Chapter 17: A Macroscopic Description of Matter

Physics 23

Faridian

Learning Goals for Chapter 17

Looking forward at …

- the meaning of thermal equilibrium, and what thermometers really measure.
- the physics behind the absolute, or Kelvin, temperature scale.
- how the dimensions of an object change as a result of a temperature change.
- how to do calculations that involve heat flow, temperature changes, and changes of phase.
- how heat is transferred by conduction, convection, and radiation.

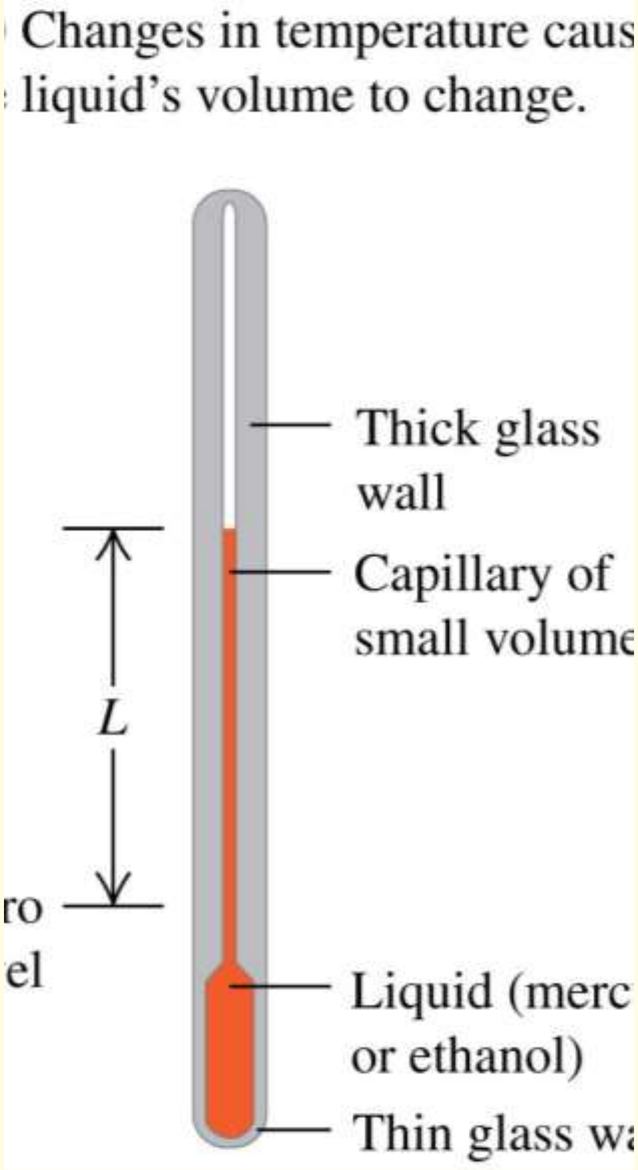
Macroscopic and Microscopic descriptions

- Thermodynamics: Branch of Physics dealing with temperature, heat , and related macroscopic properties (i.e. pressure, volume)

- Statistical Mechanics: Branch of Physics dealing with microscopic processes, mechanics of atoms and molecules.

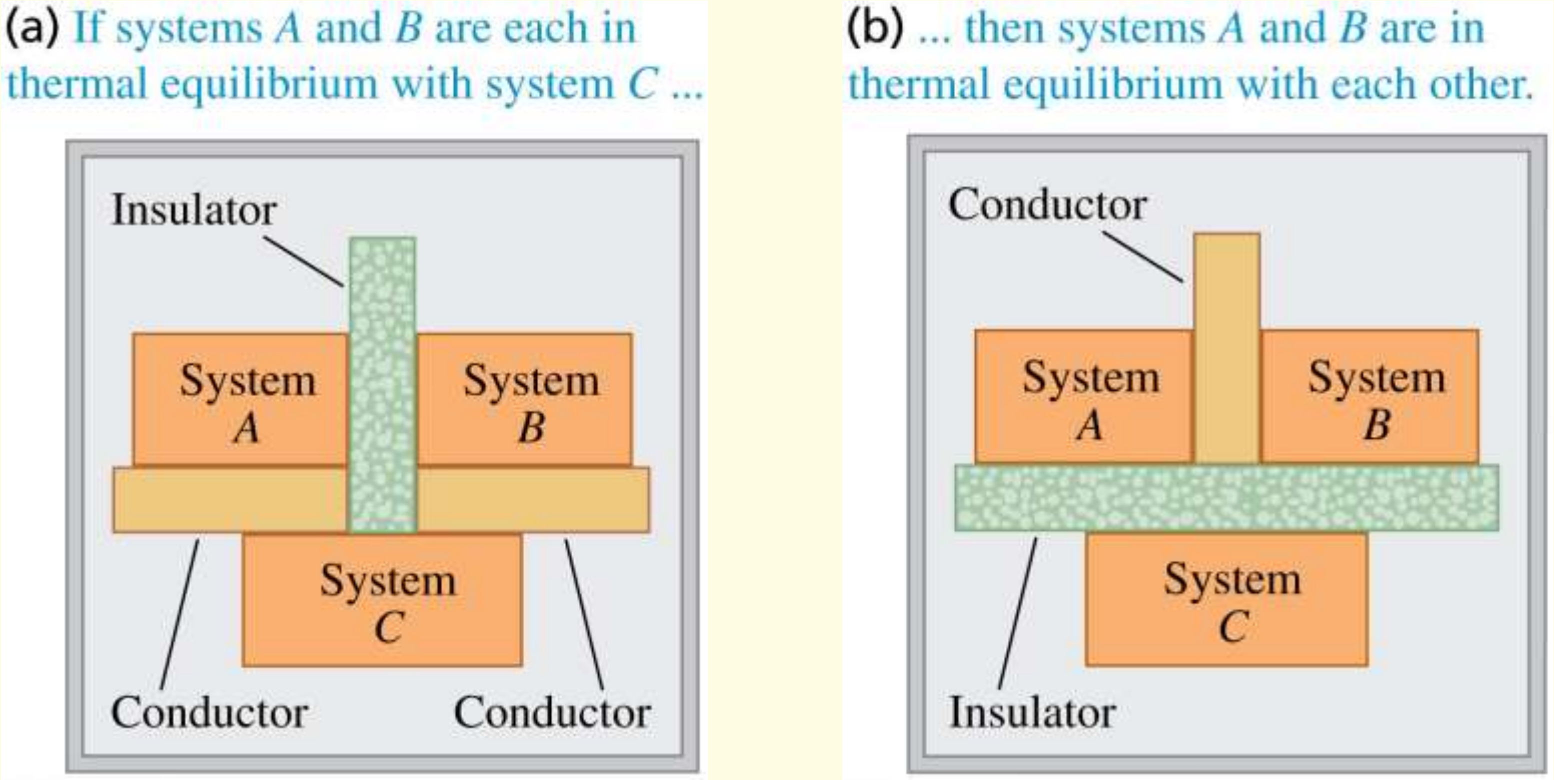
Temperature and thermal equilibrium

- We use a **thermometer** to measure **temperature**.
- For example, the volume of the liquid in the thermometer to the right changes with temperature.
- Two systems are in **thermal equilibrium** if and only if they have the same temperature.



