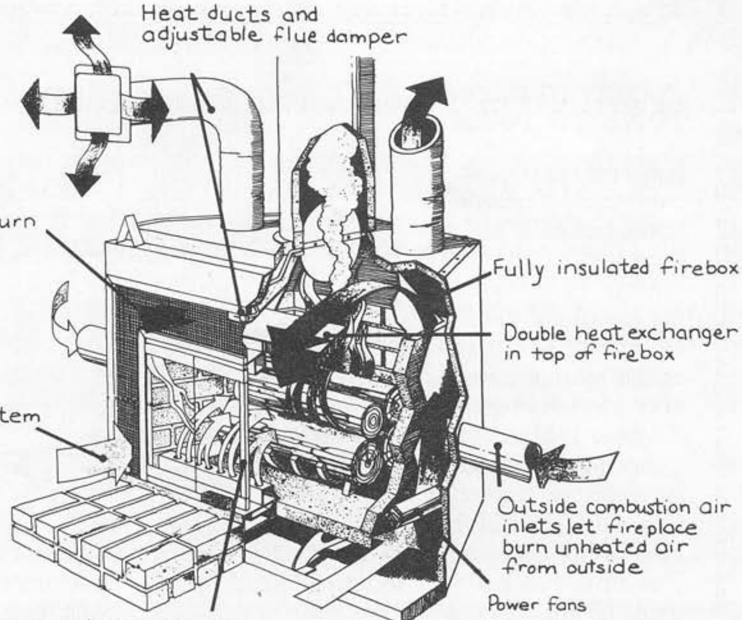


Figure 11-7
Devices that minimize the flow of warmed room air into the fireplace or that actually return warmed air to the room make the fireplace a much more useful energy source.

chimney, and in most homes this replacement air has been heated by a furnace. Oil, gas, or electricity has been used to heat air that ultimately must be exhausted out the chimney. The furnace must then heat more air that is again exhausted out the chimney, and so forth. Consequently, a fireplace will make the furnace run more, consuming more fuel instead of less.

You may object that fireplaces do make you feel warmer if you are close to them. True—some thermal energy does enter the room, but by the process of radiation-absorption rather than convection. The trick to turning a fireplace into an energy source rather than an energy drain is to minimize the flow of heated room air into the fireplace. A variety of designs are now available for this purpose (Figure 11-7).

CONDUCTION

You have probably used old wire coat hangers to cook hot dogs over campfires. You placed the hot dog on one end of the wire and held on to the other. Even though the end with the hot dog was the only part of the coat hanger actually in the fire, the end you were holding eventually got hot. Much the same process occurs when we place a pan on the stove. The bottom of the pan is the only surface in direct contact with the burner. Yet if the pan handle is metal, it quickly becomes too hot to touch. Thermal energy is transferred from one end of the wire to the other and from the bottom of the pan to the handle.

In each example, only one part of the metal is heated. Yet thermal energy is transferred throughout. Since solids do not flow like liquids or gases, we cannot use convection to explain the transfer of thermal energy. Instead we introduce a second process, called *conduction*.

Thermal Conduction and Insulation

Conduction is the process by which thermal energy is transferred without significant motion of the material's molecules away from their original locations. In convection, molecules carry thermal energy with them as they move about. In conduction, molecules transfer thermal energy without moving permanently from their original locations. When one end of a solid is placed near a heat source, for example, adjacent molecules gain kinetic energy and start to move faster and farther. They collide with neighboring molecules, transferring some of their kinetic energy. These molecules then interact with their neighbors and the thermal energy is gradually transferred along the solid. Thermometers placed along a solid (Figure 11-8) show evidence of the transfer of thermal energy throughout. Since molecules are free to move about in liquids and gases, thermal transfer by convection usually exceeds thermal transfer by conduction. Consequently, conduction describes thermal transfer in solids and is generally insignificant in describing thermal transfer in liquids and gases.

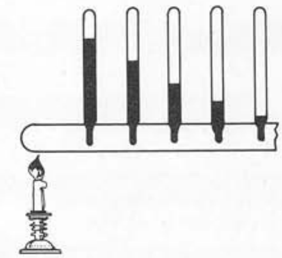


Figure 11-8
Thermometers placed along a solid show the transfer of thermal energy by conduction.

While all solids transfer some thermal energy by conduction, they do not do so equally well. If our hot-dog wire and pan become too hot to handle, we use hot pads to protect our hands. Likewise, when the hot dog is burned to our satisfaction, we wrap a bun around it before pulling it off the wire. Some solids transfer thermal energy more easily than others.

The terms *conductor* and *insulator* provide us with a way of categorizing materials according to their abilities to transfer thermal energy. **Thermal conductors** are materials that conduct thermal energy easily, like coat hangers or metal pans. Materials that do not conduct thermal energy easily, such as hot pads or hot-dog buns, are called **thermal insulators**. Differences in molecular structure and bonding lead to the differences between thermal conductors and insulators.

Thermal Resistivity

Insulating ourselves from the cold is a major goal in winter. When paying for thermal energy, we need a way of comparing the insulating ability of materials in order to determine which are the most cost-effective. The concept of thermal resistivity provides us a quantitative way of comparing the extent to which different materials transfer thermal energy.

