INTRODUCTION TO THERMODYNAMICS

By

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INTRODUCTION

- Thermodynamics: Science of energy
- Greek words: *therme* (heat) and *dynamics* (power)
- Energy can change from one form to another

Energy cannot be created nor destroyed

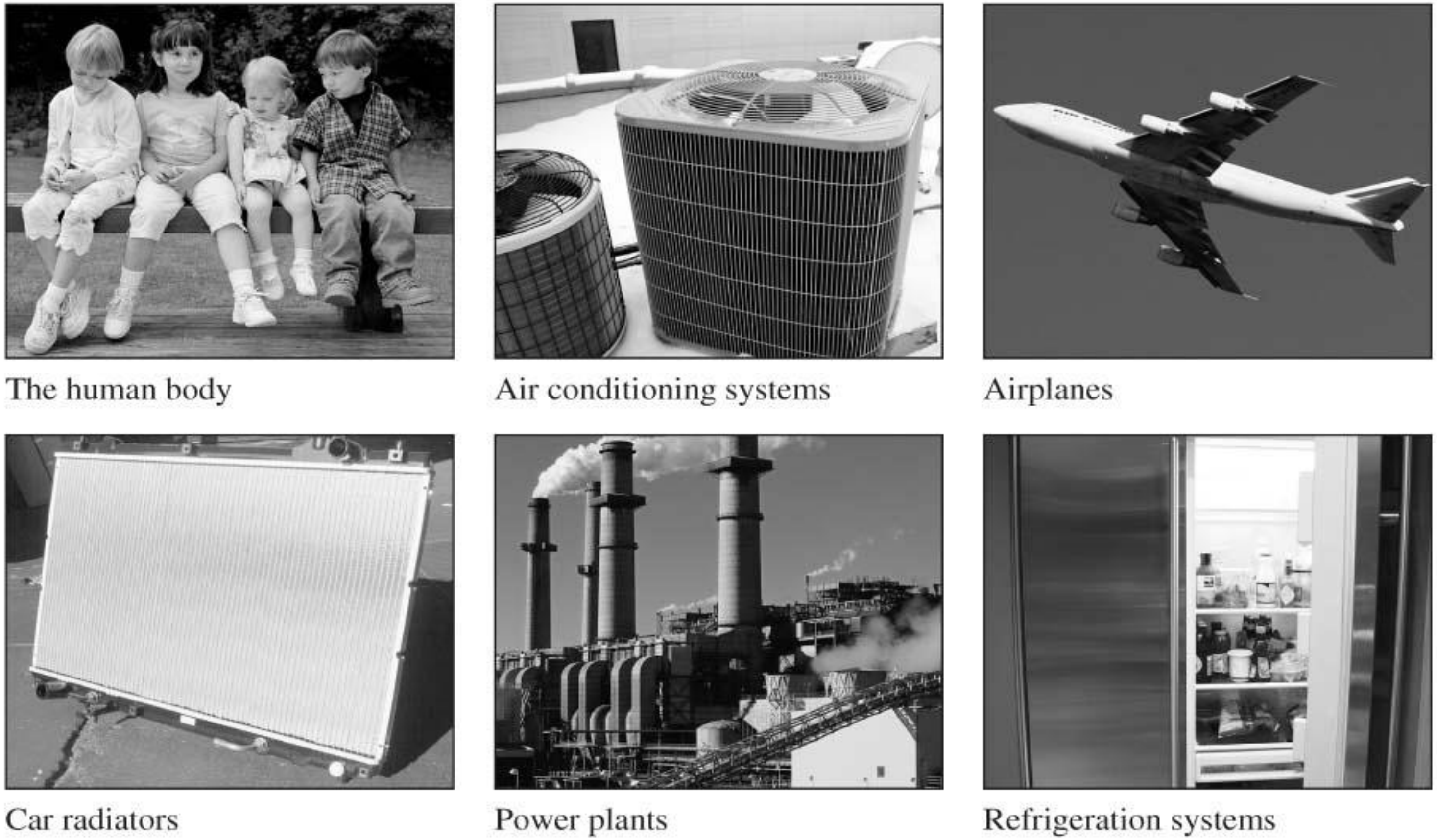


FIGURE 1–5

Some application areas of thermodynamics.

A/C unit, fridge, radiator: © The McGraw-Hill Companies, Inc./Jill Braaten, photographer; Plane: © Vol. 14/PhotoDisc; Humans: © Vol. 121/PhotoDisc; Power plant: © Corbis Royalty Free

Dimensions and units

The seven fundamental (or primary) dimensions and their units in SI

Dimension	Unit
Length	meter (m)
Mass	kilogram (kg)
Time	second (s)
Temperature	kelvin (K)
Electric current	ampere (A)
Amount of light	candela (cd)
Amount of matter	mole (mol)

Standard prefixes in SI units

Multiple	Prefix
10^{12}	tera, T
10^{9}	giga, G
10^{6}	mega, M
10^{3}	kilo, k
10^{2}	hecto, h
10^{1}	deka, da
10^{-1}	deci, d
10^{-2}	centi, c
10^{-3}	milli, m
10^{-6}	micro, μ
10^{-9}	nano, n
10^{-12}	pico, p

Table A.1: Conversion Factors

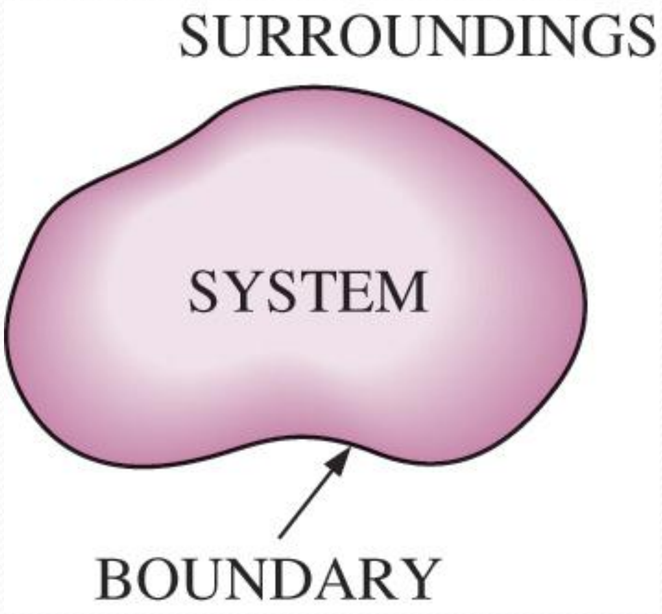
Quantity	Conversion
Length	$1\ \text{m} = 100\ \text{cm}$ $= 3.28084(\text{ft}) = 39.3701(\text{in})$
Mass	$1\ \text{kg} = 10^3\ \text{g}$ $= 2.20462(\text{lb}_\text{m})$
Force	$1\ \text{N} = 1\ \text{kg m s}^{-2}$ $= 10^5(\text{dyne})$ $= 0.224809(\text{lb}_\text{f})$
Pressure	$1\ \text{bar} = 10^5\ \text{kg m}^{-1}\ \text{s}^{-2} = 10^5\ \text{N m}^{-2}$ $= 10^5\ \text{Pa} = 10^2\ \text{kPa}$ $= 10^6(\text{dyne})\ \text{cm}^{-2}$ $= 0.986923(\text{atm})$ $= 14.5038(\text{psia})$ $= 750.061(\text{torr})$
Volume	$1\ \text{m}^3 = 10^6\ \text{cm}^3 = 10^3\ \text{liters}$ $= 35.3147(\text{ft})^3$ $= 264.172(\text{gal})$
Density	$1\ \text{g cm}^{-3} = 10^3\ \text{kg m}^{-3}$ $= 62.4278(\text{lb}_\text{m})(\text{ft})^{-3}$
Energy	$1\ \text{J} = 1\ \text{kg m}^2\ \text{s}^{-2} = 1\ \text{N m}$ $= 1\ \text{m}^3\ \text{Pa} = 10^{-5}\ \text{m}^3\ \text{bar} = 10\ \text{cm}^3\ \text{bar}$ $= 9.86923\ \text{cm}^3(\text{atm})$ $= 10^7(\text{dyne})\ \text{cm} = 10^7(\text{erg})$ $= 0.239006(\text{cal})$ $= 5.12197 \times 10^{-3}(\text{ft})^3(\text{psia}) = 0.737562(\text{ft})(\text{lb}_\text{f})$ $= 9.47831 \times 10^{-4}(\text{Btu}) = 2.77778 \times 10^{-7}\ \text{kWhr}$
Power	$1\ \text{kW} = 10^3\ \text{W} = 10^3\ \text{kg m}^2\ \text{s}^{-3} = 10^3\ \text{J s}^{-1}$ $= 239.006(\text{cal})\ \text{s}^{-1}$ $= 737.562(\text{ft})(\text{lb}_\text{f})\ \text{s}^{-1}$ $= 0.947831(\text{Btu})\ \text{s}^{-1}$ $= 1.34102(\text{hp})$

