Chapter 11

Energy in Thermal Processes

Energy Transfer

- When two objects of different temperatures are placed in thermal contact, the temperature of the warmer decreases and the temperature of the cooler increases
- The energy exchange ceases when the objects reach thermal equilibrium
- The concept of energy was broadened from just mechanical to include internal
  - Made Conservation of Energy a universal law of nature

Heat Compared to Internal Energy

- Important to distinguish between them
  - They are not interchangeable
- They mean very different things when used in physics

Internal Energy

- *Internal Energy*, U, is the energy associated with the microscopic components of the system
  - Includes kinetic and potential energy associated with the random translational, rotational and vibrational motion of the atoms or molecules
  - Also includes any potential energy bonding the particles together

Heat

- *Heat* is the transfer of energy between a system and its environment because of a temperature difference between them
  - The symbol Q is used to represent the amount of energy transferred by heat between a system and its environment

Units of Heat

- Calorie
  - An historical unit, before the connection between thermodynamics and mechanics was recognized
  - A *calorie* is the amount of energy necessary to raise the temperature of 1 g of water from 14.5° C to 15.5° C .
    - A Calorie (food calorie) is 1000 cal

Units of Heat, cont.

- US Customary Unit – BTU
- BTU stands for British Thermal Unit
  - A *BTU* is the amount of energy necessary to raise the temperature of 1 lb of water from 63° F to 64° F
- 1 cal = 4.186 J
  - This is called the *Mechanical Equivalent of Heat*

James Prescott Joule

- 1818 – 1889
- British physicist
- Conservation of Energy
- Relationship between heat and other forms of energy transfer

Specific Heat

- Every substance requires a unique amount of energy per unit mass to change the temperature of that substance by 1° C
- The *specific heat, c,* of a substance is a measure of this amount

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

Units of Specific Heat

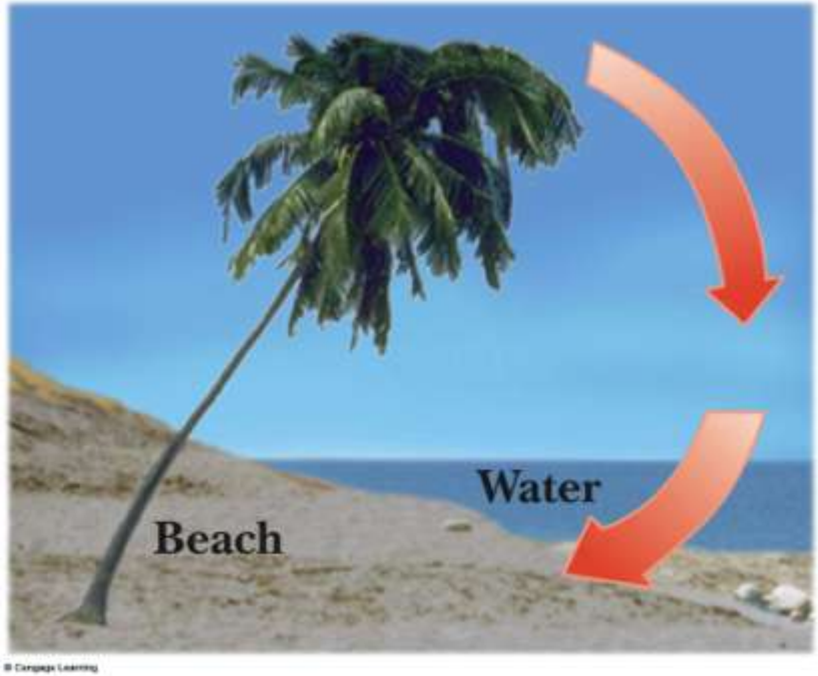
- SI units
  - J / kg °C
- Historical units
  - cal / g °C

Heat and Specific Heat

- $Q = m\,c\,\Delta T$
- ΔT is always the final temperature minus the initial temperature
- When the temperature increases, ΔT and ΔQ are considered to be positive and energy flows into the system
- When the temperature decreases, ΔT and ΔQ are considered to be negative and energy flows out of the system