The **thermal resistivity** of a material is a numerical value that describes the resistance of that material to the conduction of thermal energy. A high thermal resistivity means that thermal energy moves through the material very slowly. A low thermal resistivity indicates that thermal energy is easily conducted. Good thermal insulators have thermal resistivities in the range of 5 to 100 $m^2 \cdot s \cdot {}^\circ C/J \cdot m$, while good thermal conductors have values of about 0.002 to 0.01 $m^2 \cdot s \cdot {}^\circ C/J \cdot m$. (More will be said about these cumbersome units in the next section.) Thermal resistivities of typical materials are included in Table 11-1.

Table 11-1 Typical Values of Thermal Resistivities

Material	Thermal Resistivity (r_t) Metric Units ($m^2 \cdot s \cdot °C/J \cdot m$)	Lumber Yard Units ($ft^2 \cdot h \cdot °F/BTU \cdot in.$)
Silver	0.0023	0.00033
Copper	0.0025	0.00036
Steel	0.0030	0.00043
Gold	0.0032	0.00046
Aluminum	0.0125	0.00180
Brick	1.4	0.02
Wallboard	4.8	0.69
Oak	4.9	0.71
Linoleum	5.1	0.74
Hard maple	5.5	0.79
White pine	9.1	1.31
Balsa wood	21.7	3.13
Asbestos	3.5	0.5
Fiberglass	22.3	3.2
Cork	24.8	3.6
Rock wool	26.7	3.8
Styrofoam	31.5	4.5
Polyurethane foam	43.3	6.2
Leather	6.3	0.91
Linen	11.4	1.64
Silk	17.4	2.51
Air	39.6	5.71
Water	1.6	0.24
Ice	0.58	0.08
Snow	1.4	0.20

Figure 11-9
Styrofoam is a good insulator because it traps air and uses the insulating ability of still air.

The thermal resistivities listed in Table 11-1 match our experiences pretty well. Styrofoam is a better insulator than aluminum. Wool is a better insulator than cotton. One surprise is the high thermal resistivity of still air. We seldom think of air as an insulator because air transfers thermal energy by convection as well as by conduction. Whatever insulating ability air has by virtue of its high thermal resistivity is offset by the large amount of thermal energy it transfers by convection. When air is trapped so that its molecules are held in relatively fixed locations, like solids, it becomes an excellent insulator. Some materials are good insulators because they trap air, thus taking advantage of its insulating abilities.

A close look at styrofoam (Figure 11-9) reveals lots of tiny pockets. These pockets trap small quantities of air, preventing it from circulating. Fur traps air near the surface of an animal's body; this still air insulates the animal from the cold. The colder it is, the more the animal fluffs out its fur. Many other insulators—goose down, fiberglass, even hot-dog buns—use the insulating ability of still air.

SELF-CHECK 11B

To keep warm in winter we are told to wear several layers of clothing. Why is layering advantageous, other than because you can take the layers off one at a time?

R-values

Home builders, lumber yards, and energy auditors usually describe the insulating ability of solids in terms of R-values. The R-value of a solid is the product of the thermal resistivity of the material and the distance through which the thermal energy moves, usually the thickness of the solid.

Thermal resistivity of material

$$\text{R-value} = r_t d$$

Distance energy travels

$$\begin{matrix}\text{R-value of} \\ \text{a solid}\end{matrix} = \begin{pmatrix}\text{thermal resistivity} \\ \text{of material}\end{pmatrix} \times \begin{pmatrix}\text{distance energy} \\ \text{travels}\end{pmatrix}$$

Using the thermal resistivities listed in Table 11-1, the R-value of a slab of styrofoam 0.1 meters (m) thick is $(31.5 \text{ m}^2 \cdot \text{s} \cdot {}^\circ\text{C/J} \cdot \text{m})(0.10 \text{ m}) = 3.15 \text{ m}^2 \cdot \text{s} \cdot {}^\circ\text{C/J}$.

Using R-values, you can directly compare the insulating properties of different thicknesses of different materials, assuming that they will be used under identical conditions. Insulating materials to be used in attics and walls can be compared in this manner. When you buy insulation from a lumber yard, look at the R-values listed for each type of insulation—the higher the R-value, the better the insulator.

Many common applications involve solids that consist of several different materials. In dressing warmly for winter weather, we wear several different layers of clothing—shirts, sweaters, jackets, and coats. Walls typically consist of drywall, insulation, and wood or brick siding. To determine the R-value of a combination of materials, you add the separate R-values of each material:

$$\text{Total R-value} = \text{R-value}_1 + \text{R-value}_2 + \text{R-value}_3 + \ldots$$

For example, the wall of a typical house consists of 0.02 m of drywall, 0.09 m of fiberglass insulation, and 0.02 m of wood (pine) siding. Using the thermal resistivities in Table 11-1, the total R-value of the wall is:

$$\begin{aligned}\begin{matrix}\text{Total R-value} \\ \text{of wall}\end{matrix} &= \begin{pmatrix}\text{R-value of} \\ \text{drywall}\end{pmatrix} + \begin{pmatrix}\text{R-value of} \\ \text{insulation}\end{pmatrix} + \begin{pmatrix}\text{R-value of} \\ \text{wood siding}\end{pmatrix} \\ &= [(4.8)(0.02) + (22.3)(0.09) + (9.1)(0.02)] \text{ m}^2 \cdot \text{s} \cdot {}^\circ\text{C/J} \\ &= 2.28 \text{ m}^2 \cdot \text{s} \cdot {}^\circ\text{C/J}\end{aligned}$$

