

# Thermodynamics: An Engineering Approach

8th Edition

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## Topic 5

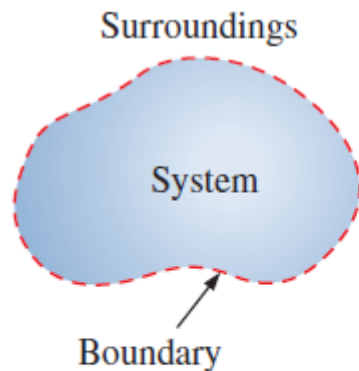
# First Law of Thermodynamics

# Objectives

- Explain the basic concepts of thermodynamics such as system, process, and cycle.
- 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.

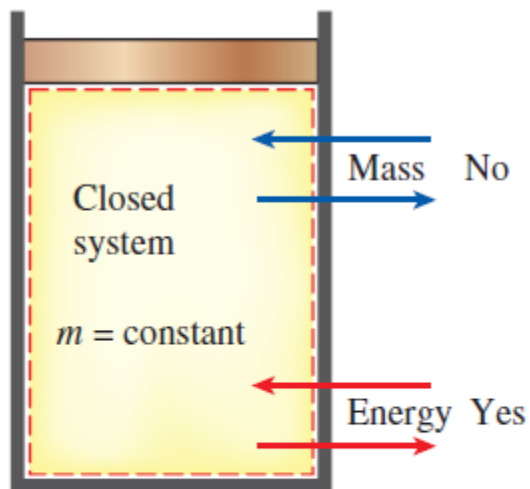
# SYSTEMS AND CONTROL VOLUMES

- **System:** A quantity of matter or a region in space chosen for study.
- **Surroundings:** The mass or region outside the system
- **Boundary:** The real or imaginary surface that separates the system from its surroundings.
- The boundary of a system can be *fixed* or *movable*.
- Systems may be considered to be *closed* or *open*.
- **Closed system (Control mass):** A fixed amount of mass, and no mass can cross its boundary



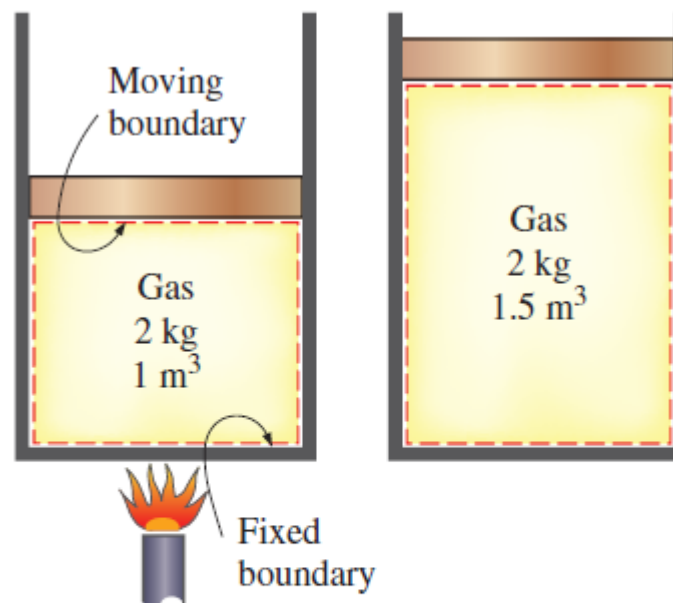
**FIGURE 1-18**

System, surroundings, and boundary.



**FIGURE 1-19**

Mass cannot cross the boundaries of a closed system, but energy can.



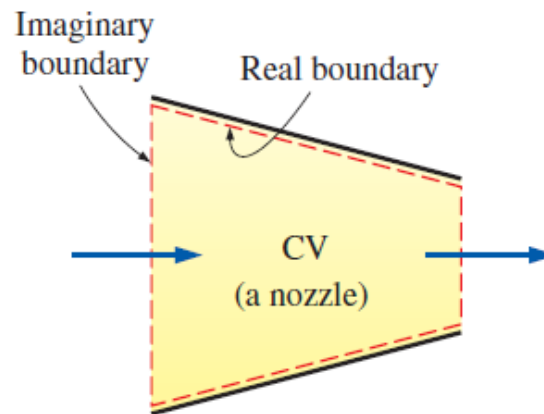
**FIGURE 1-20**

A closed system with a moving boundary.

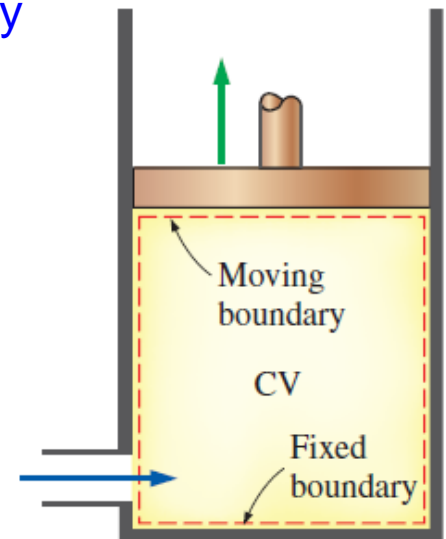


- **Open system (control volume):** A properly selected region in space.
- It usually encloses a device that involves mass flow such as a compressor, turbine, or nozzle.
- Both mass and energy can cross the boundary of a control volume.
- **Control surface:** The boundaries of a control volume. It can be real or imaginary.

A control volume can involve fixed, moving, real, and imaginary boundaries.



(a) A control volume (CV) with real and imaginary boundaries



(b) A control volume (CV) with fixed and moving boundaries as well as real and imaginary boundaries

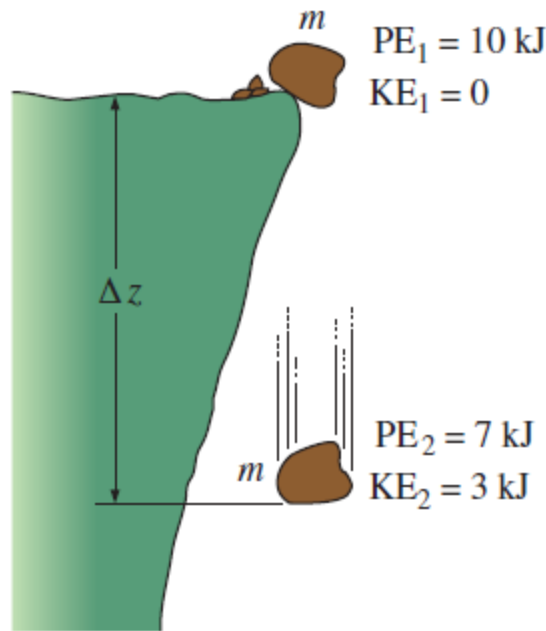
**FIGURE 1–22**

An open system (a control volume) with one inlet and one exit.

