Thermal radiation is involved in the numerous medical cases of a dead rattlesnake striking a hand reaching toward it. Pits between each eye and nostril of a rattlesnake (Fig. 18-21) serve as sensors of thermal radiation. When, say, a mouse moves close to a rattlesnake’s head, the thermal radiation from the mouse triggers these sensors, causing a reflex action in which the snake strikes the mouse with its fangs and injects its venom. The thermal radiation from a reaching hand can cause the same reflex action even if the snake has been dead for as long as 30 min because the snake’s nervous system continues to function. As one snake expert advised, if you must remove a recently killed rattlesnake, use a long stick rather than your hand.

**Sample Problem**

**Thermal conduction through a layered wall**

Figure 18-22 shows the cross section of a wall made of white pine of thickness $L_a$ and brick of thickness $L_d$ ($= 2.0 L_a$), sandwiching two layers of unknown material with identical thicknesses and thermal conductivities. The thermal conductivity of the pine is $k_a$ and that of the brick is $k_d$ ($= 5.0 k_a$). The face area $A$ of the wall is unknown. Thermal conduction through the wall has reached the steady state; the only known interface temperatures are $T_1 = 25^\circ C$, $T_2 = 20^\circ C$, and $T_5 = -10^\circ C$. What is interface temperature $T_4$?

(1) Temperature $T_4$ helps determine the rate $P_d$ at which energy is conducted through the brick, as given by Eq. 18-32. However, we lack enough data to solve Eq. 18-32 for $T_4$. (2) Because the conduction is steady, the conduction rate $P_d$ through the brick must equal the conduction rate $P_a$ through the pine. That gets us going.

**Calculations:** From Eq. 18-32 and Fig. 18-22, we can write

$$P_a = k_a A \frac{T_1 - T_2}{L_a} \quad \text{and} \quad P_d = k_d A \frac{T_4 - T_5}{L_d}$$

Setting $P_a = P_d$ and solving for $T_4$ yield

$$T_4 = \frac{k_d L_d}{k_a L_a} (T_1 - T_2) + T_5.$$  

Letting $L_d = 2.0 L_a$ and $k_d = 5.0 k_a$, and inserting the known temperatures, we find

$$T_4 = \frac{k_d (2.0 L_a)}{(5.0 k_a) L_a} (25^\circ C - 20^\circ C) + (-10^\circ C)$$

$$= -8.0^\circ C.$$  

(Answer)

**KEY IDEAS**

(1) Temperature $T_4$ helps determine the rate $P_d$ at which energy is conducted through the brick, as given by Eq. 18-32. However, we lack enough data to solve Eq. 18-32 for $T_4$. (2) Because the conduction is steady, the conduction rate $P_d$ through the brick must equal the conduction rate $P_a$ through the pine. That gets us going.

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$$T_4 = \frac{k_d (2.0 L_a)}{(5.0 k_a) L_a} (25^\circ C - 20^\circ C) + (-10^\circ C)$$

$$= -8.0^\circ C.$$  

(Answer)

**Temperature; Thermometers** Temperature is an SI base quantity related to our sense of hot and cold. It is measured with a thermometer, which contains a working substance with a measurable property, such as length or pressure, that changes in a regular way as the substance becomes hotter or colder.

**Zeroth Law of Thermodynamics** When a thermometer and some other object are placed in contact with each other, they eventually reach thermal equilibrium. The reading of the thermometer is then taken to be the temperature of the other object. The process provides consistent and useful temperature measurements because of the zeroth law of thermodynamics: If bodies $A$ and $B$ are each in thermal equilibrium with a third body $C$ (the thermometer), then $A$ and $B$ are in thermal equilibrium with each other.

**The Kelvin Temperature Scale** In the SI system, temperature is measured on the Kelvin scale, which is based on the triple point of water (273.16 K). Other temperatures are then defined by
use of a constant-volume gas thermometer, in which a sample of gas is maintained at constant volume so its pressure is proportional to its temperature. We define the temperature $T$ as measured with a gas thermometer to be

$$T = (273.16 \text{ K}) \left( \lim_{p \to 0} \frac{p}{p_0} \right).$$

Here $T$ is in kelvins, and $p_0$ and $p$ are the pressures of the gas at 273.16 K and the measured temperature, respectively.

**Celsius and Fahrenheit Scales** The Celsius temperature scale is defined by

$$T_C = T - 273.15^\circ,$$

with $T$ in kelvins. The Fahrenheit temperature scale is defined by

$$T_F = \frac{9}{5}T_C + 32^\circ.$$

**Thermal Expansion** All objects change size with changes in temperature. For a temperature change $\Delta T$, a change $\Delta L$ in any linear dimension $L$ is given by

$$\Delta L = L_0 \alpha \Delta T,$$

in which $\alpha$ is the coefficient of linear expansion. The change $\Delta V$ in the volume $V$ of a solid or liquid is

$$\Delta V = V_0 \beta \Delta T.$$

Here $\beta = 3\alpha$ is the material’s coefficient of volume expansion.

