Physics 1501

Fall 2008

Mechanics, Thermodynamics, Waves, Fluids

Lecture 30: Thermal Behavior of Matter

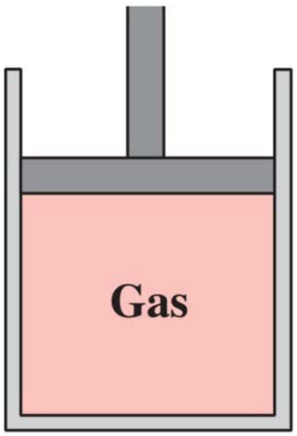
Recap: temperature and heat

- **Thermodynamic equilibrium** is the state reached when macroscopic properties of a system or systems don't change.
- Systems in thermodynamic equilibrium are at the same **temperature.**
  - The **kelvin** (K) is the SI unit of temperature.
- **Heat** is energy in transit because of a temperature difference alone.
  - The heat required to heat an object by an amount ΔT depends on its mass and its **specific heat**, c: $\Delta Q = mc\,\Delta T$.
  - Heat transfer mechanisms include conduction, convection, and radiation.
  - **Thermal energy balance** is a state in which the rate at which energy is delivered to a system is equal to the rate at which the system loses energy. A system in energy balance maintains a constant temperature.

The ideal gas law

- Experiment shows that a gas of N molecules in a closed container obeys a simple relation between pressure p, volume V, and temperature T:

$$pV = NkT$$



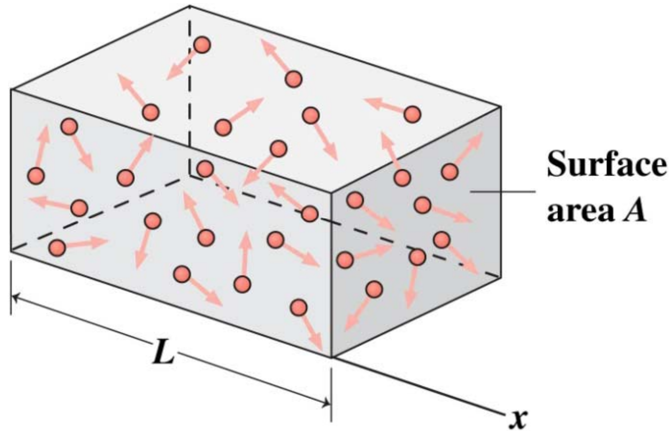
A piston-cylinder system for exploring gas behavior

  - This is the **ideal gas law**, and the behavior of most real gases closely approximates this ideal.
  - Here k is **Boltzmann's constant**; $k = 1.38\times10^{-23}$ J/K.
  - The ideal gas law may also be written $pV = nRT$, where n is the number of moles of gas, and $R = 8.314$ J/K·mol.

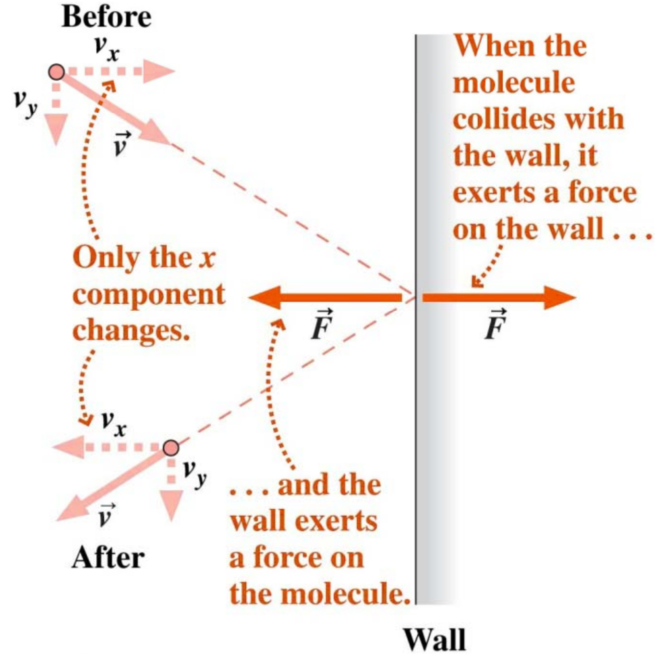
Kinetic theory of the ideal gas

- The ideal gas law follows by considering a gas to consist of particles that obey Newton's laws.
  - Gas pressure arises from the average force the particles exert when they collide with the container walls.
  - The temperature of the gas is a measure of the average kinetic energy of the gas molecules:

$$\frac{1}{2}m\overline{v^2} = \frac{3}{2}kT$$



Gas molecules confined to a rectangular box



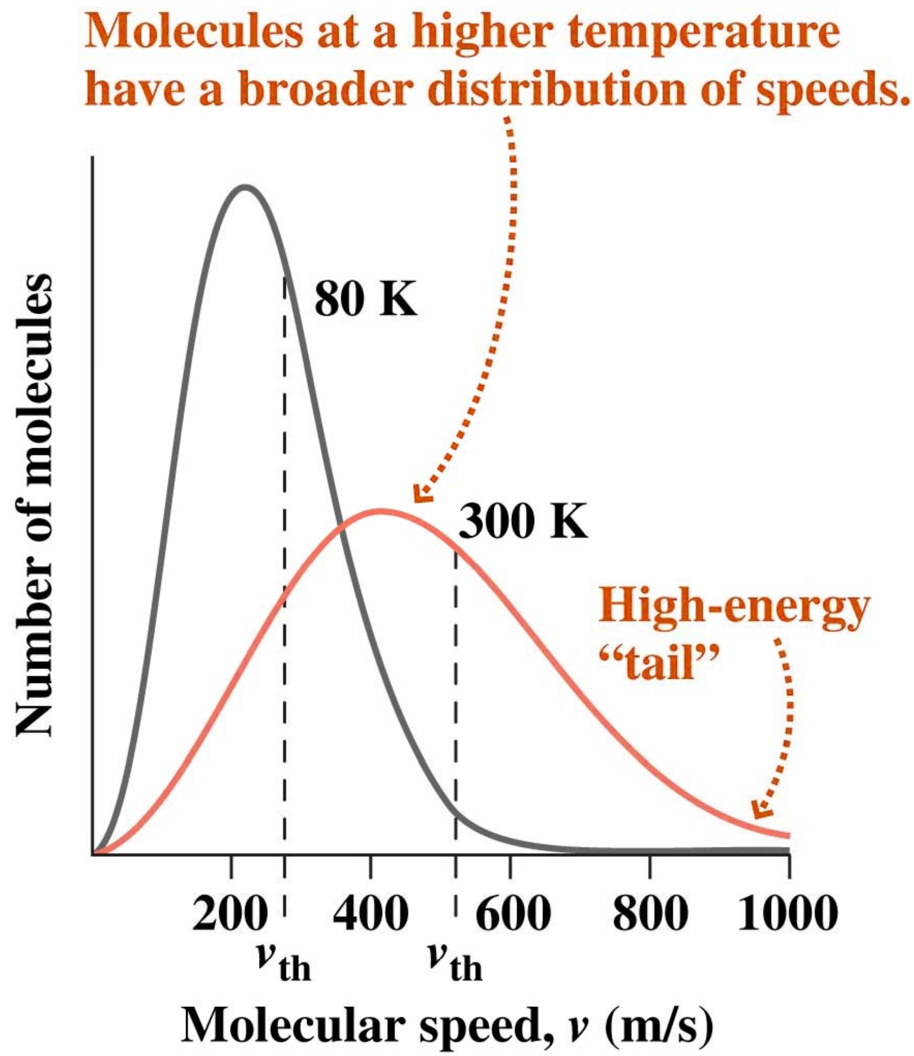
Pressure arises from collisions with the walls; here one collision is examined in detail.