System and Surroundings

- System – quantity of matter or region in space chosen for study

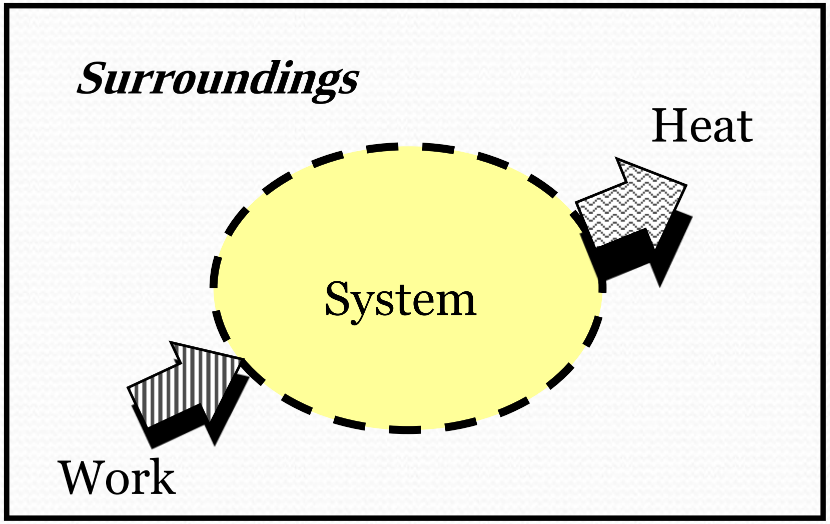
- Surroundings – mass or region outside the system

- Boundary – surface separate system from surrounding (imaginary @ real)



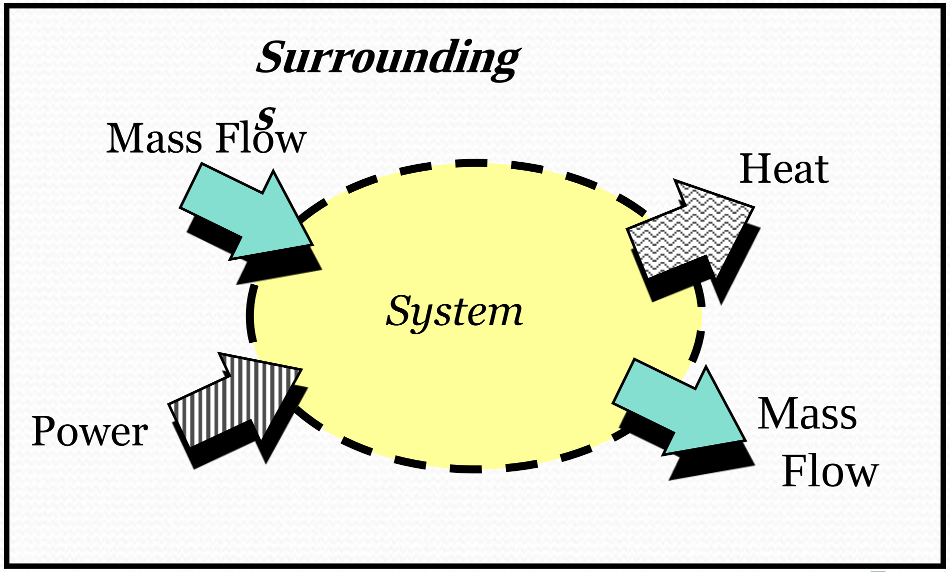
Types of Thermodynamics System

- Closed system
- Open system



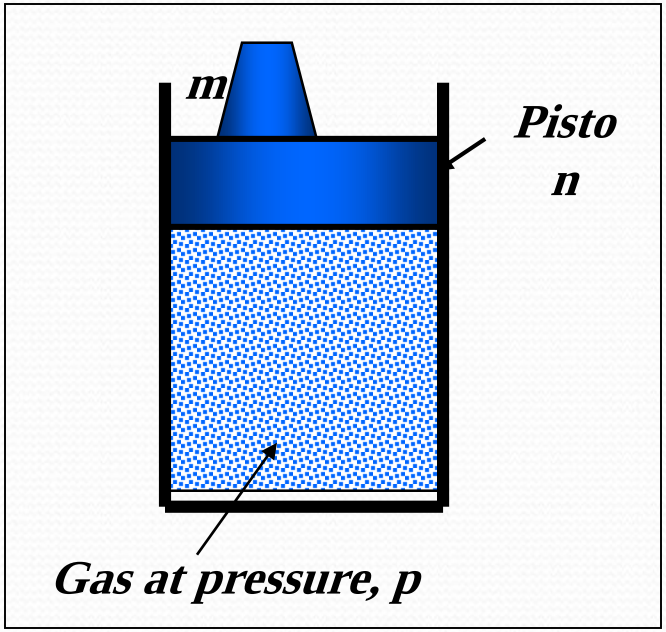
•Closed system (control mass) – no mass can enter or leave a system

•Open system (control volume) – usually encloses a device that involves mass flow such as compressor, turbine or nozzle.

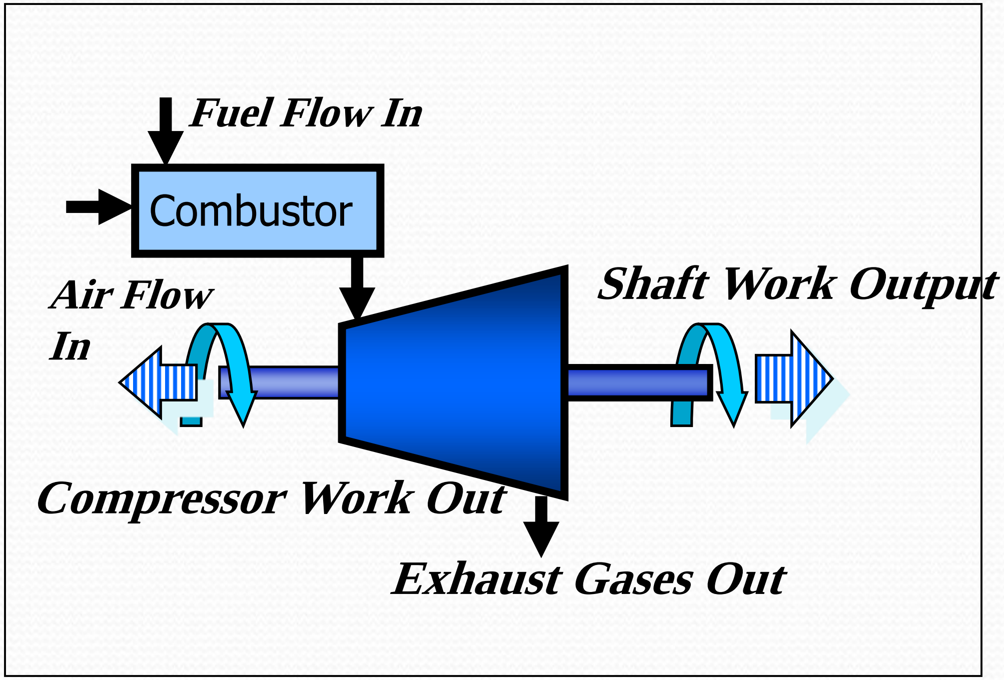


Example of Open System & Closed System…

•Closed system (Piston and Cylinder)



•Open system (Gas Turbine Engine)



Properties of Thermodynamics System

- Any characteristic of a system is called a property
- *E.g: P, T, V, m*, viscosity, thermal conductivity, thermal expansion coefficient, velocity etc.
- Properties are consider to be either intensive or extensive.

