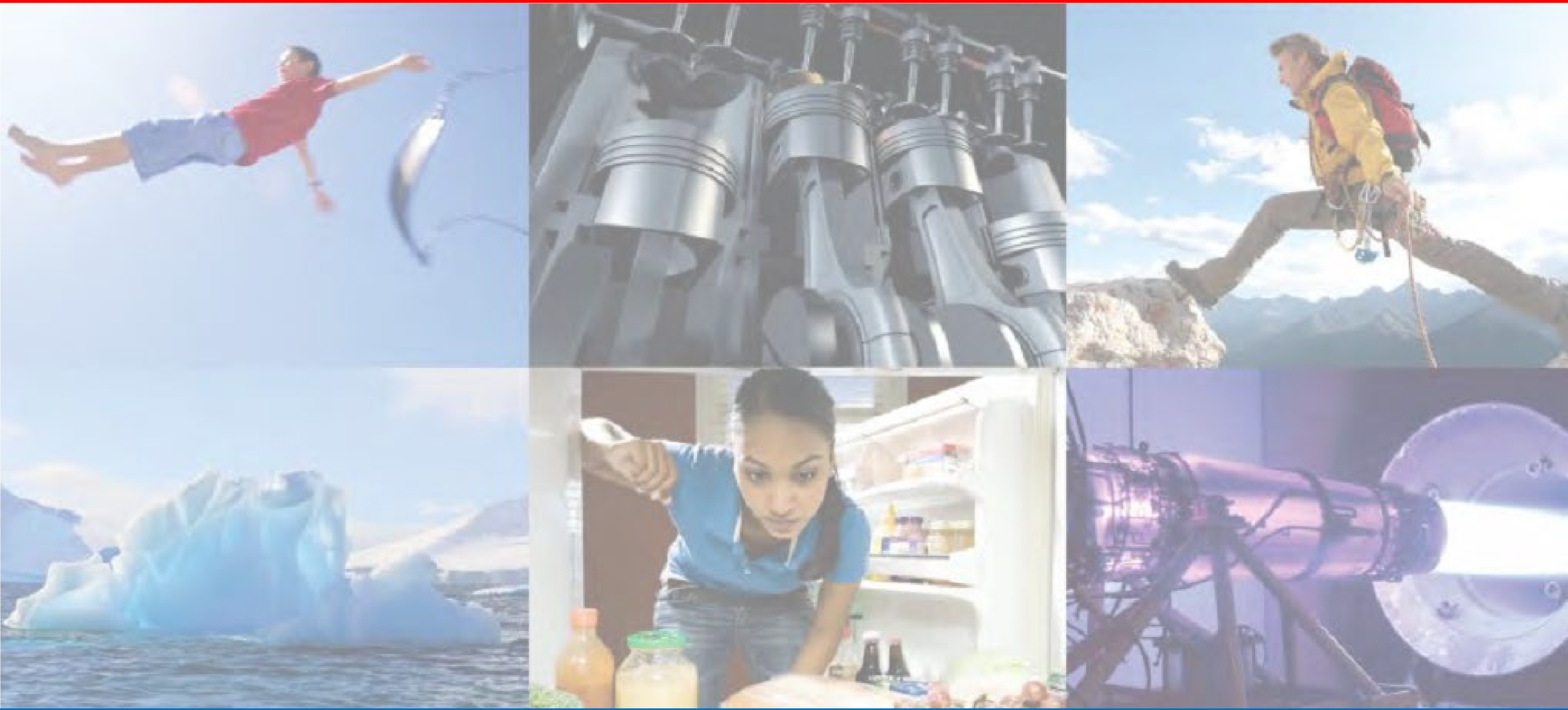


ENERGY AND FIRST LAW OF THERMODYNAMICS

By Ertanto Vetra

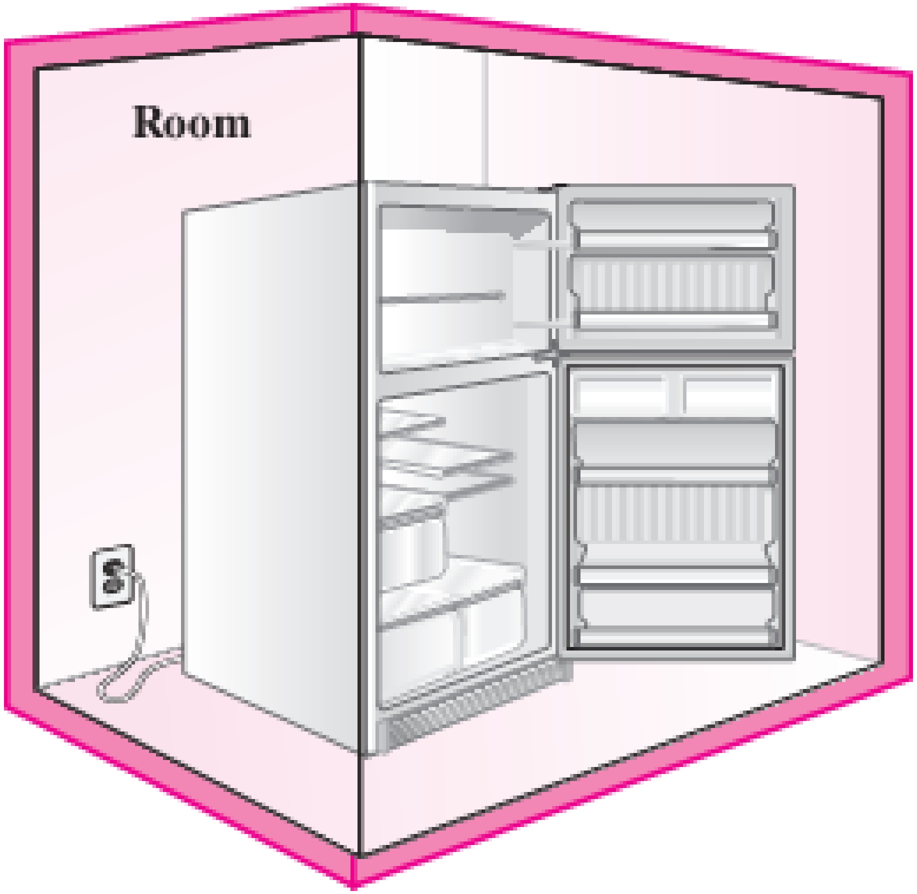
Objective

- Introduce the concept of energy and define its various forms.
- Discuss the nature of internal energy.
- Define the concept of heat and the terminology associated with energy transfer by heat.
- Discuss the three mechanisms of heat transfer: conduction, convection, and radiation.
- Define the concept of work, including electrical work and several forms of mechanical work.
- Introduce the first law of thermodynamics, energy balances, and mechanisms of energy transfer to or from a system.
- Determine that a fluid flowing across a control surface of a control volume carries energy across the control surface in addition to any energy transfer across the control surface that may be in the form of heat and/or work.
- Define energy conversion efficiencies.
- Discuss the implications of energy conversion on the environment

Outlines

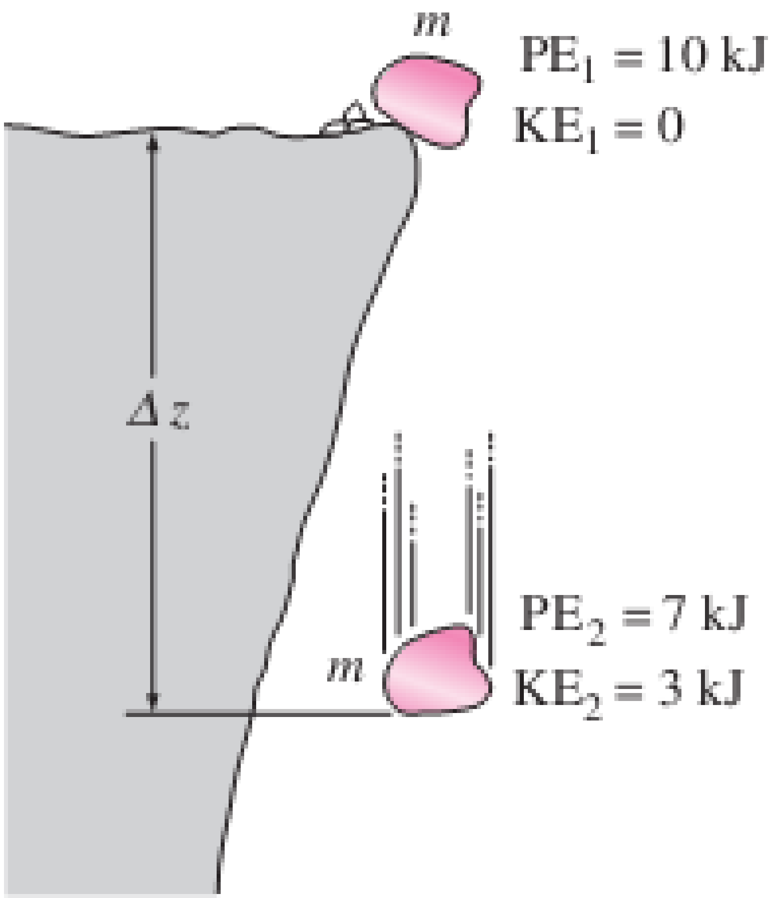
- First Law of Thermodynamics
- Energy
- Heat
- Work
- Energy Balance

Case



- A refrigerator is located inside a perfectly insulated room.
- What do you think would happen if the refrigerator door left open continuously?
- Will it get colder inside the room?
- Or the opposite?

