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.

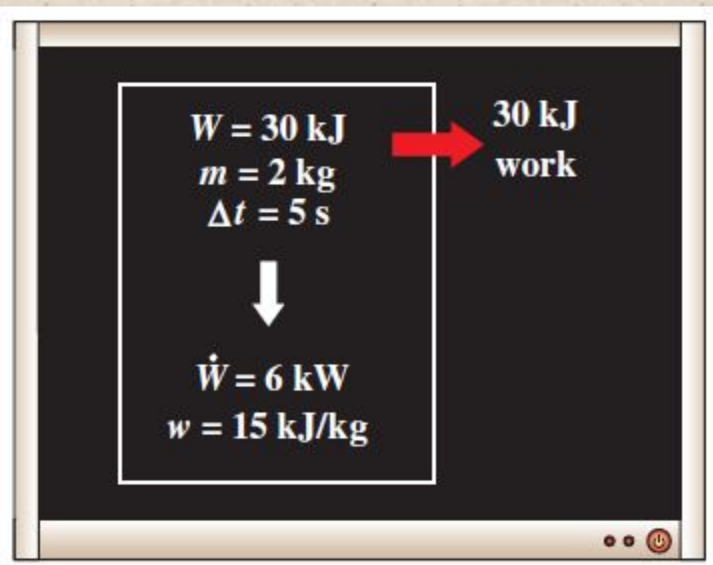

FIGURE 2–20
The relationships among w, W, and $\dot{W}$.

Work done per unit mass

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

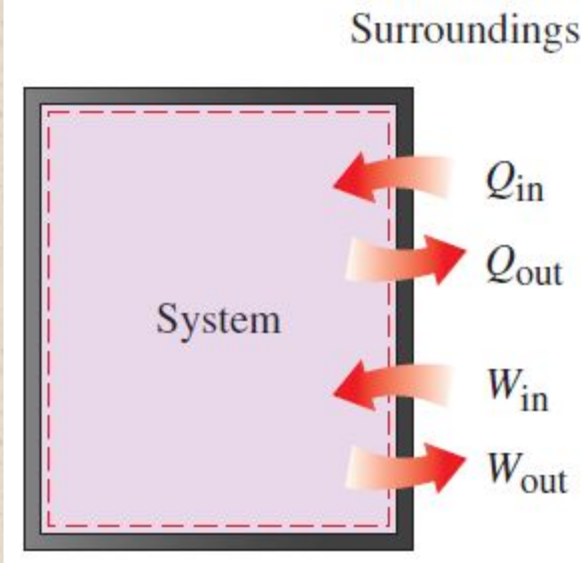

FIGURE 2–21
Specifying the directions of heat and work.

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*, 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).

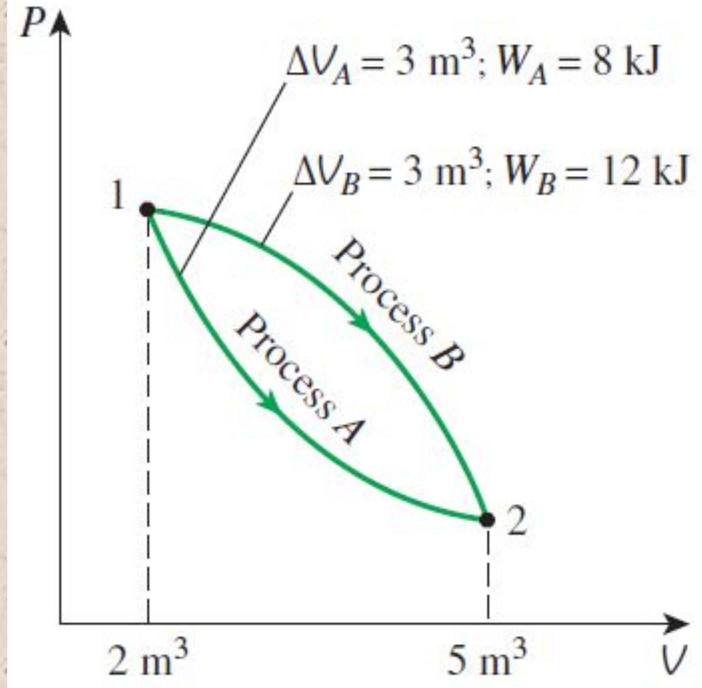

FIGURE 2–22
Properties are point functions; but heat and work are path functions (their magnitudes depend on the path followed).