**Heat** Heat $Q$ is energy that is transferred between a system and its environment because of a temperature difference between them. It can be measured in joules (J), calories (cal), kilocalories (Cal or kcal), or British thermal units (Btu), with

$$1 \text{ cal} = 3.968 \times 10^{-3} \text{ Btu} = 4.1868 \text{ J}.$$

**Heat Capacity and Specific Heat** If heat $Q$ is absorbed by an object, the object’s temperature change $T_f - T_i$ is related to $Q$ by

$$Q = C(T_f - T_i),$$

in which $C$ is the heat capacity of the object. If the object has mass $m$, then

$$Q = cm(T_f - T_i),$$

where $c$ is the specific heat of the material making up the object. The molar specific heat of a material is the heat capacity per mole, which means per $6.02 \times 10^{23}$ elementary units of the material.

**Heat of Transformation** Heat absorbed by a material may change the material’s physical state—for example, from solid to liquid or from liquid to gas. The amount of energy required per unit mass to change the state (but not the temperature) of a particular material is its heat of transformation $L$. Thus,

$$Q = Lm.$$

The heat of vaporization $L_v$ is the amount of energy per unit mass that must be added to vaporize a liquid or that must be removed to condense a gas. The heat of fusion $L_f$ is the amount of energy per unit mass that must be added to melt a solid or that must be removed to freeze a liquid.

**Work Associated with Volume Change** A gas may exchange energy with its surroundings through work. The amount of work $W$ done by a gas as it expands or contracts from an initial volume $V_i$ to a final volume $V_f$ is given by

$$W = \int_{V_i}^{V_f} p \, dV.$$

The integration is necessary because the pressure $p$ may vary during the volume change.

**First Law of Thermodynamics** The principle of conservation of energy for a thermodynamic process is expressed in the first law of thermodynamics, which may assume either of the forms

$$\Delta E_{int} = E_{int,f} - E_{int,i} = Q - W \quad \text{(first law)}$$

or

$$dE_{int} = dQ - dW \quad \text{(first law)}.$$

$E_{int}$ represents the internal energy of the material, which depends only on the material’s state (temperature, pressure, and volume). $Q$ represents the energy exchanged as heat between the system and its surroundings; $W$ is positive if the system absorbs heat and negative if the system loses heat. $W$ is the work done by the system; $W$ is positive if the system expands against an external force from the surroundings and negative if the system contracts because of an external force. $Q$ and $W$ are path dependent; $\Delta E_{int}$ is path independent.

**Applications of the First Law** The first law of thermodynamics finds application in several special cases:

- **adiabatic processes**: $Q = 0$, $\Delta E_{int} = -W$
- **constant-volume processes**: $W = 0$, $\Delta E_{int} = Q$
- **cyclical processes**: $\Delta E_{int} = 0$, $Q = W$
- **free expansions**: $Q = W = \Delta E_{int} = 0$

**Conduction, Convection, and Radiation** The rate $P_{\text{cond}}$ at which energy is conducted through a slab for which one face is maintained at the higher temperature $T_H$ and the other face is maintained at the lower temperature $T_C$ is

$$P_{\text{cond}} = \frac{Q}{t} = kA \frac{T_H - T_C}{L}.$$  

Here each face of the slab has area $A$, the length of the slab (the distance between the faces) is $L$, and $k$ is the thermal conductivity of the material.

**Convection** occurs when temperature differences cause an energy transfer by motion within a fluid.

**Radiation** is an energy transfer via the emission of electromagnetic energy. The rate $P_{\text{rad}}$ at which an object emits energy via thermal radiation is

$$P_{\text{rad}} = \sigma \epsilon A T^4,$$

where $\sigma = 5.6704 \times 10^{-8}$ W/m$^2$·K$^4$ is the Stefan–Boltzmann constant, $\epsilon$ is the emissivity of the object’s surface, $A$ is its surface area, and $T$ is its surface temperature (in kelvins). The rate $P_{\text{abs}}$ at which an object absorbs energy via thermal radiation from its environment, which is at the uniform temperature $T_{\text{env}}$ (in kelvins), is

$$P_{\text{abs}} = \sigma \epsilon A T_{\text{env}}^4.$$
1. The initial length $L$, change in temperature $\Delta T$, and change in length $\Delta L$ of four rods are given in the following table. Rank the rods according to their coefficients of thermal expansion, greatest first.

<table>
<thead>
<tr>
<th>Rod</th>
<th>$L$ (m)</th>
<th>$\Delta T$ ($^\circ$C)</th>
<th>$\Delta L$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>2</td>
<td>10</td>
<td>$4 \times 10^{-4}$</td>
</tr>
<tr>
<td>$b$</td>
<td>1</td>
<td>20</td>
<td>$4 \times 10^{-4}$</td>
</tr>
<tr>
<td>$c$</td>
<td>2</td>
<td>10</td>
<td>$8 \times 10^{-4}$</td>
</tr>
<tr>
<td>$d$</td>
<td>4</td>
<td>5</td>
<td>$4 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

2. Figure 18-23 shows three linear temperature scales, with the freezing and boiling points of water indicated. Rank the three scales according to the size of one degree on them, greatest first.

