Chapter 2
ENERGY, ENERGY TRANSFER, AND GENERAL ENERGY ANALYSIS

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- The total energy of a system, can be *contained* or *stored* in a system, and thus can be viewed as the **static forms of energy**.

- The forms of energy not stored in a system can be viewed as the **dynamic forms of energy** or as **energy interactions**.

- The dynamic forms of energy are recognized at the system boundary as they cross it, and they represent the energy gained or lost by a system during a process.

- The only two forms of energy interactions associated with a closed system are **heat transfer** and **work**.

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

- **The difference between heat transfer and work:** An energy interaction is heat transfer if its driving force is a temperature difference. Otherwise it is work.

Summary:

➢*Static Forms of Energy:* These are the energy forms contained or stored within the system, such as internal energy, kinetic energy, and potential energy.

➢ *Dynamic Forms of Energy:* These are the forms of energy transferred across the system boundaries, such as heat transfer, work, and energy carried by mass flow.
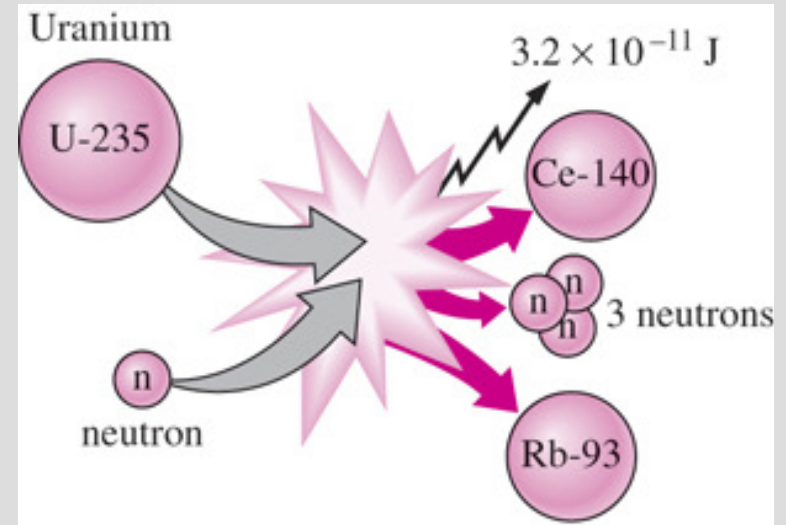
➢*Microscopic Kinetic Energy*

•Scale: Refers to the energy at the level of individual particles, such as atoms and molecules.

•Nature: It's the energy due to the random motion of particles within a substance.
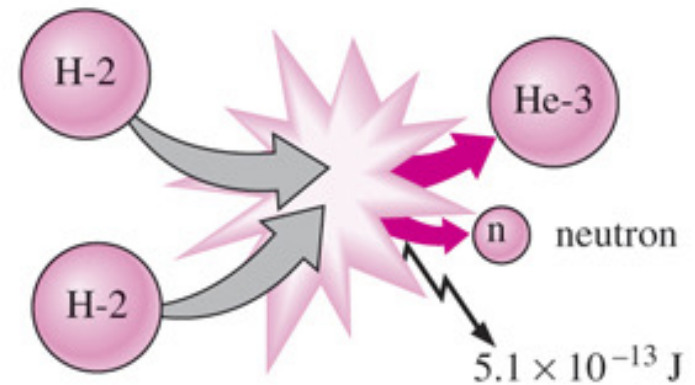
➢*Macroscopic Kinetic Energy*

•Scale: Refers to the energy at the level of the whole object or system.

•Nature: It's the energy due to the bulk motion of an object or system.

More on Nuclear Energy

- The best known **fission** reaction involves the split of the uranium atom (the U-235 isotope) into other elements and is commonly used to generate electricity in nuclear power plants (440 of them in 2004, generating 363,000 MW worldwide), to power nuclear submarines and aircraft carriers, and even to power spacecraft as well as building nuclear bombs.

- Nuclear energy by **fusion** is released when two small nuclei combine into a larger one.

- The uncontrolled fusion reaction was achieved in the early 1950s, but all the efforts since then to achieve controlled fusion by massive lasers, powerful magnetic fields, and electric currents to generate power have failed.

Uranium

U-235

3.2×10^{-11} J

Ce-140

n n n 3 neutrons

n

neutron

Rb-93

(a) Fission of uranium

H-2

He-3

n neutron

H-2

5.1×10^{-13} J

(b) Fusion of hydrogen

The fission of uranium and the fusion of hydrogen during nuclear reactions, and the release of nuclear energy.

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Summary

- **Fission of Uranium-235 to Cerium and Rubidium**: A nuclear reaction where uranium-235 absorbs a neutron, becomes uranium-236, and splits into cerium-140, rubidium-94, additional neutrons, and releases energy.

- **Fusion of Hydrogen to Helium:** A nuclear reaction where deuterium and tritium combine to form helium-4, a neutron, and release energy.

- Both reactions release significant amounts of energy, but they differ in their processes, byproducts, and practical applications.

Cerium :

- Used in alloys to improve heat resistance and strength, particularly in aluminum and magnesium alloys.

- Used to polish glass and in the production of certain types of glass and ceramics

Rubidium

- Used in the production of specialty glass

- Used in some types of photoelectric

- Used in some applications in biomedical research and diagnostics

Mechanical Energy

Mechanical energy: The form of energy that can be converted to mechanical work completely and directly by an ideal mechanical device such as an ideal turbine.

Kinetic and potential energies: The familiar forms of mechanical energy.

$$e_{\text{mech}} = \frac{P}{\rho} + \frac{V^2}{2} + gz$$

•Mechanical energy of a flowing fluid per unit mass

$$\dot{E}_{\text{mech}} = \dot{m} e_{\text{mech}} = \dot{m}\left(\frac{P}{\rho} + \frac{V^2}{2} + gz\right)$$

Rate of mechanical energy of a flowing fluid

Mechanical energy change of a fluid during incompressible flow per unit mass

$$\Delta e_{\text{mech}} = \frac{P_2 - P_1}{\rho} + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1) \qquad (\text{kJ/kg})$$

Rate of mechanical energy change of a fluid during incompressible flow

$$\Delta \dot{E}_{\text{mech}} = \dot{m}\Delta e_{\text{mech}} = \dot{m}\left(\frac{P_2 - P_1}{\rho} + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)\right) \qquad (\text{kW})$$
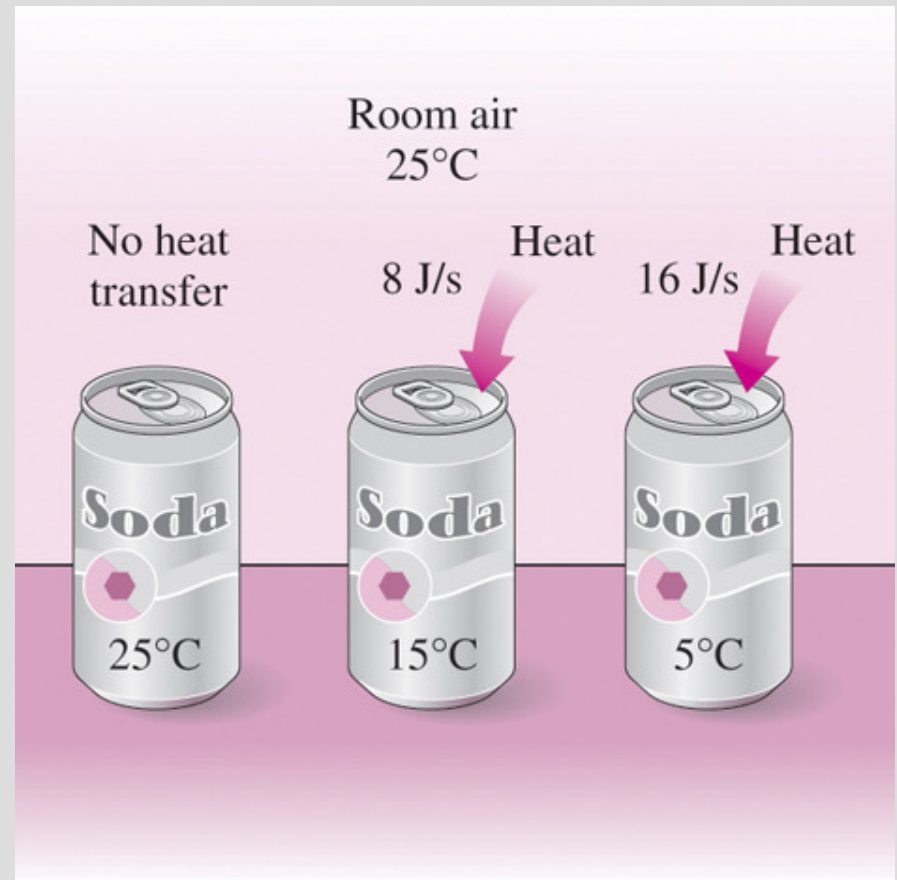
Pressure Energy (Flow Work or Flow Energy): The energy stored in a fluid due to its pressure; it's the work done by the fluid in pushing through a boundary.