First Law of Thermodynamics

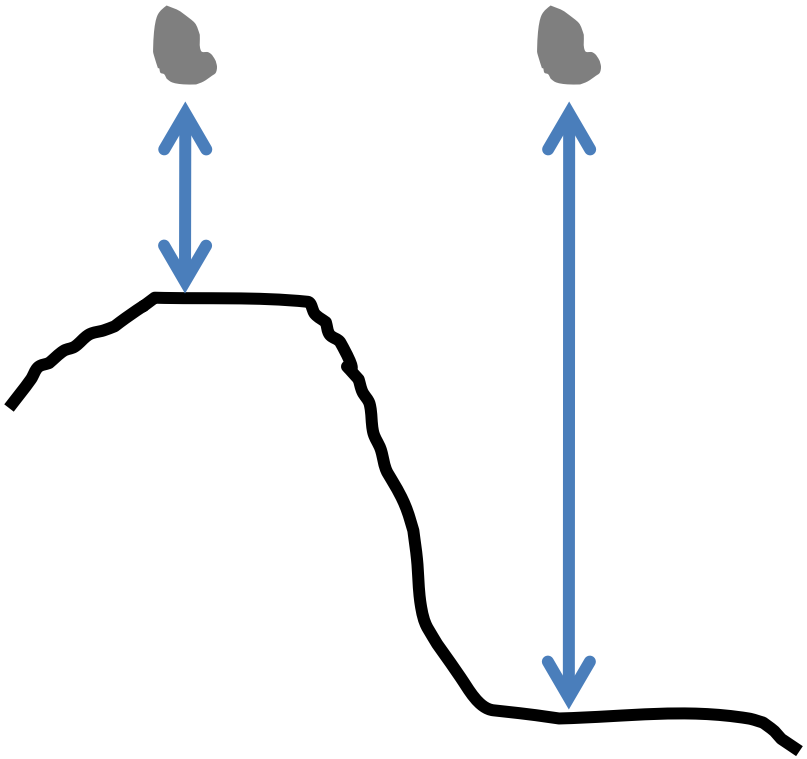


- energy can be neither created nor destroyed during a process; it can only change forms
- Therefore, every bit of energy **<u>should be accounted for</u>** during a process

Energy

- Energy can exist in numerous forms such as thermal, mechanical, kinetic, potential, electric, magnetic, chemical, nuclear, etc
- Thermodynamics provides no information about the **absolute value** of the total energy
- What matters is **the change** of the total energy → dependent on some reference point

Point of Reference



- Which one has he highest potential energy?

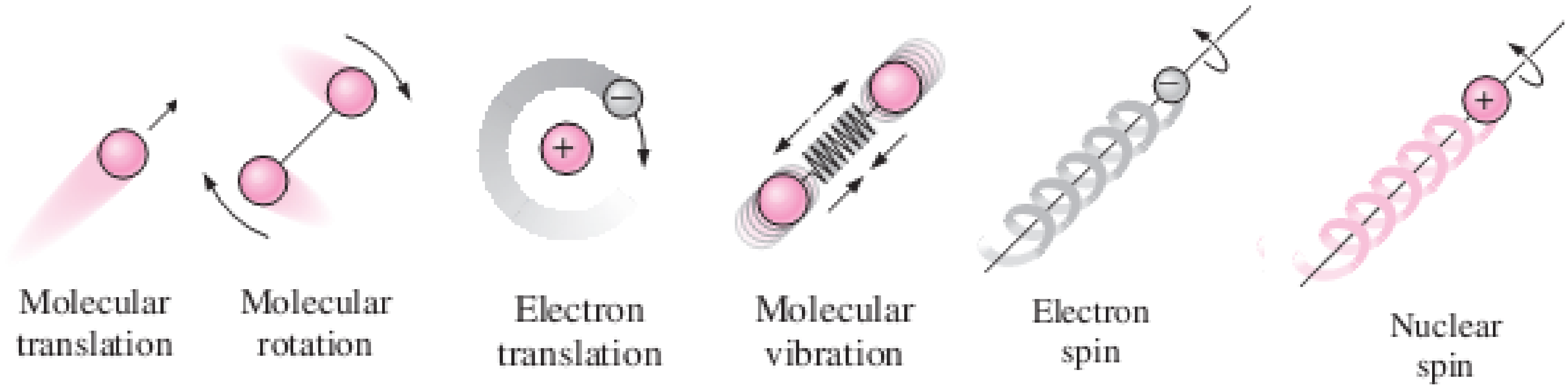
Macro vs. Micro

- **Macroscopic** forms of energy
  - related to motion and the influence of some external effects such as gravity, magnetism, electricity, and surface tension
  - e.g. Potential Energy, Kinetic Energy
- **Microscopic** forms of energy
  - related to the molecular structure of a system and the degree of the molecular activity
  - sum of all the microscopic forms of energy is called the **internal energy** of a system and is denoted by U

Macroscopic Energy

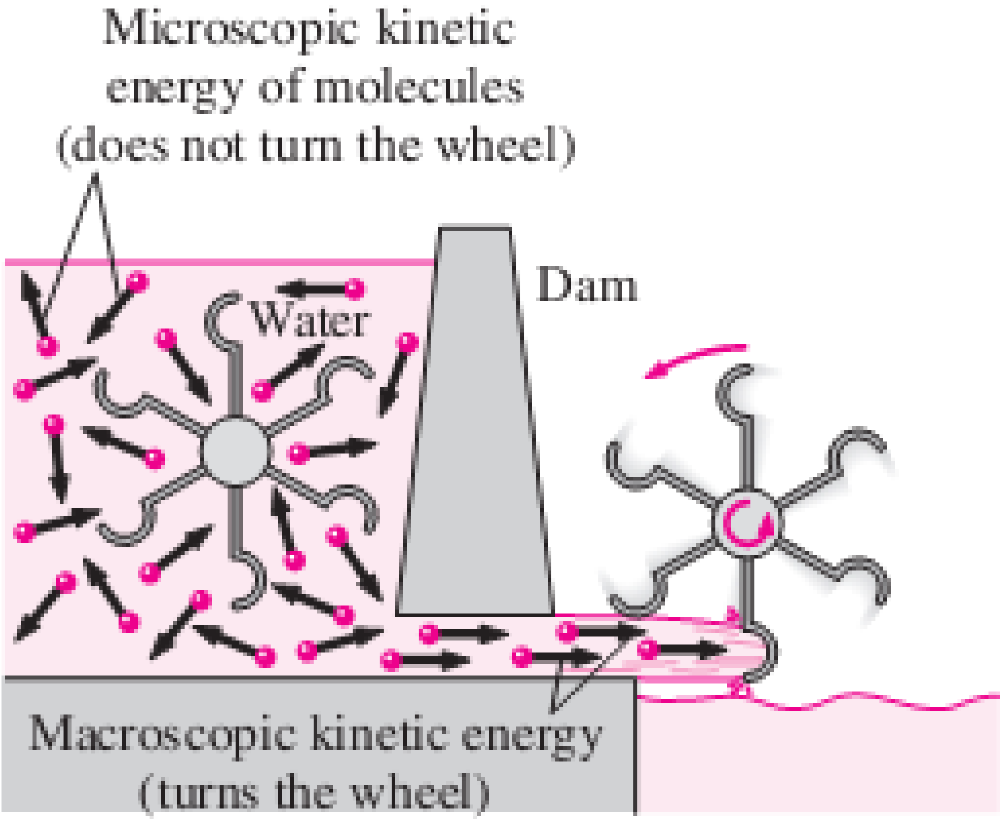
- Kinetic Energy: Result of its velocity relative to some reference frame
  - $E_K = \frac{1}{2}\, m\, v^2$ or $e_K = \frac{1}{2}\, v^2$ (Energy per unit mass)
- Potential Energy: Result of its position to some reference frame
  - $E_P = m.g.h$ or $e_P = g.h$ (Energy per unit mass)

Microscopic Energy



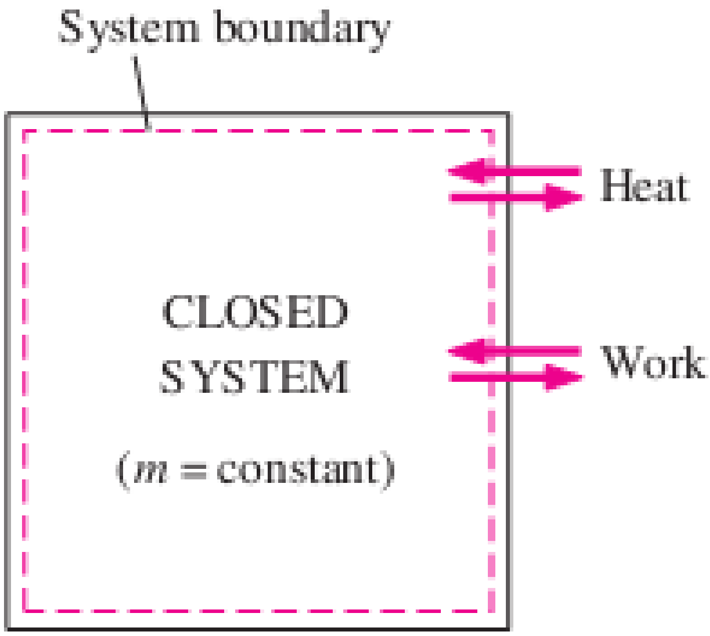
- Internal Energy = Molecular translation + Molecular Rotation + Electron translation + Molecular Vibration + Electron spin + …

