

## Heat Transfer Methods

Equally as interesting as the effects of heat transfer on a system are the methods by which this occurs. Whenever there is a temperature difference, heat transfer occurs. Heat transfer may occur rapidly, such as through a cooking pan, or slowly, such as through the walls of a picnic ice chest. We can control rates of heat transfer by choosing materials (such as thick wool clothing for the winter), controlling air movement (such as the use of weather stripping around doors), or by choice of color (such as a white roof to reflect summer sunlight). So many processes involve heat transfer, so that it is hard to imagine a situation where no heat transfer occurs. Yet every process involving heat transfer takes place by only three methods:

1. Conduction is heat transfer through stationary matter by physical contact. (The matter is stationary on a macroscopic scale—we know there is thermal motion of the atoms and molecules at any temperature above absolute zero.) Heat transferred between the electric burner of a stove and the bottom of a pan is transferred by conduction.
2. Convection is the heat transfer by the macroscopic movement of a fluid. This type of transfer takes place in a forced-air furnace and in weather systems, for example.
3. Heat transfer by radiation occurs when microwaves, infrared radiation, visible light, or another form of electromagnetic radiation is emitted or absorbed. An obvious example is the warming of the Earth by the Sun. A less obvious example is thermal radiation from the human body.

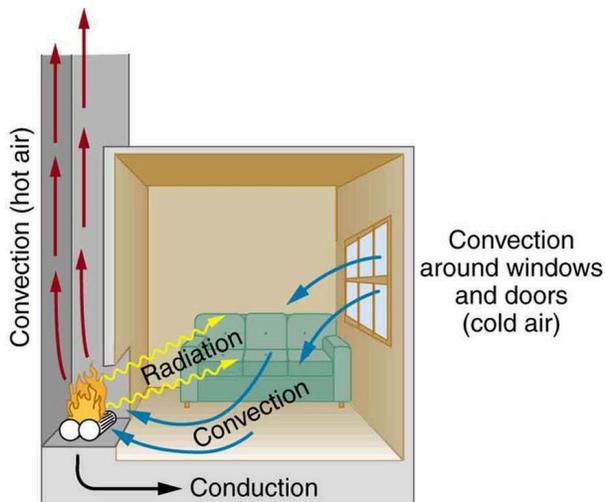


Figure 14.12 In a fireplace, heat transfer occurs by all three methods: conduction, convection, and radiation. Radiation is responsible for most of the heat transferred into the room. Heat transfer also occurs through conduction into the room, but at a much slower rate. Heat transfer by convection also occurs through cold air entering the room around windows and hot air leaving the room by rising up the chimney.

We examine these methods in some detail in the three following modules. Each method has unique and interesting characteristics, but all three do have one thing in common: they transfer heat solely because of a temperature difference [Figure 14.12](#).

### Check Your Understanding

Name an example from daily life (different from the text) for each mechanism of heat transfer.

#### *Solution*

Conduction: Heat transfers into your hands as you hold a hot cup of coffee.

Convection: Heat transfers as the barista “steams” cold milk to make hot *cocoa*.

Radiation: Reheating a cold cup of coffee in a microwave oven.

## Conduction



Figure 14.13 Insulation is used to limit the conduction of heat from the inside to the outside (in winters) and from the outside to the inside (in summers). (credit: Giles Douglas)

Your feet feel cold as you walk barefoot across the living room carpet in your cold house and then step onto the kitchen tile floor. This result is intriguing, since the carpet and tile floor are both at the same temperature. The different sensation you feel is explained by the different rates of heat transfer: the heat loss during the same time interval is greater for skin in contact with the tiles than with the carpet, so the temperature drop is greater on the tiles.

Some materials conduct thermal energy faster than others. In general, good conductors of electricity (metals like copper, aluminum, gold, and silver) are also good heat conductors, whereas insulators of electricity (wood, plastic, and rubber) are poor heat conductors. Figure 14.14 shows molecules in two bodies at different temperatures. The (average) kinetic energy of a molecule in the hot body is higher than in the colder body. If two molecules collide, an energy transfer from the molecule with greater kinetic energy to the molecule with less kinetic energy occurs. The cumulative effect from all collisions results in a net flux of heat from the hot body to the colder body. The heat flux thus depends on the temperature difference  $\Delta T = T_{hot} - T_{cold}$ . Therefore, you will get a more severe burn from boiling water than from hot tap water. Conversely, if the temperatures are the same, the net heat transfer rate falls to zero, and equilibrium is achieved. Owing to the fact that the number of collisions increases with increasing area, heat conduction depends on the cross-sectional area. If you touch a cold wall with your palm, your hand cools faster than if you just touch it with your fingertip.

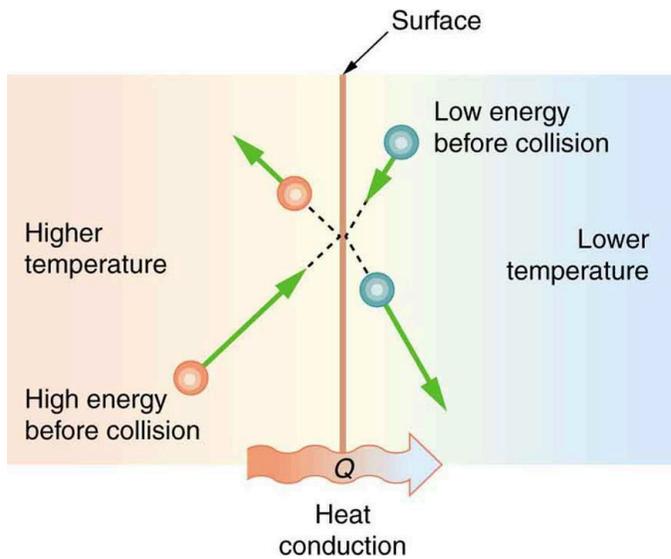


Figure 14.14 The molecules in two bodies at different temperatures have different average kinetic energies. Collisions occurring at the contact surface tend to transfer energy from high-temperature regions to low-temperature regions. In this illustration, a molecule in the lower temperature region (right side) has low energy before collision, but its energy increases after colliding with the contact surface. In contrast, a molecule in the higher temperature region (left side) has high energy before collision, but its energy decreases after colliding with the contact surface.