- ***Intensive properties*** – those that are independent of the size of the system: **temperature, pressure and density**

- ***Extensive properties*** – those whose values depend on the size or extent of the system: **mass, volume and total energy**

Reversible & Irreversible Process

- **Process:** system undergoes from one equilibrium state to another.
- **Reversible:** Process that can be reversed without leaving any trace on the surrounding
  - eg: Pendulum

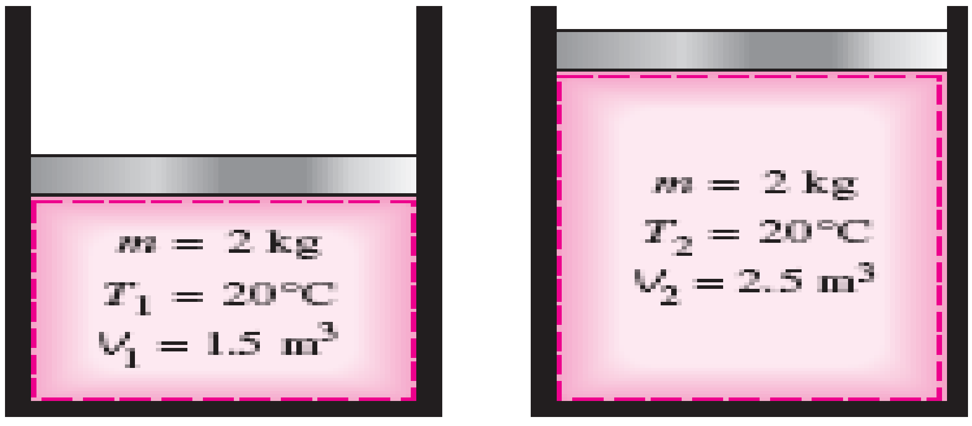
- System and surrounding return to their initial state.

- **Irreversible**: Surrounding do some work on the system & therefore does not return to their initial state.
- eg: hot coffee

State of System

- State of system: a set of properties that completely describes the system condition

- If the value of even one properties changes, the state will change to a different one



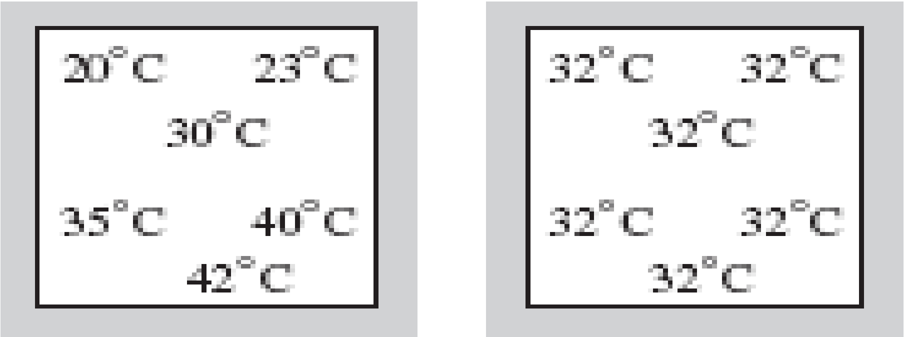
(a) State 1 (b) State 2

Thermodynamics Equilibrium

- Equilibrium: no changes
- *Thermodynamic equilibrium* refers to particular states of a macroscopic system, called equilibrium states, which are independent of time (stationary states) and in which no macroscopic flow of any physical quantity exists.

Thermal Equilibrium

- Temperature is the same throughout the entire system



(*a*) Before (*b*) After

Mechanical Equilibrium

- (Related to pressure): a system is in mechanical equilibrium if there is no change in pressure at any point of the system with time.

Phase Equilibrium

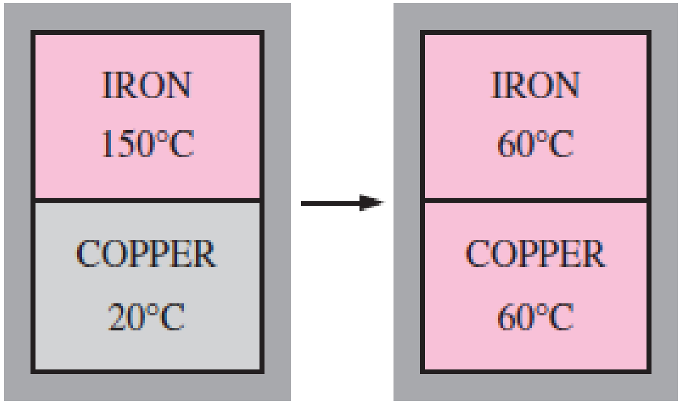
- **Phase equilibrium**: If a system involves two phases, it is in phase equilibrium when the mass of each phase reaches an equilibrium level and stays there.

Chemical Equilibrium

- Chemical composition does not change with time, that is, no chemical reactions occur.

The Zeroth Law of Thermodynamics

The **zeroth law of thermodynamics** states that if two bodies are in thermal equilibrium with a third body, they are also in thermal equilibrium with each other.



Temperature Scales

$$T(\text{K}) = T(°\text{C}) + 273.15$$

$$T(\text{R}) = 1.8T(\text{K})$$

$$T(\text{R}) = T(°\text{F}) + 459.67$$

$$T(°\text{F}) = 1.8T(°\text{C}) + 32$$

Forms of Energy

Energy can exist in numerous forms such as thermal, mechanical, kinetic, potential, electric, magnetic, chemical, and nuclear, and their sum constitutes the **total energy** E of a system.

In thermodynamic analysis, it is often helpful to consider the various forms of energy that make up the total energy of a system in two groups: ***macroscopic*** and ***microscopic***.

The **macroscopic** forms of energy are those a system possesses as a whole with respect to some outside reference frame, such as kinetic and potential energies

The macroscopic energy of an object changes with velocity and elevation.

The macroscopic energy of a system is related to motion and the influence of some external effects such as gravity, magnetism, electricity, and surface tension. The energy that a system possesses as a result of its motion relative to some reference frame is called **kinetic energy** (KE).

$$KE = m\frac{V^2}{2} \qquad (kJ)$$

The energy that a system possesses as a result of its elevation in a gravitational field is called **potential energy** (PE) and is expressed as

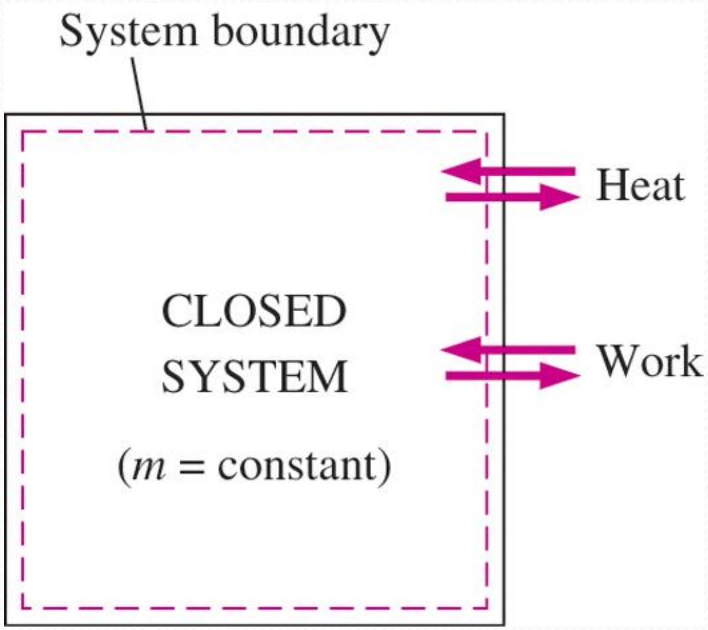
$$PE = mgz \qquad (kJ)$$

The magnetic, electric, and surface tension effects are significant in some specialized cases only and are usually ignored. In the absence of such effects, the total energy of a system consists of the kinetic, potential, and internal energies and is expressed as