A Consequence of Different Specific Heats

- Water has a high specific heat compared to land
- On a hot day, the air above the land warms faster
- The warmer air flows upward and cooler air moves toward the beach



Calorimeter

- One technique for determining the specific heat of a substance
- A *calorimeter* is a vessel that is a good insulator which allows a thermal equilibrium to be achieved between substances without any energy loss to the environment

Calorimetry

- Analysis performed using a calorimeter
- Conservation of energy applies to the isolated system
- The energy that leaves the warmer substance equals the energy that enters the water
  - $Q_{cold} = -Q_{hot}$
  - Negative sign keeps consistency in the sign convention of ΔT

Calorimetry with More Than Two Materials

- In some cases it may be difficult to determine which materials gain heat and which materials lose heat
- You can start with $\Sigma Q = 0$
  - Each $Q = m\ c\ \Delta T$
  - Use $T_f - T_i$
  - You don't have to determine before using the equation which materials will gain or lose heat

Problem Solving Hint

- It is important to organize the information in a problem
- A table will be helpful
- Headings can be
  - $Q_{material}$
  - m
  - c
  - T_f
  - T_i

Phase Changes

- A *phase change* occurs when the physical characteristics of the substance change from one form to another
- Common phases changes are
  - Solid to liquid – melting
  - Liquid to gas – boiling
- Phases changes involve a change in the internal energy, but *no change in temperature*

Latent Heat

- During a phase change, the amount of heat is given as
  - $Q = \pm m L$
- L is the *latent heat* of the substance
  - Latent means hidden
  - L depends on the substance and the nature of the phase change
- Choose a positive sign if you are adding energy to the system and a negative sign if energy is being removed from the system

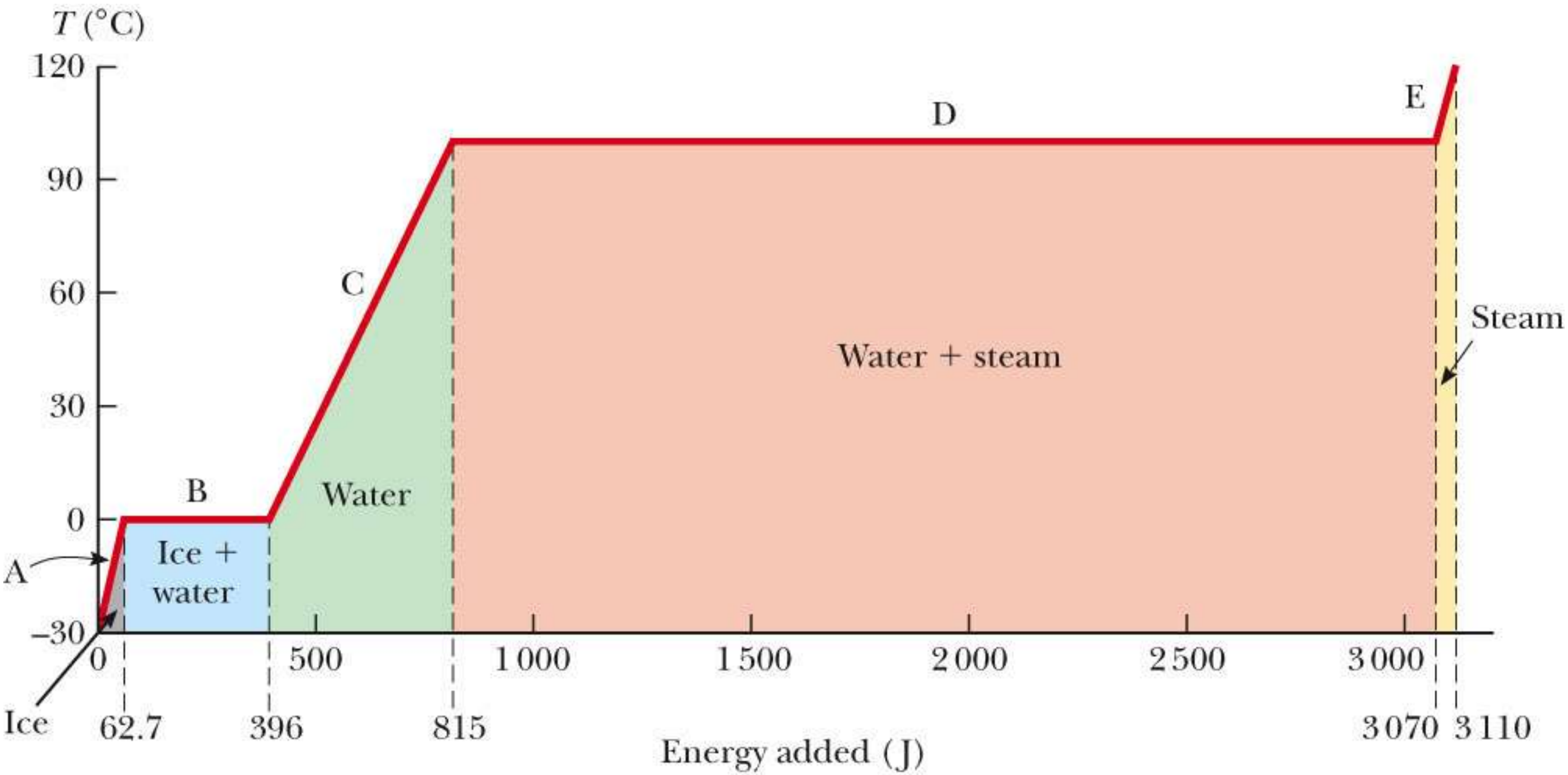
Latent Heat, cont.

