Chapter 20

The First Law of Thermodynamics

20.1 Heat and Internal Energy

20.2 Specific Heat and Calorimetry

20.7 Energy Transfer Mechanisms in Thermal Processes

Thermodynamics – Historical Background

- A connection was found between the transfer of energy by heat in thermal processes and the transfer of energy by work in mechanical processes
- The concept of energy was generalized to include internal energy
- The Law of Conservation of Energy emerged as a universal law of nature

Internal Energy

- **Internal energy** is all the energy of a system that is associated with its microscopic components
  - These components are its atoms and molecules

Internal Energy and Other Energies

- Internal energy does include kinetic energies due to:
  - Random translational motion
  - Rotational motion
  - Vibrational motion
- Internal energy also includes potential energy between molecules

Heat

- **Heat** is defined as the transfer of energy across the boundary of a system due to a temperature difference between the system and its surroundings
- The term heat will also be used to represent the amount of energy transferred by this method

Changing Internal Energy

- Both heat and work can change the internal energy of a system
- The internal energy can be changed even when no energy is transferred by heat, but just by work
  - Example, compressing gas with a piston
  - Energy is transferred by work

Units of Heat

- Historically, the **calorie** was the unit used for heat
  - One calorie is the amount of energy transfer necessary to raise the temperature of 1 g of water from 14.5^{o}C to 15.5^{o}C
    - The “Calorie” used for food is actually 1 kilocalorie
- In the US Customary system, the unit is a BTU (British Thermal Unit)
  - One BTU is the amount of energy transfer necessary to raise the temperature of 1 lb of water from 63^{o}F to 64^{o}F
- The standard in the text is to use Joules

Mechanical Equivalent of Heat, cont

- Joule found that it took approximately 4.18 J of mechanical energy to raise the water 1°C
- Later, more precise, measurements determined the amount of mechanical energy needed to raise the temperature of water from 14.5°C to 15.5°C
- 1 cal = 4.186 J
  - This is known as the **mechanical equivalent of heat**

Heat Capacity

- The **heat capacity**, C, of a particular sample is defined as the amount of energy needed to raise the temperature of that sample by 1^{o}C
- If energy Q produces a change of temperature of ΔT, then

$$Q = C\,\Delta T$$

Specific Heat

- **Specific heat**, c, is the heat capacity per unit mass
- If energy Q transfers to a sample of a substance of mass m and the temperature changes by ΔT, then the specific heat is

$$c \equiv \frac{Q}{m\,\Delta T}$$

Specific Heat, cont

- The equation is often written in terms of Q :

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

Some Specific Heat Values

Substance	Specific Heat c J/kg · °C	Specific Heat c cal/g · °C
Elemental solids		
Aluminum	900	0.215
Beryllium	1 830	0.436
Cadmium	230	0.055
Copper	387	0.092 4
Germanium	322	0.077
Gold	129	0.030 8
Iron	448	0.107
Lead	128	0.030 5
Silicon	703	0.168
Silver	234	0.056

More Specific Heat Values

Substance	Specific Heat c J/kg · °C	Specific Heat c cal/g · °C
Other solids		
Brass	380	0.092
Glass	837	0.200
Ice (−5°C)	2 090	0.50
Marble	860	0.21
Wood	1 700	0.41
Liquids		
Alcohol (ethyl)	2 400	0.58
Mercury	140	0.033
Water (15°C)	4 186	1.00
Gas		
Steam (100°C)	2 010	0.48

Sign Conventions

- If the temperature increases:
  - Q and ΔT are positive
  - Energy transfers into the system
- If the temperature decreases:
  - Q and ΔT are negative
  - Energy transfers out of the system

Specific Heat of Water

- Water has the highest specific heat of common materials
- This is in part responsible for many weather phenomena
  - Moderate temperatures near large bodies of water
  - Global wind systems
  - Land and sea breezes

Calorimetry

- One technique for measuring specific heat involves heating a material, adding it to a sample of water, and recording the final temperature
- This technique is known as **calorimetry**
  - A calorimeter is a device in which this energy transfer takes place
  - Conservation of Energy gives a mathematical expression of this:

    $Q_{\text{cold}} = -Q_{\text{hot}}$

Calorimetry, final

- The negative sign in the equation is critical for consistency with the established sign convention
- Since each $Q = mc\Delta T$, c_{sample} can be found by:

$$c_s = \frac{m_w c_w \left(T_f - T_w\right)}{m_s \left(T_s - T_f\right)}$$

  - Technically, the mass of the container should be included, but if $m_w >> m_{container}$ it can be neglected

