Chapter 10

Thermal Physics

Thermal Physics

- Thermal physics is the study of
  - Temperature
  - Heat
  - How these affect matter

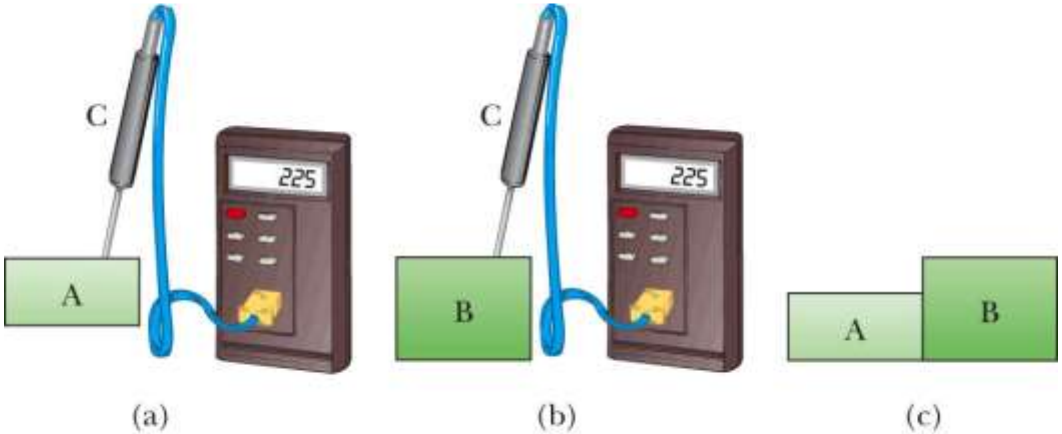
Thermal Physics, cont

- Descriptions require definitions of temperature, heat and internal energy
- Heat leads to changes in internal energy and therefore to changes in temperature
- Gases are critical in harnessing internal energy to do work

Heat

- The process by which energy is exchanged between objects because of temperature differences is called *heat*
- Objects are in *thermal contact* if energy can be exchanged between them
- *Thermal equilibrium* exists when two objects in thermal contact with each other cease to exchange energy

Zeroth Law of Thermodynamics



- If objects A and B are separately in thermal equilibrium with a third object, C, then A and B are in thermal equilibrium with each other
  - Object C could be the thermometer
- Allows a definition of temperature

Temperature from the Zeroth Law

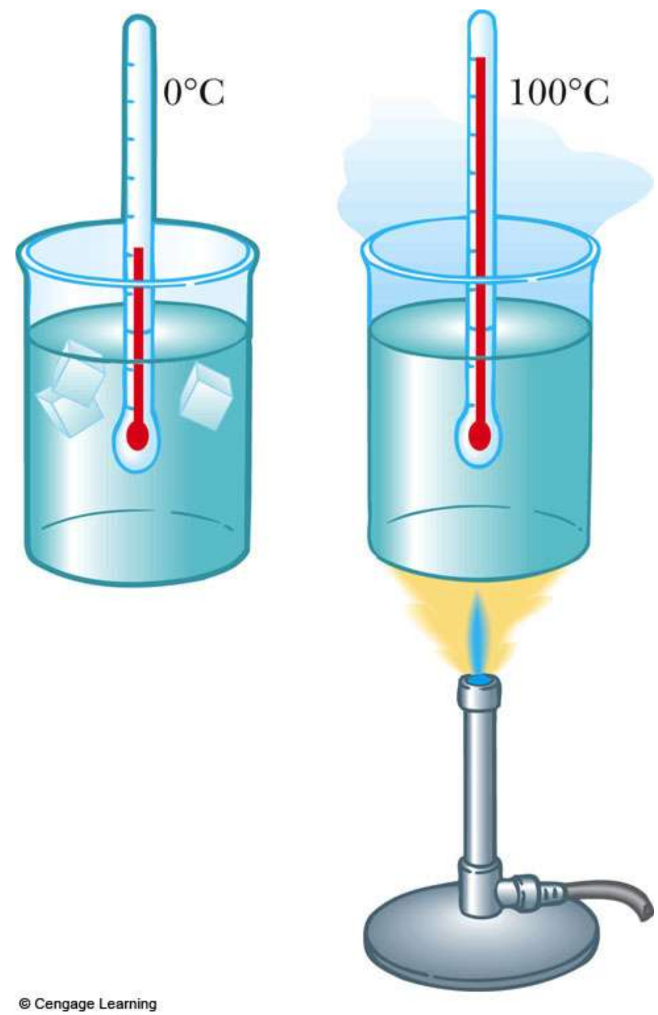
- *Temperature* is the property that determines whether or not an object is in thermal equilibrium with other objects
- Two objects in thermal equilibrium with each other are at the *same temperature*