# THE FIRST LAW OF THERMODYNAMICS

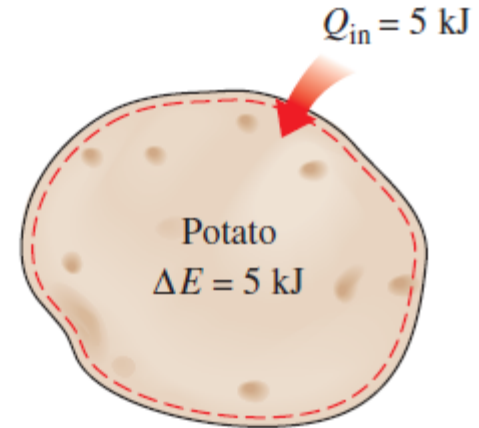
- The *first law of thermodynamics (the conservation of energy principle)* provides a sound basis for studying the relationships among the various forms of energy and energy interactions.
- The first law states that *energy can be neither created nor destroyed during a process; it can only change forms.*

**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.



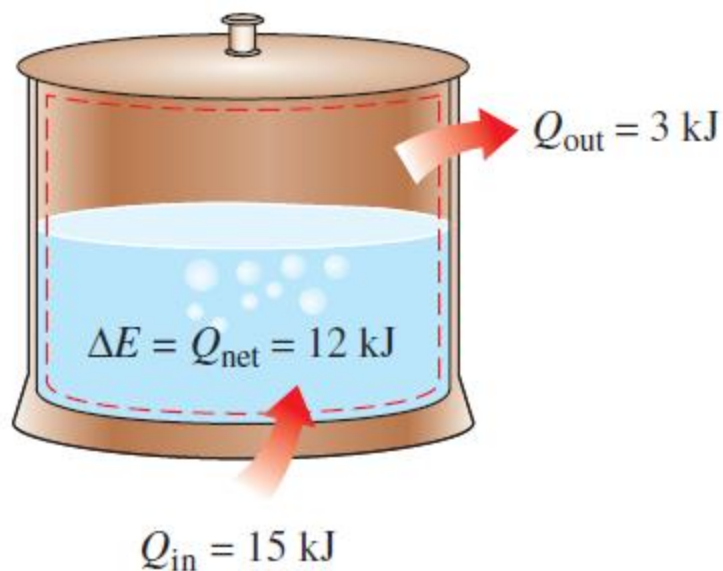
**FIGURE 2–39**

Energy cannot be created or destroyed; it can only change forms.