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.

System boundary

CLOSED
SYSTEM

$(m = \text{constant})$
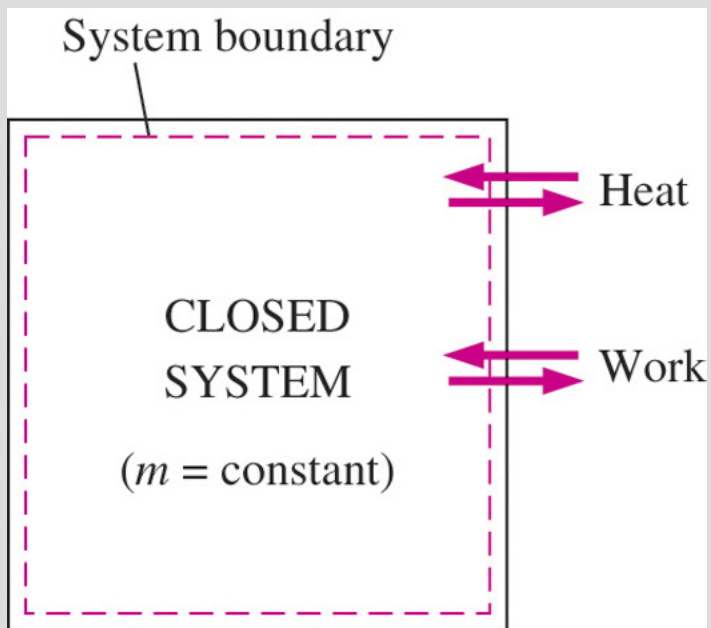
Heat

Work

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

Room air
25°C

No heat transfer

Heat
8 J/s

Heat
16 J/s

Soda
25°C

Soda
15°C

Soda
5°C

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

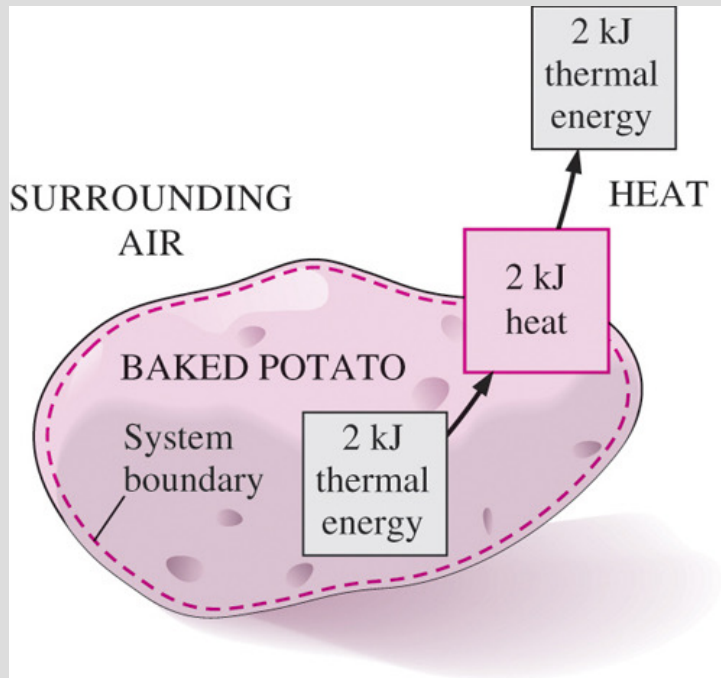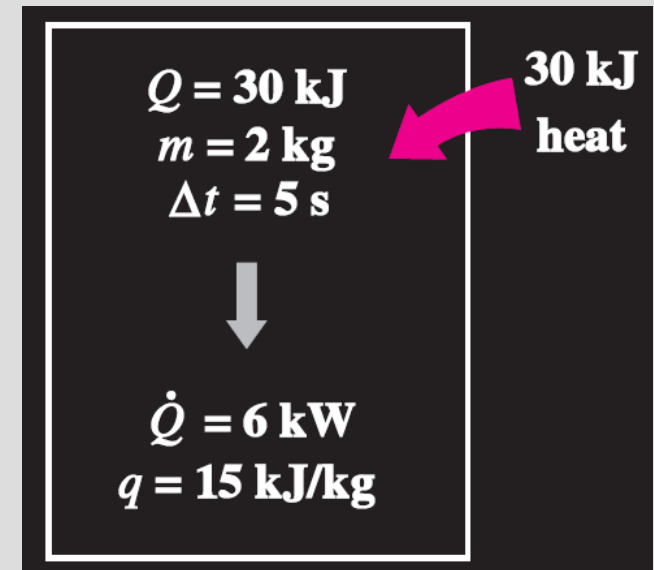$$q = \frac{Q}{m} \quad \text{(kJ/kg)}$$

Heat transfer per unit mass

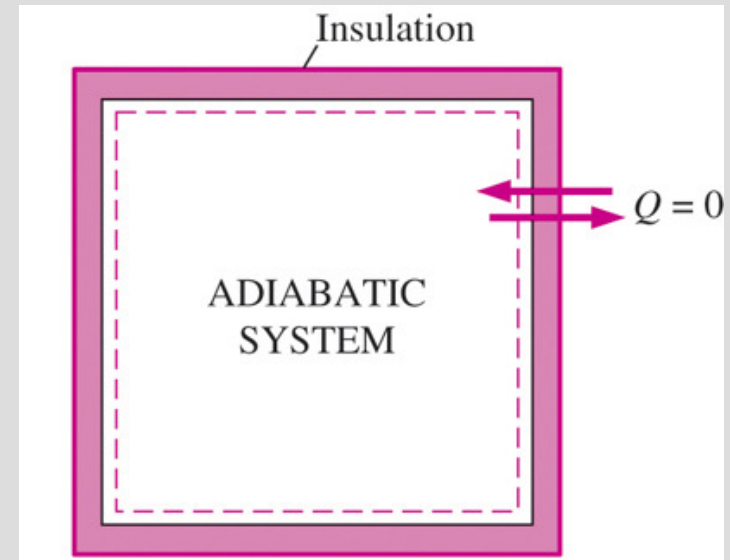$$Q = \dot{Q} \, \Delta t \quad \text{(kJ)}$$

Amount of heat transfer when heat transfer rate is constant

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

Amount of heat transfer when heat transfer rate changes with time

$Q = 30 \text{ kJ}$
$m = 2 \text{ kg}$
$\Delta t = 5 \text{ s}$

30 kJ heat

$\dot{Q} = 6 \text{ kW}$
$q = 15 \text{ kJ/kg}$

2 kJ thermal energy

HEAT

SURROUNDING AIR

2 kJ heat

BAKED POTATO

System boundary

2 kJ thermal energy

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

Insulation

$Q = 0$

ADIABATIC SYSTEM

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

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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.