Thermometers

- Used to measure the temperature of an object or a system
- Make use of physical properties that change with temperature
- Many physical properties can be used
  - Volume of a liquid
  - Length of a solid
  - Pressure of a gas held at constant volume
  - Volume of a gas held at constant pressure
  - Electric resistance of a conductor
  - Color of a very hot object

Thermometers, cont

- A mercury thermometer is an example of a common thermometer
- The level of the mercury rises due to thermal expansion
- Temperature can be defined by the height of the mercury column



Temperature Scales

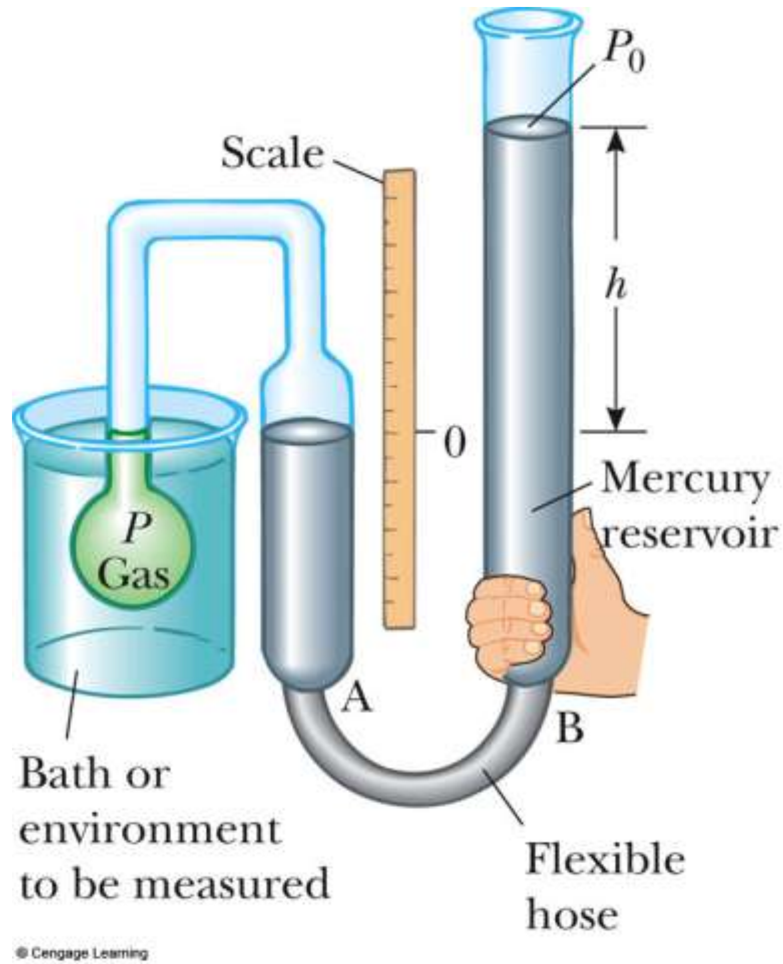
- Thermometers can be calibrated by placing them in thermal contact with an environment that remains at constant temperature
  - Environment could be mixture of ice and water in thermal equilibrium
  - Also commonly used is water and steam in thermal equilibrium

Celsius Scale

- Temperature of an ice-water mixture is defined as 0º C
  - This is the *freezing point* of water
- Temperature of a water-steam mixture is defined as 100º C
  - This is the *boiling point* of water
- Distance between these points is divided into 100 segments or degrees

Gas Thermometer

- Temperature readings are nearly independent of the gas
- Pressure varies with temperature when maintaining a constant volume