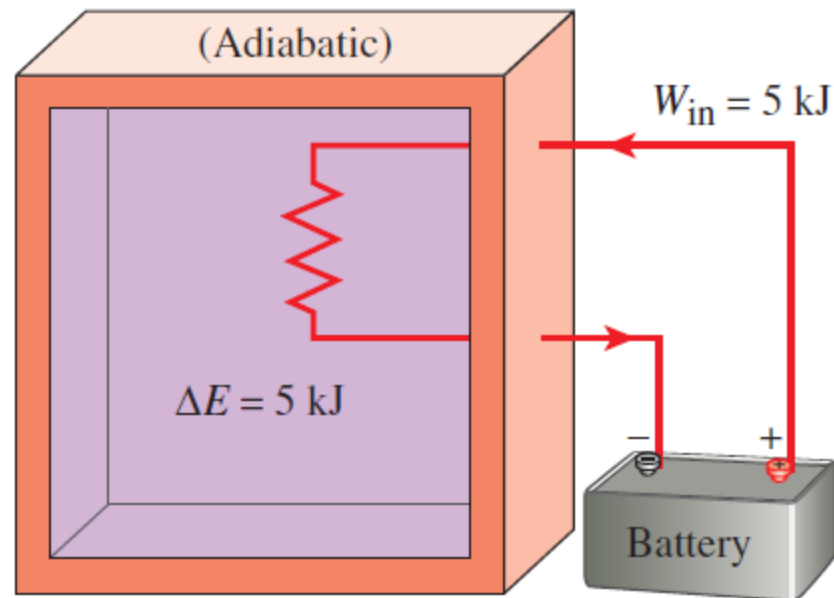
**FIGURE 2–40**

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



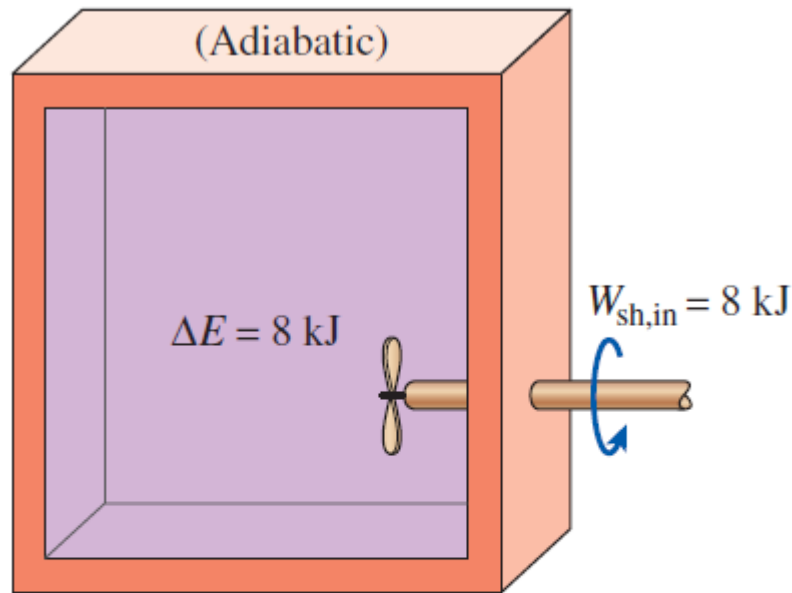
**FIGURE 2–41**

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



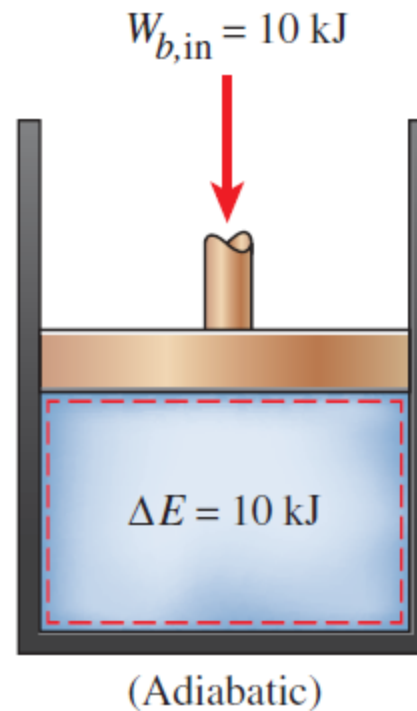
**FIGURE 2–42**

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



**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.

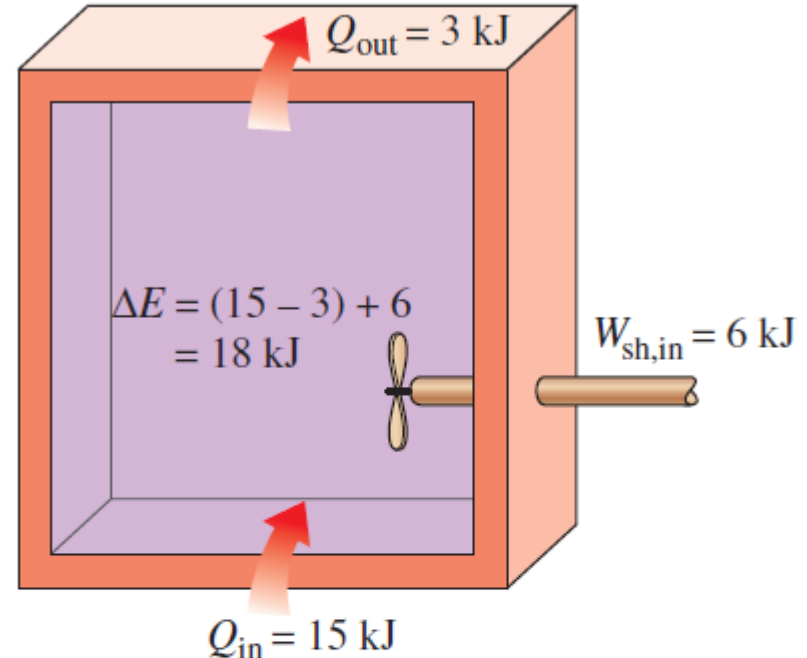


# Energy Balance

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

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

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.



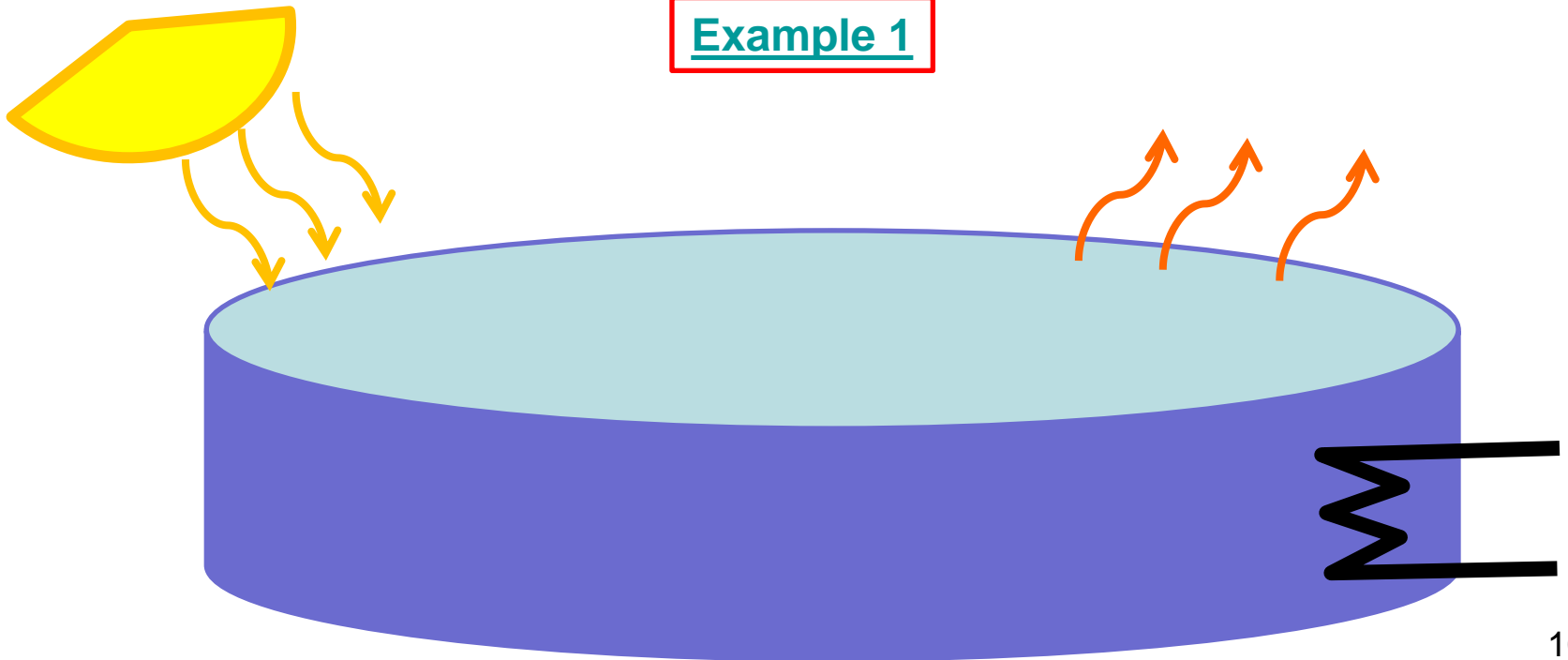
**FIGURE 2–45**

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

# Example

A heater running off 120 V and 5 A with an efficiency of 70% is used to heat a pool. The pool loses heat at a constant rate of 120 W. Over the course of the day, the sun provides 500 kJ of heat over a 6 hour period. Determine the rate of heating (or cooling) in the pool. What is the net energy gain (or lost) by the pool after the 6 hour sunny period?

## Example 1



# Energy Change of a System, $\Delta E_{\text{system}}$

Energy change = Energy at final state – Energy at initial state

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

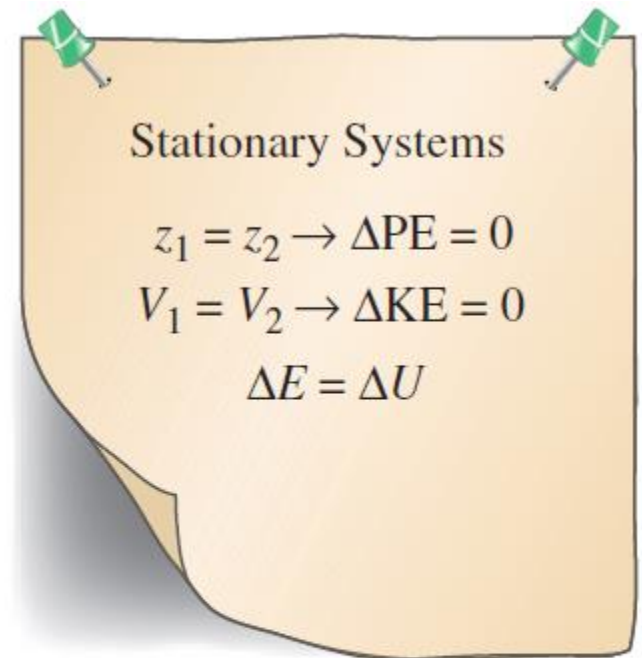
$$\Delta E = \Delta U + \Delta \text{KE} + \Delta \text{PE}$$