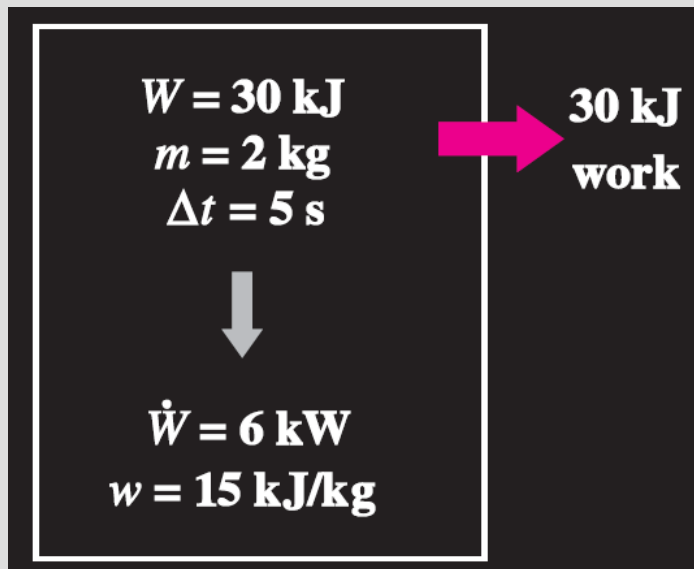- **Radiation:** The transfer of energy due to the emission of electromagnetic waves (or photons).
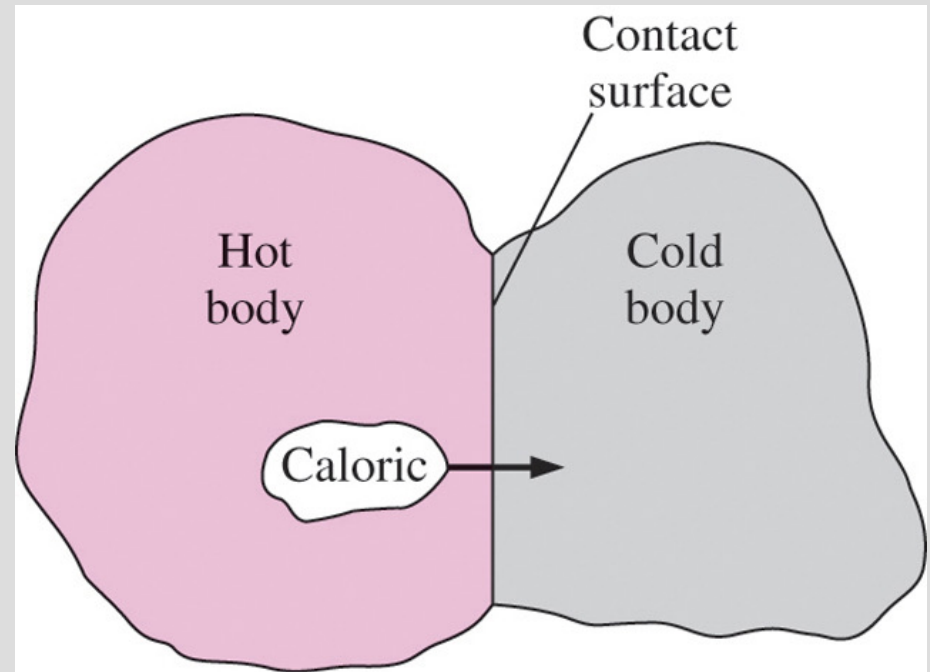
In the early nineteenth century, heat was thought to be an invisible fluid called the *caloric* that flowed from warmer bodies to the cooler ones.
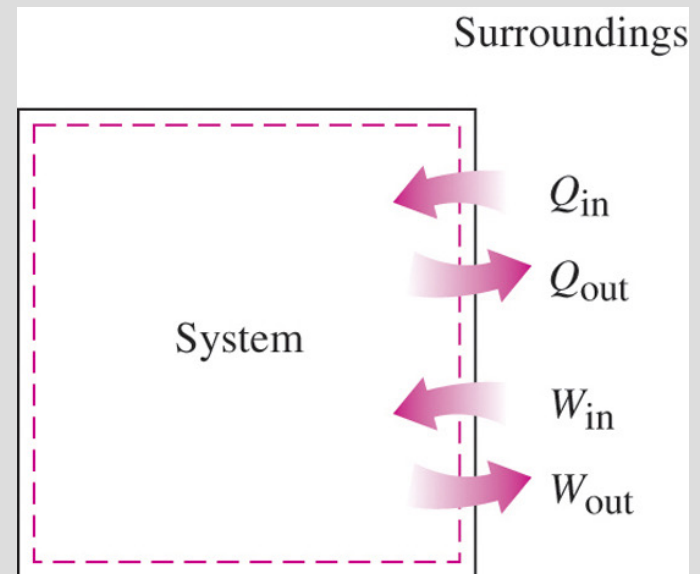
ENERGY TRANSFER BY WORK

- **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. This is the primary approach in this text.

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

Work done per unit mass

$$W = 30 \text{ kJ}$$
$$m = 2 \text{ kg}$$
$$\Delta t = 5 \text{ s}$$

30 kJ work

$$\dot{W} = 6 \text{ kW}$$
$$w = 15 \text{ kJ/kg}$$

Power is the work done per unit time (kW)

Surroundings

System

Q_{in}

Q_{out}

W_{in}

W_{out}
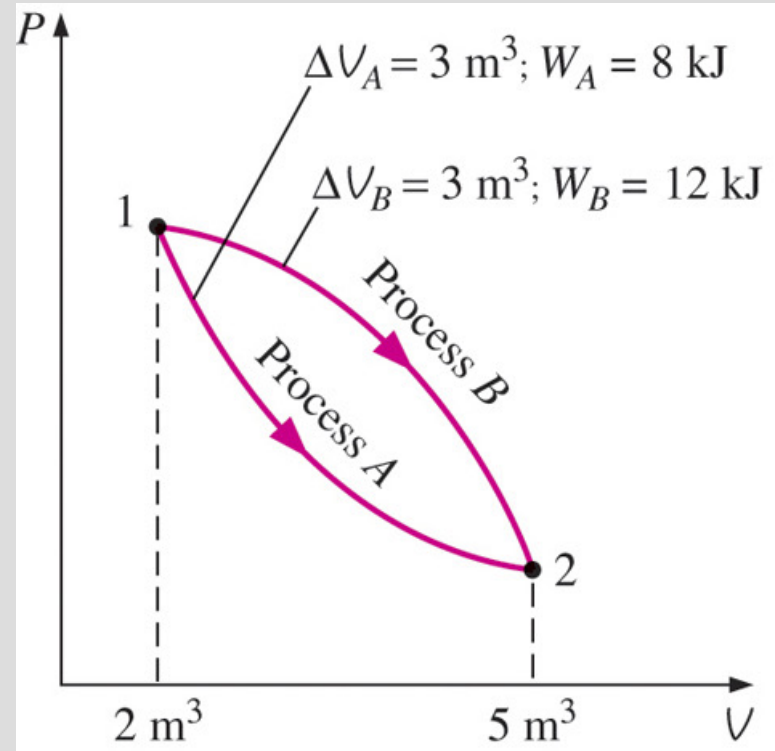
Specifying the directions of heat and work.

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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*, 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).