3. Materials $A$, $B$, and $C$ are solids that are at their melting temperatures. Material $A$ requires 200 J to melt 4 kg, material $B$ requires 300 J to melt 5 kg, and material $C$ requires 300 J to melt 6 kg. Rank the materials according to their heats of fusion, greatest first.

4. A sample $A$ of liquid water and a sample $B$ of ice, of identical mass, are placed in a thermally insulated container and allowed to come to thermal equilibrium. Figure 18-24a is a sketch of the temperature $T$ of the samples versus time $t$. (a) Is the equilibrium temperature above, below, or at the freezing point of water? (b) In reaching equilibrium, does the liquid partly freeze, fully freeze, or undergo no freezing? (c) Does the ice partly melt, fully melt, or undergo no melting?

5. Question 4 continued: Graphs (b) through (f) of Fig. 18-24 are additional sketches of $T$ versus $t$, of which one or more are impossible to produce. (a) Which is impossible and why? (b) In the possible ones, is the equilibrium temperature above, below, or at the freezing point of water? (c) As the possible situations reach equilibrium, does the liquid partly freeze, fully freeze, or undergo no freezing? Does the ice partly melt, fully melt, or undergo no melting?

6. Figure 18-25 shows three different arrangements of materials 1, 2, and 3 to form a wall. The thermal conductivities are $k_1 > k_2 > k_3$. The left side of the wall is 20 $^\circ$C higher than the right side. Rank the arrangements according to (a) the (steady state) rate of energy conduction through the wall and (b) the temperature difference across material 1, greatest first.

7. Figure 18-26 shows two closed cycles on $p$-$V$ diagrams for a gas. The three parts of cycle 1 are of the same length and shape as those of cycle 2. For each cycle, should the cycle be traversed clockwise or counterclockwise if (a) the net work $W$ done by the gas is to be positive and (b) the net energy transferred by the gas as heat $Q$ is to be positive?

8. For which cycle in Fig. 18-26, traversed clockwise, is (a) $W$ greater and (b) $Q$ greater?

9. Three different materials of identical mass are placed one at a time in a special freezer that can extract energy from a material at a certain constant rate. During the cooling process, each material begins in the liquid state and ends in the solid state; Fig. 18-27 shows the temperature $T$ versus time $t$. (a) For material 1, is the specific heat for the liquid state greater than or less than that for the solid state? Rank the materials according to (b) freezing-point temperature, (c) specific heat in the liquid state, (d) specific heat in the solid state, and (e) heat of fusion, all greatest first.

10. A solid cube of edge length $r$, a solid sphere of radius $r$, and a solid hemisphere of radius $r$ are made of the same material, which is maintained at temperature 300 K in an environment at temperature 350 K. Rank the objects according to the net rate at which thermal radiation is exchanged with the environment, greatest first.

11. A hot object is dropped into a thermally insulated container of water, and the object and water are then allowed to come to thermal equilibrium. The experiment is repeated twice, with different hot objects. All three objects have the same mass and initial temperature, and the mass and initial temperature of the water are the same in the three experiments. For each of the experiments, Fig. 18-28 gives graphs of the temperatures $T$ of the object and the water versus time $t$. Rank the graphs according to the specific heats of the objects, greatest first.
sec. 18-4 Measuring Temperature

1. Suppose the temperature of a gas is 373.15 K when it is at the boiling point of water. What then is the limiting value of the ratio of the pressure of the gas at that boiling point to its pressure at the triple point of water? (Assume the volume of the gas is the same at both temperatures.)

2. Two constant-volume gas thermometers are assembled, one with nitrogen and the other with hydrogen. Both contain enough gas so that $p_1 = 80$ kPa. (a) What is the difference between the pressures in the two thermometers if both bulbs are in boiling water? (Hint: See Fig. 18-6.) (b) Which gas is at higher pressure?

3. A gas thermometer is constructed of two gas-containing bulbs, each in a water bath, as shown in Fig. 18-29. The pressure difference between the two bulbs is measured by a mercury manometer as shown. Appropriate reservoirs, not shown in the diagram, maintain constant gas volume in the two bulbs. There is no difference in pressure when both baths are at the triple point of water. The pressure difference is 120 torr when one bath is at the triple point and the other is at the boiling point of water. It is 90.0 torr when one bath is at the triple point and the other is at an unknown temperature to be measured. What is the unknown temperature?

sec. 18-5 The Celsius and Fahrenheit Scales

4. (a) In 1964, the temperature in the Siberian village of Oymyakon reached $-71^\circ$C. What temperature is this on the Fahrenheit scale? (b) The highest officially recorded temperature in the continental United States was $134^\circ$F in Death Valley, California. What is this temperature on the Celsius scale?

5. At what temperature is the Fahrenheit scale reading equal to (a) twice that of the Celsius scale and (b) half that of the Celsius scale?

6. On a linear X temperature scale, water freezes at $-125.0^\circ$X and boils at $375.0^\circ$X. On a linear Y temperature scale, water freezes at $-70.00^\circ$Y and boils at $-30.00^\circ$Y. A temperature of $50.00^\circ$Y corresponds to what temperature on the X scale?