The Maxwell-Boltzmann distribution

- Molecules in a gas exhibit a range of speeds that result from random collisions among the molecules.
  - This is the **Maxwell-Boltzmann distribution.**
  - At high temperatures the distribution is broader and peaks at a higher speed.
  - The mean thermal speed is

$$v_{th} = \sqrt{\frac{3kT}{m}}$$

where m is the molecular mass.



question

- If you double the kelvin temperature of a gas, what happens to the thermal speed of the gas molecules?

  A. It doubles.

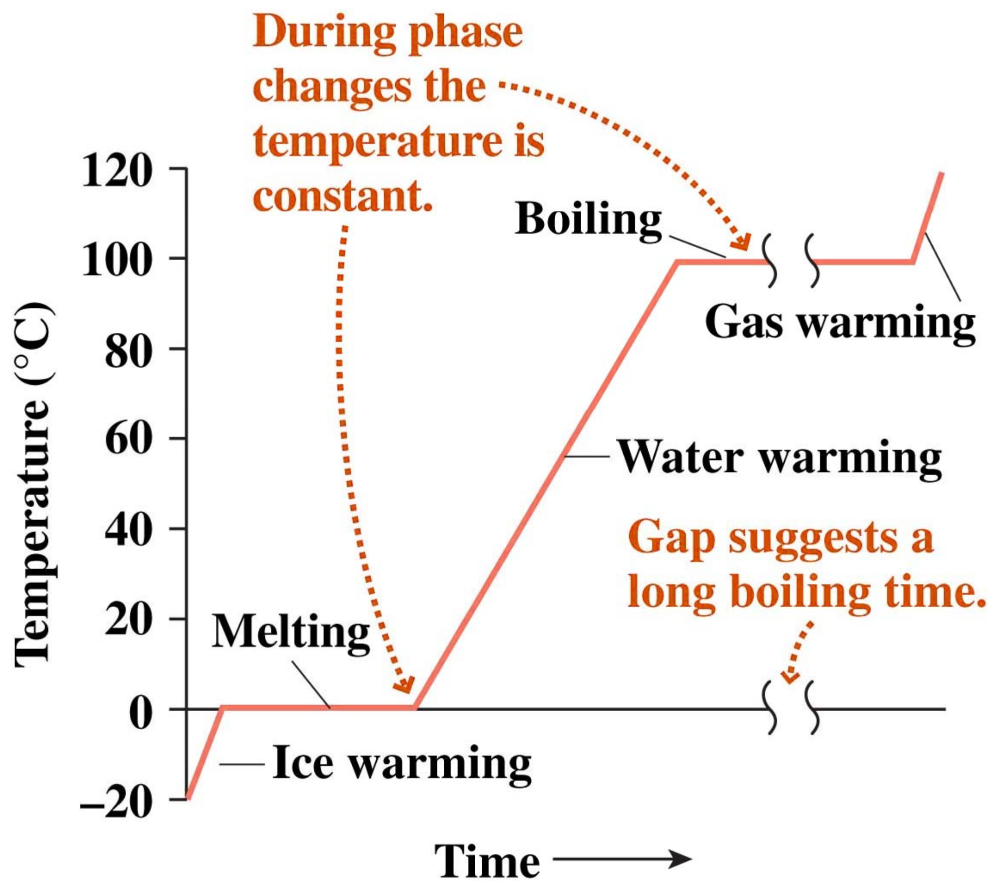
  B. It is halved.

