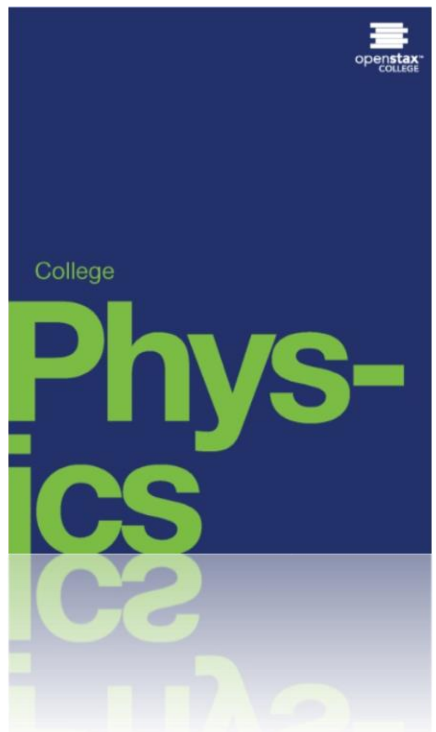
COLLEGE PHYSICS

Chapter 14 HEAT AND HEAT TRANSFER METHODS

PowerPoint Image Slideshow



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- Heat As Energy Transfer
- Internal Energy
- Specific Heat
- Calorimetry—Solving Problems
- Latent Heat
- Heat Transfer: Conduction
- Heat Transfer: Convection
- Heat Transfer: Radiation

We often speak of heat as though it were a material that flows from one object to another; it is not. Rather, it is a form of energy.

Unit of heat: calorie (cal)

1 cal is the amount of heat necessary to raise the temperature of 1 g of water by 1 Celsius degree.

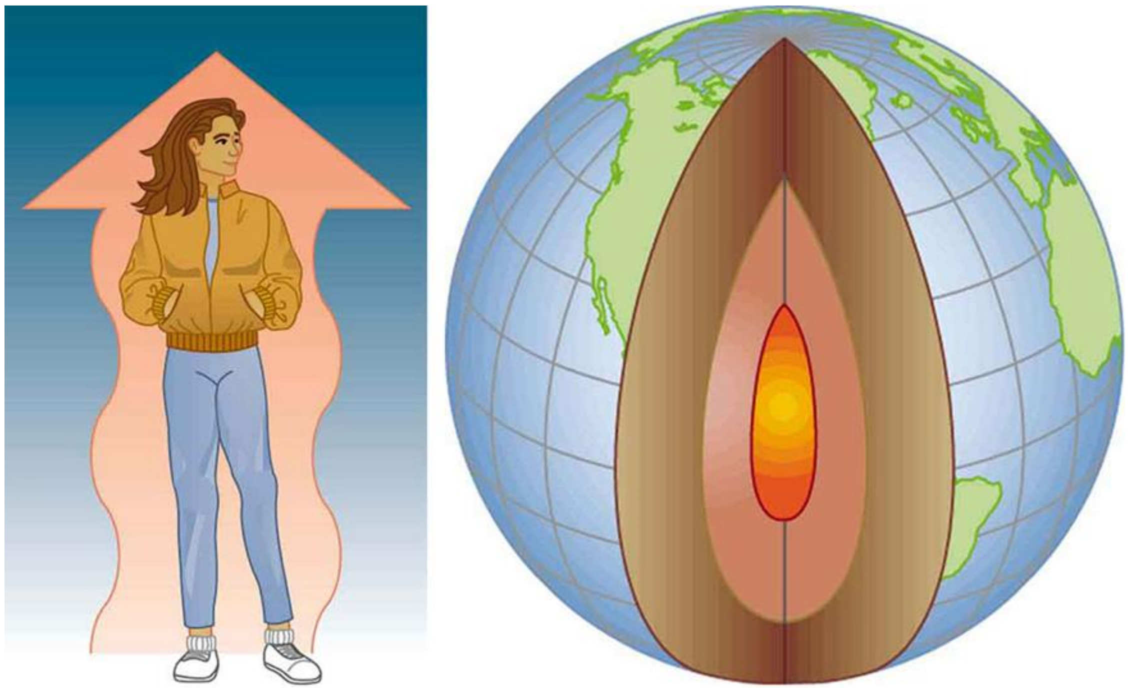
Don’t be fooled—the calories on our food labels are really kilocalories (kcal or Calories), the heat necessary to raise 1 kg of water by 1 Celsius degree.

Definition of heat:

Heat is energy transferred from one object to another because of a difference in temperature.

- Remember that the temperature of a gas is a measure of the kinetic energy of its molecules.

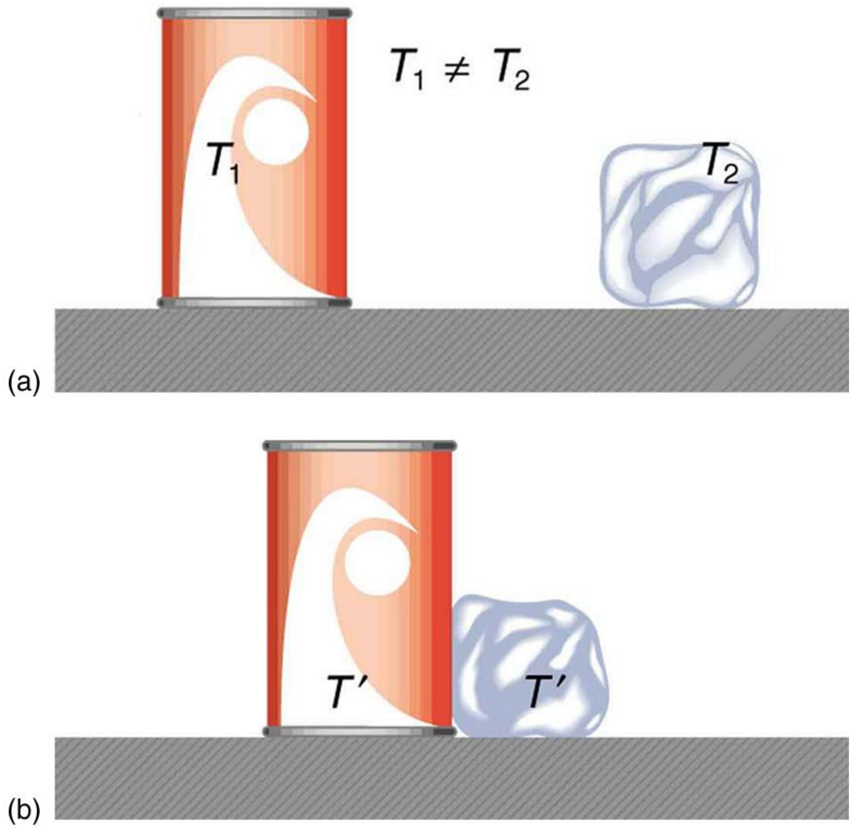
FIGURE 14.1



(a) The chilling effect of a clear breezy night is produced by the wind and by radiative heat transfer to cold outer space.

(b) There was once great controversy about the Earth's age, but it is now generally accepted to be about 4.5 billion years old. Much of the debate is centered on the Earth's molten interior. According to our understanding of heat transfer, if the Earth is really that old, its center should have cooled off long ago. The discovery of radioactivity in rocks revealed the source of energy that keeps the Earth's interior molten, despite heat transfer to the surface, and from there to cold outer space.

FIGURE 14.2



In figure (a) the soft drink and the ice have different temperatures, T_1 and T_2 , and are not in thermal equilibrium. In figure (b), when the soft drink and ice are allowed to interact, energy is transferred until they reach the same temperature T', achieving equilibrium. Heat transfer occurs due to the difference in temperatures. In fact, since the soft drink and ice are both in contact with the surrounding air and bench, the equilibrium temperature will be the same for both.