7. Suppose that on a linear temperature scale X, water boils at $-53.5^\circ$X and freezes at $-170^\circ$X. What is a temperature of 340 K on the X scale? (Approximate water’s boiling point as 373 K.)

sec. 18-6 Thermal Expansion

8. At 20°C, a brass cube has an edge length of 30 cm. What is the increase in the cube’s surface area when it is heated from 20°C to 75°C?

9. A circular hole in an aluminum plate is 2.725 cm in diameter at 0.000°C. What is its diameter when the temperature of the plate is raised to 100.0°C?

10. An aluminum flagpole is 33 m high. By how much does its length increase as the temperature increases by 15°C?

11. What is the volume of a lead ball at 30.00°C if the ball’s volume at 60.00°C is 50.00 cm³?

12. An aluminum-alloy rod has a length of 10.000 cm at 20.000°C and a length of 10.015 cm at the boiling point of water. (a) What is the length of the rod at the freezing point of water? (b) What is the temperature if the length of the rod is 10.009 cm?

13. Find the change in volume of an aluminum sphere with an initial radius of 10 cm when the sphere is heated from 0.0°C to 100°C.

14. When the temperature of a copper coin is raised by 100°C, its diameter increases by 0.18%. To two significant figures, give the percent increase in (a) the area of a face, (b) the thickness, (c) the volume, and (d) the mass of the coin. (e) Calculate the coefficient of linear expansion of the coin.

15. A steel rod is 3.000 cm in diameter at 25.00°C. A brass ring has an interior diameter of 2.992 cm at 25.00°C. At what common temperature will the ring just slide onto the rod?

16. When the temperature of a metal cylinder is raised from 0.0°C to 100°C, its length increases by 0.23%. (a) Find the percent change in density. (b) What is the metal? Use Table 18-2.

17. An aluminum cup of 100 cm³ capacity is completely filled with glycerin at 22°C. How much glycerin, if any, will spill out of the cup if the temperature of both the cup and the glycerin is increased to 28°C? (The coefficient of volume expansion of glycerin is $5.1 \times 10^{-4}/\text{C}^\circ$.)

18. At 20°C, a rod is exactly 20.05 cm long on a steel ruler. Both the rod and the ruler are placed in an oven at 270°C, where the rod now measures 20.11 cm on the same ruler. What is the coefficient of linear expansion for the material of which the rod is made?

19. A vertical glass tube of length $L = 1.280 \text{ cm}$ is half filled with a liquid at $20.00 \text{ K}$. How much will the height of the liquid column change when the tube and liquid are heated to $30.00 \text{ K}$? Use coefficients $\alpha_{\text{glass}} = 1.000 \times 10^{-5} / \text{K}$ and $\beta_{\text{liquid}} = 4.000 \times 10^{-5} / \text{K}$.

20. In a certain experiment, a small radioactive source must move at selected, extremely slow speeds. This motion is accomplished by fastening the source to one end of an aluminum rod and heating the central section of the rod in a controlled way. If the effective heated section of the rod in Fig. 18-30 has length $d = 2.00 \text{ cm}$, at what constant rate must the temperature of the rod be changed if the source is to move at a constant speed of 100 nm/s?
** View All Solutions Here **
water to boil, with 5.00 g being converted to steam. The final temperature of the system is 100°C. Neglect energy transfers with the environment. (a) How much energy (in calories) is transferred to the water as heat? (b) How much to the bowl? (c) What is the original temperature of the cylinder?

**37** A person makes a quantity of iced tea by mixing 500 g of hot tea (essentially water) with an equal mass of ice at its melting point. Assume the mixture has negligible energy exchanges with its environment. (a) How much energy (in calories) is transferred to the water to boil, with 5.00 g being converted to steam. The final temperature of the system is 100°C. Neglect energy transfers with the environment. (a) How much energy (in calories) is transferred to the water as heat? (b) How much to the bowl? (c) What is the original temperature of the cylinder?

**38** A 0.530 kg sample of liquid water and a sample of ice are placed in a thermally insulated container. The container also contains a device that transfers energy as heat from the liquid water to the ice at a constant rate, until thermal equilibrium is reached. The temperatures of the liquid water and the ice are given in Fig. 18-34 as functions of time t. The horizontal scale is set by t = 80.0 min. (a) What is rate P? (b) What is the initial mass of the ice in the container? (c) When thermal equilibrium is reached, what is the mass of the ice produced in this process?

![Fig. 18-34 Problem 38.](image)

**39** Ethyl alcohol has a boiling point of 78.0°C, a freezing point of −114°C, a heat of vaporization of 879 kJ/kg, a heat of fusion of 109 kJ/kg, and a specific heat of 2.43 kJ/kg·K. How much energy must be removed from 0.510 kg of ethyl alcohol that is initially a gas at 78.0°C so that it becomes a solid at −114°C?

**40** Calculate the specific heat of a metal from the following data. A container made of the metal has a mass of 3.6 kg and contains 14 kg of water. A 1.8 kg piece of the metal initially at a temperature of 180°C is dropped into the water. The container and water initially have a temperature of 16.0°C, and the final temperature of the entire (insulated) system is 18.0°C.