Calorimetry, Example

- An ingot of metal is heated and then dropped into a beaker of water. The equilibrium temperature is measured

$$c_s = \frac{m_w c_w \left(T_f - T_w\right)}{m_s \left(T_s - T_f\right)}$$

$$= \frac{(0.400\,\text{kg})(4186\,\text{J/kg}\cdot{}^\circ\text{C})(22.4\,{}^\circ\text{C} - 20.0\,{}^\circ\text{C})}{(0.0500\,\text{kg})(200.0\,{}^\circ C - 22.4\,{}^\circ C)}$$

$$= 453\ \text{J/kg}\cdot{}^\circ\text{C}$$

Example 20.2 Cooling a Hot Ingot

A 0.050 0-kg ingot of metal is heated to 200.0°C and then dropped into a calorimeter containing 0.400 kg of water initially at 20.0°C. The final equilibrium temperature of the mixed system is 22.4°C. Find the specific heat of the metal.

SOLUTION

Conceptualize Imagine the process occurring in the isolated system of Figure 20.2. Energy leaves the hot ingot and goes into the cold water, so the ingot cools off and the water warms up. Once both are at the same temperature, the energy transfer stops.

Categorize We use an equation developed in this section, so we categorize this example as a substitution problem.

Use Equation 20.4 to evaluate each side of Equation 20.5:

$$m_w c_w (T_f - T_w) = -m_x c_x (T_f - T_x)$$

Solve for c_x:

$$c_x = \frac{m_w c_w (T_f - T_w)}{m_x (T_x - T_f)}$$

Substitute numerical values:

$$c_x = \frac{(0.400 \text{ kg})(4\,186 \text{ J/kg}\cdot{}^\circ\text{C})(22.4^\circ\text{C} - 20.0^\circ\text{C})}{(0.050\,0 \text{ kg})(200.0^\circ\text{C} - 22.4^\circ\text{C})}$$

$$= 453 \text{ J/kg}\cdot{}^\circ\text{C}$$

Mechanisms of Energy Transfer by Heat

- We want to know the rate at which energy is transferred
- There are various mechanisms responsible for the transfer:
  - Conduction
  - Convection
  - Radiation

Conduction

- The transfer can be viewed on an atomic scale
  - It is an exchange of kinetic energy between microscopic particles by collisions
    - The microscopic particles can be atoms, molecules or free electrons
  - Less energetic particles gain energy during collisions with more energetic particles
- Rate of conduction depends upon the characteristics of the substance

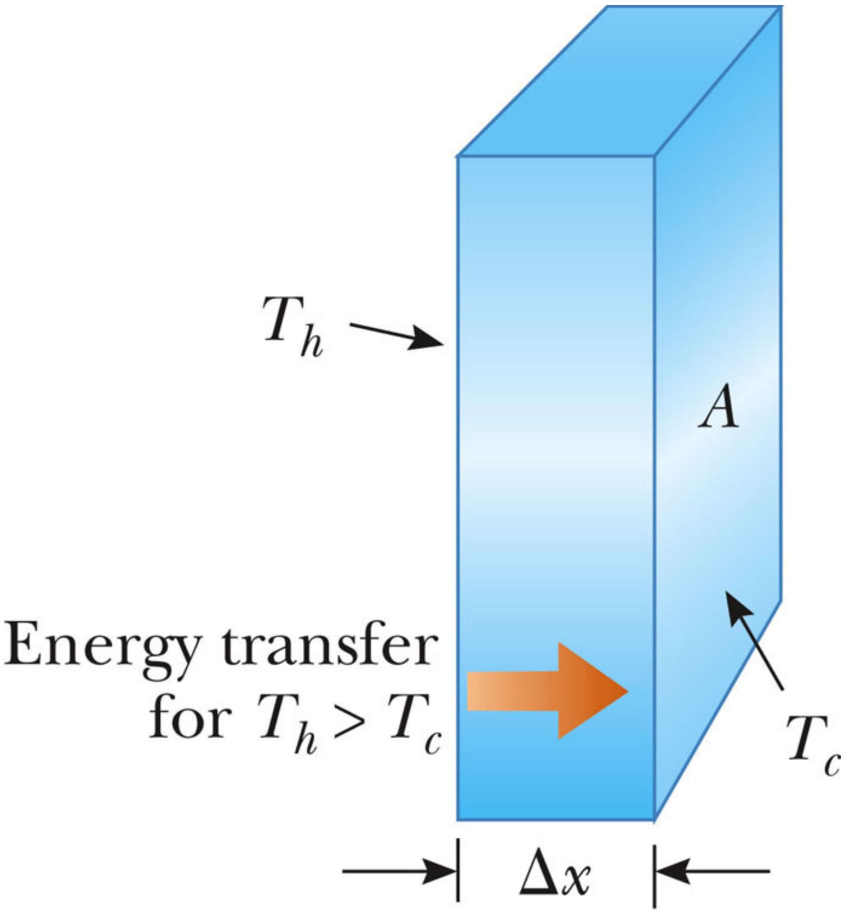
Conduction, cont.