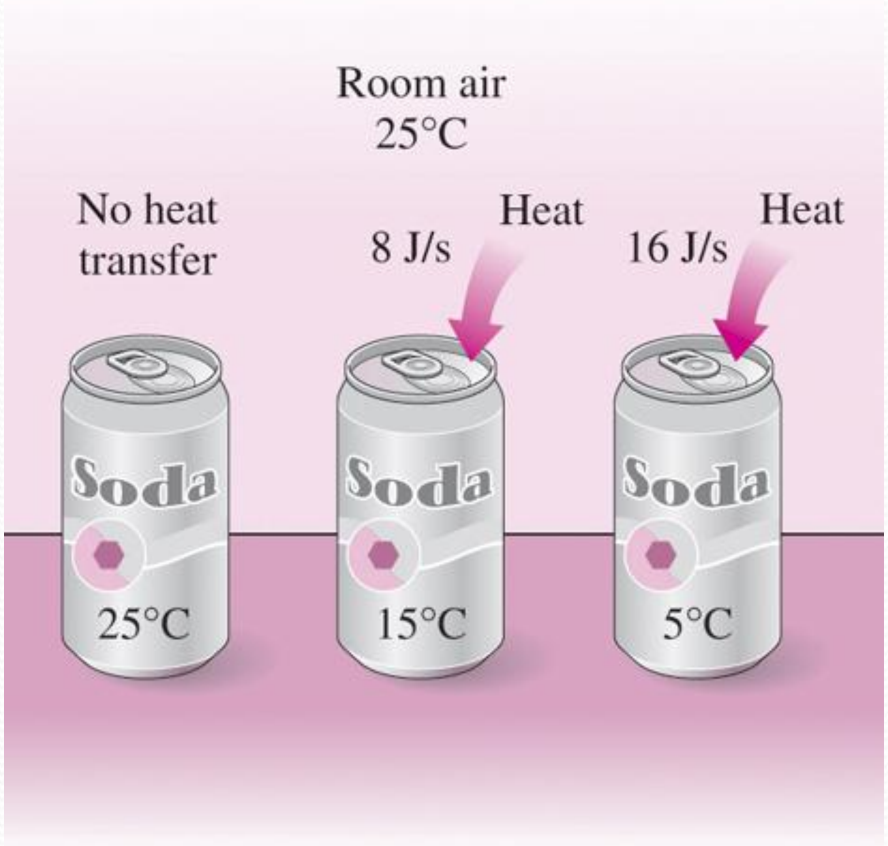
$$E = U + KE + PE = U + m\frac{V^2}{2} + mgz \qquad (kJ)$$

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



Temperature difference is the driving force for heat transfer. The larger the temperature difference, the higher is the rate of heat transfer.

$$q = \frac{Q}{m} \qquad (\text{kJ/kg})$$

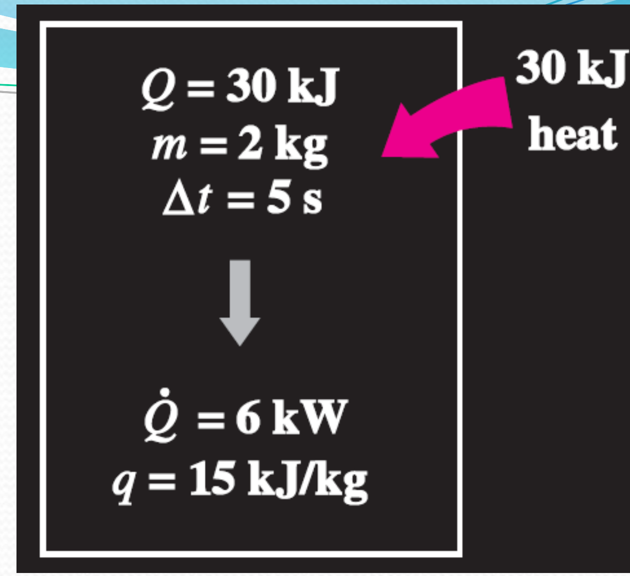
Heat transfer per unit mass

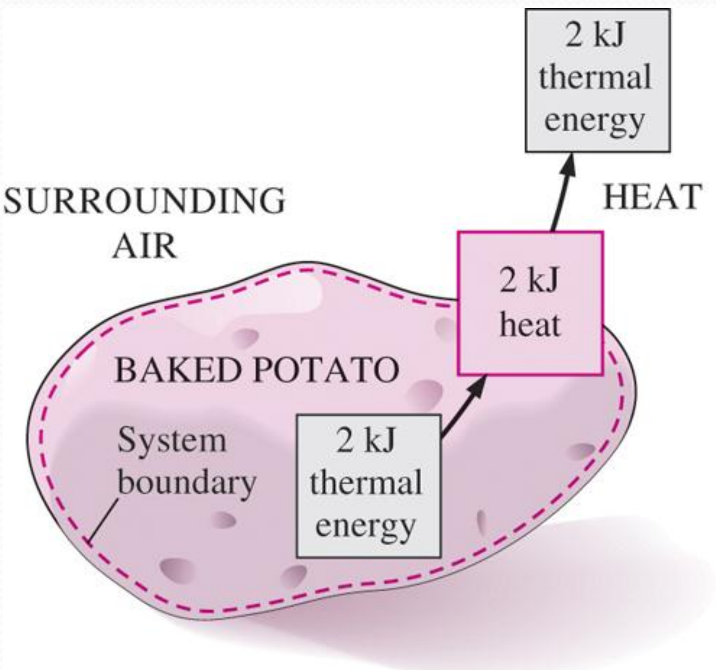
$$Q = \dot{Q}\,\Delta t \qquad (\text{kJ})$$

Amount of heat transfer when heat transfer rate is constant

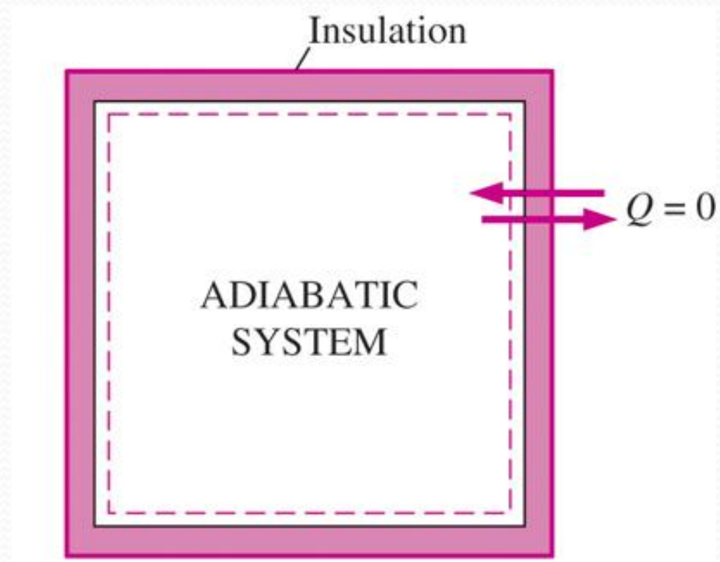
$$Q = \int_{t_1}^{t_2} \dot{Q}\,dt \qquad (\text{kJ})$$

Amount of heat transfer when heat transfer rate changes with time





Energy is recognized as heat transfer only as it crosses the system boundary.



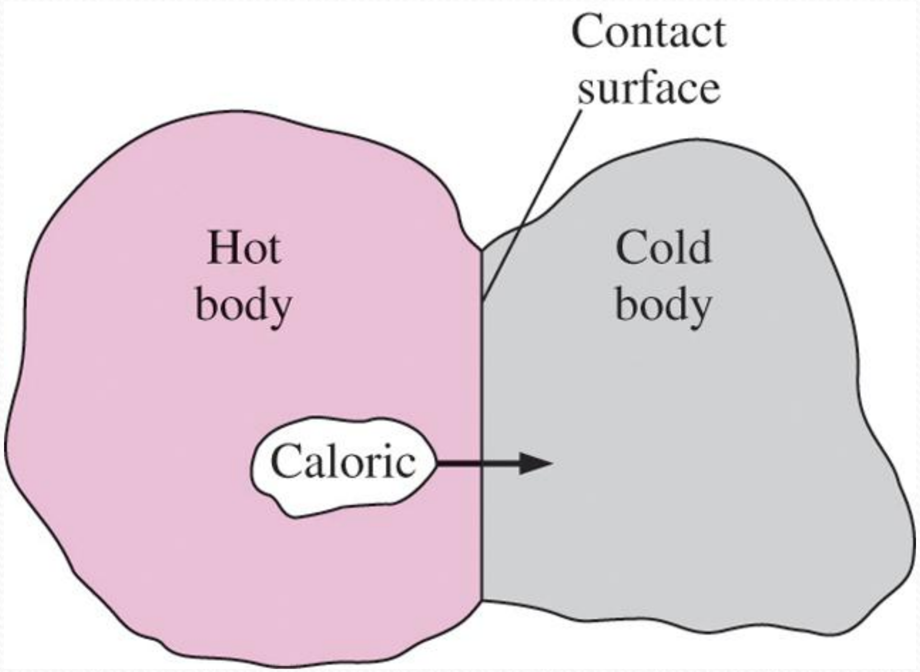
During an adiabatic process, a system exchanges no heat with its surroundings.