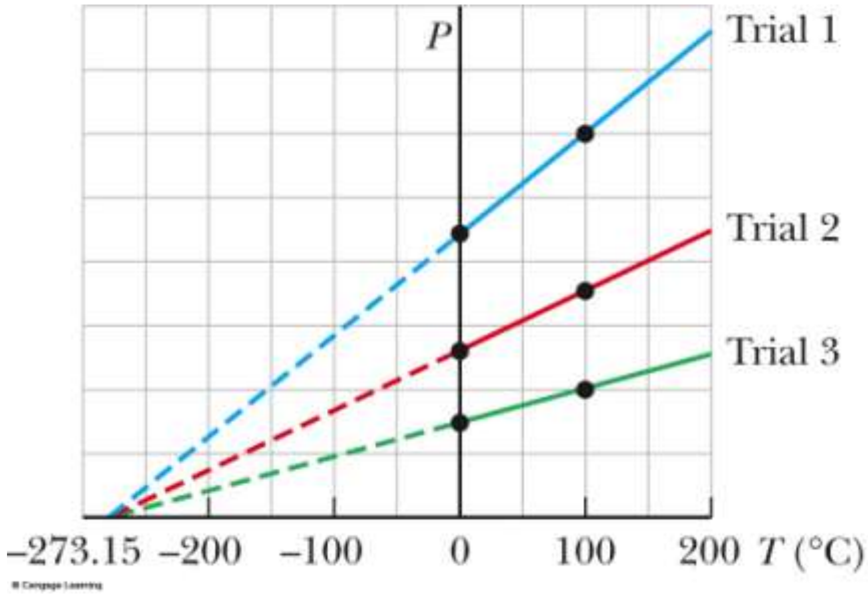


Kelvin Scale

- When the pressure of a gas goes to zero, its temperature is -273.15° C
- This temperature is called *absolute zero*
- This is the zero point of the Kelvin scale
  - $-273.15^\circ \text{ C} = 0 \text{ K}$
- To convert: $T_C = T - 273.15$
  - The size of the degree in the Kelvin scale is the same as the size of a Celsius degree

Pressure-Temperature Graph

- All gases extrapolate to the same temperature at zero pressure
- This temperature is *absolute zero*



Modern Definition of Kelvin Scale

- Defined in terms of two points
  - Agreed upon by International Committee on Weights and Measures in 1954
- First point is absolute zero
- Second point is the *triple point* of water
  - Triple point is the single point where water can exist as solid, liquid, and gas in equilibrium
  - Single temperature and pressure
  - Occurs at 0.01° C and P = 4.58 mm Hg

