Lecture 37
(Ch. 11: 3)

- **Units of heat (Q):**
  - *calorie* (cal): heat 1 gram of water from 14.5° C to 15.5° C
  - *British thermal unit* (Btu): heat 1 lb of water from 63° F to 64° F
  - *Joule* (J): SI unit ; 1 cal = 4.186 J

$$1 \text{ cal} = 3.969 \times 10^{-3} \text{ Btu} = 4.186 \text{ J}$$

1 Food Calorie = 1,000 cal = 4186 J

Topic Summary

- **Heat and Internal Energy**
- **Specific Heat** and **Calorimetry**

$$Q = mc\Delta T \qquad\qquad \Sigma Q_k = 0$$

- **Latent Heat and Phase Change**

$$Q = \pm mL$$

P 25. Calculate the amount of energy, in joules, required to completely melt 130 g silver initially at 15 C°.

$T\,K = T\,°C + 273.15$

- 25. The melting point of silver is 1235 K, so the temperature of the silver must first be raised from 15.0° C (= 288 K) to 1235 K. This requires heat

$$Q = cm(T_f - T_i) = (236\,\text{J/kg}\cdot\text{K})(0.130\,\text{kg})(1235°K - 288°K) = 2.91\times10^4\ \text{J.}$$

- Now the silver at its melting point must be melted. If *LF* is the heat of fusion for silver this requires

$$Q = mL_F = (0.130\,\text{kg})(105\times10^3\ \text{J/kg}) = 1.36\times10^4\ \text{J.}$$

- The total heat required is (2.91 x 10^4 J + 1.36 x 10^4 J) = 4.27 x 10^4 J.

You have 300 g of coffee at 55 °C. How much 10 °C water do you need to add in order to reduce the coffee's temperature to a more bearable 49 °C ? Note the specific heat, c, of coffee and water are the same ($c = 4186$ J. kg.$^{-1}$.°C^{-1})

Heat is exchanged between the hot coffee and the cold water, but the whole system does not lose or receive heat. Therefore, $Q_{hot} + Q_{cold} = 0$. The temperature of the coffee drops, while that of the added water rises:

$$\Delta T_{hot} = 49°C - 55°C = -6°C$$
$$\Delta T_{cold} = 49°C - 10°C = 39°C$$

Known: $m_{hot} = 300$ g

SOLVE The heat exchange is written:

$$Q_{hot} + Q_{cold} = m_{hot} c \Delta T_{hot} + m_{cold} c \Delta T_{cold} = 0$$; $m_{cold} c \Delta T_{cold} = -m_{hot} c \Delta T_{hot}$

The specific heat of coffee is the same as water, so the c's will cancel out of the equation. Solving for the cold water mass:

$$m_{cold} = -m_{hot} \frac{\Delta T_{hot}}{\Delta T_{cold}} = -(300\text{ g}) \frac{(-6°C)}{(39°C)} = 46\text{ g}$$

Sample Problem 18-3

(a) How much heat must be absorbed by ice of mass $m = 720$ g at $T_1 = -10^oC$ to take it to liquid state at $T_3 = 15^oC$?

Let $T_2 = 0^oC$. Then

→ Table 13.1

$Q_{12} = c_{ice} m(T_2 - T_1) = (2{,}220 \text{ J/kg K})(0.72 \text{ kg})[0^oC - (-10^oC)]$

$= 15{,}984 \text{ J} = 15.98 \text{ kJ}$

→ Table 13.3

$Q_F = L_F\, m = (333 \text{ kJ/kg})(0.720 \text{ kg}) = 239.8 \text{ kJ}$

→ Table 13.1

$Q_{23} = c_w\, m\, (T_3 - T_2) = (4{,}190 \text{ J/kg K})(0.720 \text{ kg})(15^oC - 0^oC)$

$= 45{,}252 \text{ J} = 45.25 \text{ kJ}$

$Q = Q_{12} + Q_F + Q_{23} = 15.98 \text{ kJ} + 239.8 \text{ kJ} + 45.25 \text{ kJ} = 300 \text{ kJ}$

Sample Problem 18-3 (cont)

(b) If we supply the ice with a total energy of only 210 kJ (as heat), what then are the final state and the temperature of the water?