FIGURE 14.3

(a) Schematic depiction of Joule's experiment that established the equivalence of heat and work.

$$4.186 \text{ J} = 1 \text{ cal}$$

$$4.186 \text{ kJ} = 1 \text{ kcal}$$

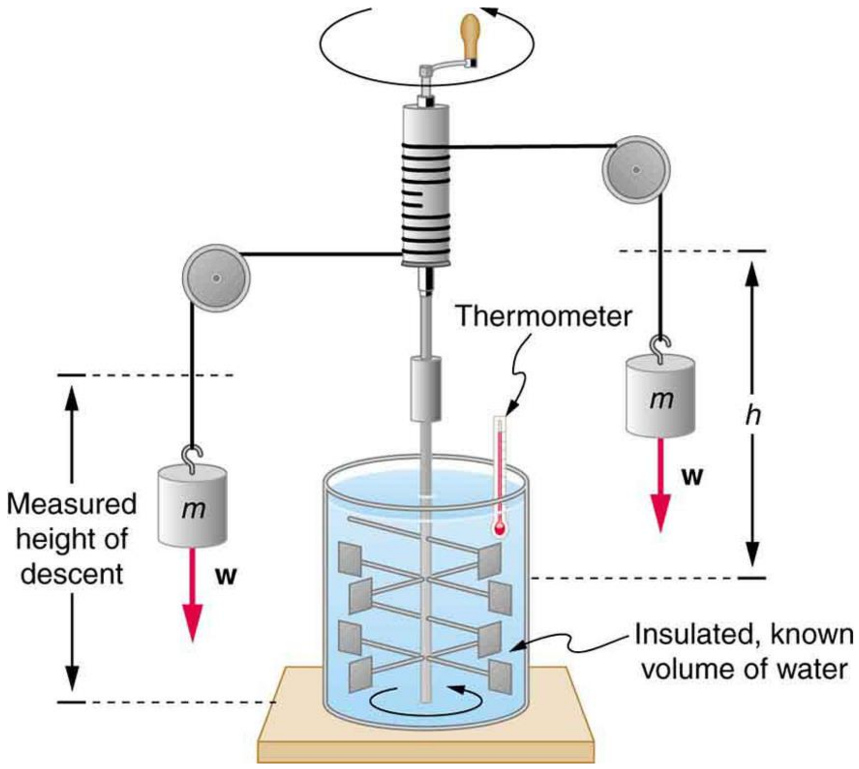


FIGURE 14.5

The smoking brakes on this truck are a visible evidence of the mechanical equivalent of heat.

FIGURE 14.6

Heat from the air transfers to the ice causing it to melt. (credit: Mike Brand)

The sum total of all the energy of all the molecules in a substance is its internal (or thermal) energy.

Temperature: measures molecules' average kinetic energy

Internal energy: total energy of all molecules

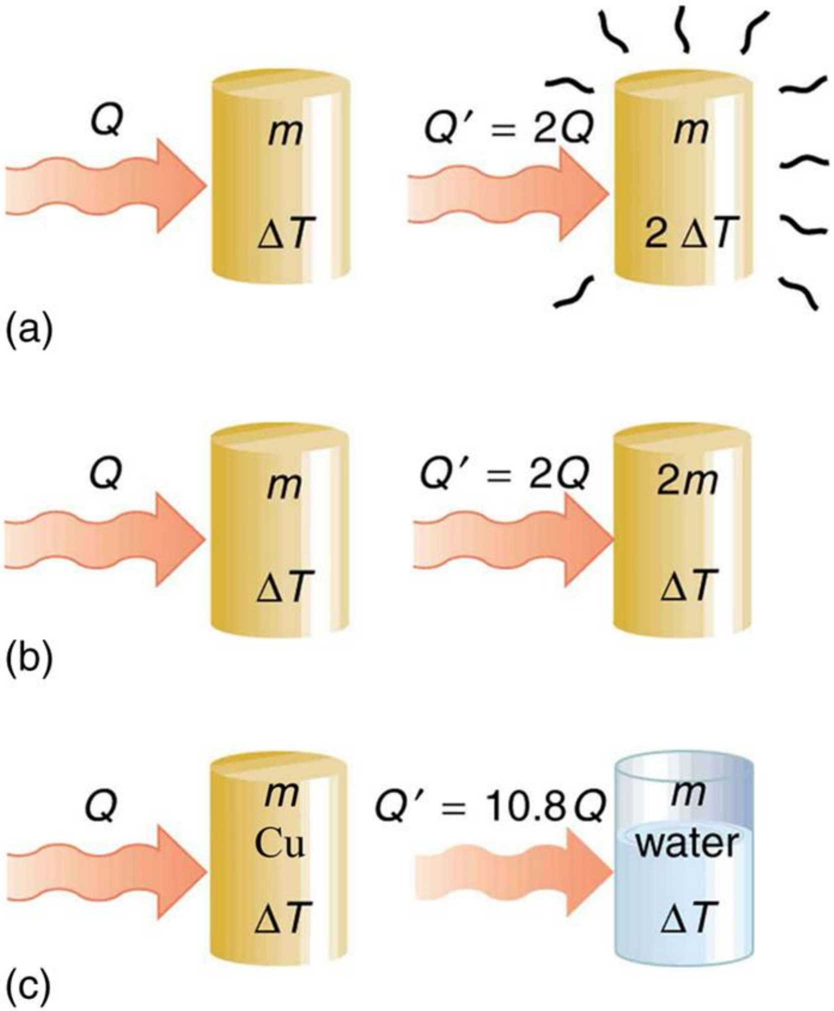
Heat: transfer of energy due to difference in temperature

Internal energy of an ideal (atomic) gas is equal to the average kinetic energy per molecule multiplied by the number of molecules.

But since we know the average kinetic energy in terms of the temperature, we can write:

$U = 3nRT/2$ – internal energy of ideal monoatomic gas

FIGURE 14.4



The heat Q transferred to cause a temperature change depends on the magnitude of the temperature change, the mass of the system, and the substance and phase involved.

(a) The amount of heat transferred is directly proportional to the temperature change. To double the temperature change of a mass m , you need to add twice the heat.

(b) The amount of heat transferred is also directly proportional to the mass. To cause an equivalent temperature change in a doubled mass, you need to add twice the heat.

(c) The amount of heat transferred depends on the substance and its phase. If it takes an amount Q of heat to cause a temperature change ΔT in a given mass of copper, it will take 10.8 times that amount of heat to cause the equivalent temperature change in the same mass of water assuming no phase change in either substance.

SPECIFIC HEAT

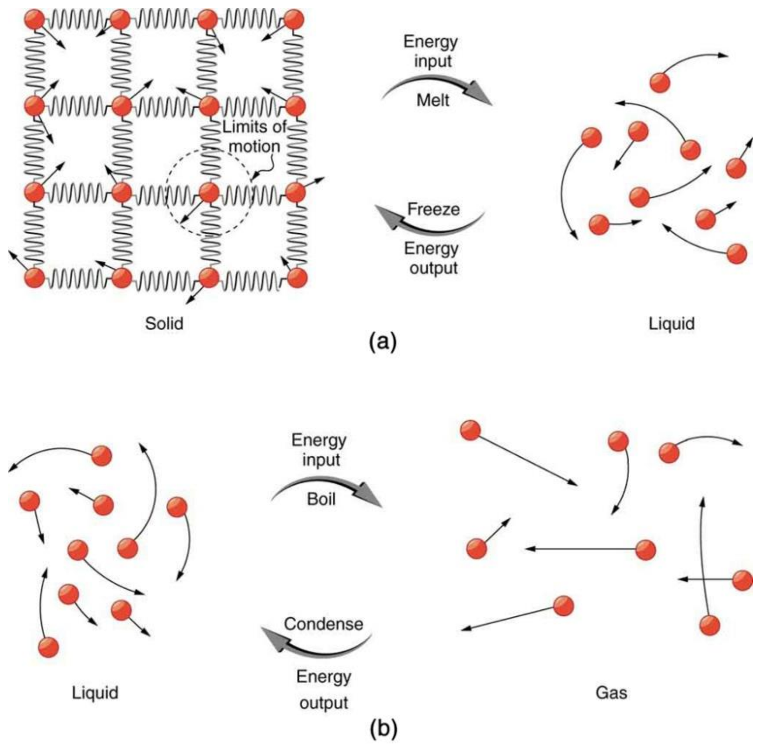
Substance	Specific Heat, c	
	$\mathrm{J/kg \cdot C^\circ}$	$\mathrm{kcal/kg \cdot C^\circ}$ $(= \mathrm{cal/g \cdot C^\circ})$
Aluminum	900	0.22
Alcohol (ethyl)	2400	0.58
Copper	390	0.093
Glass	840	0.20
Iron or steel	450	0.11
Lead	130	0.031
Marble	860	0.21
Mercury	140	0.033
Silver	230	0.056
Wood	1700	0.4
Water		
Ice (−5°C)	2100	0.50
Liquid (15°C)	4186	1.00
Steam (110°C)	2010	0.48
Human body (average)	3470	0.83
Protein	1700	0.4

The amount of heat required to change the temperature of a material is proportional to the mass and to the temperature change:

$Q = m\,c\,\Delta T$

The specific heat, c, is characteristic of the material. Some values are listed at left.

FIGURE 14.7



(a) Energy is required to partially overcome the attractive forces between molecules in a solid to form a liquid. That same energy must be removed for freezing to take place.

(b) Molecules are separated by large distances when going from liquid to vapor, requiring significant energy to overcome molecular attraction. The same energy must be removed for condensation to take place. There is no temperature change until a phase change is complete.

