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
  - **1BTU = 1055 J**
  - **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

Specific Heats of Some Materials at Atmospheric Pressure

Substance	J/kg·°C	cal/g·°C
Aluminum	900	0.215
Beryllium	1 820	0.436
Cadmium	230	0.055
Copper	387	0.092 4
Ethyl Alcohol	2 430	0.581
Germanium	322	0.077
Glass	837	0.200
Gold	129	0.030 8
Ice	2 090	0.500
Iron	448	0.107
Lead	128	0.030 5
Mercury	138	0.033
Silicon	703	0.168
Silver	234	0.056
Steam	2 010	0.480
Tin	227	0.054 2
Water	4 186	1.00

Example 1

A steel strut is 2 m long, with a mass of 1.57 kg and cross-sectional area of 1×10^{-4} m^2. During the operation of the furnace the strut absorbs the net thermal energy of 2.5×10^5J. Find the change in temperature of the strut. (specific heat of steel is 448 J/kg·^{o}C)

Example 2

What is the temperature increase of 4.0 kg of water when heated by an 800-W immersion heater for 10 min? (c_w = 4 186 J/kg·°C)

Example 3

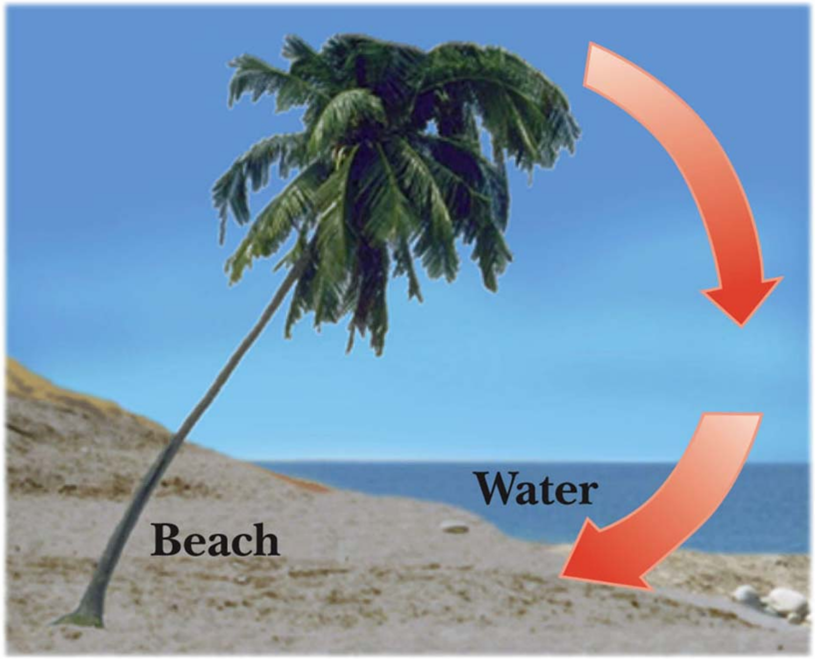
A solar heating system has a 25.0% conversion efficiency; the solar radiation incident on the panels is 800 W/m^2. What is the increase in temperature of 30.0 kg of water in a 1.00-h period by a 4.00-m^2-area collector? (c_w = 4 186 J/kg·°C)

Example 4

A 2.00-kg copper rod is 50.00 cm long at 23°C. If 40 000 J are transferred to the rod by heat, what is its change in length? c_{copper} = 387 J/kg·°C and $\alpha_{copper} = 17 \times 10^{-6}$/°C.

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

Example 5

A 125-g block of unknown substance with a temperature of 90^{o}C is placed in a Styrofoam cup containing 0.326 kg of water at 20^{0}C. The system reaches an equilibrium temperature of 22.4^{0}C. What is the specific heat of the substance, if the heat capacity of the cup is neglected?

