Thermal & Statistical Physics

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PHYS 343

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LECTURE 2

Work and Heat

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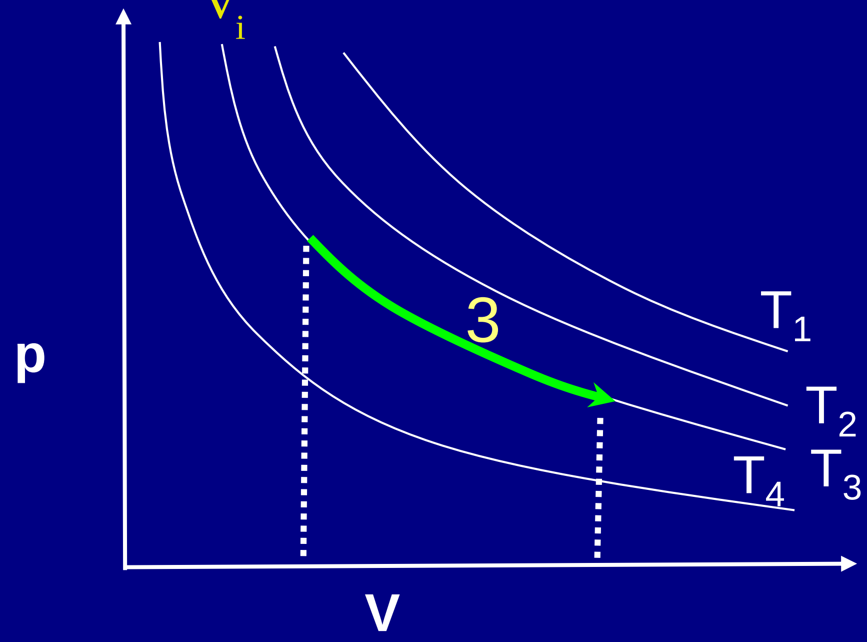
Isothermal processes

- Work done when PV = nRT = constant → P = nRT / V

$$W = -\int_{\text{initial}}^{\text{final}} p\, dV = -(\text{area under curve})$$