Latent Heat

Heat of fusion, L_F: heat required to change 1.0 kg of material from solid to liquid

Heat of vaporization, L_V: heat required to change 1.0 kg of material from liquid to vapor

Substance	Melting Point (°C)	Heat of Fusion		Boiling Point (°C)	Heat of Vaporization	
		kJ/kg	kcal/kg†		kJ/kg	kcal/kg†
Oxygen	−218.8	14	3.3	−183	210	51
Nitrogen	−210.0	26	6.1	−195.8	200	48
Ethyl alcohol	−114	104	25	78	850	204
Ammonia	−77.8	33	8.0	−33.4	137	33
Water	0	333	79.7	100	2260	539
Lead	327	25	5.9	1750	870	208
Silver	961	88	21	2193	2300	558
Iron	1538	289	69.1	3023	6340	1520
Tungsten	3410	184	44	5900	4800	1150

Latent Heat

The total heat required for a phase change depends on the total mass and the latent heat:

$$Q = m\,L$$

The latent heat of vaporization is relevant for evaporation as well as boiling.

On a molecular level, the heat added during a change of state does not go to increasing the kinetic energy of individual molecules, but rather to break the close bonds between them so the next phase can occur.

Calorimetry—Solving Problems

Closed system: no mass enters or leaves, but energy may be exchanged

Open system: mass may transfer as well

Isolated system: closed system where no energy in any form is transferred

For an isolated system,

Energy out of one part = energy into another part

Or: heat lost = heat gained

Problem Solving: Calorimetry

1. Is the system isolated? Are all significant sources of energy transfer known or calculable?

2. Apply conservation of energy.

3. If no phase changes occur, the heat transferred will depend on the mass, specific heat, and temperature change.

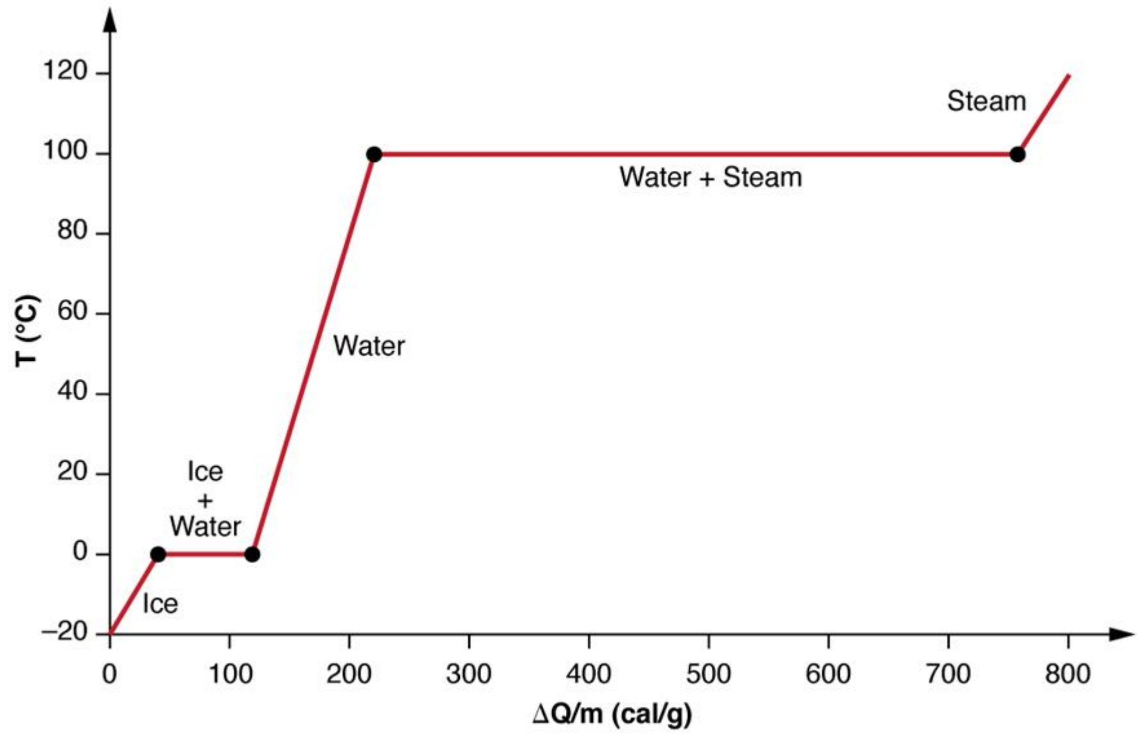
4. If there are, or may be, phase changes, terms that depend on the mass and the latent heat may also be present. Determine or estimate what phase the final system will be in.

5. Make sure that each term is in the right place and that all the temperature changes are positive.

6. There is only one final temperature when the system reaches equilibrium.

7. Solve.

FIGURE 14.8

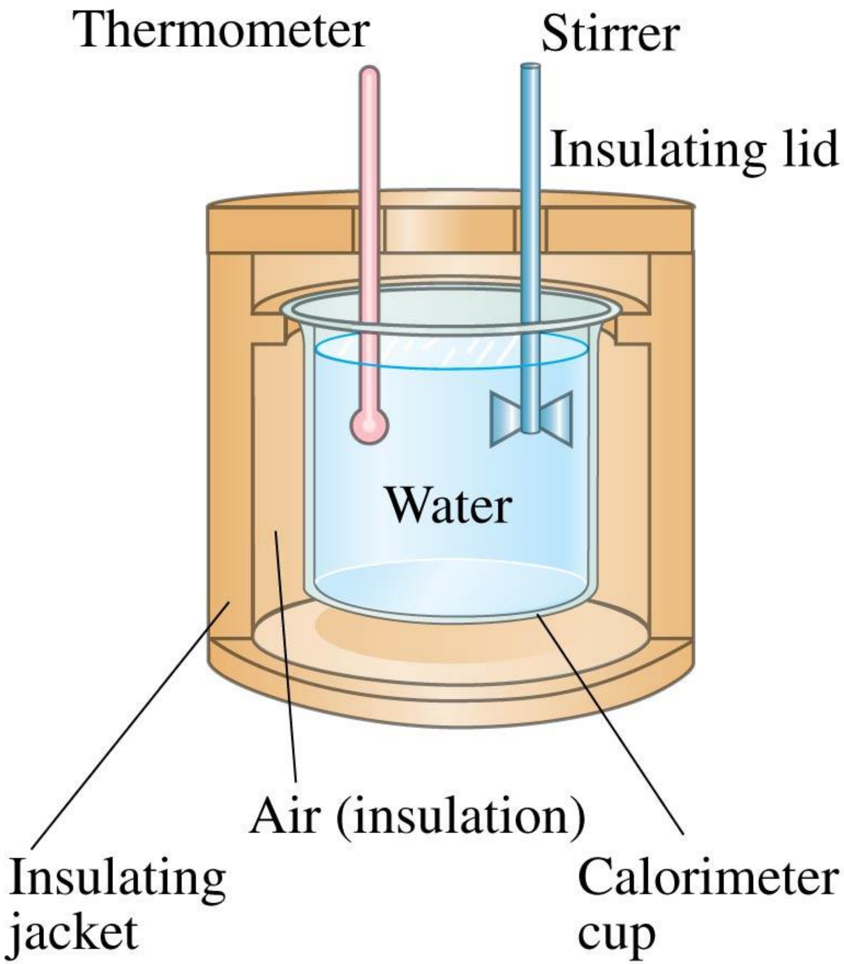


A graph of temperature versus energy added. The system is constructed so that no vapor evaporates while ice warms to become liquid water, and so that, when vaporization occurs, the vapor remains in of the system. The long stretches of constant temperature values at 0ºC and 100ºC reflect the large latent heat of melting and vaporization, respectively.

FIGURE 14.22

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

Calorimetry – Solving Problems



The instrument to the left is a calorimeter, which makes quantitative measurements of heat exchange. A sample is heated to a well-measured high temperature, plunged into the water, and the equilibrium temperature measured. This gives the specific heat of the sample.

FIGURE 14.9

Condensation forms on this glass of iced tea because the temperature of the nearby air is reduced to below the dew point. The air cannot hold as much water as it did at room temperature, and so water condenses. Energy is released when the water condenses, speeding the melting of the ice in the glass. (credit: Jenny Downing)

FIGURE 14.10

The ice on these trees released large amounts of energy when it froze, helping to prevent the temperature of the trees from dropping below $0^{\circ}C$. Water is intentionally sprayed on orchards to help prevent hard frosts. (credit: Hermann Hammer) openstax COLLEGE

FIGURE 14.11

Direct transitions between solid and vapor are common, sometimes useful, and even beautiful.

