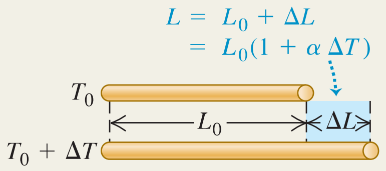
**Thermal expansion and thermal stress:** A temperature change $\Delta T$ causes a change in any linear dimension $L_0$ of a solid body. The change $\Delta L$ is approximately proportional to $L_0$ and $\Delta T$. Similarly, a temperature change causes a change $\Delta V$ in the volume $V_0$ of any solid or liquid; $\Delta V$ is approximately proportional to $V_0$ and $\Delta T$. The quantities $\alpha$ and $\beta$ are the coefficients of linear expansion and volume expansion, respectively. For solids, $\beta = 3\alpha$. (See Examples 17.2 and 17.3.)

When a material is cooled or heated and held so it cannot contract or expand, it is under a tensile stress $F/A$. (See Example 17.4.)

$$\Delta L = \alpha L_0 \, \Delta T \tag{17.6}$$

$$\Delta V = \beta V_0 \, \Delta T \tag{17.8}$$

$$\frac{F}{A} = -Y\alpha \, \Delta T \tag{17.12}$$




**Heat, phase changes, and calorimetry:** Heat is energy in transit from one body to another as a result of a temperature difference. Equations (17.13) and (17.18) give the quantity of heat $Q$ required to cause a temperature change $\Delta T$ in a quantity of material with mass $m$ and specific heat $c$ (alternatively, with number of moles $n$ and molar heat capacity $C = Mc$, where $M$ is the molar mass and $m = nM$). When heat is added to a body, $Q$ is positive; when it is removed, $Q$ is negative. (See Examples 17.5 and 17.6.)

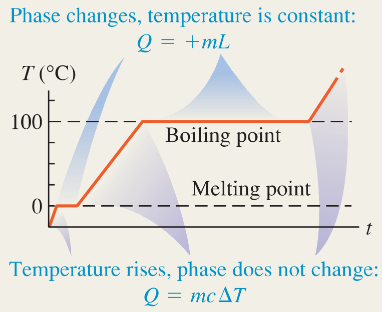
To change a mass $m$ of a material to a different phase at the same temperature (such as liquid to vapor), a quantity of heat given by Eq. (17.20) must be added or subtracted. Here $L$ is the heat of fusion, vaporization, or sublimation.

In an isolated system whose parts interact by heat exchange, the algebraic sum of the $Q$'s for all parts of the system must be zero. (See Examples 17.7–17.10.)

$$Q = mc \, \Delta T \tag{17.13}$$

$$Q = nC \, \Delta T \tag{17.18}$$

$$Q = \pm mL \tag{17.20}$$



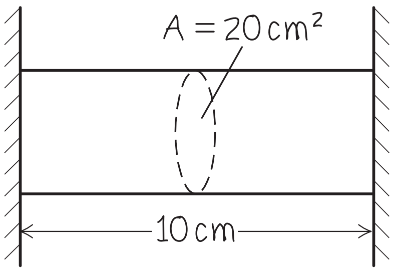
## Example 17.4 Thermal stress

An aluminum cylinder 10 cm long, with a cross-sectional area of 20 $cm^2$, is used as a spacer between two steel walls. At 17.2°C it just slips between the walls. Calculate the stress in the cylinder and the total force it exerts on each wall when it warms to 22.3°C, assuming that the walls are perfectly rigid and a constant distance apart.

### SOLUTION

**IDENTIFY and SET UP:** Figure 17.14 shows our sketch of the situation. Our target variables are the thermal stress $F/A$ in the cylinder, whose cross-sectional area $A$ is given, and the associated force $F$ it exerts on the walls. We use Eq. (17.12) to relate $F/A$ to the temperature change $\Delta T$, and from that calculate $F$. (The length of the cylinder is irrelevant.) We find Young's modulus $Y_{Al}$ and the coefficient of linear expansion $\alpha_{Al}$ from Tables 11.1 and 17.1, respectively.