The zeroth law of thermodynamics

- If C is initially in thermal equilibrium with both A and B, then A and B are in thermal equilibrium with each other.



17.2 Temperature scales/ Thermometers

- Thermometer: A system with an easily observed macroscopic property that changes with temperature
  - Change in volume of a liquid (mercury thermometer, or alcohol thermometer)
  - Change in length of a solid (bi-metallic strip)
  - Change in pressure of a gas at constant volume (constant-volume thermometer)
  - Change in volume of a gas at constant pressure
  - Change in electrical resistance of a conductor
  - Change in color of some object.

Thermometers cont.

- A thermometer can be calibrated by placing it in thermal contact with some natural systems that remain at constant temperature. Ex: Ice point of water: Mixture of water and ice at thermal equilibrium at atmospheric pressure yields 0°C, and the mixture of water and steam at thermal equilibrium at atmospheric pressure yields the steam point of water, 100 °C.

- For Celsius, the distance between these two points is divided into 100 equal sections.

Thermometers con. 2

- Problems: Limited temperature range: Mercury thermometer can't be used below freezing point of mercury: - 39°C, Alcohol not useful for temperatures over 85 °C, so we need a thermometer independent of the substance used.

- Place thermometer in contact with system whose temperature we want, and let them reach thermal equilibrium, read temperature.

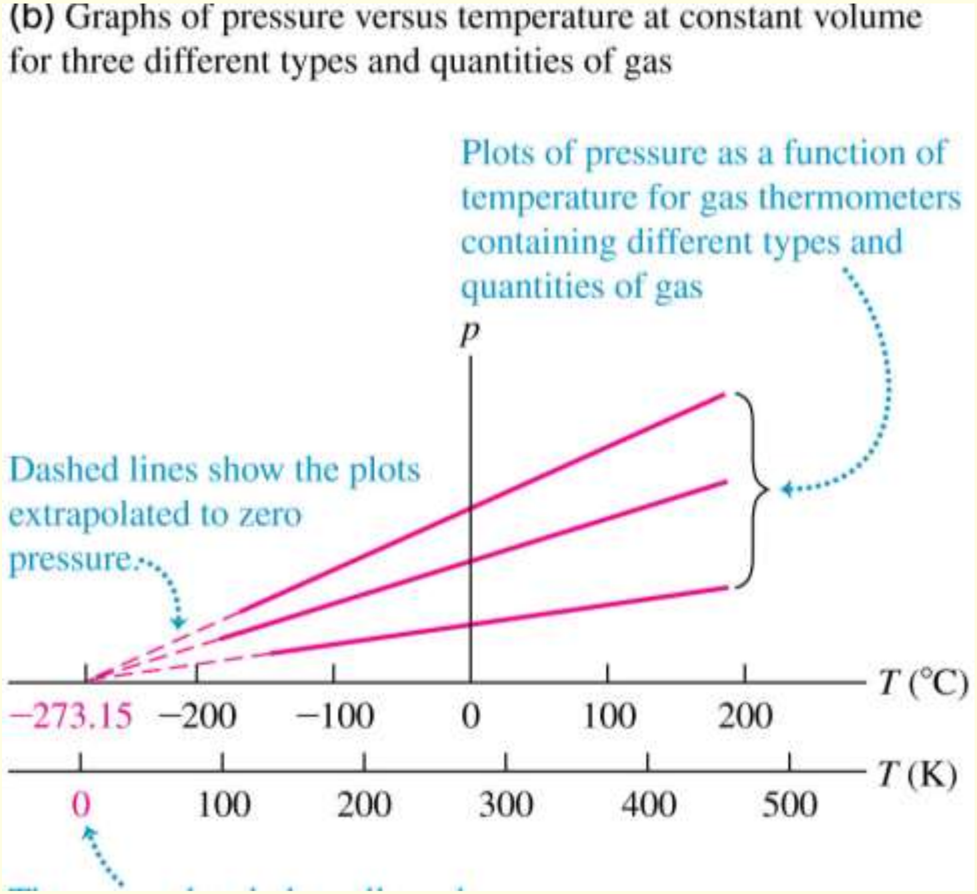
17.3 Gas Thermometers and Kelvin Scale

- Gas thermometer: Use either pressure or volume of gas to indicate temperature. Example: Constant-volume gas thermometer. Volume of gas is held constant. Temperature is a linear function of the gas pressure   (fig 19.5 p. 475)

- Two points needed to define linear function: Zero gas pressure, and triple point of water (when the solid, liquid, and gas phases of water are at equilibrium).

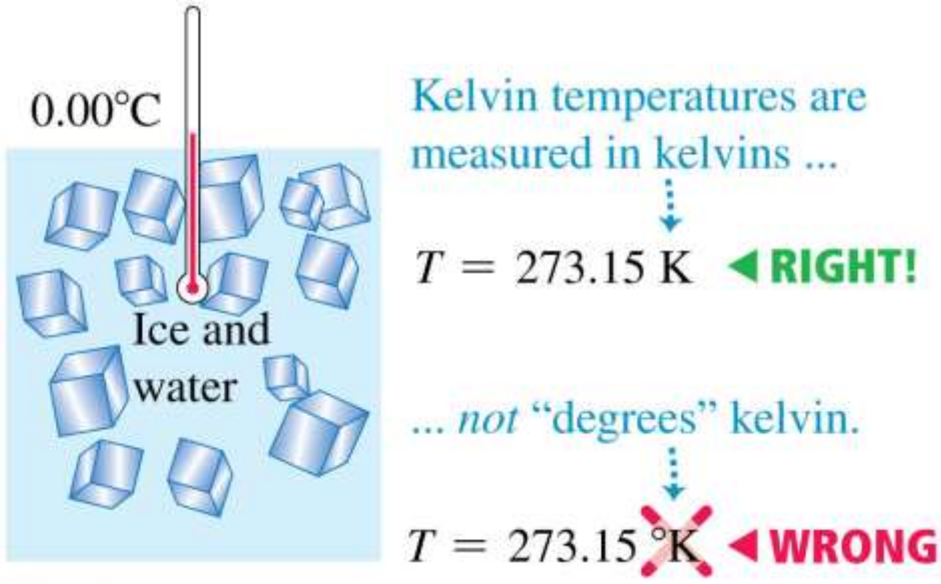
Absolute zero

There is a temperature, −273.15°C, at which the absolute pressure of any gas would become zero.