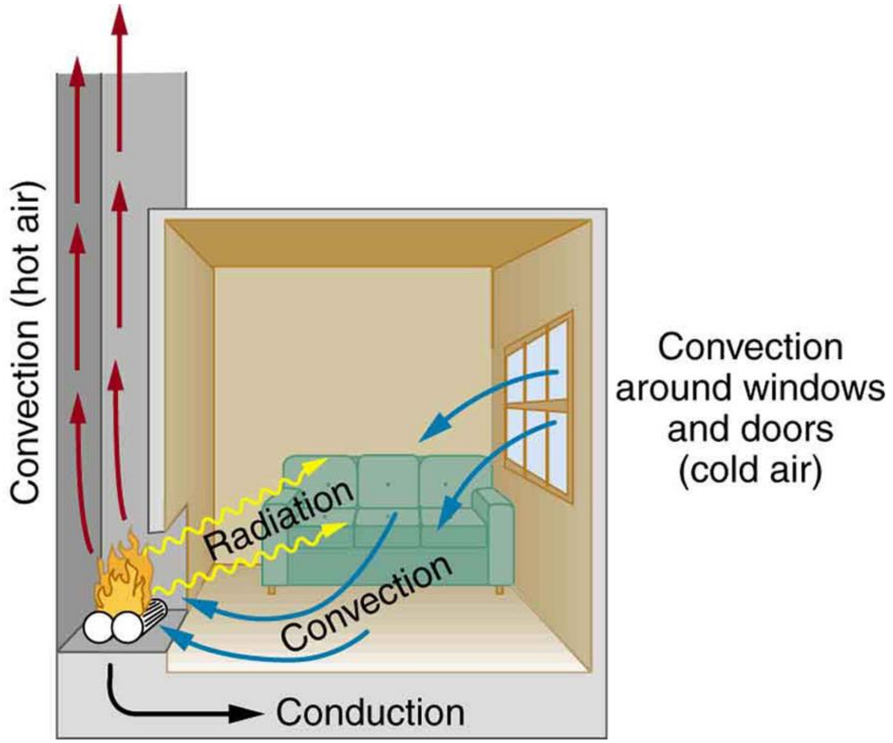
(a) Dry ice sublimates directly to carbon dioxide gas. The visible vapor is made of water droplets. (credit: Windell Oskay)

(b) Frost forms patterns on a very cold window, an example of a solid formed directly from a vapor. (credit: Liz West)

(a)

(b)

FIGURE 14.12

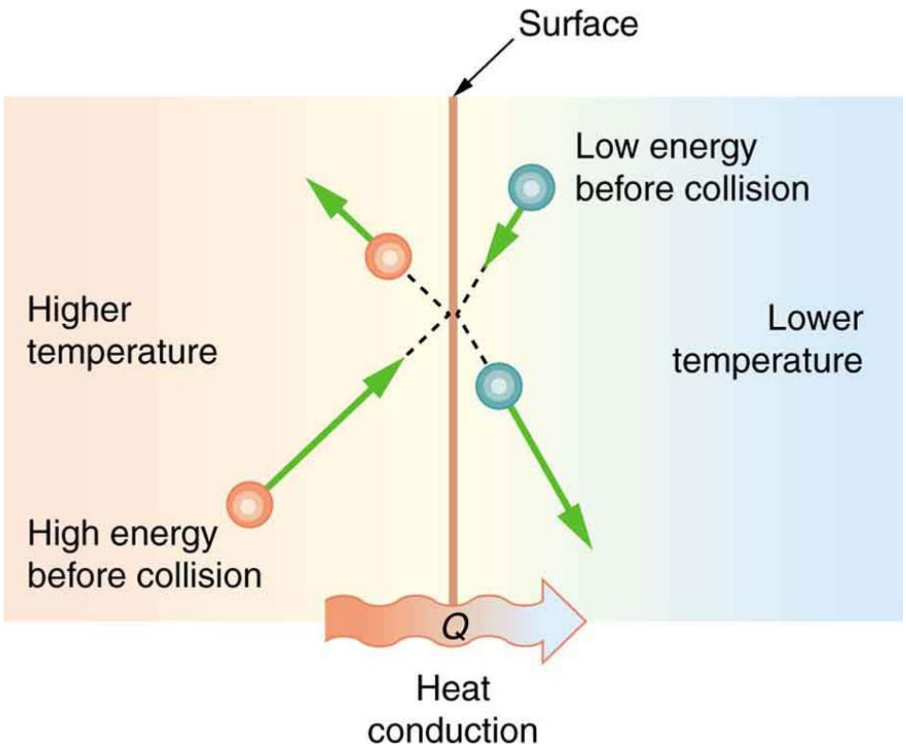


In a fireplace, heat transfer occurs by all three methods: conduction, convection, and radiation. Radiation is responsible for most of the heat transferred into the room. Heat transfer also occurs through conduction into the room, but at a much slower rate. Heat transfer by convection also occurs through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

FIGURE 14.13

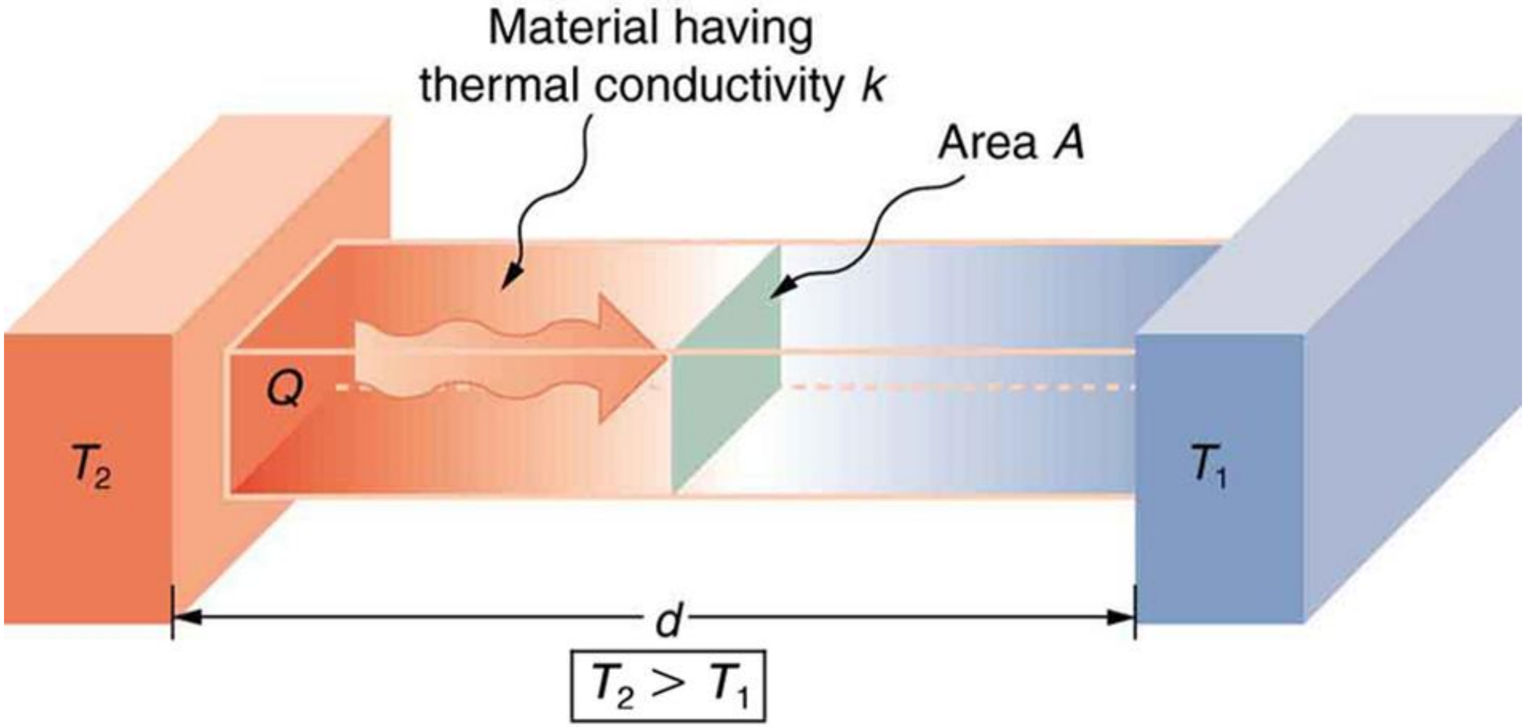
Insulation is used to limit the conduction of heat from the inside to the outside (in winters) and from the outside to the inside (in summers). (credit: Giles Douglas)