A third factor in the mechanism of conduction is the thickness of the material through which heat transfers. The figure below shows a slab of material with different temperatures on either side. Suppose that  $T_2$  is greater than  $T_1$ , so that heat is transferred from left to right. Heat transfer from the left side to the right side is accomplished by a series of molecular collisions. The thicker the material, the more time it takes to transfer the same amount of heat. This model explains why thick clothing is warmer than thin clothing in winters, and why Arctic mammals protect themselves with thick blubber.

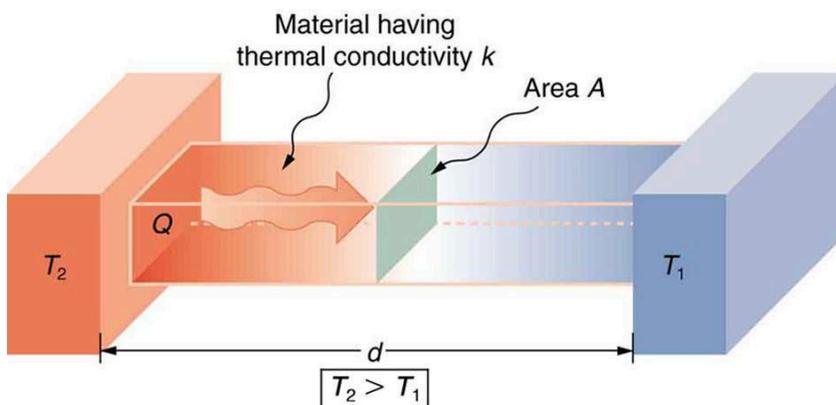


Figure 14.15 Heat conduction occurs through any material, represented here by a rectangular bar, whether window glass or walrus blubber. The temperature of the material

is  $T_2$  on the left and  $T_1$  on the right, where  $T_2$  is greater than  $T_1$ . The rate of heat transfer by conduction is directly proportional to the surface area  $A$ , the temperature difference  $T_2 - T_1$ , and the substance's conductivity  $k$ . The rate of heat transfer is inversely proportional to the thickness  $d$ .

Lastly, the heat transfer rate depends on the material properties described by the coefficient of thermal conductivity. All four factors are included in a simple equation that was deduced from and is confirmed by experiments. The rate of conductive heat transfer through a slab of material, such as the one in [Figure 14.15](#), is given by

$$\frac{Q}{t} = \frac{kA(T_2 - T_1)}{d},$$

14.26

where  $Q/t$  is the rate of heat transfer in watts or kilocalories per second,  $k$  is the thermal conductivity of the material,  $A$  and  $d$  are its surface area and thickness, as shown in [Figure 14.15](#), and  $(T_2 - T_1)$  is the temperature difference across the slab. [Table 14.3](#) gives representative values of thermal conductivity.

### Example 14.5

#### *Calculating Heat Transfer Through Conduction: Conduction Rate Through an Ice Box*

A Styrofoam ice box has a total area of  $0.950 \text{ m}^2$  and walls with an average thickness of 2.50 cm. The box contains ice, water, and canned beverages at  $0^\circ\text{C}$ . The inside of the box is kept cold by melting ice. How much ice melts in one day if the ice box is kept in the trunk of a car at  $35.0^\circ\text{C}$ ?

#### *Strategy*

This question involves both heat for a phase change (melting of ice) and the transfer of heat by conduction. To find the amount of ice melted, we must find the net heat transferred. This value can be obtained by calculating the rate of heat transfer by conduction and multiplying by time.

#### *Solution*

1. Identify the knowns.

$$A = 0.950 \text{ m}^2;$$

$$d = 2.50 \text{ cm} = 0.0250 \text{ m};$$

$$T_1 = 0^\circ\text{C};$$

$$T_2 = 35.0^\circ\text{C}, t = 1 \text{ day} = 24 \text{ hours} = 86,400 \text{ s}.$$

14.27

2. Identify the unknowns. We need to solve for the mass of the ice,  $m$ . We will also need to solve for the net heat transferred to melt the ice,  $Q$ .
3. Determine which equations to use. The rate of heat transfer by conduction is given by

$$\frac{Q}{t} = \frac{kA(T_2 - T_1)}{d}$$

14.28

4. The heat is used to melt the ice:  $Q = mL_f$ .

5. Insert the known values:

$$\frac{Q}{t} = \frac{0.010 \text{ J/s}\cdot\text{m}\cdot^{\circ}\text{C} \cdot 0.950 \text{ m}^2 \cdot 35.0^{\circ}\text{C} - 0^{\circ}\text{C}}{0.0250 \text{ m}} = 13.3 \text{ J/s}$$

14.29

6. Multiply the rate of heat transfer by the time (1 day = 86,400 s):

$$Q = Q/tt = 13.3 \text{ J/s} \cdot 86,400 \text{ s} = 1.15 \times 10^6 \text{ J}$$

14.30

7. Set this equal to the heat transferred to melt the ice:  $Q = mL_f$ . Solve for the mass  $m$ :

$$m = \frac{Q}{L_f} = \frac{1.15 \times 10^6 \text{ J}}{334 \times 10^3 \text{ J/kg}} = 3.44 \text{ kg}$$

14.31

### Discussion

The result of 3.44 kg, or about 7.6 lbs, seems about right, based on experience. You might expect to use about a 4 kg (7–10 lb) bag of ice per day. A little extra ice is required if you add any warm food or beverages.

Inspecting the conductivities in [Table 14.3](#) shows that Styrofoam is a very poor conductor and thus a good insulator. Other good insulators include fiberglass, wool, and goose-down feathers. Like Styrofoam, these all incorporate many small pockets of air, taking advantage of air's poor thermal conductivity.

Substance	Thermal conductivity $k$ (J/s·m·°C)
Silver	420
Copper	390
Gold	318
Aluminum	220
Steel iron	80
Steel (stainless)	14
Ice	2.2
Glass (average)	0.84
Concrete brick	0.84
Water	0.6

Fatty tissue (without blood)	0.2
Asbestos	0.16
Plasterboard	0.16
Wood	0.08–0.16
Snow (dry)	0.10
Cork	0.042
Glass wool	0.042
Wool	0.04
Down feathers	0.025
Air	0.023
Styrofoam	0.010

Table 14.3 Thermal Conductivities of Common Substances<sup>7</sup>

7

At temperatures near 0°C.