**17.14** Our sketch for this problem.



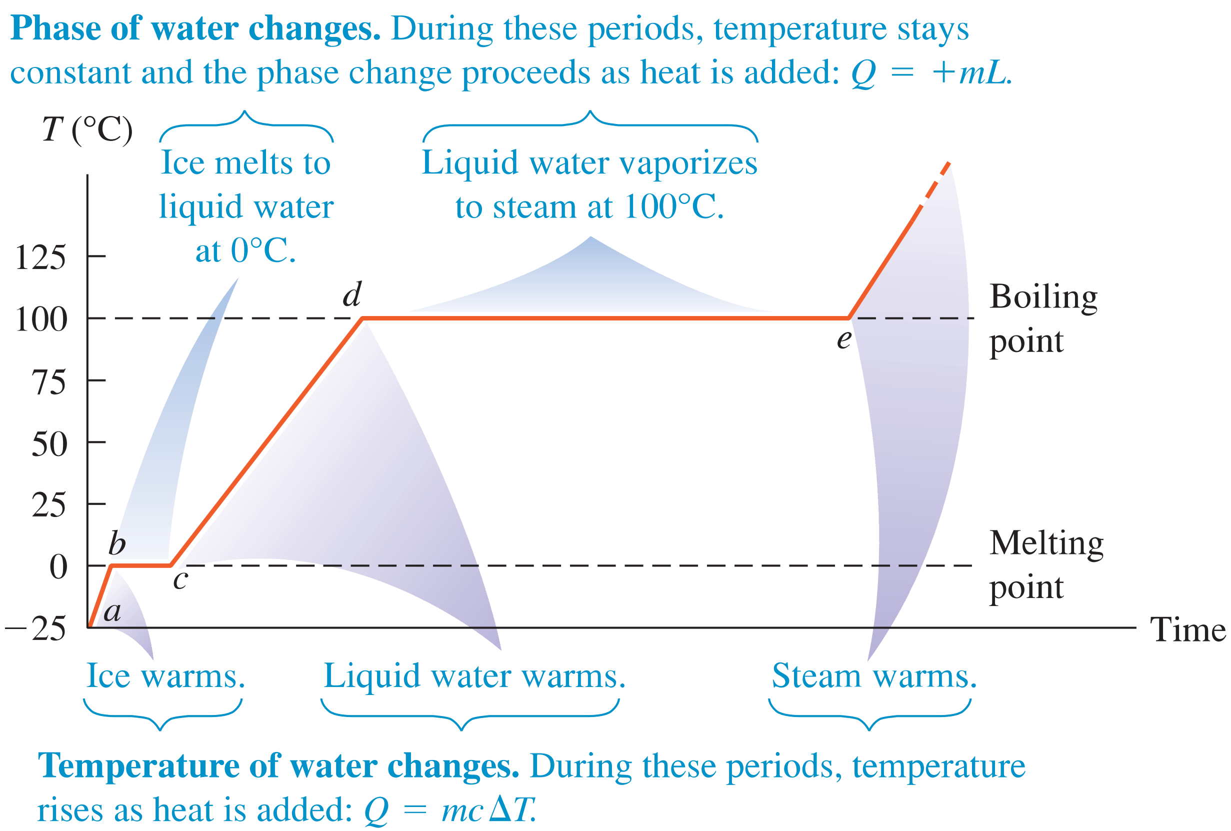

**EXECUTE:** We have $Y_{Al} = 7.0 \times 10^{10}$ Pa and $\alpha_{Al} = 2.4 \times 10^{-5}\ K^{-1}$, and $\Delta T = 22.3°C - 17.2°C = 5.1\ C° = 5.1$ K. From Eq. (17.12), the stress is

$$\frac{F}{A} = -Y_{Al}\alpha_{Al}\Delta T$$
$$= -(7.0 \times 10^{10}\ \text{Pa})(2.4 \times 10^{-5}\ \text{K}^{-1})(5.1\ \text{K})$$
$$= -8.6 \times 10^{6}\ \text{Pa} = -1200\ \text{lb/in.}^2$$

The total force is the cross-sectional area times the stress:

$$F = A\left(\frac{F}{A}\right) = (20 \times 10^{-4}\ \text{m}^2)(-8.6 \times 10^{6}\ \text{Pa})$$
$$= -1.7 \times 10^{4}\ \text{N} = 1.9\ \text{tons}$$

**EVALUATE:** The stress on the cylinder and the force it exerts on each wall are immense. Such thermal stresses must be accounted for in engineering.




**17.21** Graph of temperature versus time for a specimen of water initially in the solid phase (ice). Heat is added to the specimen at a constant rate. The temperature remains constant during each change of phase, provided that the pressure remains constant.

## Example 17.8 Changes in both temperature and phase

A glass contains 0.25 kg of Omni-Cola (mostly water) initially at 25°C. How much ice, initially at −20°C, must you add to obtain a final temperature of 0°C with all the ice melted? Neglect the heat capacity of the glass.

### SOLUTION

**IDENTIFY and SET UP:** The Omni-Cola and ice exchange heat. The cola undergoes a temperature change; the ice undergoes both a temperature change and a phase change from solid to liquid. We use subscripts C for cola, I for ice, and W for water. The target variable is the mass of ice, $m_I$. We use Eq. (17.13) to obtain an expression for the amount of heat involved in cooling the drink to $T = 0°C$ and warming the ice to $T = 0°C$, and Eq. (17.20) to obtain an expression for the heat required to melt the ice at 0°C. We have $T_{0C} = 25°C$ and $T_{0I} = -20°C$, Table 17.3 gives $c_W = 4190\ J/kg \cdot K$ and $c_I = 2100\ J/kg \cdot K$, and Table 17.4 gives $L_f = 3.34 \times 10^5\ J/kg$.