Example 6

Find the final equilibrium temperature when 10.0 g of milk at 10.0°C is added to 160 g of coffee at 90.0°C. (Assume the specific heats of coffee and milk are the same as water and neglect the heat capacity of the container.) c_{water} = 1.00 cal/g·°C = 4186 J/kg·°C

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

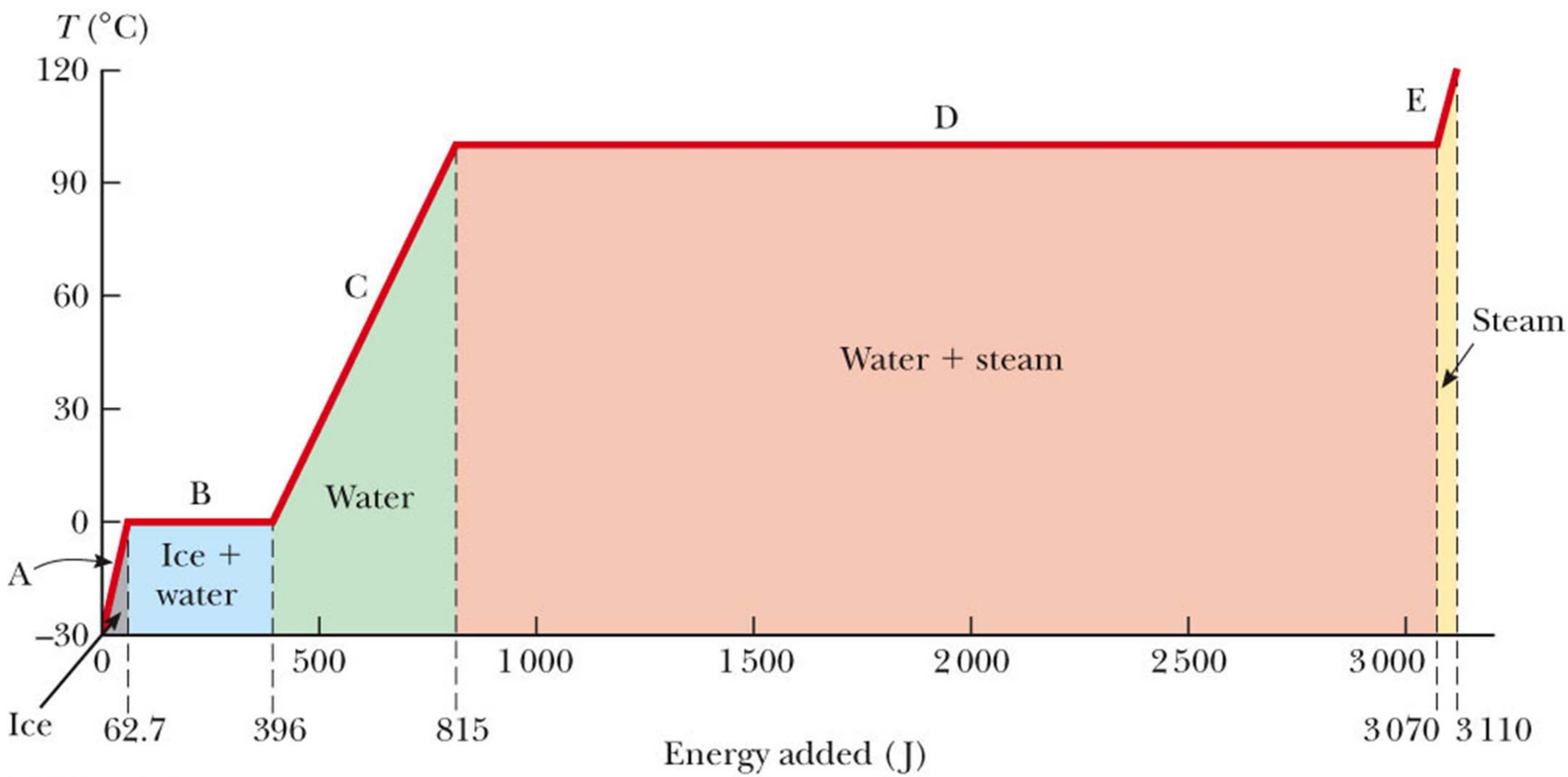
Sublimation

- 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

Latent Heats of Fusion and Vaporization

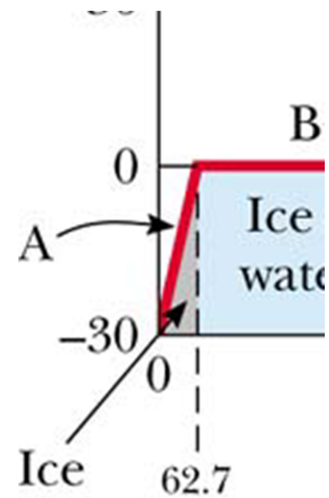
Substance	Melting Point (°C)	Latent Heat of Fusion (J/kg)	Latent Heat of Fusion cal/g	Boiling Point (°C)	Latent Heat of Vaporization (J/kg)	Latent Heat of Vaporization cal/g
Helium	−269.65	5.23×10^3	1.25	−268.93	2.09×10^4	4.99
