PHYS1001B College Physics IB

Thermodynamics I — Temperature and Heat (Ch. 17)

Introduction

? At a steelworks, molten iron is heated to 1500° Celsius to remove impurities. Is it accurate to say that the molten iron contains heat?

Introduction

The terms “temperature” and “heat” are often used interchangeably in everyday language. In physics, however, these two terms have very different meanings. In this chapter we’ll define temperature in terms of how it’s measured and see how temperature changes affect the dimensions of objects. We’ll see that heat refers to energy transfer caused by temperature differences and learn how to calculate and control such energy transfers.

Outline

- 17-1 Temperature and Thermal Equilibrium
- 17-2 Thermometers and Temperature Scales
- 17-3 Gas Thermometers and the Kelvin Scale
- 17-4 Thermal Expansion
- 17-5 Quantity of Heat
- 17-6 Calorimetry and Phase Changes
- 17-7 Mechanisms of Heat Transfer

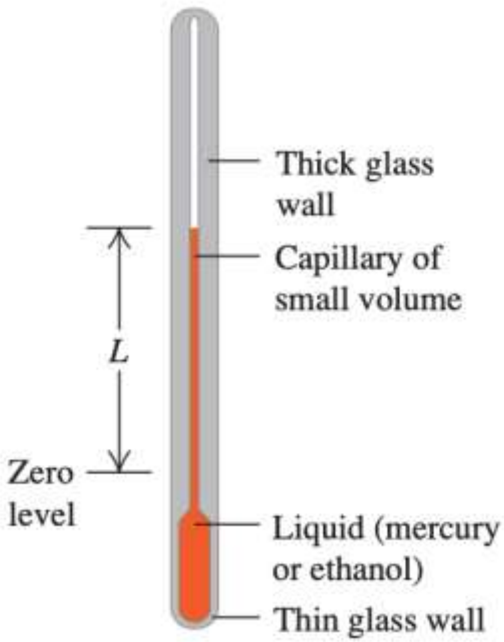
17-1 Temperature and Thermal Equilibrium

The concept of **temperature** is rooted in qualitative ideas of "hot" and "cold" based on our sense of touch. A body that feels hot usually has a higher temperature than a similar body that feels cold.

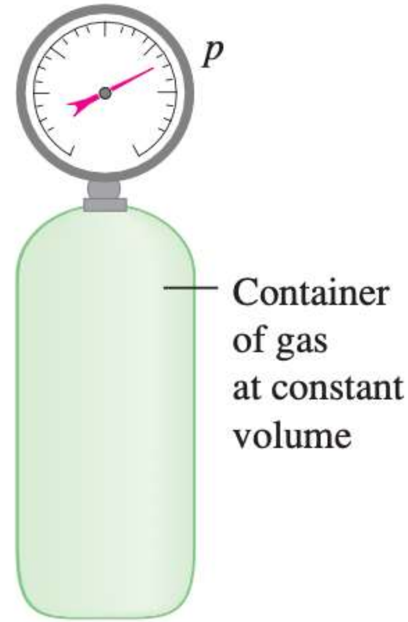
To use temperature as a measure of hotness or coldness, we need to construct a temperature scale. To do this, we can use any measurable property of a system that varies with its "hotness" or "coldness."

17-1 Temperature and Thermal Equilibrium

(a) Changes in temperature cause the liquid's volume to change.



(b) Changes in temperature cause the pressure of the gas to change.

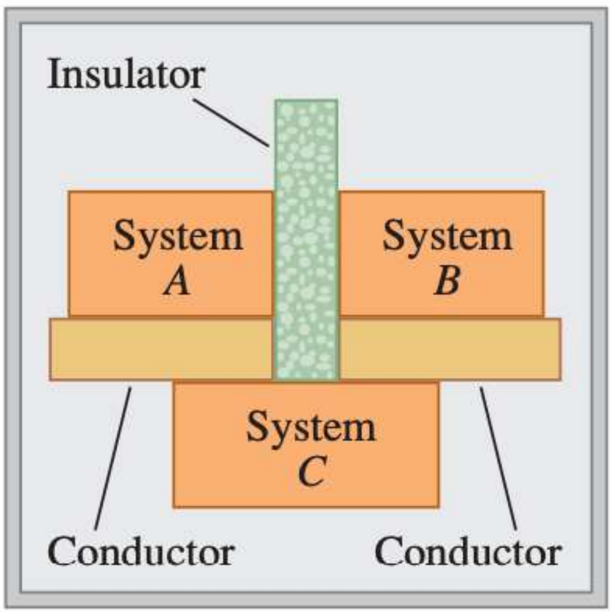


Each of these properties gives us a number (L, p, or R) that varies with hotness and coldness, so each property can be used to make a **thermometer**.

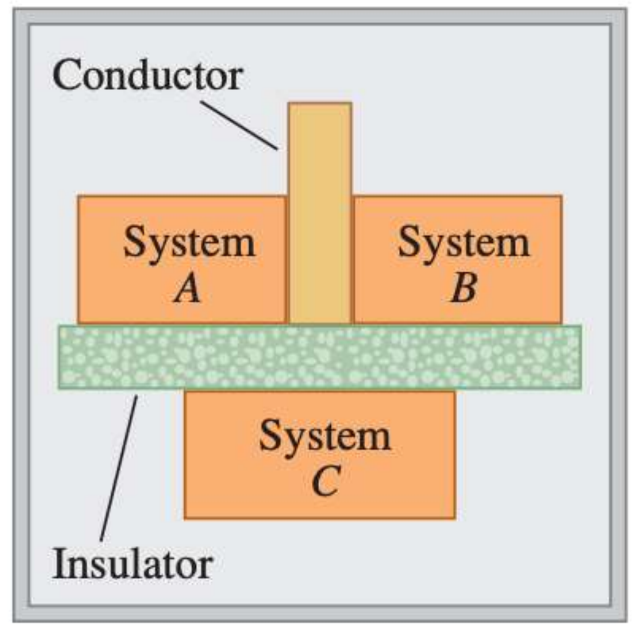
17-1 Temperature and Thermal Equilibrium

The zeroth law of thermodynamics.

(a) If systems A and B are each in thermal equilibrium with system C …

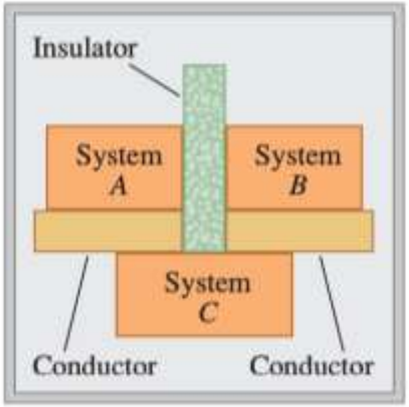


(b) … then systems A and B are in thermal equilibrium with each other.



17-1 Temperature and Thermal Equilibrium

The zeroth law of thermodynamics.