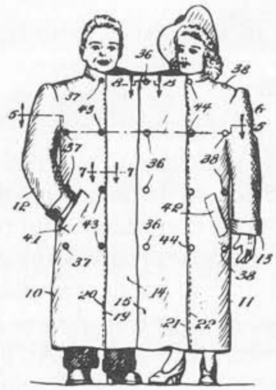
SELF-CHECK 11C

When home heating fuels were not so expensive, contractors frequently left the walls hollow. Calculate the total R-value for a wall that consists of 0.02 m of drywall, 0.09 m of moving air, and 0.02 m of pine siding. (Moving air, regardless of its thickness, has an effective R-value of $0.18 \text{ m}^2 \cdot \text{s} \cdot {}^\circ\text{C/J}$.)

Thermal Conduction Equation

The rising cost of energy has made nearly everyone concerned about utility bills. The primary way to decrease utility bills is to decrease the amount of energy conducted through the walls. A quick look at the variables that contribute to higher utility bills tells us what factors affect the conduction of thermal energy through a solid, like the walls of a house.

CLOSER IS WARMER



Because the conduction of thermal energy depends on surface area, we can decrease the loss of heat from our bodies by decreasing the surface area between us and the cold outside world. One common example of using this idea is the mitten, which has a smaller surface area than the glove. Howard C. Ross applied this same concept in 1953 when he patented the two-person overcoat. By standing close together, the two people can attach a panel (14) to the buttons (43 and 44) of each of their coats. Then, one side of each person's body is right next to the other's and does not present any surface area to the lower temperature air. Less surface area means less thermal energy conducted. Reaching out and touching someone can be warmer as well as friendlier.

If we always maintain the same temperature inside the house during the winter, utility bills will be higher for:

Colder weather than for warmer weather	(ΔT, the difference between the inside and outside temperatures)
Long winters than for short ones	(t, the total time)
Houses with greater outside wall area	(A, the outside wall area)
Houses with no insulation	(R-value)
Houses with thin walls	(d, the distance the heat has to travel)

When you are trying to maintain the inside of your home at a constant temperature, the amount of thermal energy transferred through the wall depends on the difference between the inside and outside temperatures and the total time during which this difference exists. Long, cold winters result in much higher heating costs than short, mild winters. The remaining factors include the area of the walls, the effective R-value of the materials from which the walls are made, and the thickness of the walls. Architects and contractors take these factors into account in designing and building energy-efficient homes.

The effects of these factors can be combined into a single equation, called the **thermal conduction equation,** that describes the amount of thermal energy conducted through a material.

Thermal energy transferred

Cross-sectional area

Time

Temperature difference

$$TE = \frac{A t \Delta T}{\text{R-value}}$$

R-value of material

$$\text{Thermal energy conducted} = \frac{\begin{pmatrix}\text{cross-sectional}\\ \text{area}\end{pmatrix} \times (\text{time}) \times \begin{pmatrix}\text{temperature}\\ \text{difference}\end{pmatrix}}{\text{R-value}}$$

While we have justified this equation by examining an application from home heating, it is a general equation that applies to the conduction of thermal energy in any solid.

The variables included in the thermal conduction equation help explain the rather cumbersome units we introduced with the concepts of thermal resistivity and R-value. In order to make a fair comparison of the insulating abilities of two materials, we must measure the amounts of thermal energy they transfer when all the other variables involved in our equation are kept constant. We need to compare the amounts of thermal energy conducted during equal time intervals by solids equal in cross-sectional area and thickness and whose two sides are exposed to the same temperature difference. As illustrated in Figure 11-10, we generally use a cross-sectional area of 1 square meter (m^2), a time interval of 1 second (s), a temperature difference of 1°C, and a thickness of 1 m. Thermal resistivities are measured in square meters (area) times seconds (time) times degrees Celsius (temperature difference) divided by joules (energy) times meters (thickness). The equivalent units used in the United States are square feet (area) times hours (time) times degrees Fahrenheit (temperature difference) divided by British Thermal Units (BTU) (energy) times inches (thickness).

Thermal resistivities, R-values, and the thermal conduction equation give us a concrete way to evaluate advice given on decreasing home heating costs. There are lots of suggestions: Insulate your walls; keep your thermostat at 20°C (68°F) in the winter and 25.6°C (78°F) in the summer; buy an automatic timer to turn your thermostat down at night; heat rooms on only one floor; and so on. We can evaluate some of this advice by calculating the thermal energy transferred with and without the advised action and comparing the results.

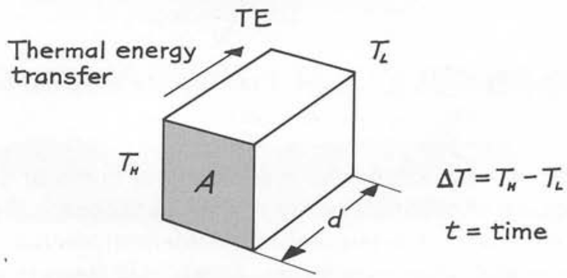


Figure 11-10

Thermal resistivities are measured in terms of the thermal energy conducted by a slab of material with a cross-sectional area (A) of 1 m^2, a distance (d) of 1 m, a temperature difference (ΔT) of 1°C, and a time interval (t) of 1 s.

