ME 200 – Thermodynamics 1
Chapter 2 In-Class Notes
for Spring 2023

Energy and 1st Law

- Mechanical Energy
- Work Transfer
- Total and Internal Energy
- Heat Transfer
- Closed System Energy Balances

Lecture 4
Mechanical Energy

- Mechanical Work
- Kinetic Energy
- Potential Energy

Mechanical Work

- Energy transfer associated with force acting through a distance

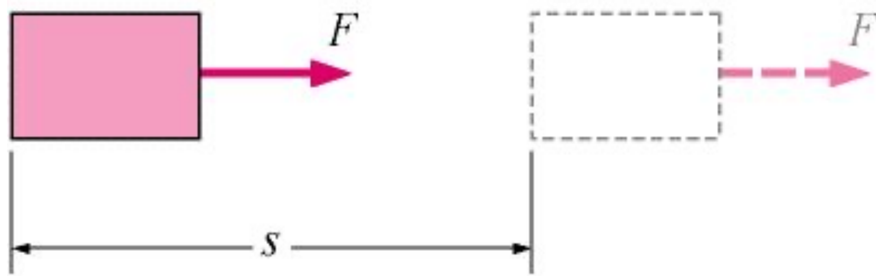
Examples

- Work required to raise a weight in a gravitational field
- Work to accelerate a mass (e.g., a car)
- Frictional work (e.g., friction between tire and road)
- Spring work (expansion or compression)
- Boundary work (e.g., a gas working against a moving piston
- Shaft work (e.g., a rotating crankshaft on a motor)

Sign Convention

$W > 0$: work done by the system
$W < 0$: work done on the system
$W = 0$: no work

Work Done on an Object

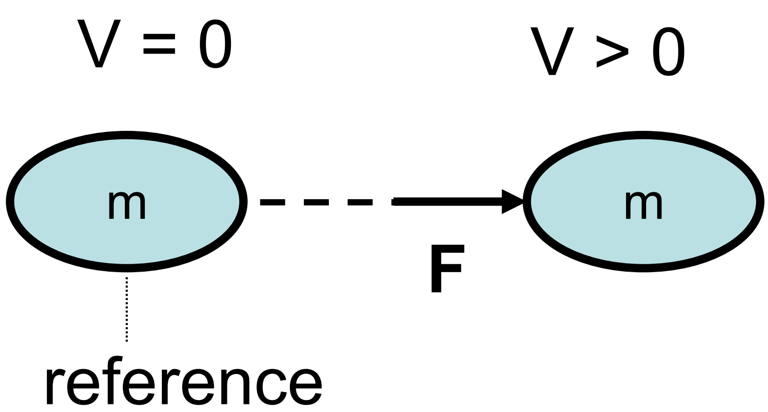


Units

– N-m or J; usually kJ in SI units
– lbf-ft or Btu in English units
– 1 Btu = 778.169 lbf-ft = 1.055056 kJ

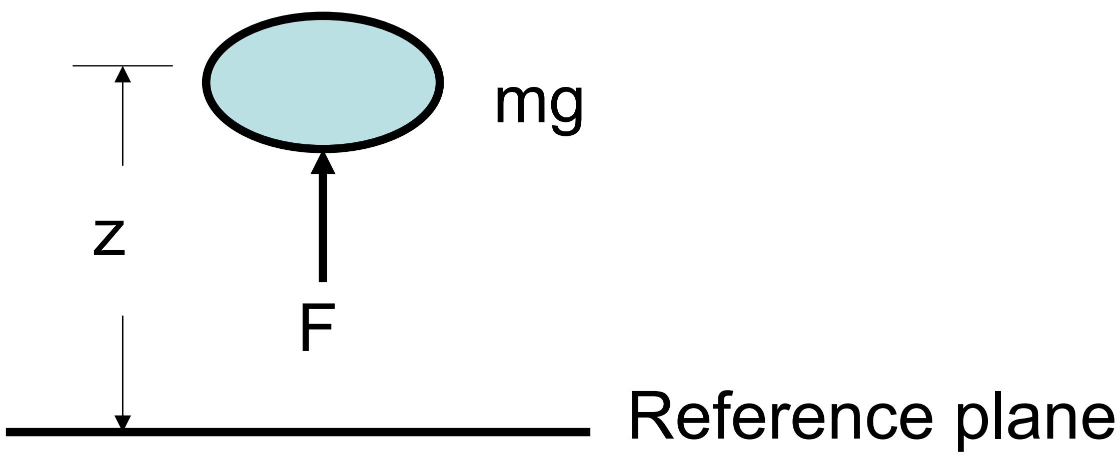
Kinetic Energy

- Minimum mechanical work required to accelerate an object of fixed mass (m) from rest to a given velocity (V) in the absence of gravity and frictional effects
- Property of the system