Historical Background on Heat

- **Kinetic theory**: Treats molecules as tiny balls that are in motion and thus possess kinetic energy.
- **Heat**: The energy associated with the random motion of atoms and molecules.

Heat transfer mechanisms:

- **Conduction:** The transfer of energy from the more energetic particles of a substance to the adjacent less energetic ones as a result of interaction between particles.
- **Convection:** The transfer of energy between a solid surface and the adjacent fluid that is in motion, and it involves the combined effects of conduction and fluid motion.
- **Radiation:** The transfer of energy due to the emission of electromagnetic waves (or photons).



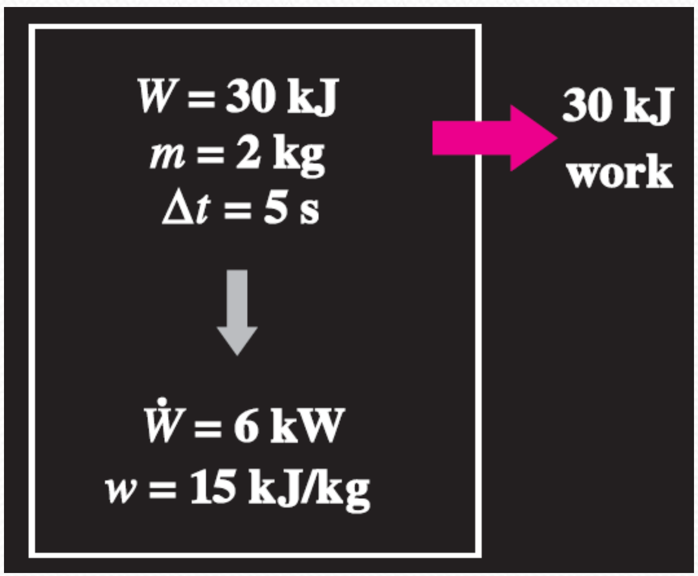
In the early nineteenth century, heat was thought to be an invisible fluid called the ***caloric*** that flowed from warmer bodies to the cooler ones.

ENERGY TRANSFER BY WORK

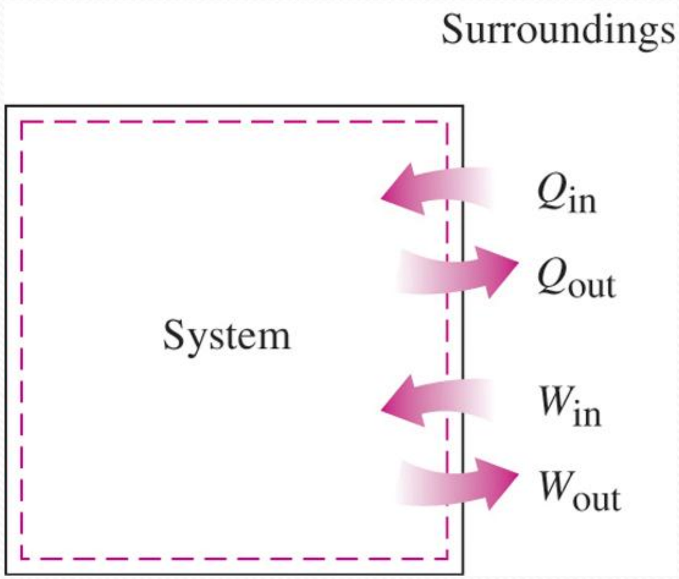
- **Work**: The energy transfer associated with a force acting through a distance.
  - **A rising piston, a rotating shaft,** and **an electric wire crossing the system boundaries** are all associated with work interactions
- **Formal sign convention**: *Heat transfer to a system and work done by a system are positive; heat transfer from a system and work done on a system are negative*.
- Alternative to sign convention is to use the subscripts ***in*** and ***out*** to indicate direction.

$$w = \frac{W}{m} \qquad (\text{kJ/kg})$$

Work done per unit mass



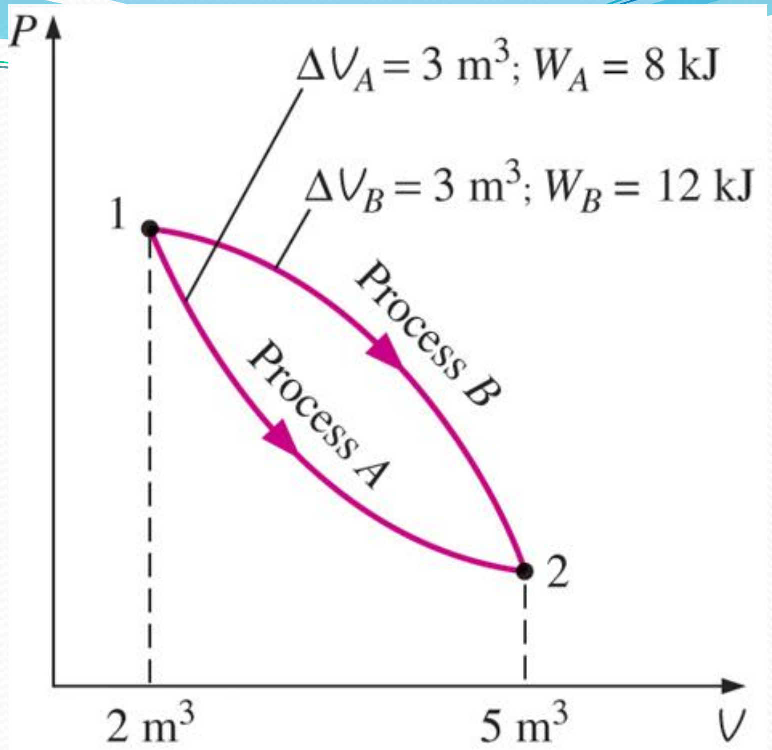
Power is the work done per unit time (kW)



Specifying the directions of heat and work.

Heat vs. 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*
- Both are *path functions* (i.e., their magnitudes depend on the path followed during a process as well as the end states).



Properties are point functions; but heat and work are path functions (their magnitudes depend on the path followed).

Properties are point functions have exact differentials (d).

$$\int_1^2 dV = V_2 - V_1 = \Delta V$$

Path functions have inexact differentials (δ)

$$\int_1^2 \delta W = W_{12} \qquad (not\ \Delta W)$$

Electrical Work

Electrical work

$$W_e = \mathbf{V}N$$

Electrical power

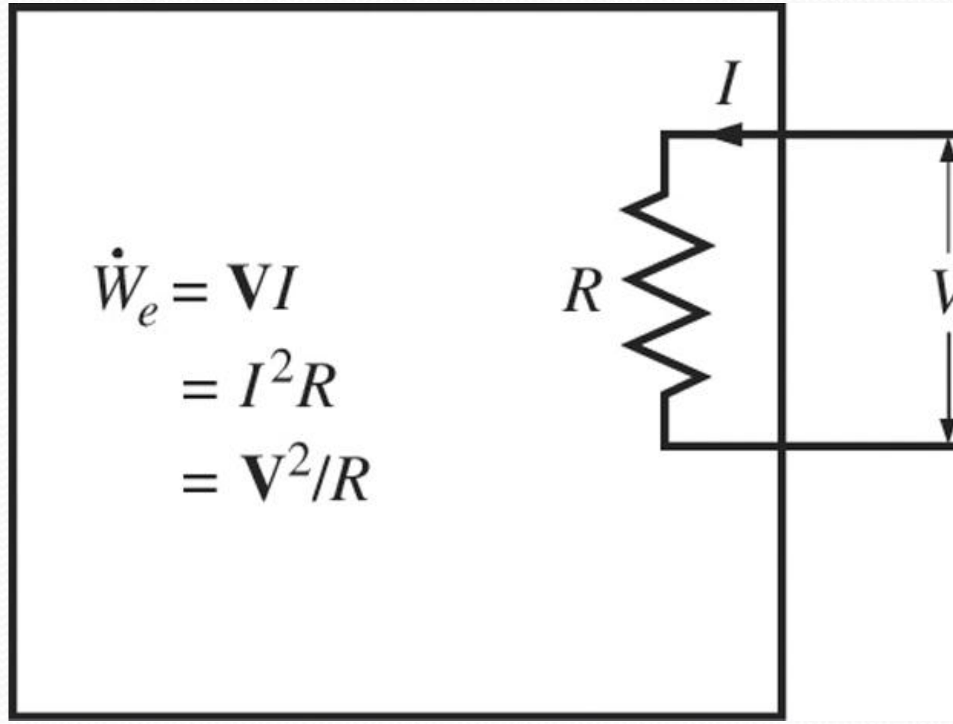
$$\dot{W}_e = \mathbf{V}I \qquad (\mathrm{W})$$

When potential difference and current change with time

$$W_e = \int_1^2 \mathbf{V}I\,dt \qquad (\mathrm{kJ})$$

When potential difference and current remain constant

$$W_e = \mathbf{V}I\,\Delta t \qquad (\mathrm{kJ})$$



Electrical power in terms of resistance *R*, current *I*, and potential difference **V**.