Internal, kinetic, and  
potential energy changes

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

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

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



**FIGURE 2–46**

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

# Mechanisms of Energy Transfer, $E_{\text{in}}$ and $E_{\text{out}}$

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

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

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

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

For constant rates, the total quantities during a time interval  $\Delta t$  are related to the quantities per unit time as

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

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

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

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

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

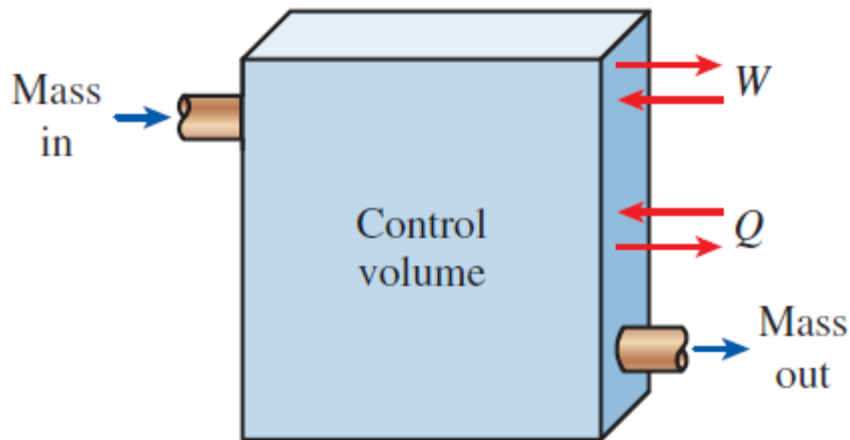
Mechanisms  
of energy  
transfer:

- Heat transfer
- Work transfer
- Mass flow

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

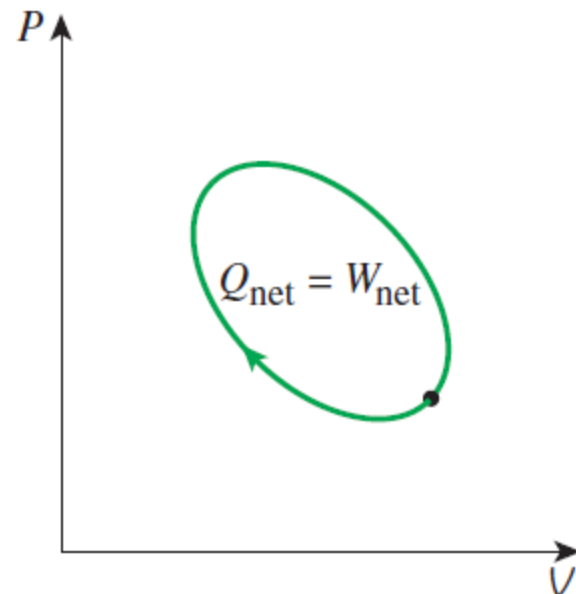
$$E_{\text{in}} - E_{\text{out}} = (Q_{\text{in}} - Q_{\text{out}}) + (W_{\text{in}} - W_{\text{out}}) + (E_{\text{mass,in}} - E_{\text{mass,out}}) = \Delta E_{\text{system}}$$

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



**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  $Q = W$ .

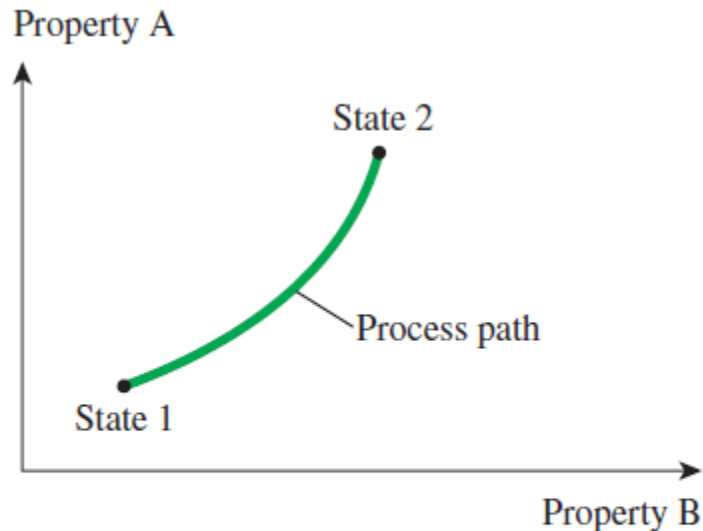
# PROCESSES AND CYCLES

**Process:** Any change that a system undergoes from one equilibrium state to another.

**Path:** The series of states through which a system passes during a process.

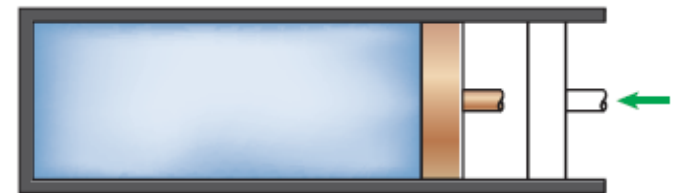
To describe a process completely, one should specify the initial and final states, as well as the path it follows, and the interactions with the surroundings.

**Quasistatic or quasi-equilibrium process:** When a process proceeds in such a manner that the system remains infinitesimally close to an equilibrium state at all times.

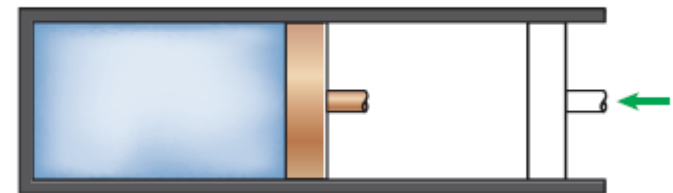


**FIGURE 1–29**

A process between states 1 and 2 and the process path.