FIGURE 14.14



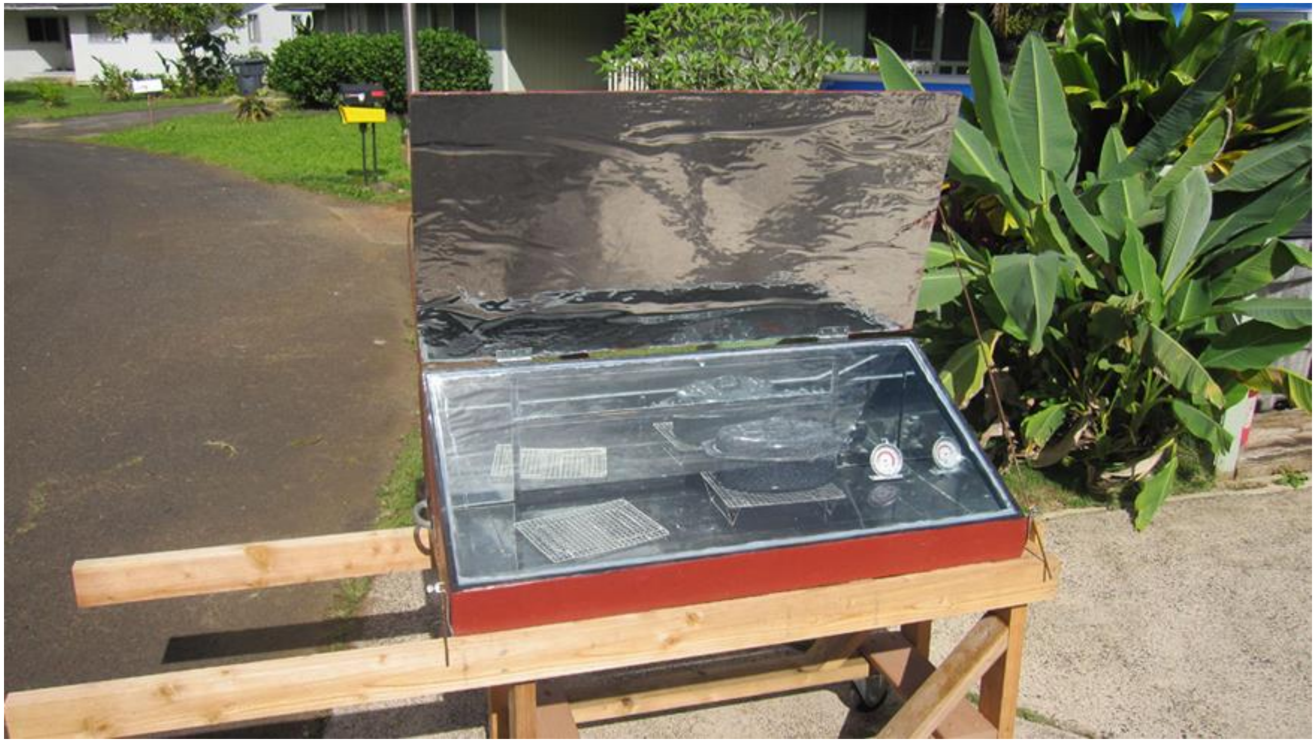
The molecules in two bodies at different temperatures have different average kinetic energies. Collisions occurring at the contact surface tend to transfer energy from high-temperature regions to low-temperature regions. In this illustration, a molecule in the lower temperature region (right side) has 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.

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 .

FIGURE 14.29



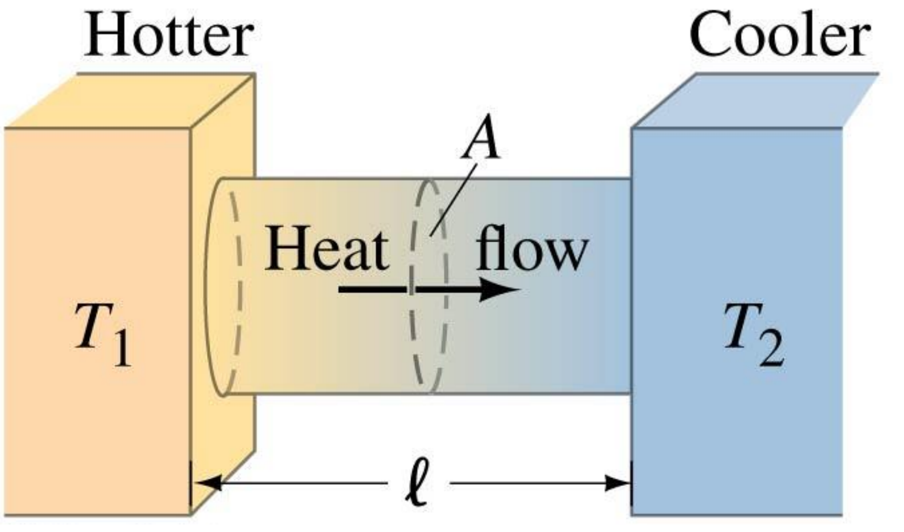
This simple but effective solar cooker uses the greenhouse effect and reflective material to trap and retain solar energy. Made of inexpensive, durable materials, it saves money and labor, and is of particular economic value in energy-poor developing countries. (credit: E.B. Kauai)

Heat Transfer: Conduction

Heat conduction can be visualized as occurring through molecular collisions.

The heat flow per unit time is given by:

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



Heat Transfer: Conduction

Thermal Conductivities

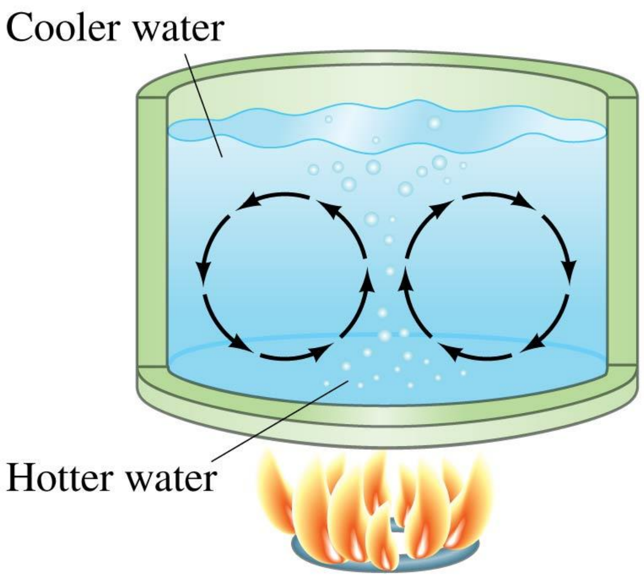
Substance	Thermal Conductivity, k: $\frac{\text{J}}{(\text{s}\cdot\text{m}\cdot\text{C}^\circ)}$	Thermal Conductivity, k: $\frac{\text{kcal}}{(\text{s}\cdot\text{m}\cdot\text{C}^\circ)}$
Silver	420	10×10^{-2}
Copper	380	9.2×10^{-2}
Aluminum	200	5.0×10^{-2}
Steel	40	1.1×10^{-2}
Ice	2	5×10^{-4}
Glass	0.84	2.0×10^{-4}
Brick	0.84	2.0×10^{-4}
Concrete	0.84	2.0×10^{-4}
Water	0.56	1.4×10^{-4}
Human tissue	0.2	0.5×10^{-4}
Wood	0.1	0.3×10^{-4}
Fiberglass	0.048	0.12×10^{-4}
Cork	0.042	0.10×10^{-4}
Wool	0.040	0.10×10^{-4}
Goose down	0.025	0.060×10^{-4}
Polyurethane	0.024	0.057×10^{-4}
Air	0.023	0.055×10^{-4}

The constant k is called the thermal conductivity.

Materials with large k are called conductors; those with small k are called insulators.

Heat Transfer: Convection

Convection occurs when heat flows by the mass movement of molecules from one place to another. It may be natural or forced; both these examples are natural convection.