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

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

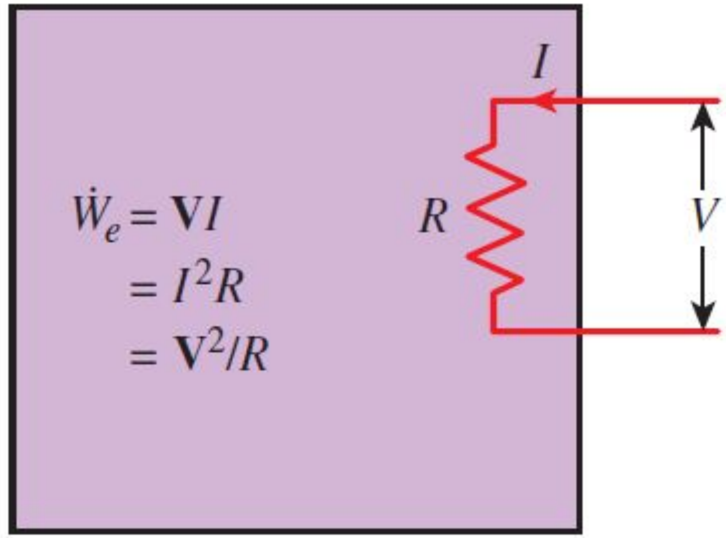

FIGURE 2–27
Electrical power in terms of resistance R, current I, and potential difference $\mathbf{V}$.

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

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

When force is not constant

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

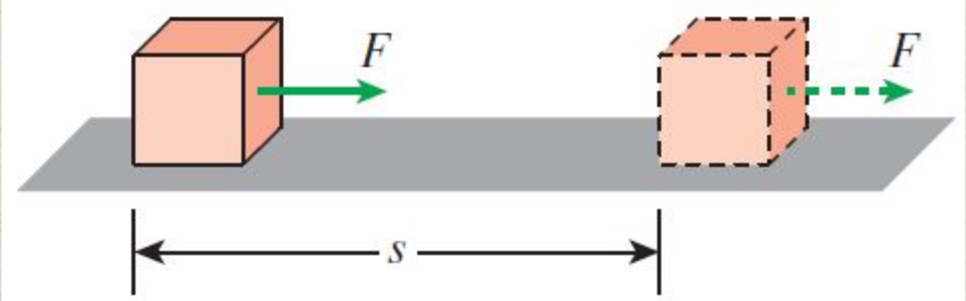

FIGURE 2–28
The work done is proportional to the force applied (F) and the distance traveled (s).

Shaft Work

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

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

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

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

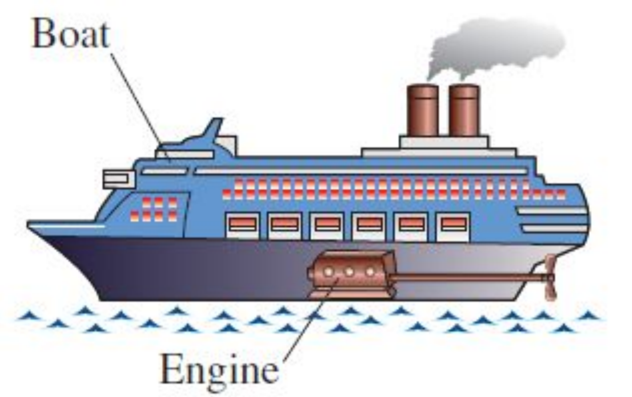

FIGURE 2–29
Energy transmission through rotating shafts is commonly encountered in practice.

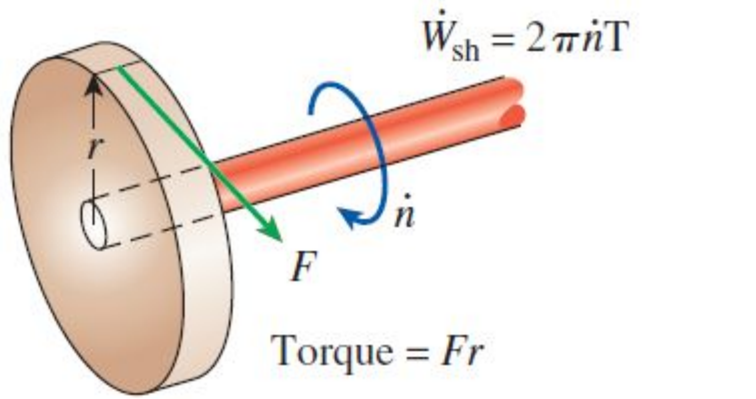

FIGURE 2–30
Shaft work is proportional to the torque applied and the number of revolutions of the shaft.