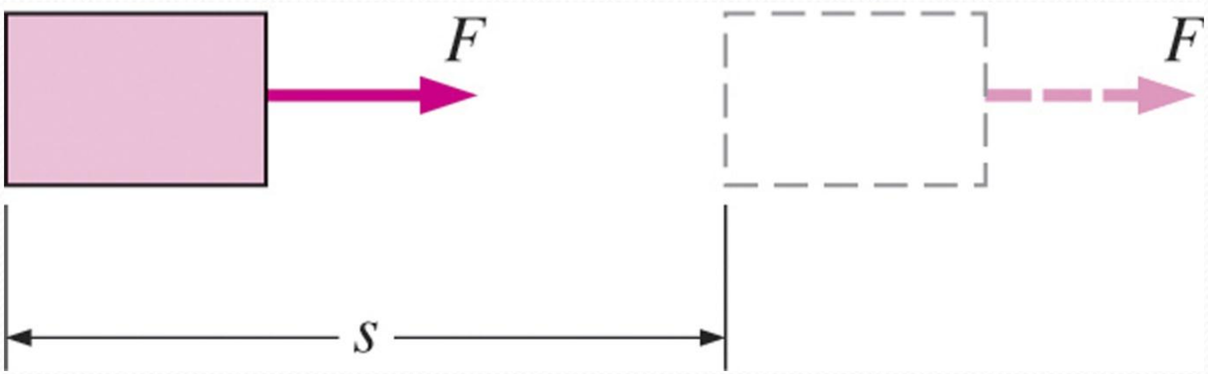
MECHANICAL FORMS OF WORK

- There are two requirements for a work interaction between a system and its surroundings to exist:
  - there must be a ***force*** acting on the boundary.
  - the boundary must ***move***.

Work = Force × Distance

$$W = Fs \qquad (\text{kJ})$$

When force is not constant



The work done is proportional to the force applied (*F*) and the distance traveled (*s*).

If there is no movement, no work is done.

Shaft Work

A force F acting through a moment arm r generates a torque T

$$\mathrm{T} = Fr \quad \rightarrow \quad F = \frac{\mathrm{T}}{r}$$

This force acts through a distance s

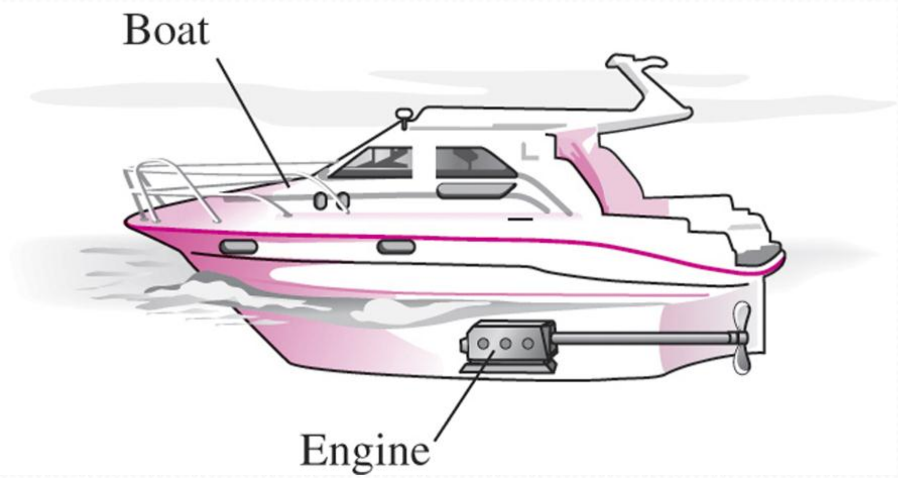
$$s = (2\pi r)n$$

Shaft work

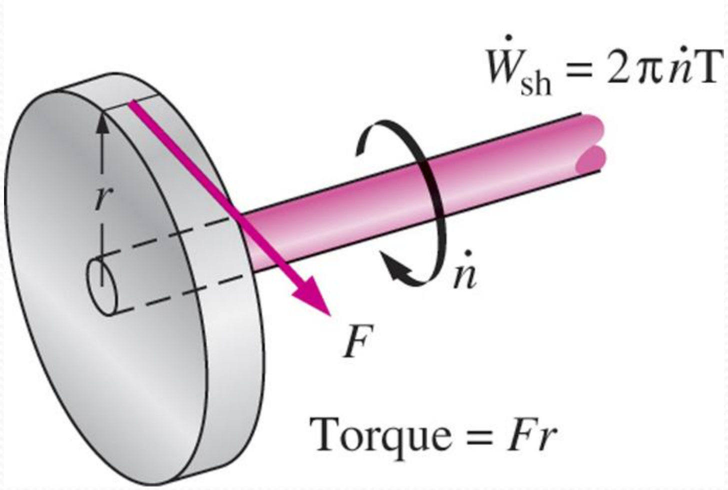
$$W_{sh} = Fs = \left(\frac{\mathrm{T}}{r}\right)(2\pi rn) = 2\pi n\mathrm{T} \qquad (\mathrm{kJ})$$

The power transmitted through the shaft is the shaft work done per unit time

$$\dot{W}_{sh} = 2\pi\dot{n}\mathrm{T} \qquad (\mathrm{kW})$$



Energy transmission through rotating shafts is commonly encountered in practice.



Shaft work is proportional to the torque applied and the number of revolutions of the shaft.

Spring Work

When the length of the spring changes by a differential amount *dx* under the influence of a force *F*, the work done is

$$\delta W_{\text{spring}} = F\,dx$$

For linear elastic springs, the displacement *x* is proportional to the force applied

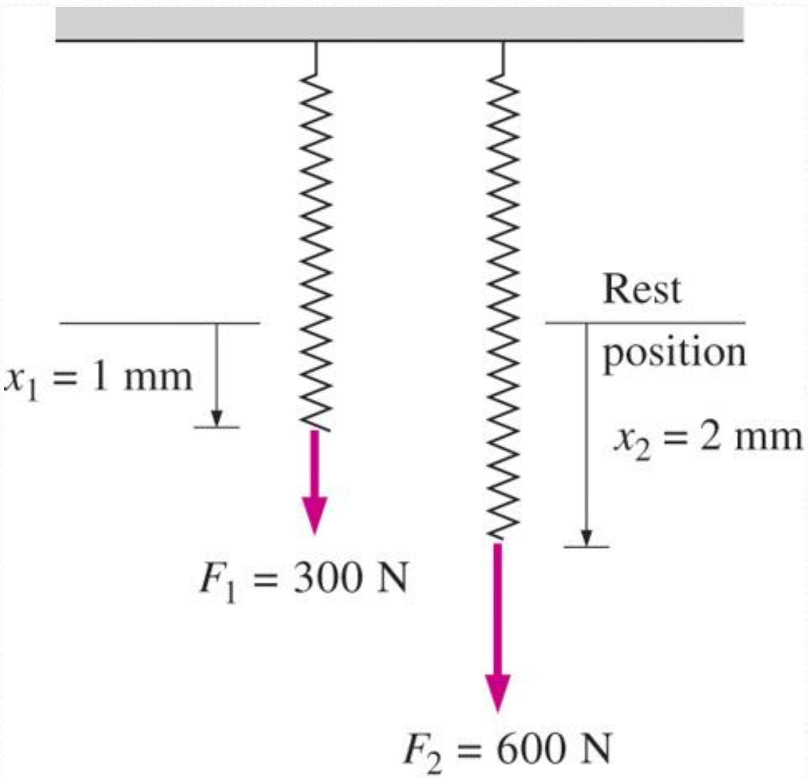
$$F = kx \qquad (\text{kN})$$

k: spring constant (kN/m)