Temperature scales

- On the *Kelvin* (or *absolute*) *temperature scale*, 0 K is the extrapolated temperature at which a gas would exert no pressure.
- To convert from Celsius to Kelvin:



$$\underset{\text{Kelvin temperature}}{T_K} = \underset{\text{Celsius temperature}}{T_C} + 273.15$$

Temperature scales

- Kelvin scale: Triple point 273.16 K

  $T = 273.16\ P / P_3$

  Where P =Thermometer pressure at temperatureT

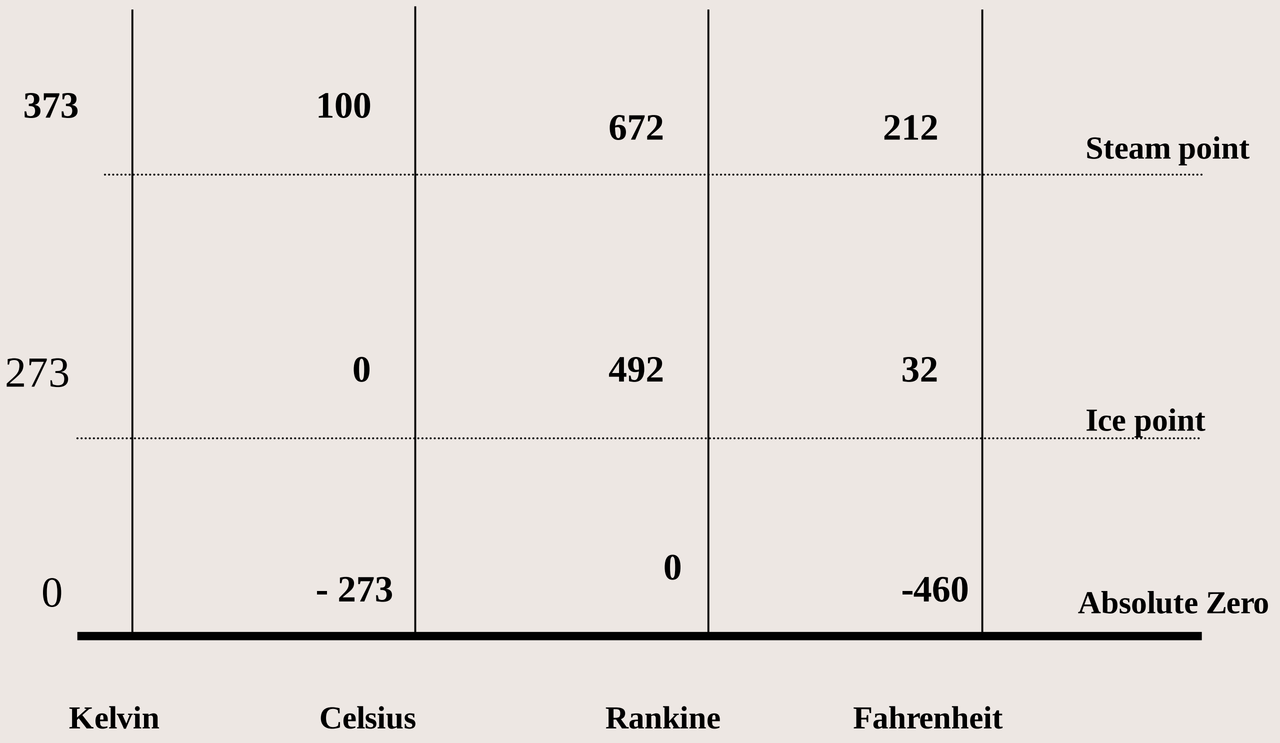
  P_3 = Pressure at triple point
- Absolute zero: zero of Kelvin scale

- Other scales: Celsius (^{o} C), Fahrenheit (^{o} F), Rankine (^{o}R)
- $Tc = T_K – 273.15$

Temperature scales cont.

- Celsius: - Melting point of ice 0 ºC
  - Boiling point of water 100 ºC
  - Triple point of water 0.01 ºC
  - Absolute zero at –273.15 ºC
- Fahrenheit: - British system
  - Melting point of ice: 32ºF
  - Boiling point of water: 212 ºF
  - $T_f = 9/5\ T_c + 32$
- Rankine: Same as Fahrenheit, but zero Rankine is absolute zero

Temp scales 2



Example 1

- On a day when the temperature reaches 50 F, What is the temperature in degrees Celsius and in Kelvins:

Example 1: ans

- We have:

$$T_f = \frac{9}{5}T_c + 32^\circ F$$

$$50 = \frac{9}{5}T_c + 32^\circ F$$

$$T_c = \frac{5}{9}(50 - 32) = 10^\circ C$$

$$T_k = T_c + 273.15 = 283K$$

Example 2

- A pan of water is heated from 25°C to 80°C. What is the change in its temperature on the Kelvin scale and on the Fahrenheit scale?

Example 2 ans.

- We have:

$$\Delta T_k = \Delta T_c = 80 - 25 = 55^\circ C = 55K$$

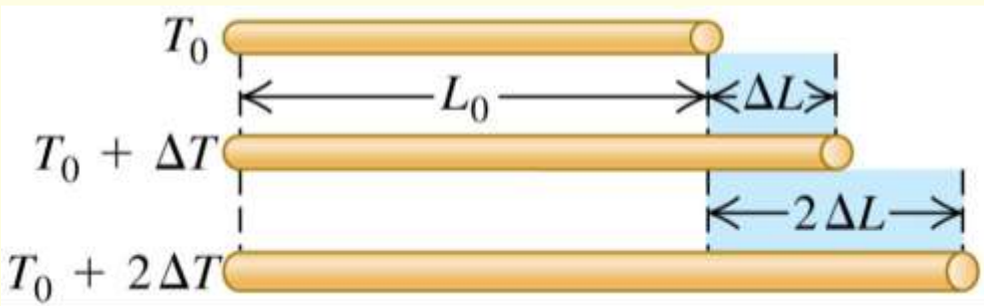
$$\Delta T_F = \frac{9}{5}\Delta T_c + 32 = \frac{9}{5}(55) + 32$$

$$= 99 + 32 = 131^\circ F$$

17.4 Thermal expansion

- When a solid is subjected to a rise in temperature ΔT, its increase in length ΔL is equal to:
- $\Delta L = \alpha L_0 \Delta T$
- In 3 dimensions, the change in volume of a substance with temperature is given by: The coefficient of volume expansion β:
- $\beta = (\Delta V/V)/\Delta T = 3\alpha$

Linear thermal expansion



- Increasing the temperature of a rod causes it to expand.
- For moderate changes in temperature, the change in length is given by:

Linear thermal expansion:

$$\Delta L = \alpha L_0 \Delta T$$

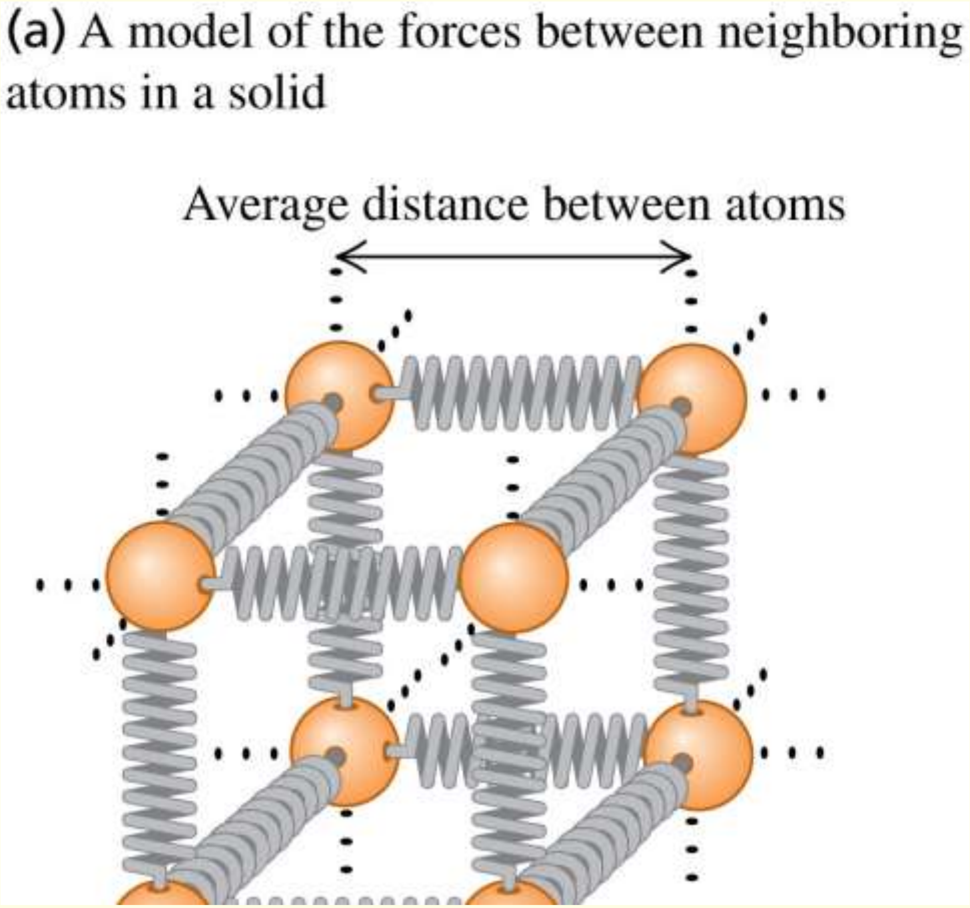
Change in length

Original length

Temperature change

Coefficient of linear expansion

Molecular basis for thermal expansion



- We can understand linear expansion if we model the atoms as being held together by springs.
- When the temperature increases, the average distance between atoms also increases.
- As the atoms get farther apart, every dimension increases.

Expanding holes and volume expansion

- If an object has a hole in it, the hole also expands with the object, as shown.
- The hole does *not shrink*.
- The change in volume due to thermal expansion is given by
- $$\Delta V = \beta V_0 \, \Delta T,$$

where β is the **coefficient of volume expansion** and is equal to 3α.

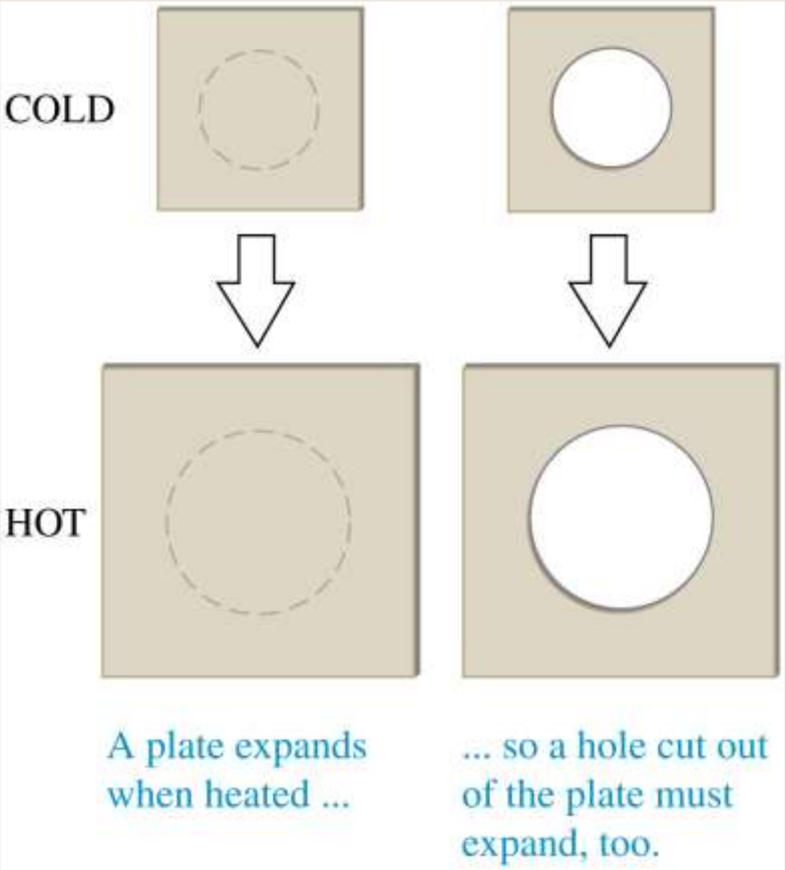


Table 17.1: Coefficients of linear expansion

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

Example of thermal expansion

- This railroad track has a gap between segments to allow for thermal expansion.
- On hot days, the segments expand and fill in the gap.
- If there were no gaps, the track could buckle under very hot conditions.

Example 3

- A copper bas is 80 cm long at 15 °C. What is the increase in length when it is heated to 35 °C? The linear expansion coefficient for copper is 1.7 x 10^{-5} °C^{-1}

Example 4

- A steel television-broadcasting tower is taller in the daytime when it is warm than it is at night. Steel expands or contracts about 1 part in 100,000 for each degree Celsius change. What is the change in height for a 500 m steel tower when its temperature changes by 20 °C from day to night?