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)

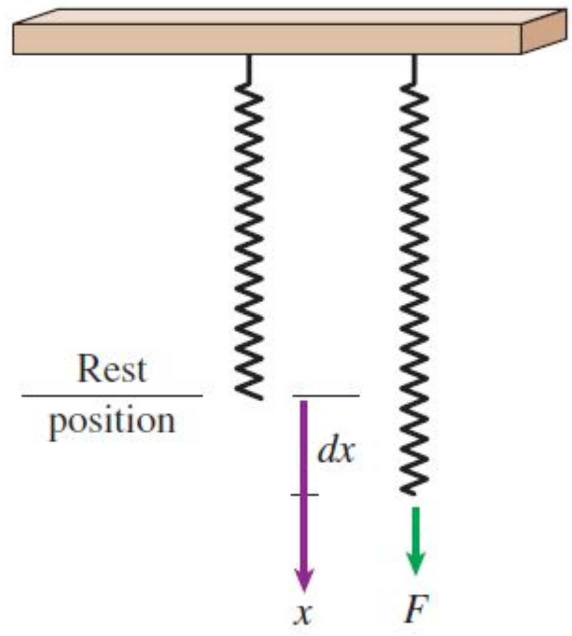

FIGURE 2–32
Elongation of a spring under the influence of a force.

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

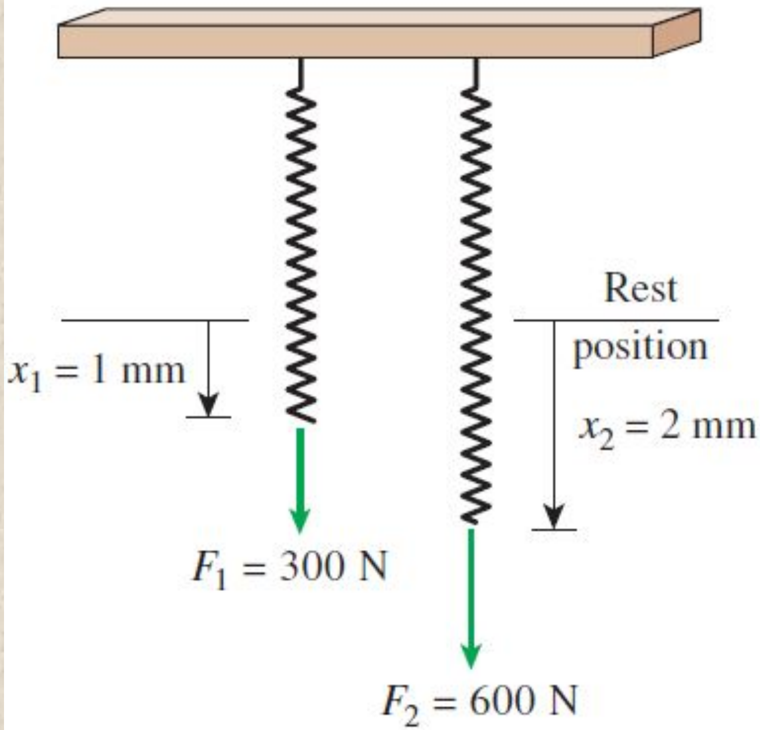

FIGURE 2–33
The displacement of a linear spring doubles when the force is doubled.

Work Associated with the Stretching of a Liquid Film

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

Work Done on Elastic Solid Bars

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

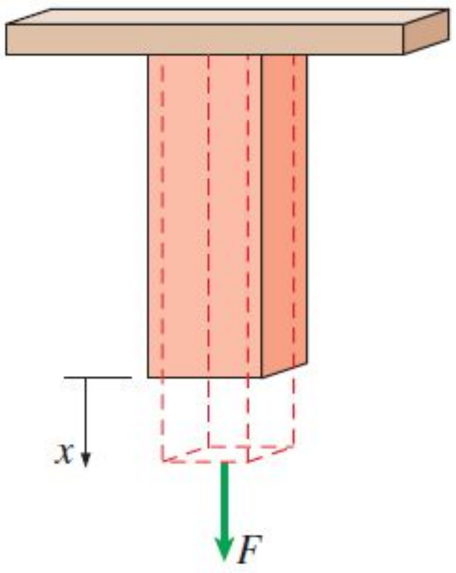

FIGURE 2–34
Solid bars behave as springs under the influence of a force.