A combination of material and thickness is often manipulated to develop good insulators—the smaller the conductivity  $k$  and the larger the thickness  $d$ , the better. The ratio of  $d/k$  will thus be large for a good insulator. The ratio  $d/k$  is called the  $R$  factor. The rate of conductive heat transfer is inversely proportional to  $R$ . The larger the value of  $R$ , the better the insulation.  $R$  factors are most commonly quoted for household insulation, refrigerators, and the like—unfortunately, it is still in non-metric units of  $\text{ft}^2 \cdot \text{°F} \cdot \text{h} / \text{Btu}$ , although the unit usually goes unstated (1 British thermal unit [Btu] is the amount of energy needed to change the temperature of 1.0 lb of water by 1.0 °F). A couple of representative values are an  $R$  factor of 11 for 3.5-in-thick fiberglass batts (pieces) of insulation and an  $R$  factor of 19 for 6.5-in-thick fiberglass batts. Walls are usually insulated with 3.5-in batts, while ceilings are usually insulated with 6.5-in batts. In cold climates, thicker batts may be used in ceilings and walls.

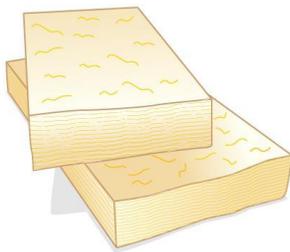


Figure 14.16 The fiberglass batt is used for insulation of walls and ceilings to prevent heat transfer between the inside of the building and the outside environment.

Note that in Table 14.3, the best thermal conductors—silver, copper, gold, and aluminum—are also the best electrical conductors, again related to the density of free electrons in them. Cooking utensils are typically made from good conductors.

### Example 14.6

#### Calculating the Temperature Difference Maintained by a Heat Transfer: Conduction Through an Aluminum Pan

Water is boiling in an aluminum pan placed on an electrical element on a stovetop. The sauce pan has a bottom that is 0.800 cm thick and 14.0 cm in diameter. The boiling water is evaporating at the rate of 1.00 g/s. What is the temperature difference across (through) the bottom of the pan?

#### Strategy

Conduction through the aluminum is the primary method of heat transfer here, and so we use the equation for the rate of heat transfer and solve for the temperature difference.

$$T_2 - T_1 = \frac{Q}{t} \frac{d}{kA}.$$

14.32

#### Solution

1. Identify the knowns and convert them to the SI units.

The thickness of the pan,  $d = 0.800 \text{ cm} = 8.0 \times 10^{-3} \text{ m}$ , the area of the pan,  $A = \pi(0.14/2)^2 \text{ m}^2 = 1.54 \times 10^{-2} \text{ m}^2$ , and the thermal conductivity,  $k = 220 \text{ J/s} \cdot \text{m} \cdot ^\circ\text{C}$ .

2. Calculate the necessary heat of vaporization of 1 g of water:

$$Q = mL_v = 1.00 \times 10^{-3} \text{ kg} 2256 \times 10^3 \text{ J/kg} = 2256 \text{ J}.$$

14.33

3. Calculate the rate of heat transfer given that 1 g of water melts in one second:

$$Q/t = 2256 \text{ J/s or } 2.26 \text{ kW}.$$

14.34

4. Insert the knowns into the equation and solve for the temperature difference:

$$T_2 - T_1 = \frac{Q}{t} \frac{d}{kA} = 2256 \text{ J/s} \frac{8.00 \times 10^{-3} \text{ m}}{220 \text{ J/s} \cdot \text{m} \cdot ^\circ\text{C} 1.54 \times 10^{-2} \text{ m}^2} = 5.33^\circ\text{C}.$$

14.35

#### Discussion

The value for the heat transfer  $Q/t = 2.26 \text{ kW or } 2256 \text{ J/s}$  is typical for an electric stove. This value gives a remarkably small temperature difference between the stove and the pan. Consider that the stove burner is red hot while the inside of the pan is nearly  $100^\circ\text{C}$

because of its contact with boiling water. This contact effectively cools the bottom of the pan in spite of its proximity to the very hot stove burner. Aluminum is such a good conductor that it only takes this small temperature difference to produce a heat transfer of 2.26 kW into the pan.

Conduction is caused by the random motion of atoms and molecules. As such, it is an ineffective mechanism for heat transport over macroscopic distances and short time distances. Take, for example, the temperature on the Earth, which would be unbearably cold during the night and extremely hot during the day if heat transport in the atmosphere was to be only through conduction. In another example, car engines would overheat unless there was a more efficient way to remove excess heat from the pistons.

### Check Your Understanding

How does the rate of heat transfer by conduction change when all spatial dimensions are doubled?

#### Solution

Because area is the product of two spatial dimensions, it increases by a factor of four when each dimension is doubled  $A_{final} = (2d)^2 = 4d^2 = 4A_{initial}$ . The distance, however, simply doubles. Because the temperature difference and the coefficient of thermal conductivity are independent of the spatial dimensions, the rate of heat transfer by conduction increases by a factor of four divided by two, or two:

$$\frac{Q}{t}_{final} = \frac{kA_{final}T_2 - T_1}{d_{final}} = \frac{k4A_{initial}T_2 - T_1}{2d_{initial}} = 2 \frac{kA_{initial}T_2 - T_1}{d_{initial}} = 2 \frac{Q}{t}_{initial}.$$

14.36

## Convection

Convection is driven by large-scale flow of matter. In the case of Earth, the atmospheric circulation is caused by the flow of hot air from the tropics to the poles, and the flow of cold air from the poles toward the tropics. (Note that Earth's rotation causes the observed easterly flow of air in the northern hemisphere). Car engines are kept cool by the flow of water in the cooling system, with the water pump maintaining a flow of cool water to the pistons. The circulatory system is used the body: when the body overheats, the blood vessels in the skin expand (dilate), which increases the blood flow to the skin where it can be cooled by sweating. These vessels become smaller when it is cold outside and larger when it is hot (so more fluid flows, and more energy is transferred).