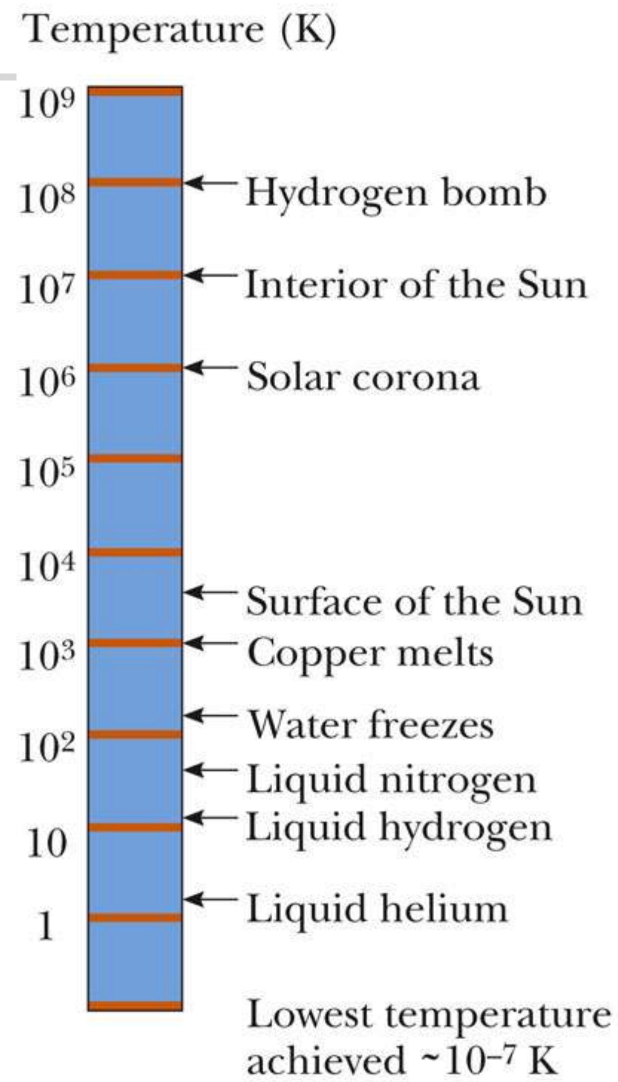
Modern Definition of Kelvin Scale, cont

- The temperature of the triple point on the Kelvin scale is 273.16 K
- Therefore, the current definition of of the Kelvin is defined as

  1/273.16 of the temperature of the triple point of water

Some Kelvin Temperatures

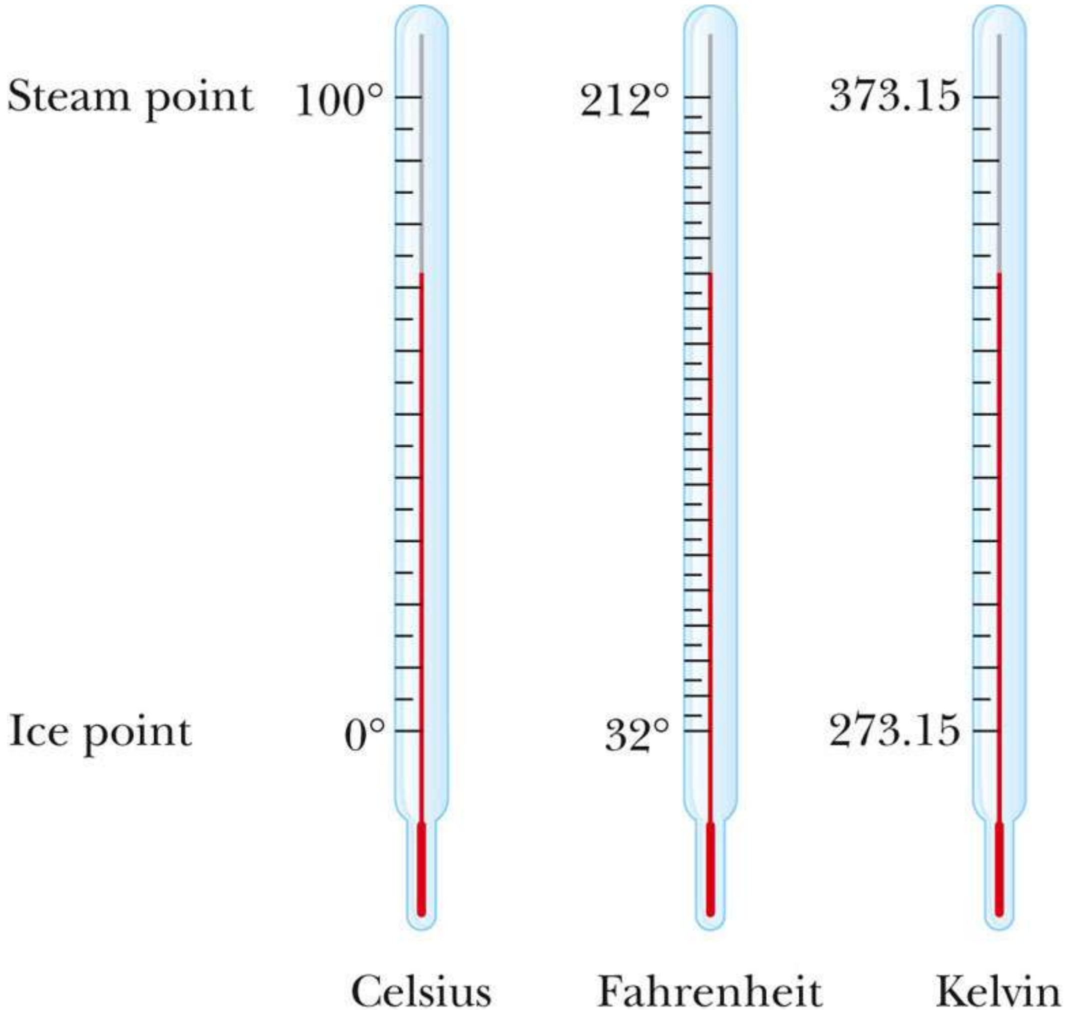
- Some representative Kelvin temperatures
- Note, this scale is logarithmic
- Absolute zero has never been reached