$\Delta V_A = 3 \text{ m}^3; W_A = 8 \text{ kJ}$

$\Delta V_B = 3 \text{ m}^3; W_B = 12 \text{ kJ}$

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)

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

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Electrical Work
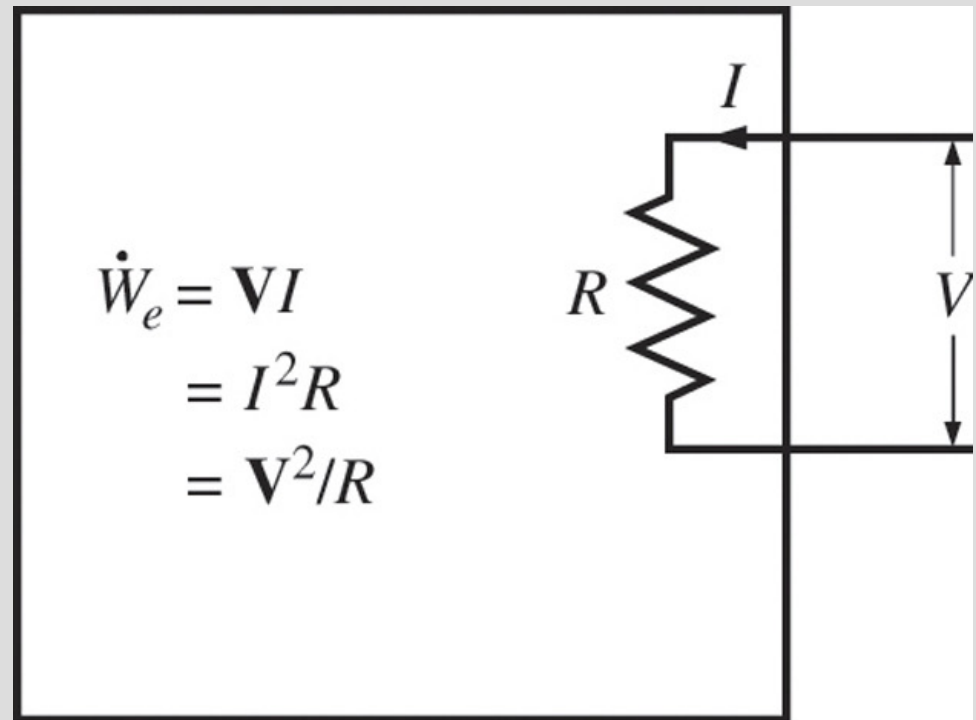
Electrical work

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

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

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

$$\dot{W}_e = \mathbf{V}I$$
$$= I^2 R$$
$$= \mathbf{V}^2/R$$

Electrical power in terms of resistance R, current I, and potential difference $\mathbf{V}$.
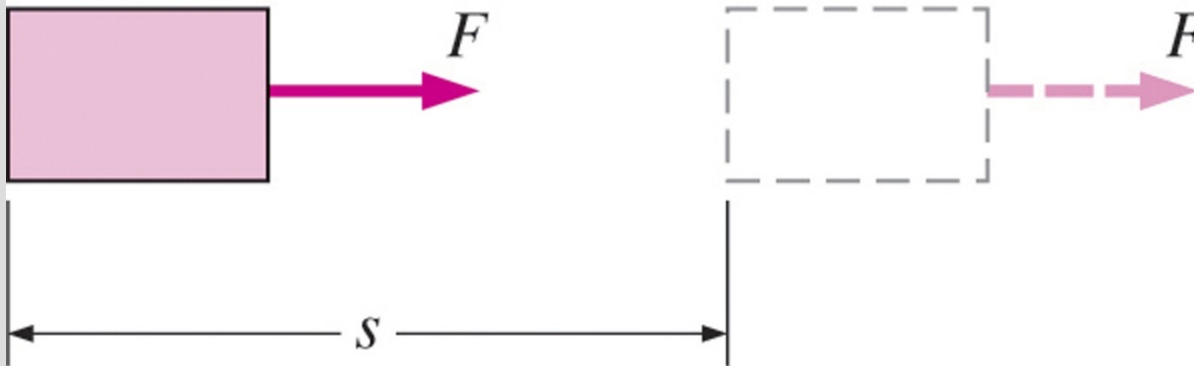
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MECHANICAL FORMS OF WORK

- 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

$$W = Fs \qquad (kJ)$$

When force is not constant

$$W = \int_1^2 F \, ds \qquad (kJ)$$

If there is no movement, no work is done.

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

Shaft Work

A force *F* acting through a moment arm *r* generates a torque T
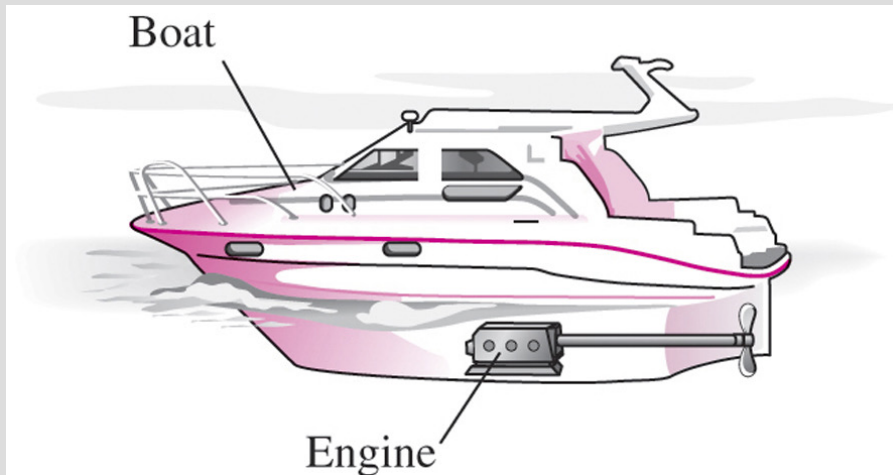
$$T = Fr \rightarrow F = \frac{T}{r}$$

This force acts through a distance *s*

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

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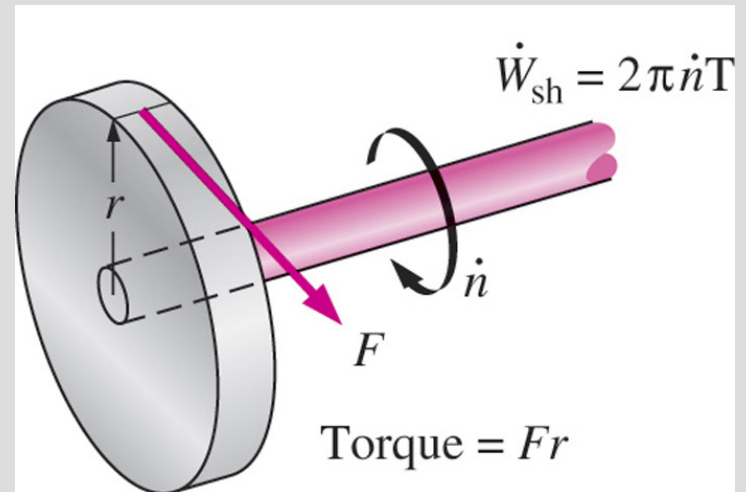
$$W_{sh} = Fs = \left(\frac{T}{r}\right)(2\pi rn) = 2\pi nT \qquad (kJ)$$