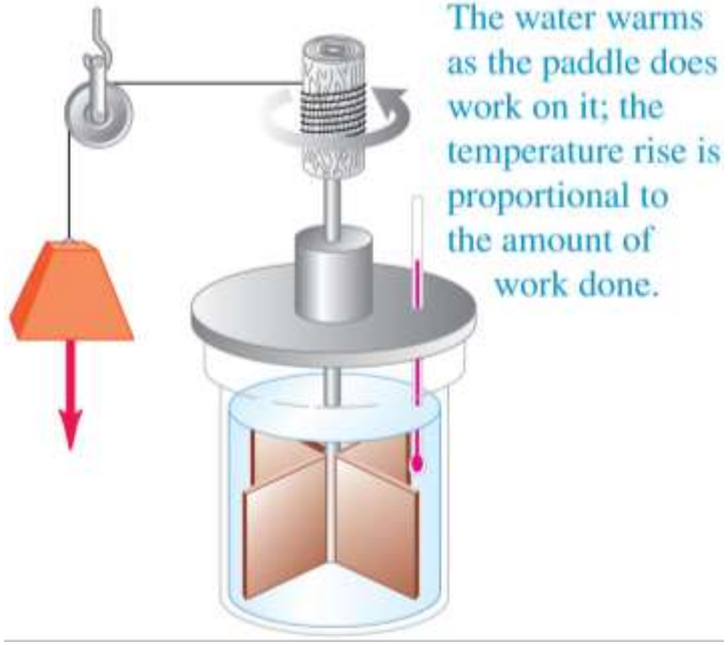
17-5 Quantity of heat

- Heat transferred to an object and the resulting change ΔT in the object's temperature are proportional.

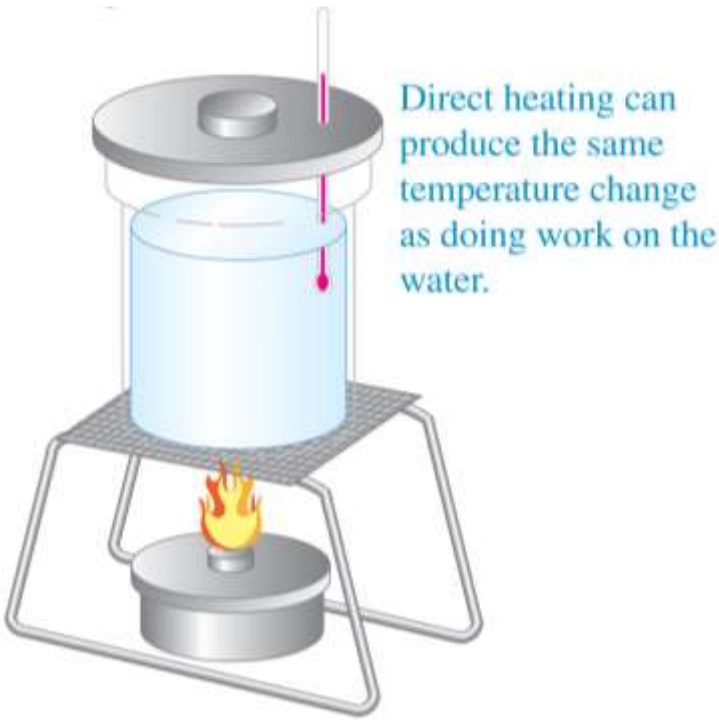
$\Delta Q = C\,\Delta T = mc\Delta T$

- Specific Heat: The amount of energy that raises the temperature of 1 kg of a substance by 1K. Symbol: c
- For water: c = 1k cal / kg °C = 4180 J /kg °C (specific heat)

Raising the temperature of a system mechanically



- Sir James Joule (1818–1889) studied how water can be warmed by vigorous stirring with a paddle wheel.



Raising temperature by direct heating

- The same temperature change caused by stirring can also be caused by putting the water in contact with some hotter body.
- The **calorie** (abbreviated cal)
  is the amount of heat required to raise the temperature of 1 gram of water from 14.5°C to 15.5°C.

Specific heat

- The quantity of heat Q required to increase the temperature of a mass m of a certain material by ΔT is:

Heat required to change temperature of a certain mass

Mass of material

$$Q = mc\,\Delta T$$

Temperature change

Specific heat of material

- The **specific heat** c has different values for different materials.
- The specific heat of water is approximately 4190 J/kg · K.

17-5 cont. 2

<u>Heat Capacity and Specific Heat</u>

c_{water} = 1 cal/g°C = 4184 J/kg K

- Specific heat does vary with temperature, but for small temperature intervals, c can be treated as a constant. Water has the highest specific heat of common earth materials, which explains the moderate temperatures near large bodies of water.

Molar heat capacity

- The quantity of heat Q required to increase the temperature of n moles of a certain material by ΔT is:

Heat required to change temperature of a certain number of moles

$$Q = nC\,\Delta T$$

Number of moles of material

Temperature change

Molar heat capacity of material

- The **molar heat capacity** C has different values for different materials.
- The molar heat capacity of water is approximately 75.4 J/mol · K.

Table 17.3: Specific heats and molar heat capacities

Substance	Specific Heat, c (J/kg · K)	Molar Mass, M (kg/mol)	Molar Heat Capacity, C (J/mol · K)
Aluminum	910	0.0270	24.6
Beryllium	1970	0.00901	17.7
Copper	390	0.0635	24.8
Ethanol	2428	0.0461	111.9
Ethylene glycol	2386	0.0620	148.0
Ice (near 0°C)	2100	0.0180	37.8
Iron	470	0.0559	26.3
Lead	130	0.207	26.9
Marble ($CaCO_3$)	879	0.100	87.9
Mercury	138	0.201	27.7
Salt (NaCl)	879	0.0585	51.4
Silver	234	0.108	25.3
Water (liquid)	4190	0.0180	75.4