$Q_{12} = 15.98$ kJ, $Q_F = 239.8$ kJ, $Q_{23} = 45.25$ kJ

Final state: ICE and WATER, $T_f = 0^o$ C

$Q_{rem} = 210 \text{ kJ} - 15.98 \text{ kJ} = 194 \text{ kJ}$

$Q_{rem} = m_w L_F$

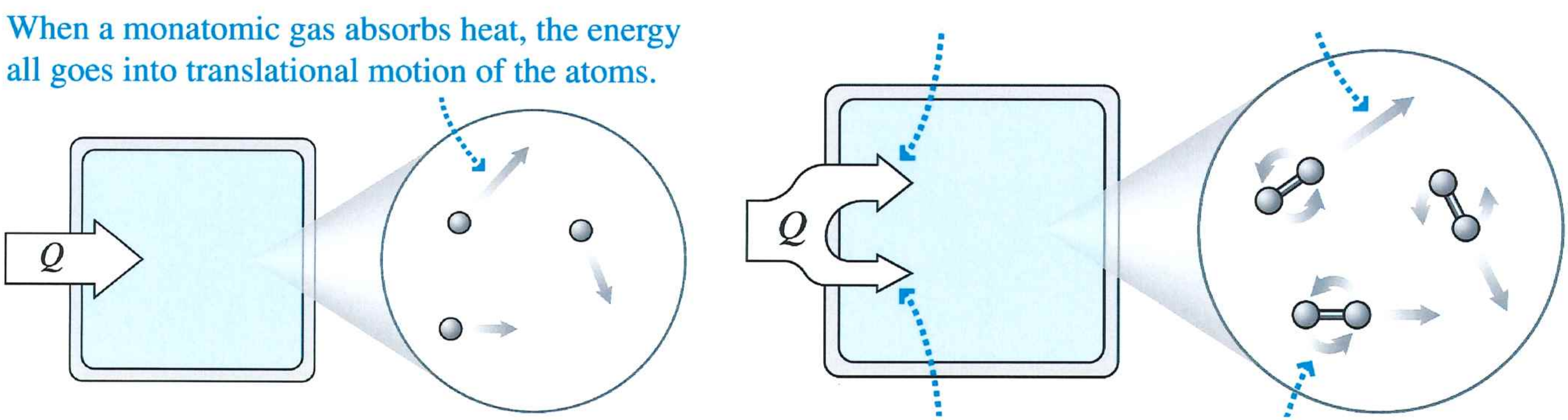
$m_w = Q_{rem} / L_F = 194 \text{ kJ}/333 \text{ kJ/kg} = 0.583 \text{ kg}$

$m_{ice} = 0.720 \text{ kg} - 0.583 \text{ kg} = 0.137 \text{ kg}$

Chapter 11: Heat – Specific Heat of Gases

Monoatomic gases vs diatomic

In the case of a monoatomic gas (a molecule contains a single atom), all the energy received becomes translation energy of the gas molecules. For a gas with molecules that contain more atoms, some thermal energy received is converted into rotation, so more heat can be received that does not contribute to increasing the temperature.



Chapter 11: Heat – Specific Heat of Gases

Molar Specific Heat of Gases

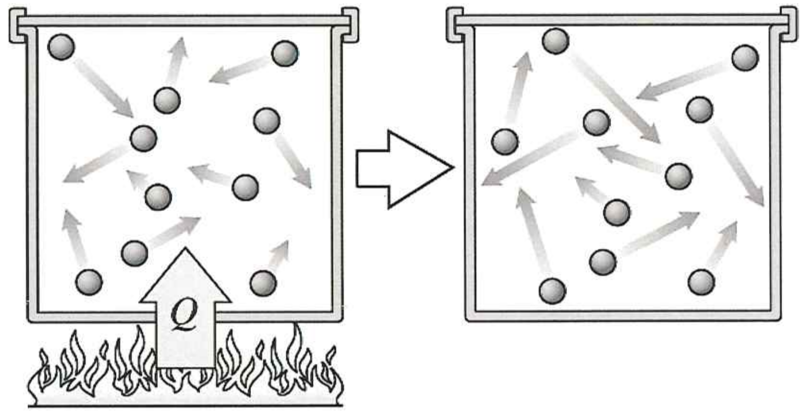
Because the behavior of gases depends a lot on its state variables, we treat them separately from solids and liquids.
Thus, when dealing with gases, we consider the specific heat at constant pressure, and the specific heat at constant volume.

$Q = n \cdot c_V \cdot \Delta T, c_V$ in SI: J/(mol·K)

$Q = n \cdot c_P \cdot \Delta T, c_V$ in SI: J/(mol·K)

Gas	c_V in J/(mol · °C)	c_P in J/(mol · °C)
Monatomic gases		
He	12.5	20.8
Ne	12.5	20.8
Ar	12.5	20.8
Diatomic gases		
H_2	20.4	28.7
N_2	20.8	29.1
O_2	20.9	29.2
Air (a predominantly diatomic mixture)	20.8	29.1