SELF-CHECK 11D

Use the thermal conduction equation to argue that large picture windows would be less energy efficient than wooden walls.

A STEP FURTHER—MATH

COST OF HEATING A HOME

Nearly everyone accepts the need to insulate walls. Let's use the thermal conduction equation to compare the amount of thermal energy transferred across insulated and uninsulated walls. We assume that the wall has a cross-sectional area of 120 m^2, that we are maintaining an indoor temperature of 20°C, and that the outdoor temperature is a moderate 0°C. As shown earlier, the total R-value for a wall insulated with fiberglass is 2.28 $m^2 \cdot s \cdot °C/J$, while the R-value for an uninsulated wall is 0.46 $m^2 \cdot s \cdot °C/J$. For comparison's sake, we calculate the thermal energy lost during 1 minute. Substituting these values into the thermal conduction equation, we have:

$$\text{Insulated:} \quad TE = \frac{(A) \times (t) \times (\Delta T)}{\text{R-value}} = \frac{(120\ \text{m}^2)(60\ \text{s})(20°\text{C} - 0°\text{C})}{2.28\ \text{m}^2 \cdot \text{s} \cdot °\text{C/J}}$$

$$= 63{,}160\ \text{J (each minute)}$$

$$\text{Uninsulated:} \quad TE = \frac{(A) \times (t) \times (\Delta T)}{\text{R-value}} = \frac{(120\ \text{m}^2)(60\ \text{s})(20°\text{C} - 0°\text{C})}{0.46\ \text{m}^2 \cdot \text{s} \cdot °\text{C/J}}$$

$$= 320{,}000\ \text{J (each minute)}$$

The thermal energy flow across uninsulated walls is five times that across insulated walls.

One recommendation acted upon by the federal government is that thermostats be set at 20°C (68°F) in winter and 25.6°C (78°F) in summer. Most people set their thermostats at 23°C in winter and 20°C in summer. We can use the thermal conduction equation to determine just how much energy is used at various thermostat settings.

Assume that your house has insulated walls and that you are trying to cool your house on a typical August day in Kansas. The outdoor temperature is 40°C (104°F). Using the thermal conduction equation, we can calculate the thermal energy conducted through the walls when the thermostat is set at 20°C:

$$TE = \frac{(A) \times (t) \times (\Delta T)}{\text{R-value}} = \frac{(120\ \text{m}^2)(60\ \text{s})(40°\text{C} - 20°\text{C})}{2.28\ \text{m}^2 \cdot \text{s} \cdot °\text{C/J}}$$

$$= 63{,}160\ \text{J (each minute)}$$

We can make similar calculations for thermostat settings of 25°C, 30°C, 35°C, and 40°C. Table 11-2 includes the thermal energy transferred per minute for each of these inside temperatures when the outside temperature is 40°C. Significant savings occur for each 5°C increase in the thermostat setting. In winter, we could just reverse the advice and reduce our thermostat setting in order to save energy.

We can use the thermal conduction equation to investigate other recommendations. Of course, in real-life applications, more factors are often involved and have to be taken into consideration. Arguments continue about turning the thermostat up and down several times a day because of the additional energy required to bring a house up 10°C compared to maintaining it at a constant temperature all day. Regardless of this complexity, the thermal energy equation remains a useful tool for evaluating advice.

Table 11-2 Thermal Energy Conducted Per Minute for Various Thermostat Settings

Description	Inside Temperature	Outside Temperature	Temperature Difference	Thermal Energy Conducted/Minute (kJ/min)
Cool	20°C	40°C	20°C	6.3
Warm	25°C	40°C	15°C	4.7
Very warm	30°C	40°C	10°C	3.2
Hot	35°C	40°C	5°C	1.6
Very hot	40°C	40°C	0°C	0

Conduction at Boundaries

In the wall of a home, thermal energy is conducted from the air in the room through the inner wall to the insulation, to the outer wall, and then finally to the air outside. This conduction occurs within each material and between materials. Whenever two substances are in contact, thermal energy passes from the warmer substance to the cooler one by conduction—whether the substances are solids, liquids, or gases.

As another example, consider the interaction of air and a black asphalt road on a sunny day. The road is hot. Some of its thermal energy is transferred by conduction to the air immediately above the road. The warmed air then rises. Thermal energy must be conducted from the road to the air before convection can carry it away. But how did the road get hot to begin with? That is our next topic.

RADIATION-ABSORPTION

Your bicycle with its black seat has been sitting in the sun on a hot day. Wearing a pair of jogging shorts, you hop on the bike to go home. OUCH! Thermal energy has been transferred from the bike seat to you. The next day is equally hot. Wanting to avoid that uncomfortable sensation, you park the bike in the shade. That evening the ride home is much more comfortable. Since the air temperature was about the same on both days, the difference in the temperature of the seat must have been related to the seat's exposure to the sun. One day the seat was in the sun, and the next it was in the shade. Your bike gained thermal energy from the sun.