The body also loses a significant fraction of its heat through the breathing process.

While convection is usually more complicated than conduction, we can describe convection and do some straightforward, realistic calculations of its effects. Natural convection is driven by buoyant forces: hot air rises because density decreases as temperature increases. The house in [Figure 14.17](#) is kept warm in this manner, as is the pot of water on the stove in [Figure 14.18](#). Ocean currents and large-scale atmospheric circulation transfer energy from one part of the globe to another. Both are examples of natural convection.

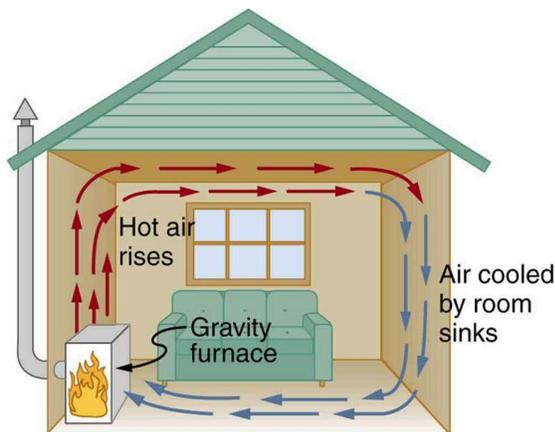


Figure 14.17 Air heated by the so-called gravity furnace expands and rises, forming a convective loop that transfers energy to other parts of the room. As the air is cooled at the ceiling and outside walls, it contracts, eventually becoming denser than room air and sinking to the floor. A properly designed heating system using natural convection, like this one, can be quite efficient in uniformly heating a home.

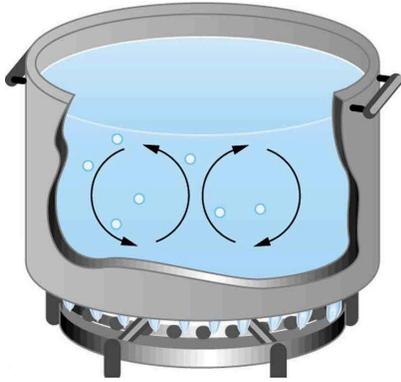


Figure 14.18 Convection plays an important role in heat transfer inside this pot of water. Once conducted to the inside, heat transfer to other parts of the pot is mostly by convection. The hotter water expands, decreases in density, and rises to transfer heat to other regions of the water, while colder water sinks to the bottom. This process keeps repeating.

#### Take-Home Experiment: Convection Rolls in a Heated Pan

Take two small pots of water and use an eye dropper to place a drop of food coloring near the bottom of each. Leave one on a bench top and heat the other over a stovetop. Watch how the color spreads and how long it takes the color to reach the top. Watch how convective loops form.

#### Example 14.7

##### *Calculating Heat Transfer by Convection: Convection of Air Through the Walls of a House*

Most houses are not airtight: air goes in and out around doors and windows, through cracks and crevices, following wiring to switches and outlets, and so on. The air in a typical house is completely replaced in less than an hour. Suppose that a moderately-sized house has inside dimensions  $12.0\text{ m} \times 18.0\text{ m} \times 3.00\text{ m}$  high, and that all air is replaced in 30.0 min. Calculate the heat transfer per unit time in watts needed to warm the incoming cold air by  $10.0^\circ\text{C}$ , thus replacing the heat transferred by convection alone.

##### *Strategy*

Heat is used to raise the temperature of air so that  $Q = mc\Delta T$ . The rate of heat transfer is then  $Q/t$ , where  $t$  is the time for air turnover. We are given that  $\Delta T$  is  $10.0^\circ\text{C}$ , but we must still find values for the mass of air and its specific heat before we can calculate  $Q$ . The specific heat of air is a weighted average of the specific heats of nitrogen and oxygen, which gives  $c = c_p \cong 1000\text{ J/kg} \cdot ^\circ\text{C}$  from Table 14.1 (note that the specific heat at constant pressure must be used for this process).

##### *Solution*

1. Determine the mass of air from its density and the given volume of the house. The density is given from the density  $\rho$  and the volume

$$m = \rho V = 1.29\text{ kg/m}^3 12.0\text{ m} \times 18.0\text{ m} \times 3.00\text{ m} = 836\text{ kg}.$$

14.37

2. Calculate the heat transferred from the change in air temperature:  $Q = mc\Delta T$  so that

$$Q = 836 \text{ kg} \cdot 1000 \text{ J/kg} \cdot ^\circ\text{C} \cdot 10.0^\circ\text{C} = 8.36 \times 10^6 \text{ J}.$$

14.38

3. Calculate the heat transfer from the heat  $Q$  and the turnover time  $t$ . Since air is turned over in  $t = 0.500 \text{ h} = 1800 \text{ s}$ , the heat transferred per unit time is

$$\frac{Q}{t} = \frac{8.36 \times 10^6 \text{ J}}{1800 \text{ s}} = 4.64 \text{ kW}.$$

14.39

### Discussion

This rate of heat transfer is equal to the power consumed by about forty-six 100-W light bulbs. Newly constructed homes are designed for a turnover time of 2 hours or more, rather than 30 minutes for the house of this example. Weather stripping, caulking, and improved window seals are commonly employed. More extreme measures are sometimes taken in very cold (or hot) climates to achieve a tight standard of more than 6 hours for one air turnover. Still longer turnover times are unhealthy, because a minimum amount of fresh air is necessary to supply oxygen for breathing and to dilute household pollutants. The term used for the process by which outside air leaks into the house from cracks around windows, doors, and the foundation is called "air infiltration."

A cold wind is much more chilling than still cold air, because convection combines with conduction in the body to increase the rate at which energy is transferred away from the body. The table below gives approximate wind-chill factors, which are the temperatures of still air that produce the same rate of cooling as air of a given temperature and speed. Wind-chill factors are a dramatic reminder of convection's ability to transfer heat faster than conduction. For example, a 15.0 m/s wind at  $0^\circ\text{C}$  has the chilling equivalent of still air at about  $-18^\circ\text{C}$ .