(a) Slow compression  
(quasi-equilibrium)

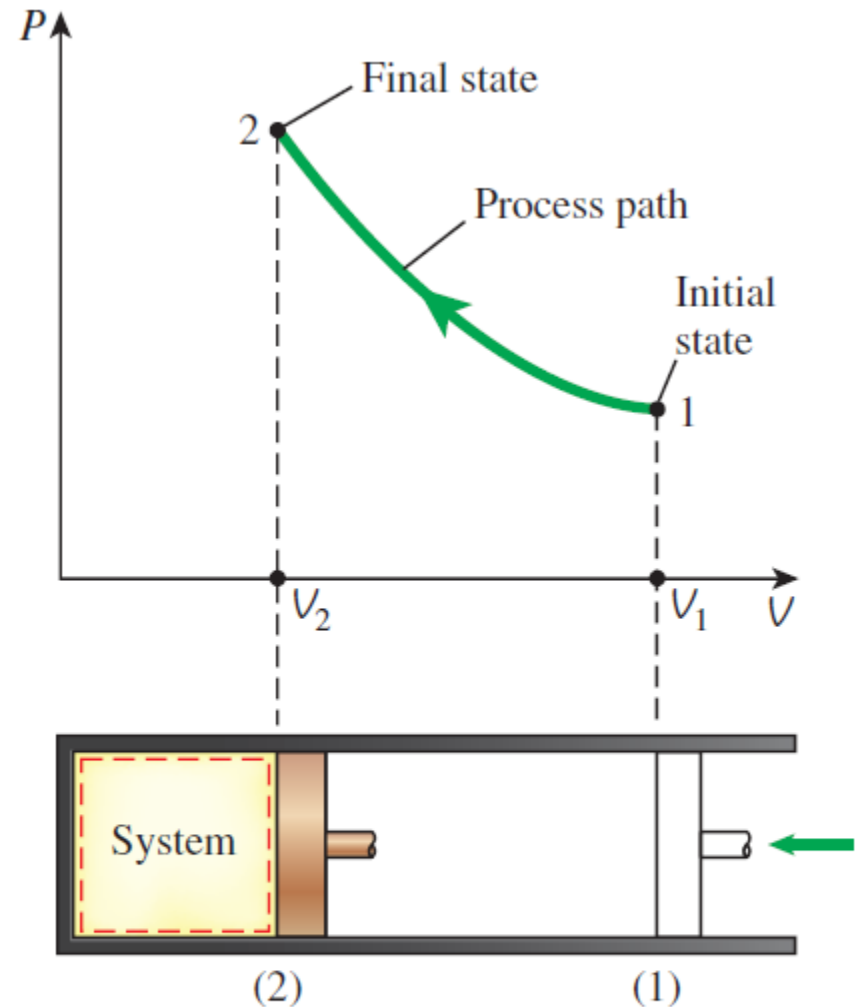


(b) Very fast compression  
(nonquasi-equilibrium)

**FIGURE 1–30**

Quasi-equilibrium and nonquasi-equilibrium compression processes.

- Process diagrams plotted by employing thermodynamic properties as coordinates are very useful in visualizing the processes.
- Some common properties that are used as coordinates are temperature  $T$ , pressure  $P$ , and volume  $V$  (or specific volume  $v$ ).
- The prefix *iso-* is often used to designate a process for which a particular property remains constant.
- **Isothermal process:** A process during which the temperature  $T$  remains constant.
- **Isobaric process:** A process during which the pressure  $P$  remains constant.
- **Isochoric (or isometric) process:** A process during which the specific volume  $v$  remains constant.
- **Cycle:** A process during which the initial and final states are identical.

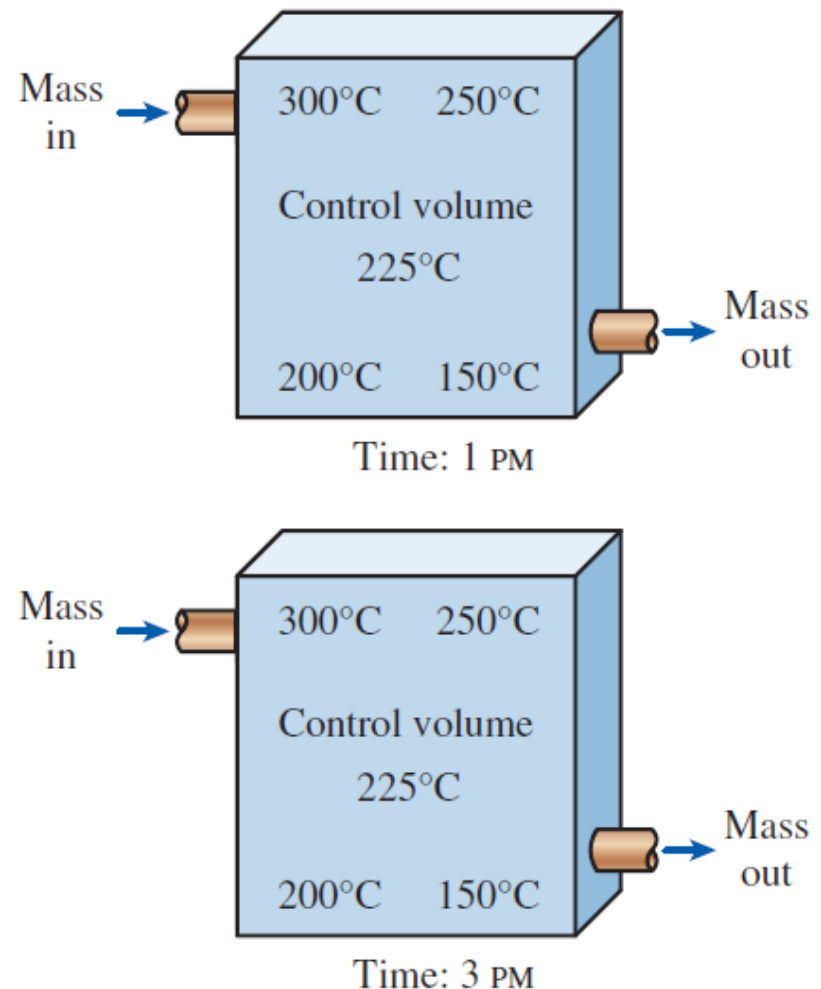


**FIGURE 1–31**

The  $P$ - $V$  diagram of a compression process.

# The Steady-Flow Process

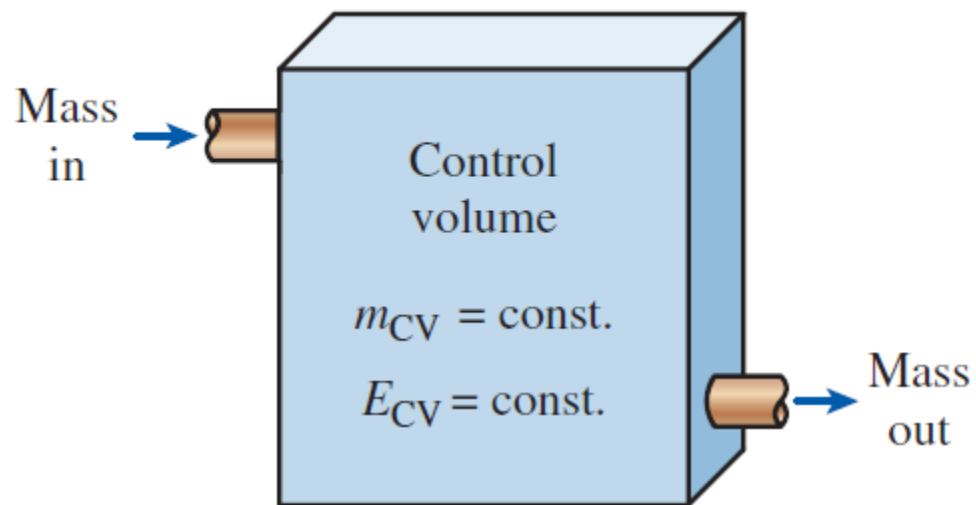
- The term *steady* implies *no change with time*. The opposite of steady is *unsteady*, or *transient*.
- A large number of engineering devices operate for long periods of time under the same conditions, and they are classified as *steady-flow devices*.
- **Steady-flow process:** A process during which a fluid flows through a control volume steadily.
- Steady-flow conditions can be closely approximated by devices that are intended for continuous operation such as *turbines, pumps, boilers, condensers, and heat exchangers or power plants or refrigeration systems*.