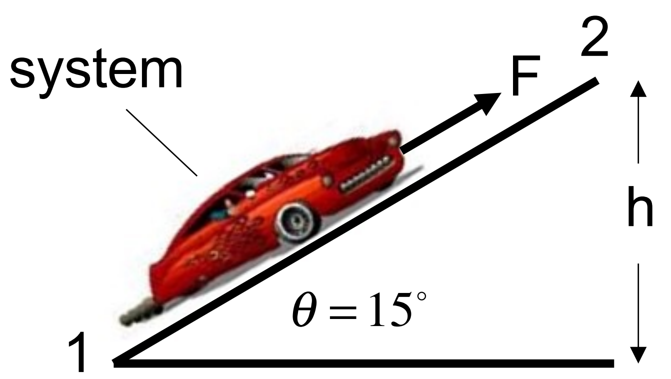
Potential Energy

- Minimum mechanical work required to raise an object of fixed mass (m) a given elevation (h) within a gravitational field
- Property of a system



Car Example

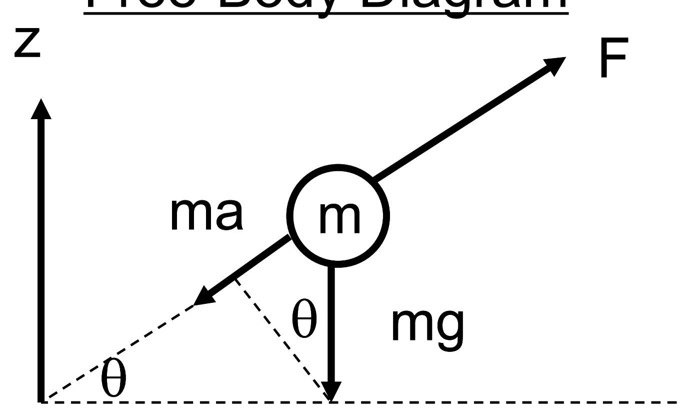
Given: Driving up a hill with

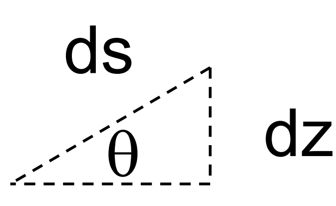


h = 20 m
V_1 = 27 m/s (~60 mph)
V_2 = 24 m/s (~54 mph)
θ = 15°
m = 1000 kg (~2200 lbm)

Find: (a) work required to “push” car up the hill,
(b) final car speed if coasting up entire hill
Assumptions: Neglect drag and friction

Free-Body Diagram





Lecture 5
Work Transfer

- Definitions
- Compression/Expansion Work
- Other Types of Work

What is Work?

- Energy transfer where the sole effect could be raising of a weight
  - Mechanical work (force acting through a distance)
  - Electricity
  - …
- Energy crossing the boundary of a closed system that is not heat must be work

- Work is not a property → it is a transfer of energy that depends on the path of a process

Quantifying Work

- Work transfer depends on the path of a process

$$W = W_{12} = \int_1^2 \delta W$$

where δW is an inexact work differential because the integral can not be evaluated without specifying the details of the process

- Rate of work transfer or power

$$\dot{W} = \frac{\delta W}{dt} \quad \text{(kW, Btu/h)}$$

Amount of work transfer during a process

$$W_{12} = \int_1^2 \dot{W}\, dt$$

and for constant power (i.e., constant net force)