$$W = -\int_{V_i}^{V_f} \text{nRT}\, dV/V = -\,\text{nRT}\int_{V_i}^{V_f} dV/V$$

$$\boxed{W = -\text{nRT}\ \ell n(V_f/V_i)}$$



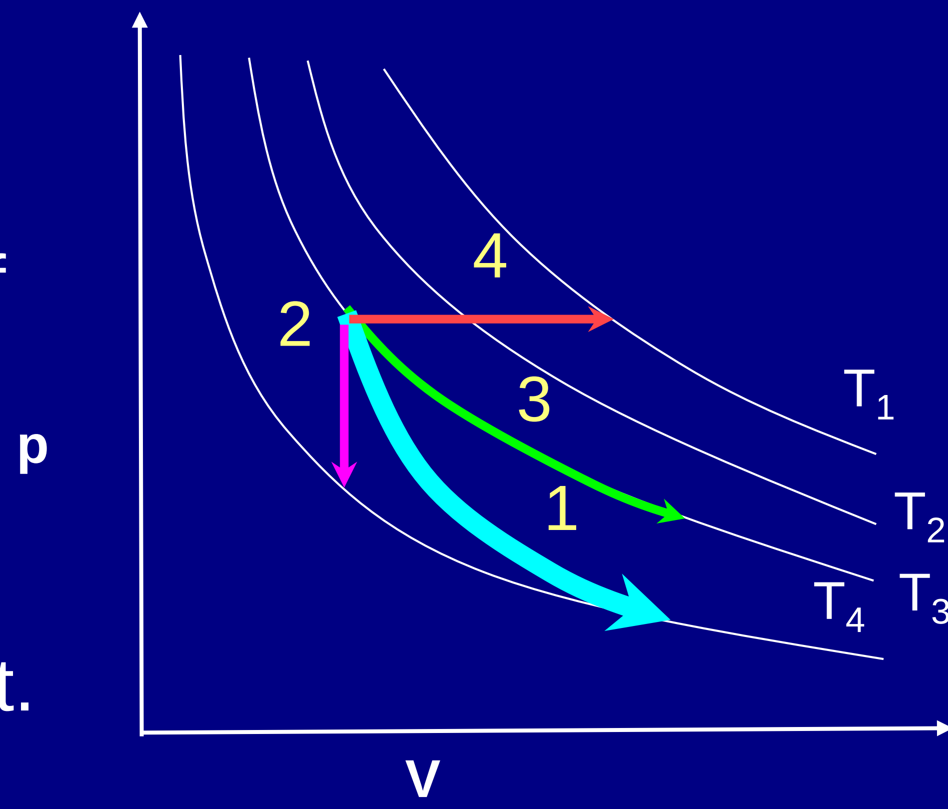
Adiabatic Processes

- An adiabatic process is process in which there is **no** thermal energy transfer to or from a system ($Q = 0$)

- A **reversible** adiabatic process involves a "worked" expansion in which we can return all of the energy transferred.
- In this case

  PV^{γ} = const.

- All **real** processes are not.



Work and Ideal Gas Processes (on system)

- Isothermal

$$W = -\mathrm{nRT}\ \ell n(\mathrm{V_f}/\mathrm{V_i})$$

- Isobaric

$$W = -\mathrm{p}\ (\mathrm{V_f} - \mathrm{V_i})$$

- Isochoric

$$W = 0$$

- FYI: Adiabatic (and reversible)

$$W = -\int_{V_1}^{V_2} PdV = -\int_{V_1}^{V_2} \frac{\text{const}}{V^{\gamma}}\frac{dV}{V} = \frac{\text{const}}{\gamma}(V_2^{-\gamma} - V_1^{-\gamma})$$

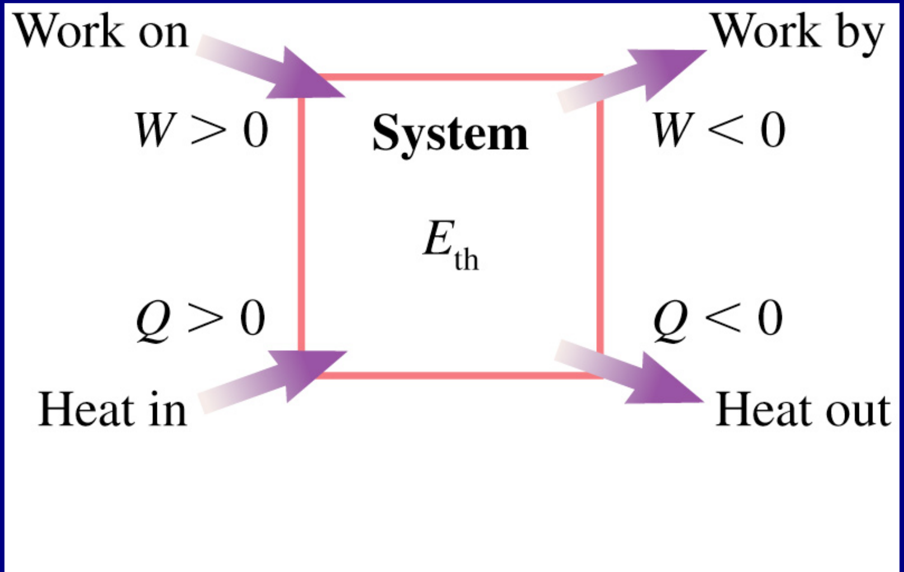
Combinations of Isothermal & Adiabatic Processes