- In general, metals are good thermal conductors
  - They contain large numbers of electrons that are relatively free to move through the metal
  - They can transport energy from one region to another
- Poor conductors include paper, and gases
- Conduction can occur only if there is a difference in temperature between two parts of the conducting medium

Conduction, equation

- The slab at right allows energy to transfer from the region of higher temperature to the region of lower temperature
- The rate of transfer is given by:

$$\wp = \frac{Q}{\Delta t} = kA\left|\frac{dT}{dx}\right|$$



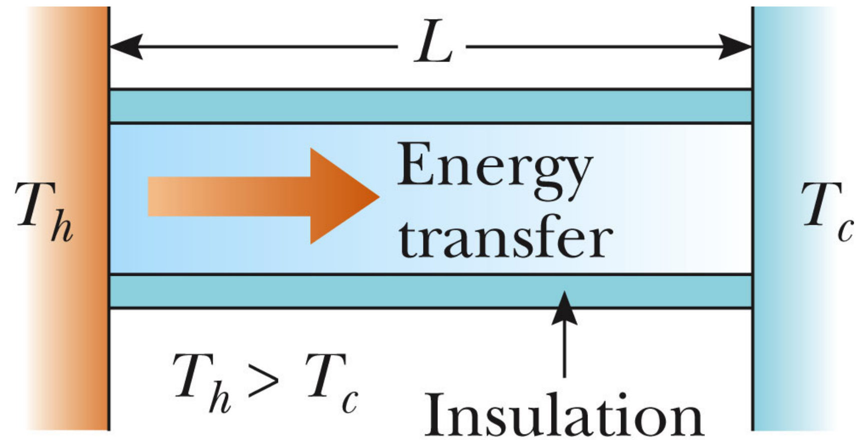
Conduction, equation explanation

- A is the cross-sectional area
- Δx is the thickness of the slab
  - Or the length of a rod
- $\wp$ is in Watts when Q is in Joules and t is in seconds
- k is the thermal conductivity of the material
  - Good conductors have high k values and good insulators have low k values

Temperature Gradient

- The quantity $|dT / dx|$ is called the **temperature gradient** of the material
  - It measures the rate at which temperature varies with position
- For a rod, the temperature gradient can be expressed as:

$$\left|\frac{dT}{dx}\right| = \frac{T_h - T_c}{L}$$



Rate of Energy Transfer in a Rod

- Using the temperature gradient for the rod, the rate of energy transfer becomes:

$$\wp = kA\left(\frac{T_h - T_c}{L}\right)$$

Compound Slab

- For a compound slab containing several materials of various thicknesses (L_1, L_2, …) and various thermal conductivities (k_1, k_2, …) the rate of energy transfer depends on the materials and the temperatures at the outer edges:

$$\wp = \frac{A\left(T_h - T_c\right)}{\sum_i \left(L_i / k_i\right)}$$

Some Thermal Conductivities

TABLE 20.3

Thermal Conductivities

Substance	Thermal Conductivity (W/m · °C)
Metals (at 25°C)	
Aluminum	238
Copper	397
Gold	314
Iron	79.5
Lead	34.7
Silver	427