- SI units of latent heat are J / kg
- *Latent heat of fusion*, L_f, is used for melting or freezing
- *Latent heat of vaporization*, L_v, is used for boiling or condensing
- Table 11.2 gives the latent heats for various substances

Sublimation

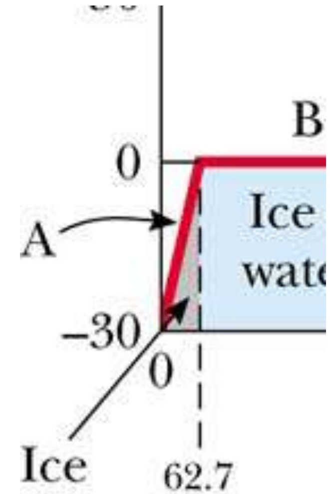
- Some substances will go directly from solid to gaseous phase
  - Without passing through the liquid phase
- This process is called *sublimation*
  - There will be a latent heat of sublimation associated with this phase change

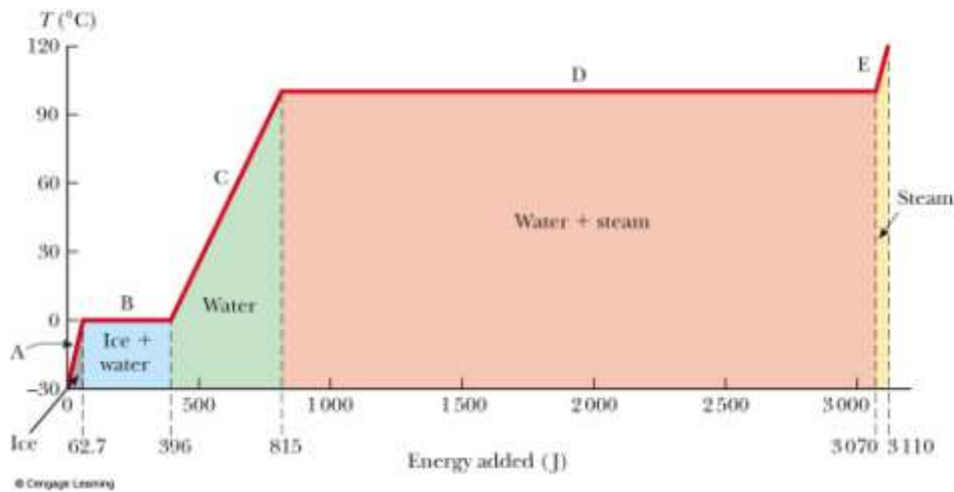
Graph of Ice to Steam



Warming Ice

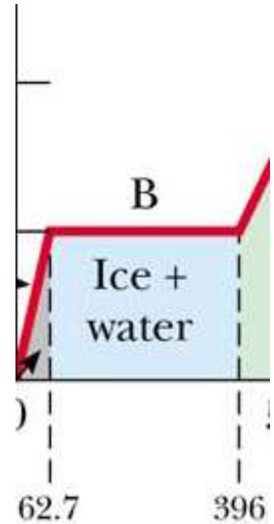
- Start with one gram of ice at −30.0º C
- During A, the temperature of the ice changes from −30.0º C to 0º C
- Use Q = m c ΔT
- Will add 62.7 J of energy

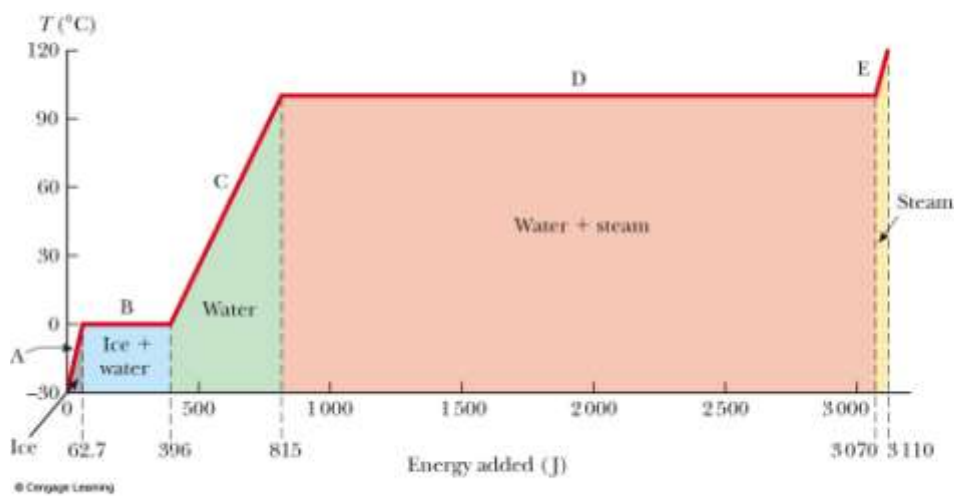




Melting Ice

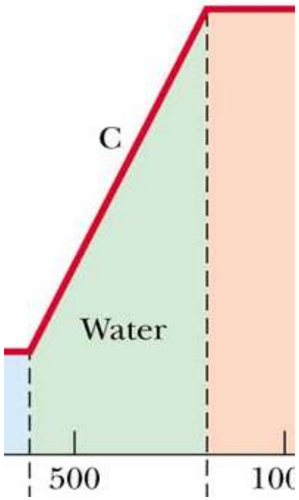
- Once at 0º C, the phase change (melting) starts
- The temperature stays the same although energy is still being added
- Use $Q = m\,L_f$
- Needs 333 J of energy