Nitrogen	−209.97	2.55×10^4	6.09	−195.81	2.01×10^5	48.0
Oxygen	−218.79	1.38×10^4	3.30	−182.97	2.13×10^5	50.9
Ethyl alcohol	−114	1.04×10^5	24.9	78	8.54×10^5	204
Water	0.00	3.33×10^5	79.7	100.00	2.26×10^6	540
Sulfur	119	3.81×10^4	9.10	444.60	3.26×10^5	77.9
Lead	327.3	2.45×10^4	5.85	1 750	8.70×10^5	208
Aluminum	660	3.97×10^5	94.8	2 450	1.14×10^7	2 720
Silver	960.80	8.82×10^4	21.1	2 193	2.33×10^6	558
Gold	1 063.00	6.44×10^4	15.4	2 660	1.58×10^6	377
Copper	1 083	1.34×10^5	32.0	1 187	5.06×10^6	1 210

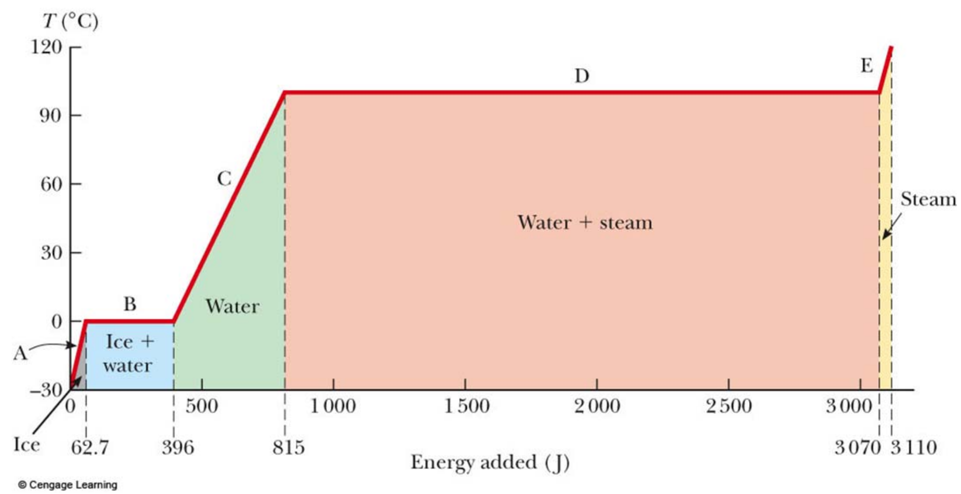
Graph of Ice to Steam



Warming Ice

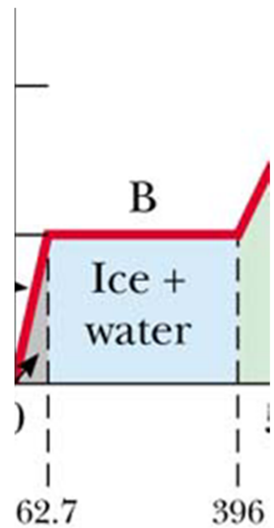
- Start with one gram of ice at −30.0º C
- During A, the temperature of the ice changes from −30.0º C to 0º C
- Use Q = m c ΔT
- Will add 62.7 J of energy