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

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

$$\dot{W}_{sh} = 2\pi \dot{n}T$$

Torque = Fr

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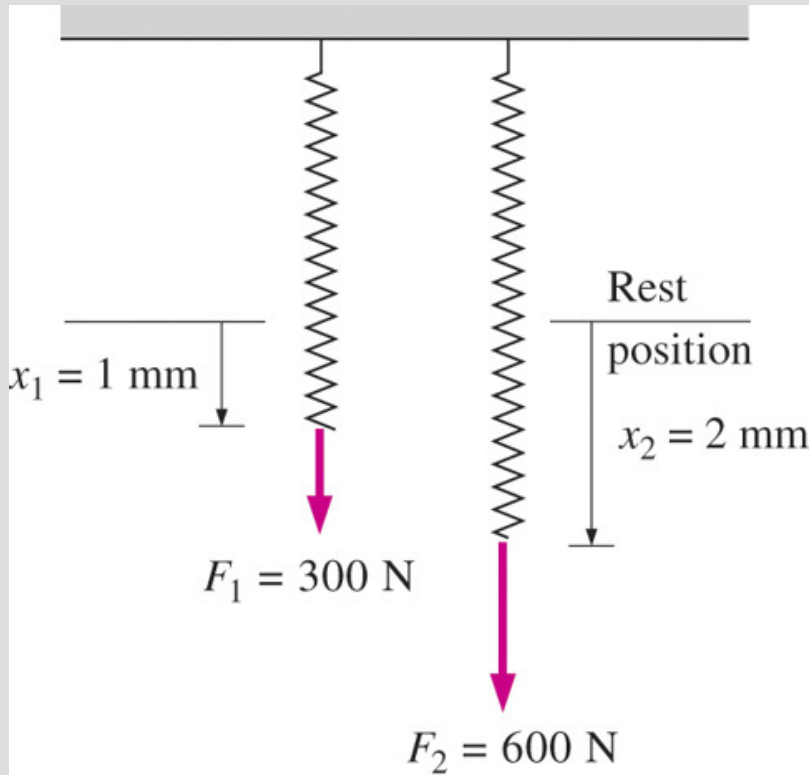
$$\delta W_{spring} = F\, dx$$

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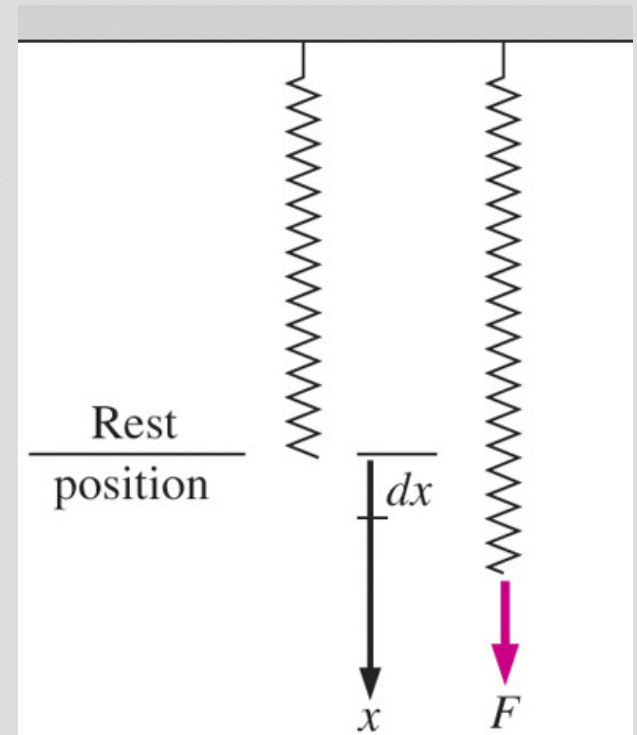
$$W_{spring} = \tfrac{1}{2}k(x_2^2 - x_1^2) \qquad (\text{kJ})$$

x_1 and x_2: the initial and the final displacements

Elongation of a spring under the influence of a force.

$x_1 = 1$ mm

$F_1 = 300$ N

Rest position

$x_2 = 2$ mm

$F_2 = 600$ N

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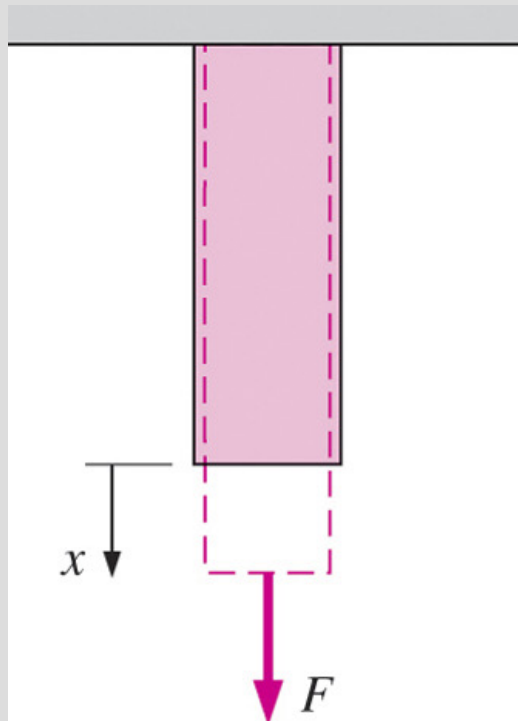
Rest position

dx

x F

Work Done on Elastic Solid Bars

$$W_{\text{elastic}} = \int_1^2 F\,dx = \int_1^2 \sigma_n A\,dx \qquad \text{(kJ)}$$
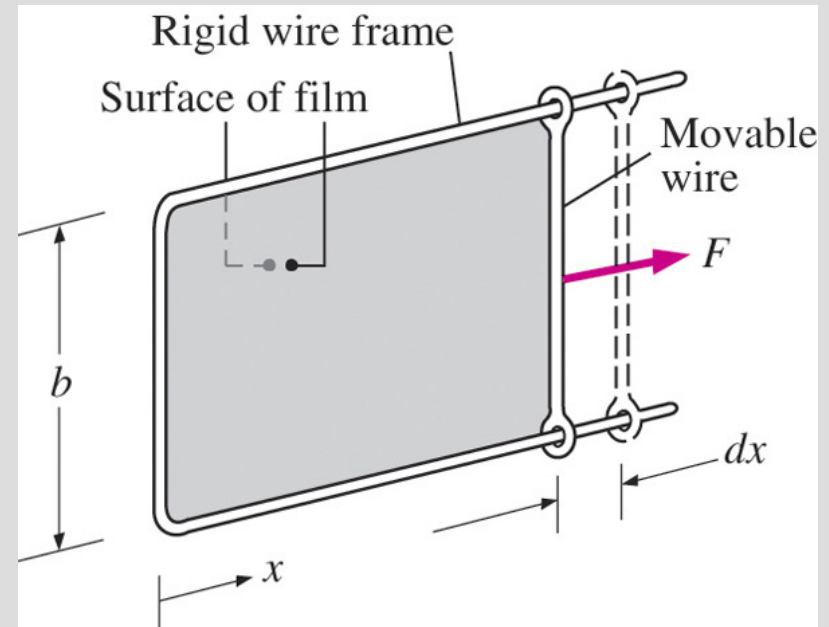
Work Associated with the Stretching of a Liquid Film

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

Stretching a liquid film with a movable wire.

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

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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.

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* (vector quantity that represents the strength and orientation of a magnetic source such as a magnet)

Electrical polarization work: The generalized force is the *electric field strength* and the generalized displacement is the *polarization of the medium* (The electric dipole moment is a measure of the separation of positive and negative electrical charges within a system)


Motor

Elevator car

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

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THE FIRST LAW OF THERMODYNAMICS

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

- **The *First Law*:** For all adiabatic processes between two specified states of a closed system, the net work done is the same regardless of the nature of the closed system and the details of the process.

m

$PE_1 = 10$ kJ
$KE_1 = 0$

Δz

m $PE_2 = 7$ kJ
$KE_2 = 3$ kJ
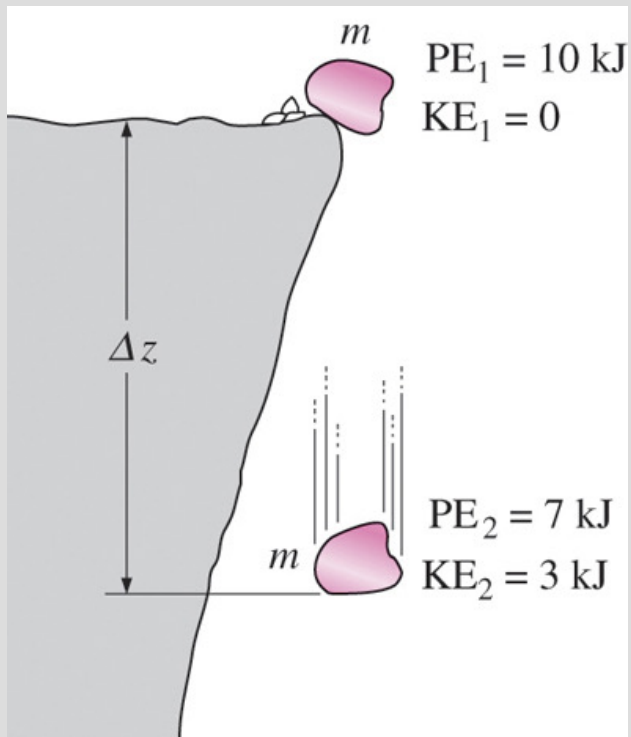
Energy cannot be created or destroyed; it can only change forms.