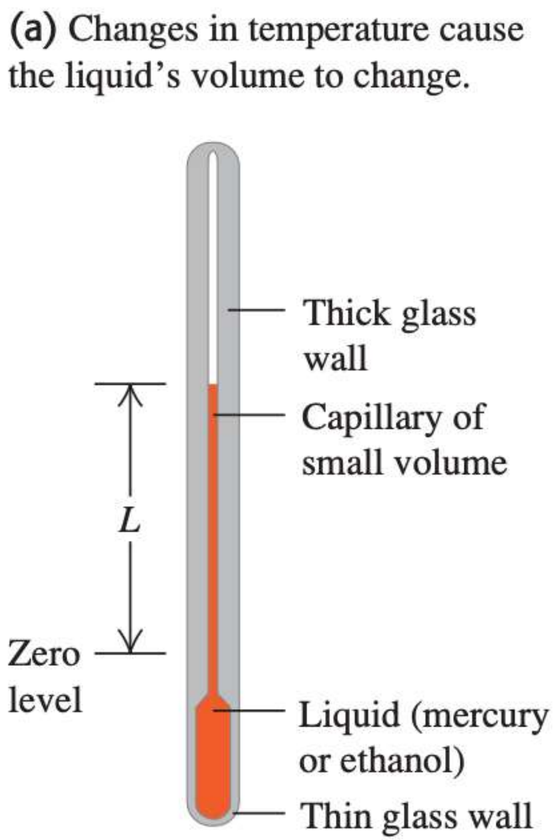


If *C* is initially in thermal equilibrium with both *A* and *B*, then *A* and *B* are also in thermal equilibrium with each other. This result is called the zeroth law of thermodynamics.

Two systems are in thermal equilibrium if and only if they have the same temperature.

This is what makes a thermometer useful; a thermometer actually measures *its own* temperature, but when a thermometer is in thermal equilibrium with another body, the temperatures must be equal. When the temperatures of two systems are different, they *cannot* be in thermal equilibrium.

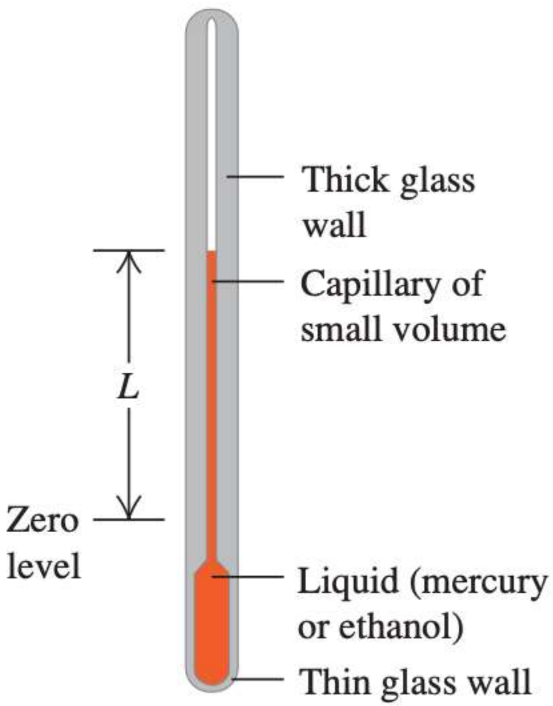
17-2 Thermometers and Temperature Scales



Suppose we label the thermometer's liquid level at the freezing temperature of pure water "zero" and the level at the boiling temperature "100," and divide the distance between these two points into 100 equal intervals called *degrees*. The result is the **Celsius temperature scale** (formerly called the *centigrade* scale in English- speaking countries). The Celsius temperature for a state colder than freezing water is a negative number.

17-2 Thermometers and Temperature Scales

(a) Changes in temperature cause the liquid's volume to change.



In the **Fahrenheit temperature scale,** still used in everyday life in the United States, the freezing temperature of water is 32°F (thirty-two degrees Fahrenheit) and the boiling temperature is 212°F, both at standard atmospheric pressure.

There are 180 degrees between freezing and boiling, compared to 100 on the Celsius scale.

17-2 Thermometers and Temperature Scales

Conversion between temperature scales

Fahrenheit temperature scale

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

Celsius temperature scale

$$T_C = \tfrac{5}{9} (T_F - 32^\circ)$$

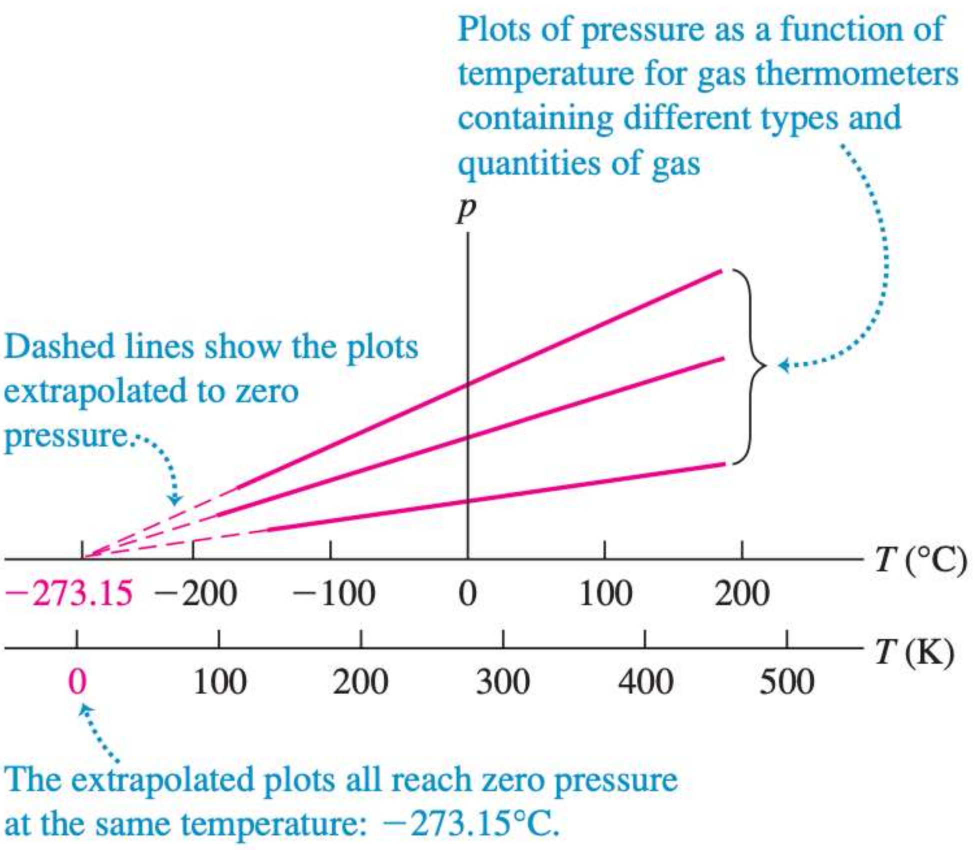
17-2 Thermometers and Temperature Scales

Most mammals maintain body temperatures in the range from 36°C to 40°C (309 K to 313 K). A high metabolic rate warms the animal from within, and insulation (such as fur, feathers, and body fat) slows heat loss.