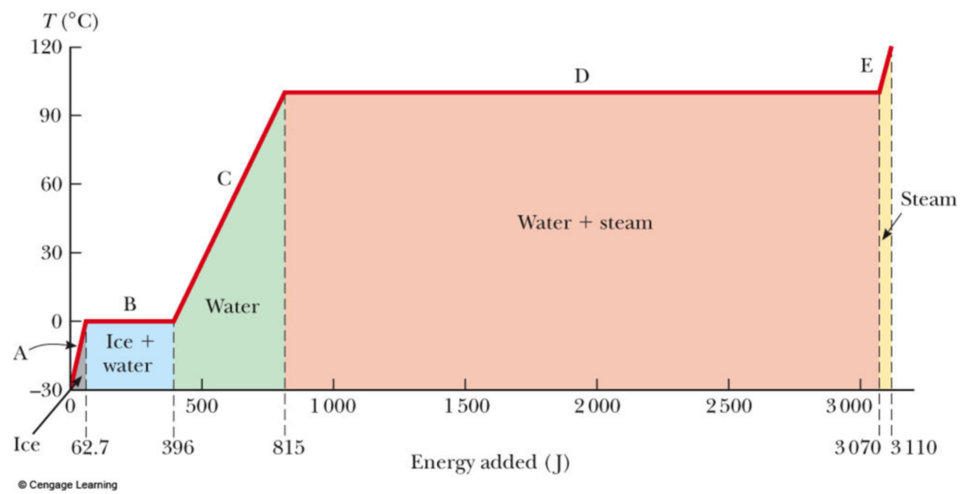




Melting Ice

- 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



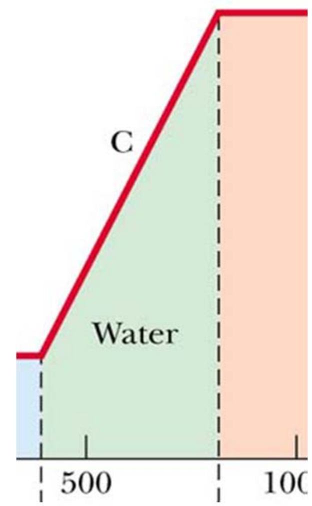


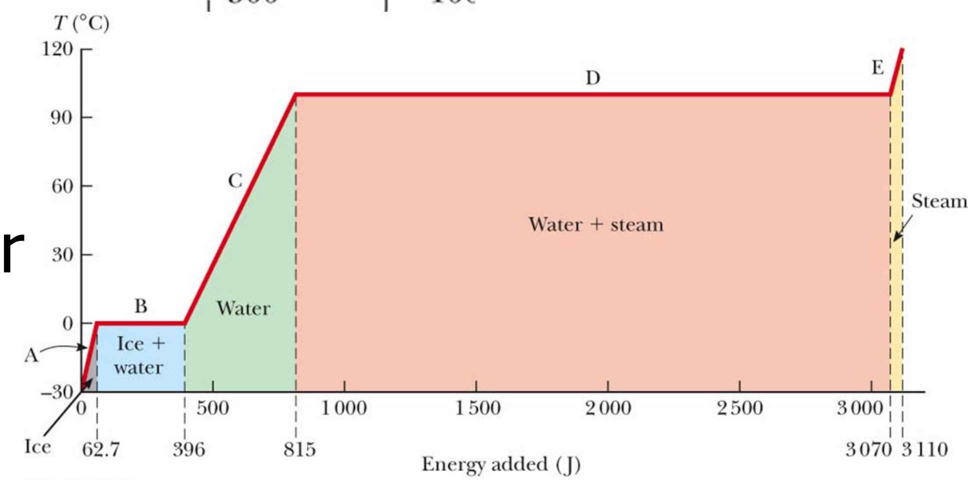
Example 7

Iced tea is made by adding ice to 1.8 kg of hot tea, initially at 80°C. How many kg of ice, initially at 0°C, are required to bring the mixture to 10°C? (L_f = 3.33 x 10^5 J/kg, c_w = 4 186 J/kg·°C)