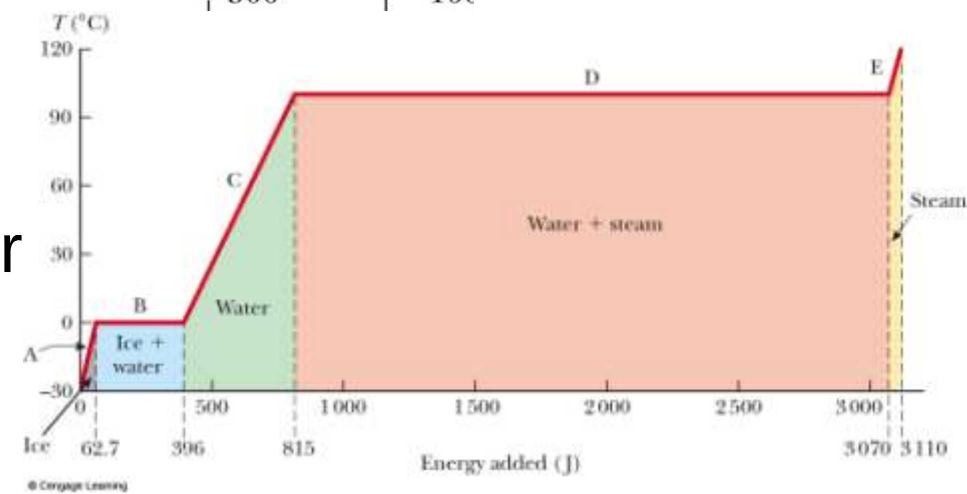




Warming Water

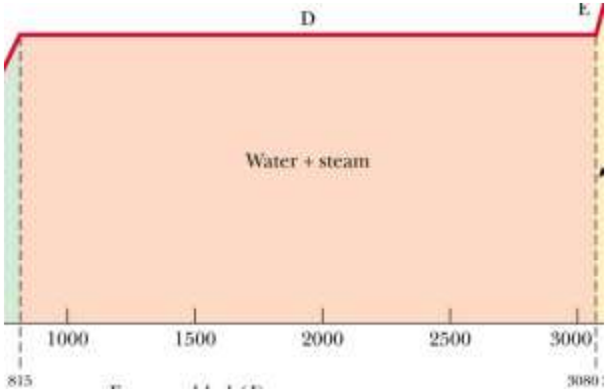
- Between 0º C and 100º C, the material is liquid and no phase changes take place
- Energy added increases the temperature
- Use Q = m c ΔT
- 419 J of energy ar added

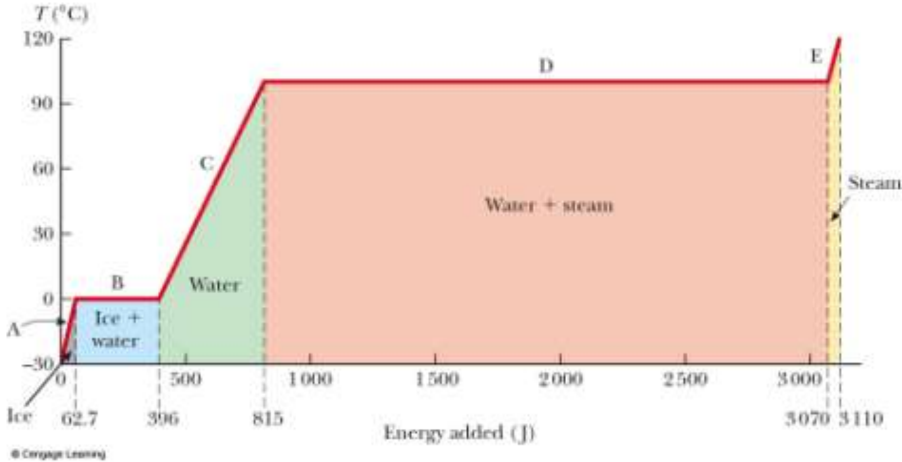




Boiling Water

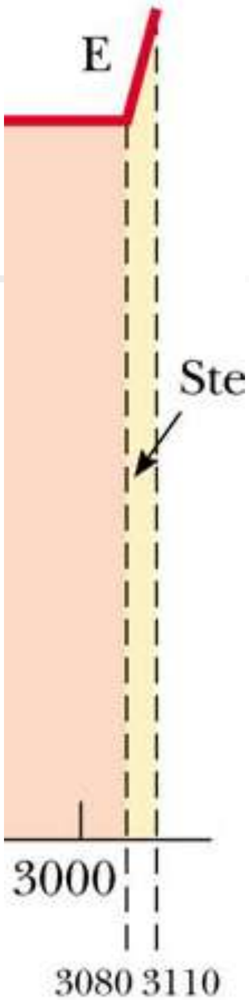
- At 100º C, a phase change occurs (boiling)
- Temperature does not change
- Use Q = m Lv
- 2 260 J of energy are needed