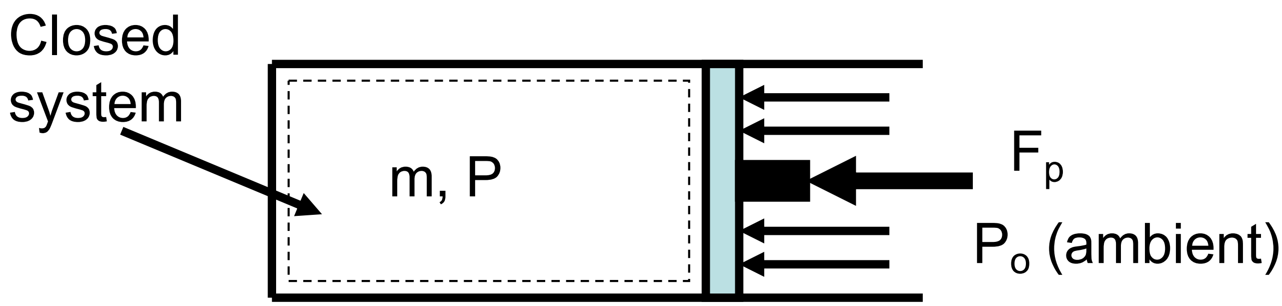
$$W = \dot{W}\,\Delta t$$

- Mechanical Power (force through a distance)

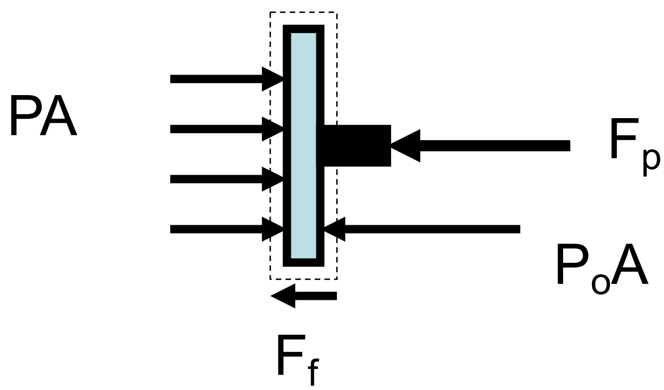
$$\delta W = F \cdot ds \Rightarrow \dot{W} = \frac{\delta W}{dt} = \mathrm{F} \cdot \frac{ds}{dt} = F \cdot V$$

Expansion/Compression (Boundary) Work

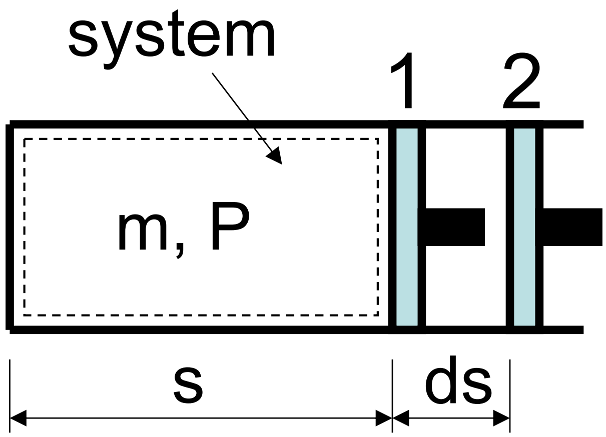
- Consider a piston-cylinder device



- Forces on piston: (for no acceleration of piston)



Work by gas on piston (expansion work)



Important Points

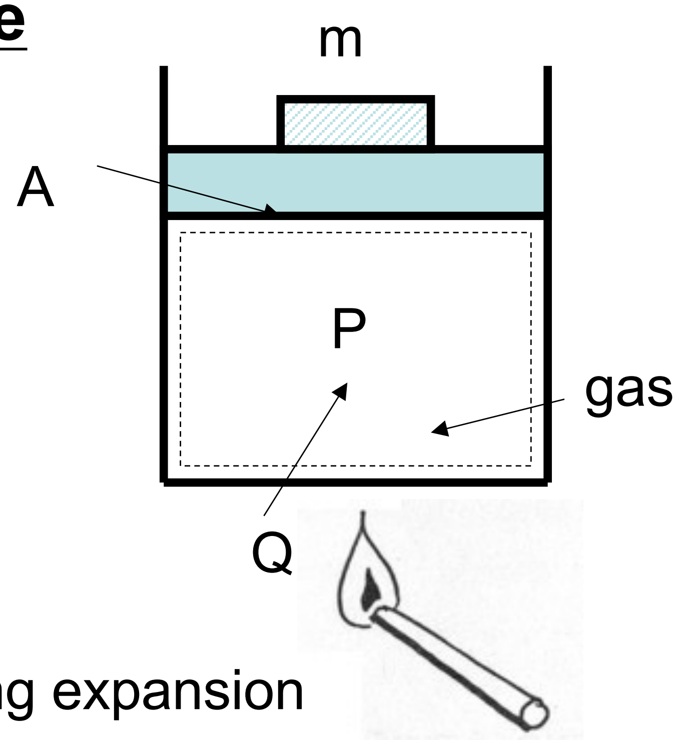
- Work depends on path for process (how P varies with V)