A bicycle seat gaining thermal energy from the sun is no surprise. Our sunburns, the growth of plants, and the evaporation of puddles all provide evidence that the sun is a significant energy source. The puzzle is how thermal energy is transferred from the sun, which is separated from us by some 155 million kilometers of essentially empty space. Both convection and conduction require matter with which to transfer thermal energy. Clearly, a third mechanism is needed to explain the transfer of thermal energy from the sun.

Transfer of Thermal Energy by Radiation-Absorption

Radiation-absorption is the process by which thermal energy is transferred by electromagnetic waves. As the name *electromagnetic* implies, these waves are best described in terms of electricity and magnetism, so we save a detailed discussion of them for Chapter 15. A thermal energy source, such as the sun, converts thermal energy into electromagnetic waves. These waves travel to an energy receiver, which converts the electromagnetic wave energy back into thermal energy. The energy source is said to **radiate** the energy and the energy receiver to **absorb** it. Consequently, the entire process is called radiation-absorption. Electromagnetic waves can be transmitted in materials as well as through empty space. While radiation-absorption describes the process by which thermal energy is transferred to us from the sun, it is also a common process of transferring thermal energy between objects on earth. Since the process does not require any matter, radiation-absorption acts separately from the processes of convection and conduction.

The thermal energy that warms us as we stand near a fireplace has been transferred by radiation-absorption. We feel this radiation in spite of convection (which is busy pulling thermal energy up the chimney) because radiation is transferred without using air as the vehicle. Lamps, toasters, electrical heaters—all radiate thermal energy, which our bodies absorb. We, in turn, also radiate thermal energy. Infrared film shows the thermal energy radiated by plants, animals, and even human beings.

Radiation-absorption is one of the processes by which objects exchange thermal energy with their surroundings. All objects radiate and absorb thermal energy continually. If they radiate more thermal energy than they absorb, the objects become cooler. If, like the bicycle seat in the sun, they absorb more energy than they radiate, the objects warm up. Most objects maintain an energy balance between absorption and radiation, always remaining at about the same temperature.

Dependence of Radiation-Absorption on Color

The ability to absorb and radiate thermal energy depends on one important factor—color. Consider an alternate solution to your problem of the bicycle seat. If you could not find any shade, another approach would be to cover the seat. A white seat cover keeps the seat cooler. Both black and white seats absorb radiated energy, but the white seat absorbs less than the black seat.

We can demonstrate the role of color in radiation-absorption with an experiment first performed by Benjamin Franklin. Franklin placed a black cloth and a white cloth on snow during a sunny day. After several hours he observed that the white cloth remained near the top of the snow, while the black cloth had sunk several centimeters. Dark-colored objects absorb radiation more readily than light-colored objects.

We take advantage of this difference in ability to absorb radiant energy when we choose clothing for different climates. In tropical climates, clothing is nearly always light in color. In more temperate climates, people wear light clothes in the summer and dark clothes in winter. Cold climates demand darker shades. Sometimes we even mix light and dark materials to obtain the best combination for maintaining a comfortable body temperature.

SELF-CHECK 11E

If you lived in Arizona, would you prefer to own a black car or a white one? Use the concept of radiation-absorption to explain your choice.

Good Absorbers are Good Radiators

Dark colors are good absorbers; light colors are not. How do both perform as radiators? A brief experiment provides us with an answer. We begin with two pans of fudge. One is vanilla flavored, so it is almost white. The other is chocolate flavored and dark in color. Both are removed from the oven at the same time and placed in a draft-free location to cool. Figure 11-11 shows the change in temperature in each as a function of time. The chocolate fudge cools much more rapidly than the vanilla. While some thermal energy can be carried away by convection or conduction, equal amounts should have been carried away from both the chocolate and vanilla fudge. The rate of temperature change differs because chocolate fudge is a better radiator of thermal energy than vanilla fudge. (Try it. You can eat the experiment when you finish!)

The difference between the two kinds of fudge is color. Dark colors are good radiators and good absorbers. Light colors are poor radiators and poor

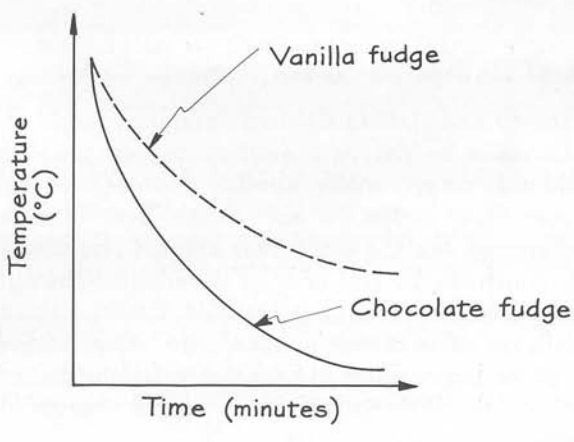


Figure 11-11
The chocolate fudge cools more rapidly than the vanilla fudge. Good absorbers are also good radiators.

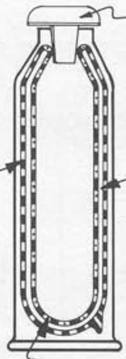


Figure 11-12
Thermos bottles are designed to minimize thermal energy transfer by all three processes.

absorbers. The two processes—radiation and absorption—go hand in hand. A good radiator is a good absorber; a poor radiator is a poor absorber.