Macroscopic kinetic energy is more useful



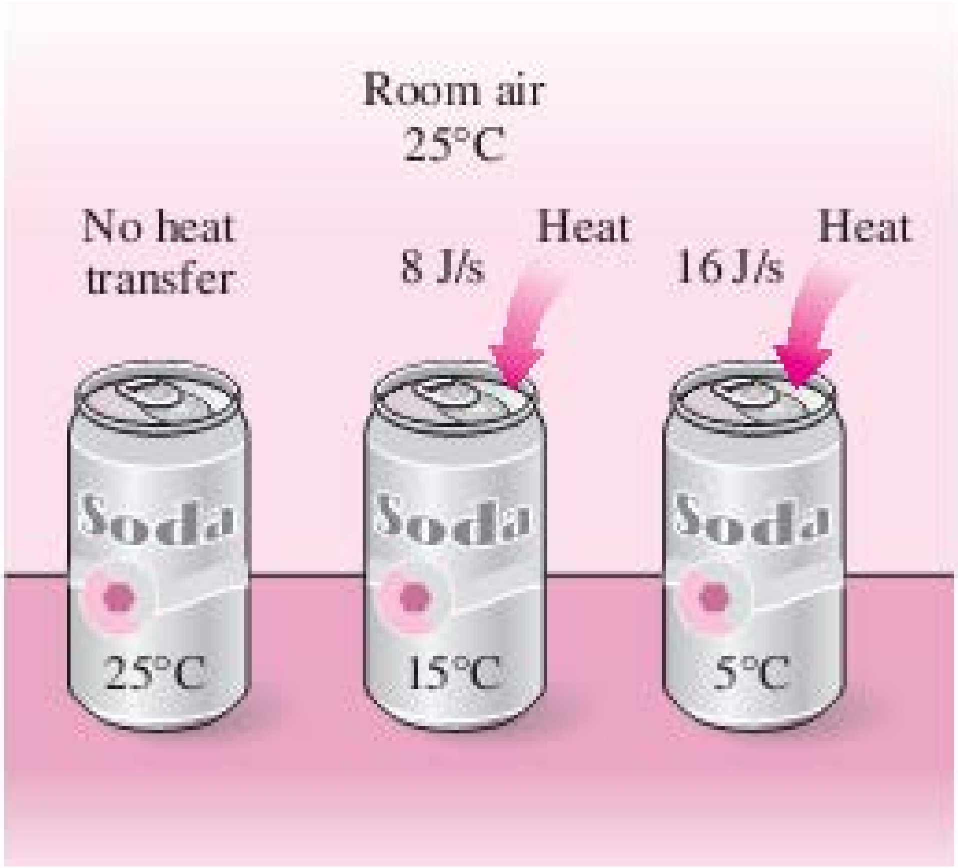
The *macroscopic* kinetic energy is an organized form of energy and is much more useful than the disorganized *microscopic* kinetic energies of the molecules.

Energy Transfer



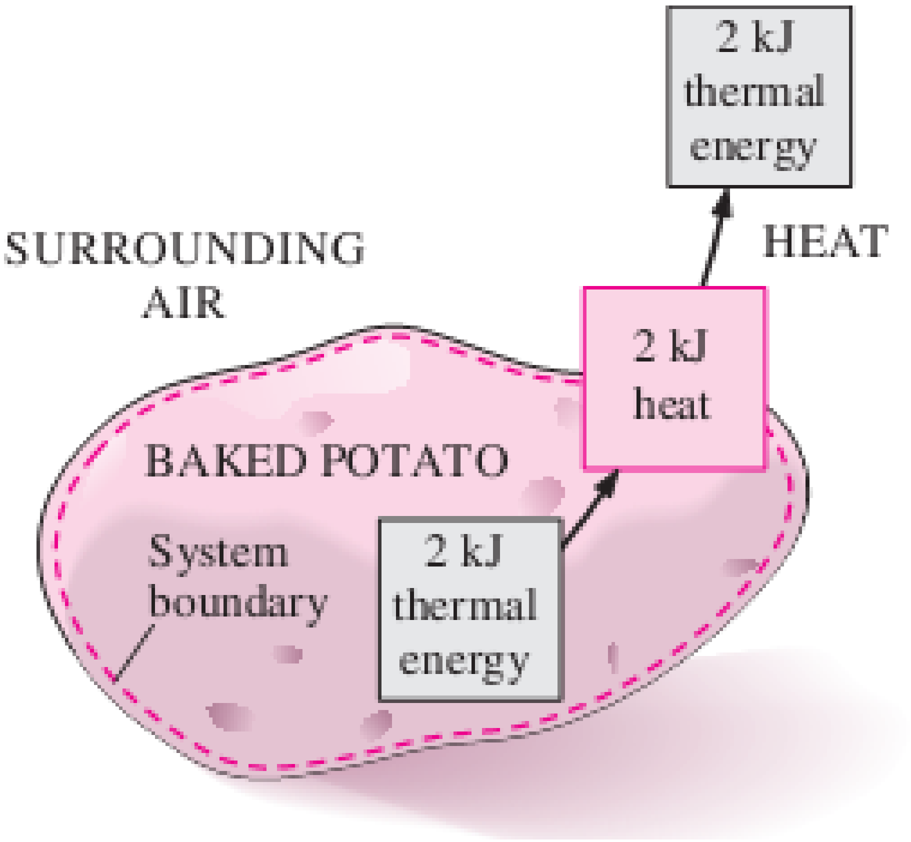
Energy can cross the boundaries of a closed system in the form of heat and work.

Energy Transfer by Heat



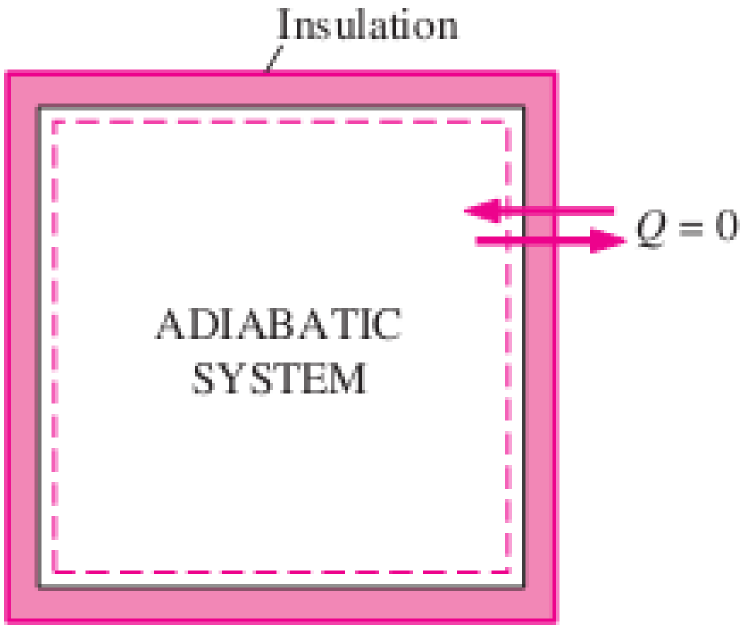
- Heat = the form of energy that is transferred between two systems (or a system and its surroundings) by **virtue of a temperature difference**

Energy Transfer by Heat



- Heat is energy in transition. It is recognized only as it crosses the boundary of a system
- Once in the surroundings, the transferred heat becomes part of the **internal energy** of the surroundings