$Q_{in} = 5$ kJ
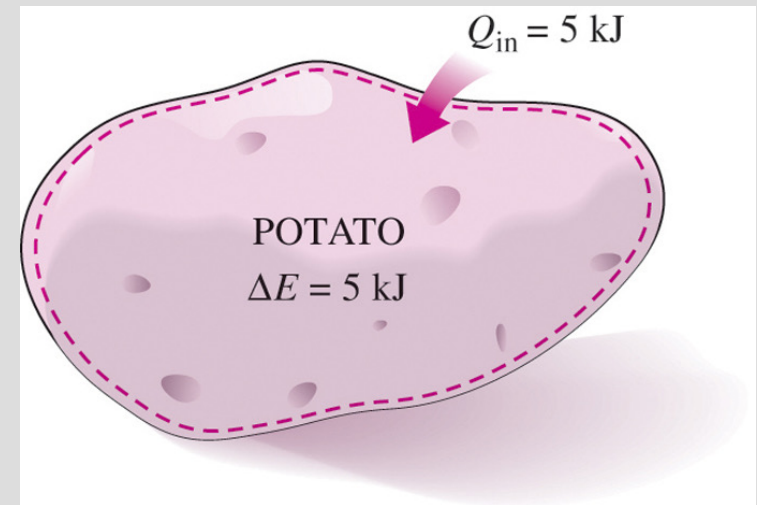
POTATO
$\Delta E = 5$ kJ

The increase in the energy of a potato in an oven is equal to the amount of heat transferred to it.

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$Q_{out} = 3$ kJ

$\Delta E = Q_{net} = 12$ kJ

$Q_{in} = 15$ kJ
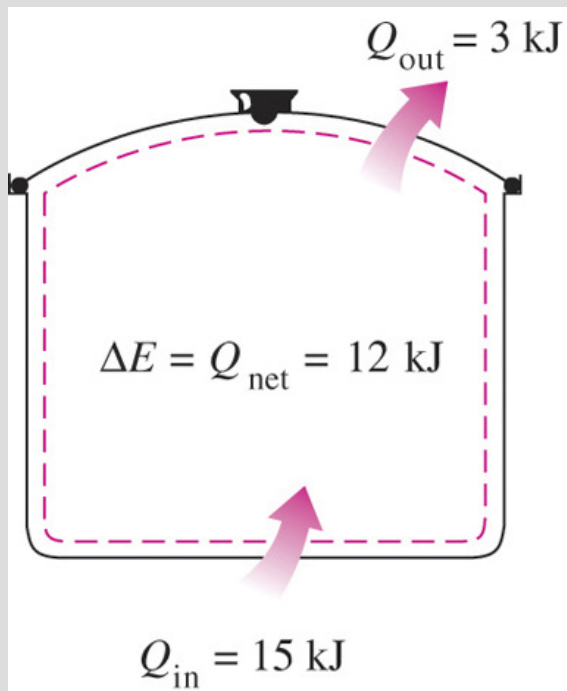
In the absence of any work interactions, the energy change of a system is equal to the net heat transfer.

(Adiabatic)

$W_{in} = 5$ kJ

$\Delta E = 5$ kJ

Battery
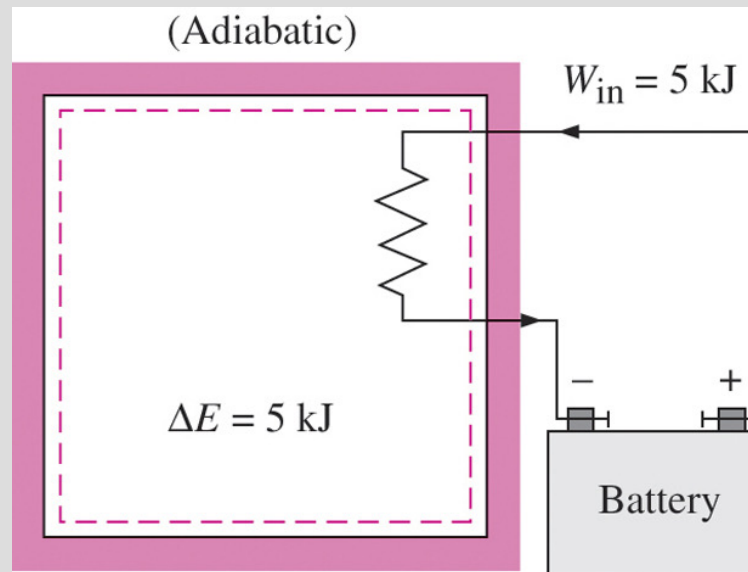
The work (electrical) done on an adiabatic system is equal to the increase in the energy of the system.

(Adiabatic)

$\Delta E = 8$ kJ

$W_{sh,\, in} = 8$ kJ
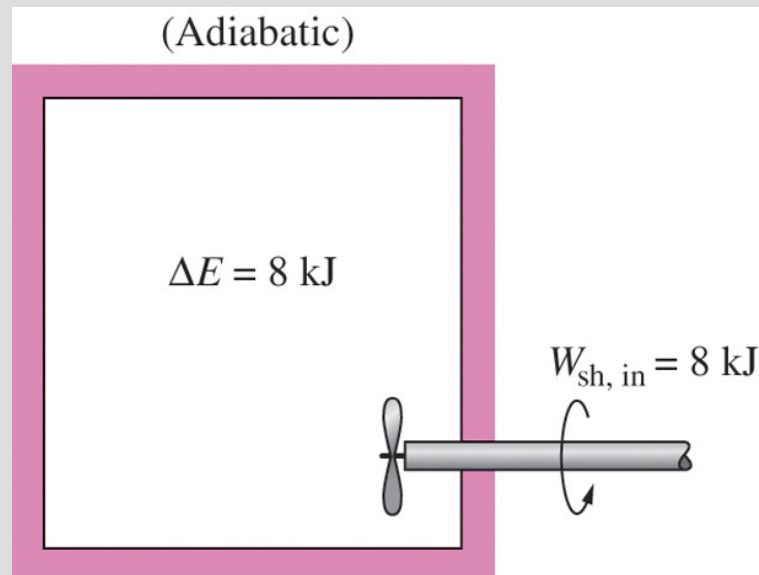
The work (shaft) done on an adiabatic system is equal to the increase in the energy of the system.