Moving air temperature $^\circ\text{C}$	Wind speed (m/s)	2	5	10	15	20
5	3	-1	-8	-10	-12	-12
2	0	-7	-12	-16	-18	-18
0	-2	-9	-15	-18	-20	-20
-5	-7	-15	-22	-26	-29	-29

– 10	– 12	– 21	– 29	– 34	– 36
– 20	– 23	– 34	– 44	– 50	– 52
– 40	– 44	– 59	– 73	– 82	– 84

Table 14.4 Wind-Chill Factors

Although air can transfer heat rapidly by convection, it is a poor conductor and thus a good insulator. The amount of available space for airflow determines whether air acts as an insulator or conductor. The space between the inside and outside walls of a house, for example, is about 9 cm (3.5 in) —large enough for convection to work effectively. The addition of wall insulation prevents airflow, so heat loss (or gain) is decreased. Similarly, the gap between the two panes of a double-paned window is about 1 cm, which prevents convection and takes advantage of air’s low conductivity to prevent greater loss. Fur, fiber, and fiberglass also take advantage of the low conductivity of air by trapping it in spaces too small to support convection, as shown in the figure. Fur and feathers are lightweight and thus ideal for the protection of animals.

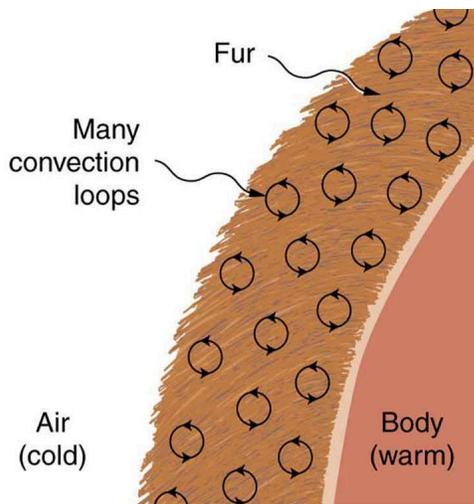


Figure 14.19 Fur is filled with air, breaking it up into many small pockets. Convection is very slow here, because the loops are so small. The low conductivity of air makes fur a very good lightweight insulator.

Some interesting phenomena happen *when convection is accompanied by a phase change*. It allows us to cool off by sweating, even if the temperature of the surrounding air exceeds body temperature. Heat from the skin is required for sweat to evaporate from the skin, but without air flow, the air becomes saturated and evaporation stops. Air flow caused by convection replaces the saturated air by dry air and evaporation continues.

### Example 14.8

#### *Calculate the Flow of Mass during Convection: Sweat-Heat Transfer away from the Body*

The average person produces heat at the rate of about 120 W when at rest. At what rate must water evaporate from the body to get rid of all this energy? (This evaporation might occur when a person is sitting in the shade and surrounding temperatures are the same as skin temperature, eliminating heat transfer by other methods.)

#### *Strategy*

Energy is needed for a phase change ( $Q = mL_v$ ). Thus, the energy loss per unit time is

$$\frac{Q}{t} = \frac{mL_v}{t} = 120 \text{ W} = 120 \text{ J/s.}$$

14.40

We divide both sides of the equation by  $L_v$  to find that the mass evaporated per unit time is

$$\frac{m}{t} = \frac{120 \text{ J/s}}{L_v}.$$

14.41

#### *Solution*

(1) Insert the value of the latent heat from [Table 14.2](#),  $L_v = 2430 \text{ kJ/kg} = 2430 \text{ J/g}$ . This yields

$$\frac{m}{t} = \frac{120 \text{ J/s}}{2430 \text{ J/g}} = 0.0494 \text{ g/s} = 2.96 \text{ g/min.}$$

14.42

#### *Discussion*

Evaporating about 3 g/min seems reasonable. This would be about 180 g (about 7 oz) per hour. If the air is very dry, the sweat may evaporate without even being noticed. A significant amount of evaporation also takes place in the lungs and breathing passages.

Another important example of the combination of phase change and convection occurs when water evaporates from the oceans. Heat is removed from the ocean when water evaporates. If the water vapor condenses in liquid droplets as clouds form, heat is released in the atmosphere. Thus, there is an overall transfer of heat from the ocean to the atmosphere. This process is the driving power behind thunderheads, those great cumulus clouds that rise as much as 20.0 km into the stratosphere. Water vapor carried in by convection condenses, releasing tremendous amounts of energy. This energy causes the air to expand and rise, where it is colder. More condensation occurs in these colder regions, which in turn drives the cloud even higher. Such a mechanism is called positive feedback, since the process reinforces and accelerates itself. These systems sometimes produce violent storms, with lightning and hail, and constitute the mechanism driving hurricanes.



Figure 14.20 Cumulus clouds are caused by water vapor that rises because of convection. The rise of clouds is driven by a positive feedback mechanism. (credit: Mike Love)



Figure 14.21 Convection accompanied by a phase change releases the energy needed to drive this thunderhead into the stratosphere. (credit: Gerardo García Moretti )



Figure 14.22 The phase change that occurs when this iceberg melts involves tremendous heat transfer. (credit: Dominic Alves)

The movement of icebergs is another example of convection accompanied by a phase change. Suppose an iceberg drifts from Greenland into warmer Atlantic waters. Heat is removed from the warm ocean water when the ice melts and heat is released to the land mass when the iceberg forms on Greenland.

### Check Your Understanding

Explain why using a fan in the summer feels refreshing!

#### *Solution*

Using a fan increases the flow of air: warm air near your body is replaced by cooler air from elsewhere. Convection increases the rate of heat transfer so that moving air “feels” cooler than still air.

## Radiation

You can feel the heat transfer from a fire and from the Sun. Similarly, you can sometimes tell that the oven is hot without touching its door or looking inside—it may just warm you as you walk by. The space between the Earth and the Sun is largely empty, without any possibility of heat transfer by convection or conduction. In these examples, heat is transferred by radiation. That is, the hot body emits electromagnetic waves that are absorbed by our skin: no medium is required for electromagnetic waves to propagate. Different names are used for electromagnetic waves of different wavelengths: radio waves, microwaves, infrared radiation, visible light, ultraviolet radiation, X-rays, and gamma rays.