Adiabatic system

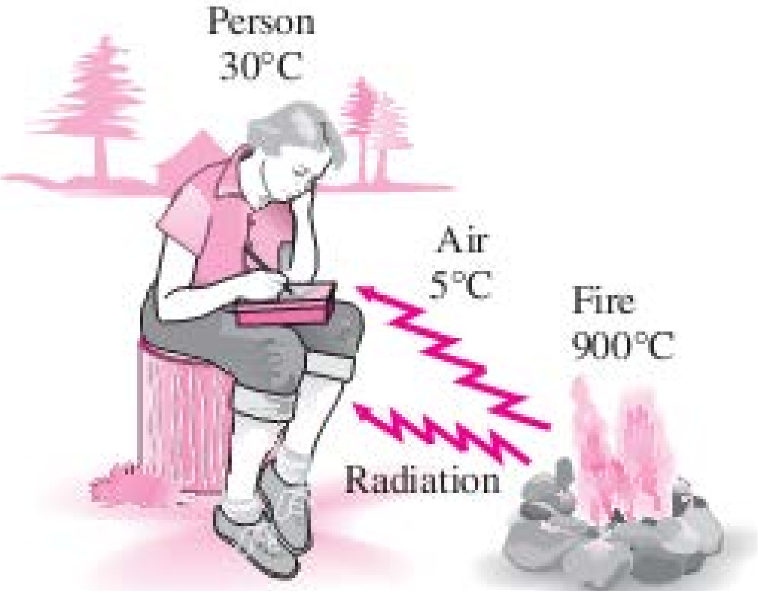


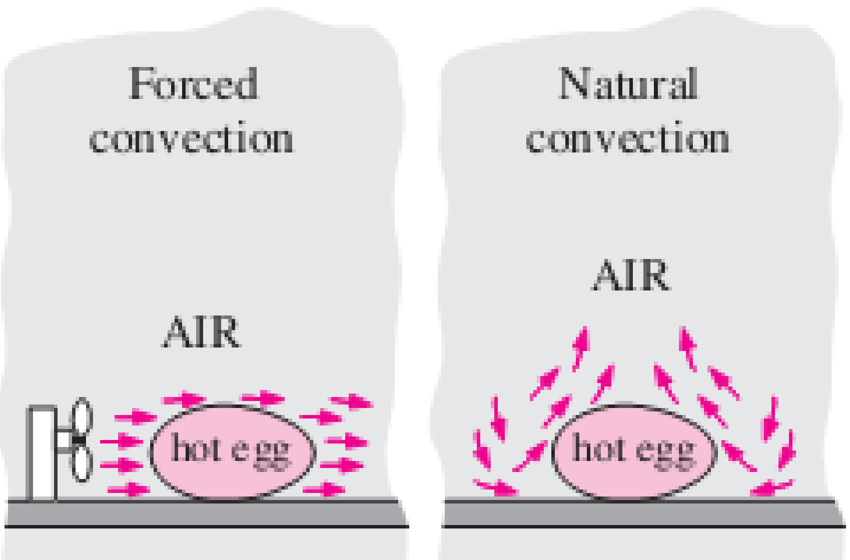
- *Adiabatos* = not to be passed
- Adiabatic = A process during which there is no heat transfer

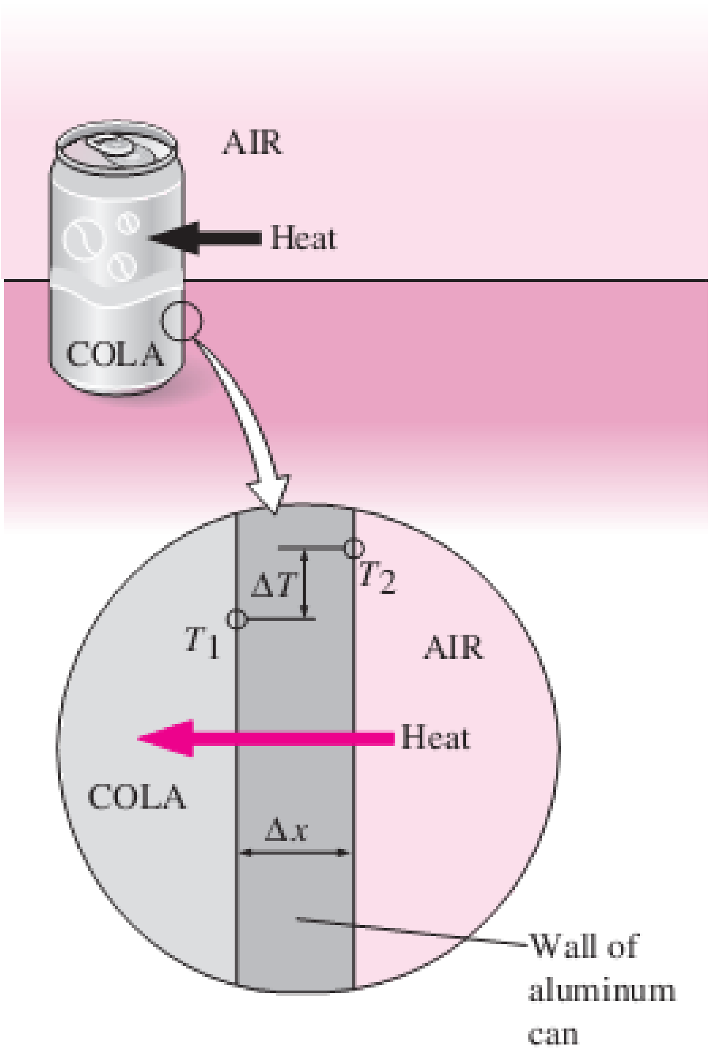
Heat

- The unit of heat is the same as energy:
  - kJ or kJ/kg (per unit mass) or kJ/hr (rate or per unit time)
- Heat is transferred through 3 mechanism:
  - Conduction: adjacent material/molecules
  - Convection : fluid motion
  - Radiation: emission of electromagnetic waves

Heat Transfer







Energy transfer by Work

- Work, like heat, is an energy interaction between a **system** and its **surroundings**.
- As mentioned earlier, energy can cross the boundary of a closed system in the form of heat **<u>or</u>** work.
- Therefore, if the energy crossing the boundary of a closed system is not heat, it must be work
- More specifically, work is the energy transfer associated with a **<u>force acting</u>** through a **<u>distance</u>**

Energy Balance

$$\begin{bmatrix} \textit{change} \text{ in the amount} \\ \text{of energy contained} \\ \text{within a system} \\ \text{during some time} \\ \text{interval} \end{bmatrix} = \begin{bmatrix} \textit{net} \text{ amount of energy} \\ \text{transferred } \textit{in} \text{ across} \\ \text{the system boundary by} \\ \textit{heat} \text{ transfer during} \\ \text{the time interval} \end{bmatrix} + \begin{bmatrix} \textit{net} \text{ amount of energy} \\ \text{transferred } \textit{out} \text{ across} \\ \text{the system boundary} \\ \text{by } \textit{work} \text{ during the} \\ \text{time interval} \end{bmatrix}$$

$$\Delta E = Q + W$$

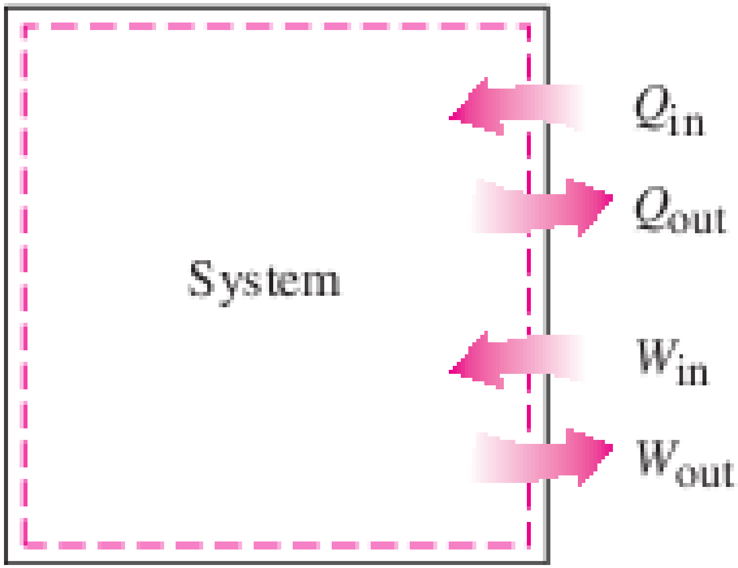
$$\Delta EK + \Delta EP + \Delta U = Q + W$$

**normally in thermodynamics, EK and EP is neglected, and the equation became:*

$$\Delta U = Q + W$$

Work

- Heat and Work are directional quantity
  - – Magnitude (Large/small)
  - – Direction (in/out)



- To specify direction
  - Using subscript in/out
  - Using +/- sign → convention

Sign Conventions (as per IUPAC convention)

- Positive (+) for:
  - Heat entering the system (Q_{in})
  - Work done to the system (W_{in})
- Negative (-) for:
  - Heat from the system to surroundings (Q_{out})
  - Work done by the system (W_{out})