**EXECUTE:** From Eq. (17.13), the (negative) heat gained by the Omni-Cola is $Q_C = m_C c_W \Delta T_C$. The (positive) heat gained by the ice in warming is $Q_I = m_I c_I \Delta T_I$. The (positive) heat required to melt the ice is $Q_2 = m_I L_f$. We set $Q_C + Q_I + Q_2 = 0$, insert $\Delta T_C = T - T_{0C}$ and $\Delta T_I = T - T_{0I}$, and solve for $m_I$:

$$m_C c_W \Delta T_C + m_I c_I \Delta T_I + m_I L_f = 0$$

$$m_C c_W (T - T_{0C}) + m_I c_I (T - T_{0I}) + m_I L_f = 0$$

$$m_I [c_I (T - T_{0I}) + L_f] = -m_C c_W (T - T_{0C})$$

$$m_I = m_C \frac{c_W (T_{0C} - T)}{c_I (T - T_{0I}) + L_f}$$

Substituting numerical values, we find that $m_I = 0.070\ kg = 70\ g$.

**EVALUATE:** Three or four medium-size ice cubes would make about 70 g, which seems reasonable given the 250 g of Omni-Cola to be cooled.

**Conduction, convection, and radiation:** Conduction is the transfer of heat within materials without bulk motion of the materials. The heat current $H$ depends on the area $A$ through which the heat flows, the length $L$ of the heat-flow path, the temperature difference $(T_H - T_C)$, and the thermal conductivity $k$ of the material. (See Examples 17.11–17.13.)

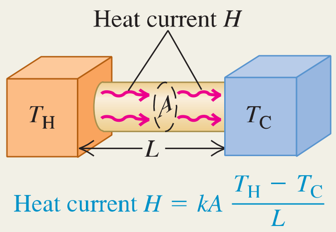
Convection is a complex heat-transfer process that involves mass motion from one region to another.

Radiation is energy transfer through electromagnetic radiation. The radiation heat current $H$ depends on the surface area $A$, the emissivity $e$ of the surface (a pure number between 0 and 1), and the Kelvin temperature $T$. Here σ is the Stefan–Boltzmann constant. The *net* radiation heat current $H_{net}$ from a body at temperature $T$ to its surroundings at temperature $T_s$ depends on both $T$ and $T_s$. (See Examples 17.14 and 17.15.)

$$H = \frac{dQ}{dt} = kA\frac{T_H - T_C}{L} \quad (17.21)$$

$$H = Ae\sigma T^4 \quad (17.25)$$

$$H_{net} = Ae\sigma(T^4 - T_s^4) \quad (17.26)$$



## Example 17.11 Conduction into a picnic cooler

A Styrofoam cooler (Fig. 17.24a) has total wall area (including the lid) of 0.80 $m^2$ and wall thickness 2.0 cm. It is filled with ice, water, and cans of Omni-Cola, all at 0°C. What is the rate of heat flow into the cooler if the temperature of the outside wall is 30°C? How much ice melts in 3 hours?

### SOLUTION

**IDENTIFY and SET UP:** The target variables are the heat current $H$ and the mass $m$ of ice melted. We use Eq. (17.21) to determine $H$ and Eq. (17.20) to determine $m$.

**EXECUTE:** We assume that the total heat flow is the same as it would be through a flat Styrofoam slab of area 0.80 $m^2$ and thickness 2.0 cm = 0.020 m (Fig. 17.24b). We find $k$ from Table 17.5. From Eq. (17.21),

$$H = kA\frac{T_H - T_C}{L} = (0.027\ \text{W/m}\cdot\text{K})(0.80\ \text{m}^2)\frac{30°\text{C} - 0°\text{C}}{0.020\ \text{m}}$$
$$= 32.4\ \text{W} = 32.4\ \text{J/s}$$