  C. It changes by a factor of $\sqrt{2}$.

  D. It changes by a factor of $1/\sqrt{2}$.

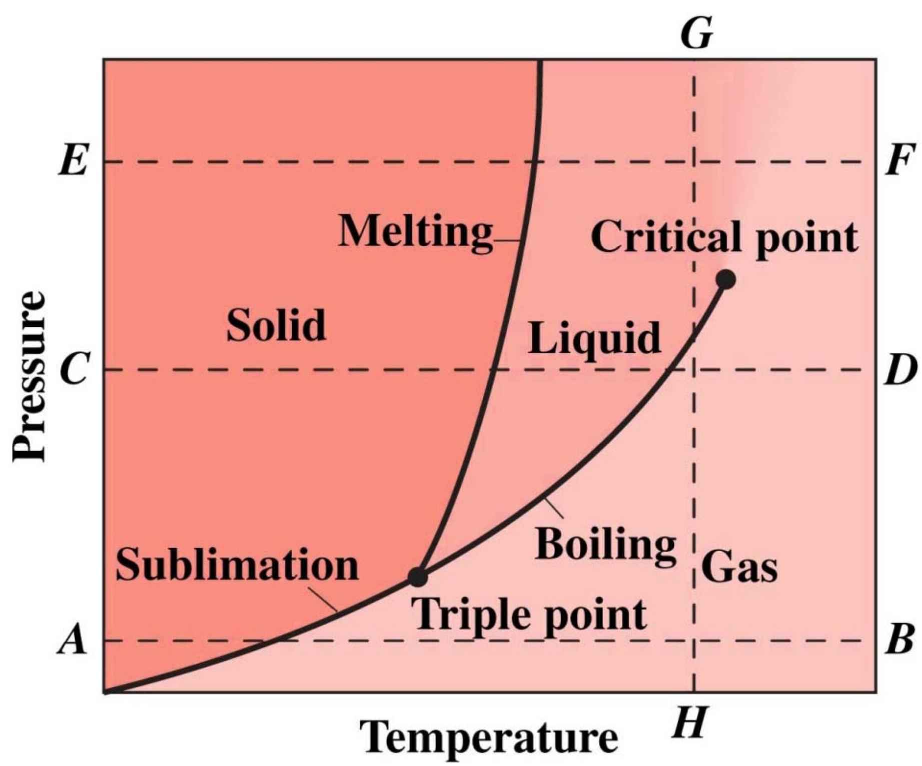
Phase changes

- Most substances occur in three **phases**—solid, liquid, gas.
  - It takes energy, called the **heat of transformation**, L, to effect phase changes from solid to liquid and liquid to gas.
    - Heat of transformation measures the energy Q required to change the phase of a mass m: $Q = mL$.
    - Energy must be removed to go the other way.
    - The solid-liquid transition involves the **heat of fusion**, L_f.
    - The liquid-gas transition involves the **heat of vaporization**, L_v.
    - The direct transition from solid to gas involves the **heat of sublimation**, L_s.
  - During a phase change, temperature remains constant as energy goes into breaking molecular bonds.

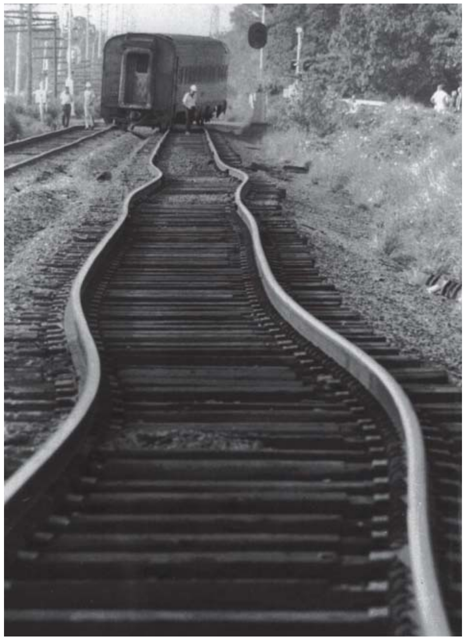


Phase diagrams

- The phases of a substance can be displayed on a plot of pressure versus temperature.
  - Curves separate regions characterizing the different phases.
    - The curves meet at the **triple point**, where all three phases coexist in equilibrium.
    - The liquid-gas curve ends at the **critical point**, where the sharp distinction between liquid and gas disappears.
    - Different paths in the phase diagram take the material through different phase sequences:
      - Path *CD* shows the familiar solid-liquid-gas.
      - Path *AB* goes directly from solid to gas.
      - Path *GH* shows that changing pressure can result in phase changes.