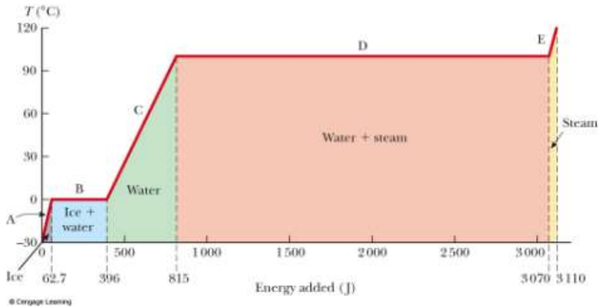




Heating Steam

- After all the water is converted to steam, the steam will heat up
- No phase change occurs
- The added energy goes to increasing the temperature
- Use $Q = m\ c\ \Delta T$
- To raise the temperature of the steam to 120°, 40.2 J of energy are needed





Problem Solving Strategies

- Make a table
  - A column for each quantity
  - A row for each phase and/or phase change
  - Use a final column for the combination of quantities
- Use consistent units

Problem Solving Strategies, cont

- Apply Conservation of Energy
  - Transfers in energy are given as $Q=mc\Delta T$ for processes with no phase changes
  - Use $Q = m L_f$ or $Q = m L_v$ if there is a phase change
  - Start with $\Sigma Q = 0$
    - Or $Q_{cold} = - Q_{hot}$, but be careful of sign
  - ΔT is $T_f - T_i$
- Solve for the unknown

Methods of Heat Transfer

- Need to know the rate at which energy is transferred
- Need to know the mechanisms responsible for the transfer
- Methods include
  - Conduction
  - Convection
  - Radiation

Conduction

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

Conduction example

- The molecules vibrate about their equilibrium positions
- Particles near the stove coil vibrate with larger amplitudes
- These collide with adjacent molecules and transfer some energy
- Eventually, the energy travels entirely through the pan and its handle

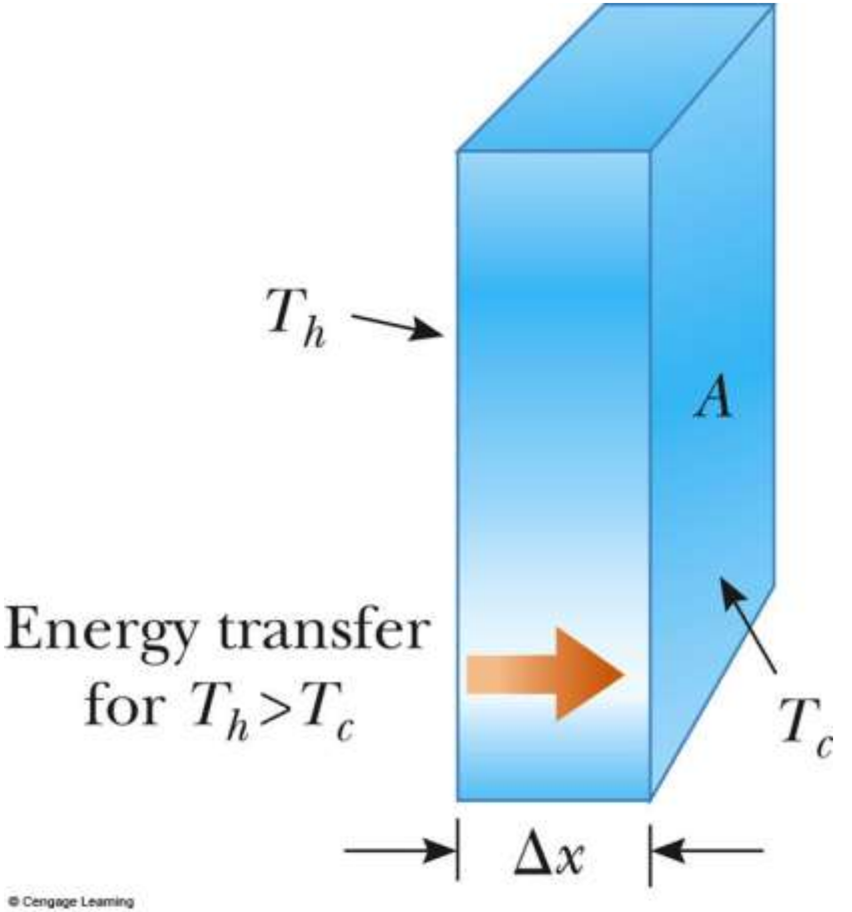
Conduction, cont.