17-5 Units of heat

- Units of heat: Calorie, BTU, and Joule

- Calorie (cal) = heat needed to raise the temperature of 1 g of water by 1 °C

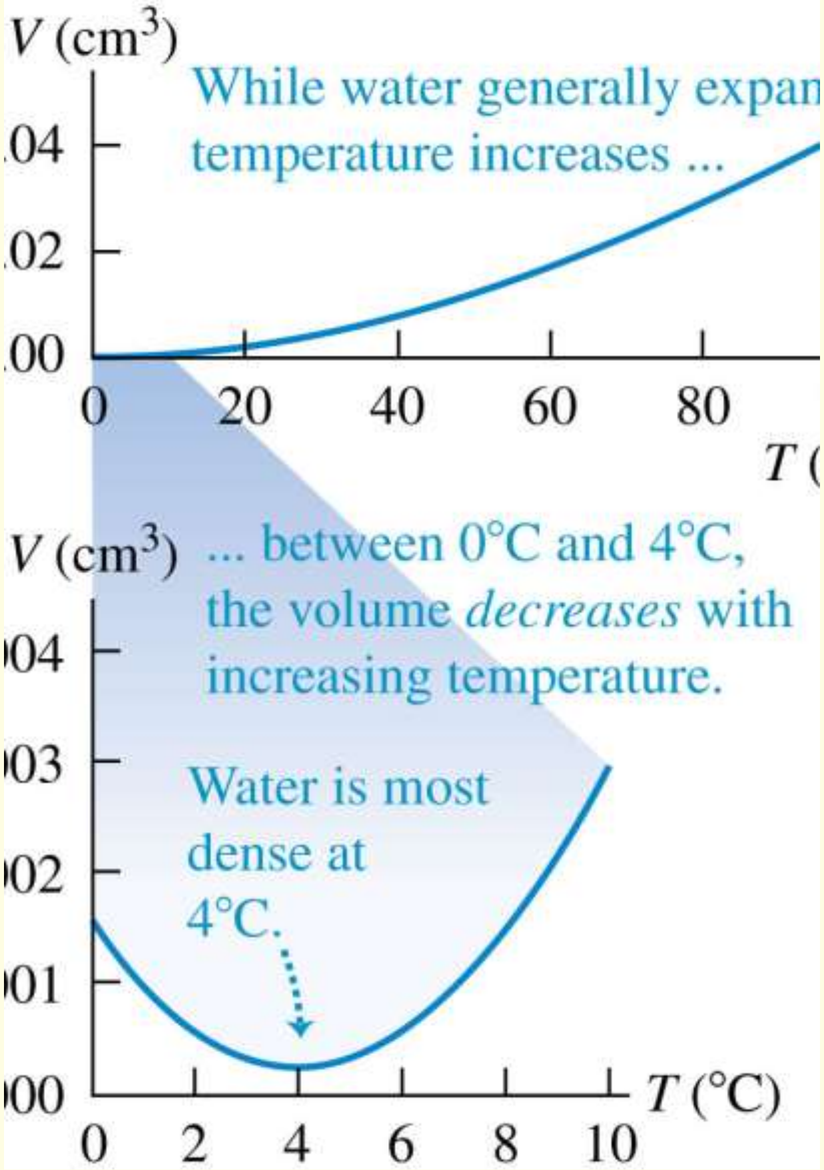
1 calorie = 4.184 J

- BTU = British Thermal Unit = Amount of heat needed to raise the temperature of one pound of water by 1°F .

1 BTU = 1055 J

Thermal expansion of water

- Between 0°C and 4°C, water *decreases* in volume with increasing temperature.
- Because of this anomalous behavior, lakes freeze from the top down instead of from the bottom up.



17-5 cont.

- Values of heat capacity and specific heat depend on an object's pressure or volume changes as it is heated:
  - In solids and liquids there is no major change
  - In gases, we will need to define two specific heats:
    - C_p pressure constant
    - C_v Volume constant

17.5 Equilibrium Temperature

- When two objects are placed in thermal contact with each other and are thermally isolated form the environment, all the energy leaving the hotter object goes to the cooler object.
- $Q_1 = - Q_2$
- $m_1 c_1 \Delta T_1 + m_2 c_2 \Delta T_2 = 0$
- Where ΔT is negative for the hotter object.

Example 5

- A student eats a dinner rated at 2000 food Calories. He wishes to do an equivalent amount of work at the gym by lifting a 50.0 kg mass. How many times must he raise the mass to expend this much energy? Assume he raises it a distance of 2.00 m each time and no energy is gained when it is dropped on the floor.

Example 5 ans:

- 1Cal= 1000cal

$$2000Cal = 2\times10^6 cal \times \frac{4.186J}{1cal} = 8.37\times10^6 J$$

Work done in lifting the mass a distance h : mgh

n times : nmgh

$\mathrm{W = nmgh} = 8.37\times10^6 J$

$$n = \frac{W}{mgh} = \frac{8.37\times10^6 J}{(50kg)(9.8m/s^2)(2.00m)} = 8.54\times10^3 times$$

If he is in good shape and lifts the weight once every 5 s,

it will take hime about 12 hours to do this

17.6 Phase changes

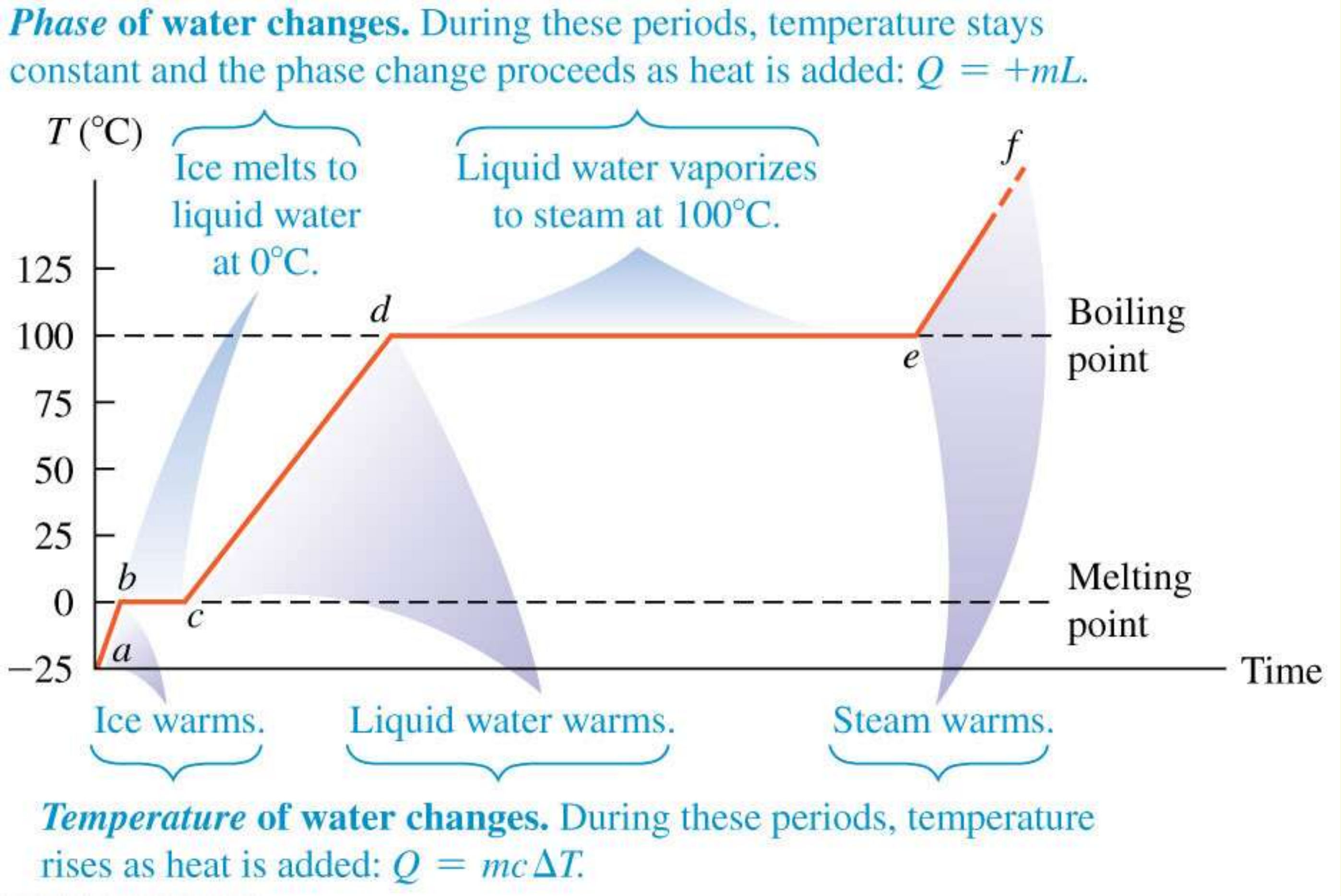
- The **phases** (or states) of matter are solid, liquid, and gas.
- A **phase change** is a transition from one phase to another.
- The temperature does not change during a phase change.
- The **latent heat**, *L*, is the heat per unit mass that is transferred in a phase change.