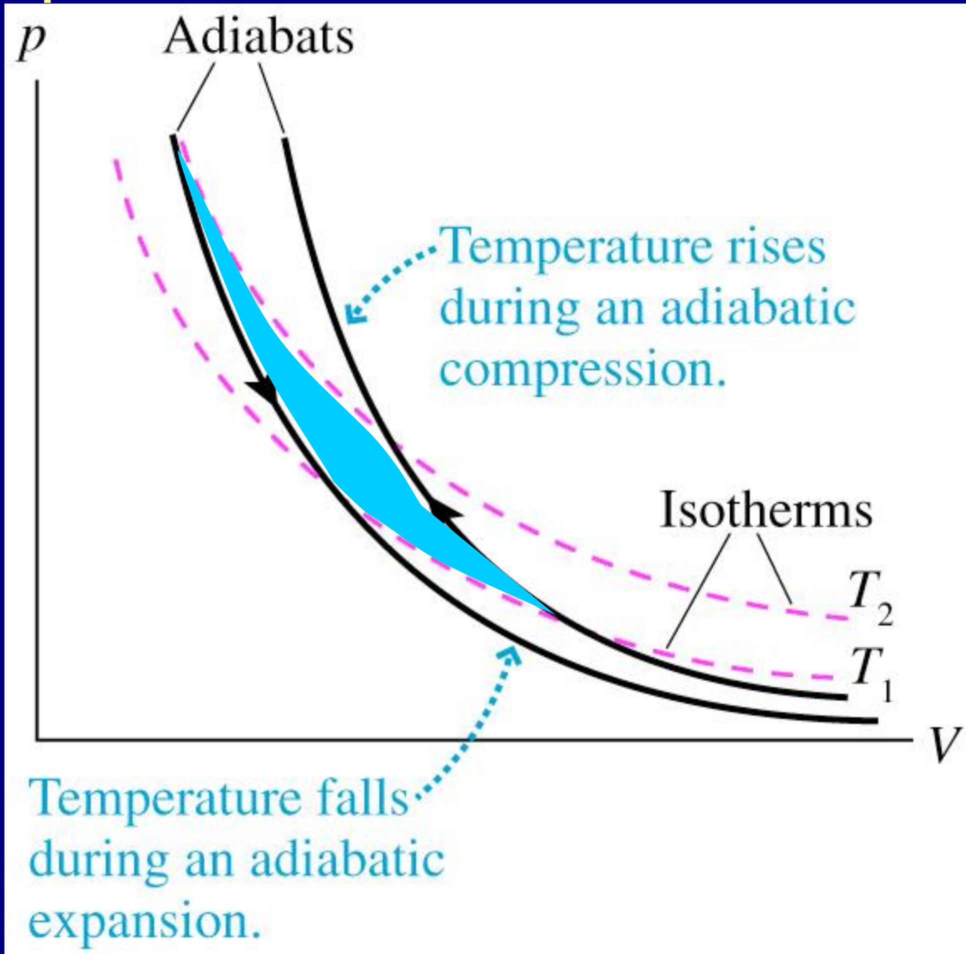
All engines employ a <u>thermodynamic</u> cycle

W = ± (area under each pV curve)