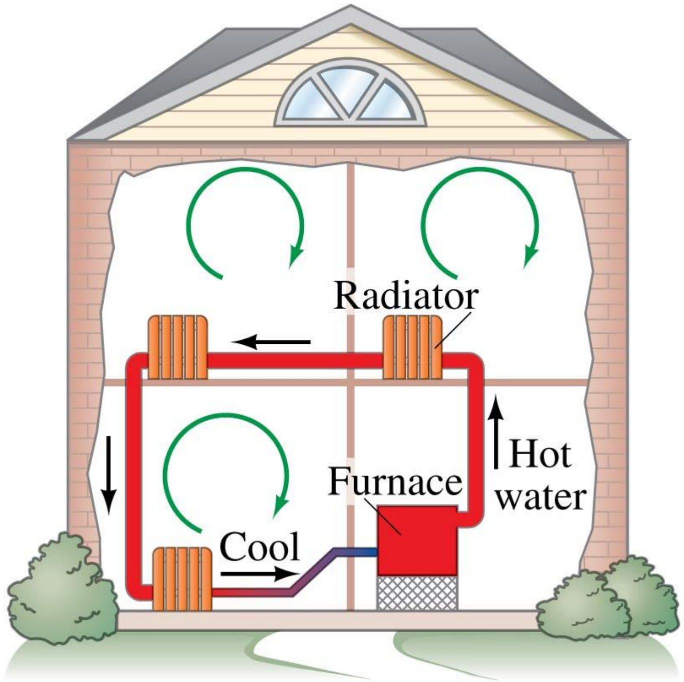
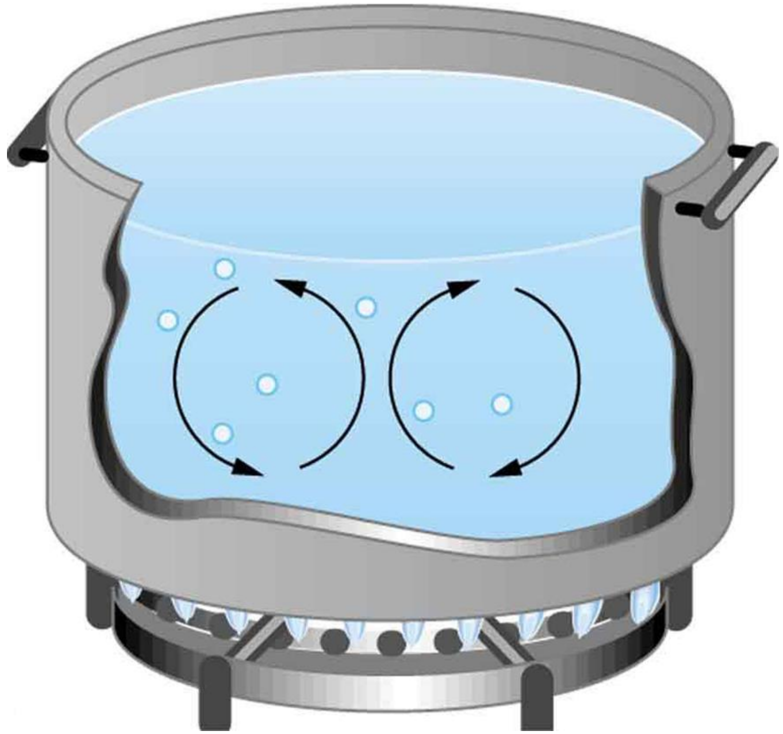
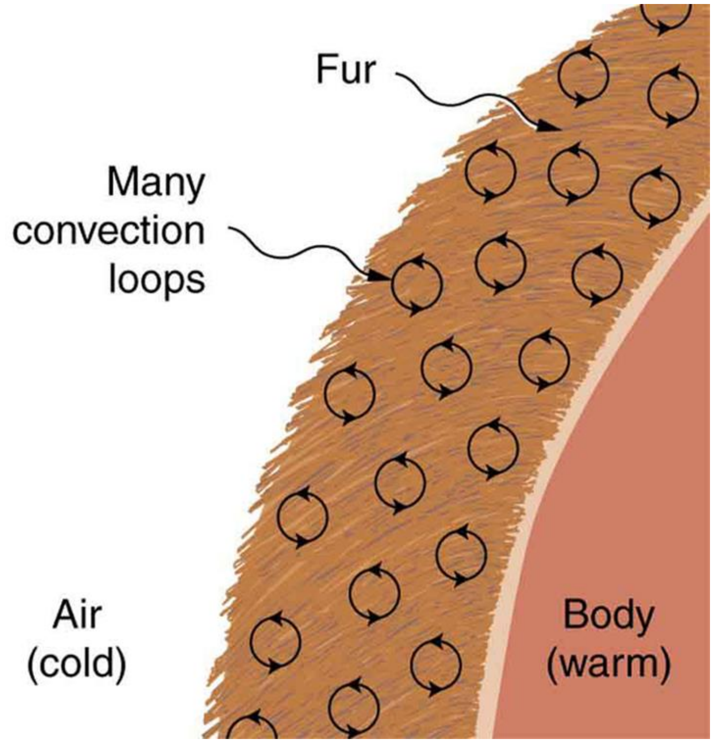


FIGURE 14.18



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.

FIGURE 14.19



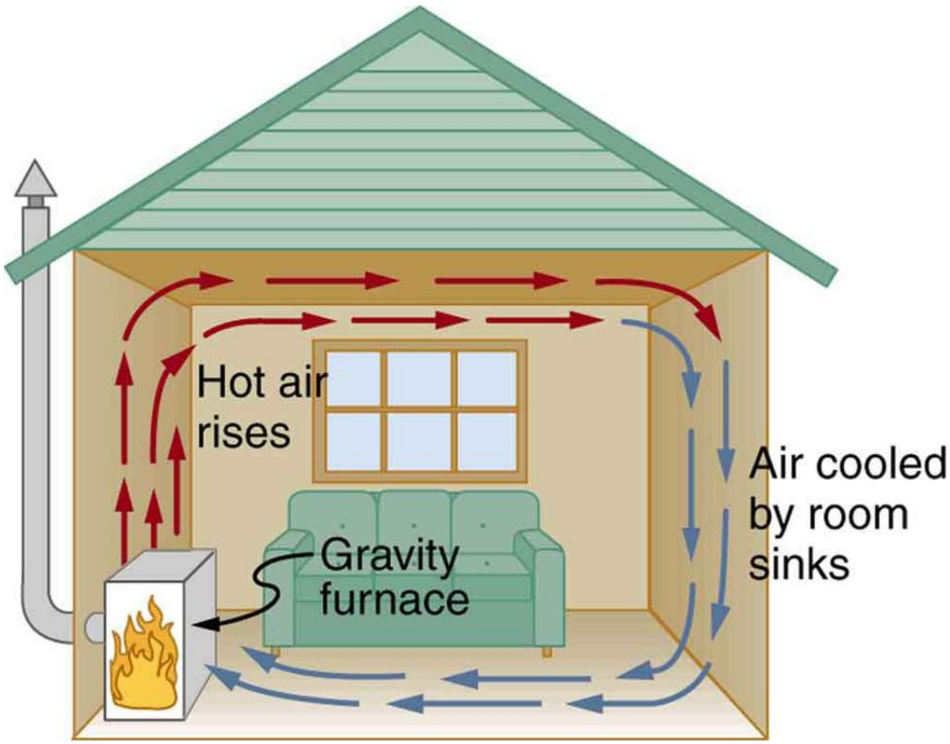
Fur is filled with air, breaking it up into many small pockets. Convection is very slow here, because the loops are so small. The low conductivity of air makes fur a very good lightweight insulator.

Heat Transfer: Convection

Many home heating systems are forced hot-air systems; these have a fan that blows the air out of registers, rather than relying completely on natural convection.

Our body temperature is regulated by the blood; it runs close to the surface of the skin and transfers heat. Once it reaches the surface of the skin, the heat is released through convection, evaporation, and radiation.

FIGURE 14.17

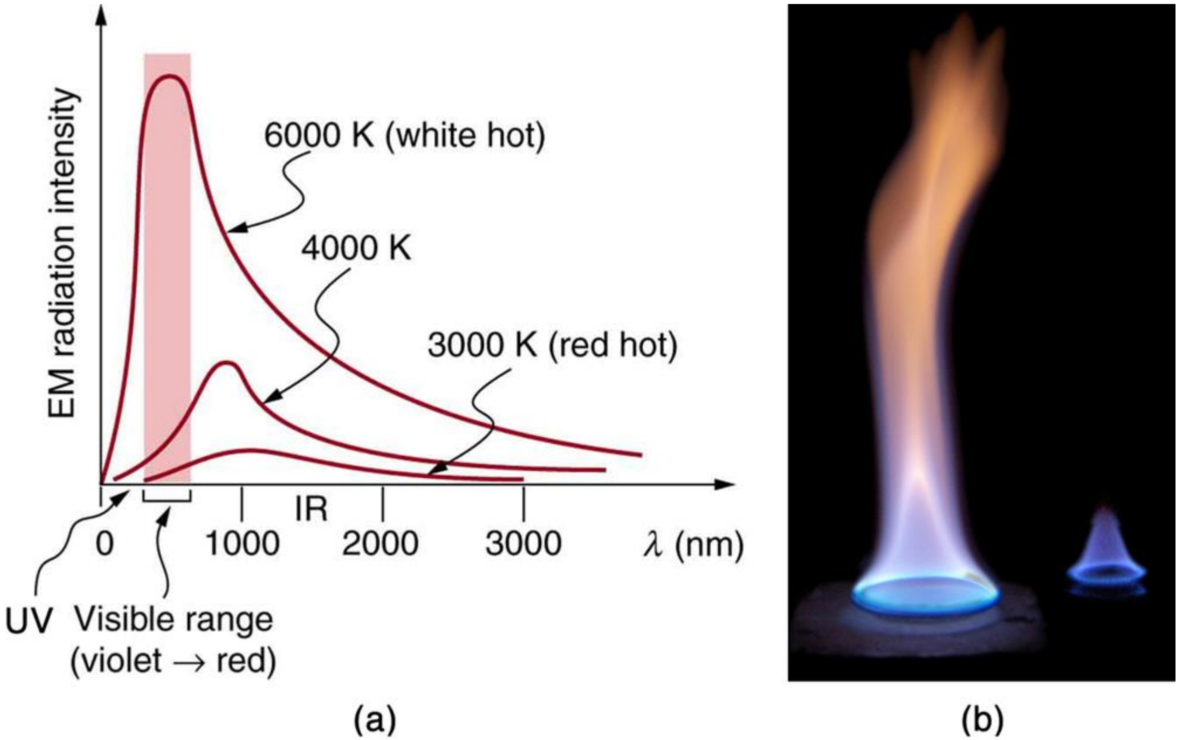


Air heated by the so-called gravity furnace expands and rises, forming a convective loop that transfers energy to other parts of the room. As the air is cooled at the ceiling and outside walls, it contracts, eventually becoming denser than room air and sinking to the floor.
A properly designed heating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

Heat Transfer: Radiation

The most familiar example of radiation is our own Sun, which radiates at a temperature of almost 6000 K.