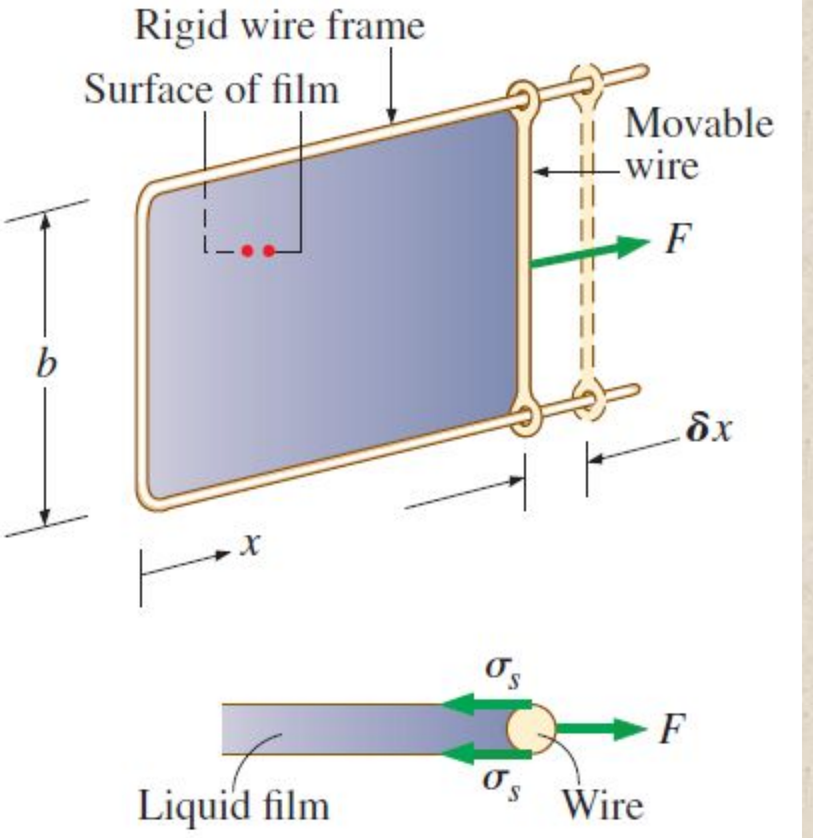

FIGURE 2–35
Stretching a liquid film with a U-shaped wire, and the forces acting on the movable wire of length *b*.

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*. $\boxed{W = B\mu}$

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

→ electric field strength

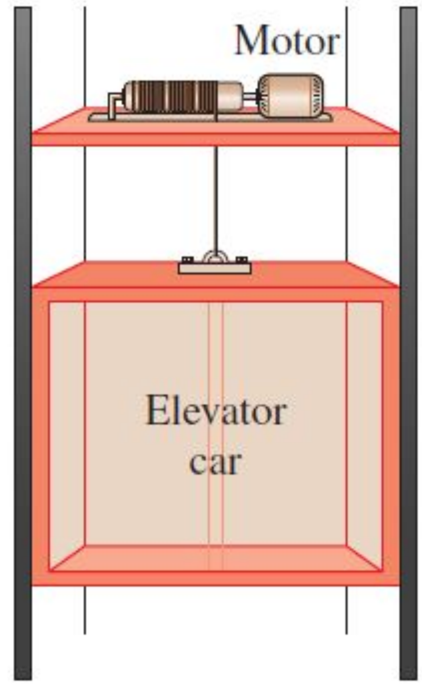

FIGURE 2–36
The energy transferred to a body while being raised is equal to the change in its potential energy.

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.

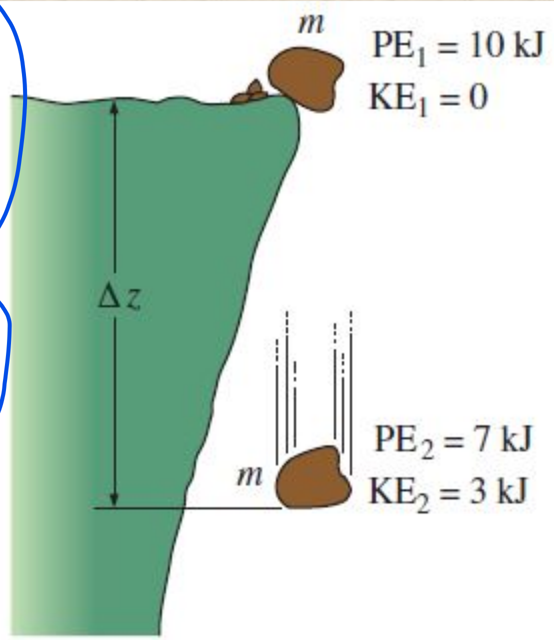

FIGURE 2–39
Energy cannot be created or destroyed; it can only change forms.

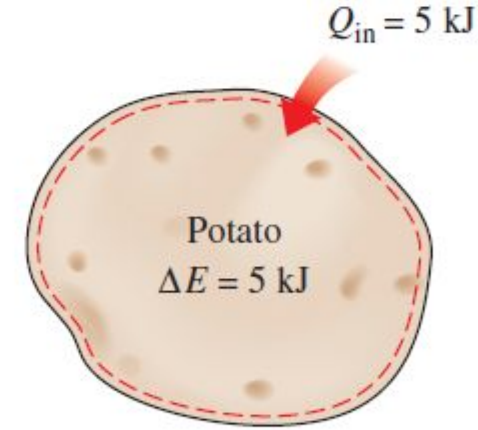

FIGURE 2–40
The increase in the energy of a potato in an oven is equal to the amount of heat transferred to it.