Warming Water

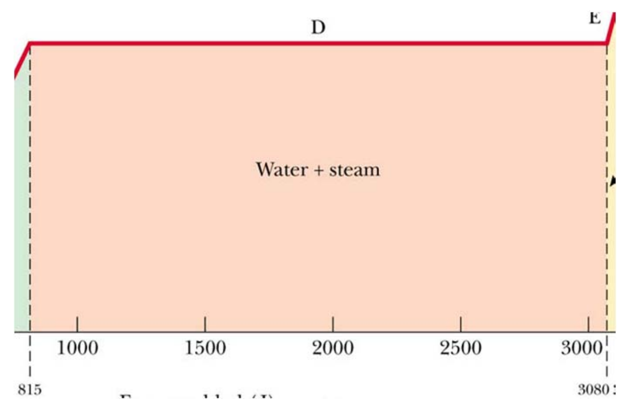
- Between 0º C and 100º C, the material is liquid and no phase changes take place
- Energy added increases the temperature
- Use Q = m c ΔT
- 419 J of energy ar added

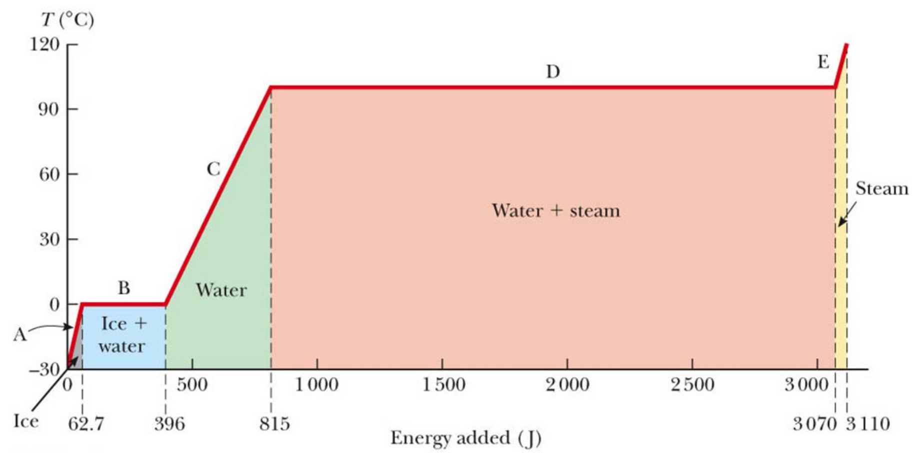




Boiling Water

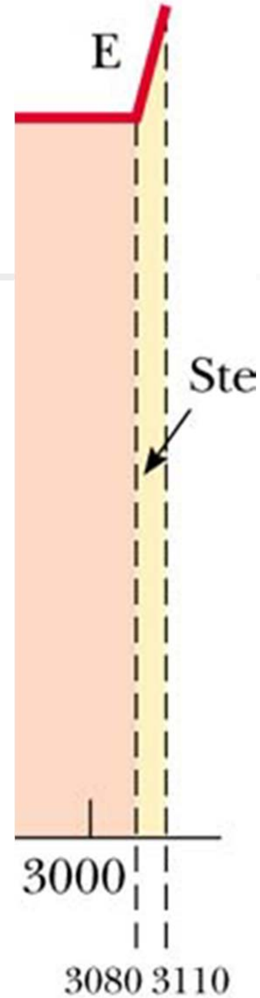
- At 100º C, a phase change occurs (boiling)
- Temperature does not change
- Use Q = m Lv
- 2 260 J of energy are needed