17-3 Gas Thermometers and the Kelvin Scale

(a) A constant-volume gas thermometer

(b) Graphs of pressure versus temperature at constant volume for three different types and quantities of gas

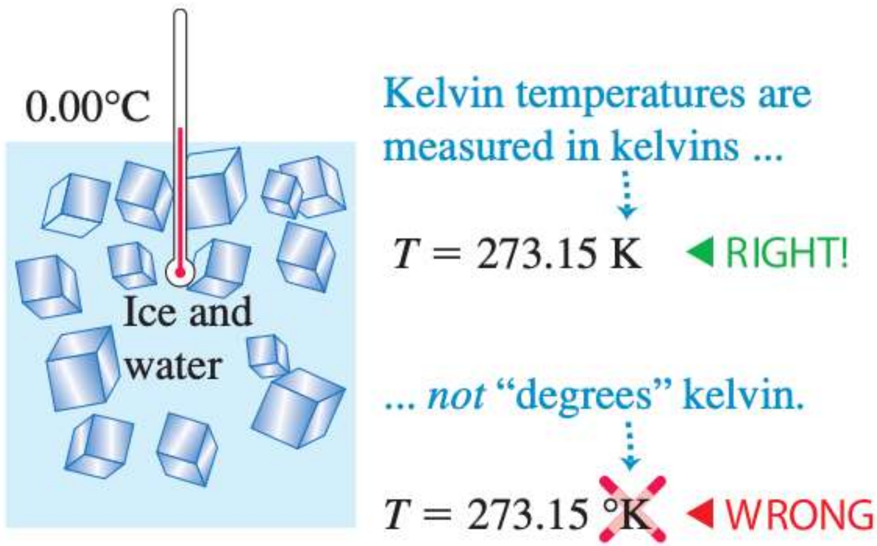


17-3 Gas Thermometers and the Kelvin Scale

We use this extrapolated zero-pressure temperature as the basis for a temperature scale with its zero at this temperature. This is the **Kelvin temperature scale,** named for the British physicist Lord Kelvin (1824–1907). The units are the same size as those on the Celsius scale, but the zero is shifted so that 0 K = - 273.15°C and 273.15 K = 0°C

$$T_K = T_C + 273.15$$

17-3 Gas Thermometers and the Kelvin Scale

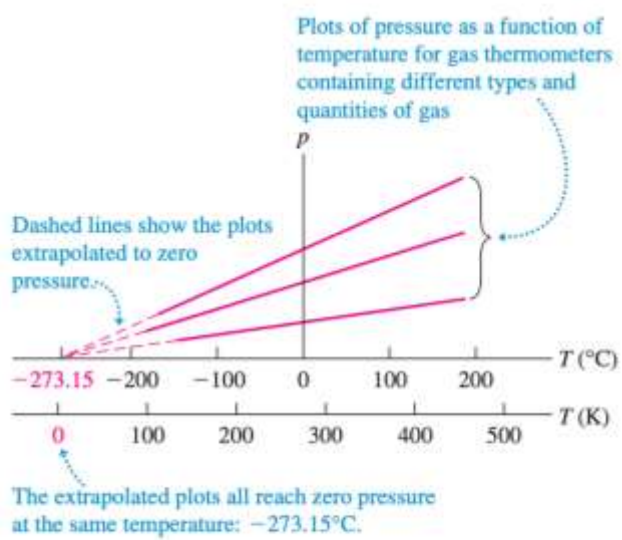


CAUTION **Never say "degrees kelvin"** In SI nomenclature, "degree" is not used with the Kelvin scale; the temperature mentioned above is read "293 kelvins," not "degrees kelvin" (Fig. 17.6). We capitalize Kelvin when it refers to the temperature scale; however, the *unit* of temperature is the *kelvin,* which is not capitalized (but is nonetheless abbreviated as a capital K).

17-3 Gas Thermometers and the Kelvin Scale

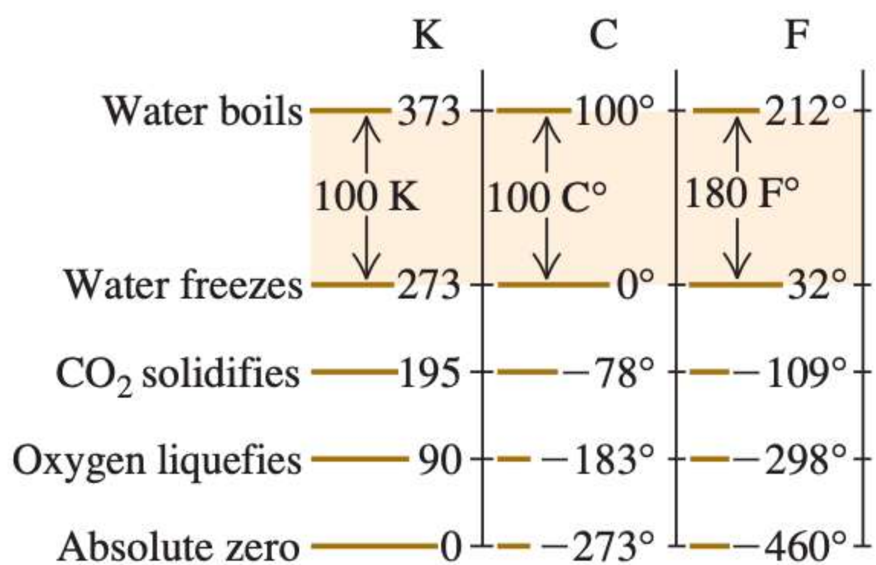
The Celsius scale has two fixed points: the normal freezing and boiling temperatures of water. But we can define the Kelvin scale using a gas thermometer with only a single reference temperature. We define the ratio of any two temperatures T_1 and T_2 on the Kelvin scale as the ratio of the corresponding gas-thermometer pressures p_1 and p_2:

$$\frac{T_2}{T_1} = \frac{p_2}{p_1} \qquad \text{(constant-volume gas thermometer, } T \text{ in kelvins)}$$



17-3 Gas Thermometers and the Kelvin Scale

The Kelvin scale is called an **absolute temperature scale,** and its zero point (T = 0 K = -273.15°C) is called **absolute zero.** At absolute zero a system of molecules (such as a quantity of a gas, a liquid, or a solid) has its *minimum* possible total energy (kinetic plus potential); because of quantum effects, however, it is *not* correct to say that all molecular motion ceases at absolute zero.



17.7 Relationships among Kelvin (K), Celsius (C), and Fahrenheit (F) temperature scales. Temperatures have been rounded off to the nearest degree.