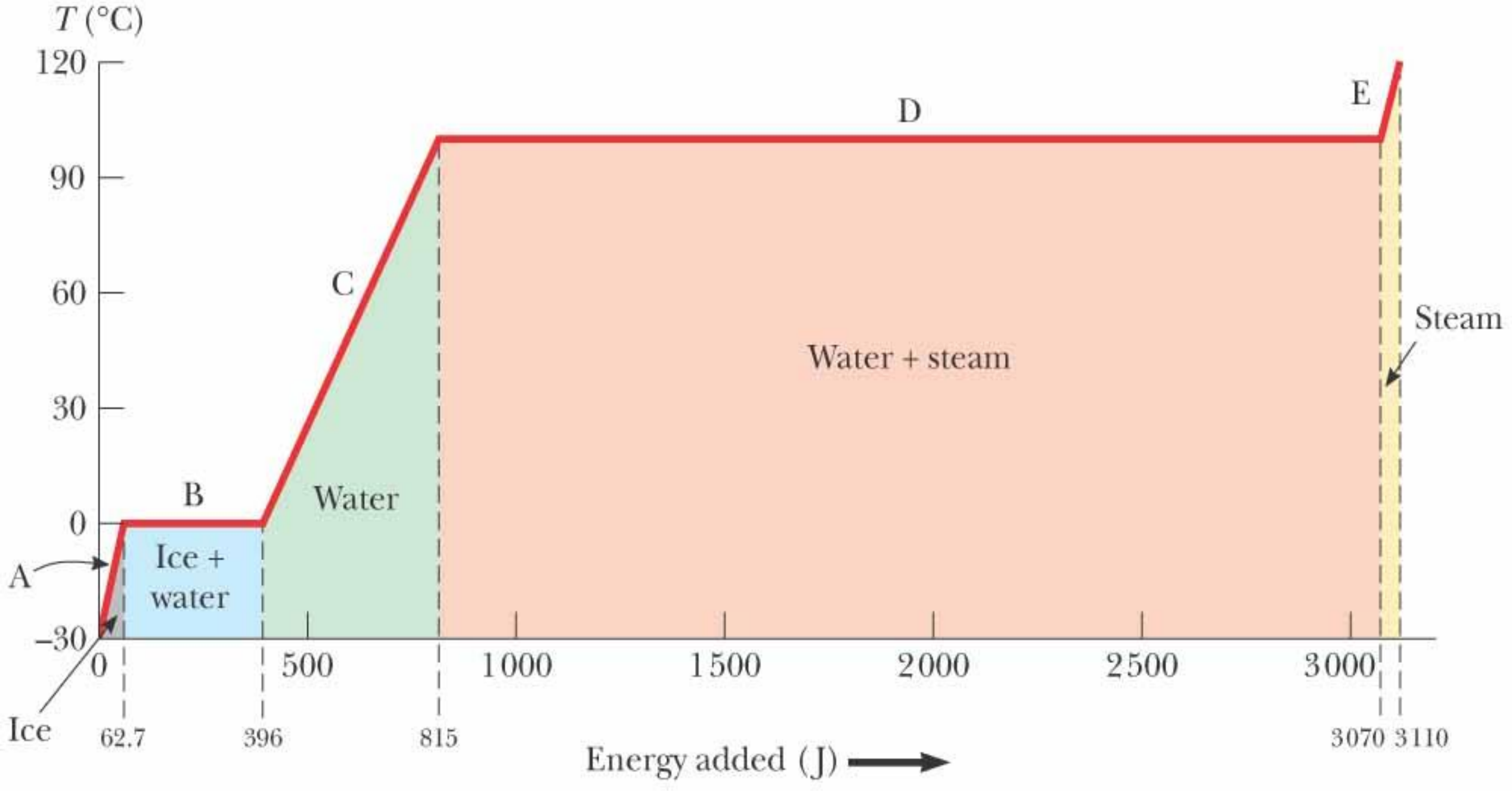
W_{cycle} = area shaded in turquoise

Watch sign of the work!





Relationship between energy transfer and T



Heat and Latent Heat

- Latent heat of transformation L is the energy required for 1 kg of substance to undergo a phase change. (J / kg)

$$Q = \pm ML$$

- Specific heat c of a substance is the energy required to raise the temperature of 1 kg by 1 K. (Units: J / K kg)

$$Q = M\,c\,\Delta T$$

- Molar specific heat C of a gas at constant volume is the energy required to raise the temperature of 1 mol by 1 K.

$$Q = n\,C_V\,\Delta T$$

If a phase transition involved then the heat transferred is

$$Q = \pm ML + M\,c\,\Delta T$$

Q : Latent heat and specific heat

- The molar specific heat of gasses depends on the process path
- C_V= molar specific heat at constant volume
- C_p= molar specific heat at constant pressure
- $C_p = C_V + R$ (R is the universal gas constant)

$$\boxed{\gamma = \frac{C_p}{C_V}}$$

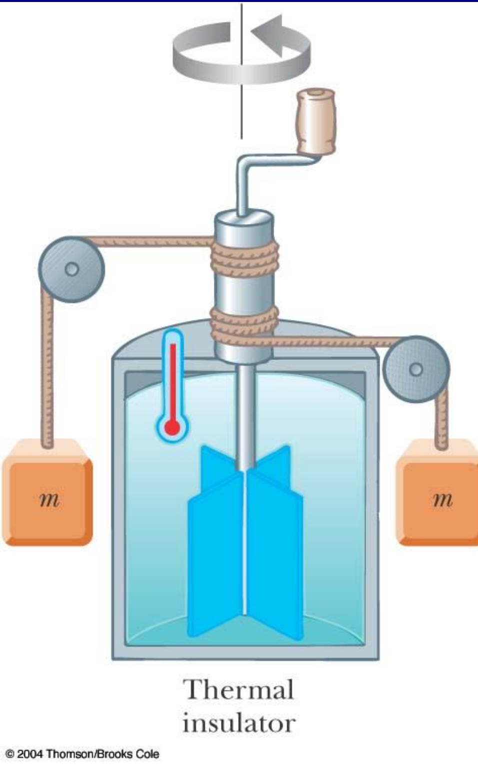
Mechanical equivalent of heat

- Heating liquid water:
  - Q = amount of heat that must be supplied to raise the temperature by an amount ΔT.
  - [Q] = Joules or calories.