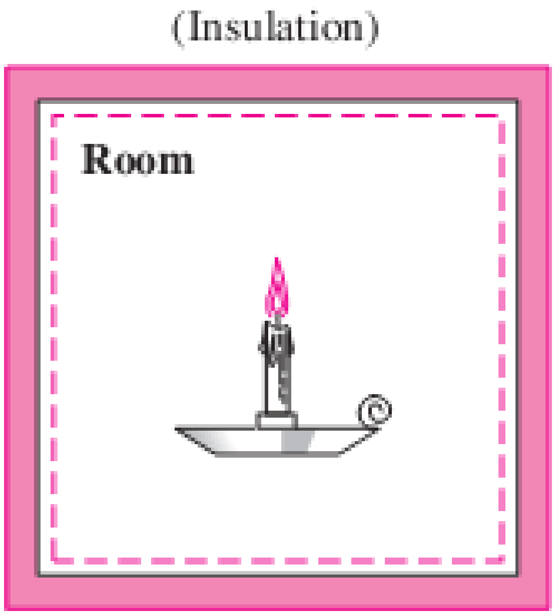
$$\Delta U = Q + W$$

- Some references may state the opposite, so the equation becomes

$$\Delta U = Q - W$$

- Both convention is valid as long **as its consistent**

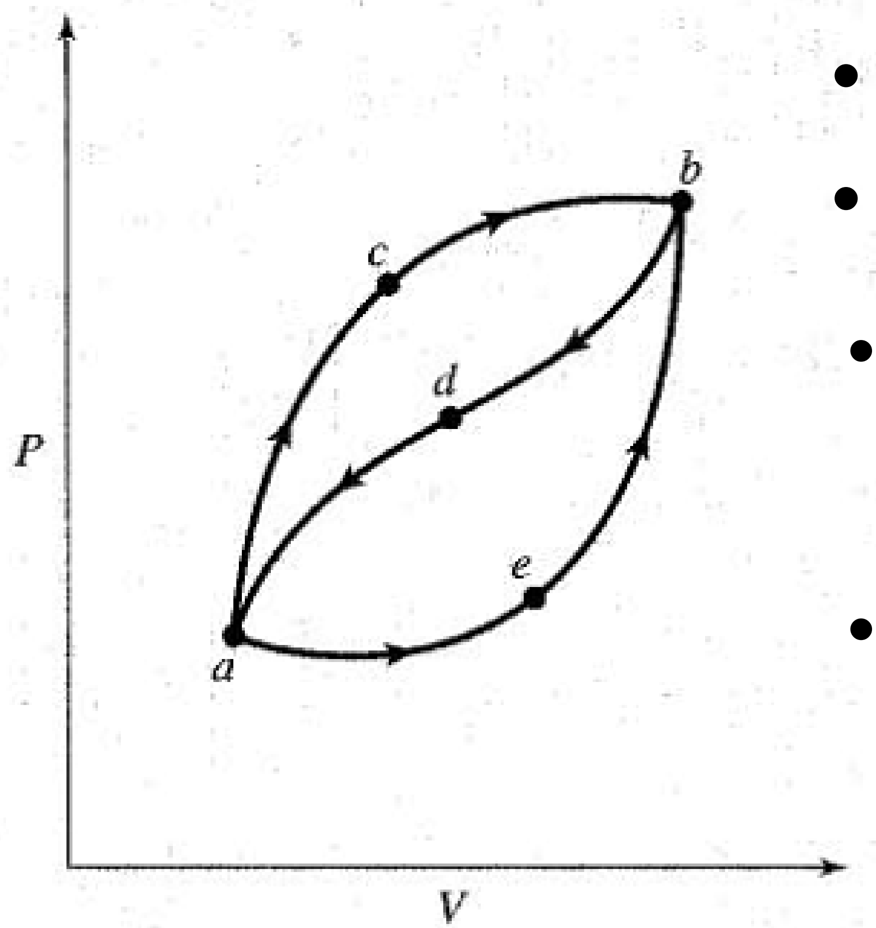
Exercise (1)



- A candle is burning in a well-insulated room. Taking the room (the air plus the candle) as the system, determine:
  a. if there is any heat transfer during this burning process
  b. if there is any change in the internal energy of the system.

Path vs. point/state function

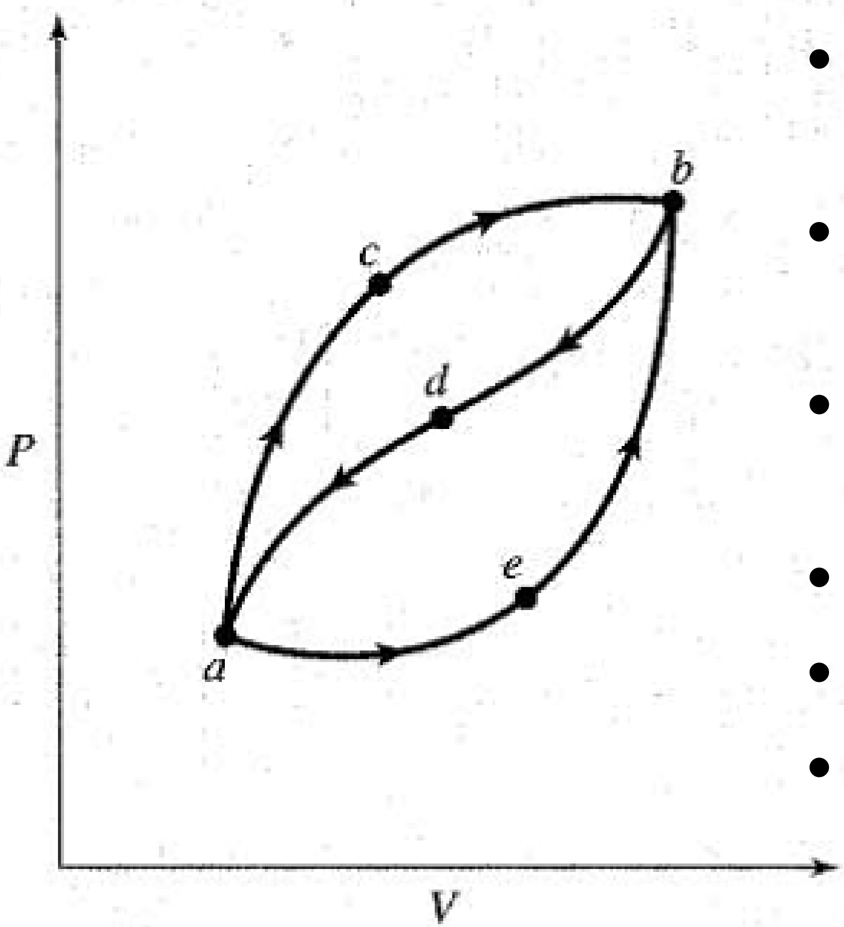
- Heat and Work is **Path** Function



- $Q_{acb} \neq Q_{bda} \neq Q_{aeb}$
- $W_{acb} \neq W_{bda} \neq W_{aeb}$
- they only have a value when change/process occurs
- there is no such as thing as Qa, Qb, Qc and so on

Path vs. point/state function

- The opposite of path function is **point or state function**

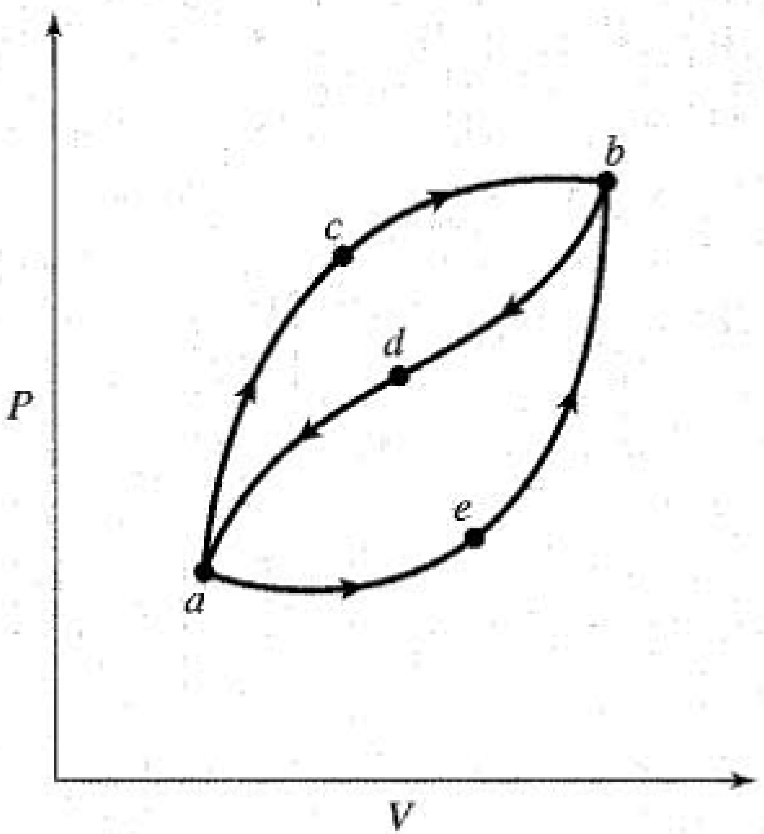


- They do not depend on the path taken
- They only depend on the **initial** and **final** state
- Example: Pressure, Volume, Internal Energy, Enthalpy
- $\Delta P_{acb} = \Delta P_{adb} = \Delta P_{aeb} = \Delta P_{ab}$
- $\Delta V_{acb} = \Delta V_{adb} = \Delta V_{aeb} = \Delta V_{ab}$
- $\Delta U_{acb} = \Delta U_{adb} = \Delta U_{aeb} = \Delta U_{ab}$

Summary of heat and work

- Both are recognized at the boundaries of a system as they cross the boundaries. That is, both heat and work are **boundary phenomena**.
- **Systems possess energy**, but not heat or work.
- **Both are associated with a process, not a state.** Unlike properties, heat or work has no meaning at a state.
- **Both are path functions** (i.e., their magnitudes depend on the path followed during a process as well as the end states)