Figure 14.23 Most of the heat transfer from this fire to the observers is through infrared radiation. The visible light, although dramatic, transfers relatively little thermal energy. Convection transfers energy away from the observers as hot air rises, while conduction is negligibly slow here. Skin is very sensitive to infrared radiation, so that you can sense the presence of a fire without looking at it directly. (credit: Daniel X. O’Neil)

The energy of electromagnetic radiation depends on the wavelength (color) and varies over a wide range: a smaller wavelength (or higher frequency) corresponds to a higher energy. Because more heat is radiated at higher temperatures, a temperature change is accompanied by a color change. Take, for example, an electrical element on a stove, which glows from red to orange, while the higher-temperature steel in a blast furnace glows from yellow to white. The radiation you feel is mostly infrared, which corresponds to a lower temperature than that of the electrical element and the steel. The radiated energy depends on its intensity, which is represented in the figure below by the height of the distribution.

[Electromagnetic Waves](#) explains more about the electromagnetic spectrum and [Introduction to Quantum Physics](#) discusses how the decrease in wavelength corresponds to an increase in energy.

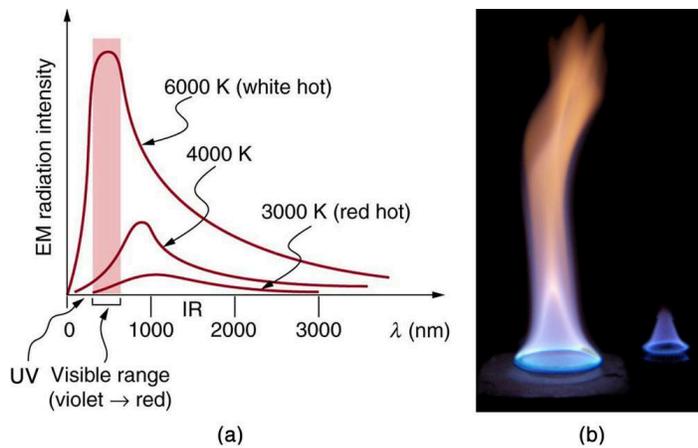


Figure 14.24 (a) A graph of the spectra of electromagnetic waves emitted from an ideal radiator at three different temperatures. The intensity or rate of radiation emission increases dramatically with temperature, and the spectrum shifts toward the visible and ultraviolet parts of the spectrum. The shaded portion denotes the visible part of the spectrum. It is apparent that the shift toward the ultraviolet with temperature makes the visible appearance shift from red to white to blue as temperature increases. (b) Note the variations in color corresponding to variations in flame temperature. (credit: Tuohirulla)

All objects absorb and emit electromagnetic radiation. The rate of heat transfer by radiation is largely determined by the color of the object. Black is the most effective, and white is the least effective. People living in hot climates generally avoid wearing black clothing, for instance. Similarly, black asphalt in a parking lot will be hotter than adjacent gray sidewalk on a summer day, because black absorbs better than gray. The reverse is also true—black radiates better than gray. Thus, on a clear summer night, the asphalt will be colder than the gray sidewalk, because black radiates the energy more rapidly than gray. An *ideal radiator* is the same color as an *ideal absorber*, and captures all the radiation that falls on it. In contrast, white is a poor absorber and is also a poor radiator. A white object reflects all radiation, like a mirror. (A perfect, polished white surface is mirror-like in appearance, and a crushed mirror looks white.)

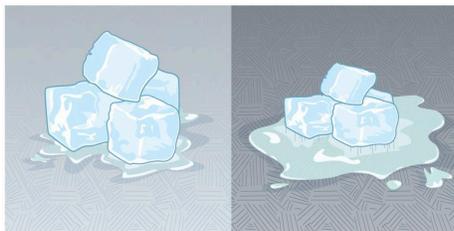


Figure 14.25 This illustration shows that the darker pavement is hotter than the lighter pavement (much more of the ice on the right has melted), although both have been in the sunlight for the same time. The thermal conductivities of the pavements are the same.

Gray objects have a uniform ability to absorb all parts of the electromagnetic spectrum. Colored objects behave in similar but more complex ways, which gives them a particular color in the visible range and may make them special in other ranges of the nonvisible

spectrum. Take, for example, the strong absorption of infrared radiation by the skin, which allows us to be very sensitive to it.

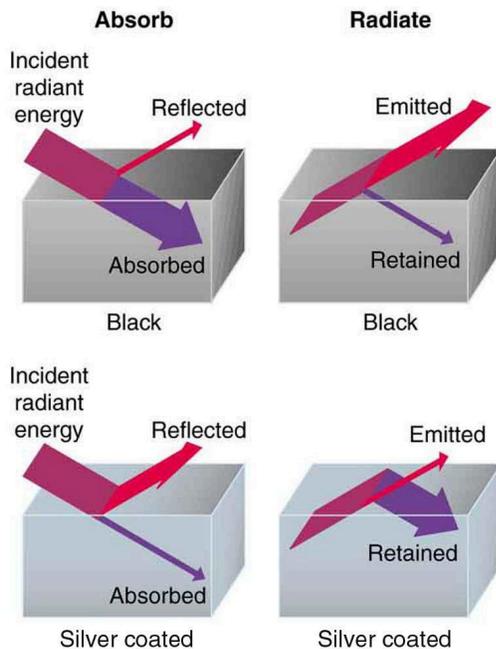


Figure 14.26 A black object is a good absorber and a good radiator, while a white (or silver) object is a poor absorber and a poor radiator. It is as if radiation from the inside is reflected back into the silver object, whereas radiation from the inside of the black object is “absorbed” when it hits the surface and finds itself on the outside and is strongly emitted.

The rate of heat transfer by emitted radiation is determined by the Stefan-Boltzmann law of radiation:

$$\frac{Q}{t} = \sigma eAT^4,$$

14.43

where  $\sigma = 5.67 \times 10^{-8} \text{ J/s} \cdot \text{m}^2 \cdot \text{K}^4$  is the Stefan-Boltzmann constant,  $A$  is the surface area of the object, and  $T$  is its absolute temperature in kelvin. The symbol  $e$  stands for the emissivity of the object, which is a measure of how well it radiates. An ideal jet-black (or black body) radiator has  $e = 1$ , whereas a perfect reflector has  $e = 0$ . Real objects fall between these two values. Take, for example, tungsten light bulb filaments which have an  $e$  of about 0.5, and carbon black (a material used in printer toner), which has the (greatest known) emissivity of about 0.99.