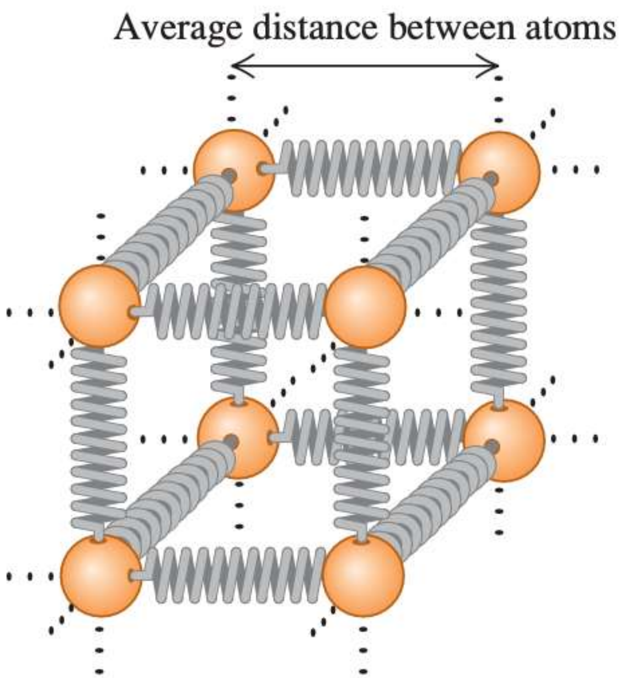
17-4 Thermal Expansion

17.13 Expansion joints on bridges are needed to accommodate changes in length that result from thermal expansion.

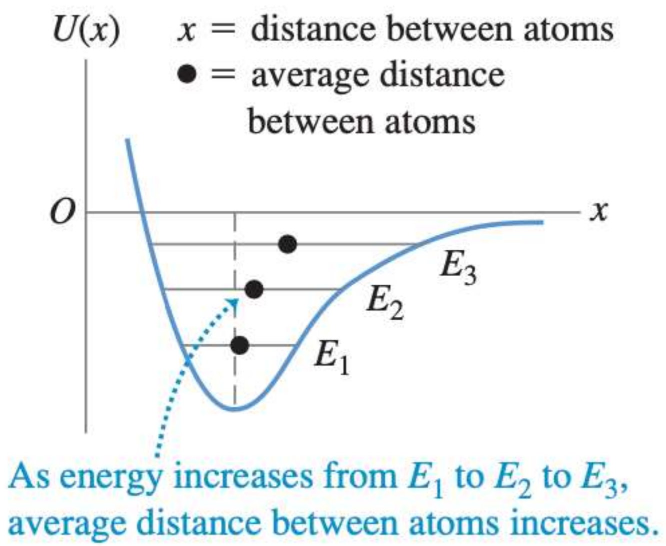
17-4 Thermal Expansion

Most materials expand when their temperatures increase

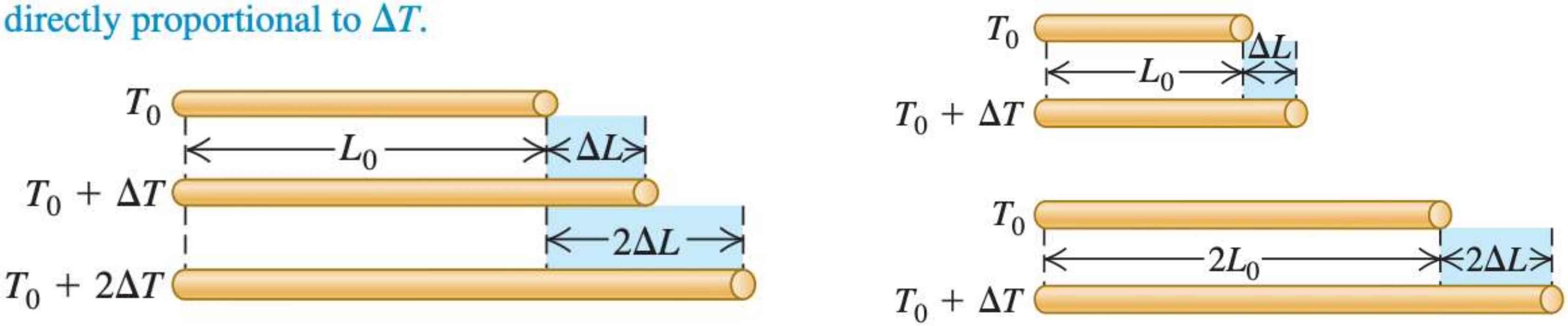
(a) A model of the forces between neighboring atoms in a solid



(b) A graph of the "spring" potential energy $U(x)$



17-4 Thermal Expansion



(a) For moderate temperature changes, ΔL is directly proportional to ΔT.

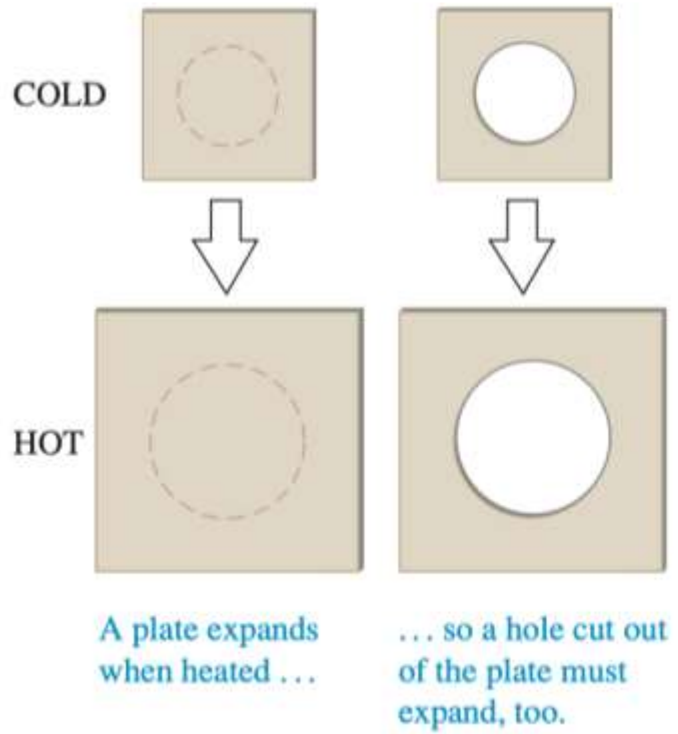
(b) ΔL is also directly proportional to L_0.

$$\Delta L = \alpha L_0 \Delta T \qquad \text{(linear thermal expansion)}$$

$$L = L_0 + \Delta L = L_0 + \alpha L_0 \Delta T = L_0(1 + \alpha \Delta T) \tag{17.7}$$

The constant α, which describes the thermal expansion properties of a particular material, is called the **coefficient of linear expansion.** The units of α are K^{-1} or

17-4 Thermal Expansion



$$\Delta V = \beta V_0 \, \Delta T \qquad \text{(volume thermal expansion)} \qquad (17.8)$$

The constant β characterizes the volume expansion properties of a particular material; it is called the **coefficient of volume expansion.** The units of β are K^{-1}

17-4 Thermal Expansion

Table 17.1 Coefficients of Linear Expansion

Material	α [K^{-1} or $(C°)^{-1}$]
Aluminum	2.4×10^{-5}
Brass	2.0×10^{-5}
Copper	1.7×10^{-5}
Glass	$0.4\text{–}0.9 \times 10^{-5}$
Invar (nickel–iron alloy)	0.09×10^{-5}
Quartz (fused)	0.04×10^{-5}
Steel	1.2×10^{-5}

Table 17.2 Coefficients of Volume Expansion

Solids	β [K^{-1} or $(C°)^{-1}$]	Liquids	β [K^{-1} or $(C°)^{-1}$]
Aluminum	7.2×10^{-5}	Ethanol	75×10^{-5}
Brass	6.0×10^{-5}	Carbon disulfide	115×10^{-5}
Copper	5.1×10^{-5}	Glycerin	49×10^{-5}
Glass	$1.2\text{–}2.7 \times 10^{-5}$	Mercury	18×10^{-5}
Invar	0.27×10^{-5}		
Quartz (fused)	0.12×10^{-5}		
Steel	3.6×10^{-5}		

Why beta 3 times alpha?