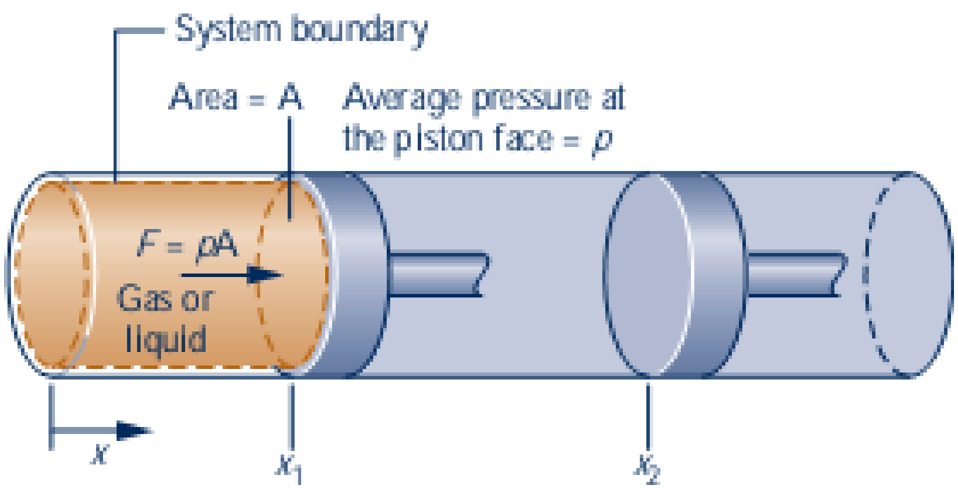
Exercise

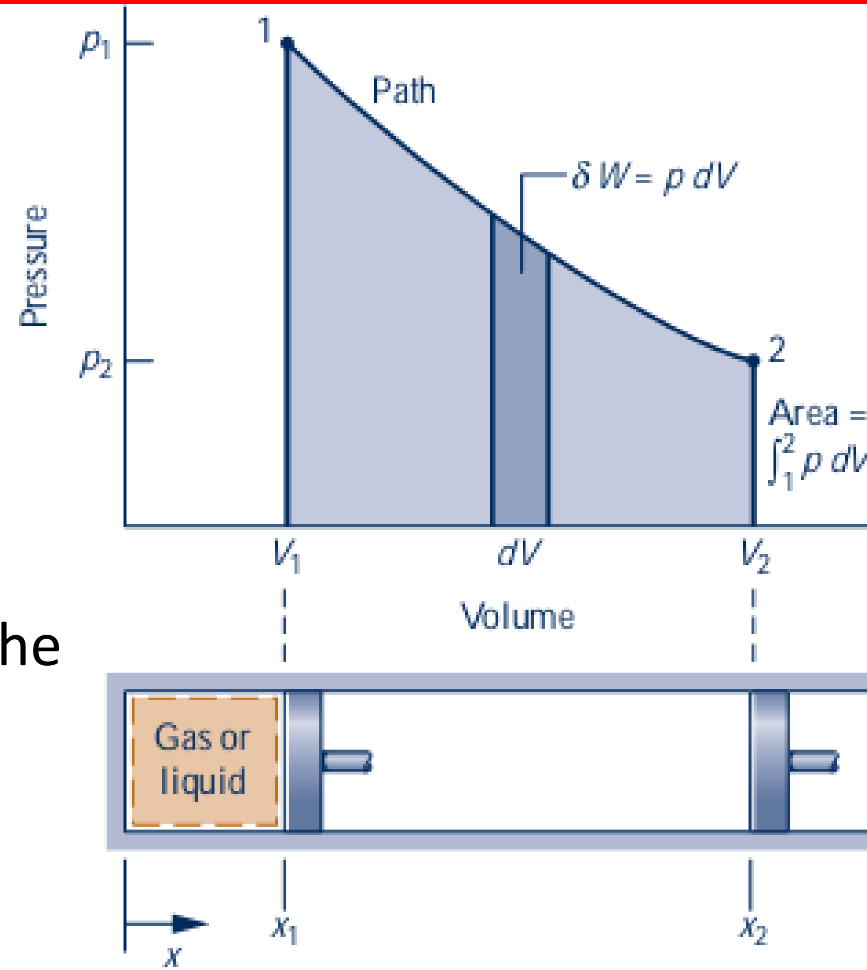


- When a system is taken from state a to state b along path *acb*, 100 J of heat flows into the system and the system does 40 J work.
  - How much heat flows into the system along path *aeb* if the work done by the system is 20 J
  - If the system returns from b to a along path *bda*. If the work done on the system is 30 J, does the system absorb or liberate heat? how much?

- After introducing the concept of heat, work, internal energy, and energy balance the next step is to evaluate each of the value described before

Modeling expansion or compression work





- The force is exerted by the pressure inside
- dW = - F dx

  dW = - P A dx

  dW = - P dV

$$W = -\int_{V_1^t}^{V_2^t} P\,dV^t$$

Example, Problem 2.31

2.31 Air contained within a piston–cylinder assembly is slowly heated. As shown in Fig. P2.31, during this process the pressure first varies linearly with volume and then remains constant. Determine the total work, in kJ.

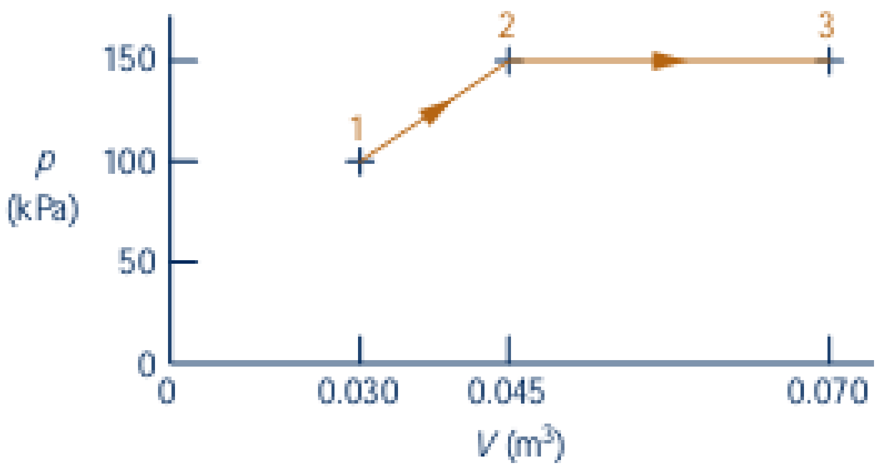


Fig. P2.31

$$\text{kPa} \cdot \text{m}^3 \equiv \text{kJ}$$

$$\text{kPa} \cdot \text{m}^3/\text{kg} \equiv \text{kJ/kg}$$

$$\text{bar} \cdot \text{m}^3 \equiv 100 \text{ kJ}$$

$$\text{MPa} \cdot \text{m}^3 \equiv 1000 \text{ kJ}$$

$$\text{psi} \cdot \text{ft}^3 \equiv 0.18505 \text{ Btu}$$

Example, Problem 2.32

2.32 A gas contained within a piston–cylinder assembly undergoes three processes in series:

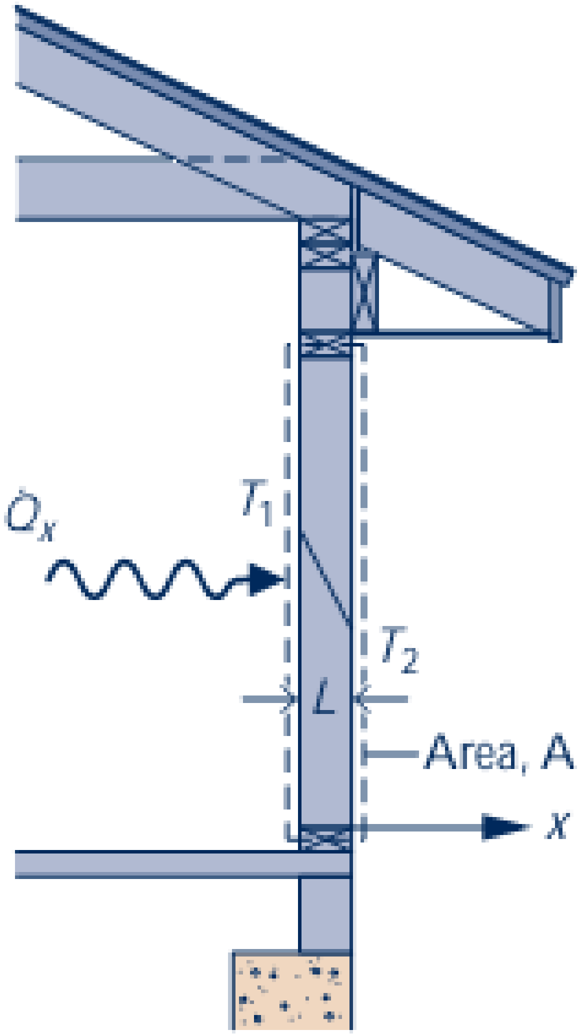
Process 1–2: Constant volume from $p_1 = 1$ bar, $V_1 = 4$ m^3 to state 2, where $p_2 = 2$ bar.

Process 2–3: Compression to $V_3 = 2$ m^3, during which the pressure–volume relationship is $pV = constant$.

Process 3–4: Constant pressure to state 4, where $V_4 = 1$ m^3.

Sketch the processes in series on p–V coordinates and evaluate the work for each process, in kJ.