1 Cal = 4.186 J
1 kcal = 1 Cal = 4186 J

  - calorie: energy to raise 1 g of water from 14.5 to 15.5 °C

(James Prescott Joule found the mechanical equivalent of heat.)



Sign convention:

+Q : heat gained
- Q : heat lost

Exercise

- The specific heat ($Q = M\,c\,\Delta T$) of aluminum is about **twice** that of iron. Consider two blocks of equal mass, one made of aluminum and the other one made of iron, initially in thermal equilibrium.
- Heat is added to each block at the same constant rate until it reaches a temperature of 500 K. Which of the following statements is true?

(a) The iron takes less time than the aluminum to reach 500 K

(b) The aluminum takes less time than the iron to reach 500 K

(c) The two blocks take the same amount of time to reach 500 K

Heat and Ideal Gas Processes (on system)

- Isothermal Expansion/Contraction

$$\Delta E_{\mathrm{Th}} = 0 = W + Q \qquad Q = -W$$

- Isobaric

$$Q = nC_p \Delta T = n(C_V + R)\Delta T$$

- Isochoric

$$Q = nC_V \Delta T$$

- Adiabatic

$$Q = 0$$

Two process are shown that take an ideal gas from state 1 to state 3.

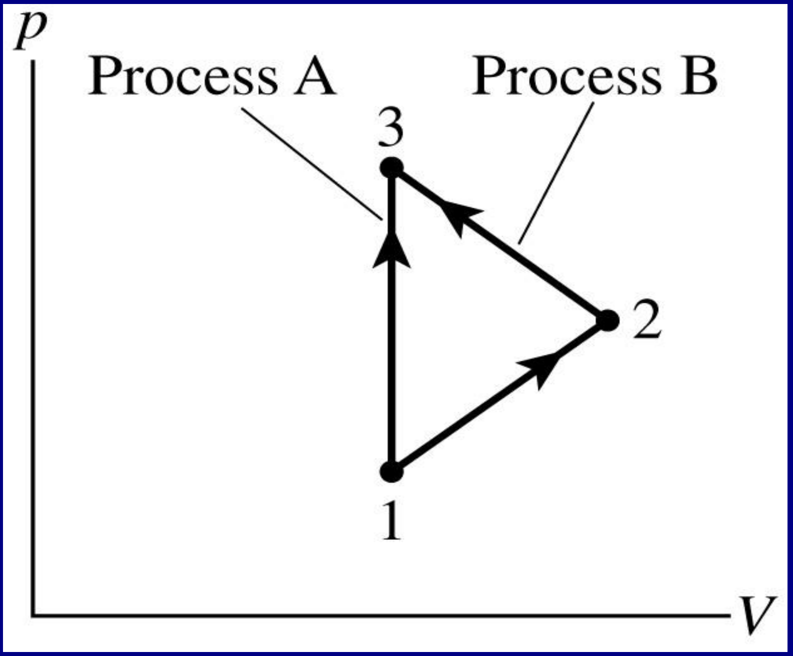
Compare the work done **by** process A to the work done **by** process B.

A. $\boldsymbol{W_A > W_B}$

B. $W_A < W_B$

C. $W_A = W_B = 0$

D. $W_A = W_B$ but neither is zero



	ON	BY
A $1 \rightarrow 3$	$W_{1\rightarrow 2} = 0$ (isochoric)	
B $1 \rightarrow 2$	$W_{1\rightarrow 2} = -\frac{1}{2}(p_1+p_2)(V_2-V_1) < 0$	$-W_{1\rightarrow 2} > 0$
B $2 \rightarrow 3$	$W_{2\rightarrow 3} = -\frac{1}{2}(p_2+p_3)(V_1-V_2) > 0$	$-W_{2\rightarrow 3} < 0$
B $1 \rightarrow 3$	$= \frac{1}{2}(p_3 - p_1)(V_2-V_1) > 0$	< 0

Exercise Latent Heat

- Most people were at least once burned by hot water or steam.
- Assume that water and steam, initially at 100°C, are cooled down to skin temperature, 37°C, when they come in contact with your skin. Assume that the steam condenses extremely fast, and that the specific heat $c = 4190$ J/ kg K is constant for both liquid water and steam.
- Under these conditions, which of the following statements is true?