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)

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)

Heat Transfer: Radiation

The energy radiated has been found to be proportional to the fourth power of the temperature:

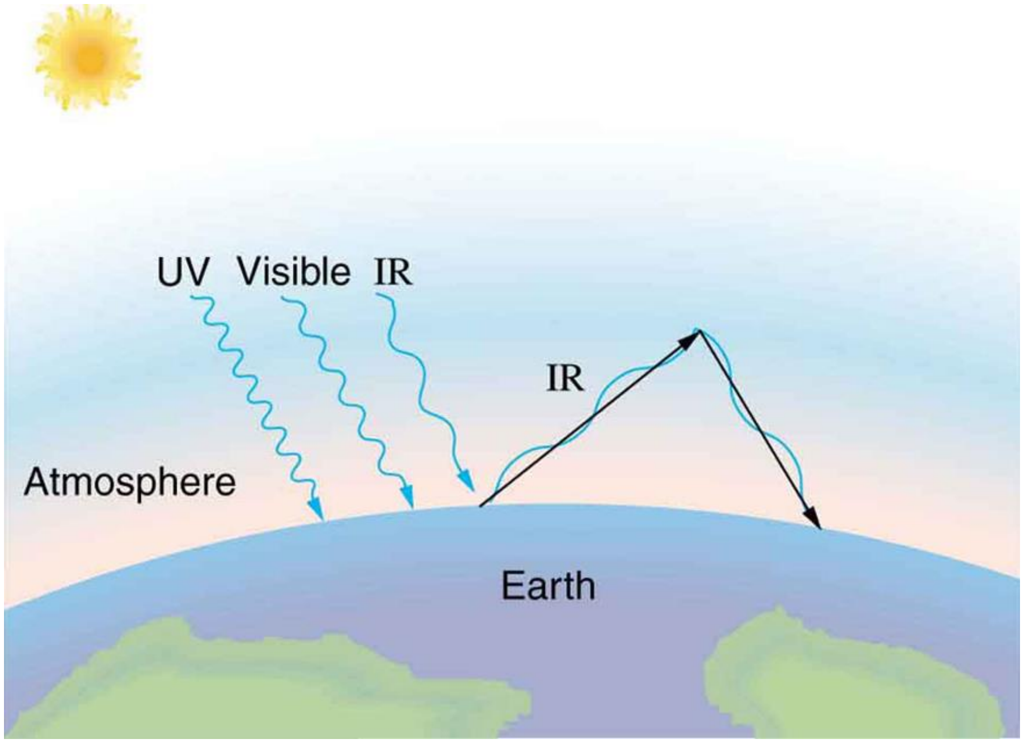
$$\frac{Q}{t} = \epsilon \sigma A T^4.$$

The constant σ is called the Stefan-Boltzmann constant:

$$\sigma = 5.67 \times 10^{-8}\ \mathrm{W/m^2 \cdot K^4}$$

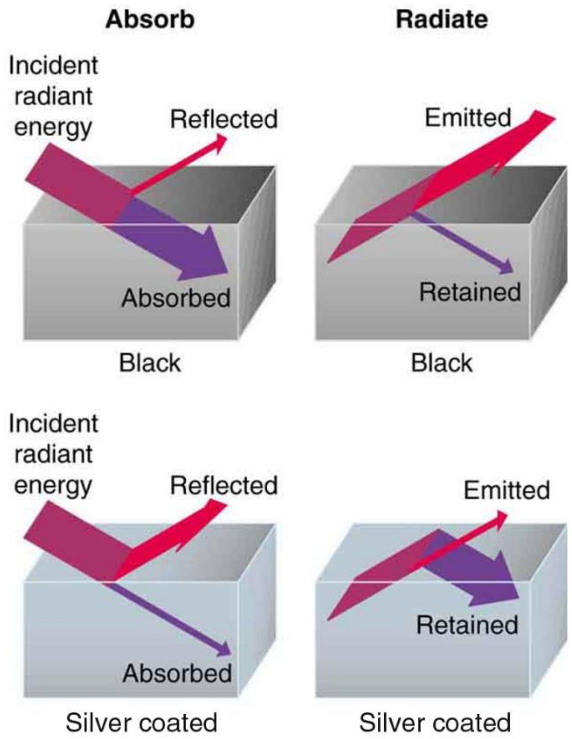
The emissivity e is a number between zero and one characterizing the surface; black objects have an emissivity near one, while shiny ones have an emissivity near zero.

FIGURE 14.28



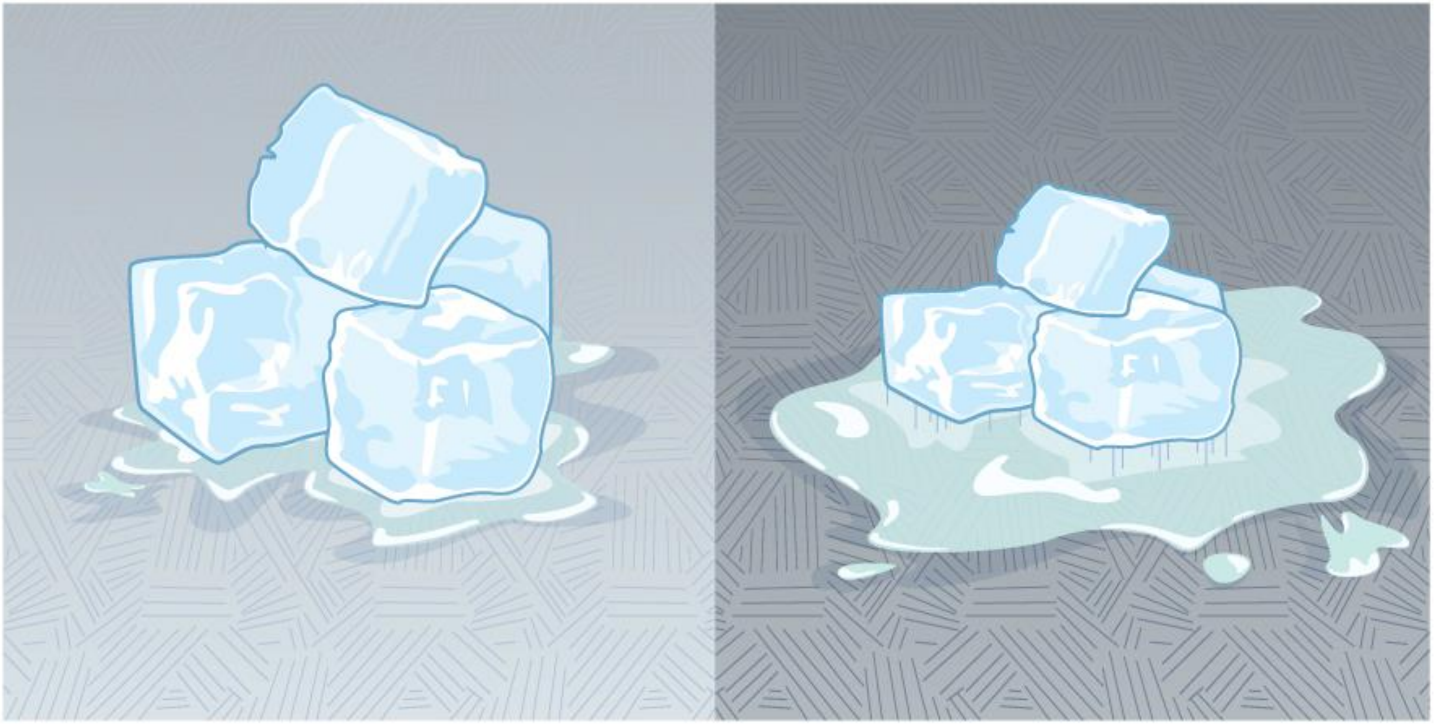
The greenhouse effect is a name given to the trapping of energy in the Earth's atmosphere by a process similar to that used in greenhouses. The atmosphere, like window glass, is transparent to incoming visible radiation and most of the Sun's infrared. These wavelengths are absorbed by the Earth and re-emitted 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.

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.

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.