**41** (a) Two 50 g ice cubes are dropped into 200 g of water in a thermally insulated container. If the water is initially at 25°C, and the ice comes directly from a freezer at −15°C, what is the final temperature at thermal equilibrium? (b) What is the final temperature if only one ice cube is used?

**42** A 20.0 g copper ring at 0.000°C has an inner diameter of D = 2.5400 cm. An aluminum sphere at 100.0°C has a diameter of d = 2.545 08 cm. The sphere is put on top of the ring (Fig. 18-35), and the two are allowed to come to thermal equilibrium, with no heat lost to the surroundings. The sphere just passes through the ring at the equilibrium temperature. What is the mass of the sphere?

**43** In Fig. 18-36, a gas sample expands from V_a to 4.0V_a while its pressure decreases from p_a to p_b/4.0. If V_a = 1.0 m³ and p_a = 40 Pa, how much work is done by the gas if its pressure changes with volume via (a) path A, (b) path B, and (c) path C?

**44** A thermodynamic system is taken from state A to state B to state C, and then back to A, as shown in the p-V diagram of Fig. 18-37a. The vertical scale is set by p_0 = 40 Pa, and the horizontal scale is set by V_0 = 4.0 m³. (a)–(g) Complete the table in Fig. 18-37b by inserting a plus sign, a minus sign, or a zero in each indicated cell. (h) What is the net work done by the system as it moves once through the cycle ABCA?

![Fig. 18-36 Problem 43.](image)

**45** (a) Two 50 g ice cubes are dropped into 200 g of water in a thermally insulated container. If the water is initially at 25°C, and the ice comes directly from a freezer at −15°C, what is the final temperature at thermal equilibrium? (b) What is the final temperature if only one ice cube is used?

**46** Suppose 200 J of work is done on a system and 70.0 cal is extracted from the system as heat. In the sense of the first law of thermodynamics, what are the values (including algebraic signs) of (a) W, (b) Q, and (c) ΔE_{int}?
When a system is taken from state $i$ to state $f$ along path $ab$ in Fig. 18-39, $Q = 50$ cal and $W = 20$ cal. Along path $ib$, $Q = 36$ cal. (a) What is $W$ along path $ib$? (b) If $W = -13$ cal for the return path $fi$, what is $Q$ for this path? (c) If $E_{int,i} = 10$ cal, what is $E_{int,f}$? If $E_{int,b} = 22$ cal, what is $Q$ for (d) path $ib$ and (e) path $fc$?

Gas held within a chamber passes through the cycle shown in Fig. 18-40. Determine the energy transferred by the system as heat during process $CA$ if the energy added as heat $Q_{1b}$ during process $AB$ is $20.0$ J, no energy is transferred as heat during process $BC$, and the net work done during the cycle is $15.0$ J.

Figure 18-41 represents a closed cycle for a gas (the figure is not drawn to scale). The change in the internal energy of the gas as it moves from $a$ to $c$ along the path $abc$ is $-200$ J. As it moves from $c$ to $d$, $180$ J must be transferred to it as heat. An additional transfer of $80$ J to it as heat is needed as it moves from $d$ to $a$. How much work is done on the gas as it moves from $c$ to $d$?

A lab sample of gas is taken through cycle $abca$ shown in the $p-V$ diagram of Fig. 18-42. The net work done is $+1.2$ J. Along path $ab$, the change in the internal energy is $+3.0$ J and the magnitude of the work done is $5.0$ J. Along path $ca$, the energy transferred to the gas as heat is $+2.5$ J. How much energy is transferred as heat along (a) path $ab$ and (b) path $bc$?

A sphere of radius $0.500$ m, temperature $27.0$°C, and emissivity $0.850$ is located in an environment of temperature $77.0$°C. At what rate does the sphere (a) emit and (b) absorb thermal radiation? (c) What is the sphere’s net rate of energy exchange?

The ceiling of a single-family dwelling in a cold climate should have an $R$-value of $30$. To give such insulation, how thick would a layer of (a) polyurethane foam and (b) silver have to be?

Consider the slab shown in Fig. 18-18. Suppose that $L = 25.0$ cm, $A = 90.0$ cm$^2$, and the material is copper. If $T_H = 125$°C, $T_C = 10.0$°C, and a steady state is reached, find the conduction rate through the slab.

If you were to walk briefly in space without a spacesuit while far from the Sun (as an astronaut does in the movie 2001, A Space Odyssey), you would feel the cold of space — while you radiated energy, you would absorb almost none from your environment. (a) At what rate would you lose energy? (b) How much energy would you lose in 30 s? Assume that your emissivity is 0.90, and estimate other data needed in the calculations.

A cylindrical copper rod of length $1.2$ m and cross-sectional area $4.8$ cm$^2$ is insulated to prevent heat loss through its surface. The ends are maintained at a temperature difference of $100$°C by having one end in a water–ice mixture and the other in a mixture of boiling water and steam. (a) At what rate is energy conducted along the rod? (b) At what rate does ice melt at the cold end?