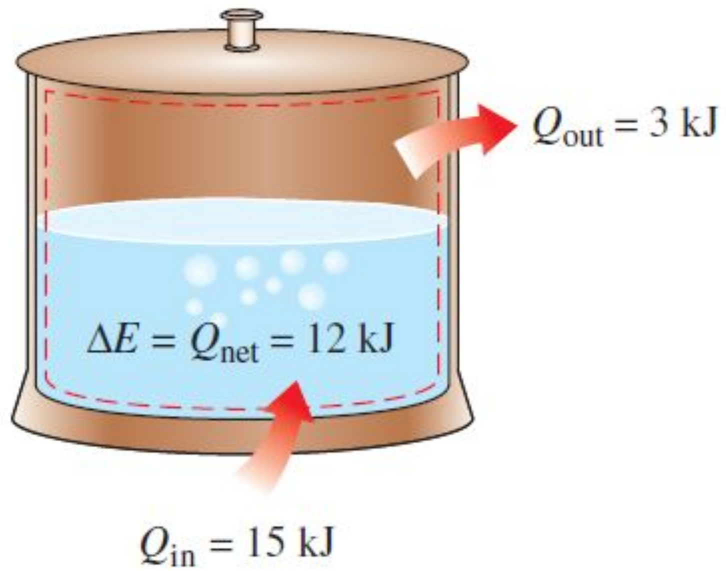

FIGURE 2–41
In the absence of any work interactions, the energy change of a system is equal to the net heat transfer.

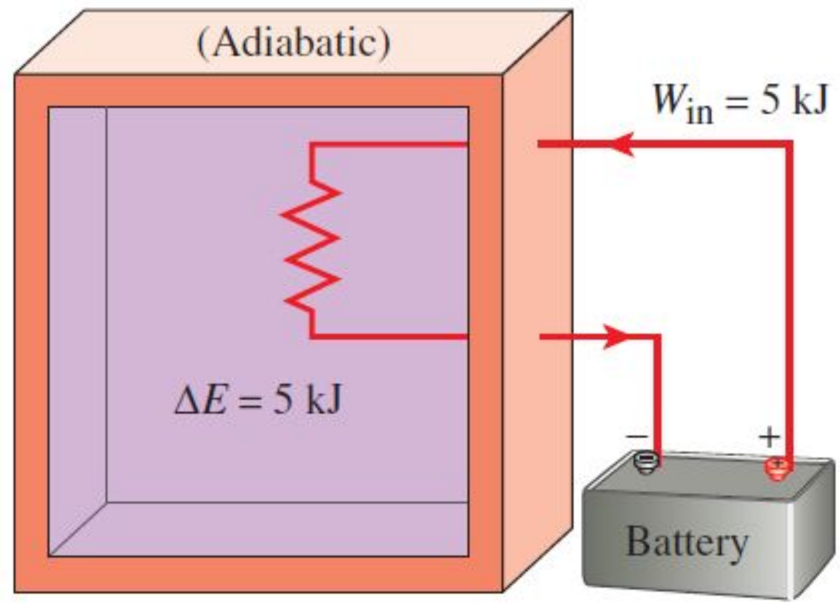

FIGURE 2–42
The work (electrical) done on an adiabatic system is equal to the increase in the energy of the system.

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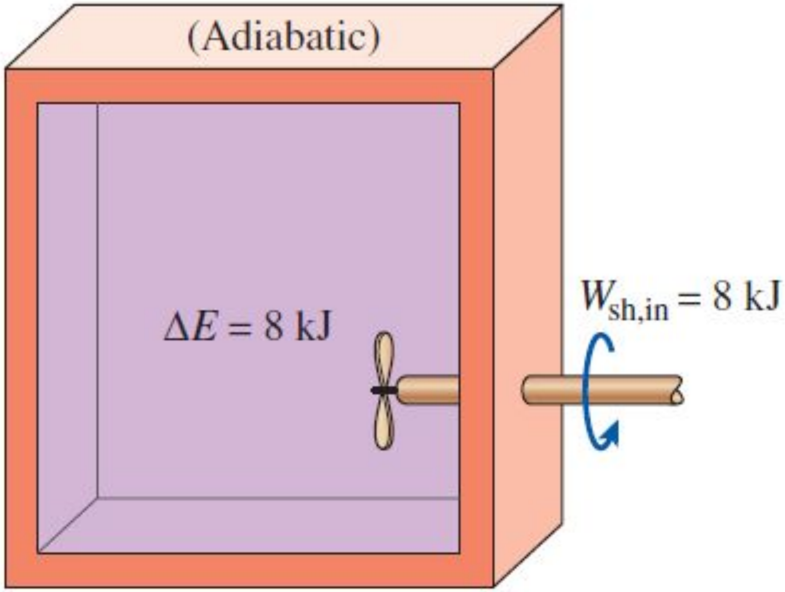

FIGURE 2–43
The work (shaft) done on an adiabatic system is equal to the increase in the energy of the system.