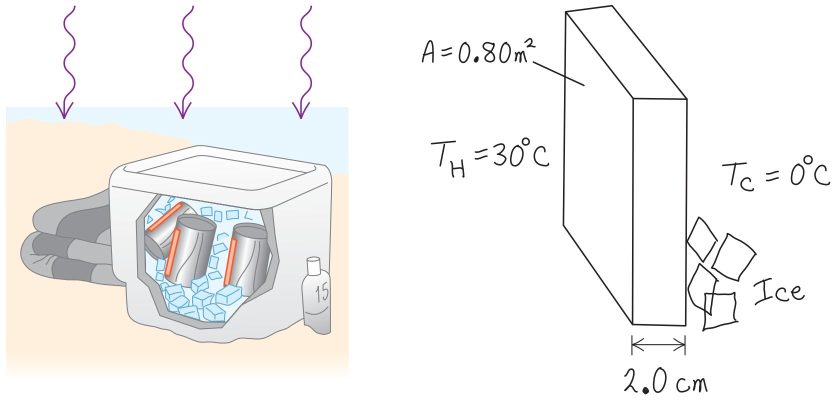
The total heat flow is $Q = Ht$, with $t = 3\ \text{h} = 10{,}800\ \text{s}$. From Table 17.4, the heat of fusion of ice is $L_f = 3.34 \times 10^5$ J/kg, so from Eq. (17.20) the mass of ice that melts is

$$m = \frac{Q}{L_f} = \frac{(32.4\ \text{J/s})(10{,}800\ \text{s})}{3.34 \times 10^5\ \text{J/kg}} = 1.0\ \text{kg}$$

**EVALUATE:** The low heat current is a result of the low thermal conductivity of Styrofoam.

**17.24** Conduction of heat across the walls of a Styrofoam cooler.

(a) A cooler at the beach (b) Our sketch for this problem



## Example 17.12 Conduction through two bars I

A steel bar 10.0 cm long is welded end to end to a copper bar 20.0 cm long. Each bar has a square cross section, 2.00 cm on a side. The free end of the steel bar is kept at 100°C by placing it in contact with steam, and the free end of the copper bar is kept at 0°C by placing it in contact with ice. Both bars are perfectly insulated on their sides. Find the steady-state temperature at the junction of the two bars and the total rate of heat flow through the bars.

### SOLUTION

**IDENTIFY and SET UP:** Figure 17.25 shows the situation. The heat currents in these end-to-end bars must be the same (see Problem-Solving Strategy 17.3). We are given "hot" and "cold" temperatures $T_H = 100°C$ and $T_C = 0°C$. With subscripts S for steel and Cu for copper, we write Eq. (17.21) separately for the heat currents $H_S$ and $H_{Cu}$ and set the resulting expressions equal to each other.

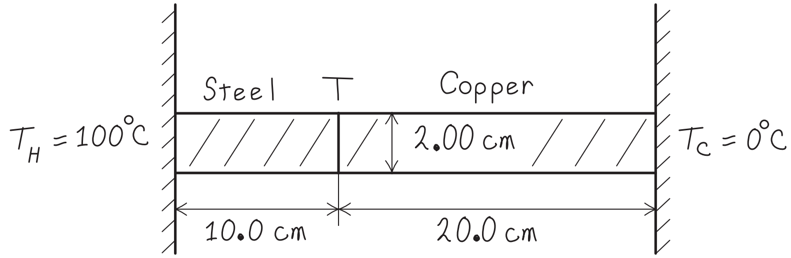
**EXECUTE:** Setting $H_S = H_{Cu}$, we have from Eq. (17.21)

$$H_S = k_S A \frac{T_H - T}{L_S} = H_{Cu} = k_{Cu} A \frac{T - T_C}{L_{Cu}}$$

We divide out the equal cross-sectional areas $A$ and solve for $T$:

$$T = \frac{\dfrac{k_S}{L_S} T_H + \dfrac{k_{Cu}}{L_{Cu}} T_C}{\left(\dfrac{k_S}{L_S} + \dfrac{k_{Cu}}{L_{Cu}}\right)}$$

**17.25** Our sketch for this problem.




Substituting $L_S = 10.0$ cm and $L_{Cu} = 20.0$ cm, the given values of $T_H$ and $T_C$, and the values of $k_S$ and $k_{Cu}$ from Table 17.5, we find $T = 20.7°C$.

We can find the total heat current by substituting this value of $T$ into either the expression for $H_S$ or the one for $H_{Cu}$:

$$H_S = (50.2 \text{ W/m·K})(0.0200 \text{ m})^2 \frac{100°C - 20.7°C}{0.100 \text{ m}}$$
$$= 15.9 \text{ W}$$

$$H_{Cu} = (385 \text{ W/m·K})(0.0200 \text{ m})^2 \frac{20.7°C}{0.200 \text{ m}} = 15.9 \text{ W}$$

**EVALUATE:** Even though the steel bar is shorter, the temperature drop across it is much greater (from 100°C to 20.7°C) than across the copper bar (from 20.7°C to 0°C). That's because steel is a much poorer conductor than copper.

## Example 17.15 Radiation from the human body

What is the total rate of radiation of energy from a human body with surface area $1.20\ \text{m}^2$ and surface temperature $30°\text{C} = 303\ \text{K}$? If the surroundings are at a temperature of 20°C, what is the *net* rate of radiative heat loss from the body? The emissivity of the human body is very close to unity, irrespective of skin pigmentation.