The poor radiating ability of light colors is often combined with materials with high R-values to retain thermal energy. For example, styrofoam coffee cups are usually white. The relatively high R-value for styrofoam prevents thermal energy from being conducted through the walls of the cup. What little thermal energy is conducted to the outside of the cup will be radiated away more slowly because the cup is white.

ALL THREE PROCESSES

We have considered the three mechanisms by which thermal energy can be transferred from one place to another—convection, conduction, and radiation-absorption. Rarely will a transfer process involve only one of these mechanisms. A warm drink, for example, loses energy by convection as air along its surface is warmed and rises, by conduction through the walls of the container, and by radiation at its surface and along the outside walls of the container.

Thermos bottles are designed to minimize thermal energy transfer by all three processes, as shown in Figure 11-12. The lid prevents convection of the air above the liquid. The walls of the container are made of materials with high R-values, and many thermos bottles use a semivacuum between the outer and inner walls. Both of these characteristics minimize the energy loss due to conduction. Finally, the inner walls are made of a light-colored metal to reduce the thermal energy loss arising from radiation-absorption. This careful consideration of all three transfer processes has led to a very effective container that keeps hot drinks hot and cold ones cold.

Designers of solar energy systems must take all three transfer processes into consideration in their designs. The solar collector itself must operate using the radiation-absorption transfer process, since solar energy is radiated to us.

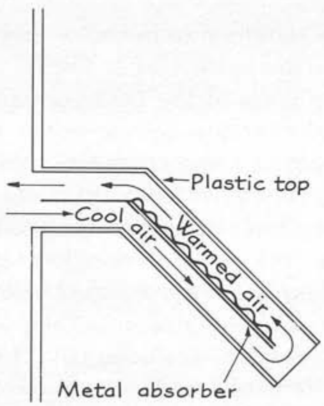
Once collected, the processes of conduction and convection are needed to transfer the thermal energy from the collector to the building. We can see how these processes are involved in the design of a simple solar collector used as a window heater (Figure 11-13).

The collector is essentially a wooden box with a metal strip down the center and transparent plastic across one side. The sun's radiation passes through the transparent plastic and is absorbed by the metal surface. The metal strip is painted black to increase the amount of radiant energy absorbed. Metal is chosen because its low specific heat capacity allows it to get much hotter than most other materials. An insulator placed below the metal strip limits the flow of thermal energy to the air above the plate. This establishes a path along which convection can occur. As shown in Figure 11-13, cool air is drawn in through the lower opening, circulated past the top of the metal plate (where it is warmed), and exhausted back into the room through the upper opening. The process continues as long as the metal plate absorbs solar radiation.

All three transfer processes—convection, conduction, and radiation-absorption—are involved. Solar energy is transferred to the metal by radiation-absorption. The air in contact with the metal strip is warmed by conduction. The flow of warmed air into the room and replacement air into the heater is accomplished by convection. Most solar collectors are more sophisticated, but even a design as simple as this can warm the air by some 50°F.

Figure 11-13

A solar collector, used here as a window heater, incorporates all three thermal-energy transfer processes in its design. Air circulates through the collector, where it is warmed by the black metal absorber in the center.



Fireplaces increase your home heating costs; insulating your walls decreases them. The three energy-transfer processes—convection, conduction, and radiation-absorption—enable us to audit our use of thermal energy. From the complexities of a solar power plant to the simplicity of hot bicycle seats, understanding the ways in which thermal energy moves from one object to another gives us control over what has become an increasingly expensive part of our lives.

CHAPTER SUMMARY

Thermal energy is transferred from one place to another by three processes: convection, conduction, and radiation-absorption.

Convection is the process of transferring thermal energy by the movement of warmed gases or liquids. It relies upon two characteristics of matter: (1) the ability of gases and liquids to flow, and (2) the ability of warmed gases and liquids to rise in their cooler surroundings. Thermal energy is transferred as the warmed gas or liquid circulates.

Conduction is the process by which thermal energy is transferred in solids, where the molecules remain in relatively restricted locations. Molecules in a solid transfer energy only to their immediate neighbors. *Thermal conductors* transfer thermal energy easily; *thermal insulators* do not. *Thermal resistivity* is a numerical value that describes the resistance of a material to the conduction of thermal energy. The higher the thermal resistivity of a substance, the less thermal energy it conducts. In most home heating applications, the thermal resistivity of a material and the thickness of the solid are combined to give an *R-value* for the solid:

$$\text{R-value} = \text{thermal resistivity} \times \text{distance energy travels}$$

If a solid consists of several different substances, its R-value is the sum of R-values for each substance:

$$\text{Total R-value} = \text{R-value}_1 + \text{R-value}_2 + \text{R-value}_3 + \cdots$$

The thermal energy transferred by a solid depends on the cross-sectional area of the solid, the time, the temperature difference between the two sides of the solid, and the R-value of the solid. The *thermal conduction equation* is

$$\begin{matrix}\text{Thermal energy} \\ \text{conducted}\end{matrix} = \frac{\begin{pmatrix}\text{cross-sectional} \\ \text{area}\end{pmatrix} \times (\text{time}) \times \begin{pmatrix}\text{temperature} \\ \text{difference}\end{pmatrix}}{\text{R-value}}$$

Radiation-absorption is the process by which thermal energy is transferred by electromagnetic waves. These waves can be transmitted through materials or empty space. An energy source radiates energy and an energy receiver absorbs this energy. The ability to absorb and radiate thermal energy depends on the color of the material. Black is a good absorber-radiator; white is a poor absorber-radiator.