- Need a quasi-equilibrium process to evaluate P at each point

Example

Given:

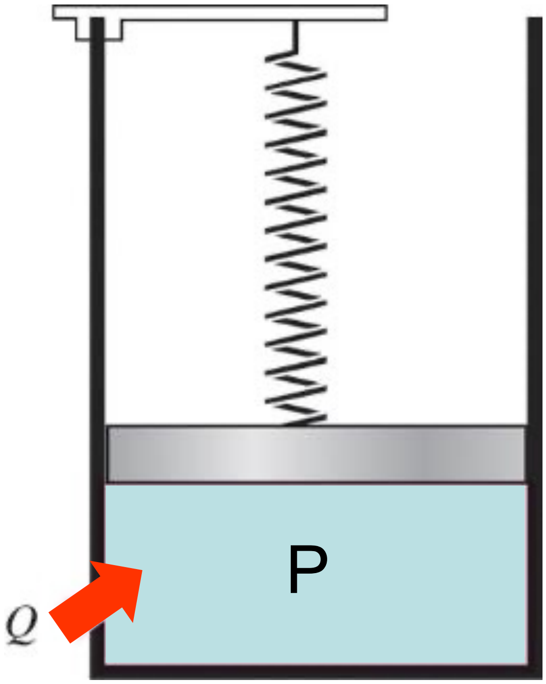
- $m = 100$ kg
- $A = 0.01\ m^2$
- $P_o = 100$ kPa
- $V_1 = 0.02\ m^3$
- $V_2 = 0.04\ m^3$



Find: work done by gas during expansion

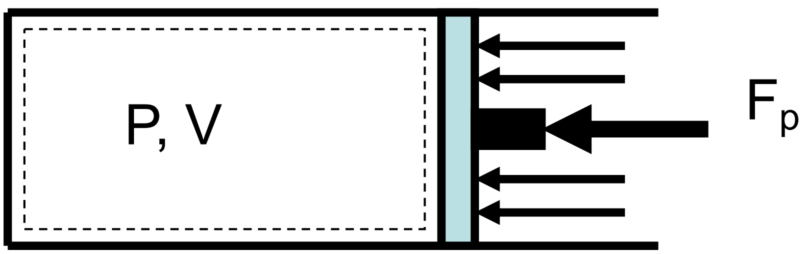
Assumptions:

Piston-Cylinder with a Spring

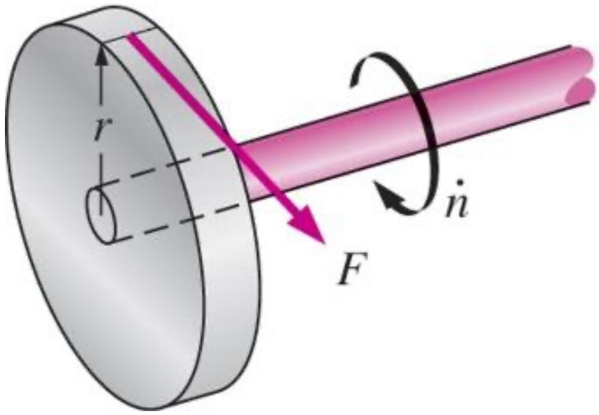


Polytropic Compression or Expansion

$$PV^n = \text{constant, n = polytropic coefficient}$$



Torsion or Shaft Work



Shaft work for incremental rotation, $d\theta$

$$\delta W_{sh} = F \cdot r \cdot d\theta = \mathrm{T} \cdot d\theta$$

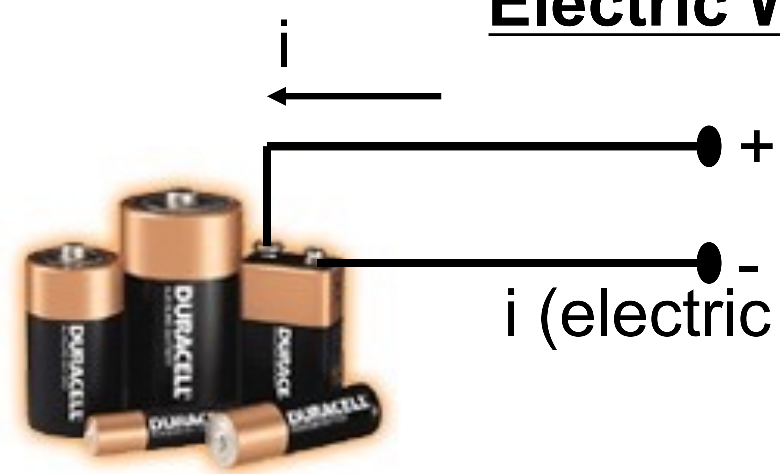
Then shaft power is

$$\dot{W}_{sh} = \frac{\delta W_{sh}}{dt} = \mathrm{T} \cdot \frac{d\theta}{dt}$$

$$\boxed{\dot{W}_{sh} = \mathrm{T} \cdot \omega = \mathrm{T}(2\pi\dot{n})}$$

$\dot{n}$ = rev. per unit time (e.g., rpm)
T = torque
ω = angular velocity

Electric Work



ξ (voltage, volts)

i (electric current, amps)

Instantaneous electrical power: $\dot{W}_e = -\xi \cdot i$

Electrical work over time: $W_e = -\int_0^t \xi \cdot i \cdot dt$

Lecture 6
Total Energy, Heat Transfer, 1st Law

- Total Energy
- Heat Transfer
- Path vs. Point Functions
- 1st Law for Closed Systems

Total Energy of a System

- Sum of kinetic, potential, and internal energy
- Changes due to energy transfers (work and heat transfer)

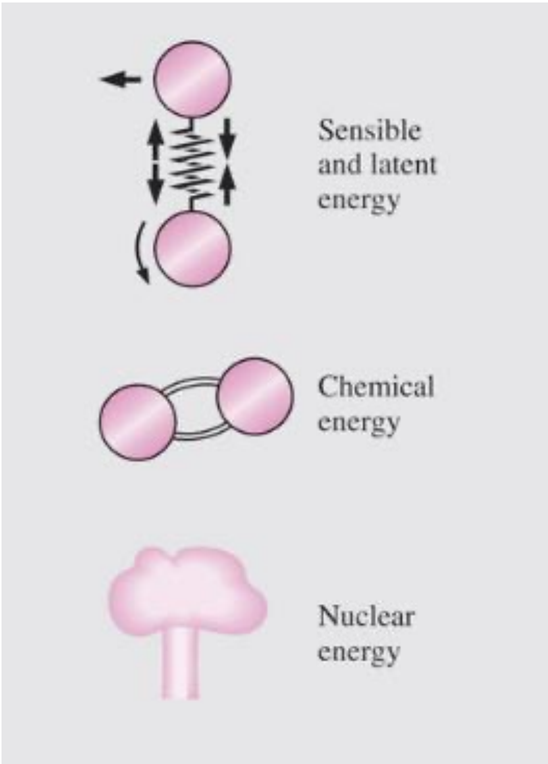
$$E = U + PE + KE \quad \text{(kJ, Btu)}$$

