Lecture 11
Chapter 17: Work, Heat and 1st Law of Thermodynamics

• today:
  work, heat as energy transfers between system and environment
  how state of system changes in response to work, heat
(1st law of Thermodynamics: energy conservation)

• next lecture:
  1st law for specific ideal-gas processes
  Calorimetry(specific heat, heat of transformation)
  Specific heat of gases
  heat transfer
Work-Energy Theorem

\[ \Delta K = W_c + W_{diss} + W_{ext} \]

conservative forces: \( \Delta U = -W_c \)  

dissipative: \( \Delta E_{th} = -W_{diss} \)

\( E_{mech} = K + U \) (motion of system as a whole: macroscopic)

vs. \( E_{th} \) (microscopic energy of atoms and bonds)

\( \Delta E_{sys} = \Delta E_{th} + \Delta E_{mech} = W_{ext} \)

**isolated** system: \( W_{ext} = 0 \Rightarrow \Delta E_{sys} = 0 \) (energy conservation)

- earlier: how K and U is transformed into each other
- now: energy is transferred between system and environment (work and heat)

**Thermal energy**

moving atoms \( E_{th} = K_{micro} + U_{micro} \)

spring-like bonds

\( E_{int} = E_{th} + E_{chem} + E_{nucl} \Rightarrow E_{sys} = E_{mech} + E_{int} \) (here, \( E_{int} = E_{th} \))

- associated with T: \( \Delta E_{th} = 0 \) for isothermal (except phase changes)
Work

- energy transferred due to net force over a distance (mechanical interaction): sign tells us which way transfer

- not a state variable

Energy transfer

(a) Lift at steady speed

\[ K_i + U_i + W_{ext} = K_f + U_f + \Delta E_{th} \]

The energy transferred to the system goes entirely to the system's mechanical energy.

(b) Drag at steady speed

\[ K_i + U_i + W_{ext} = K_f + U_f + \Delta E_{th} \]

The energy transferred to the system goes entirely to the system's thermal energy.

Heat

- energy transferred in thermal interaction e.g.

  water on stove: \( W_{ext} = 0; \Delta E_{mech} = 0, \) but \( \Delta E_{th} \neq 0 \)
Work in Ideal-gas Processes (I)

\[ W = \int_{s_i}^{s_f} \dot{F_s} ds \]  (force parallel to or opposite to displacement)

\[ F_{ext} = F_{gas} = -pA \]  (piston in equilibrium)

\[ dW = F_{ext} dx = -pA dx = -pdV \]

\(< (>)0 \) (expansion/compression)

quasi-static process:

\[ W = -\int_{V_i}^{V_f} pdV \]

(cannot take \( p \) out of \( \int \) in general)

= negative of area under \( pV \) curve between \( V_i \) and \( V_f \)

As the piston moves \( dx \), the external force does work \( F_{ext} dx \) on the gas.

The volume changes by \( dV = Adx \) as the piston moves \( dx \).

For an expanding gas \((V_f > V_i)\), the area under the \( pV \) curve is positive (integration direction is to the right). Thus the environment does negative work on the gas.

For a compressed gas \((V_f < V_i)\), the area is negative because the integration direction is to the left. Thus the environment does positive work on the gas.
Work in Ideal-gas Processes (II)

- isochoric (constant V)

\[ W = 0 \quad \text{(isochoric process)} \]

- isobaric (constant p)

\[ W = -p\Delta V \quad \text{(isobaric process)} \]

- isothermal (constant T)

\[
W = -\int_{V_i}^{V_f} pdV = -\int_{V_i}^{V_f} \frac{nRT}{V} dV = -nRT \ln \frac{V_f}{V_i} \\
= -p_iV_i \ln \frac{V_f}{V_i} = -p_fV_f \ln \frac{V_f}{V_i}
\]

Work done depends on path and not just initial and final states: forces not conservative; path is of thermodynamic states, not particle

multi-step process(1→2→3): calculate \( W \) for each step and add: not equal to \( W \) in 1 step (1→3)
Example

- A 2000 cubic-cm container holds 0.1 mol of helium gas at 300 degrees Celsius. How much work must be done to compress the gas to 1000 cubic-cm at (a) constant pressure and (b) constant temperature?
Heat

- more elusive than work: “something” flows from hot to cold object (heat fluid or caloric)

- Joule...heat is energy transferred: raise temperature by heating or doing work (different ways of transferring energy to/from system)

- thermal interaction (temperature difference): faster molecules collider with slower (no macro.motion)

- heat is not state variable: energy transferred; units joule or calorie: 1 cal = heat to change 1 g water by 1 C

  1 food calorie = 1 Cal = 1000 cal
Thermal energy vs. heat vs. temperature

- Thermal energy (state variable): energy due to motion of atoms (even for isolated system)
- Heat: energy transferred between system and environment; heat is not a form of energy or state variable; heat can cause thermal energy to change
- Temperature: state variable, related to thermal energy per molecule; temperature difference required for thermal interaction (observed temperature difference can be due to work done on system or heating)
1st Law of Thermodynamics

\[ W + Q = \Delta E_{sys} = \Delta E_{mech} + \Delta E_{th} \]

here, \( \Delta E_{mech} = 0 \)

- basic energy model (work included, but not heat)
  vice versa in thermodynamic...

- 1st law does not tell us \( \mathcal{E}_{th} \), only \( \Delta \mathcal{E}_{th} \)

- \( \Delta \mathcal{E}_{th} \) \( \rightarrow \) change in other state variables
  (use other laws such as ideal-gas)