ANSWERS TO SELF-CHECKS

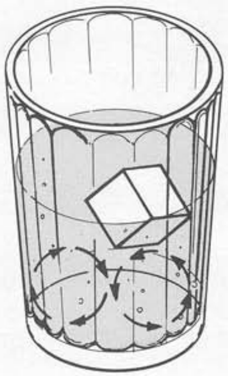


Figure 11-11A

11A. Water near the ice will be cooled. It will become heavier than the surrounding water and will sink. At the bottom of the glass this cooler water gains thermal energy conducted through the glass walls and from the surrounding molecules. As it warms up, this water rises back to the top to be cooled once again.

11B. Each layer of clothing traps air. Several layers of clothing provide layers of still air to insulate your body further.

11C.
$$\begin{aligned}\text{Total R-value} &= \text{R-value}_1 + \text{R-value}_2 + \text{R-value}_3 \\ &= [(4.8)(0.02) + 0.18 + (9.1)(0.02)]\ \text{m}^2 \cdot \text{s} \cdot {}^\circ\text{C/J} \\ &= 0.46\ \text{m}^2 \cdot \text{s} \cdot {}^\circ\text{C/J}\end{aligned}$$

11D. The R-value of glass is lower than that of walls because of the thermal resistivity of glass and the fact that glass windows are usually thinner than walls. The thermal energy equation states that the thermal energy conducted by a solid is inversely proportional to the R-value. The lower the R-value, the more thermal energy conducted across the material.

11E. You would prefer a white car. White is a poor absorber of radiant energy. Since the environment in Arizona is so hot, you would want cars to absorb as little thermal energy as possible.

PROBLEMS AND QUESTIONS

A. Review of Chapter Material

A1. Define the following terms:

Convection	Insulator
Conduction	Conductor
Radiation-absorption	R-value
Thermal resistivity	Buoyant force

A2. How is the weight of a gas used to determine if it will rise or fall in its surroundings?

A3. Describe the process of convection.

A4. What variables affect the thermal energy transferred through a solid?

A5. How is the R-value related to thermal resistivity?

A6. How would you calculate the total R-value of a wall composed of several layers of material?

A7. How does radiation-absorption differ from the other two processes?

A8. What factor is important in determining if an object will be a good absorber?

A9. How is a good radiator related to a good absorber?

A10. Describe how the design of the thermos bottle takes all three thermal energy transfer processes into account.

B. Using the Chapter Material

B1. Our 5-year-old notices that Cheerios rise in milk and Granola sinks. If you had equal volumes of the three substances (Granola, Cheerios, and milk), which would weigh the most? The least? Explain how you arrived at your conclusion.

B2. The total weight of a balloon and the gas inside it is 3.5 newtons (N). The volume of air it replaces weighs 3.0 N. Will the balloon and its contents rise?

B3. Draw the circulation of water in a pan sitting on a hot stove burner.

B4. A desk lamp has small holes near the top of the metal lampshade. How do these holes help to keep the lamp cool?

B5. When installing insulation in a home, you should be sure that it is fluffy rather than packed tightly. Why?

B6. Why will a potato with a nail stuck in it cook more rapidly than one without the nail?

B7. Many electronic parts become warm when operating. Metal is used to conduct heat away from them as rapidly as possible. If cost were not a factor, which of the metals listed in Table 11-1 would you choose?

B8. A homemade ice chest is made of 0.02 m of pine and 0.03 m of styrofoam. What is its total R-value?

B9. Twenty years ago refrigerator walls were 0.10 m thick and were filled with fiberglass. Today many refrigerator walls are 0.03 m thick and filled with styrofoam. Which provides better insulation?

B10. The outside temperature is 30°C; the inside is 20°C. A wall consists of a material with a thermal resistivity of 6 $m^2 \cdot s \cdot °C/J \cdot m$ and is 0.10 m thick. In 100 s how much energy is transferred through a 1 m^2 wall? Through a 2 m^2 wall? Which direction does the energy move: inside to outside or outside to inside?

B11. The earth's atmosphere provides protection from much of the sun's radiation. Why do astronauts wear light-colored suits on the moon, where no atmosphere exists?

B12. When it snows in Montana and Pennsylvania, the state highway departments spread coal dust on top of the snow. When the sun comes out, the snow melts rapidly. Why?

C. Extensions to New Situations

C1. A thermos bottle is used to keep cold drinks cold or hot drinks hot. To do so, it must decrease all forms of thermal energy transfer. The bottle has a light-colored interior, a tight-fitting stopper, and styrofoam walls.

a. Explain how each method of thermal energy transfer is decreased by the design.

b. Before styrofoam was popular, the thermos bottle had a vacuum between its inner and outer walls. How did this help?