**FIGURE 1–32**

During a steady-flow process, fluid properties within the control volume may change with position but not with time.



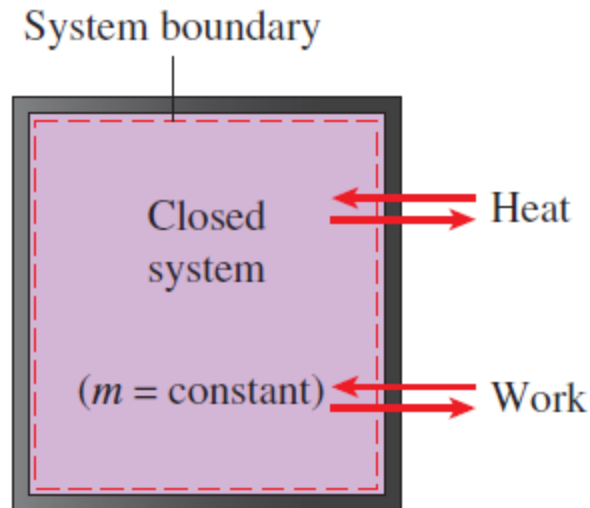


**FIGURE 1–33**

Under steady-flow conditions, the mass and energy contents of a control volume remain constant.

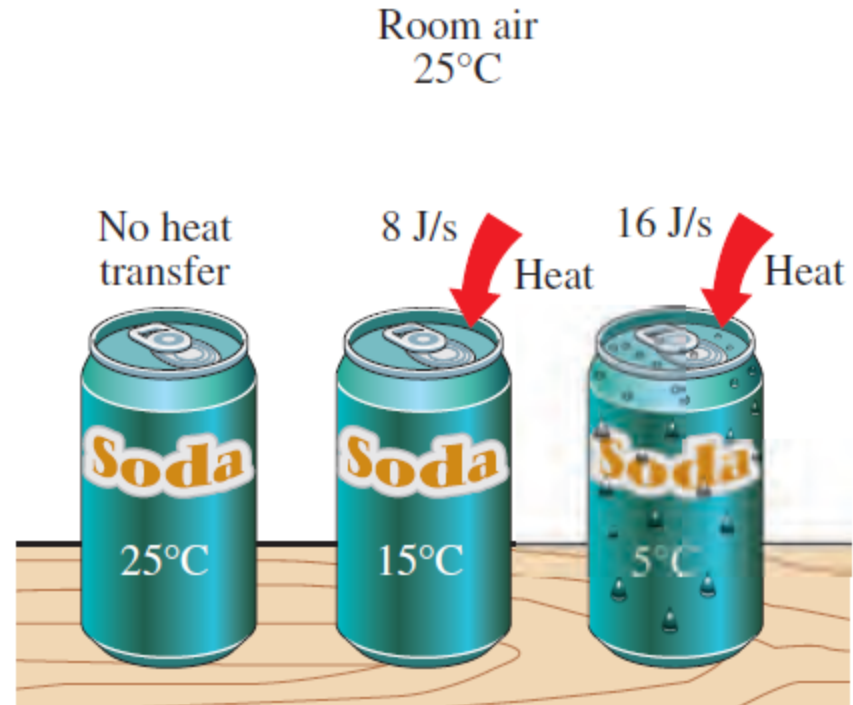
# ENERGY TRANSFER BY HEAT

**Heat:** The form of energy that is transferred between two systems (or a system and its surroundings) by virtue of a temperature difference.



**FIGURE 2–14**

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



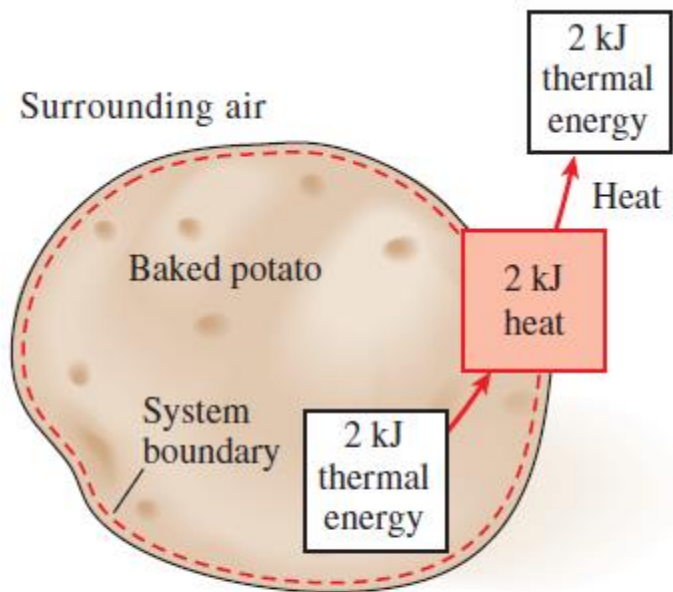
**FIGURE 2–15**

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

$$q = \frac{Q}{m} \quad (\text{kJ/kg}) \quad \text{Heat transfer per unit mass}$$

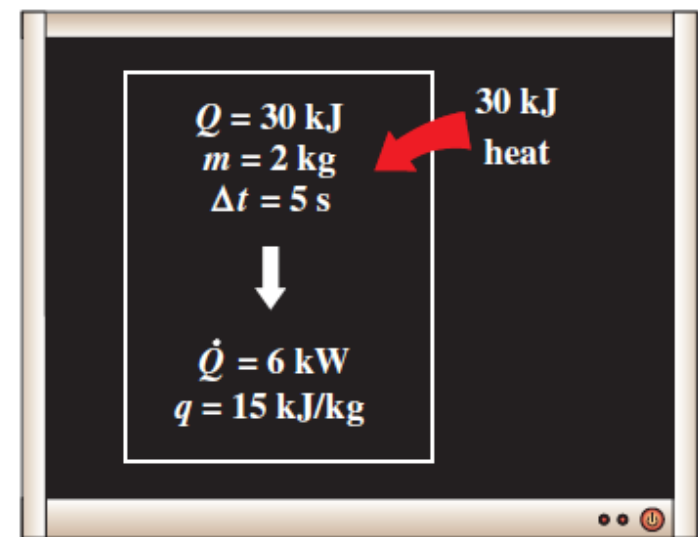
$$Q = \dot{Q} \Delta t \quad (\text{kJ}) \quad \text{Amount of heat transfer when heat transfer rate is constant}$$

$$Q = \int_{t_1}^{t_2} \dot{Q} dt \quad (\text{kJ}) \quad \text{Amount of heat transfer when heat transfer rate changes with time}$$