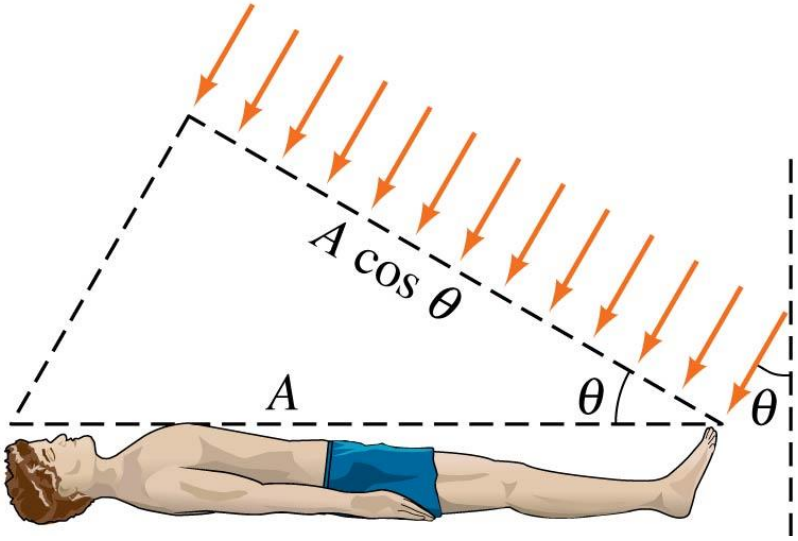
Heat Transfer: Radiation

If you are sitting in a place that is too cold, your body radiates more heat than it can produce. You will start shivering and your metabolic rate will increase unless you put on warmer clothing.

Heat Transfer: Radiation

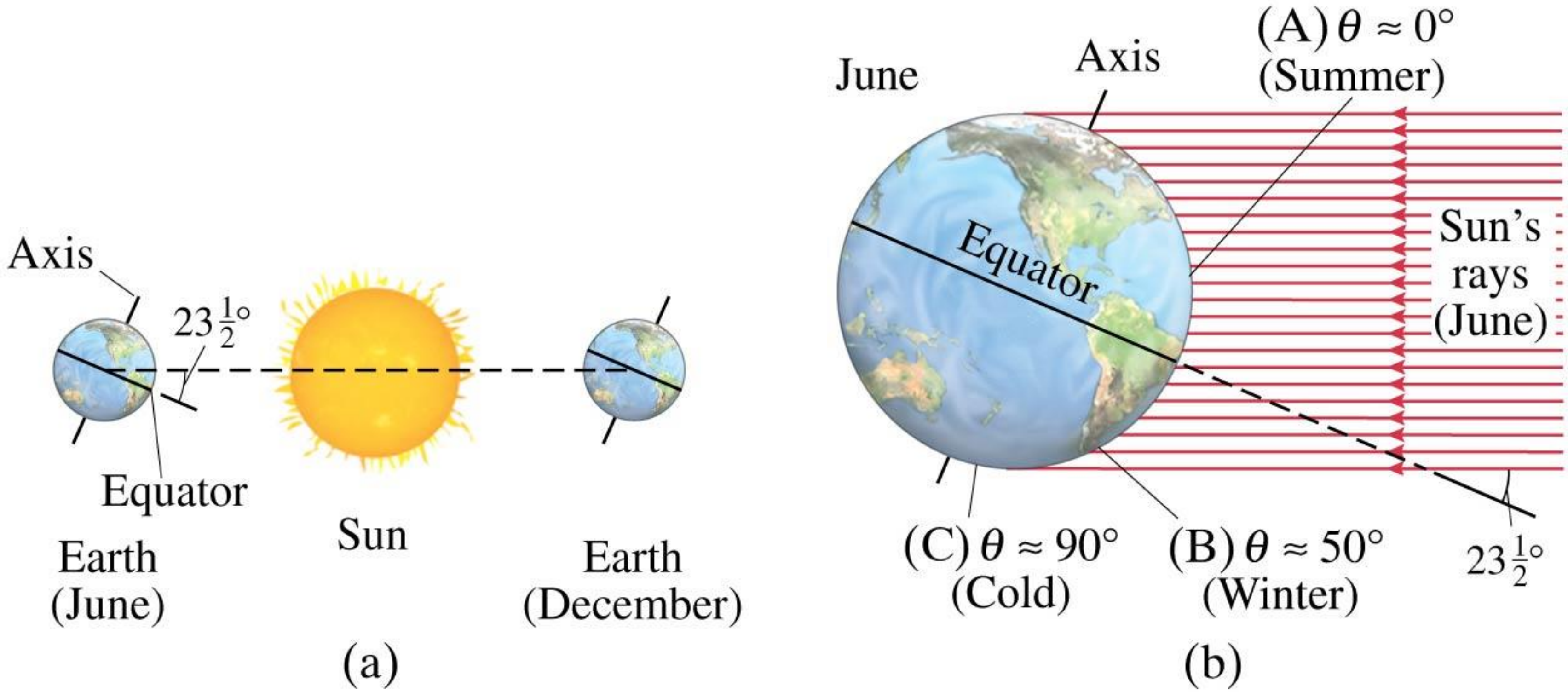
If you are in the sunlight, the Sun's radiation will warm you. In general, you will not be perfectly perpendicular to the Sun's rays, and will absorb energy at the rate:

$$\frac{Q}{t} = (1000\ \mathrm{W/m^2})\epsilon A \cos\theta,$$



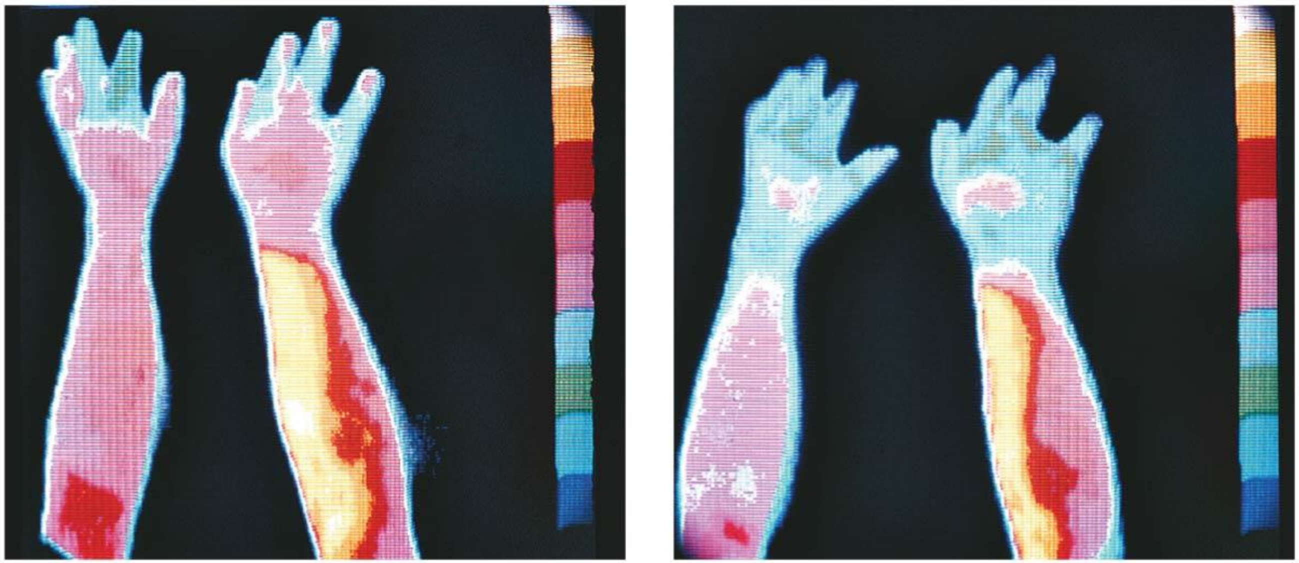
Heat Transfer: Radiation

This cos θ effect is also responsible for the seasons.



Heat Transfer: Radiation

Thermography—the detailed measurement of radiation from the body—can be used in medical imaging. Warmer areas may be a sign of tumors or infection; cooler areas on the skin may be a sign of poor circulation.



(a) (b)

Summary of Chapter 14

- Internal energy U refers to the total energy of all molecules in an object. For an ideal monatomic gas, $U = 3nRT/2$ – Internal energy of ideal monoatomic gas.
- Heat is the transfer of energy from one object to another due to a temperature difference. Heat can be measured in joules or in calories.
- Specific heat of a substance is the energy required to change the temperature of a fixed amount of matter by 1° C.

Summary of Chapter 14

- In an isolated system, heat gained by one part of the system must be lost by another.
- Calorimetry measures heat exchange quantitatively.
- Phase changes require energy even though the temperature does not change.
- Heat of fusion: amount of energy required to melt 1 kg of material.
- Heat of vaporization: amount of energy required to change 1 kg of material from liquid to vapor.

Summary of Chapter 14

- Heat transfer takes place by conduction, convection, and radiation.
- In conduction, energy is transferred through the collisions of molecules in the substance.
- In convection, bulk quantities of the substance flow to areas of different temperature.
- Radiation is the transfer of energy by electromagnetic waves.