Fahrenheit Scales

- Most common scale used in the US
- Temperature of the freezing point is 32º
- Temperature of the boiling point is 212º
- 180 divisions between the points

Comparing Temperature Scales



Converting Among Temperature Scales

$$T_C = T_K - 273.15$$

$$T_F = \frac{9}{5} T_C + 32$$

$$T_C = \frac{5}{9}\left(T_F - 32\right)$$

$$\Delta T_F = \frac{9}{5} \Delta T_C$$

Thermal Expansion

- The thermal expansion of an object is a consequence of the change in the average separation between its constituent atoms or molecules
- At ordinary temperatures, molecules vibrate with a small amplitude
- As temperature increases, the amplitude increases
  - This causes the overall object as a whole to expand

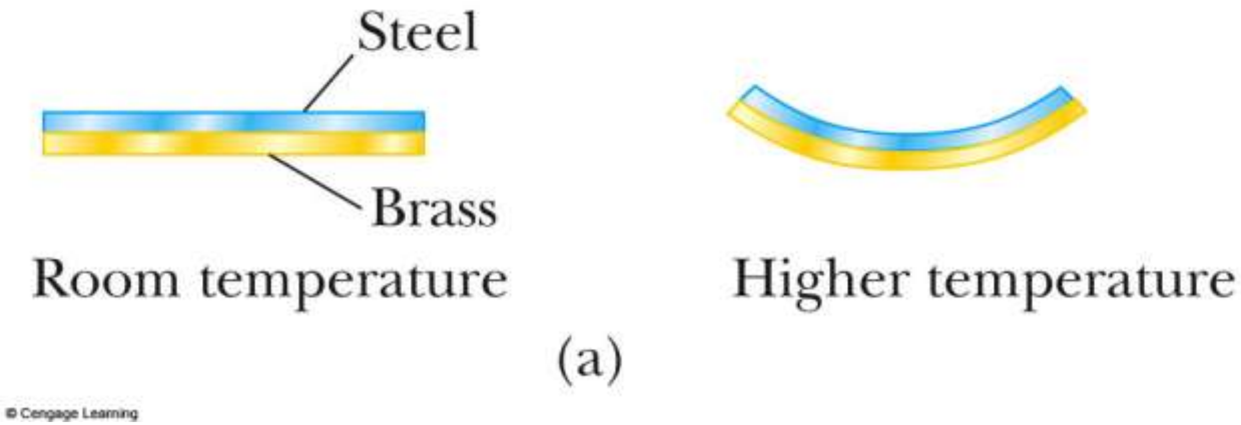
Linear Expansion

- For small changes in temperature

$$\Delta L = \alpha\, L_o\, \Delta T \text{ or } L - L_o = \alpha\, L_o\, (T - T_o)$$

- α, the coefficient of linear expansion, depends on the material
  - See table 10.1
  - These are average coefficients, they can vary somewhat with temperature

Applications of Thermal Expansion – Bimetallic Strip



- Thermostats
  - Use a *bimetallic strip*
  - Two metals expand differently
    - Since they have different coefficients of expansion