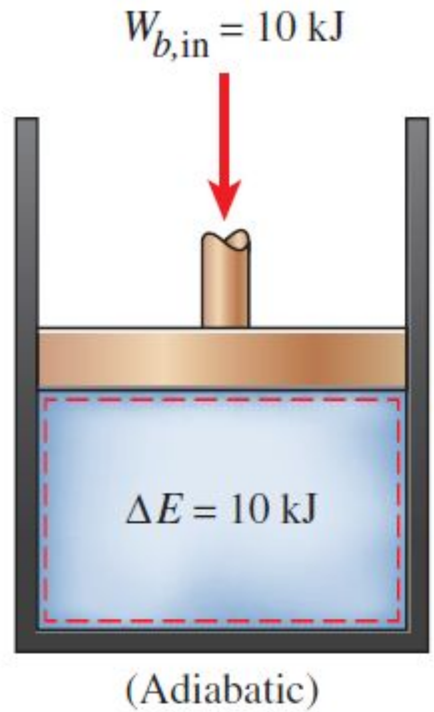

FIGURE 2–44
The work (boundary) done on an adiabatic system is equal to the increase in the energy of the system.

Energy Balance

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

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

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.

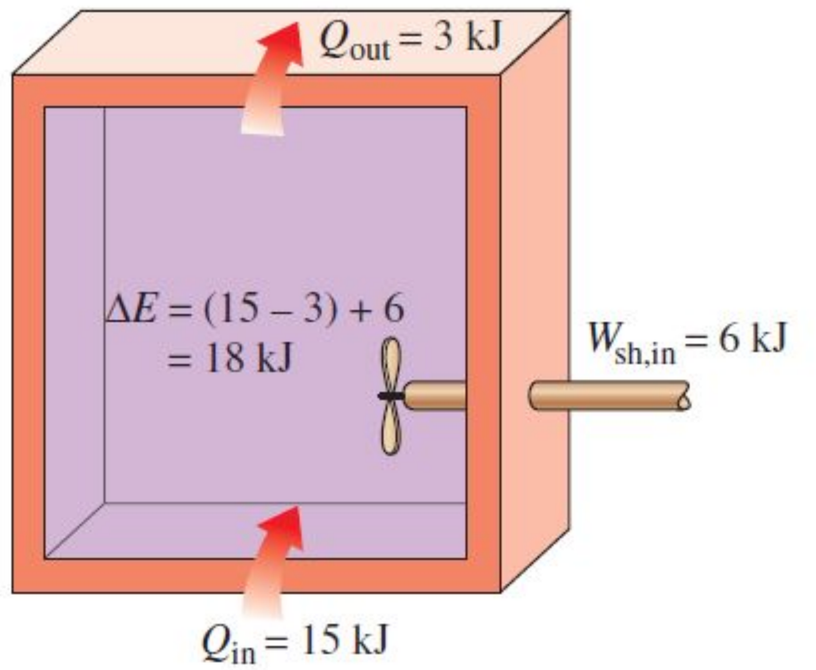

FIGURE 2–45
The energy change of a system during a process is equal to the *net* work and heat transfer between the system and its surroundings.

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

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

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

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

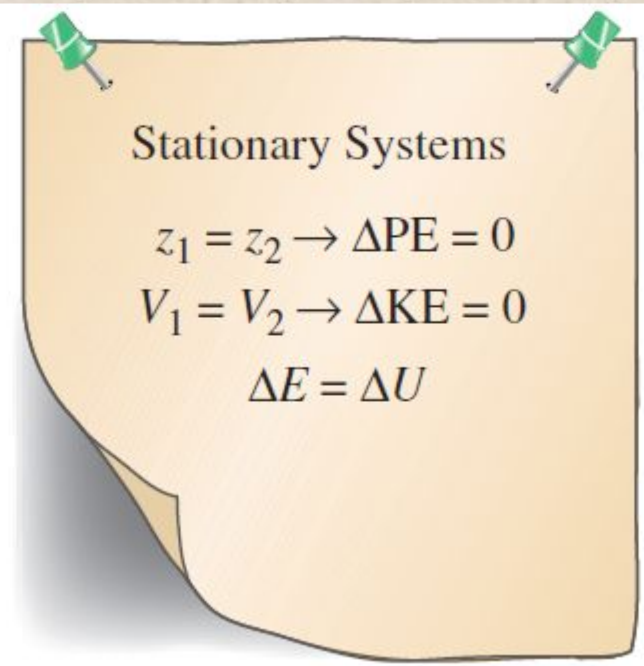

FIGURE 2–46

For stationary systems, $\Delta\text{KE} = \Delta\text{PE} = 0$; thus $\Delta E = \Delta U$.