Figure 13.7

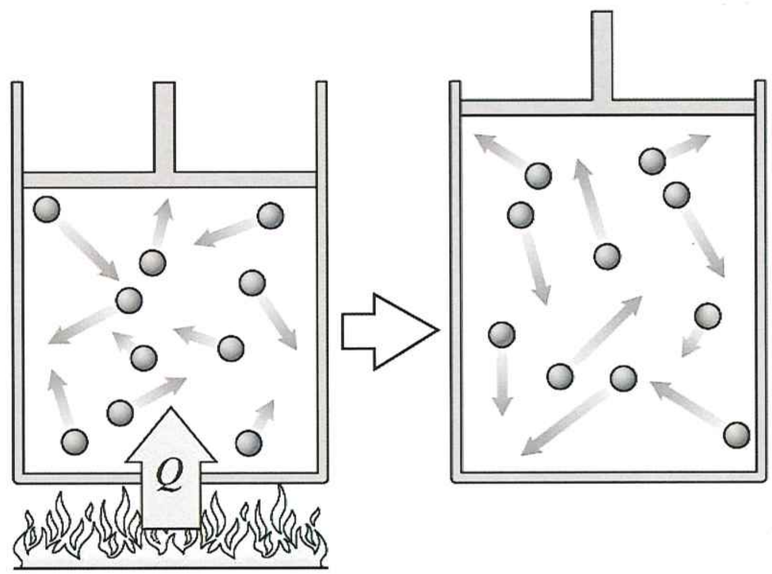


(a) When heat is added at constant volume, all the energy goes into thermal motion.

$Q = mc_v \Delta T$

② why $c_p > c_v$

$Q = mc_p \Delta T$



(b) When heat is added at constant pressure, some of the energy goes into thermal motion and some into expanding the container.

Chapter 11: Heat – Specific Heat of Gases

Example

A container of nitrogen gas (N_2) at 23 °C contains 425 L at a pressure of 3.5 atm. If 26.6 kJ of heat are added to the container, what will be the new temperature of the gas?

$$\boxed{Q = n \cdot c_V \cdot \Delta T}$$

$$c_V = \frac{Q}{n \Delta T} = \frac{5}{2} R = 20.7875 \frac{J}{mol\, K}$$

Chapter 11: Heat – Specific Heat of Gases

Example

A container of nitrogen gas (N_2) at 23 °C contains 425 L at a pressure of 3.5 atm. If 26.6 kJ of heat are added to the container, what will be the new temperature of the gas?

The number of moles n is given by the ideal gas law:

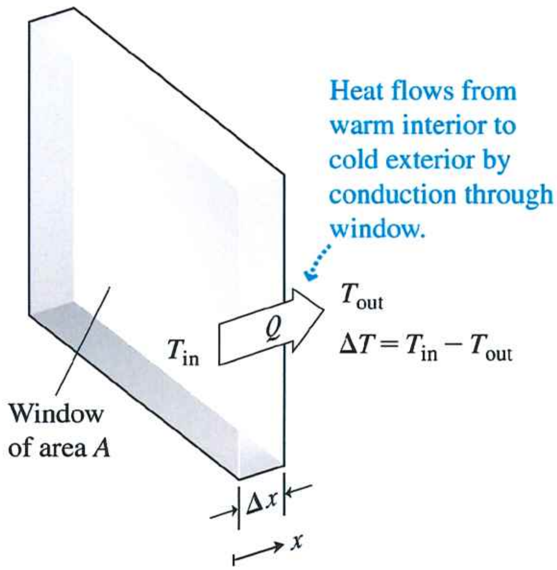
$$n = \frac{P_i V_i}{R T_i}$$

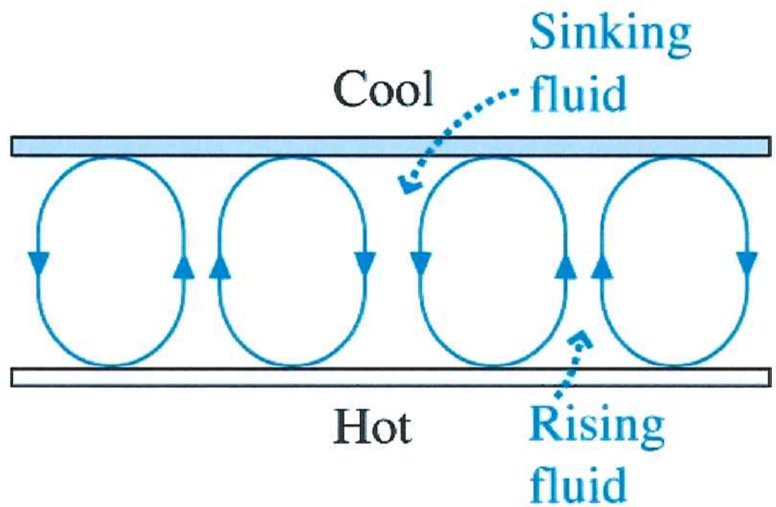
$$\Delta T = \frac{Q}{n \cdot c_V} = \frac{Q \cdot R \cdot T_i}{\frac{5}{2} R \cdot P_i \cdot V_i} = \frac{2 \cdot 26.6 \cdot 10^3 (23 + 273)}{5 \cdot 3.5 \cdot 10^5 \cdot 0.425} = 21.17$$