or

$$e = \frac{E}{m} \quad \text{(kJ/kg, Btu/lbm)}$$

Internal Energy

Sum of all microscopic forms of energy

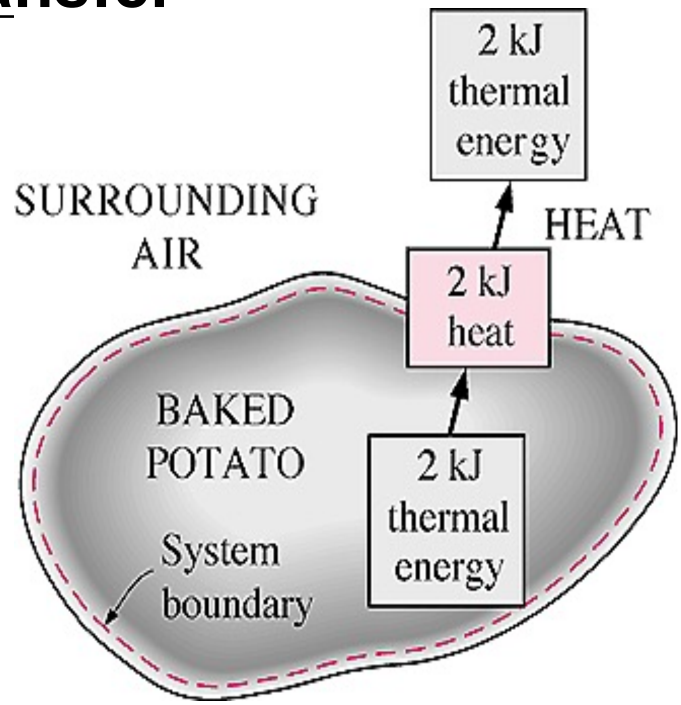


Important Notes about Energy

1. Energy is always measured relative to a reference point
   1. reference plane for PE
   2. reference frame for KE
   3. reference state for U
2. We care about changes in E, not absolute values
3. Reference for U will depend on nature of the problem
   - thermal vs. chemical vs. nuclear

Heat Transfer

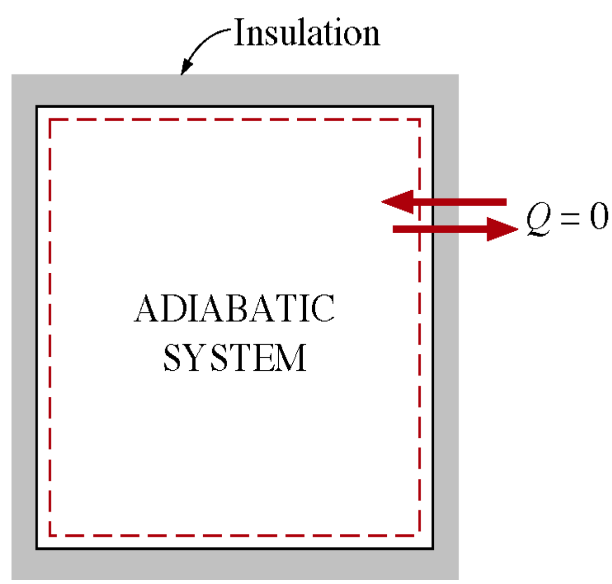
- Heat is energy in transition and is only recognized as it crosses the boundary



- 3 types of heat transfer all due to temperature differences: conduction, convection, radiation
- Units of kJ or Btu (1 kJ=0.94782 Btu)

Adiabatic Processes

- Adiabatic process = no heat transfer
- Two cases for adiabatic process
  - "Well-insulated" system
  - No temperature difference (no driving force)



Quantifying Heat Transfer

- Heat transfer depends on path of process

$$Q = Q_{12} = \int_1^2 \delta Q$$

where δQ is an inexact heat transfer differential because the integral can not be evaluated without specifying the details of the process

- Rate of heat transfer

$$\dot{Q} = \frac{\delta Q}{dt} \quad (\mathrm{kW, Btu/h})$$

Amount of heat transfer during a process

$$Q = \int_1^2 \dot{Q}\, dt$$

For constant heat transfer rate

$$Q = \dot{Q}\Delta t$$

- Sign Convention

$Q > 0$: heat transfer <u>to</u> the system

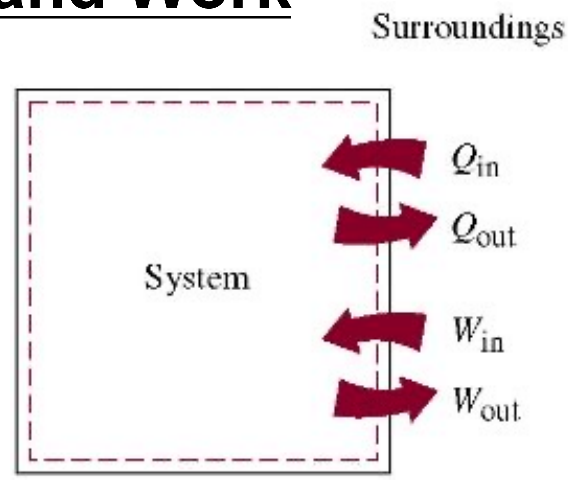
$Q < 0$: heat transfer <u>from</u> the system