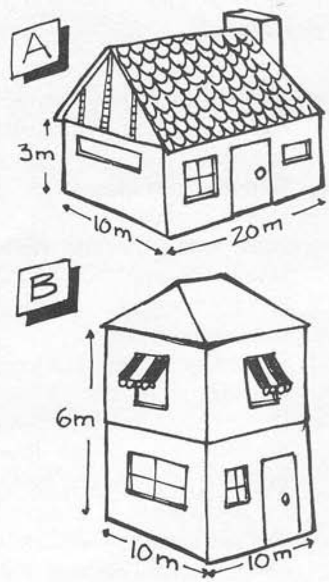
C2. Prior to the 1950s, most large homes were multistory dwellings. Then the ranch-style home was designed, so that every room was on the same floor. Consider two homes with the same living space, shown in the figure below.

a. What is the effect of convection on heating and on energy losses in the two homes?

b. If all the outside walls and the roofs in both houses have total R-values of 3 $m^2 \cdot s \cdot °C/J$, how much energy from each house is transferred in 100 seconds on a day when the outside temperature is 0°C and the inside temperature is 20°C?

c. A larger area provides greater radiation-absorption. Which roof will radiate more energy at night? Which will absorb more energy during the day?

d. Use the answers to parts (a)–(c) to discuss which house has lower utility bills.



C3. On sunny days, pilots of hot-air balloons find that their balloons are pushed up when they are over an asphalt (black) road. This phenomenon can be understood in terms of thermal energy transfer processes.

a. Why will the road be hot on a sunny day?

b. How will the energy from the road be transferred to the air immediately above the road?
c. What happens to the heated air? Why?
d. How is the balloon forced up?

C4. On a cold, sunny day you need to decide whether you have a better energy balance with the curtains open or closed. For a 1 m^2 window (no storm window) on the south side, use the following information:

R-value of glass	$= 0.16\ m^2 \cdot s \cdot {}^\circ C/J$
R-value of air trapped between glass and curtain	$= 0.18\ m^2 \cdot s \cdot {}^\circ C/J$
R-value of curtain	$= 0.17\ m^2 \cdot s \cdot {}^\circ C/J$
Inside temperature	$= 20^\circ C$
Outside temperature	$= 0^\circ C$
Thermal energy entering window per second	$= 100$ J

a. In 1 s, how much thermal energy flows out through the window with the curtain opened?
b. Repeat the calculation in (a) for a closed curtain.
c. How much thermal energy enters or leaves through the window in one second for the curtain opened? for the curtain closed?
d. Should you have the curtain open or closed?
e. If we have a storm window on the window, we add an R-value of 0.34 $m^2 \cdot s \cdot {}^\circ C/J$ to the total R-value. But the extra layer of glass reflects some of the sun's energy and only 90 J enter each second. Repeat the calculations and decide if the curtain on the window with the storm window should be open or closed.

C5. The ice in your picnic chest is melting quickly; you can slow down the melting process by wrapping the ice in an insulator.
a. Why does wrapping the ice slow down the melting?
b. What will happen to the temperature of the air in the chest?

C6. An old tale is that hot water will freeze more rapidly than cold water.
a. Based on the concepts presented in Chapter 10, would you expect hot water to freeze more rapidly than cold water?
b. Sometimes a tray of hot water will melt through the frost on a refrigerator shelf, while the cold water tray will sit on top of the frost. Why might the hot water freeze more quickly in this situation?

C7. On clear nights the temperature during the day will be much higher than the nighttime temperature. On cloudy days the daytime and nighttime temperatures will be only slightly different. To explain why, consider absorption and radiation.
a. On a clear night what happens to the energy radiated by the earth?
b. What happens to energy radiated by the earth on a cloudy night?
c. Use the answers to (a) and (b) to explain the temperature differences.

C8. The human body creates thermal energy, which must be removed. Some of this energy is removed by evaporation; some by conduction. The body's normal temperature is 37°C.
a. How does the rate at which thermal energy is conducted away from the body depend on the air temperature?
b. Why should you keep as much of your body as possible covered when the air temperature is very cold? (Explain this in terms of conduction.)
c. When the air temperature is above 37°C, can thermal energy be conducted away from the body?
d. Use the answers to (a)–(c) to describe why conduction can lead to health problems for some people.

C9. A bowl of hot soup will cool as it sits on a table.
a. How is the thermal energy transferred from the soup to the air immediately above it?
b. What happens to the air directly above the soup to aid in the cooling process?
c. Why will more than just the top layer of soup cool?

d. Use the answers to (a)–(c) to summarize the soup-cooling process.
e. Would placing a lid on a soup bowl slow down the cooling? Explain your answer.

D. Activities

D1. While attending a football game on a cold, sunny day, you wish to have a supply of hot drinks. Design a solar drink heater. Describe how radiation-absorption, conduction, and convection are each important in your design.

D2. Design a window curtain that will be able to absorb solar radiation during winter days, not absorb during summer days, radiate on summer nights, and not radiate on winter nights. The curtain can have movable parts.

D3. Look at ads for devices that are supposed to decrease the energy loss up the chimney of fireplaces or increase the thermal energy supplied by the fireplace. Describe how each of the devices works.

D4. Using patterns of melted snow, analyze thermal energy losses from buildings. Explain why you think the energy is lost. (Reference: A. A. Bartlett, *The Physics Teacher,* January and February, 1976).