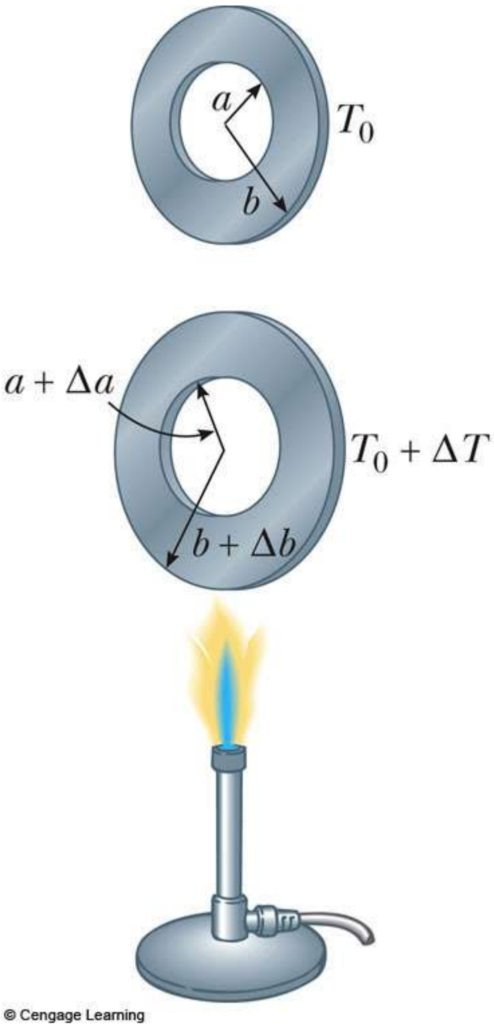
Area Expansion

- Two dimensions expand according to

$$\Delta A = A - A_o = \gamma\ A_o\ \Delta t,$$

$$\gamma = 2\alpha$$

  - γ is the coefficient of area expansion



Volume Expansion

- Three dimensions expand

$$\Delta V = \beta \, V_o \, \Delta t$$

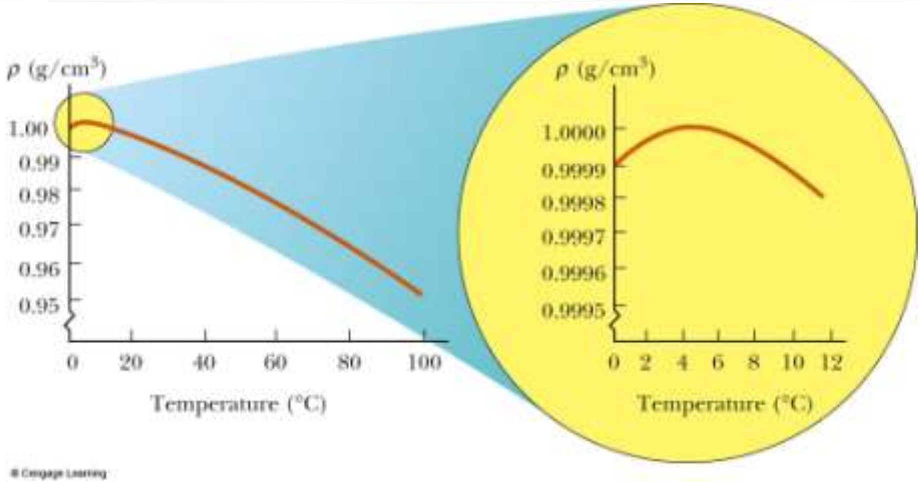
$$\text{for solids, } \beta = 3\alpha$$

  - For liquids, the coefficient of volume expansion is given in the table

More Applications of Thermal Expansion

- Pyrex Glass
  - Thermal stresses are smaller than for ordinary glass
- Sea levels
  - Warming the oceans will increase the volume of the oceans

Unusual Behavior of Water



- As the temperature of water increases from 0ºC to 4 ºC, it contracts and its density increases
- Above 4 ºC, water exhibits the expected expansion with increasing temperature
- Maximum density of water is 1000 kg/m^3 at 4 ºC

Ideal Gas

- If a gas is placed in a container
  - It expands to fill the container uniformly
  - Its pressure will depend on the
    - Size of the container
    - The temperature
    - The amount of gas
- The pressure, volume, temperature and amount of gas are related to each other by an *equation of state*

Ideal Gas, cont

- The equation of state can be complicated
- It can be simplified if the gas is maintained at a low pressure
- Most gases at room temperature and pressure behave approximately as an ideal gas

Characteristics of an Ideal Gas

- Collection of atoms or molecules that move randomly
- Exert no long-range force on one another
- Each particle is individually point-like
  - Occupying a negligible volume