(a) Steam burns the skin worse than hot water because the thermal conductivity of steam is much higher than that of liquid water.

(b) Steam burns the skin worse than hot water because the latent heat of vaporization is released as well.

(c) Hot water burns the skin worse than steam because the thermal conductivity of hot water is much higher than that of steam.

(d) Hot water and steam both burn skin about equally badly.

Ch. 18, Macro-micro connection
Molecular Speeds and Collisions

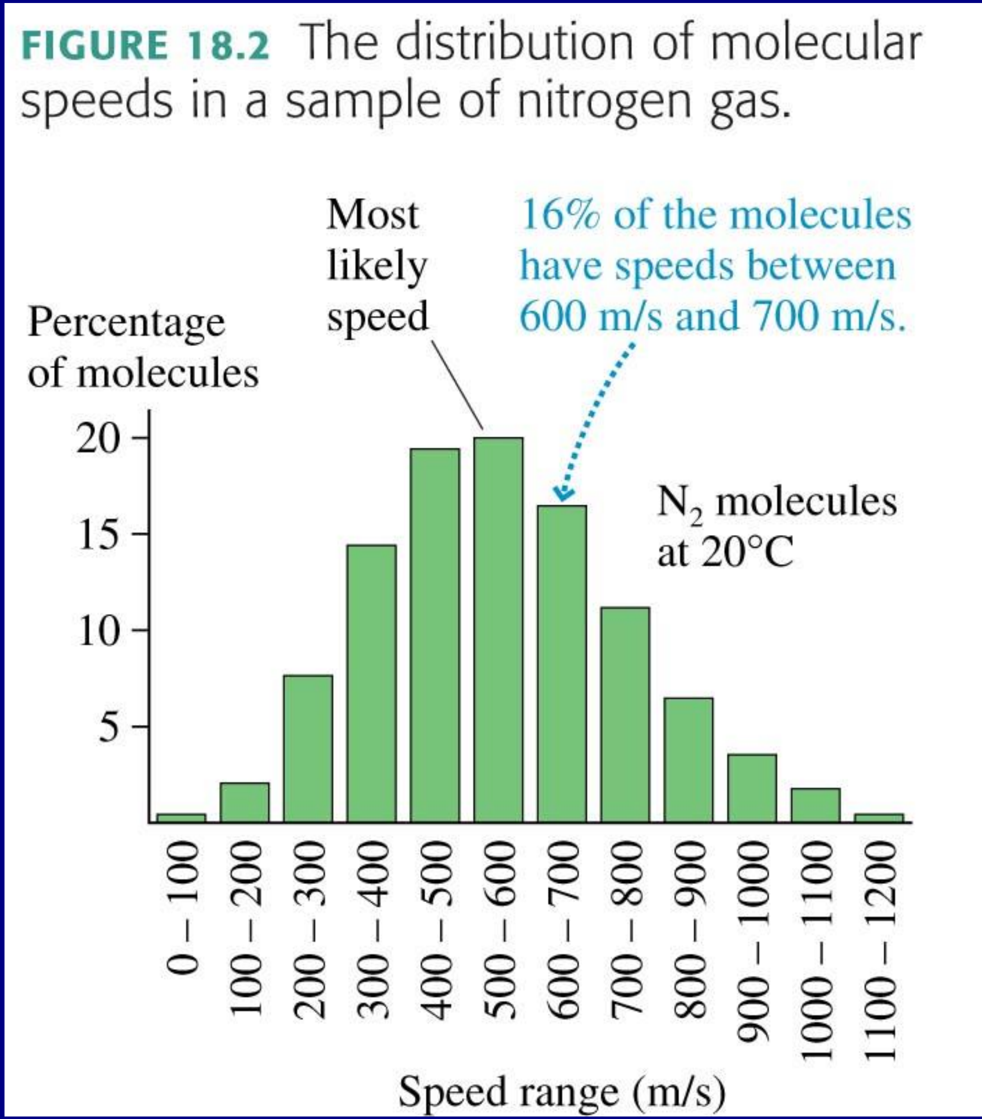
- A real gas consists of a vast number of molecules, each moving randomly and undergoing millions of collisions every second.