Heat Transfer Modes - Conduction



Fourier's Law:

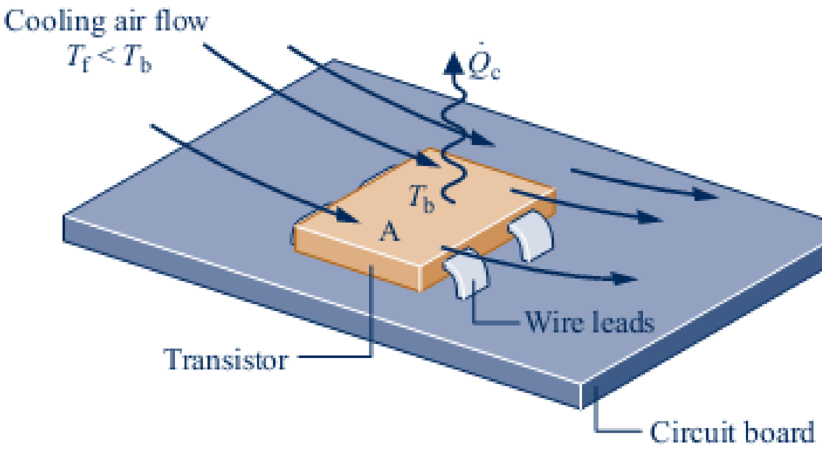
rate of heat transfer across any plane normal to the x direction, Qx, is proportional to:

– wall Area (A)

– Temperature gradient in the x direction (dT/dx)

$$\dot{Q}_x = -\kappa A \frac{dT}{dx}$$

Heat Transfer Modes - Convection



- Newton's law of cooling

$$\dot{Q}_c = hA(T_b - T_f)$$

Example

2–95 The inner and outer surfaces of a 5-m × 6-m brick wall of thickness 30 cm and thermal conductivity 0.69 W/m · °C are maintained at temperatures of 20°C and 5°C, respectively. Determine the rate of heat transfer through the wall, in W.

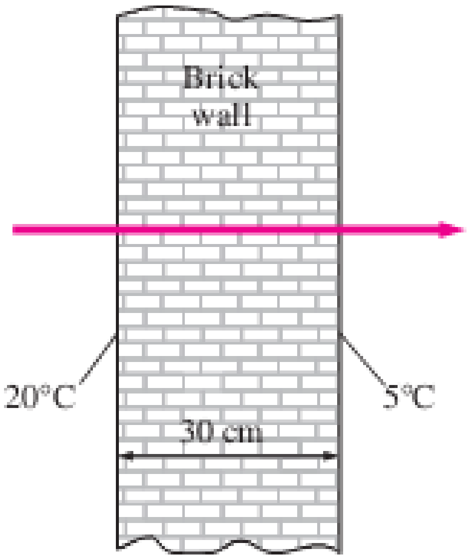


FIGURE P2–95

2–99 For heat transfer purposes, a standing man can be modeled as a 30-cm diameter, 170-cm long vertical cylinder with both the top and bottom surfaces insulated and with the side surface at an average temperature of 34°C. For a convection heat transfer coefficient of 15 W/m² · °C, determine the rate of heat loss from this man by convection in an environment at 20°C.

Heat Transfer with multiple modes

- Oftentimes heat transfer involves more than one heat transfer mechanism, e.g.:
  - Heat transfer through multiple layer of bricks
  - Combination of conductive & convective heat transfer

- At steady state, the Heat Flux is **constant**
- Heat Flux = Q/A (Energy/area)

$$(Q/A)_1 = (Q/A)_2 = (Q/A)_3 = \ldots = (Q/A)_n$$

Example, Problem 2.46

2.46 A composite plane wall consists of a 12-in.-thick layer of insulating concrete block ($\kappa_c = 0.27$ Btu/h · ft · °R) and a 0.625-in.-thick layer of gypsum board ($\kappa_b = 1.11$ Btu/h · ft · °R). The outer surface temperature of the concrete block and gypsum board are 460°R and 560°R, respectively, and there is perfect contact at the interface between the two layers. Determine at steady state the instantaneous rate of heat transfer, in Btu/h per ft^2 of surface area, and the temperature, in °R, at the interface between the concrete block and gypsum board.

Example, Problem 2.44

2.44 As shown in Fig. P2.44, the 6-in.-thick exterior wall of a building has an average thermal conductivity of 0.32 Btu/h · ft · °R. At steady state, the temperature of the wall decreases linearly from T_1 = 70°F on the inner surface to T_2 on the outer surface. The outside ambient air temperature is T_0 = 25°F and the convective heat transfer coefficient is 5.1 Btu/h · ft^2 · °R. Determine (a) the temperature T_2 in °F, and (b) the rate of heat transfer through the wall, in Btu/h per ft^2 of surface area.

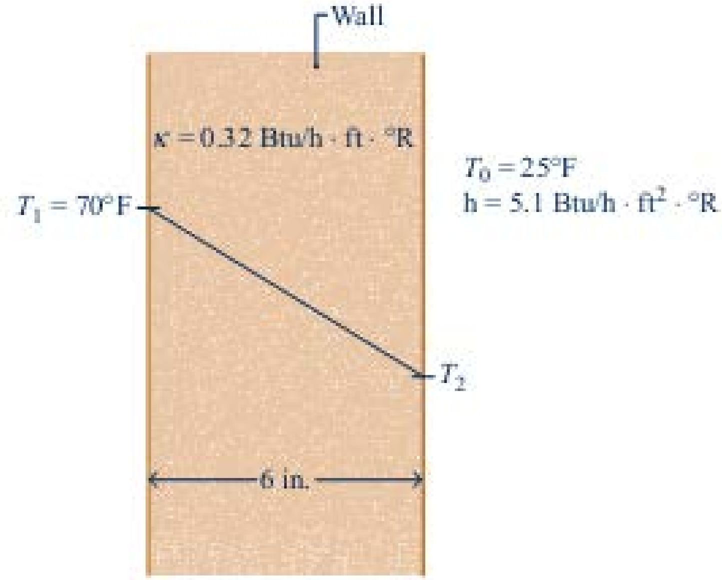


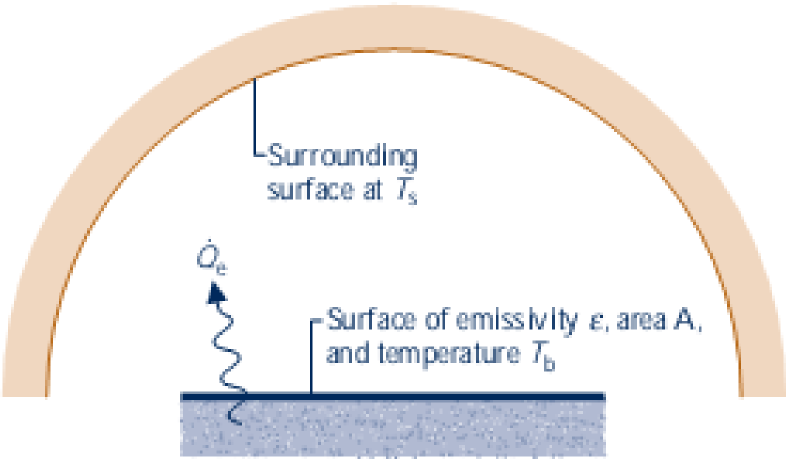
Fig. P2.44

Heat Transfer Modes - Radiation

- Stefan-Boltzmann Law

$$\dot{Q}_e = \varepsilon \sigma A T_b^4$$

- Ɛ = emissivity (0 < Ɛ < 1)
- σ = Stefan-Boltzmann Constant = 5.67 x 10^{-8} W/m^2 K^4