Energy Balance

The net change (increase or decrease) in the total energy of the system during a process is equal to the difference between the total energy entering and the total energy leaving the system during that process.

$$\left(\begin{array}{c}\text{Total energy}\\\text{entering the system}\end{array}\right) - \left(\begin{array}{c}\text{Total energy}\\\text{leaving the system}\end{array}\right) = \left(\begin{array}{c}\text{Change in the total}\\\text{energy of the system}\end{array}\right)$$

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

$W_{b,in} = 10\ \text{kJ}$

$\Delta E = 10\ \text{kJ}$

(Adiabatic)

The work (boundary) done on an adiabatic system is equal to the increase in the energy of the system.
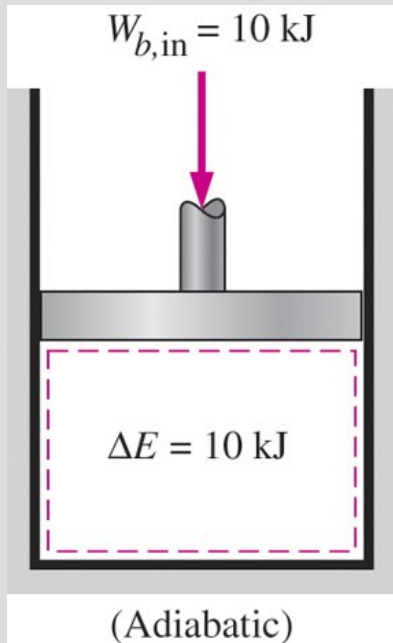
The energy change of a system during a process is equal to the *net* work and heat transfer between the system and its surroundings.

$Q_{out} = 3\ \text{kJ}$

$\Delta E = (15 - 3) + 6$
$= 18\ \text{kJ}$

$W_{sh,\ in} = 6\ \text{kJ}$

$Q_{in} = 15\ \text{kJ}$
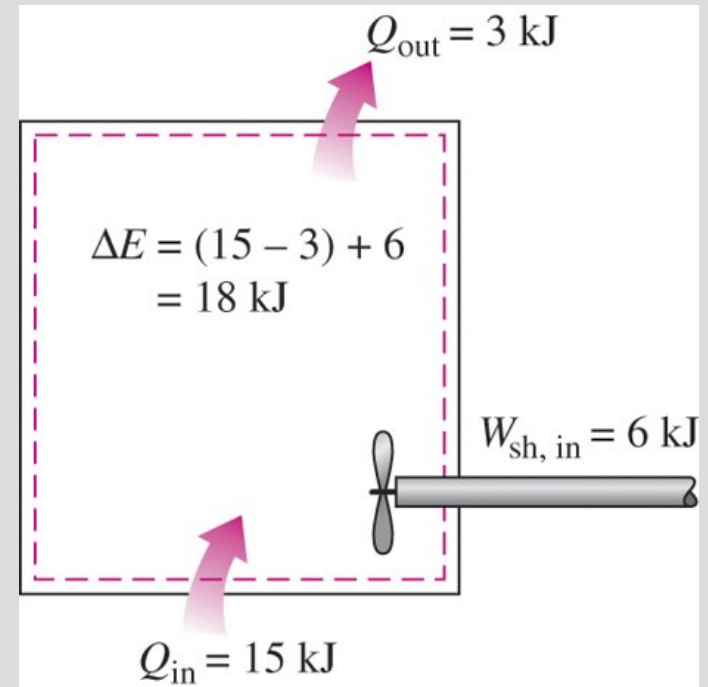
Energy Change of a System, ΔE_{system}

Energy change $=$ Energy at final state $-$ Energy at initial state

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

$$\Delta E = \Delta U + \Delta \text{KE} + \Delta \text{PE}$$

Internal, kinetic, and potential energy changes

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

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

$$\Delta \text{PE} = mg(z_2 - z_1)$$

Stationary Systems

$$z_1 = z_2 \rightarrow \Delta \text{PE} = 0$$

$$V_1 = V_2 \rightarrow \Delta \text{KE} = 0$$

$$\Delta E = \Delta U$$

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

- Heat transfer
- Work transfer
- Mass flow

A closed mass involves only *heat transfer* and *work.*

$$E_{in} - E_{out} = (Q_{in} - Q_{out}) + (W_{in} - W_{out}) + (E_{mass,in} - E_{mass,out}) = \Delta E_{system}$$

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

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

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

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

$$\Delta E = (dE/dt)\,\Delta t$$

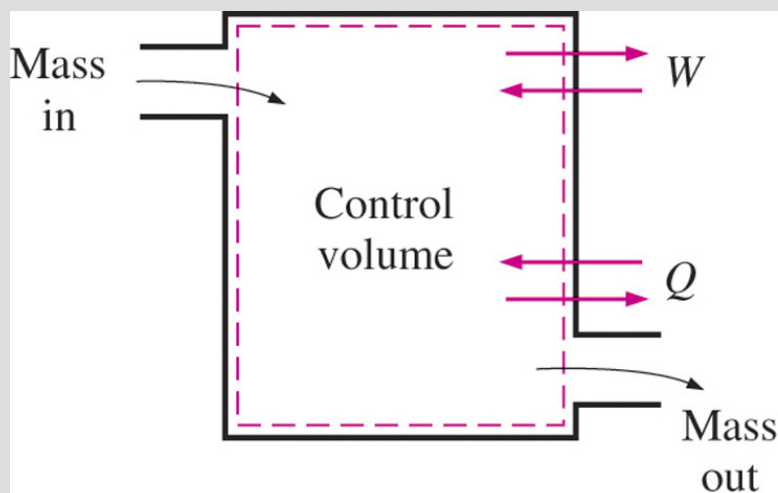$$e_{in} - e_{out} = \Delta e_{system} \quad (kJ/kg)$$

$$\delta E_{in} - \delta E_{out} = dE_{system} \qquad \delta e_{in} - \delta e_{out} = de_{system}$$

$$\dot{W}_{net,out} = \dot{Q}_{net,in} \quad (\text{for a cycle})$$
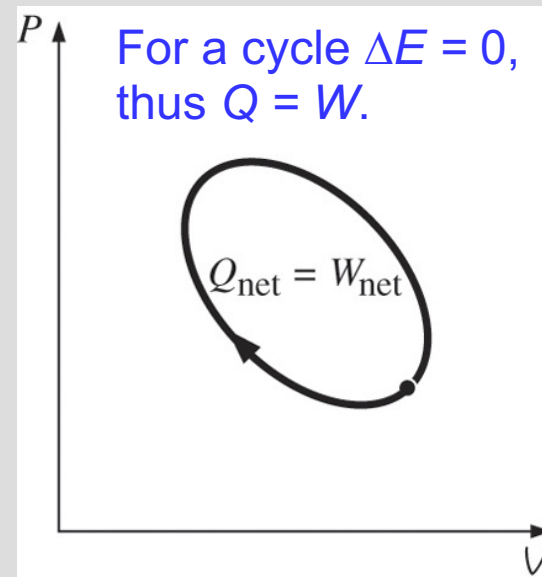
Mass in

Control volume

W

Q

Mass out

The energy content of a control volume can be changed by mass flow as well as heat and work interactions.

For a cycle $\Delta E = 0$, thus $Q = W$.

$$Q_{net} = W_{net}$$

ENERGY CONVERSION EFFICIENCIES

Efficiency is one of the most frequently used terms in thermodynamics, and it indicates how well an energy conversion or transfer process is accomplished.

$$\text{Performance} = \frac{\text{Desired output}}{\text{Required input}}$$

Efficiency of a water heater: The ratio of the energy delivered to the house by hot water to the energy supplied to the water heater.