Moles

- It's convenient to express the amount of gas in a given volume in terms of the number of moles, n

$$n = \frac{\text{mass}}{\text{molar mass}}$$

- One mole is the amount of the substance that contains as many particles as there are atoms in 12 g of carbon-12

Avogadro’s Number

- The number of particles in a mole is called *Avogadro’s Number*
  - $N_A = 6.02 \times 10^{23}$ particles / mole
  - Defined so that 12 g of carbon contains N_A atoms
- The mass of an individual atom can be calculated:

$$m_{atom} = \frac{\text{molar mass}}{N_A}$$

Avogadro’s Number and Masses

- The mass in grams of one Avogadro's number of an element is numerically the same as the mass of one atom of the element, expressed in atomic mass units, u
- Carbon has a mass of 12 u
  - 12 g of carbon consists of N_A atoms of carbon
- Holds for molecules, also

Ideal Gas Law

- $PV = nRT$
  - R is the *Universal Gas Constant*
  - $R = 8.31\ J / mol \cdot K$
  - $R = 0.0821\ L \cdot atm / mol \cdot K$
  - Is the equation of state for an ideal gas

Ideal Gas Law, Alternative Version

- $P V = N k_B T$
  - k_B is *Boltzmann's Constant*
  - $k_B = R / N_A = 1.38 \times 10^{-23}$ J/ K
  - N is the total number of molecules
- $n = N / N_A$
  - n is the number of moles
  - N is the number of molecules

Kinetic Theory of Gases – Assumptions

- The number of molecules in the gas is large and the average separation between them is large compared to their dimensions
- The molecules obey Newton's laws of motion, but as a whole they move randomly

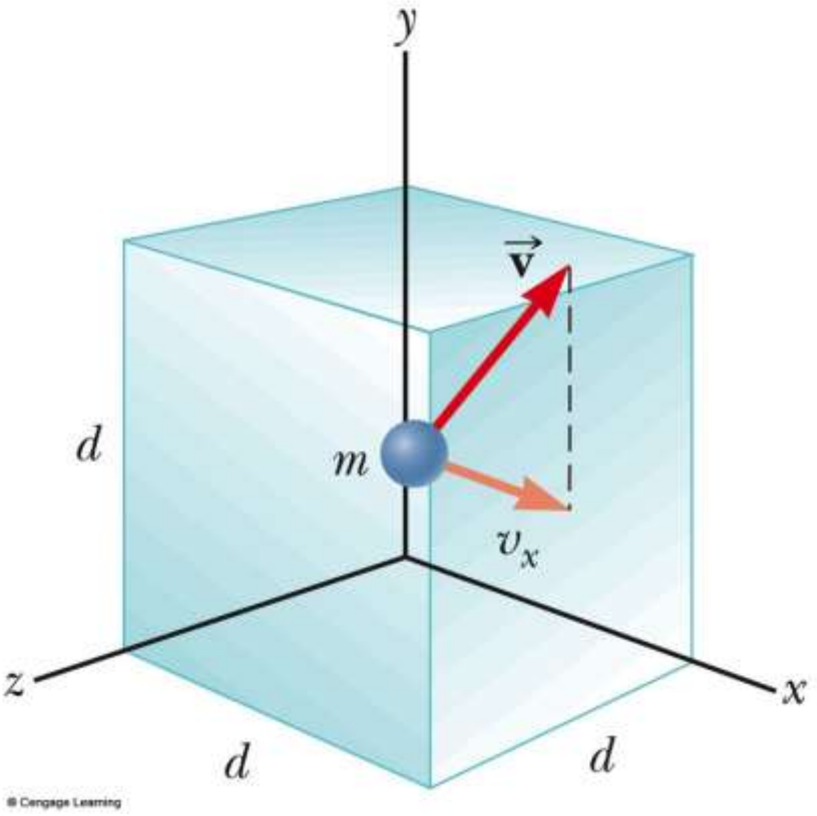
Kinetic Theory of Gases – Assumptions, cont.