**SOLUTION**

**IDENTIFY and SET UP:** We must consider both the radiation that the body emits and the radiation that it absorbs from its surroundings. Equation (17.25) gives the rate of radiation of energy from the body, and Eq. (17.26) gives the net rate of heat loss.

**EXECUTE:** Taking $e = 1$ in Eq. (17.25), we find that the body radiates at a rate

$$H = Ae\sigma T^4$$
$$= (1.20\ \text{m}^2)(1)(5.67 \times 10^{-8}\ \text{W/m}^2 \cdot \text{K}^4)(303\ \text{K})^4 = 574\ \text{W}$$

This loss is partly offset by absorption of radiation, which depends on the temperature of the surroundings. From Eq. (17.26), the *net* rate of radiative energy transfer is

$$H_{\text{net}} = Ae\sigma(T^4 - T_s{}^4)$$
$$= (1.20\ \text{m}^2)(1)(5.67 \times 10^{-8}\ \text{W/m}^2 \cdot \text{K}^4)[(303\ \text{K})^4 - (293\ \text{K})^4] = 72\ \text{W}$$

**EVALUATE:** The value of $H_{\text{net}}$ is positive because the body is losing heat to its colder surroundings.

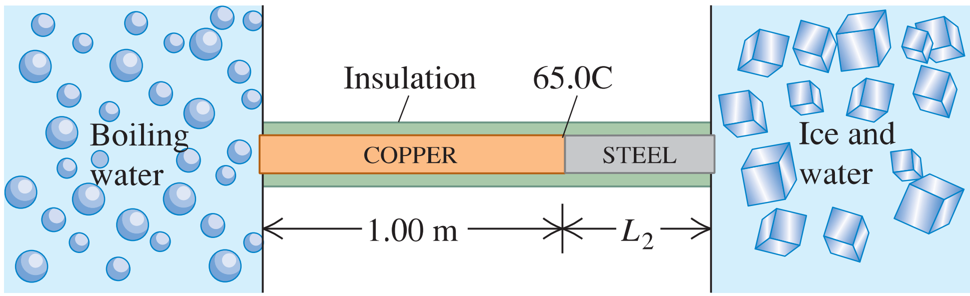
**17.19** •• A glass flask whose volume is 1000.00 $cm^3$ at 0.0°C is completely filled with mercury at this temperature. When flask and mercury are warmed to 55.0°C, 8.95 $cm^3$ of mercury overflow. If the coefficient of volume expansion of mercury is $18.0 \times 10^{-5}\ K^{-1}$, compute the coefficient of volume expansion of the glass.

**17.25** •• Steel train rails are laid in 12.0-m-long segments placed end to end. The rails are laid on a winter day when their temperature is −2.0°C. (a) How much space must be left between adjacent rails if they are just to touch on a summer day when their temperature is 33.0°C? (b) If the rails are originally laid in contact, what is the stress in them on a summer day when their temperature is 33.0°C?

**17.62** •• Two rods, one made of brass and the other made of copper, are joined end to end. The length of the brass section is 0.200 m and the length of the copper section is 0.800 m. Each segment has cross-sectional area 0.00500 $m^2$. The free end of the brass segment is in boiling water and the free end of the copper segment is in an ice and water mixture, in both cases under normal atmospheric pressure. The sides of the rods are insulated so there is no heat loss to the surroundings. (a) What is the temperature of the point where the brass and copper segments are joined? (b) What mass of ice is melted in 5.00 min by the heat conducted by the composite rod?

**17.68** • A long rod, insulated to prevent heat loss along its sides, is in perfect thermal contact with boiling water (at atmospheric pressure) at one end and with an ice–water mixture at the other (Fig. E17.68). The rod consists of a 1.00-m section of copper (one end in boiling water) joined end to end to a length $L_2$ of steel (one end in the ice–water mixture). Both sections of the rod have cross-sectional areas of 4.00 cm$^2$. The temperature of the copper–steel junction is 65.0°C after a steady state has been set up. (a) How much heat per second flows from the boiling water to the ice–water mixture? (b) What is the length $L_2$ of the steel section?