17-4 Thermal Expansion

Why beta 3 times alpha?

consider a cube of material with side length L and volume $V = L^3$

$$dV = \frac{dV}{dL}\,dL = 3L^2\,dL$$

Now we replace L and V by the initial values L_0 and V_0. From Eq. (17.6), dL is

$$dL = \alpha L_0\,dT$$

Since $V_0 = L_0^3$, this means that dV can also be expressed as

$$dV = 3L_0^2\alpha L_0\,dT = 3\alpha V_0\,dT$$

This is consistent with the infinitesimal form of Eq. (17.8), $dV = \beta V_0\,dT$, only if

$$\beta = 3\alpha \qquad (17.9)$$

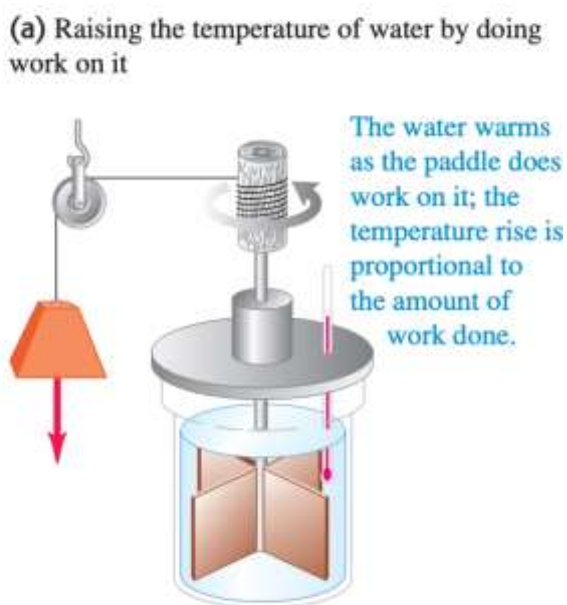
17-5 Quantity of Heat

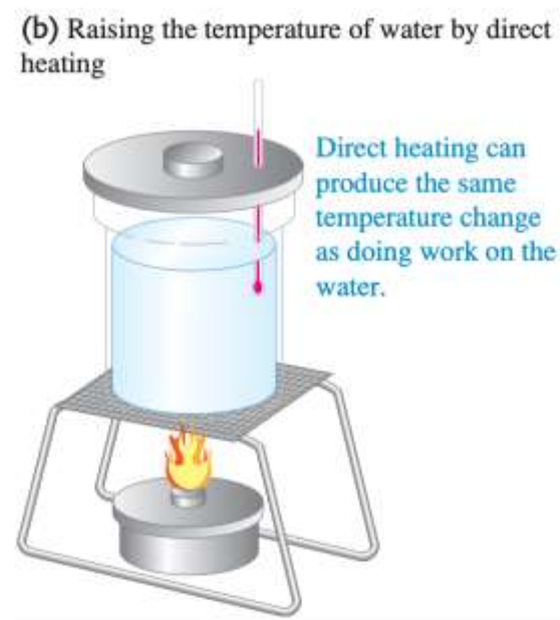
- Energy transfer that takes place solely because of a temperature difference is called *heat flow* or *heat transfer,* and energy transferred in this way is called **heat.**
- We can define a *unit* of quantity of heat based on temperature changes of some specific material. The **calorie** (abbreviated cal) is defined as *the amount of heat required to raise the temperature of 1 gram of water from 14.5 ℃ to 15.5 ℃.*

$$1 \text{ cal} = 4.186 \text{ J}$$
$$1 \text{ kcal} = 1000 \text{ cal} = 4186 \text{ J}$$

17-5 Quantity of Heat

- An understanding of the relationship between heat and other forms of energy emerged during the 18th and 19th centuries. Sir James Joule (1818–1889) studied how water can be warmed by vigorous stirring with a paddle wheel
- The paddle wheel adds energy to the water by doing *work* on it, and Joule found that *the temperature rise is directly proportional to the amount of work done.*





17-5 Quantity of Heat

We use the symbol Q for quantity of heat. When it is associated with an infinitesimal temperature change dT, we call it dQ.

$$Q = mc\,\Delta T \quad \text{(heat required for temperature change } \Delta T \text{ of mass } m) \tag{17.13}$$

where c is a quantity, different for different materials, called the **specific heat** of the material. For an infinitesimal temperature change dT and corresponding quantity of heat dQ,

$$dQ = mc\,dT \tag{17.14}$$

$$c = \frac{1}{m}\frac{dQ}{dT} \quad \text{(specific heat)} \tag{17.15}$$

Sample Problem

Example 17.5 **Feed a cold, starve a fever**

During a bout with the flu an 80-kg man ran a fever of 39.0°C (102.2°F) instead of the normal body temperature of 37.0°C (98.6°F). Assuming that the human body is mostly water, how much heat is required to raise his temperature by that amount?

IDENTIFY and SET UP: This problem uses the relationship among heat (the target variable), mass, specific heat, and temperature change. We use Eq. (17.13) to determine the required heat Q, with $m = 80$ kg, $c = 4190$ J/kg·K (for water), and $\Delta T = 39.0°\text{C} - 37.0°\text{C} = 2.0\ \text{C}° = 2.0$ K.

EXECUTE: From Eq. (17.13),

$$Q = mc\,\Delta T = (80\ \text{kg})(4190\ \text{J/kg}\cdot\text{K})(2.0\ \text{K}) = 6.7 \times 10^5\ \text{J}$$

Sample Problem

Example 17.6 Overheating electronics

You are designing an electronic circuit element made of 23 mg of silicon. The electric current through it adds energy at the rate of 7.4 mW $= 7.4 \times 10^{-3}$ J/s. If your design doesn't allow any heat transfer out of the element, at what rate does its temperature increase? The specific heat of silicon is 705 J/kg·K.

$$dQ = mc\,dT$$

IDENTIFY and SET UP: The energy added to the circuit element gives rise to a temperature increase, just as if heat were flowing into the element at the rate $dQ/dt = 7.4 \times 10^{-3}$ J/s. Our target variable is the rate of temperature change dT/dt. We can use Eq. (17.14),

which relates infinitesimal temperature changes dT to the corresponding heat dQ, to obtain an expression for dQ/dt in terms of dT/dt.