Mass of material that changes phase

Heat transfer in a phase change $Q = \pm mL$ Latent heat for this phase change

+ if heat enters material, − if heat leaves

Heat added to ice at a constant rate



17.6 Phase Changes

- During a phase change, the heat added is used to break the bonds between the molecules. The temperature remains constant. The energy that must be added to change the phase of a substance is called "latent heat" or heat of transformation.

Q = L m

- From solid to liquid:

  $L = L_f$ = Heat of fusion

  $Q = m L_f$

- From liquid to gas:

  $L = L_v$ = Heat of vaporization

  $Q = m L_v$

Heat of fusion

- The metal gallium, shown here melting in a person's hand, is one of the few elements that melts at room temperature.
- Its melting temperature is 29.8°C, and its **heat of fusion** is $L_f = 8.04 \times 10^4$ J/kg.

Heat of vaporization

- The water may be warm and it may be a hot day, but these children will feel cold when they first step out of the swimming pool.
- That's because as water evaporates from their skin, it removes the **heat of vaporization** from their bodies.
- To stay warm, they will need to dry off immediately.

Phase change for water

For water:

- L_f = 79.7 kcal / kg = 333kJ/kg (Heat of fusion)

- L_v = 539 kcal /kg = 2260 kJ/kg
(Heat of vaporization)

17-6 Calorimetry

- Equilibrium Temperature: When two objects are placed in thermal contact with each other and are thermally isolated form the environment, all the energy leaving the hotter object goes to the cooler object.
- $Q_1 = - Q_2$
- $m_1 c_1 \Delta T_1 + m_2 c_2 \Delta T_2 = 0$
- Where ΔT is negative for the hotter object.

Example 6

- A 75g block of copper, taken from a furnace, is dropped into a 300g glass beaker containing 200g of water. The temperature of the water rises from 12° to 27°C. What was the temperature of the furnace?

$$c_c = 0.092 cal / g^\circ C$$

$$c_B = 0.12 cal / g^\circ C$$

$$c_w = 1.0 cal / g^\circ C$$

Example 6 solution:

- Heat lost (from copper) = heat gained(beaker and water)

$$m_c c_c (T_c - T_e) = (m_B c_B + m_w c_w)(T_e - T_w)$$

$$(75g)(0.092cal/g^\circ C)(T_c - 27^\circ C)$$

$$= \left(\left(300g)(0.12cal/g^\circ C\right) + \left(200g)(1.0cal/g^\circ C\right)\right)(27^\circ C - 12^\circ C)$$

$$T_c = 530^\circ C$$

Example 7

- A 0.0500 kg piece of metal is heated to 200° C and then dropped into a beaker containing 0.400 kg of water initially AT 20.0°C. If the final equilibrium temperature of the mixed system is 22.4 °C, find the specific heat of the metal. (c_w= 4186 J/kg°C)

Example 7 solution

- Heat lost(by metal) = heat gained(by water)

$$m_m c_m \Delta T_m = m_w c_w \Delta T_w$$

$$(0.0500kg)c_m(200^\circ C - 22.4^\circ C) =$$

$$(0.400kg)(4186J / kg^\circ C)(22.4^\circ C - 20.0^\circ C)$$

$$c_m = 453J / kg^\circ C$$

Example 8

- Calculate the energy needed to change 25 g of ice at -15°C to steam at 130°C

Specific heat of ice = 2.06 x 10^3 J/kg °C, specific heat of steam = 2.02 x 10^3 J/kg °C

Example 9

- A 200 g piece of aluminum at 90°C is placed in a 100g glass container which holds and unknown amount of water at 20.0°C. If the equilibrium temperature is 21.6°C, determine the amount of water in the container.

c glass = 0.200 kcal/kg°C,

$c_{aluminum}$ = 0.220 kcal/kg °C

17.7 Mechanisms of Heat Transfer

Heat can be transferred in three ways:

- Conduction
- Convection
- Radiation

Mechanisms of heat transfer

In nature, energy naturally flows from higher temperature objects to lower temperature objects; this is called **heat transfer**.

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

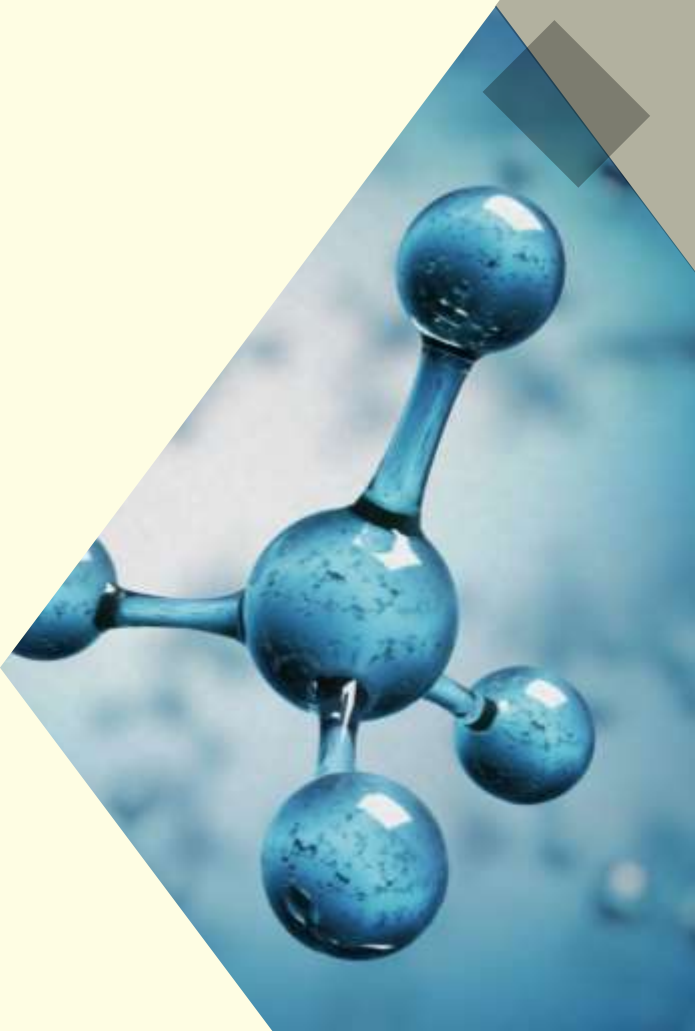
Conduction occurs within a body or between two bodies in contact.

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.