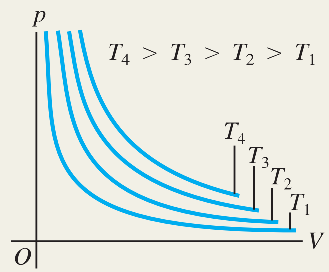
Figure **E17.68**



**17.127 ••• BIO A Walk in the Sun.** Consider a poor lost soul walking at 5 km/h on a hot day in the desert, wearing only a bathing suit. This person's skin temperature tends to rise due to four mechanisms: (i) energy is generated by metabolic reactions in the body at a rate of 280 W, and almost all of this energy is converted to heat that flows to the skin; (ii) heat is delivered to the skin by convection from the outside air at a rate equal to $k'A_{skin}(T_{air} - T_{skin})$, where $k'$ is 54 $J/h \cdot C° \cdot m^2$, the exposed skin area $A_{skin}$ is 1.5 $m^2$, the air temperature $T_{air}$ is 47°C, and the skin temperature $T_{skin}$ is 36°C; (iii) the skin absorbs radiant energy from the sun at a rate of 1400 $W/m^2$; (iv) the skin absorbs radiant energy from the environment, which has temperature 47°C. (a) Calculate the net rate (in watts) at which the person's skin is heated by all four of these mechanisms. Assume that the emissivity of the skin is $e = 1$ and that the skin temperature is initially 36°C. Which mechanism is the most important? (b) At what rate (in L/h) must perspiration evaporate from this person's skin to maintain a constant skin temperature? (The heat of vaporization of water at 36°C is $2.42 \times 10^6$ J/kg.) (c) Suppose instead the person is protected by light-colored clothing ($e \approx 0$) so that the exposed skin area is only 0.45 $m^2$. What rate of perspiration is required now? Discuss the usefulness of the traditional clothing worn by desert peoples.

**Equations of state:** The pressure $p$, volume $V$, and absolute temperature $T$ of a given quantity of a substance are related by an equation of state. This relationship applies only for equilibrium states, in which $p$ and $T$ are uniform throughout the system. The ideal-gas equation of state, Eq. (18.3), involves the number of moles $n$ and a constant $R$ that is the same for all gases. (See Examples 18.1–18.4.)

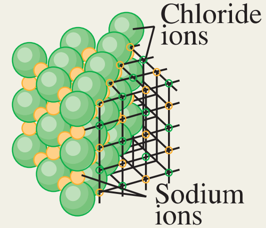
$$pV = nRT \quad (18.3)$$




**Molecular properties of matter:** The molar mass $M$ of a pure substance is the mass per mole. The mass $m_{\text{total}}$ of a quantity of substance equals $M$ multiplied by the number of moles $n$. Avogadro's number $N_A$ is the number of molecules in a mole. The mass $m$ of an individual molecule is $M$ divided by $N_A$. (See Example 18.5.)

$$m_{\text{total}} = nM \quad (18.2)$$

$$M = N_A m \quad (18.8)$$



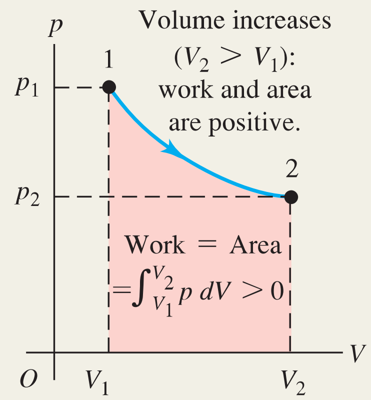
**Heat and work in thermodynamic processes:** A thermodynamic system has the potential to exchange energy with its surroundings by heat transfer or by mechanical work. When a system at pressure $p$ changes volume from $V_1$ to $V_2$, it does an amount of work $W$ given by the integral of $p$ with respect to volume. If the pressure is constant, the work done is equal to $p$ times the change in volume. A negative value of $W$ means that work is done on the system. (See Example 19.1.)

In any thermodynamic process, the heat added to the system and the work done by the system depend not only on the initial and final states, but also on the path (the series of intermediate states through which the system passes).

$$W = \int_{V_1}^{V_2} p\, dV \tag{19.2}$$

$$W = p(V_2 - V_1) \tag{19.3}$$

(constant pressure only)



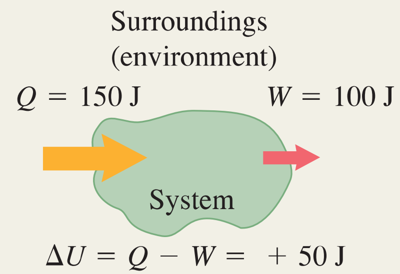

**The first law of thermodynamics:** The first law of thermodynamics states that when heat $Q$ is added to a system while the system does work $W$, the internal energy $U$ changes by an amount equal to $Q - W$. This law can also be expressed for an infinitesimal process. (See Examples 19.2, 19.3, and 19.5.)