EXECUTE: We divide both sides of Eq. (17.14) by dt and rearrange:

$$\frac{dT}{dt} = \frac{dQ/dt}{mc} = \frac{7.4 \times 10^{-3}\ \text{J/s}}{(23 \times 10^{-6}\ \text{kg})(705\ \text{J/kg}\cdot\text{K})} = 0.46\ \text{K/s}$$

17-5 Quantity of Heat

Molar heat capacity

The *molar mass* of any substance, denoted by M, is the mass per mole.

$$m = nM$$

$$Q = nMc\,\Delta T$$

$$Q = nC\,\Delta T \qquad \text{(heat required for temperature change of } n \text{ moles)}$$

$$C = \frac{1}{n}\frac{dQ}{dT} = Mc \qquad \text{(molar heat capacity)}$$ In term of specific heat

For example, the molar heat capacity of water is

$$C = Mc = (0.0180\ \text{kg/mol})(4190\ \text{J/kg}\cdot\text{K}) = 75.4\ \text{J/mol}\cdot\text{K}$$

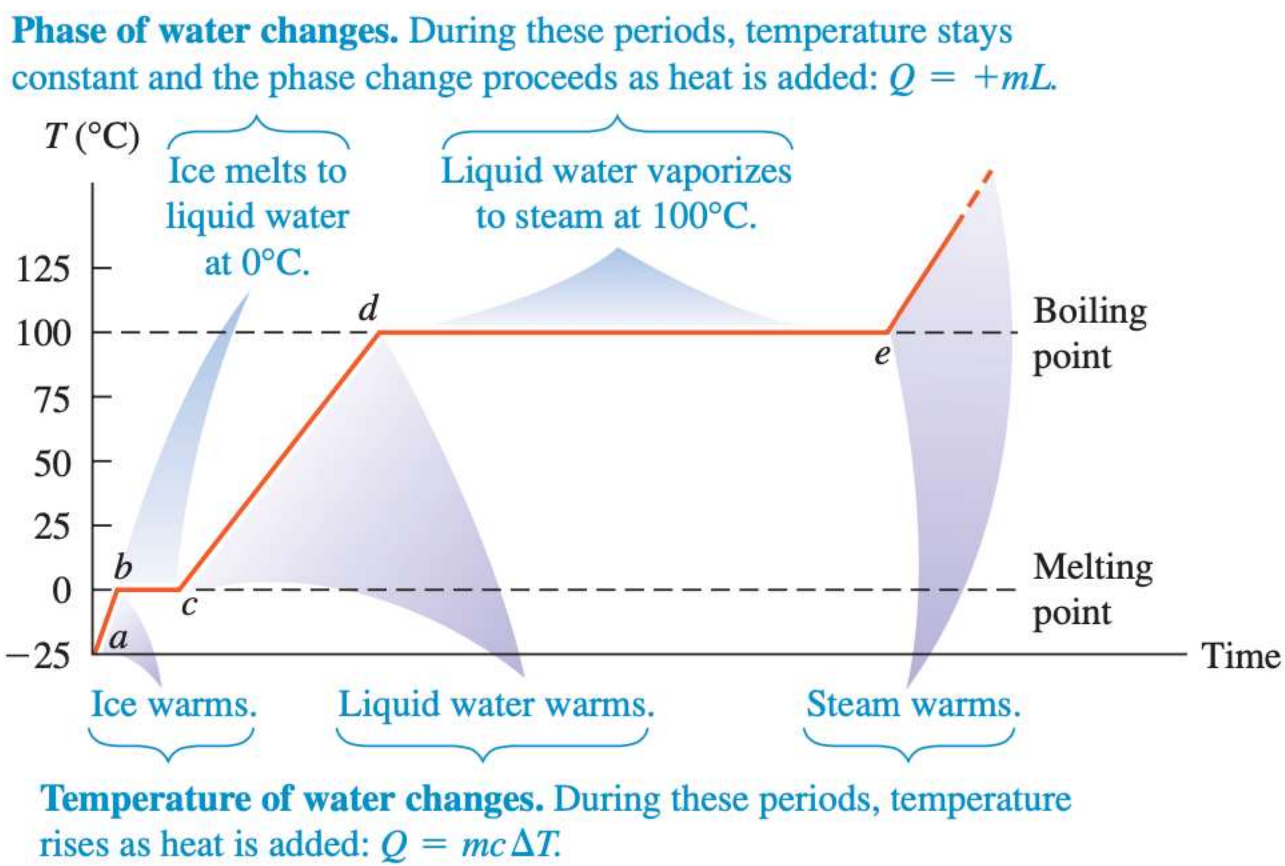
17-6 Calorimetry and Phase Changes

Calorimetry means "measuring heat."

The surrounding air is at room temperature, but this ice–water mixture remains at 0°C until all of the ice has melted and the phase change is complete.

Heat is also involved in *phase changes,* such as the melting of ice or boiling of water.

17-6 Calorimetry and Phase Changes



17-6 Calorimetry and Phase Changes

heat of fusion (or *latent heat of fusion*)

To melt a mass m of material that has a heat of fusion L requires a quantity of heat Q given by

$$Q = \pm mL \qquad \text{(heat transfer in a phase change)} \tag{17.20}$$

The plus sign (heat entering) is used when the material melts; the minus sign (heat leaving) is used when it freezes. The heat of fusion is different for different materials, and it also varies somewhat with pressure.

17-6 Calorimetry and Phase Changes

Table 17.4 **Heats of Fusion and Vaporization**

Substance	Normal Melting Point K	Normal Melting Point °C	Heat of Fusion, L_f (J/kg)	Normal Boiling Point K	Normal Boiling Point °C	Heat of Vaporization, L_v (J/kg)
Helium	*	*	*	4.216	−268.93	20.9×10^3
Hydrogen	13.84	−259.31	58.6×10^3	20.26	−252.89	452×10^3
Nitrogen	63.18	−209.97	25.5×10^3	77.34	−195.8	201×10^3
Oxygen	54.36	−218.79	13.8×10^3	90.18	−183.0	213×10^3
Ethanol	159	−114	104.2×10^3	351	78	854×10^3
Mercury	234	−39	11.8×10^3	630	357	272×10^3
Water	273.15	0.00	334×10^3	373.15	100.00	2256×10^3
Sulfur	392	119	38.1×10^3	717.75	444.60	326×10^3
Lead	600.5	327.3	24.5×10^3	2023	1750	871×10^3
Antimony	903.65	630.50	165×10^3	1713	1440	561×10^3
Silver	1233.95	960.80	88.3×10^3	2466	2193	2336×10^3
Gold	1336.15	1063.00	64.5×10^3	2933	2660	1578×10^3
Copper	1356	1083	134×10^3	1460	1187	5069×10^3

Sample Problem

Example 17.8 **Changes in both temperature and pha**

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.