- Despite the apparent chaos, *averages*, such as the average number of molecules in the speed range 600 to 700 m/s, have precise, predictable values.

- **The "micro/macro" connection is built on the idea that the macroscopic properties of a system, such as temperature or pressure, are related to the *average* behavior of the atoms and molecules.**

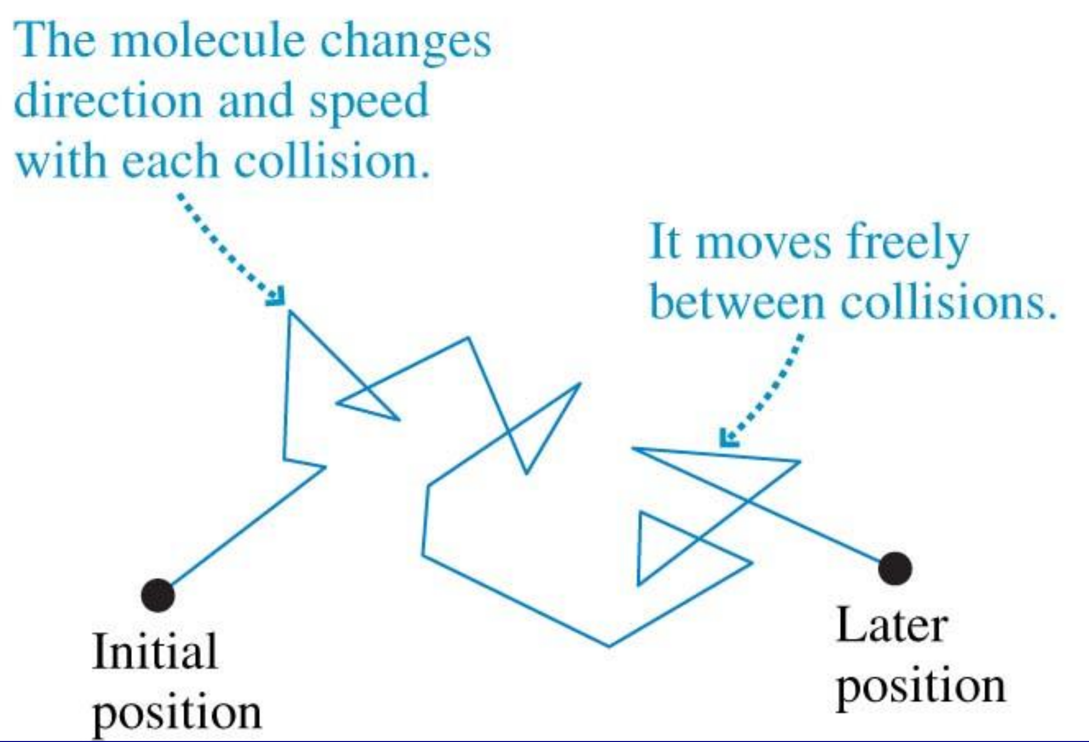
Molecular Speeds and Collisions

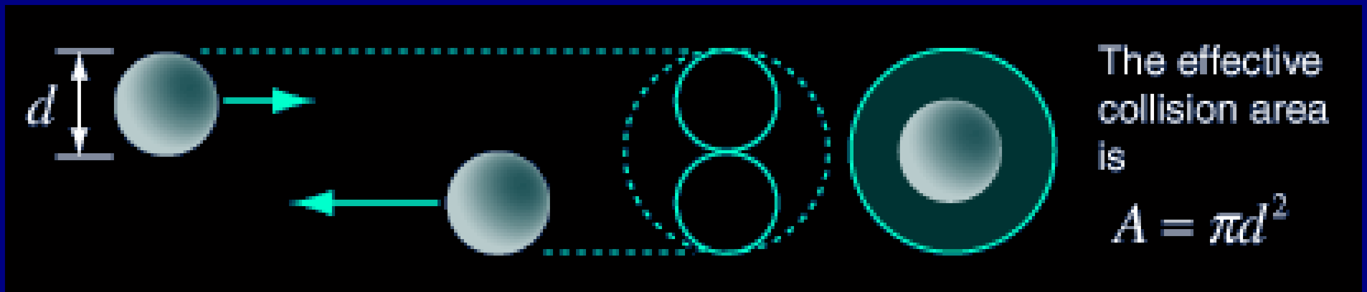
A view of a Fermi chopper



Molecular Speeds and Collisions

FIGURE 18.3 A single molecule follows a zig-zag path through a gas as it collides with other molecules.