$Q = 0$: adiabatic

More on Heat and Work

Nomenclature

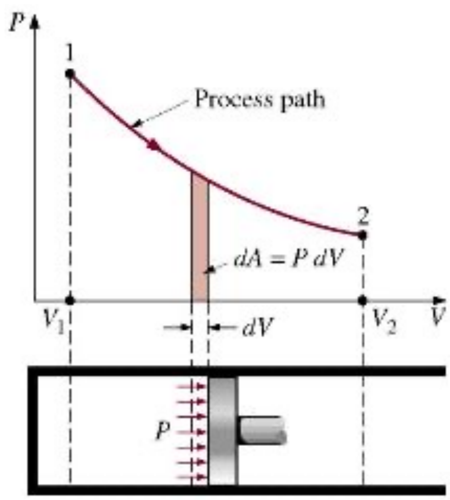
- Direction of work and heat are often depicted via arrows or subscripts in and out

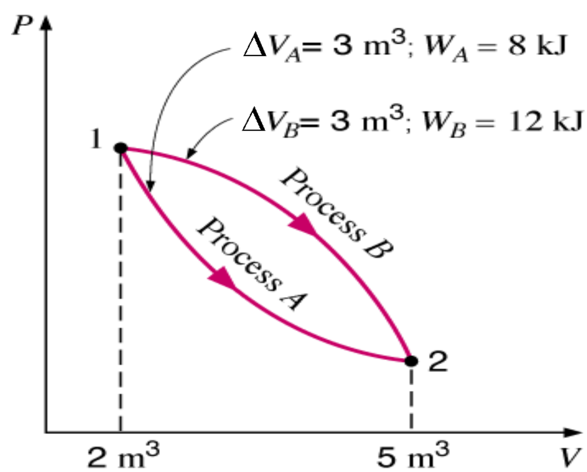


Path vs. Point Functions

- Both Q and W are path functions
  - depend on process path
- Path functions have inexact differentials $\delta W, \delta Q$
- Point functions only depend on initial/final state
  - have exact differentials dE, dV

Path vs. Point Functions for Expansion



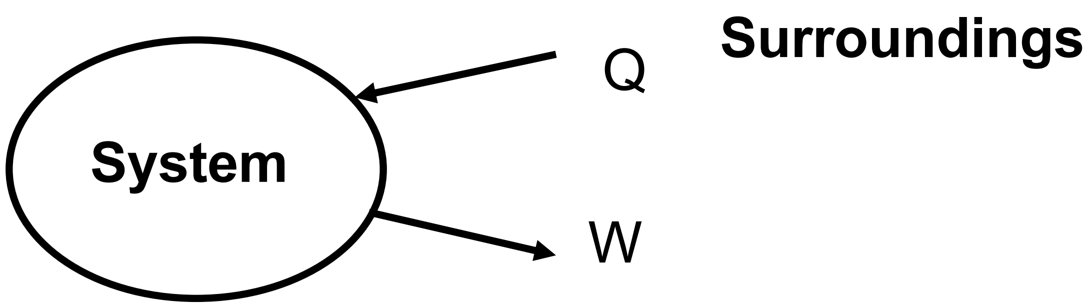


$$\Delta V_A = 3m^3, W_A = 8kJ \qquad \Delta V_B = 3m^3, W_B = 12kJ$$

$$\int_1^2 dV = V_2 - V_1 = \Delta V \text{ (for A or B)} \qquad \int_1^2 \delta W = W_{12} \neq \Delta W$$

Closed System Energy Balances

Only two types of interactions are possible between a closed system and its surroundings



At the end of any process

$$\Delta E = Q - W$$

where

$$\Delta E = E_2 - E_1 = m(u_2 - u_1) + mg(z_2 - z_1) + \frac{1}{2}m(V_2^2 - V_1^2)$$

i.e., the energy of a system (internal+PE+KE) changes due to work and heat transfers between the system and surroundings