Thermal expansion

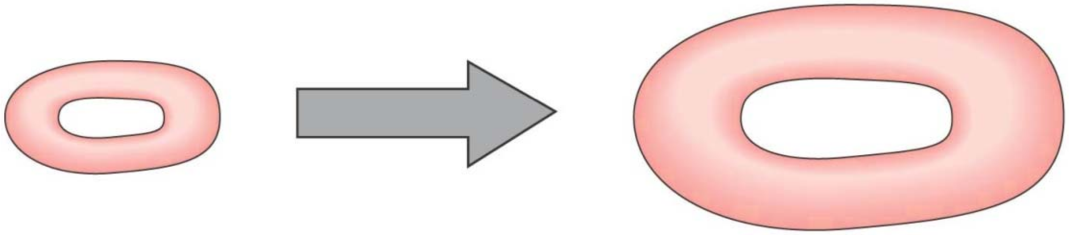


- Most materials expand when heated.
  - Liquids and solids are best characterized by the **coefficient of volume expansion**, β.
  - Solids are best characterized by the **coefficient of linear expansion**, α.
  - The coefficients are defined as the fractional change in volume over length, per unit temperature change:

$$\beta = \frac{\Delta V / V}{\Delta T} \qquad \alpha = \frac{\Delta L / L}{\Delta T}$$

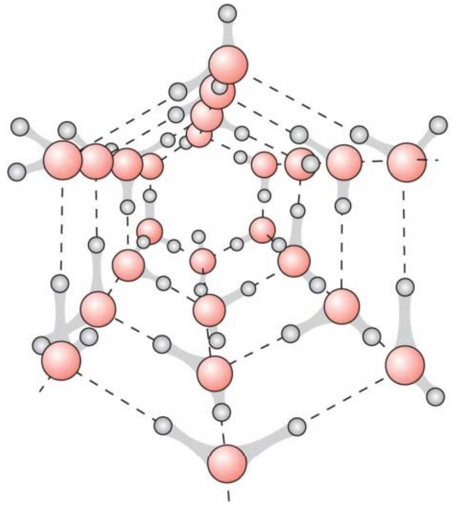
Typical $\beta \sim 10^{-3}$ Typical $\alpha \sim 10^{-5}$

  - An unconfined substance expands equally in all its dimensions.



The anomalous behavior of water

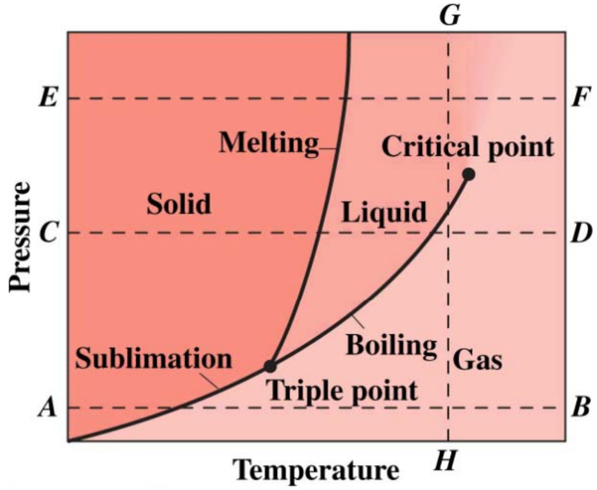
- Between 0˚C and 4˚C, water contracts on heating.
  - This is a residual effect of the hydrogen bonds that form ice crystals.
  - The open structure of the ice crystal makes ice less dense than liquid water.



  - Hence solid water, unlike most substances, floats in its liquid phase.
  - This fact has enormous consequences for aquatic life.

Summary

- The **ideal gas law** relates pressure, temperature, and volume: $PV = NkT$.
  - Derivation of the ideal gas law from Newtonian mechanics shows that temperature measures the average kinetic energy of the gas molecules.
- **Phase changes** take substances between solid and liquid, liquid and gas, solid and gas.



  - Phase diagrams require energy, described by the **heats of transformation.**
  - The phase structure of a substance is described in its **phase diagram.**
- **Thermal expansion** occurs as most substances are heated.
  - An exception is water in the range from 0˚C to 4˚C.