Conduction:

- Conduction occurs when heat energy moves through a material as a result of collisions between the molecules of the material.
- The hotter a substance is, the higher the average kinetic energy of its molecules.
- When a temperature difference exists between the materials in contact, the higher energy molecules in the warm substance transfer energy to the low-energy molecules in the cooler substance, so energy flows from hot objects to cool objects.



Conduction cont.

- Every material has a particular thermal conductivity k in W/mK that shows the effect of these collisions.
  - Copper: 400 W/mK
  - Styrofoam: 0.029 W/mK •
- Heat flow rate:

$$H = -kA\frac{\Delta T}{\Delta x}$$

Where: H= heat flow rate (W or J/s)

K=thermal conductivity depends on material (W/mK)

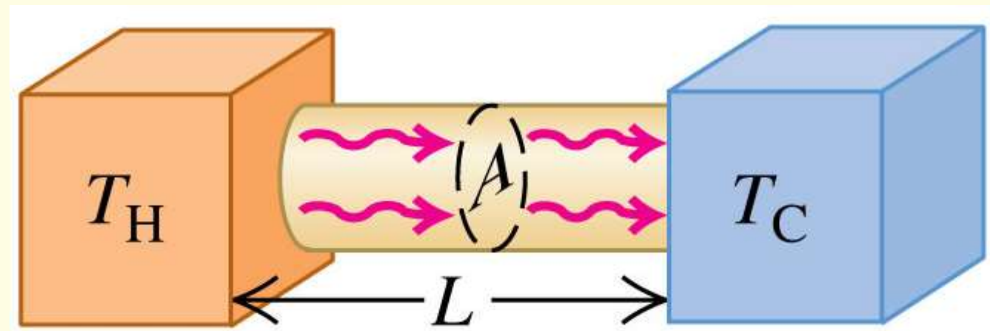
A= Surface area of slab (m^2)

Delta T = temperature difference between the two sides of slab (K)

Delta x = Thickness of slab (m)

Conduction of heat

- In conduction, heat flows from a higher to a lower temperature.
- Consider a solid rod of conducting material with cross-sectional area A and length L.
- The left end of the rod is kept at a temperature T_H and the right end at a lower temperature T_C.
- The rate that heat is transferred is:



Rate of heat flow

Temperatures of hot and cold ends of rod

Heat current in conduction

$$H = \frac{dQ}{dt} = kA\frac{T_H - T_C}{L}$$

Length of rod

Thermal conductivity of rod material

Cross-sectional area of rod

Thermal conductivities of some common substances

Substance	k (W/m · K)
Silver	406
Copper	385
Aluminum	205
Wood	0.12 – 0.04
Concrete	0.8
Fiberglass	0.04
Styrofoam	0.027

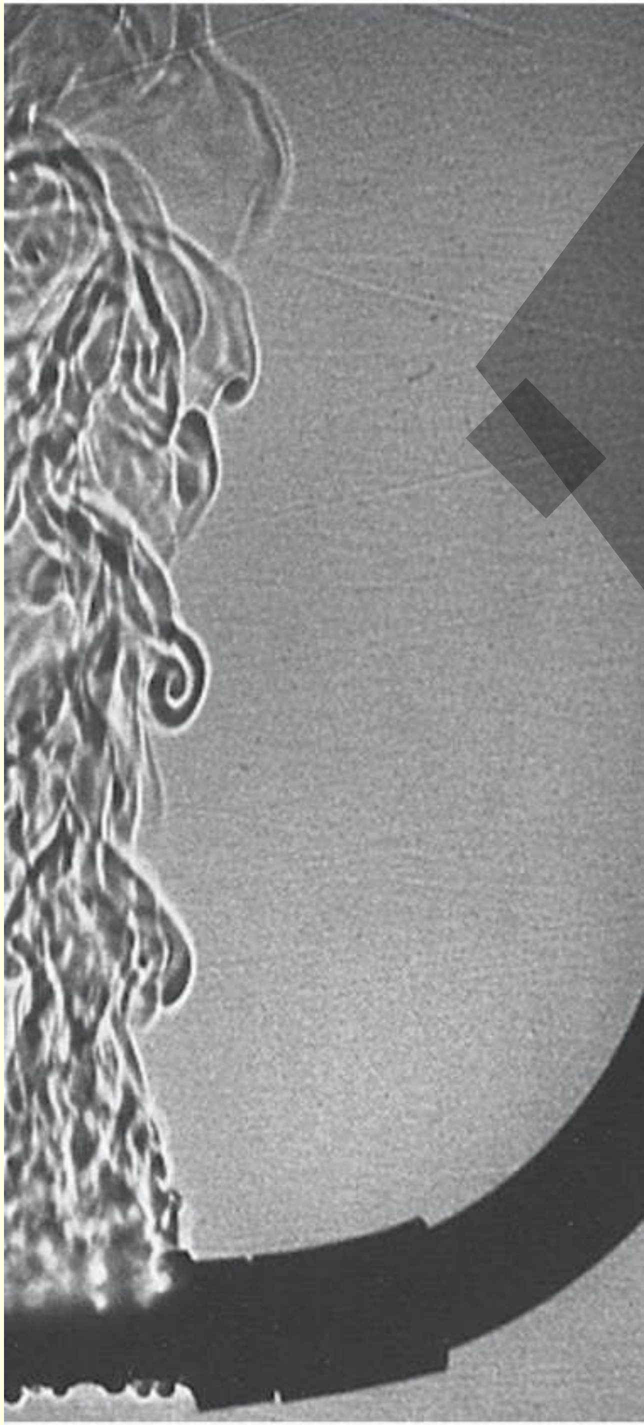
Example 10

The R value of a typical wall.

Calculate the total R value for a wall constructed with a 0.5 in layer of bricks, 0.5 in sheathing, 3.5 in air space, and 0.5 in dry wall. Don’t forget the air layers inside and outside the house.

Convection of heat

- **Convection** is the transfer of heat by the mass motion of fluid.
- A heating element in the tip of this submerged tube warms the surrounding water, producing a complex pattern of free convection.



Radiation of heat

- **Radiation** is the transfer of heat by electromagnetic waves, such as visible light or infrared.
- This false-color infrared photograph reveals radiation emitted by various parts of the man's body.
- The strongest emission comes from the warmest areas, while there is very little emission from the bottle of cold beverage.
- **Stefan-Boltzmann law**: The *heat current* in radiation is:

Area of emitting surface

Heat current in radiation

Emissivity of surface

$$H = Ae\sigma T^4$$

Absolute temperature of surface

Stefan–Boltzmann constant

Example 11:

In a 20°C room, if the skin temperature of a person is 37°C, how much heat is lost from his body in 10 min, assuming that the emissivity of skin is 0.90 and the surface area of the skin is 1.5 m^2?

Radiation and climate change

- The energy radiated by the earth's surface is mostly infrared.
- CO_2 molecules in our atmosphere readily absorb some of this infrared radiation and reradiate part of it back down toward the surface.