- The molecules interact only by short-range forces during elastic collisions
- The molecules make elastic collisions with the walls
- The gas under consideration is a pure substance, all the molecules are identical

Pressure of an Ideal Gas

- The pressure is proportional to the number of molecules per unit volume and to the average translational kinetic energy of a molecule

$$P = \frac{3}{2}\left(\frac{N}{V}\right)\left(\frac{1}{2}mv^2\right)$$



Pressure, cont

- The pressure is proportional to the number of molecules per unit volume and to the average translational kinetic energy of the molecule
- Pressure can be increased by
  - Increasing the number of molecules per unit volume in the container
  - Increasing the average translational kinetic energy of the molecules
    - Increasing the temperature of the gas

Molecular Interpretation of Temperature

- Temperature is proportional to the average kinetic energy of the molecules

$$\frac{1}{2}mv^2 = \frac{3}{2}k_B T$$

- The total kinetic energy is proportional to the absolute temperature

$$\mathrm{KE}_{\mathrm{total}} = \frac{3}{2}\mathrm{nRT}$$

Internal Energy

- In a monatomic gas, the KE is the only type of energy the molecules can have

$$U = \frac{3}{2}nRT$$

- U is the *internal energy* of the gas
- In a polyatomic gas, additional possibilities for contributions to the internal energy are rotational and vibrational energy in the molecules

Speed of the Molecules

- Expressed as the *root-mean-square* (rms) speed

$$v_{rms} = \sqrt{\frac{3 k_B T}{m}} = \sqrt{\frac{3 R T}{M}}$$

- At a given temperature, lighter molecules move faster, on average, than heavier ones
  - Lighter molecules can more easily reach escape speed from the earth

Some rms Speeds

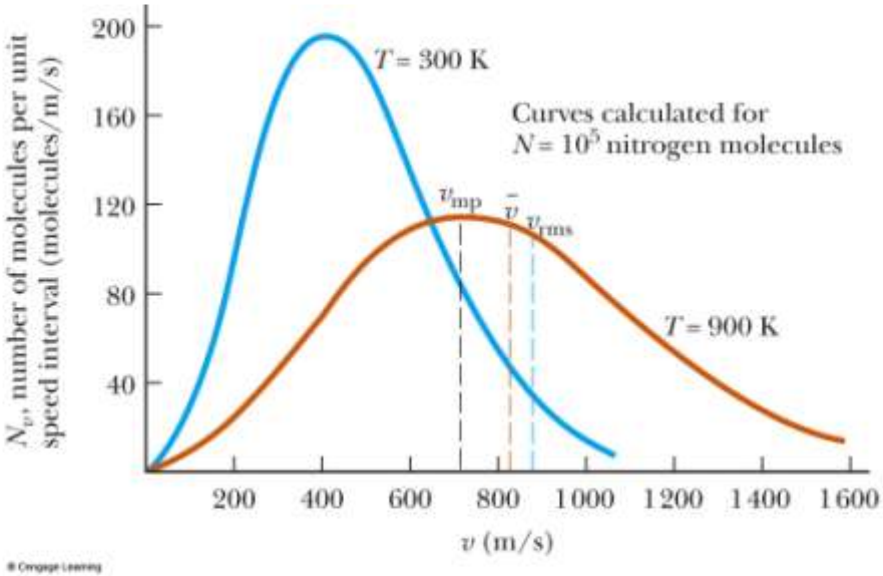
TABLE 10.2

Some rms Speeds

Gas	Molar Mass (kg/mol)	v_{rms} at 20°C (m/s)
H_2	2.02×10^{-3}	1 902
He	4.0×10^{-3}	1 352
H_2O	18×10^{-3}	637
Ne	20.2×10^{-3}	602
N_2 and CO	28.0×10^{-3}	511
NO	30.0×10^{-3}	494
O_2	32.0×10^{-3}	478
CO_2	44.0×10^{-3}	408
SO_2	64.1×10^{-3}	338

Maxwell Distribution

- A system of gas at a given temperature will exhibit a variety of speeds
- Three speeds are of interest:
  - Most probable
  - Average
  - rms



Maxwell Distribution, cont

- For every gas, $v_{mp} < v_{av} < v_{rms}$
- As the temperature rises, these three speeds shift to the right
- The total area under the curve on the graph equals the total number of molecules