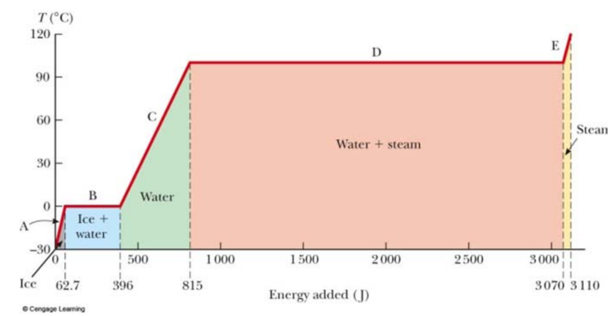




Heating Steam

- 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

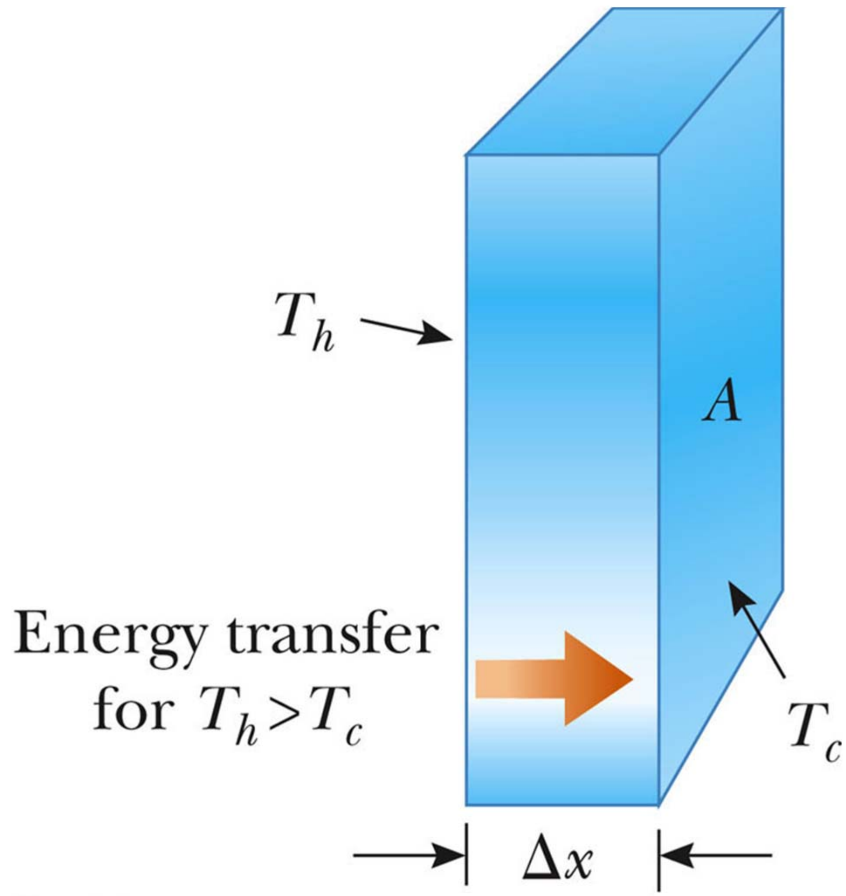
Conduction, cont.

- 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

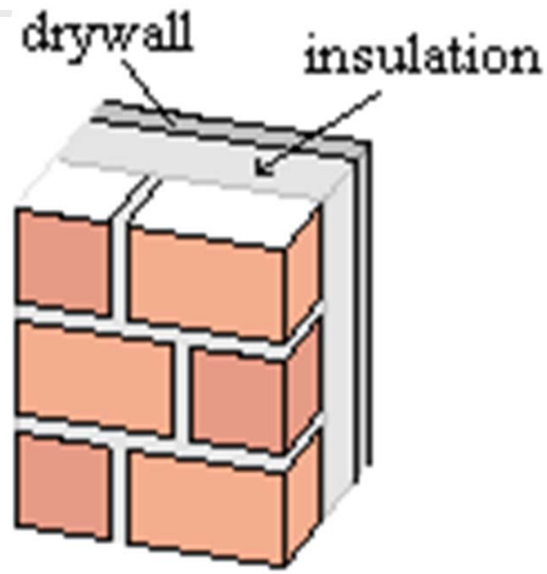
$$\frac{Q}{\Delta t} = \frac{A\left(T_h - T_c\right)}{\sum_i L_i / k_i} = \frac{A\left(T_h - T_C\right)}{\sum_i R_i}$$