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 $L_f = 3.34 \times 10^5\ J/kg$.

Sample Problem

Example 17.8 **Changes in both temperature and pha**

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.

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:

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

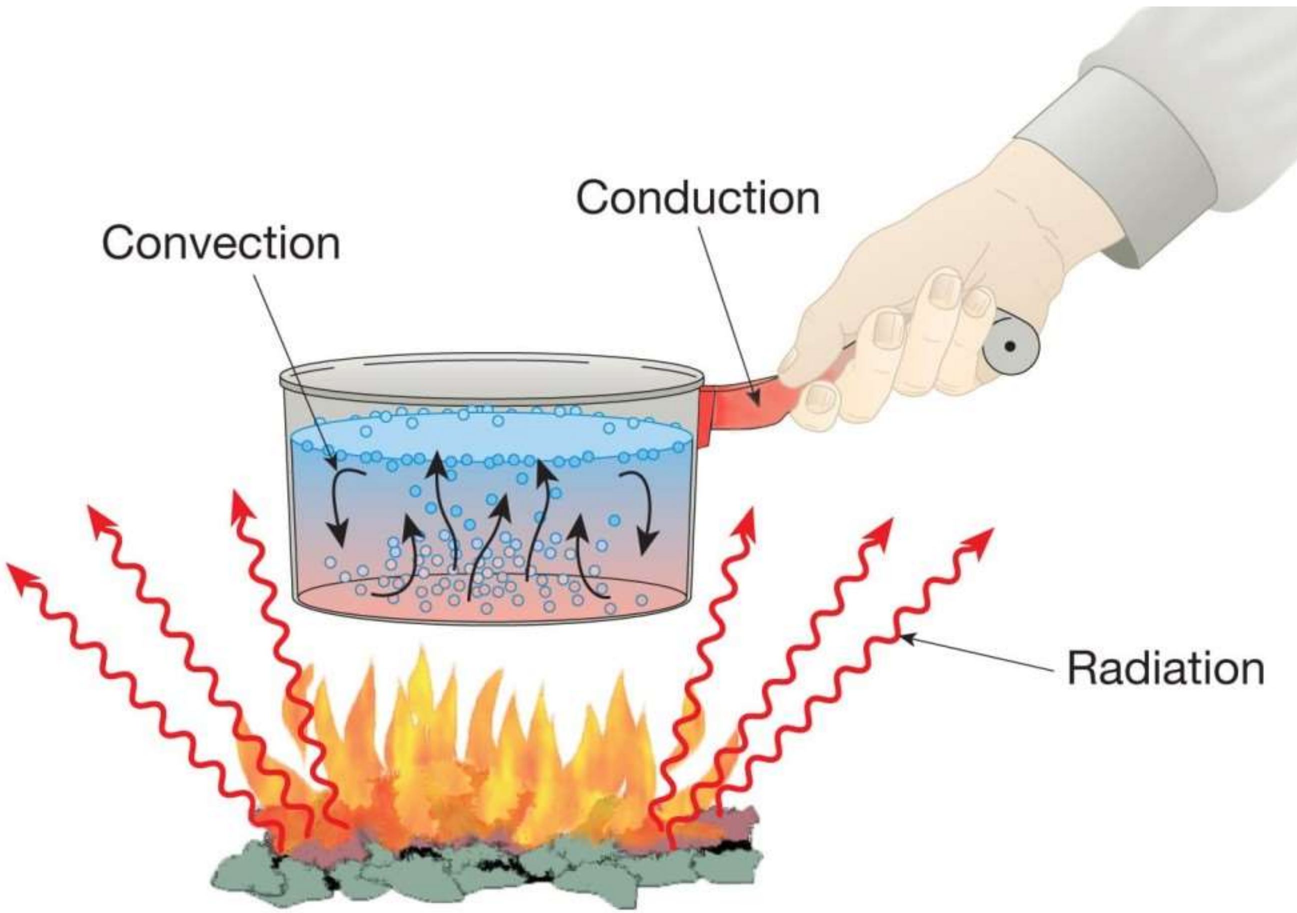
$$m_C c_W (T - T_{0C}) + m_I c_I (T - T_{0I}) + m_I L_f = 0$$

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

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

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

17-7 Mechanisms of Heat Transfer



17-7 Mechanisms of Heat Transfer

- The three mechanisms of heat transfer are conduction, convection, and radiation.

- *Conduction* occurs within a body or between two bodies in contact.

- *Convection* depends on motion of mass from one region of space to another.

- *Radiation* is heat transfer by electromagnetic radiation, such as sunshine, with no need for matter to be present in the space between bodies.

17-7 Mechanisms of Heat Transfer

When a quantity of heat dQ is transferred through the rod in a time dt, the rate of heat flow is dQ/dt. We call this rate the **heat current,** denoted by H

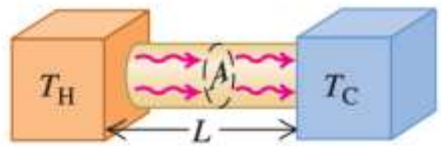
Introducing a proportionality constant k called the **thermal conductivity** of the material, we have

$$H = \frac{dQ}{dt} = kA\frac{T_H - T_C}{L} \qquad \text{(heat current in conduction)}$$

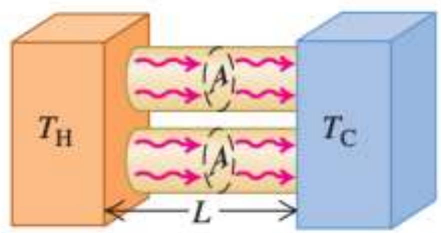
The units of heat current H are units of energy per time, or power; the SI unit of heat current is the watt (1W = 1 J/s). SI units of k are W/m K.

17-7 Mechanisms of Heat Transfer

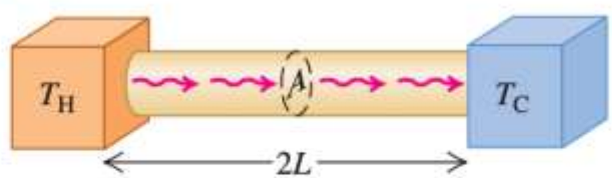
(a) Heat current H



(b) Doubling the cross-sectional area of the conductor doubles the heat current (H is proportional to A).



(c) Doubling the length of the conductor halves the heat current (H is inversely proportional to L).