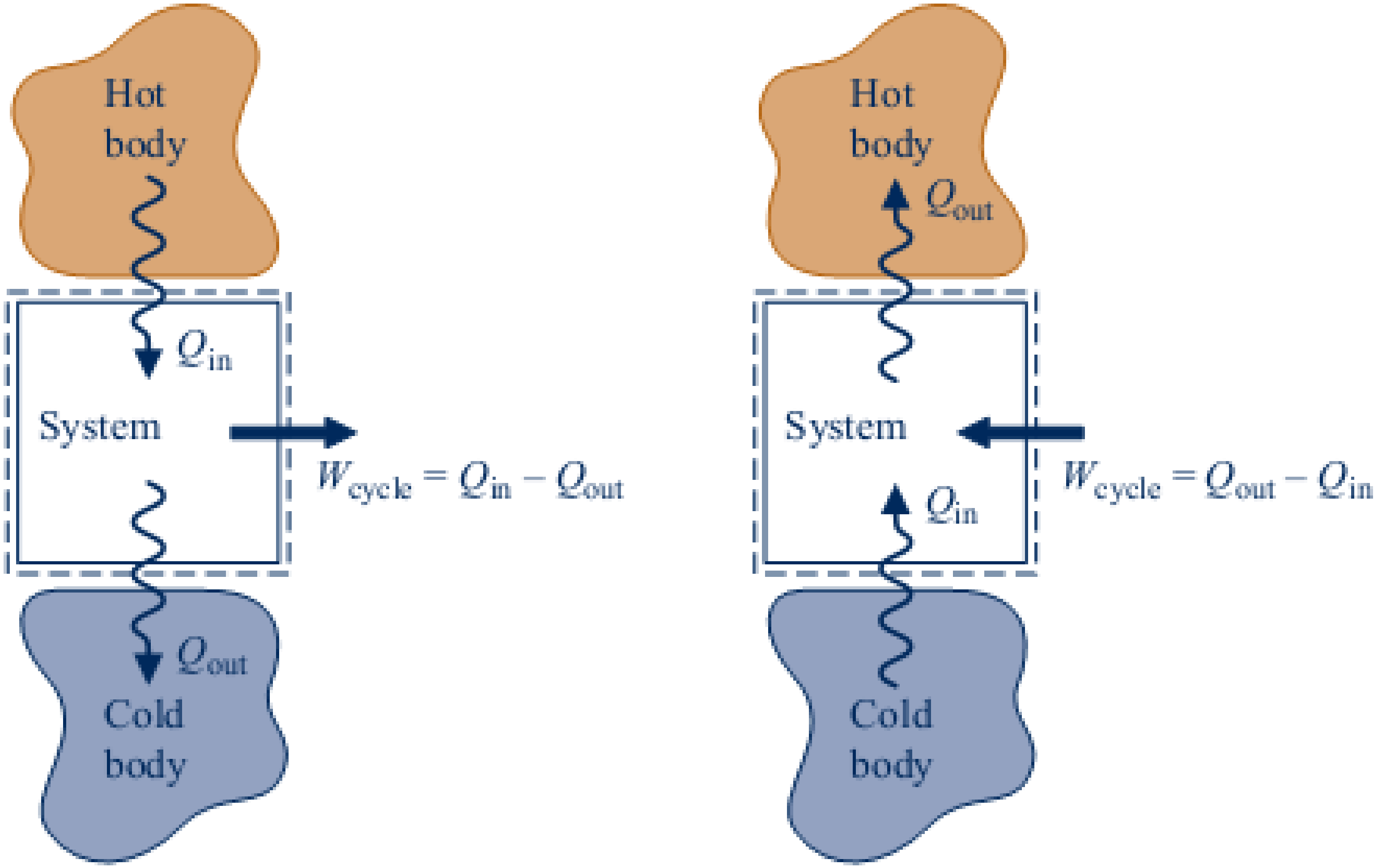


$$\dot{Q}_e = \varepsilon \sigma A[T_b^4 - T_s^4]$$

Example, Problem 2.51

2.51 A body whose surface area is 0.5 m^2, emissivity is 0.8, and temperature is 150°C is placed in a large, evacuated chamber whose walls are at 25°C. What is the rate at which radiation is *emitted* by the surface, in W? What is the *net* rate at which radiation is *exchanged* between the surface and the chamber walls, in W?

Energy balance of cycles



Energy balance of cycles

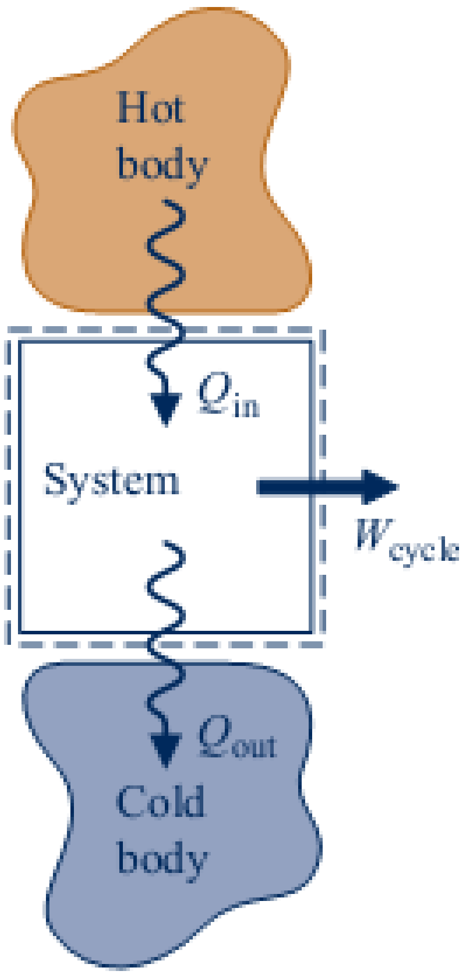
$$\Delta E_{cycle} = Q_{cycle} - W_{cycle}$$

For a cycle, initial condition = final condition, therefore $\Delta E = 0$

$$W_{cycle} = Q_{cycle}$$

Equation above is an expression of the conservation of energy principle that must be satisfied by every thermodynamic cycle, regardless of the sequence of processes followed by the system undergoing the cycle or the nature of the substances making up the system.

Power cycles



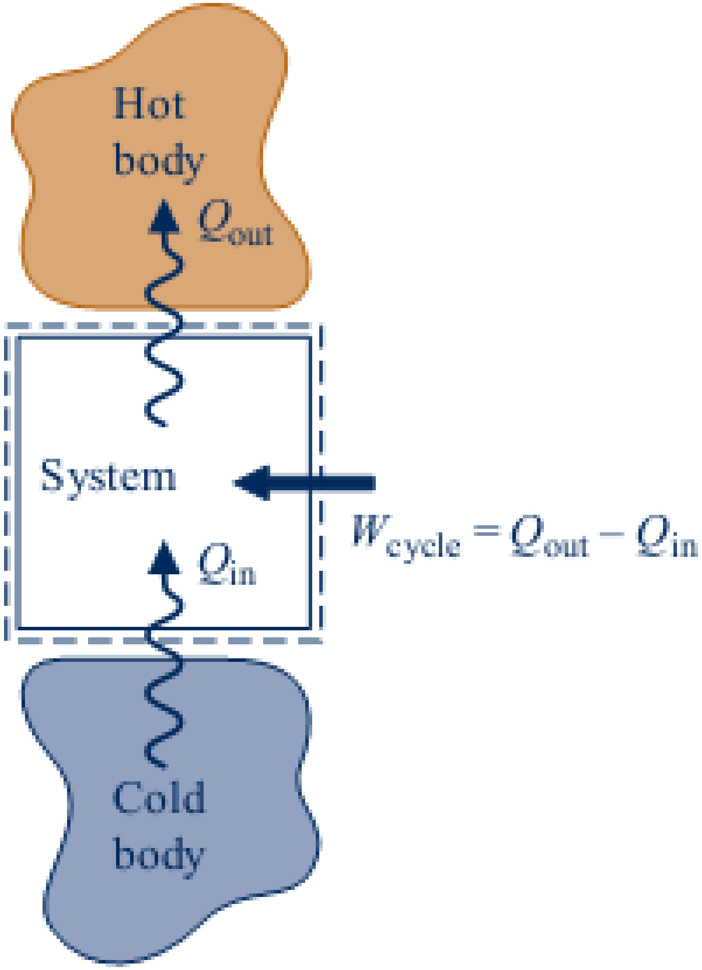
$$W_{cycle} = Q_{in} - Q_{out} \qquad \text{(power cycle)}$$

Thermal efficiency:

$$\eta = \frac{W_{cycle}}{Q_{in}} \qquad \text{(power cycle)}$$

$$\eta = \frac{Q_{in} - Q_{out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}}$$

Refrigeration Cycles



$$W_{cycle} = Q_{out} - Q_{in}$$

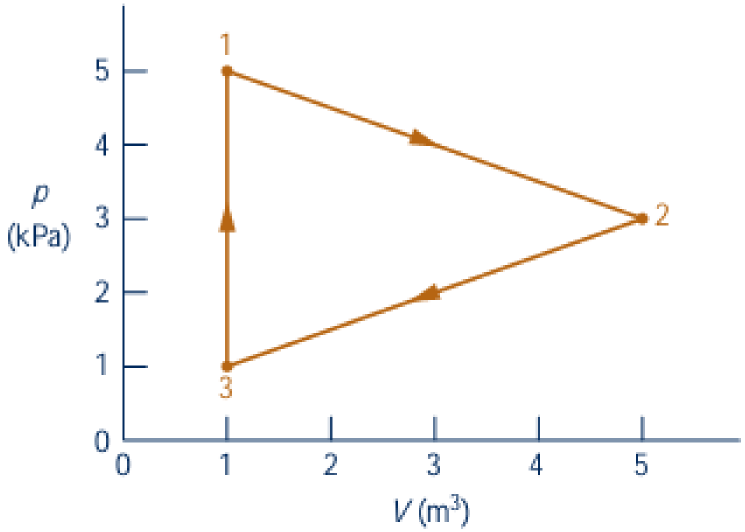
Coefficient of Performance (COP):

$$\beta = \frac{Q_{in}}{W_{cycle}}$$

$$\beta = \frac{Q_{in}}{Q_{out} - Q_{in}}$$

Example

2.73 Figure P2.73 shows a power cycle executed by a gas in a piston-cylinder assembly. For process 1–2, $U_2 - U_1 = 15$ kJ. For process 3-1, $Q_{31} = 10$ kJ. There are no changes in kinetic or potential energy. Determine (a) the work for each process, in kJ, (b) the heat transfer for processes 1–2 and 2–3, each in kJ, and (c) the thermal efficiency.



2.74 A gas within a piston–cylinder assembly undergoes a thermodynamic cycle consisting of three processes in series, beginning at state 1 where $p_1 = 1$ bar, $V_1 = 1.5$ m^3, as follows:

Process 1–2: Compression with $pV = constant$, $W_{12} = -104$ kJ, $U_1 = 512$ kJ, $U_2 = 690$ kJ.

Process 2–3: $W_{23} = 0$, $Q_{23} = -150$ kJ.

Process 3–1: $W_{31} = +50$ kJ.

There are no changes in kinetic or potential energy. (a) Determine Q_{12}, Q_{31}, and U_3, each in kJ. (b) Can this cycle be a power cycle? Explain.