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

R-Values for Some Common Building Materials

Material	*R* value ($ft^2 \cdot °F \cdot h/Btu$)
Hardwood siding (1.0 in. thick)	0.91
Wood shingles (lapped)	0.87
Brick (4.0 in. thick)	4.00
Concrete block (filled cores)	1.93
Styrofoam (1.0 in. thick)	5.0
Fiberglass batting (3.5 in. thick)	10.90
Fiberglass batting (6.0 in. thick)	18.80
Fiberglass board (1.0 in. thick)	4.35
Cellulose fiber (1.0 in. thick)	3.70
Flat glass (0.125 in. thick)	0.89
Insulating glass (0.25-in. space)	1.54
Vertical air space (3.5 in. thick)	1.01
Stagnant layer of air	0.17
Drywall (0.50 in. thick)	0.45
Sheathing (0.50 in. thick)	1.32

Example 8



A wall of a house consists of a layer of 10.2 –cm- thick layer of brick, a layer of fiber glass insulation 8.9 cm thick and a 1.25-cm-thick drywall. If inside the house the temperature is 23 ^{0}C and the outside temperature is 0^0 C, determine the rate of energy transfer through 1m^2 of the wall. (k_{brick} =0.84 J/s·m·K, k_{insul} = 0.048 J/s·m·K, $k_{drywall}$ = 0.48 J/s·m·K,)

Example 9

A thermopane window consists of two glass panes, each 0.05 m thick, with a 1-cm-thick sealed layer of air in between. If inside the room temperature is 23^0C and the outside temperature is 0^0C, determine the rate of energy transfer through $1m^2$ of the window. (k_{glass}=0.84 J/smK k_{air} = 0.0235 J/smK)

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

Example 10

A Styrofoam box has a surface of 0.72 m^2 and a wall thickness of 7.4 cm. The temperature of the inner surface is 1.3^0C, and of the outside 36^0C. If it takes 4 hours for 6 kg of ice to melt in the container, find the thermal conductivity of the Styrofoam.