The giant hornet Vespa mandarinia japonica preys on Japanese bees. However, if one of the hornets attempts to invade a beehive, several hundred of the bees quickly form a compact ball around the hornet to stop it. They don’t sting, bite, crush, or suffocate it. Rather they overheat it by quickly raising their body temperatures from the normal $35$°C to $47$°C or $48$°C, which is lethal to the hornet but not to the bees (Fig. 18-43). Assume the following: 500 bees form a ball of radius $R = 2.0$ cm for a time $t = 20$ min, the primary loss of energy by the ball is by thermal radiation, the ball’s surface has emissivity $e = 0.80$, and the ball has a uniform temperature. On average, how much additional energy must each bee produce during the 20 min to maintain $47$°C?

A sphere of radius $0.500$ m, temperature $27.0$°C, and emissivity $0.85$ is located in an environment of temperature $50$°C. (a) What is the cylinder’s net thermal radiation transfer rate $P_1$? (b) A storm window having the same thickness of glass is installed parallel to the first window, with an air gap of $7.5$ cm between the two windows. What now is the rate of energy loss if conduction is the only important energy-loss mechanism?

A solid cylinder of radius $r_1 = 2.5$ cm, length $h_1 = 5.0$ cm, emissivity 0.85, and temperature $30$°C is suspended in an environment of temperature $50$°C. (a) What is the cylinder’s net thermal radiation transfer rate $P_1$? (b) If the cylinder is stretched until its radius is $r_2 = 0.50$ cm, its net thermal radiation transfer rate becomes $P_2$. What is the ratio $P_2/P_1$?

In Fig. 18-44a, two identical rectangular rods of metal are welded end to end, with a temperature of $T_1 = 0$°C on the left side and a temperature of $T_2 = 100$°C on the right side. If the rod thickness is $0.2$ cm, calculate the temperature distribution along the rod. What is the rate of energy transfer by conduction through the rod?
the right side. In 2.0 min, 10 J is conducted at a constant rate from the right side to the left side. How much time would be required to conduct 10 J if the rods were welded side to side as in Fig. 18-44?

**60** Figure 18-45 shows the cross section of a wall made of three layers. The layer thicknesses are \(L_1 = 0.700\, L_1\), and \(L_2 = 0.350\, L_1\). The thermal conductivities are \(k_1 = 0.900\, k_1\), and \(k_3 = 0.800\, k_1\). The temperatures at the left and right sides of the wall are \(T_c = 300\,°C\) and \(T_c = -15.0\,°C\), respectively. Thermal conduction is steady. (a) What is the temperature difference \(ΔT_{12}\) across layer 2 (between the left and right sides of the layer)? If \(k_2\) were, instead, equal to \(1.1\, k_1\), (b) would the rate at which energy is conducted through the wall be greater than, less than, or the same as previously, and (c) what would be the value of \(ΔT_{12}\)?

**61 SSM** A tank of water has been outdoors in cold weather, and a slab of ice 5.0 cm thick has formed on its surface (Fig. 18-46). The air above the ice is at \(-10°C\). Calculate the rate of ice formation (in centimeters per hour) on the ice slab. Take the thermal conductivity of ice to be \(0.0040\, \text{cal/s·cm·°C}\) and its density to be \(0.92\, \text{g/cm}^3\). Assume no energy transfer through the tank walls or bottom.

**62** Leidenfrost effect. A water drop that is slung onto a skillet with a temperature between \(100°C\) and about \(200°C\) will last about 1 s. However, if the skillet is much hotter, the drop can last several minutes, an effect named after an early investigator. The longer lifetime is due to the support of a thin layer of air and water vapor that separates the drop from the metal (by distance \(L\) in Fig. 18-47). Let \(L = 0.100\, \text{mm}\), and assume that the drop is flat with height \(h = 1.50\, \text{mm}\) and bottom face area \(A = 4.00 \times 10^{-5}\, \text{m}^2\). Also assume that the skillet has a constant temperature \(T_s = 300°C\) and the drop has a temperature of \(100°C\). Water has density \(ρ = 1000\, \text{kg/m}^3\), and the supporting layer has thermal conductivity \(k = 0.026\, \text{W/m·K}\). (a) At what rate is energy conducted from the skillet to the drop through the drop’s bottom surface? (b) If conduction is the primary way energy moves from the skillet to the drop, how long will the drop last?

**63** Figure 18-48 shows (in cross section) a wall consisting of four layers, with thermal conductivities \(k_1 = 0.060\, \text{W/m·K}\), \(k_2 = 0.040\, \text{W/m·K}\), and \(k_3 = 0.12\, \text{W/m·K}\) (\(k_4\) is not known). The layer thicknesses are \(L_1 = 1.5\, \text{cm}\), \(L_2 = 2.8\, \text{cm}\), and \(L_3 = 3.5\, \text{cm}\) (\(L_4\) is not known). The known temperatures are \(T_1 = 30°C\), \(T_2 = 25°C\), and \(T_3 = -10°C\). Energy transfer through the wall is steady. What is interface temperature \(T_{40}\)?