17-7 Mechanisms of Heat Transfer

For thermal insulation in buildings, engineers use the concept of **thermal resistance,** denoted by R. The thermal resistance R of a slab of material with area A is defined so that the heat current H through the slab is

$$H = \frac{A(T_H - T_C)}{R} \tag{17.23}$$

where T_H and T_C are the temperatures on the two sides of the slab. Comparing this with Eq. (17.21), we see that R is given by

$$R = \frac{L}{k} \tag{17.24}$$

17-7 Mechanisms of Heat Transfer

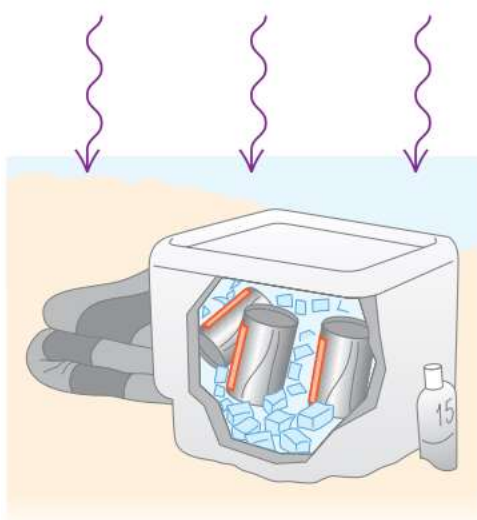
Application **Fur Versus Blubber**
The fur of an arctic fox is a good thermal insulator because it traps air, which has a low thermal conductivity k. (The value $k = 0.04\ \mathrm{W/m \cdot K}$ for fur is higher than for air, $k = 0.024\ \mathrm{W/m \cdot K}$, because fur also includes solid hairs.) The layer of fat beneath a bowhead whale's skin, called blubber, has six times the thermal conductivity of fur ($k = 0.24\ \mathrm{W/m \cdot K}$). So a 6-cm thickness of blubber ($L = 6$ cm) is required to give the same insulation as 1 cm of fur.

Sample Problem

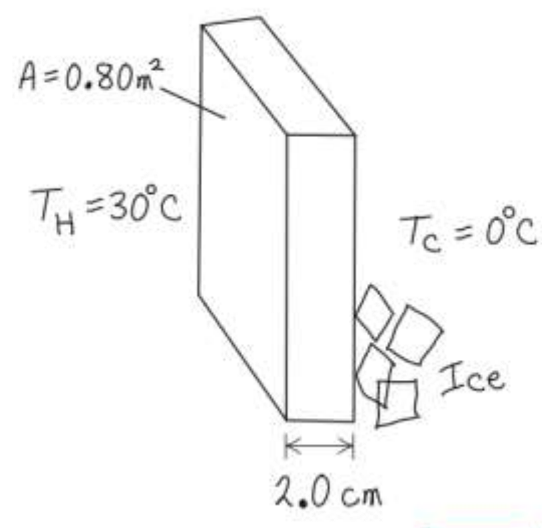
Example 17.11 **Conduction into a picnic cooler**

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?

(a) A cooler at the beach



(b) Our sketch for this problem



Sample Problem

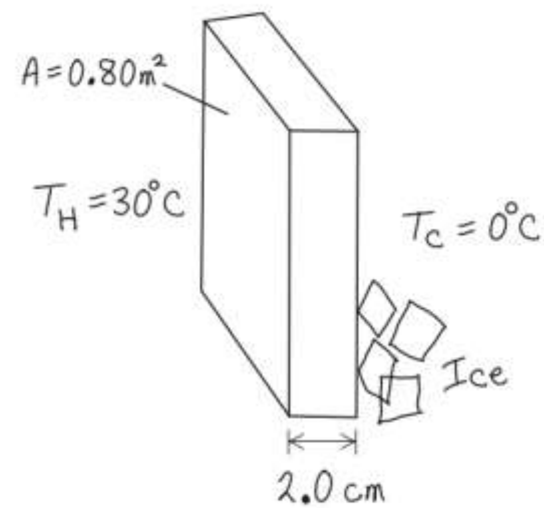
EXECUTE: We assume that the total heat flow is the same as it would be through a flat Styrofoam slab of area 0.80 m^2 and thickness 2.0 cm = 0.020 m (Fig. 17.24b). We find k from Table 17.5. From Eq. (17.21),

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

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

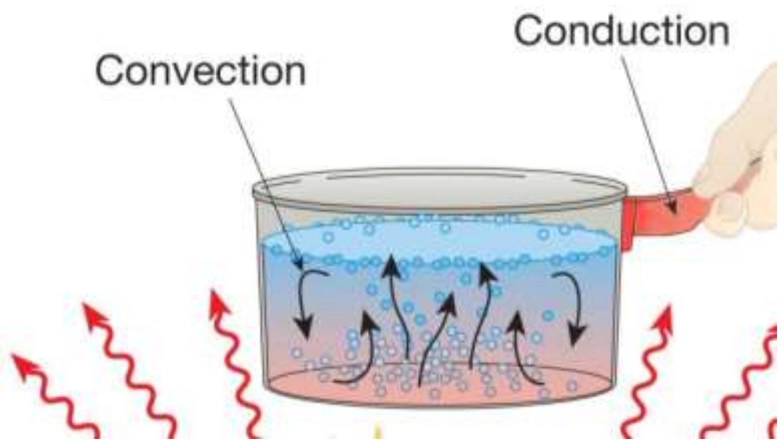
$$m = \frac{Q}{L_f} = \frac{(32.4\ \mathrm{J/s})(10{,}800\ \mathrm{s})}{3.34 \times 10^5\ \mathrm{J/kg}} = 1.0\ \mathrm{kg}$$

(b) Our sketch for this problem



17-7 Mechanisms of Heat Transfer

- **Convection** is the transfer of heat by mass motion of a fluid from one region of space to another.
- If the fluid is circulated by a blower or pump, the process is called *forced convection;*
- If the flow is caused by differences in density due to thermal expansion, such as hot air rising, the process is called *natural convection* or *free convection*



17-7 Mechanisms of Heat Transfer

Radiation is the transfer of heat by electromagnetic waves such as visible light, infrared, and ultraviolet radiation.

This heat transfer would occur even if there were nothing but vacuum between you and the source of heat.

Source: Wikipedia

17-7 Mechanisms of Heat Transfer

Stefan–Boltzmann law

$$H = Ae\sigma T^4 \qquad \text{(heat current in radiation)}$$

where σ is a fundamental physical constant called the **Stefan–Boltzmann constant.**

$$\sigma = 5.670400(40) \times 10^{-8}\ \mathrm{W/m^2 \cdot K^4}$$

Example 17.14 Heat transfer by radiation

A thin, square steel plate, 10 cm on a side, is heated in a blacksmith's forge to 800°C. If the emissivity is 0.60, what is the total rate of radiation of energy from the plate?

SOLUTION

IDENTIFY and SET UP: The target variable is H, the rate of emission of energy from the plate's two surfaces. We use Eq. (17.25) to calculate H.

EXECUTE: The total surface area is $2(0.10\ \mathrm{m})^2 = 0.020\ \mathrm{m}^2$, and $T = 800°\mathrm{C} = 1073\ \mathrm{K}$. Then Eq. (17.25) gives

$$\begin{aligned} H &= Ae\sigma T^4 \\ &= (0.020\ \mathrm{m}^2)(0.60)(5.67 \times 10^{-8}\ \mathrm{W/m^2 \cdot K^4})(1073\ \mathrm{K})^4 \\ &= 900\ \mathrm{W} \end{aligned}$$

EVALUATE: The nearby blacksmith will easily feel the heat radiated from this plate.