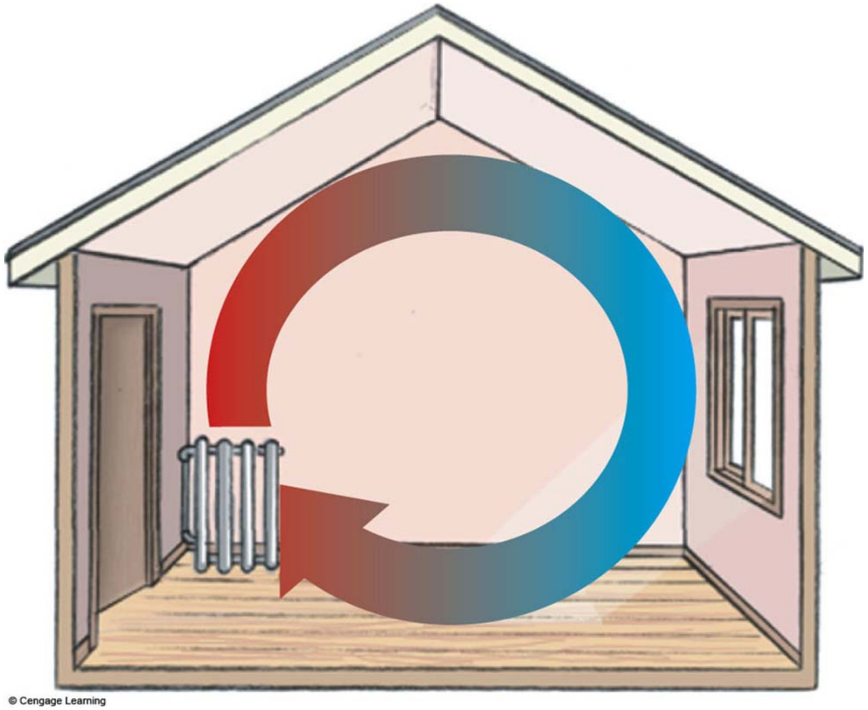
Answer: k = 0.41J/sKm

Convection applications

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

Convection Current Example

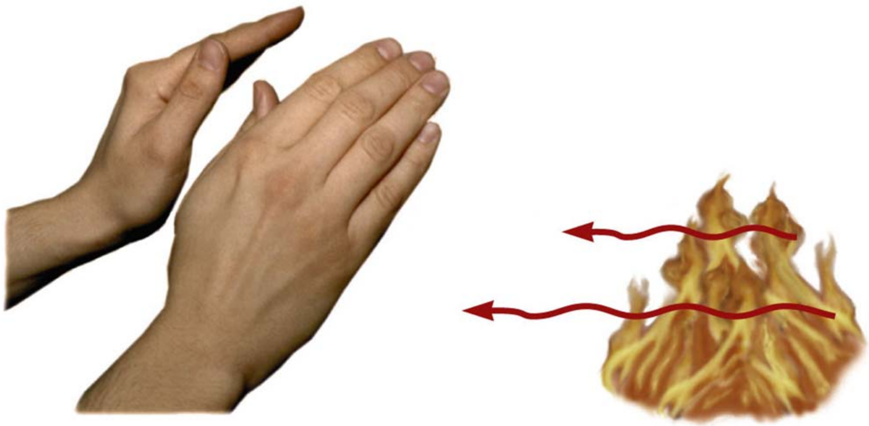
- The radiator warms the air in the lower region of the room
- The warm air is less dense, so it rises to the ceiling
- The denser, cooler air sinks
- A continuous air current pattern is set up as shown



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

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

Example 10

A radiator has an emissivity of 0.8 and its exposed area is 1.3 m^2 . The temperature of the radiator is 85^0C and the surrounding temperature is 20^0C. What is the net heat flow rate due to radiation from the radiator?

$\sigma = 5.6696 \times 10^{-8}\ W/m^2{\cdot}K^4$

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

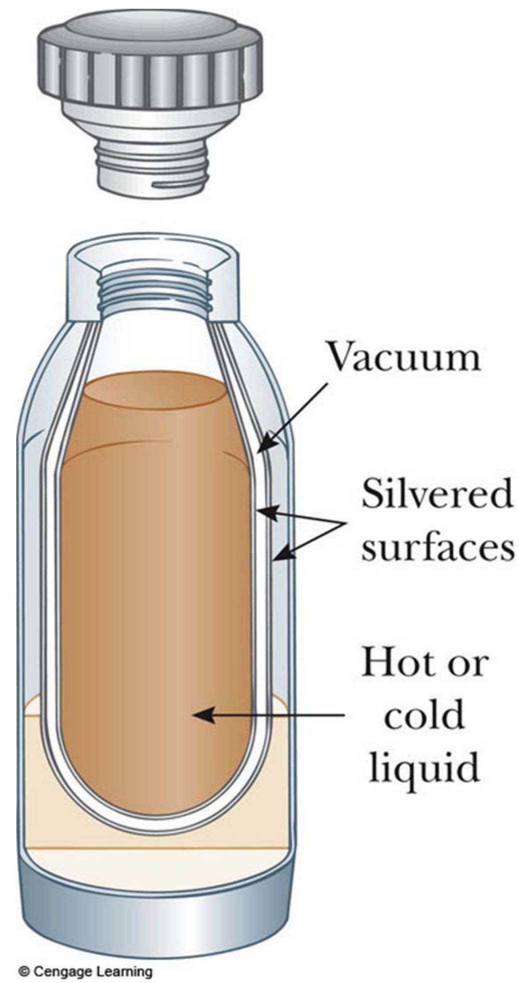
- An ideal reflector absorbs none of the energy incident on it
  - $e = 0$

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