**64** Penguin huddling. To withstand the harsh weather of the Antarctic, emperor penguins huddle in groups (Fig. 18-49). Assume that a penguin is a circular cylinder with a top surface area \(a = 0.34\, \text{m}^2\) and height \(h = 1.1\, \text{m}\). Let \(P_a\) be the rate at which an individual penguin radiates energy to the environment (through the top and the sides); thus \(NP\), is the rate at which \(N\) identical, well-separated penguins radiate. If the penguins huddle closely to form a huddled cylinder with top surface area \(Na\) and height \(h\), the cylinder radiates at the rate \(P_{a}\). If \(N = 1000\), (a) what is the value of the fraction \(P_a/\rho_{a}\), and (b) by what percentage does huddling reduce the total radiation loss?

**65** Ice has formed on a shallow pond, and a steady state has been reached, with the air above the ice at \(-5.0°C\) and the bottom of the pond at \(4.0°C\). If the total depth of ice + water is 1.4 m, how thick is the ice? (Assume that the thermal conductivities of ice and water are 0.40 and 0.12 \(\text{cal/m·°C}\), respectively.)

**66** Evaporative cooling of beverages. A cold beverage can be kept cold even on a warm day if it is slipped into a porous ceramic container that has been soaked in water. Assume that energy lost to evaporation matches the net energy gained via the radiation exchange through the top and side surfaces. The container and beverage have temperature \(T = 15°C\), the environment has temperature \(T_{env} = 32°C\), and the container is a cylinder with radius \(r = 2.2\, \text{cm}\) and height 10 cm. Approximate the emissivity as \(ε = 1\), and neglect other energy exchanges. At what rate \(dn/m/dt\) is the container losing water mass?

Additional Problems
64. In the extrusion of cold chocolate from a tube, work is done on the chocolate by the pressure applied by a ram forcing the chocolate through the tube. The work per unit mass of extruded chocolate is equal to \(p/\rho\), where \(p\) is the difference between the applied pressure and the pressure where the chocolate emerges from the tube, and \(\rho\) is the density of the chocolate.
Rather than increasing the temperature of the chocolate, this work melts cocoa fats in the chocolate. These fats have a heat of fusion of 150 kJ/kg. Assume that all of the work goes into that melting and that these fats make up 30% of the chocolate’s mass. What percentage of the fats melt during the extrusion if \( p = 5.5 \text{ MPa} \) and \( \rho = 1200 \text{ kg/m}^3 \)?

68 Icebergs in the North Atlantic present hazards to shipping, causing the lengths of shipping routes to be increased by about 30% during the iceberg season. Attempts to destroy icebergs include planting explosives, bombing, torpedoing, shelling, ramming, and coating with black soot. Suppose that direct melting of the iceberg, by placing heat sources in the ice, is tried. How much energy as heat is required to melt 10% of an iceberg that has a mass of 200 000 metric tons? (Use 1 metric ton = 1000 kg.)

69 Figure 18-50 displays a closed cycle for a gas. The change in internal energy along path \( ab \) is \(-160 \text{ J}\). The energy transferred to the gas as heat is 200 \text{ J} \) along path \( ab \), and 40 \text{ J} \) along path \( bc \). How much work is done by the gas along \( (a) \) path \( abc \) and \( (b) \) path \( ab \)?

70 In a certain solar house, energy from the Sun is stored in barrels filled with water. In a particular winter stretch of five cloudy days, \( 1.00 \times 10^6 \text{ kcal} \) is needed to maintain the inside of the house at 22.0°C. Assuming that the water in the barrels is at 50.0°C and that the water has a density of \( 1.00 \times 10^3 \text{ kg/m}^3 \), what volume of water is required? (Use 1 metric ton = 1000 kg.)

71 A 0.300 kg sample is placed in a cooling apparatus that removes energy as heat at a constant rate of 2.81 W. Figure 18-51 gives the temperature \( T \) of the sample versus time \( t \). The temperature scale is set by \( T_s = 30^\circ \text{ C} \) and the time scale is set by \( t_s = 20 \text{ min} \). What is the specific heat of the sample?

72 The average rate at which energy is conducted outward through the ground surface in North America is 54.0 mW/m², and the average thermal conductivity of the near-surface rocks is \( 2.50 \text{ W/m} \cdot \text{K} \). Assuming a surface temperature of 10.0°C, find the temperature at a depth of 35.0 km (near the base of the crust). Ignore the heat generated by the presence of radioactive elements.

73 What is the volume increase of an aluminum cube 5.00 cm on an edge when heated from 10.0°C to 60.0°C?

74 In a series of experiments, block \( B \) is to be placed in a thermally insulated container with block \( A \), which has the same mass as block \( B \). In each experiment, block \( B \) is initially at a certain temperature \( T_{B_0} \) but temperature \( T_A \) of block \( A \) is changed from experiment to experiment. Let \( T_f \) represent the final temperature of the two blocks when they reach thermal equilibrium in any of the experiments. Figure 18-52 gives temperature \( T_f \) versus the initial temperature \( T_A \) for a range of possible values of \( T_A \), from \( T_{A_1} = 0 \text{ K} \) to \( T_{A_2} = 500 \text{ K} \). The vertical axis scale is set by \( T_p = 400 \text{ K} \). What are (a) temperature \( T_R \) and (b) the ratio \( c_B/c_A \) of the specific heats of the blocks?