Substituting and integrating yield

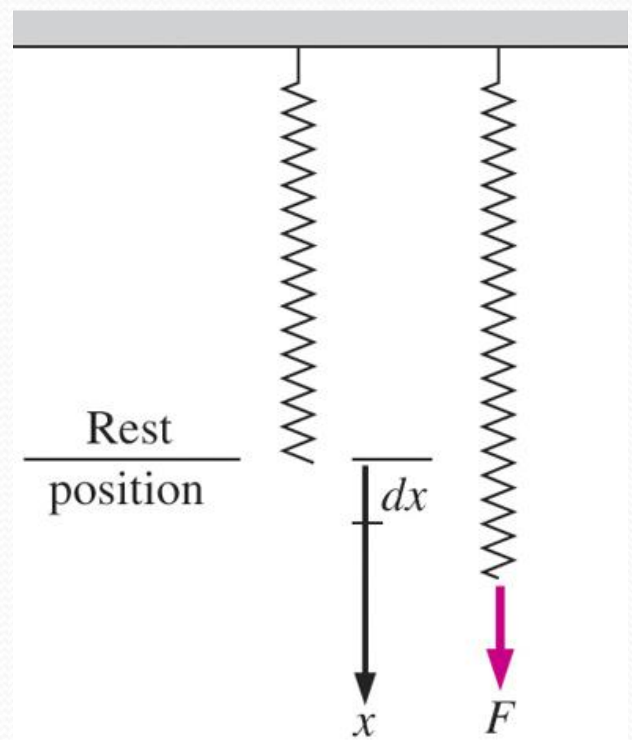
$$W_{\text{spring}} = \tfrac{1}{2}k\left(x_2^2 - x_1^2\right) \qquad (\text{kJ})$$

x_1 and x_2: the initial and the final displacements



The displacement of a linear spring doubles when the force is doubled.

Elongation of a spring under the influence of a force.

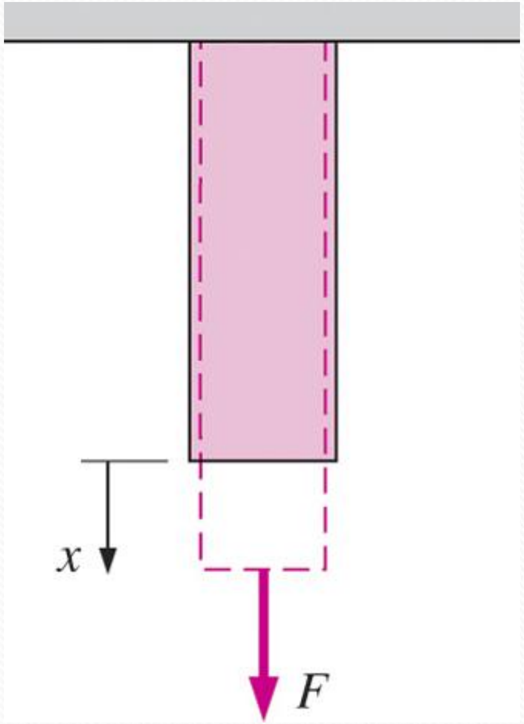


Work Done on Elastic Solid Bars

$$W_{\text{elastic}} = \int_1^2 F\,dx = \int_1^2 \sigma_n A\,dx \qquad \text{(kJ)}$$

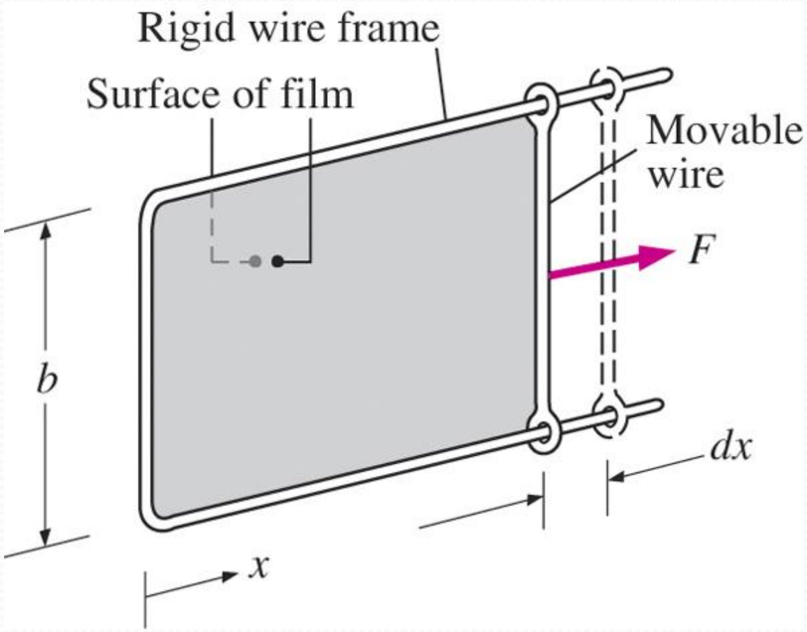
Work Associated with the Stretching of a Liquid Film

$$W_{\text{surface}} = \int_1^2 \sigma_s\,dA \qquad \text{(kJ)}$$



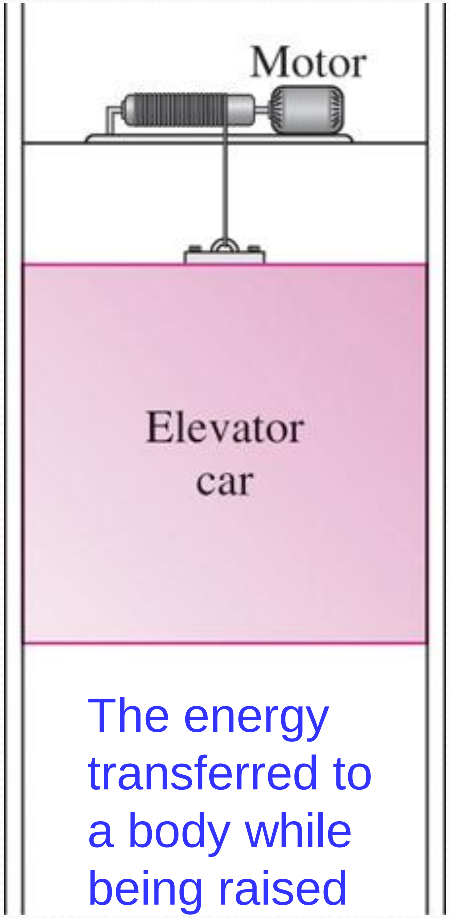
Solid bars behave as springs under the influence of a force.

Stretching a liquid film with a movable wire.



Work Done to Raise or to Accelerate a Body

1. The work transfer needed to raise a body is equal to the change in the potential energy of the body.
2. The work transfer needed to accelerate a body is equal to the change in the kinetic energy of the body.



The energy transferred to a body while being raised is equal to the change in its potential energy.

Nonmechanical Forms of Work

Electrical work: The generalized force is the *voltage* (the electrical potential) and the generalized displacement is the *electrical charge.*

Magnetic work: The generalized force is the *magnetic field strength* and the generalized displacement is the total *magnetic dipole moment*.

Electrical polarization work: The generalized force is the *electric field strength* and the generalized displacement is the *polarization of the medium*.