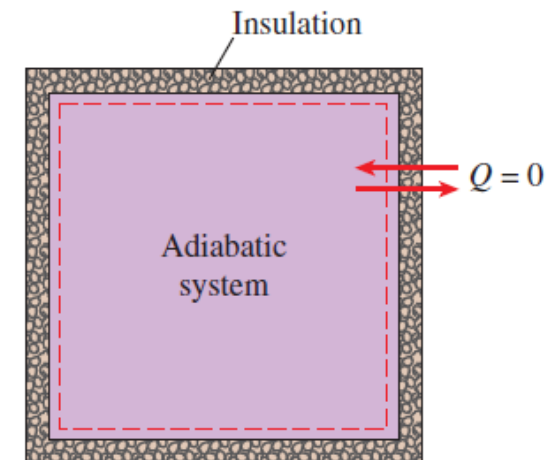
**FIGURE 2–16**

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



**FIGURE 2–18**

The relationships among  $q$ ,  $Q$ , and  $\dot{Q}$ .



**FIGURE 2–17**

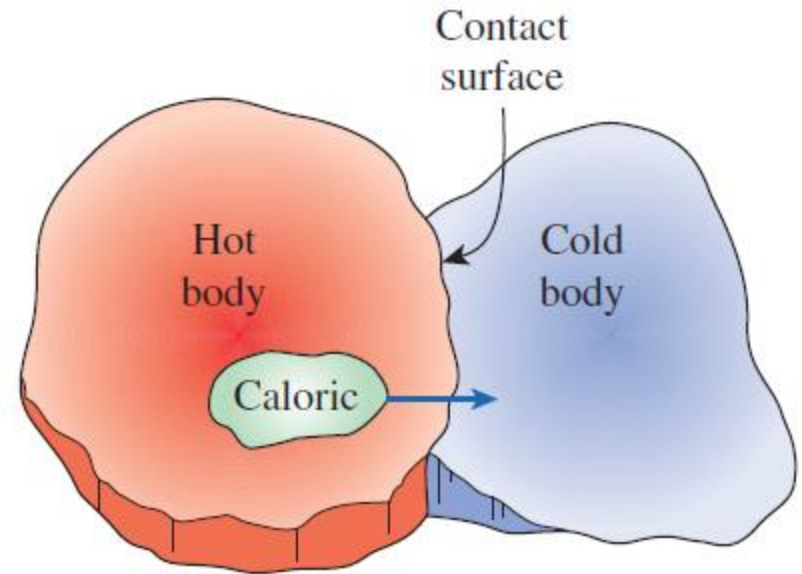
During an adiabatic process, a system exchanges no heat with its surroundings.

# 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).



**FIGURE 2–19**

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.

# Mechanisms of Heat Transfer

- There are 3 modes of heat transfer:
  - Conduction
  - Convection
  - Radiation
- All modes require temperature difference between source and sink
- Heat transfers from high temperature to low temperature

# Conduction

- Transfer of more energetic particles to less energetic particles
- Occurs in solids, liquids, and gasses
  - Liquids and gasses: collision of molecules during random motion (Brownian motion)
  - Solids: combination of crystal lattice vibrations and energy transport by free electrons

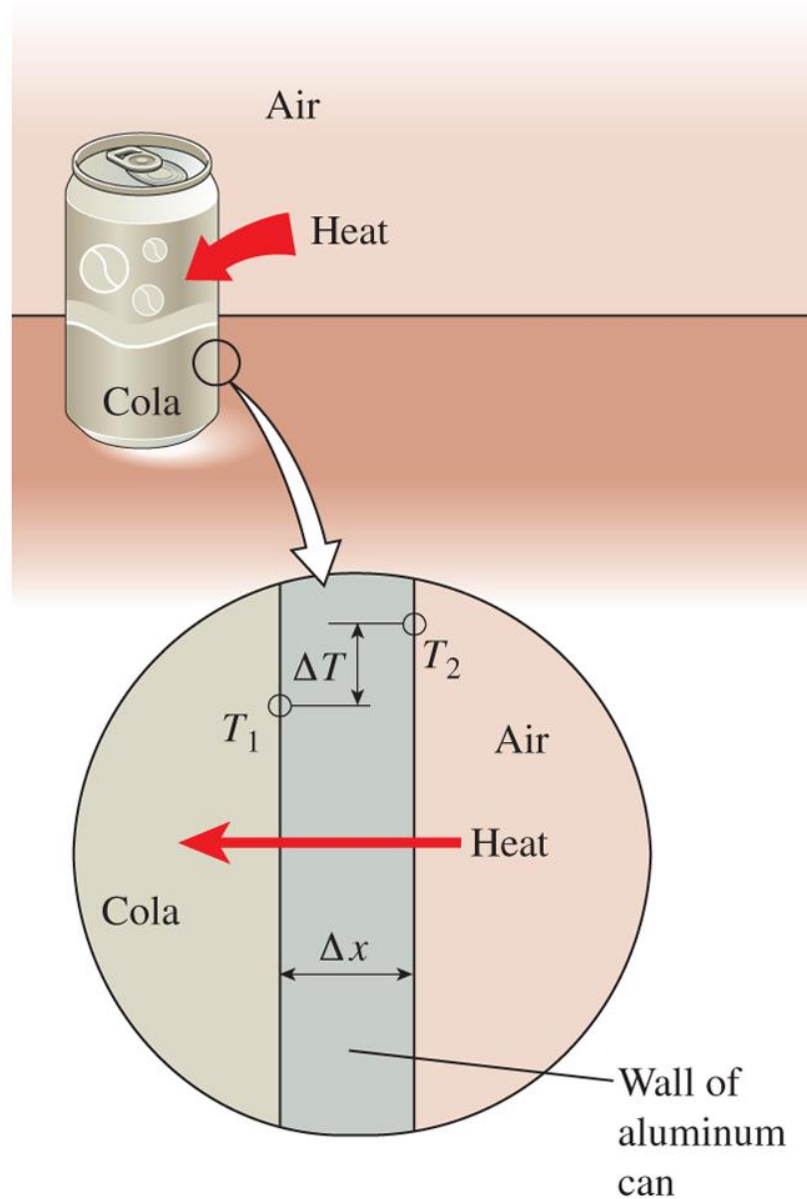
# Conduction

$$\dot{Q}_{cond} = -k_t A \frac{\Delta T}{\Delta x}$$

- Heat of conduction is proportional to temperature difference ( $\Delta T$ ) and area normal to heat transfer
- Thermal conductivity,  $k_t$ : proportionality constant measures material's ability to conduct heat
- Conductors (e.g. most metals) have high  $k_t$
- Insulators (e.g. wood, styrofoam) have low  $k_t$
- Fourier's law of heat conduction  $\dot{Q}_{cond} = -k_t A \frac{dT}{dx}$ 
  - Negative sign is used due to negative temperature gradient