The radiation rate is directly proportional to the *fourth power* of the absolute temperature—a remarkably strong temperature dependence. Furthermore, the radiated heat is proportional to the surface area of the object. If you knock apart the coals of a fire, there is a noticeable increase in radiation due to an increase in radiating surface area.



Figure 14.27 A thermograph of part of a building shows temperature variations, indicating where heat transfer to the outside is most severe. Windows are a major region of heat transfer to the outside of homes. (credit: U.S. Army)

Skin is a remarkably good absorber and emitter of infrared radiation, having an emissivity of 0.97 in the infrared spectrum. Thus, we are all nearly (jet) black in the infrared, in spite of the obvious variations in skin color. This high infrared emissivity is why we can so easily feel radiation on our skin. It is also the basis for the use of night scopes used by law enforcement and the military to detect human beings. Even small temperature variations can be detected because of the  $T^4$  dependence. Images, called *thermographs*, can be used medically to detect regions of abnormally high temperature in the body, perhaps indicative of disease. Similar techniques can be used to detect heat leaks in homes [Figure 14.27](#), optimize performance of blast furnaces, improve comfort levels in work environments, and even remotely map the Earth's temperature profile.

All objects emit and absorb radiation. The *net* rate of heat transfer by radiation (absorption minus emission) is related to both the temperature of the object and the temperature of its surroundings. Assuming that an object with a temperature  $T_1$  is surrounded by an environment with uniform temperature  $T_2$ , the net rate of heat transfer by radiation is

$$\frac{Q_{net}}{t} = \sigma eAT_2^4 - T_1^4,$$

14.44

where  $e$  is the emissivity of the object alone. In other words, it does not matter whether the surroundings are white, gray, or black; the balance of radiation into and out of the object depends on how well it emits and absorbs radiation. When  $T_2 > T_1$ , the quantity  $Q_{net}/t$  is positive; that is, the net heat transfer is from hot to cold.

### Take-Home Experiment: Temperature in the Sun

Place a thermometer out in the sunshine and shield it from direct sunlight using an aluminum foil. What is the reading? Now remove the shield, and note what the thermometer reads. Take a handkerchief soaked in nail polish remover, wrap it around the thermometer and place it in the sunshine. What does the thermometer read?

### Example 14.9

#### Calculate the Net Heat Transfer of a Person: Heat Transfer by Radiation

What is the rate of heat transfer by radiation, with an unclothed person standing in a dark room whose ambient temperature is  $22.0^\circ\text{C}$ . The person has a normal skin temperature of  $33.0^\circ\text{C}$  and a surface area of  $1.50\text{ m}^2$ . The emissivity of skin is 0.97 in the infrared, where the radiation takes place.

#### Strategy

We can solve this by using the equation for the rate of radiative heat transfer.

#### Solution

Insert the temperatures values  $T_2 = 295\text{ K}$  and  $T_1 = 306\text{ K}$ , so that

$$\frac{Q}{t} = \sigma e A T_2^4 - T_1^4$$

14.45

$$= 5.67 \times 10^{-8}\text{ J/s} \cdot \text{m}^2 \cdot \text{K}^4 0.97 1.50\text{ m}^2 [295\text{ K}^4 - 306\text{ K}^4]$$

14.46

$$= -99\text{ J/s} = -99\text{ W}.$$

14.47

#### Discussion

This value is a significant rate of heat transfer to the environment (note the minus sign), considering that a person at rest may produce energy at the rate of 125 W and that conduction and convection will also be transferring energy to the environment. Indeed, we would probably expect this person to feel cold. Clothing significantly reduces heat transfer to the environment by many methods, because clothing slows down both conduction and convection, and has a lower emissivity (especially if it is white) than skin.

The Earth receives almost all its energy from radiation of the Sun and reflects some of it back into outer space. Because the Sun is hotter than the Earth, the net energy flux is from the Sun to the Earth. However, the rate of energy transfer is less than the equation for the radiative heat transfer would predict because the Sun does not fill the sky. The average emissivity ( $e$ ) of the Earth is about 0.65, but the calculation of this value is complicated by the fact that the highly reflective cloud coverage varies greatly from day to day. There is a

negative feedback (one in which a change produces an effect that opposes that change) between clouds and heat transfer; greater temperatures evaporate more water to form more clouds, which reflect more radiation back into space, reducing the temperature. The often mentioned greenhouse effect is directly related to the variation of the Earth's emissivity with radiation type (see the figure given below). The greenhouse effect is a natural phenomenon responsible for providing temperatures suitable for life on Earth. The Earth's relatively constant temperature is a result of the energy balance between the incoming solar radiation and the energy radiated from the Earth. Most of the infrared radiation emitted from the Earth is absorbed by carbon dioxide ( $CO_2$ ) and water ( $H_2O$ ) in the atmosphere and then re-radiated back to the Earth or into outer space. Re-radiation back to the Earth maintains its surface temperature about  $40^\circ C$  higher than it would be if there was no atmosphere, similar to the way glass increases temperatures in a greenhouse.

The greenhouse effect and its causes were first predicted by Eunice Newton Foote after she designed and conducted experiments on heating of different gases. After filling flasks with carbon dioxide, hydrogen, and regular air, then also modifying moisture, she placed them in the sun and carefully measured their heating and, especially, their heat retention. She discovered that the  $CO_2$  flask gained the most temperature and held it the longest. After subsequent research, her paper "Circumstances affecting the Heat of the Sun's Rays" included conclusions that an atmosphere consisting of more carbon dioxide would be hotter resulting from the gas trapping radiation.