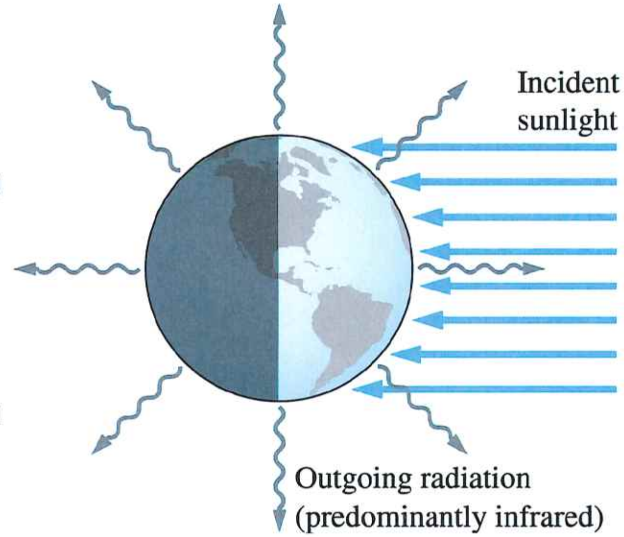
$$T_f = T_i + \Delta T = 23 + 21 = 44\,°C$$

Chapter 11: Heat

Conduction, Convection, and Radiation







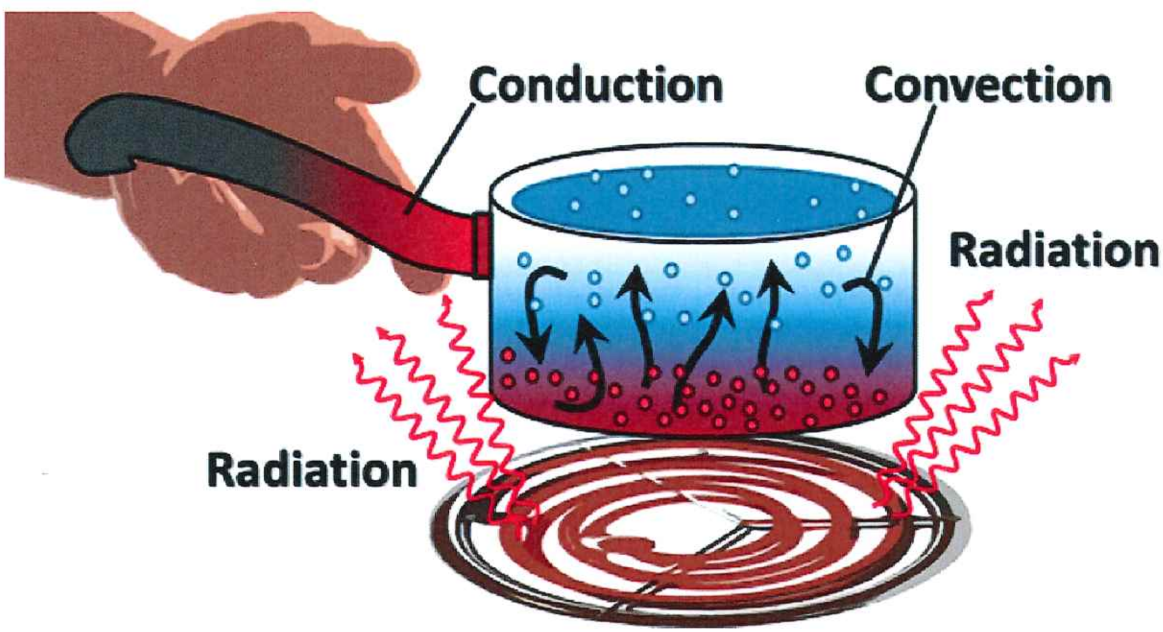
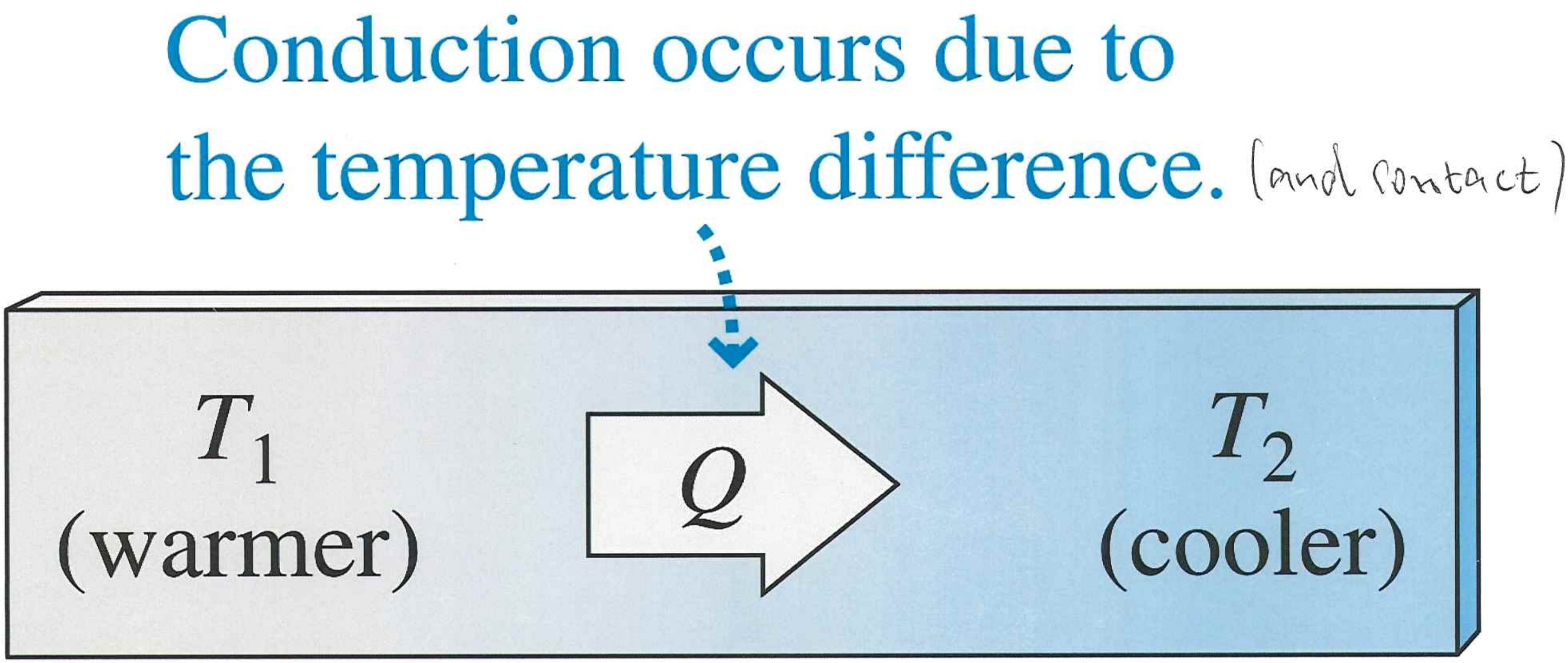