The internal energy of any thermodynamic system depends only on its state. The change in internal energy in any process depends only on the initial and final states, not on the path. The internal energy of an isolated system is constant. (See Example 19.4.)

$$\Delta U = Q - W \tag{19.4}$$

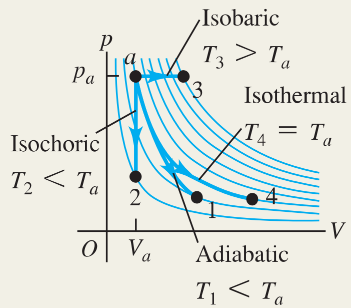
$$dU = dQ - dW \tag{19.6}$$

(infinitesimal process)



**Important kinds of thermodynamic processes:**

- Adiabatic process: No heat transfer into or out of a system; $Q = 0$.
- Isochoric process: Constant volume; $W = 0$.
- Isobaric process: Constant pressure; $W = p(V_2 - V_1)$.
- Isothermal process: Constant temperature.
- Free expansion

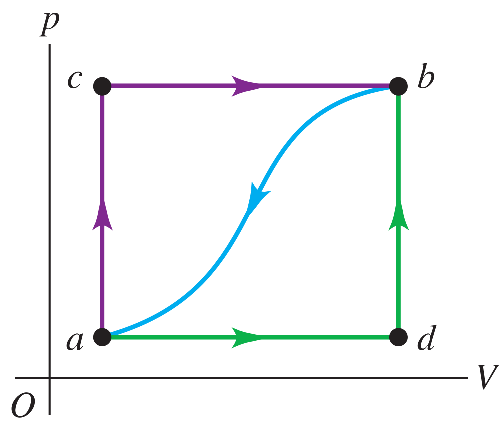


**19.1** •• Two moles of an ideal gas are heated at constant pressure from $T = 27°C$ to $T = 107°C$. (a) Draw a $pV$-diagram for this process. (b) Calculate the work done by the gas.

**19.3** •• **CALC** Two moles of an ideal gas are compressed in a cylinder at a constant temperature of 65.0°C until the original pressure has tripled. (a) Sketch a $pV$-diagram for this process. (b) Calculate the amount of work done.

**19.41** •• When a system is taken from state $a$ to state $b$ in Fig. P19.41 along the path $acb$, 90.0 J of heat flows into the system and 60.0 J of work is done by the system. (a) How much heat flows into the system along path $adb$ if the work done by the system is 15.0 J? (b) When the system is returned from $b$ to $a$ along the curved path, the absolute value of the work done by the system is 35.0 J. Does the system absorb or liberate heat? How much heat? (c) If $U_a = 0$ and $U_d = 8.0$ J, find the heat absorbed in the processes $ad$ and $db$.

Figure **P19.41**

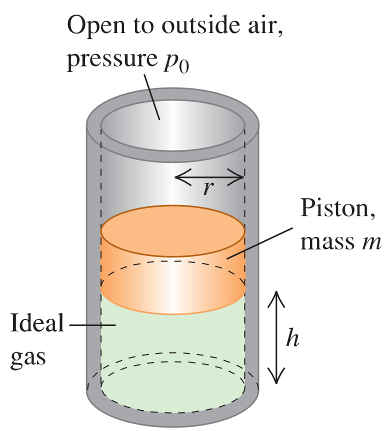


**19.57** • BIO **A Thermodynamic Process in an Insect.** The African bombardier beetle (*Stenaptinus insignis*) can emit a jet of defensive spray from the movable tip of its abdomen (Fig. P19.57). The beetle's body has reservoirs of two different chemicals; when the beetle is disturbed, these chemicals are combined in a reaction chamber, producing a compound that is warmed from 20°C to 100°C by the heat of reaction. The high pressure produced allows the compound to be sprayed out at speeds up to 19 m/s (68 km/h), scaring away predators of all kinds. (The beetle shown in the figure is 2 cm long.) Calculate the heat of reaction of the two chemicals (in J/kg). Assume that the specific heat of the two chemicals and the spray is the same as that of water, $4.19 \times 10^3$ J/kg · K, and that the initial temperature of the chemicals is 20°C.

Figure **P19.57**

**19.69 ••• CP Oscillations of a Piston.** A vertical cylinder of radius $r$ contains a quantity of ideal gas and is fitted with a piston with mass $m$ that is free to move (Fig. P19.69). The piston and the walls of the cylinder are frictionless, and the entire cylinder is placed in a constant-temperature bath. The outside air pressure is $p_0$. In equilibrium, the piston sits at a height $h$ above the bottom of the cylinder. (a) Find the absolute pressure of the gas trapped below the piston when in equilibrium. (b) The piston is pulled up by a small distance and released. Find the net force acting on the piston when its base is a distance $h + y$ above the bottom of the cylinder, where $y$ is much less than $h$. (c) After the piston is displaced from equilibrium and released, it oscillates up and down. Find the frequency of these small oscillations. If the displacement is not small, are the oscillations simple harmonic? How can you tell?