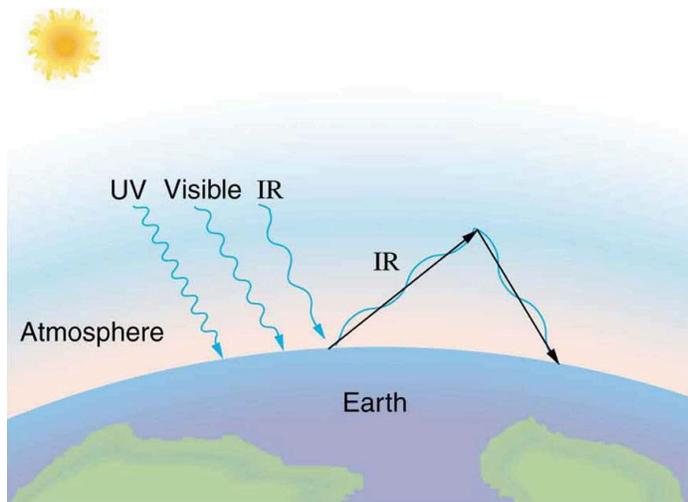


Figure 14.28 The greenhouse effect is a name given to the trapping of energy in the Earth's atmosphere by a process similar to that used in greenhouses. The atmosphere, like window glass, is transparent to incoming visible radiation and most of the Sun's infrared. These wavelengths are absorbed by the Earth and re-emitted as infrared. Since Earth's temperature is much lower than that of the Sun, the infrared radiated by the Earth has a much longer wavelength. The atmosphere, like glass, traps these longer infrared rays, keeping the Earth warmer than it would otherwise be. The amount of trapping depends on concentrations of trace gases like carbon dioxide, and a change in the concentration of these gases is believed to affect the Earth's surface temperature.

The greenhouse effect is also central to the discussion of global warming due to emission of carbon dioxide and methane (and other so-called greenhouse gases) into the Earth's atmosphere from industrial production and farming. Changes in global climate could lead to more intense storms, precipitation changes (affecting agriculture), reduction in rain forest biodiversity, and rising sea levels.

Heating and cooling are often significant contributors to energy use in individual homes. Mária Telkes, a Hungarian-born American scientist, was among the foremost developers of solar energy applications in industrial and community use. After inventing a widely deployed solar seawater distiller used on World War II life rafts, she partnered with architect Eleanor Raymond to design the first modern home to be completely heated by solar power. Air warmed on rooftop collectors transferred heat to salts, which stored the heat for later use. Telkes later worked with the Department of Energy to develop the first solar-electrically powered home. Current research efforts into developing environmentally friendly homes quite often focus on reducing conventional heating and cooling through better building materials, strategically positioning windows to optimize radiation gain from the Sun, and opening spaces to allow convection. It is possible to build a zero-energy house that allows for comfortable living in most parts of the United States with hot and humid summers and cold winters.

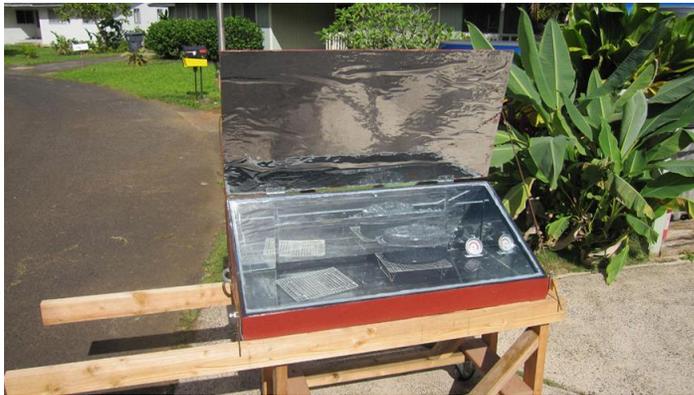


Figure 14.29 This simple but effective solar cooker uses the greenhouse effect and reflective material to trap and retain solar energy. Made of inexpensive, durable materials, it saves money and labor, and is of particular economic value in countries with lower energy availability. Mária Telkes, a pioneering innovator in solar applications, developed some of the earliest models of these cookers in the 1950s. (credit: E.B. Kauai)

Conversely, dark space is very cold, about  $3K$  ( $-454^{\circ}F$ ), so that the Earth radiates energy into the dark sky. Owing to the fact that clouds have lower emissivity than either oceans or land masses, they reflect some of the radiation back to the surface, greatly reducing heat transfer into dark space, just as they greatly reduce heat transfer into the atmosphere during the day. The rate of heat transfer from soil and grasses can be so rapid that frost may occur on clear summer evenings, even in warm latitudes.

## Check Your Understanding

What is the change in the rate of the radiated heat by a body at the temperature  $T_1 = 20^\circ\text{C}$  compared to when the body is at the temperature  $T_2 = 40^\circ\text{C}$ ?

### Solution

The radiated heat is proportional to the fourth power of the *absolute temperature*. Because  $T_1 = 293\text{ K}$  and  $T_2 = 313\text{ K}$ , the rate of heat transfer increases by about 30 percent of the original rate.

### Career Connection: Energy Conservation Consultation

The cost of energy is generally believed to remain very high for the foreseeable future. Thus, passive control of heat loss in both commercial and domestic housing will become increasingly important. Energy consultants measure and analyze the flow of energy into and out of houses and ensure that a healthy exchange of air is maintained inside the house. The job prospects for an energy consultant are strong.

### Problem-Solving Strategies for the Methods of Heat Transfer

1. Examine the situation to determine what type of heat transfer is involved.
2. Identify the type(s) of heat transfer—conduction, convection, or radiation.
3. Identify exactly what needs to be determined in the problem (identify the unknowns). A written list is very useful.
4. Make a list of what is given or can be inferred from the problem as stated (identify the knowns).
5. Solve the appropriate equation for the quantity to be determined (the unknown).
6. For conduction, equation  $\frac{Q}{t} = \frac{kA(T_2 - T_1)}{d}$  is appropriate. Table 14.3 lists thermal conductivities. For convection, determine the amount of matter moved and use equation  $Q = mc\Delta T$ , to calculate the heat transfer involved in the temperature change of the fluid. If a phase change accompanies convection, equation  $Q = mL_f$  or  $Q = mL_v$  is appropriate to find the heat transfer involved in the phase change. Table 14.2 lists information relevant to phase change. For radiation, equation  $\frac{Q_{\text{net}}}{t} = \sigma eAT_2^4 - T_1^4$  gives the net heat transfer rate.
7. Insert the knowns along with their units into the appropriate equation and obtain numerical solutions complete with units.
8. Check the answer to see if it is reasonable. Does it make sense?