Figure 13.17


Conduction occurs due to the temperature difference. (and contact)
T_1
(warmer)
Q
T_2
(cooler)

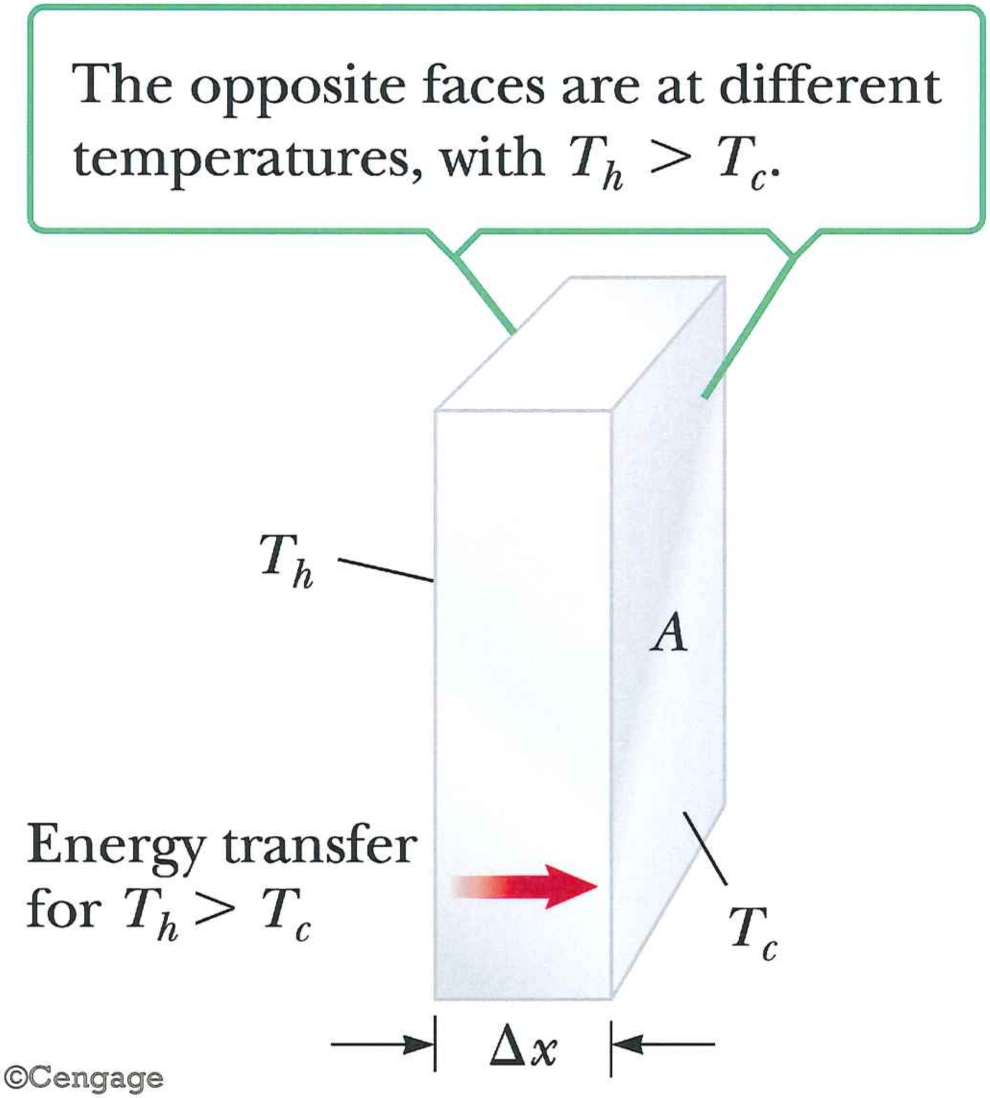
Chapter 11: Heat – Conduction

Conduction

Conduction is the process of transferring heat between two object in thermal contact, due to a temperature difference. Some substances conduct heat better than others, and even the same substance in different