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

Energy balance for any system undergoing any kind of process can be expressed more compactly as

$$\underbrace{E_{\text{in}} - E_{\text{out}}}_{\substack{\text{Net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{\text{system}}}_{\substack{\text{Change in internal, kinetic,} \\ \text{potential, etc., energies}}} \quad \text{(kJ)} \qquad \textbf{(2–35)}$$

or, in the **rate form**, as

$$\underbrace{\dot{E}_{\text{in}} - \dot{E}_{\text{out}}}_{\substack{\text{Rate of net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{dE_{\text{system}}/dt}_{\substack{\text{Rate of change in internal,} \\ \text{kinetic, potential, etc., energies}}} \quad \text{(kW)} \qquad \textbf{(2–36)}$$

For constant rates, the total quantities during a time interval Δt are related to the quantities per unit time as

$$Q = \dot{Q}\,\Delta t, \quad W = \dot{W}\,\Delta t, \quad \text{and} \quad \Delta E = (dE/dt)\,\Delta t \quad \text{(kJ)} \qquad \textbf{(2–37)}$$

The energy balance can be expressed on a **per unit mass** basis as

$$e_{\text{in}} - e_{\text{out}} = \Delta e_{\text{system}} \quad \text{(kJ/kg)} \qquad \textbf{(2–38)}$$

which is obtained by dividing all the quantities in Eq. 2–35 by the mass m of the system. Energy balance can also be expressed in the differential form as

$$\delta E_{\text{in}} - \delta E_{\text{out}} = dE_{\text{system}} \quad \text{or} \quad \delta e_{\text{in}} - \delta e_{\text{out}} = de_{\text{system}} \qquad \textbf{(2–39)}$$

Mechanisms of energy transfer:

- Heat transfer
- Work transfer
- Mass flow

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

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

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

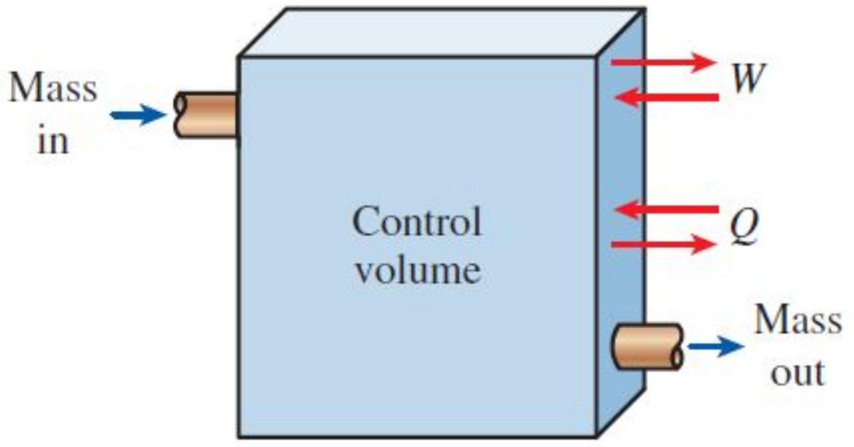

FIGURE 2–47
The energy content of a control volume can be changed by mass flow as well as heat and work interactions.

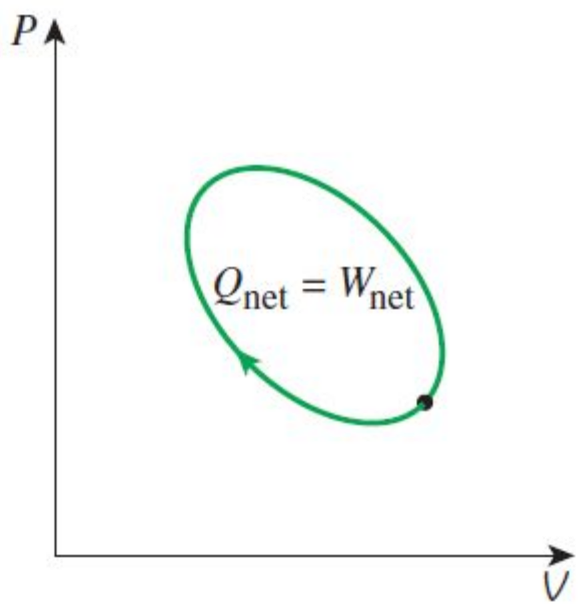

FIGURE 2–48
For a cycle $\Delta E = 0$, thus $Q = W$.

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.

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

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%

FIGURE 2–53

Typical efficiencies of conventional and high-efficiency electric and natural gas water heaters.

Water heater

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

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.