- In general, metals are good 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
- Conduction can occur only if there is a difference in temperature between two parts of the conducting medium

Conduction, equation

- The slab allows energy to transfer from the region of higher temperature to the region of lower temperature

$$\wp = \frac{Q}{\Delta t} = kA\frac{T_h - T_c}{L}$$



Conduction, equation explanation

- A is the cross-sectional area
- L = Δx is the thickness of the slab or the length of a rod
- P is in Watts when Q is in Joules and t is in seconds
- k is the *thermal conductivity* of the material
  - See table 11.3 for some conductivities
  - Good conductors have high k values and good insulators have low k values

Home Insulation

- Substances are rated by their *R values*
  - $R = L / k$
  - See table 11.4 for some R values
- For multiple layers, the total R value is the sum of the R values of each layer
- Wind increases the energy loss by conduction in a home

Conduction and Insulation with Multiple Materials

- Each portion will have a specific thickness and a specific thermal conductivity
- The rate of conduction through each portion is equal

Multiple Materials, cont.

- The rate through the multiple materials will be

$$\frac{Q}{\Delta t} = \frac{A\left(T_h - T_c\right)}{\sum_i L_i / k_i} = \frac{A\left(T_h - T_C\right)}{\sum_i R_i}$$

- T_H and T_C are the temperatures at the outer extremities of the compound material

Convection

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

Convection example

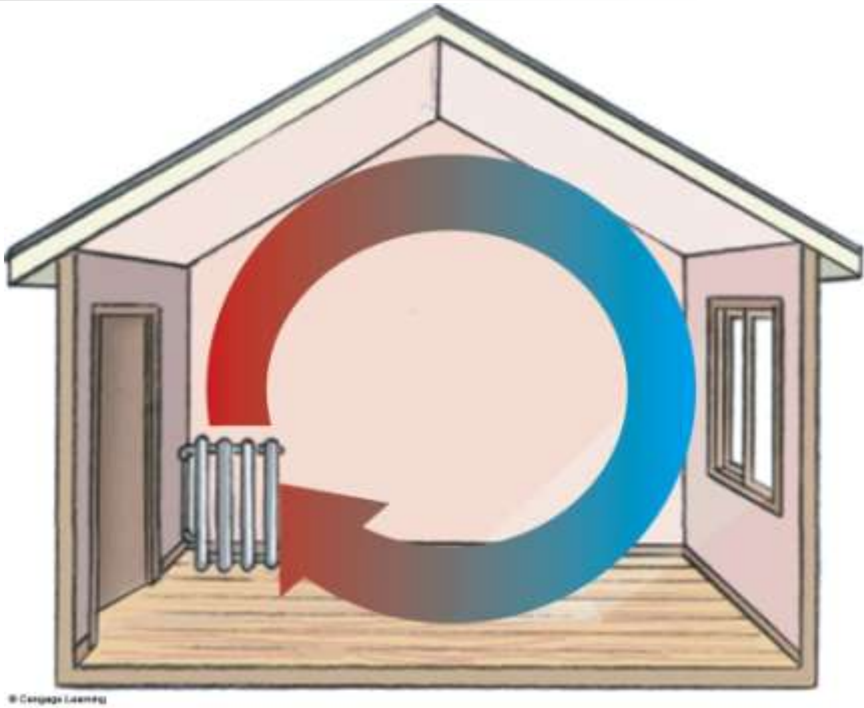
- Air directly above the flame is warmed and expands
- The density of the air decreases, and it rises
- The mass of air warms the hand as it moves by

Convection applications

- Boiling water
- Radiators
- Upwelling
- Cooling automobile engines
- Algal blooms in ponds and lakes