phases can have different heat conductive properties. At the atomic level, electrons can transport a lot of heat, making metals good thermal conductors (besides being good electrical conductors). The electrons in metals are free to roam around, as opposed to other substances.

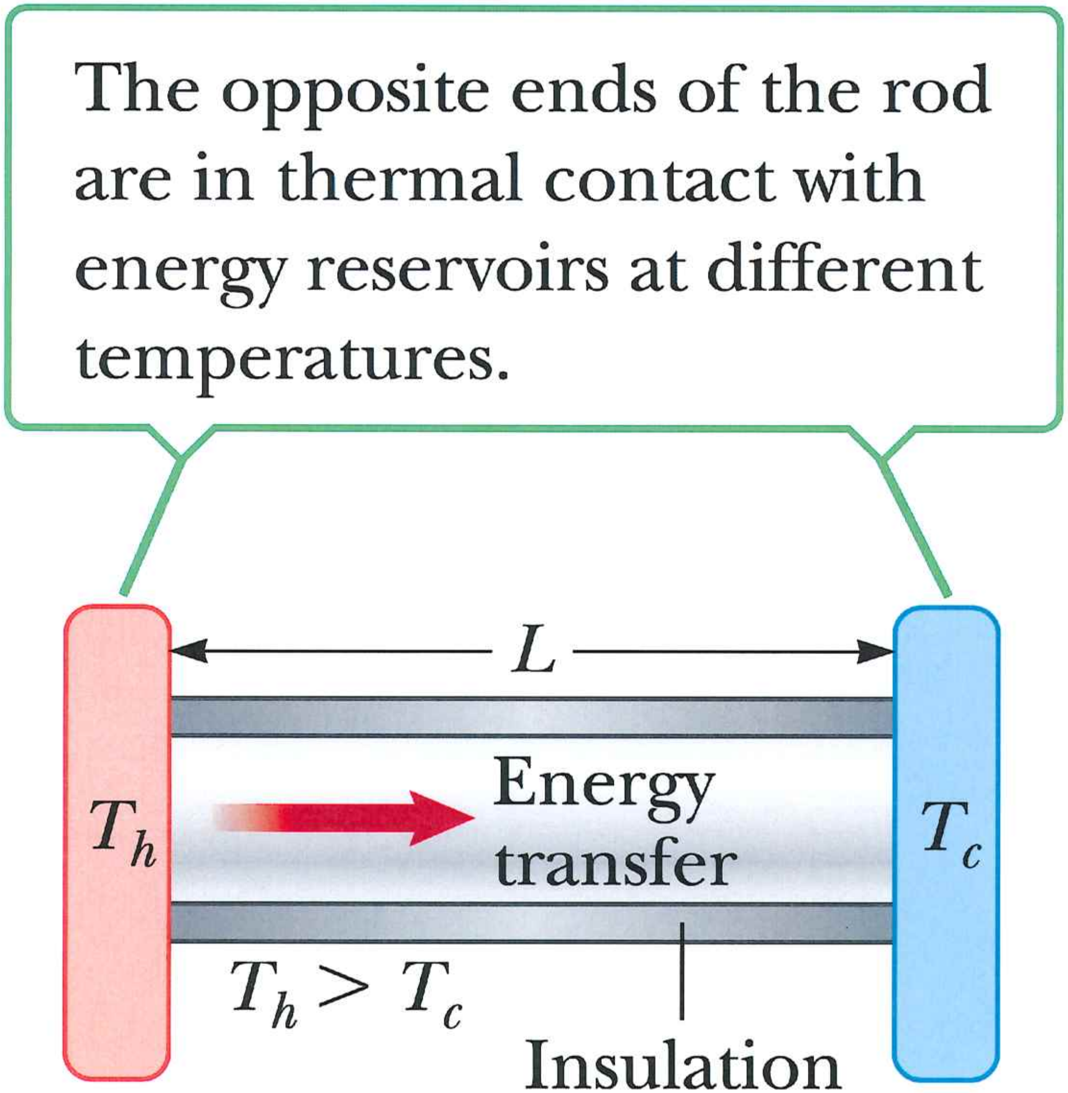
$$H = k \cdot A \frac{\Delta T}{\Delta x}$$, where H is the heat conduction; in SI: W