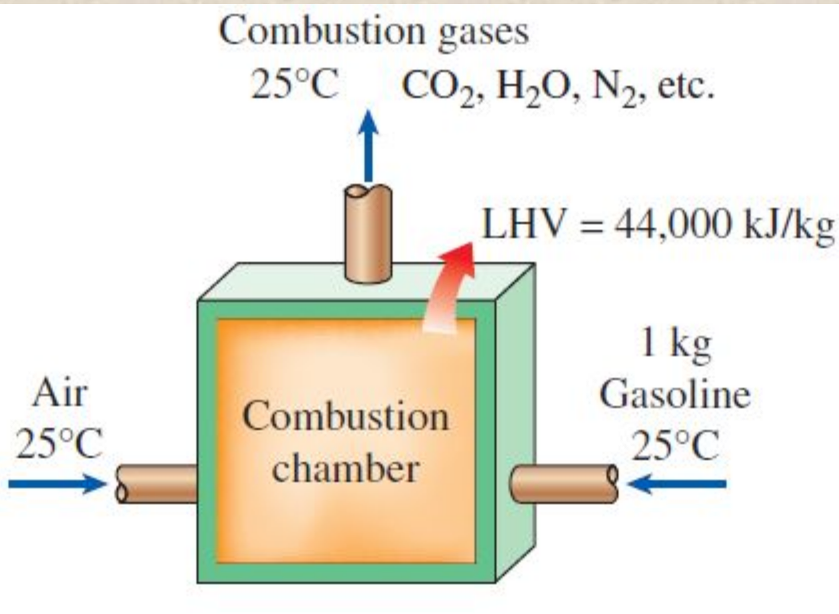

FIGURE 2–54
The definition of the heating value of gasoline.

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.

Overall efficiency of a power plant

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

- **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 shaft work output of the turbine to the rate of fuel energy input.

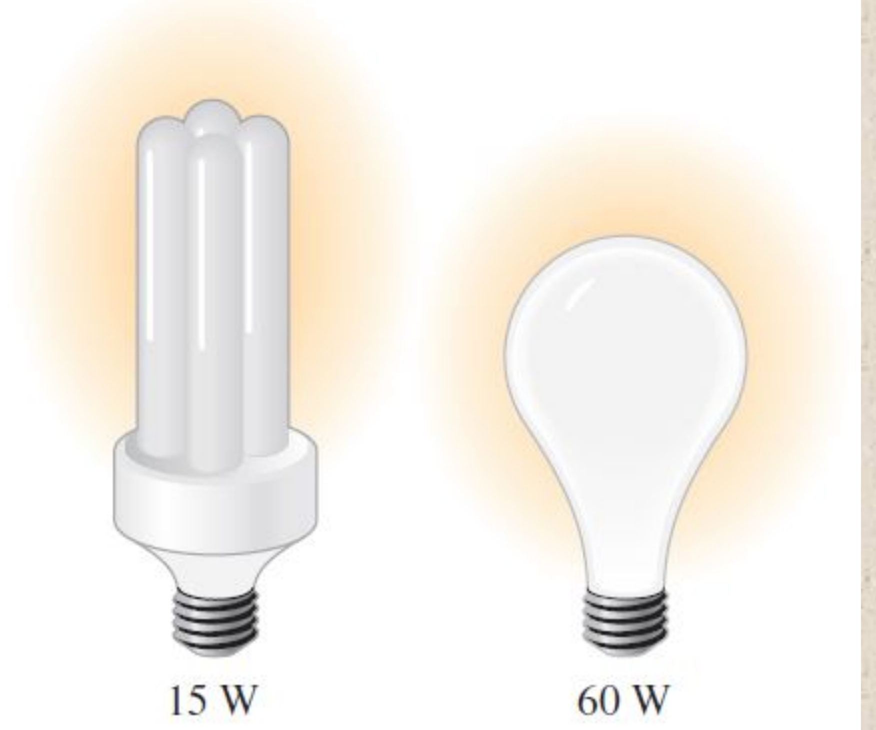

FIGURE 2–55

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

TABLE 2–1

The efficacy of different lighting systems

Type of lighting	Efficacy, lumens/W
Combustion	
Candle	0.3
Kerosene lamp	1–2
Incandescent	
Ordinary	6–20
Halogen	15–35
Fluorescent	
Compact	40–87
Tube	60–120
High-intensity discharge	
Mercury vapor	40–60
Metal halide	65–118
High-pressure sodium	85–140
Low-pressure sodium	70–200
Solid-State	
LED	20–160
OLED	15–60
Theoretical limit	300*

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

*This value depends on the spectral distribution of the assumed ideal light source. For white light sources, the upper limit is about 300 lm/W for metal halide, 350 lm/W for fluorescents, and 400 lm/W for LEDs. Spectral maximum occurs at a wavelength of 555 nm (green) with a light output of 683 lm/W.