More Thermal Conductivities

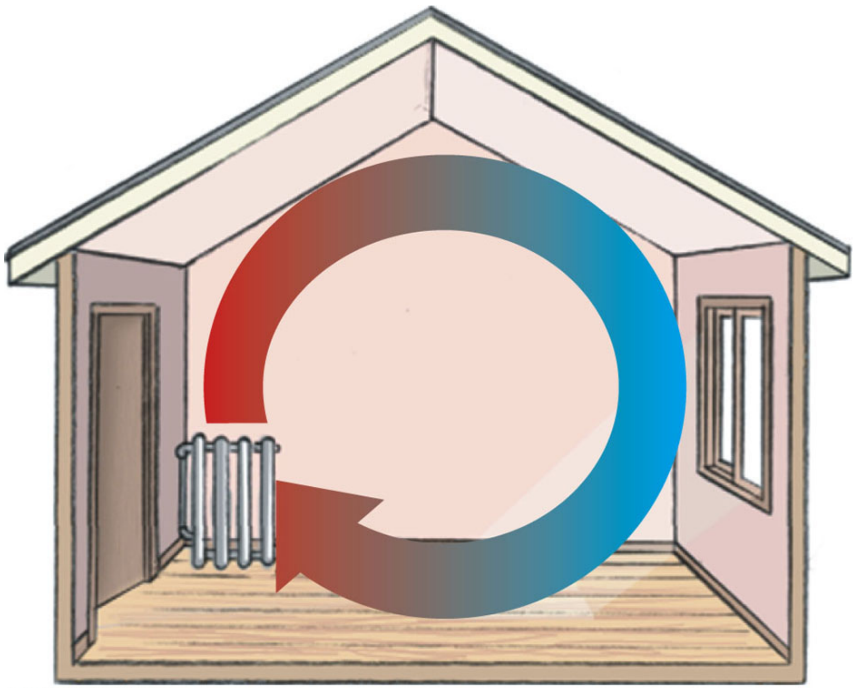
Nonmetals (approximate values)	
Asbestos	0.08
Concrete	0.8
Diamond	2 300
Glass	0.8
Ice	2
Rubber	0.2
Water	0.6
Wood	0.08
Gases (at 20°C)	
Air	0.023 4
Helium	0.138
Hydrogen	0.172
Nitrogen	0.023 4
Oxygen	0.023 8

Convection

- Energy transferred by the movement of a substance
  - When the movement results from differences in density, it is called *natural convection*
  - When the movement is forced by a fan or a pump, it is called *forced convection*

Convection example

- Air directly above the radiator is warmed and expands
- The density of the air decreases, and it rises
- A continuous air current is established



Radiation

- Radiation does not require physical contact
- All objects radiate energy continuously in the form of electromagnetic waves due to thermal vibrations of their molecules
- Rate of radiation is given by **Stefan's law**

Stefan's Law

- $P = \sigma A e T^4$
  - P is the rate of energy transfer, in Watts
  - $\sigma = 5.6696 \times 10^{-8}\ W/m^2 \cdot K^4$
  - A is the surface area of the object
  - e is a constant called the emissivity
    - e varies from 0 to 1
    - The emissivity is also equal to the absorptivity
  - T is the temperature in Kelvins

Energy Absorption and Emission by Radiation

- With its surroundings, the rate at which the object at temperature T with surroundings at T_o radiates is
  - $P_{net} = \sigma A e \, (T^4 - T_o^4)$
  - When an object is in equilibrium with its surroundings, it radiates and absorbs at the same rate
    - Its temperature will not change

Ideal Absorbers

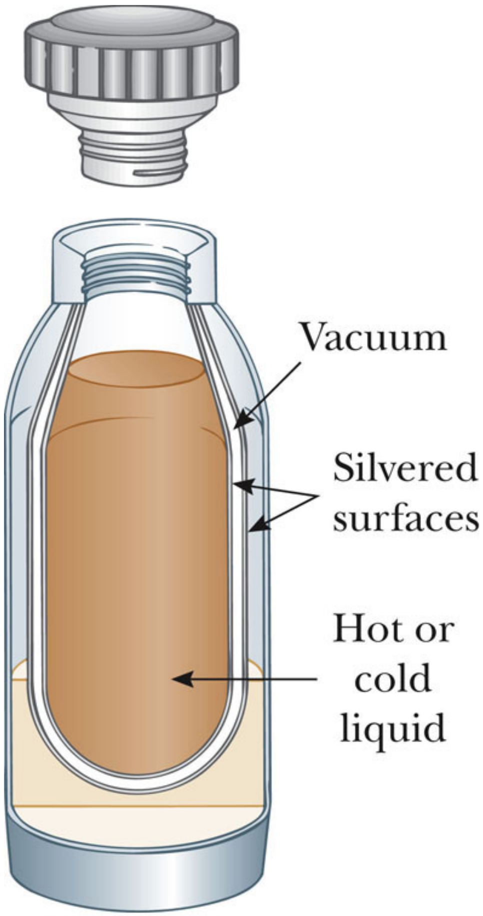
- An *ideal absorber* is defined as an object that absorbs all of the energy incident on it
  - $e = 1$
- This type of object is called a **black body**

Ideal Reflector

- An ideal reflector absorbs none of the energy incident on it
  - $e = 0$

Dewar Flask, Details

- The space between the walls is a vacuum to minimize energy transfer by conduction and convection
- The silvered surface minimizes energy transfers by radiation
  - Silver is a good reflector
- The size of the neck is reduced to further minimize energy losses



Homework

- 1. Clearly distinguish among temperature, heat, and internal energy.