Important Notes on 1st Law

1. E is always measured relative to reference point!
   - Reference plane for pe
   - Reference frame for ke
   - Reference state for u (i.e. u = 0 @ reference state)
2. Changes in E are important, not total values of E
3. ΔE depends only on beginning and end states
4. Q and W depend on process path (could get to the same end state with different combinations of Q and W)
5. The energy balance for a particular problem will depend on the system that you select → YOU MUST ALWAYS SPECIFY YOUR SYSTEM IN ORDER TO APPLY THE 1ST LAW
6. The total heat transfer is the summation of all heat transfers across the system boundary)
7. The total work is the summation of all work transfers across the system boundary)

$$Q = \sum_i Q_i \qquad W = \sum_i W_i$$

Forms of the 1st Law for Closed Systems

1. Finite Process → $$\Delta E = Q - W$$

2. Differential Form → $$dE = \delta Q - \delta W$$

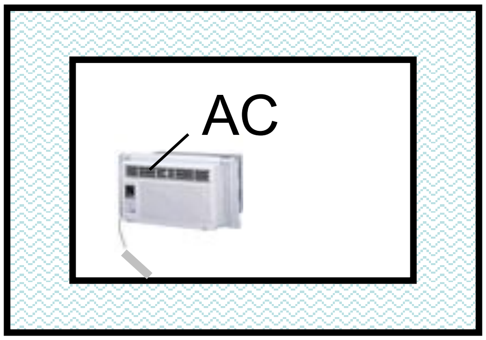
3. Rate Basis → $$\frac{dE}{dt} = \dot{Q} - \dot{W}$$

4. Steady-State → $$\dot{Q} = \dot{W}$$

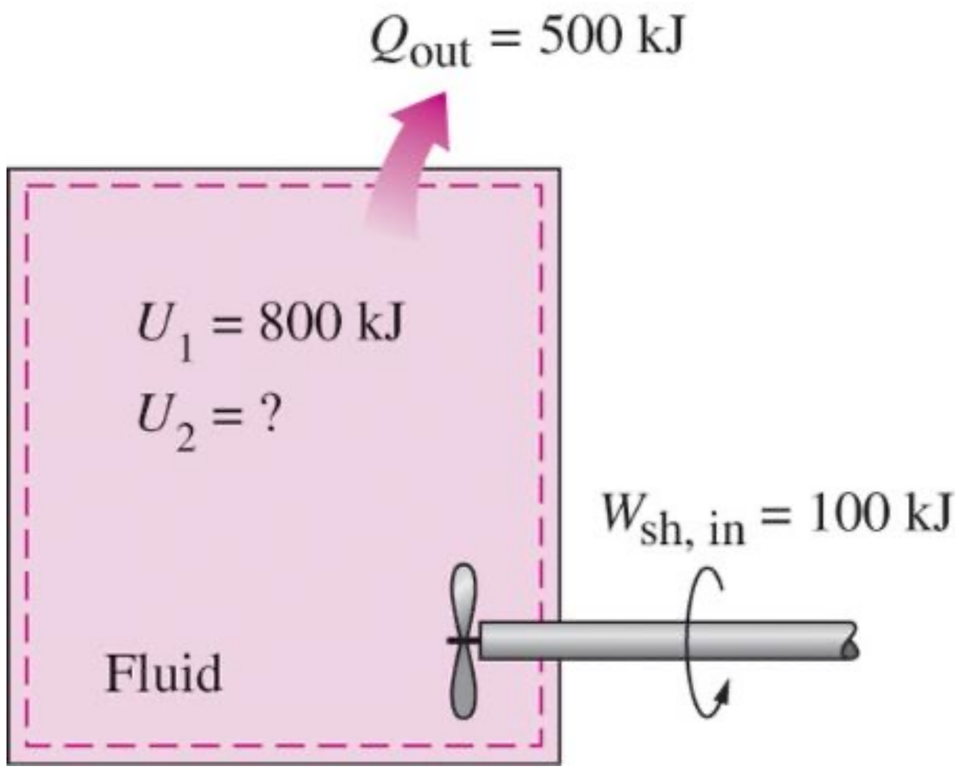
** steady-state → state does not change with time **

Simple 1st Law Example

What if you rolled a window AC into a well-insulated room that has no other air conditioner, put it on a table and plugged it in? Would you expect the room temperature to increase, decrease, or remain the same?



Another 1st Law Example



One More Example

A 10 kg weight is raised a distance of 1 m in a gravitational field with $g = 10\ m/s^2$ as shown below. What is the minimum energy storage that would need to be discharged by the battery?