75 Figure 18-53 displays a closed cycle for a gas. From \( c \) to \( b \), 40 \text{ J} \) is transferred from the gas as heat. From \( b \) to \( a \), 130 \text{ J} \) is transferred from the gas as heat, and the magnitude of the work done by the gas is 80 \text{ J} \). From \( a \) to \( c \), 400 \text{ J} \) is transferred to the gas as heat. What is the work done by the gas from \( a \) to \( c \)? (Hint: You need to supply the plus and minus signs for the given data.)

76 Three equal-length straight rods, of aluminum, Invar, and steel, all at 20.0°C, form an equilateral triangle with hinge pins at the vertices. At what temperature will the angle opposite the Invar rod be 59.95°? See Appendix E for needed trigonometric formulas and Table 18-2 for needed data.

77 SSM The temperature of a 0.700 kg cube of ice is decreased to \(-150^\circ \text{ C} \). Then energy is gradually transferred to the cube as heat while it is otherwise thermally isolated from its environment. The total transfer is 0.6993 MJ. Assume the value of \( c_{\text{ice}} \) given in Table 18-3 is valid for temperatures from \(-150^\circ \text{ C} \) to 0°C. What is the final temperature of the water?

78 Icicles. Liquid water coats an active (growing) icicle and extends up a short, narrow tube along the central axis (Fig. 18-54). Because the water–ice interface must have a temperature of 0°C, the water in the tube cannot lose energy through the sides of the icicle or down through the tip because there is no temperature change in those directions. It can lose energy and freeze only by sending energy up (through distance \( L \)) to the top of the icicle, where the temperature \( T_r \) can be below 0°C. Take \( L = 0.12 \text{ m} \) and \( T_r = -5^\circ \text{ C} \). Assume that the central tube and the upward conduction path both have cross-sectional area \( A \). In terms of \( A \), what rate is (a) energy conducted upward and (b) mass converted from liquid to ice at the top of the central tube? (c) At what rate does the top of the tube move downward because of water freezing there? The thermal conductivity of ice is 0.400 W/m·K, and the density of liquid water is 1000 kg/m³.

** View All Solutions Here **
Figure 18-55a shows a cylinder containing gas and closed by a movable piston. The cylinder is kept submerged in an ice–water mixture. The piston is quickly pushed down from position 1 to position 2 and then held at position 2 until the gas is again at the temperature of the ice–water mixture; it then is slowly raised back to position 1. Figure 18-55b is a p-V diagram for the process. If 100 g of ice is melted during the cycle, how much work has been done on the gas?

![Image](a)

**Fig. 18-55** Problem 80.

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A sample of gas undergoes a transition from an initial state a to a final state b by three different paths (processes), as shown in the p-V diagram in Fig. 18-56, where $V_a = 5.00 V$. The energy transferred to the gas as heat in process 1 is $10p_a V_a$. In terms of $p_a V_a$, what are (a) the energy transferred to the gas as heat in process 2 and (b) the change in internal energy that the gas undergoes in process 3?

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A copper rod, an aluminum rod, and a brass rod, each of 6.00 m length and 1.00 cm diameter, are placed end to end with the aluminum rod between the other two. The free end of the copper rod is maintained at water’s boiling point, and the free end of the brass rod is maintained at water’s freezing point. What is the steady-state temperature of (a) the copper–aluminum junction and (b) the aluminum–brass junction?

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The temperature of a Pyrex disk is changed from 10.0°C to 60.0°C. Its initial radius is 8.00 cm; its initial thickness is 0.500 cm. Take these data as being exact. What is the change in the volume of the disk? (See Table 18-2.)

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(a) Calculate the rate at which body heat is conducted through the clothing of a skier in a steady-state process, given the following data: the body surface area is 1.8 m², and the clothing is 1.0 cm thick; the skin surface temperature is 33°C and the outer surface of the clothing is at 1.0°C; the thermal conductivity of the clothing is 0.040 W/m·K. (b) If, after a fall, the skier’s clothes became soaked with water of thermal conductivity 0.60 W/m·K, by how much is the rate of conduction multiplied?

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A 2.50 kg lump of aluminum is heated to 92.0°C and then dropped into 8.00 kg of water at 5.00°C. Assuming that the lump–water system is thermally isolated, what is the system’s equilibrium temperature?

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A sample of gas expands from $V_1 = 1.0 m^3$ and $p_1 = 40 Pa$ to $V_2 = 4.0 m^3$ and $p_2 = 10 Pa$ along path $B$ in the p-V diagram in Fig. 18-57. It is then compressed back to $V_1$ along either path $A$ or path $C$. Compute the net work done by the gas for the complete cycle along (a) path $BA$ and (b) path $BC$.

**Fig. 18-57** Problem 95.