Section 20.2 Specific Heat and Calorimetry

- 2. The temperature of a silver bar rises by 10.0°C when it absorbs 1.23 kJ of energy by heat. The mass of the bar is 525 g. Determine the specific heat of silver.
- 3. A 50.0-g sample of copper is at 25.0°C. If 1 200 J of energy is added to it by heat, what is the final temperature of the copper?(the specific heat of copper is 387J/Kg^{o}C)

Section 20.7 Energy-Transfer Mechanisms

- 4. A box with a total surface area of 1.20 m^2 and a wall thickness of 4.00 cm is made of an insulating material. A 10.0-W electric heater inside the box maintains the inside temperature at 15.0°C above the outside temperature. Find the thermal conductivity k of the insulating material.
- 5. A glass window pane has an area of 3.00 m^2 and a thickness of 0.600 cm. If the temperature difference between its faces is 25.0°C, what is the rate?(the thermal conductivity k of the glass is 0.8 W/m^{o}C)
- 6. The surface of the Sun has a temperature of about 5800 K. The radius of the Sun is 6.96×10^8 m. Calculate the total energy radiated by the Sun each second. Assume that the emissivity of the Sun is 0.965.
- 7.The tungsten filament of a certain 100-W light bulb radiates 2.00 W of light. (The other 98 W is carried away by convection and conduction.) The filament has a surface area of 0.250 mm^2 and an emissivity of 0.950. Find the filament's temperature. (The melting point of tungsten is 3 683 K.)

1. Temperature is a measure of molecular motion. Heat is energy in the process of being transferred between objects by random molecular collisions. Internal energy is an object's energy of random molecular motion and molecular interaction.

2.

$$\Delta Q = mc_{\text{silver}}\Delta T$$

$$1.23\ \text{kJ} = (0.525\ \text{kg})c_{\text{silver}}(10.0°\text{C})$$

$$c_{\text{silver}} = \boxed{0.234\ \text{kJ/kg}\cdot°\text{C}}$$

3.

From $Q = mc\Delta T$

we find $\Delta T = \dfrac{Q}{mc} = \dfrac{1\,200\ \text{J}}{0.050\,0\ \text{kg}(387\ \text{J/kg}\cdot°\text{C})} = 62.0°\text{C}$

Thus, the final temperature is $\boxed{87.0°\text{C}}$.

4.

$$\mathcal{P} = kA\frac{\Delta T}{L}$$

$$k = \frac{\mathcal{P}L}{A\Delta T} = \frac{10.0\ \text{W}(0.040\,0\ \text{m})}{1.20\ \text{m}^2(15.0°\text{C})} = \boxed{2.22\times10^{-2}\ \text{W/m}\cdot°\text{C}}$$

5.

$$\mathcal{P} = \frac{kA\Delta T}{L} = \frac{(0.800\ \text{W/m}\cdot{}^\circ\text{C})(3.00\ \text{m}^2)(25.0^\circ\text{C})}{6.00\times10^{-3}\ \text{m}} = 1.00\times10^{4}\ \text{W} = \boxed{10.0\ \text{kW}}$$

6.

$$\mathcal{P} = \sigma A e T^4 = (5.669\,6\times10^{-8}\ \text{W/m}^2\cdot\text{K}^4)\left[4\pi(6.96\times10^{8}\ \text{m})^2\right](0.965)(5\,800\ \text{K})^4$$

$$\mathcal{P} = \boxed{3.77\times10^{26}\ \text{W}}$$

7.

$$\mathcal{P} = \sigma A e T^4$$

$$2.00\ \text{W} = (5.67\times10^{-8}\ \text{W/m}^2\cdot\text{K}^4)(0.250\times10^{-6}\ \text{m}^2)(0.950)T^4$$

$$T = (1.49\times10^{14}\ \text{K}^4)^{1/4} = \boxed{3.49\times10^{3}\ \text{K}}$$