Convection Current Example

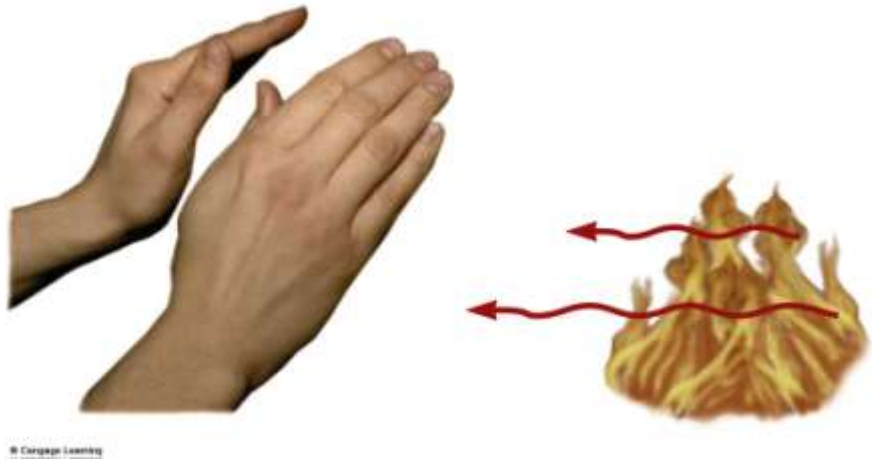
- The radiator warms the air in the lower region of the room
- The warm air is less dense, so it rises to the ceiling
- The denser, cooler air sinks
- A continuous air current pattern is set up as shown



Radiation

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

Radiation example



- The electromagnetic waves carry the energy from the fire to the hands
- No physical contact is necessary
- Cannot be accounted for by conduction or convection

Radiation equation

- $\wp = \sigma A e T^4$
  - The power 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
  - 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
  - $\wp_{net} = \sigma A e \; T^4 - T_o^4$
  - 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*
- An ideal absorber is also an ideal radiator of energy

Ideal Reflector

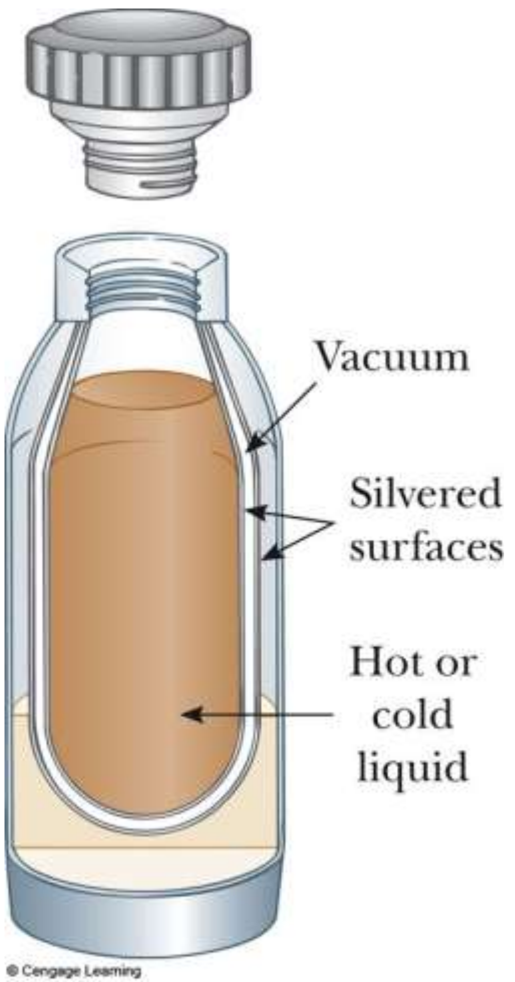
- An ideal reflector absorbs none of the energy incident on it
  - $e = 0$

Applications of Radiation

- Clothing
  - Black fabric acts as a good absorber
  - White fabric is a better reflector
- Thermography
  - The amount of energy radiated by an object can be measured with a thermograph
- Body temperature
  - Radiation thermometer measures the intensity of the infrared radiation from the eardrum

Resisting Energy Transfer

- Dewar flask/thermos bottle
- Designed to minimize energy transfer to surroundings
- Space between walls is evacuated to minimize conduction and convection
- Silvered surface minimizes radiation
- Neck size is reduced



Global Warming

- Greenhouse example
  - Visible light is absorbed and re-emitted as infrared radiation
  - Convection currents are inhibited by the glass
- Earth's atmosphere is also a good transmitter of visible light and a good absorber of infrared radiation