Thermal Conduction



$$P = \frac{Q}{\Delta t} \propto A \frac{\Delta T}{\Delta x}$$

Thermal Conduction



$$\Delta T = T_h - T_c$$

$$\Delta x = L$$

$$\frac{\Delta T}{\Delta x} = \frac{T_h - T_c}{L}$$

$$P = kA\frac{(T_h - T_c)}{L}$$

Thermal Conduction

Table 11.3 Thermal Conductivities

Substance	Thermal Conductivity (J/s · m · °C)
Metals (at 25°C)	
Aluminum	238
Copper	397
Gold	314
Iron	79.5
Lead	34.7
Silver	427
Gases (at 20°C)	
Air	0.023 4
Helium	0.138
Hydrogen	0.172
Nitrogen	0.023 4
Oxygen	0.023 8
Nonmetals (approximate values)	
Asbestos	0.08
Concrete	0.8
Glass	0.8
Ice	2
Rubber	0.2
Water	0.6
Wood	0.08

42. A glass windowpane in a home is 0.62 cm thick and has dimensions of $1.0\ \text{m} \times 2.0\ \text{m}$. On a certain day, the indoor temperature is 25°C and the outdoor temperature is 0°C.

a. What is the rate at which energy is transferred by heat through the glass?

b. How much energy is lost through the window in one day, assuming the temperatures inside and outside remain constant?

11.42 **(a)** The rate of energy transfer by conduction through a material of area A, thickness L, with thermal conductivity k, and temperatures $T_h > T_c$ on opposite sides is $P = kA(T_h - T_c)/L$. For the given windowpane, this is

$$P = \left(0.8 \frac{\text{J}}{\text{s}\cdot\text{m}\cdot{}^\circ\text{C}}\right)\left[(1.0\ \text{m})(2.0\ \text{m})\right]\frac{(25^\circ\text{C} - 0^\circ\text{C})}{0.62 \times 10^{-2}\ \text{m}} = 6 \times 10^3\ \text{J/s} = \boxed{6 \times 10^3\ \text{W}}$$

(b) The total energy lost per day is

$$E = P \cdot \Delta t = (6 \times 10^3\ \text{J/s})(8.64 \times 10^4\ \text{s}) = \boxed{5 \times 10^8\ \text{J}}$$

44. BIO The thermal conductivities of human tissues vary greatly. Fat and skin have conductivities of about $0.20\ \mathrm{W/m\cdot K}$ and $0.020\ \mathrm{W/m\cdot K}$, respectively, while other tissues inside the body have conductivities of about $0.50\ \mathrm{W/m\cdot K}$. Assume that between the core region of the body and the skin surface lies a skin layer of 1.0 mm, fat layer of 0.50 cm, and 3.2 cm of other tissues.

a. Find the R-factor for each of these layers, and the equivalent R-factor for all layers taken together, retaining two digits.

b. Find the rate of energy loss when the core temperature is $37^\circ\mathrm{C}$ and the exterior temperature is $0^\circ\mathrm{C}$. Assume that both a protective layer of clothing and an insulating layer of unmoving air are absent, and a body area of $2.0\ \mathrm{m}^2$.