Figure **P19.69**



1. A pipe of length $L = 25.0$m that is open at one end contains air at atmospheric pressure. It is thrust vertically into a freshwater lake until the water rises halfway up in the pipe, as shown in Fig. 1. What is the depth $h$ of the lower end of the pipe? Assume that the temperature is the same everywhere and does not change.

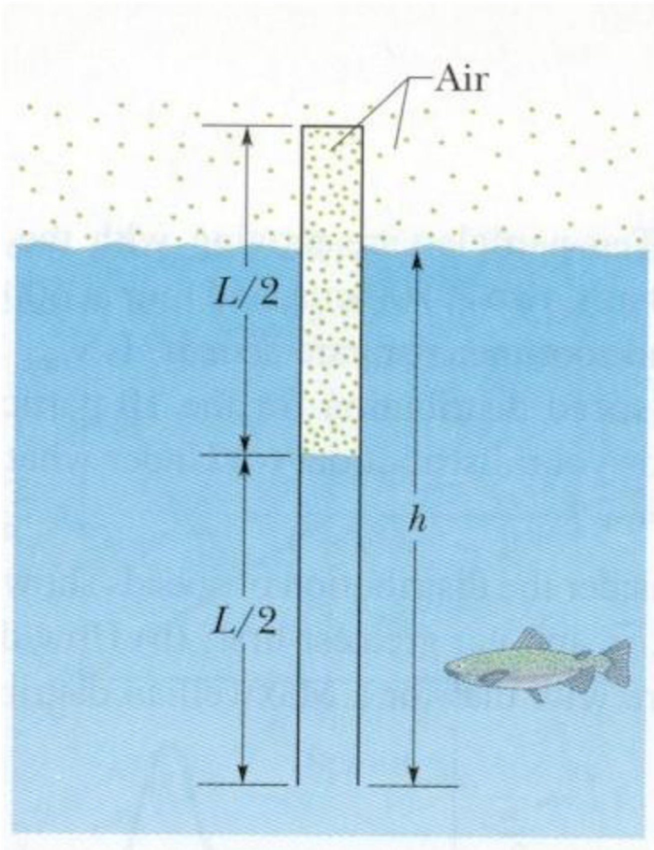



Fig. 1

2. Container A in Fig. 2 holds an ideal gas at a pressure of 5.0 x $10^5$ Pa and a temperature of 300 K. It is connected by a thin tube to container B with four times the volume of A. Container B holds the same ideal gas at a pressure of 1.0 x $10^5$ Pa and a temperature of 500 K. The connecting valve is opened, and equilibrium is achieved at a common pressure while the temperature of each container is kept constant at its initial value. What is the final pressure in the system?

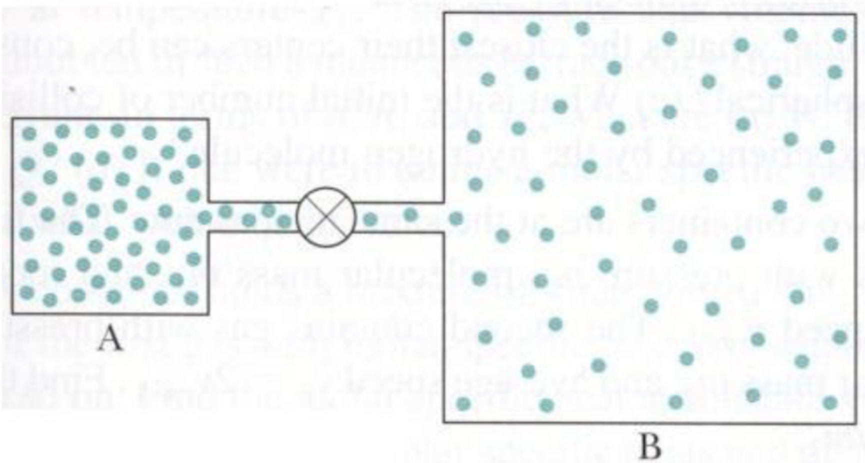



Fig. 2

6. A uniform U-shaped glass tube (Fig. 5) with a closed end on the left and an open end on the right, connected to air with the atmospheric pressure $P_0$. It is filled with mercury and the difference of mercury level between the two sides is $h$. The length of the air column on the left hand side is $L$. If we let the U-shaped glass tube fall freely vertically, what is the difference of mercury level between the two sides?

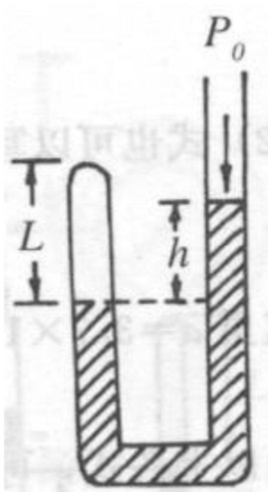



Fig. 5