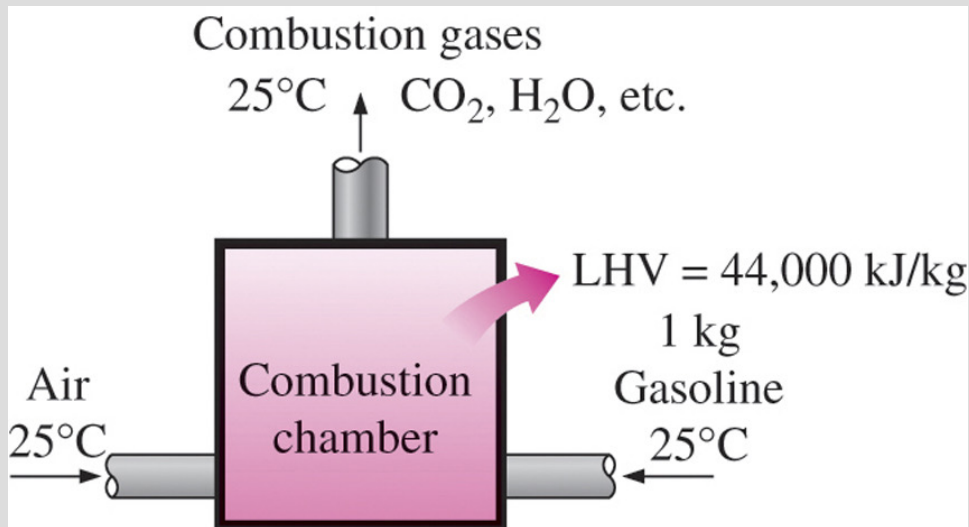| Type	Efficiency
Gas, conventional	55%
Gas, high-efficiency	62%
Electric, conventional	90%
Electric, high-efficiency	94%
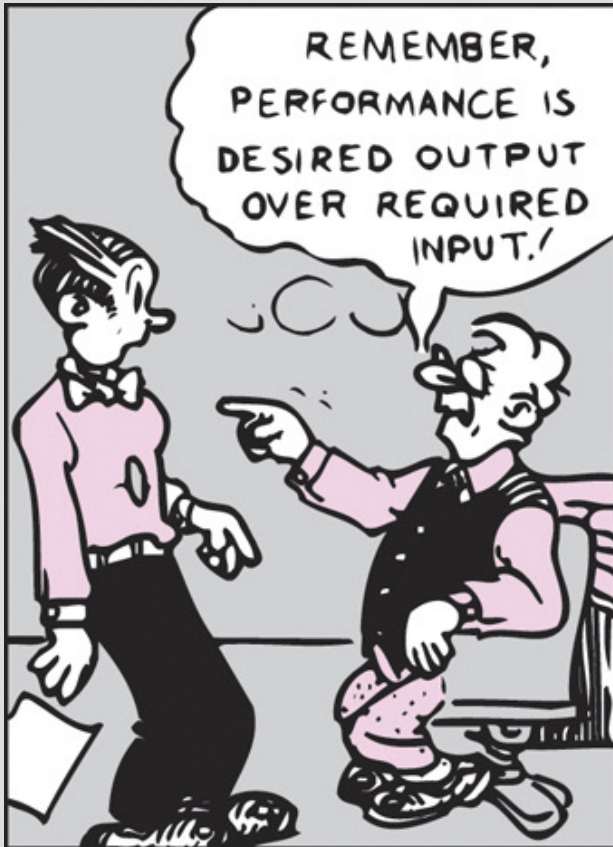
The definition of performance is not limited to thermodynamics only.

$$\eta_{combustion} = \frac{Q}{HV} = \frac{\text{Amount of heat released during combustion}}{\text{Heating value of the fuel burned}}$$

Heating value of the fuel: The amount of heat released when a unit amount of fuel at room temperature is completely burned and the combustion products are cooled to the room temperature.

Lower heating value (LHV): When the water leaves as a vapor.

Higher heating value (HHV): When the water in the combustion gases is completely condensed and thus the heat of vaporization is also recovered.

Combustion gases
25°C CO_2, H_2O, etc.

LHV = 44,000 kJ/kg
1 kg
Gasoline
25°C

Air
25°C

Combustion chamber

The definition of the heating value of gasoline.

The efficiency of space heating systems of residential and commercial buildings is usually expressed in terms of the **annual fuel utilization efficiency (AFUE)**, which accounts for the combustion efficiency as well as other losses such as heat losses to unheated areas and start-up and cooldown losses.

- **Generator:** A device that converts mechanical energy to electrical energy.
- **Generator efficiency:** The ratio of the electrical power output to the mechanical power input.
- **Thermal efficiency of a power plant:** The ratio of the net electrical power output to the rate of fuel energy input.

$$\eta_{\text{overall}} = \eta_{\text{combustion}} \, \eta_{\text{thermal}} \, \eta_{\text{generator}} = \frac{\dot{W}_{\text{net,electric}}}{\text{HHV} \times \dot{m}_{\text{net}}}$$

Overall efficiency of a power plant

TABLE 2–1

The efficacy of different lighting systems

Type of lighting	Efficacy, lumens/W
Combustion	
Candle	0.2
Incandescent	
Ordinary	6–20
Halogen	16–25
Fluorescent	
Ordinary	40–60
High output	70–90
Compact	50–80
High-intensity discharge	
Mercury vapor	50–60
Metal halide	56–125
High-pressure sodium	100–150
Low-pressure sodium	up to 200

Lighting efficacy: The amount of light output in lumens per W of electricity consumed.

A 15-W compact fluorescent lamp provides as much light as a 60-W incandescent lamp.

15 W   60 W
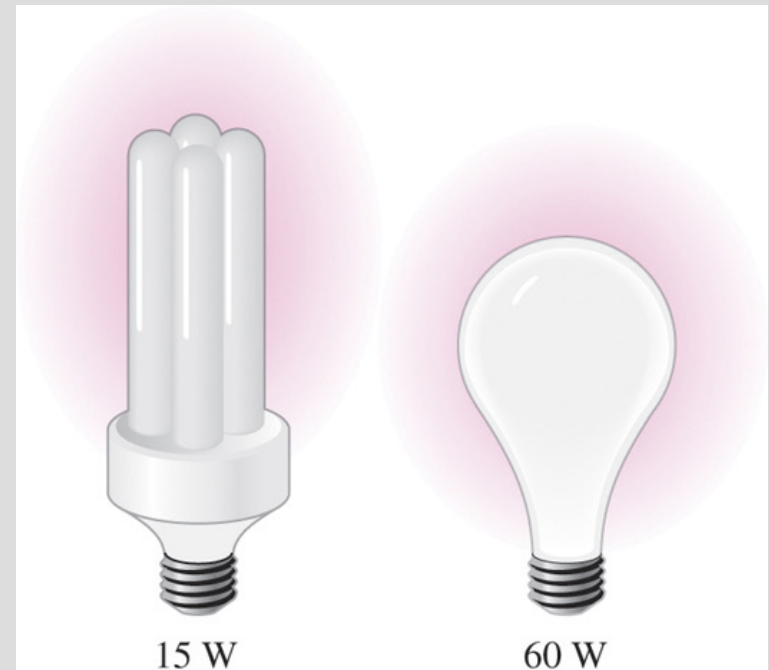
Components of Power Plant Efficiency

1. **Combustion Efficiency (η_{comb}):**

   - This efficiency measures how effectively the chemical energy in the fuel is converted into thermal energy (heat) during the combustion process. It is the ratio of the actual heat generated by combustion to the theoretical maximum heat that could be generated from the fuel.

$$\eta_{\text{comb}} = \frac{\text{Heat generated by combustion}}{\text{Theoretical maximum heat from fuel}}$$

2. **Thermal Efficiency (η_{thermal}):**

   - Thermal efficiency measures how effectively the thermal energy produced by combustion is converted into mechanical energy. For a heat engine (like a steam turbine or gas turbine), it is the ratio of the work output to the heat input.

$$\eta_{\text{thermal}} = \frac{\text{Work output}}{\text{Heat input}}$$

3. **Generator Efficiency ($\eta_{\text{generator}}$):**

   - Generator efficiency measures how effectively the mechanical energy from the turbine is converted into electrical energy. It is the ratio of the electrical energy output to the mechanical energy input to the generator.

$$\eta_{\text{generator}} = \frac{\text{Electrical energy output}}{\text{Mechanical energy input}}$$