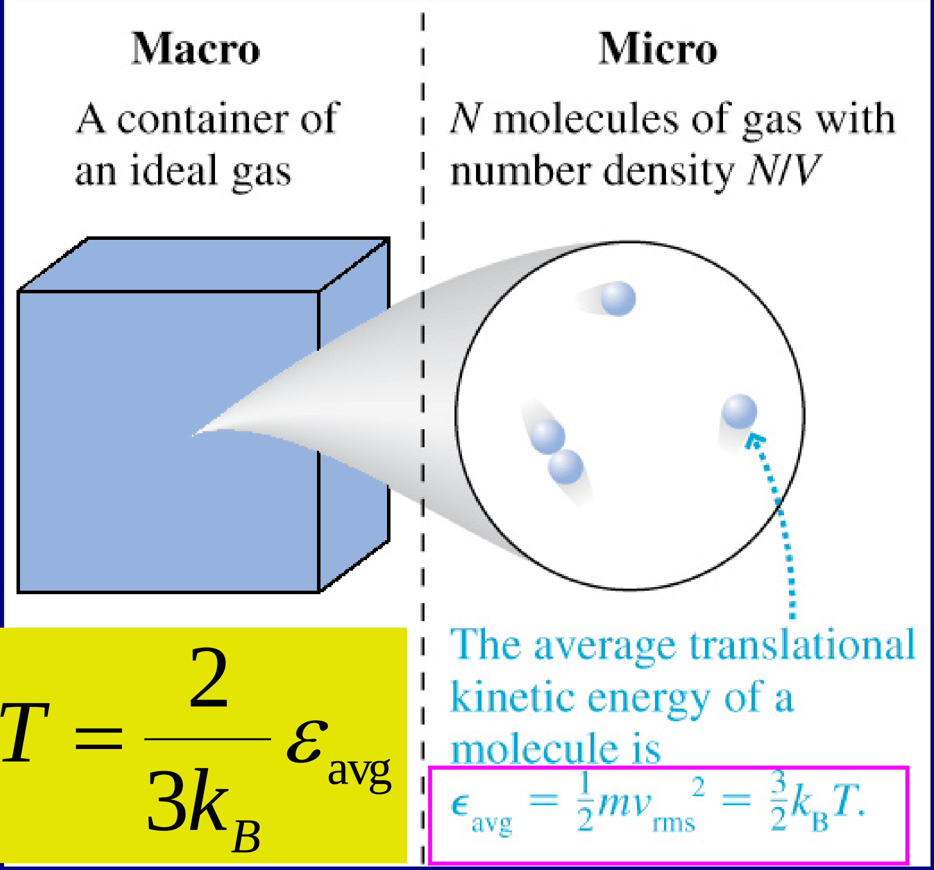
Mean Free Path

If a molecule has N_{coll} collisions as it travels distance L, the average distance between collisions, which is called the **mean free path** λ (lowercase Greek lambda), is

$$\lambda = \frac{1}{4\sqrt{2}\pi(N/V)r^2} \qquad \text{(mean free path)}$$

Macro-micro connection

- Assumptions for ideal gas:
  - # of molecules N is large
  - They obey Newton's laws
  - Short-range interactions with elastic collisions
  - Elastic collisions with walls (an impulse.....pressure)



- What we call temperature *T* is a direct measure of the average translational kinetic energy

$$T = \frac{2}{3k_B}\varepsilon_{avg}$$

- What we call pressure *p* is a direct measure of the number density of molecules, and how fast they are moving (v_{rms})

$$p = \frac{2}{3}\frac{N}{V}\varepsilon_{avg}$$

$$v_{rms} = \sqrt{(v^2)_{avg}} = \sqrt{\frac{3k_B T}{m}}$$