MOVING BOUNDARY WORK

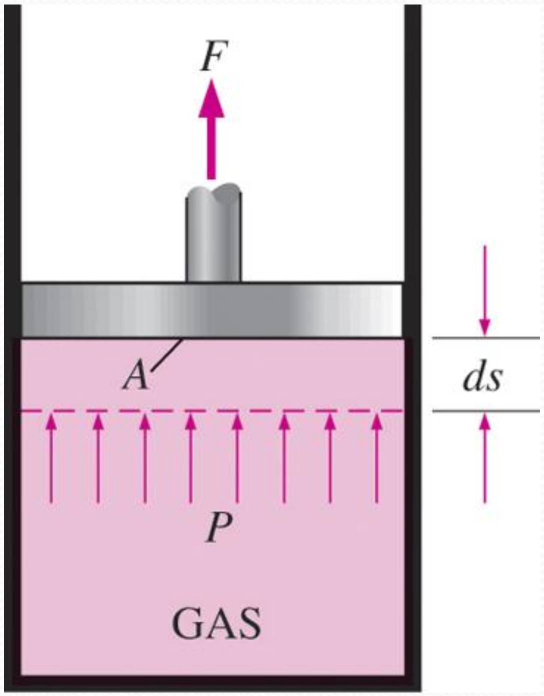
Moving boundary work (*P dV* work): The expansion and compression work in a piston-cylinder device.

$$\delta W_b = F\,ds = PA\,ds = P\,dV$$

$$W_b = \int_1^2 P\,dV \qquad \text{(kJ)}$$

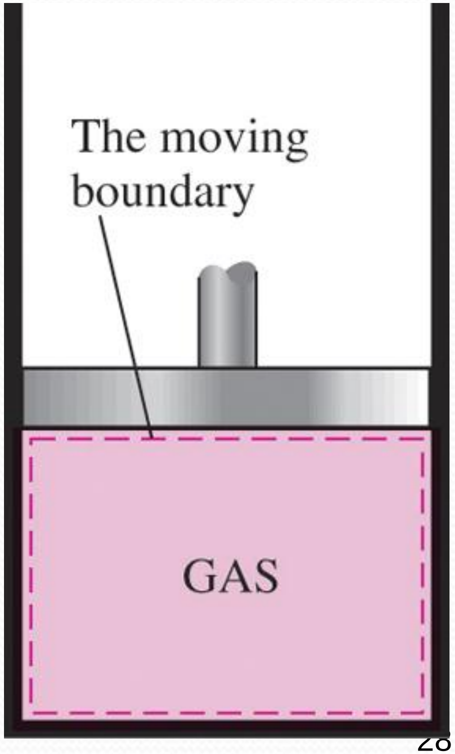
Quasi-equilibrium process: A process during which the system remains nearly in equilibrium at all times.

W_b is positive → for expansion
W_b is negative → for compression

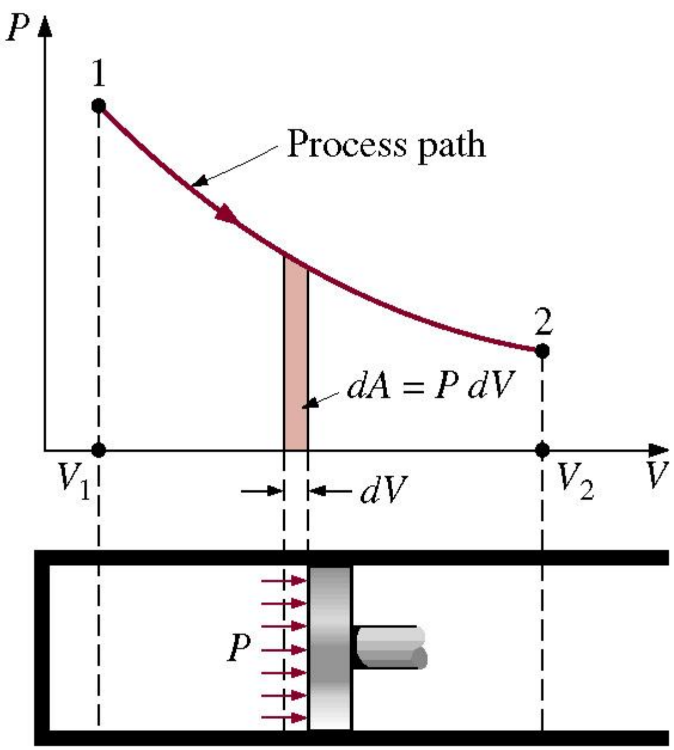


A gas does a differential amount of work δW_b as it forces the piston to move by a differential amount *ds*.

The work associated with a moving boundary is called *boundary work.*



The boundary work = the area under the process curve plotted on the pressure-volume diagram



Note from the figure:

P is the absolute pressure and is always positive.

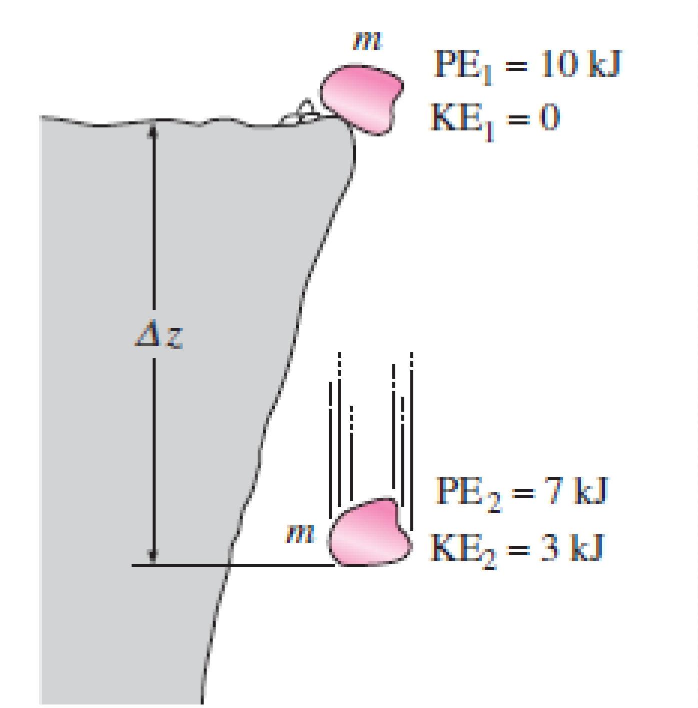
When dV is positive, W_b is positive.

When dV is negative, W_b is negative.

The First Law of Thermodynamics

The *first law of thermodynamics,* also known as *the conservation of energy principle,* provides a sound basis for studying the relationships among the various forms of energy and energy interactions.

The first law of thermodynamics states that *energy can be neither created nor destroyed during a process; it can only change forms.*



Energy Balance

$$\begin{pmatrix}\text{Total energy}\\ \text{entering the system}\end{pmatrix} - \begin{pmatrix}\text{Total energy}\\ \text{leaving the system}\end{pmatrix} = \begin{pmatrix}\text{Change in the total}\\ \text{energy of the system}\end{pmatrix}$$

or

$$E_{in} - E_{out} = \Delta E_{system}$$

Energy Change of a System

$$\text{Energy change} = \text{Energy at final state} - \text{Energy at initial state}$$

or

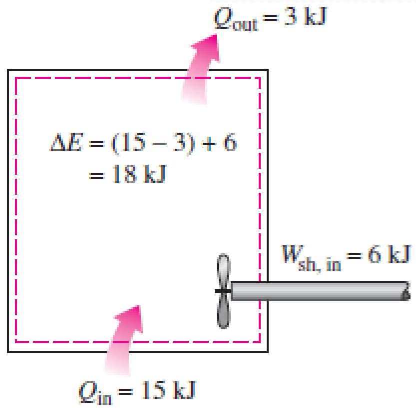
$$\Delta E_{system} = E_{final} - E_{initial} = E_2 - E_1$$

$$\Delta E = \Delta U + \Delta KE + \Delta PE$$

$$\Delta U = m(u_2 - u_1)$$

$$\Delta KE = \tfrac{1}{2} m(V_2^2 - V_1^2)$$

$$\Delta PE = mg(z_2 - z_1)$$



Mechanisms of Energy Transfer, E_{in} and E_{out}

Energy can be transferred to or from a system in three forms: *heat, work,* and *mass flow.*

$$E_{in} - E_{out} = (Q_{in} - Q_{out}) + (W_{in} - W_{out}) + (E_{mass,in} - E_{mass,out}) = \Delta E_{system} \quad \textbf{(2–34)}$$

$$\underbrace{E_{in} - E_{out}}_{\substack{\text{Net energy transfer}\\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{system}}_{\substack{\text{Change in internal, kinetic,}\\ \text{potential, etc., energies}}} \quad \text{(kJ)}$$

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\substack{\text{Rate of net energy transfer}\\ \text{by heat, work, and mass}}} = \underbrace{dE_{system}/dt}_{\substack{\text{Rate of change in internal,}\\ \text{kinetic, potential, etc., energies}}} \quad \text{(kW)}$$