11.44 **(a)** The R value of a material is $R = L/\kappa$, where L is its thickness and κ is the thermal conductivity. The R values of the three layers covering the core tissues in this body are:

$$R_{\text{skin}} = \frac{1.0\times10^{-3}\ \mathrm{m}}{0.020\ \mathrm{W/m\cdot K}} = \boxed{5.0\times10^{-2}\ \mathrm{m^2\cdot K/W}}$$

$$R_{\text{fat}} = \frac{0.50\times10^{-2}\ \mathrm{m}}{0.020\ \mathrm{W/m\cdot K}} = \boxed{2.5\times10^{-2}\ \mathrm{m^2\cdot K/W}}$$

and $$R_{\text{tissue}} = \frac{3.2\times10^{-2}\ \mathrm{m}}{0.50\ \mathrm{W/m\cdot K}} = \boxed{6.4\times10^{-2}\ \mathrm{m^2\cdot K/W}}$$

so the total R value of the three layers taken together is

$$R_{\text{total}} = \sum_{i=1}^{3} R_i = (5.0+2.5+6.4)\times10^{-2}\ \frac{\mathrm{m^2\cdot K}}{\mathrm{W}}$$
$$= 1.4\times10^{-1}\ \frac{\mathrm{m^2\cdot K}}{\mathrm{W}} = \boxed{0.14\ \frac{\mathrm{m^2\cdot K}}{\mathrm{W}}}$$

(b) The rate of energy transfer by conduction through these three layers with a surface area of $A = 2.0\ \text{m}^2$ and temperature difference of $\Delta T = (37 - 0)°\text{C} = 37°\text{C} = 37\ \text{K}$ is

$$P = \frac{A(\Delta T)}{R_{\text{total}}} = \frac{(2.0\ \text{m}^2)(37\ \text{K})}{0.14\ \text{m}^2 \cdot \text{K/W}} = \boxed{5.3 \times 10^2\ \text{W}}$$

49. T A copper rod and an aluminum rod of equal diameter are joined end to end in good thermal contact. The temperature of the free end of the copper rod is held constant at 100.°C and that of the far end of the aluminum rod is held at 0°C. If the copper rod is 0.15 m long, what must be the length of the aluminum rod so that the temperature at the junction is 50.°C?

11.49 When the temperature of the junction stabilizes, the energy transfer rate must be the same for each of the rods, or $P_{Cu} = P_{Al}$. The cross-sectional areas of the rods are equal, and if the temperature of the junction is 50°C, the temperature difference is $\Delta T = 50°C$ for each rod.

Thus, $P_{Cu} = k_{Cu} A \left(\frac{\Delta T}{L_{Cu}}\right) = k_{Al} A \left(\frac{\Delta T}{L_{Al}}\right) = P_{Al}$, which gives

$$L_{Al} = \left(\frac{k_{Al}}{k_{Cu}}\right) L_{Cu} = \left(\frac{238 \text{ W/m} \cdot °\text{C}}{397 \text{ W/m} \cdot °\text{C}}\right)(15 \text{ cm}) = \boxed{9.0 \text{ cm}}$$

75. An aluminum rod and an iron rod are joined end to end in good thermal contact. The two rods have equal lengths and radii. The free end of the aluminum rod is maintained at a temperature of 100.°C, and the free end of the iron rod is maintained at 0°C.

a. Determine the temperature of the interface between the two rods.

Answer

b. If each rod is 15 cm long and each has a cross-sectional area of $5.0\ \text{cm}^2$, what quantity of energy is conducted across the combination in 30. min?

11.75 **(a)** In steady state, the energy transfer rate is the same for each of the rods, or $P_{Al} = P_{Fe}$.

Thus,

$$k_{Al}A\left(\frac{100°\text{C}-T}{L}\right) = k_{Fe}A\left(\frac{T-0°\text{C}}{L}\right)$$

giving

$$T = \left(\frac{k_{Al}}{k_{Al}+k_{Fe}}\right)(100°\text{C}) = \left(\frac{238}{238+79.5}\right)(100°\text{C}) = \boxed{75.0°\text{C}}$$

(b) If $L = 15$ cm and $A = 5.0\ \text{cm}^2$, the energy conducted in 30 min is

$$Q = P_{Al}\cdot t = \left[\left(238\frac{\text{W}}{\text{m}\cdot°\text{C}}\right)\left(5.0\times10^{-4}\ \text{m}^2\right)\left(\frac{100°\text{C}-75.0°\text{C}}{0.15\ \text{m}}\right)\right](1\,800\ \text{s})$$

$$= 3.6\times10^4\ \text{J} = \boxed{36\ \text{kJ}}$$