# Conduction

$$\dot{Q}_{cond} = -k_t A \frac{\Delta T}{\Delta x}$$





# Example

The temperature distribution across a wall 1 m thick at a certain instant of time is given as

$$T(x) = a + bx + cx^2$$

where  $T$  is in degrees Celsius and  $x$  is in meters, while  $a$ ,  $b$ , and  $c$  are listed below. The wall has an area of  $10 \text{ m}^2$  and a thermal conductivity of  $40 \frac{\text{W}}{\text{mK}}$ .

Determine the rate of heat transfer entering the wall and leaving the wall. Is the wall gaining or losing energy?

Example 2

# Convection

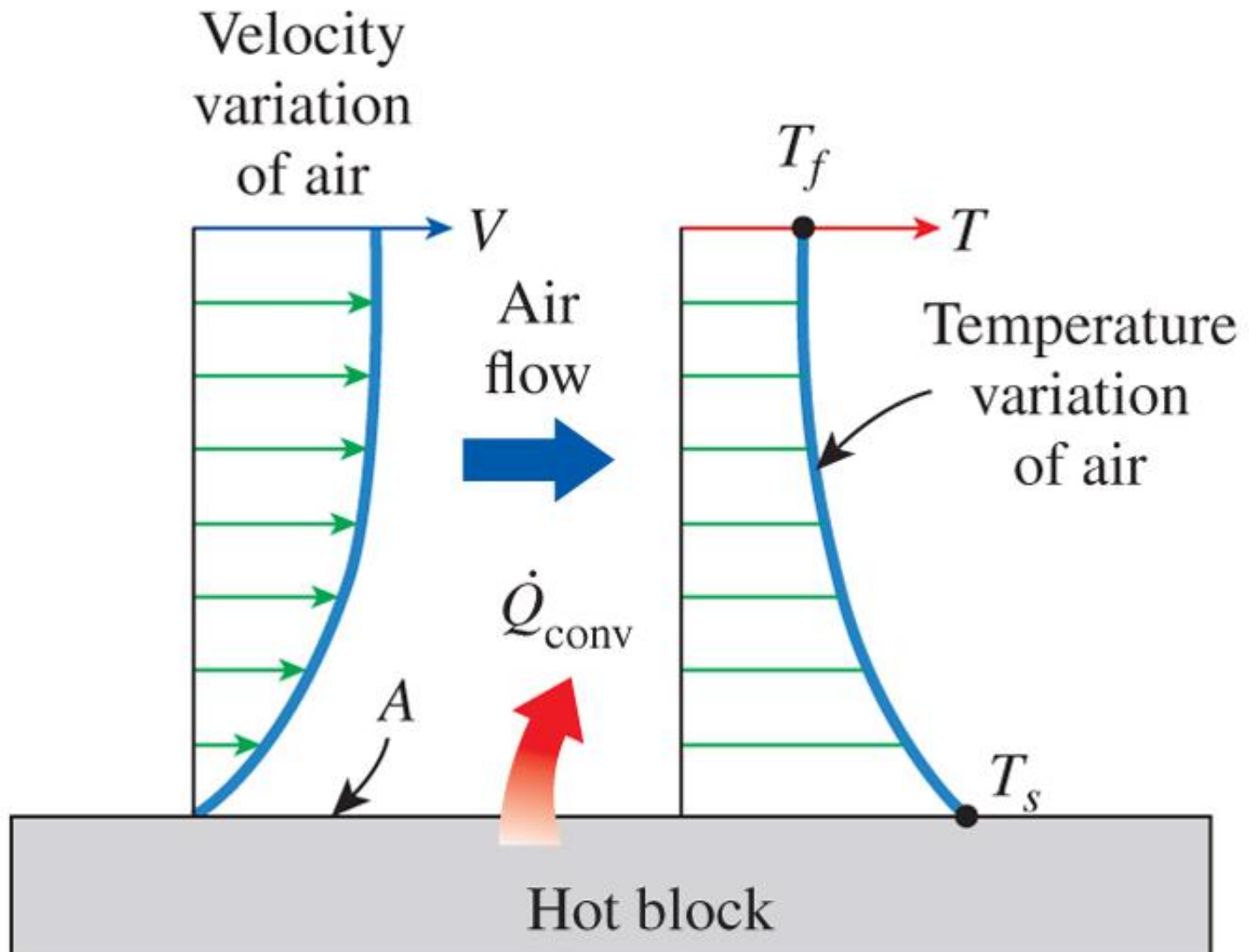
- Transfer of energy to/from a solid surface from/to an adjacent moving fluid (liquid or gas)
- Combination of conduction and fluid motion
- Faster fluid motion results in more heat transfer
- If fluid is motionless then pure conduction occurs
- Forced convection: fluid is *forced* over surface by external means (fan, pump, wind, etc.)
- Free (or natural) convection: fluid motion is caused by buoyancy force due to changes in density (e.g. warmer air rises because it is less dense)

# Convection

- Heat transfer in processes that involve phase changes in fluids are consider to be convection
  - Movement of vapor bubbles through a liquid (evaporation)
  - Falling of liquid droplets (condensation)
- Newton's Law of Cooling  $\dot{Q}_{conv} = hA(T_s - T_f)$
- Convective heat transfer coefficient,  $h$ 
  - not a property of the fluid
  - Determined experimentally; affected by surface geometry, fluid properties, fluid velocity
- $T_s$  – surface temperature;  $T_f$  – bulk fluid temperature
  - Note: the temperature of fluid at the surface is  $T_s$  not  $T_f$  (continuum)

# Convection

$$\dot{Q}_{conv} = hA(T_s - T_f)$$



# Radiation

- Energy is emitted by matter in the form of electromagnetic waves (or photons)
- Results from the change of electronic configurations of atoms or molecules
- Does not require presence of medium between source and sink; can work in a vacuum
- All bodies at a temperature above absolute zero emit thermal radiation

# Radiation

$$\sigma = 5.67 \times 10^{-8} \frac{W}{m^2 K^4}$$

- Maximum radiation from a surface: Stefan-Boltzman's Law  $\dot{Q}_{emit,max} = \sigma A T_s^4$
- Surface that emits maximum radiation is called a blackbody
- *Real* surfaces emit less than the maximum

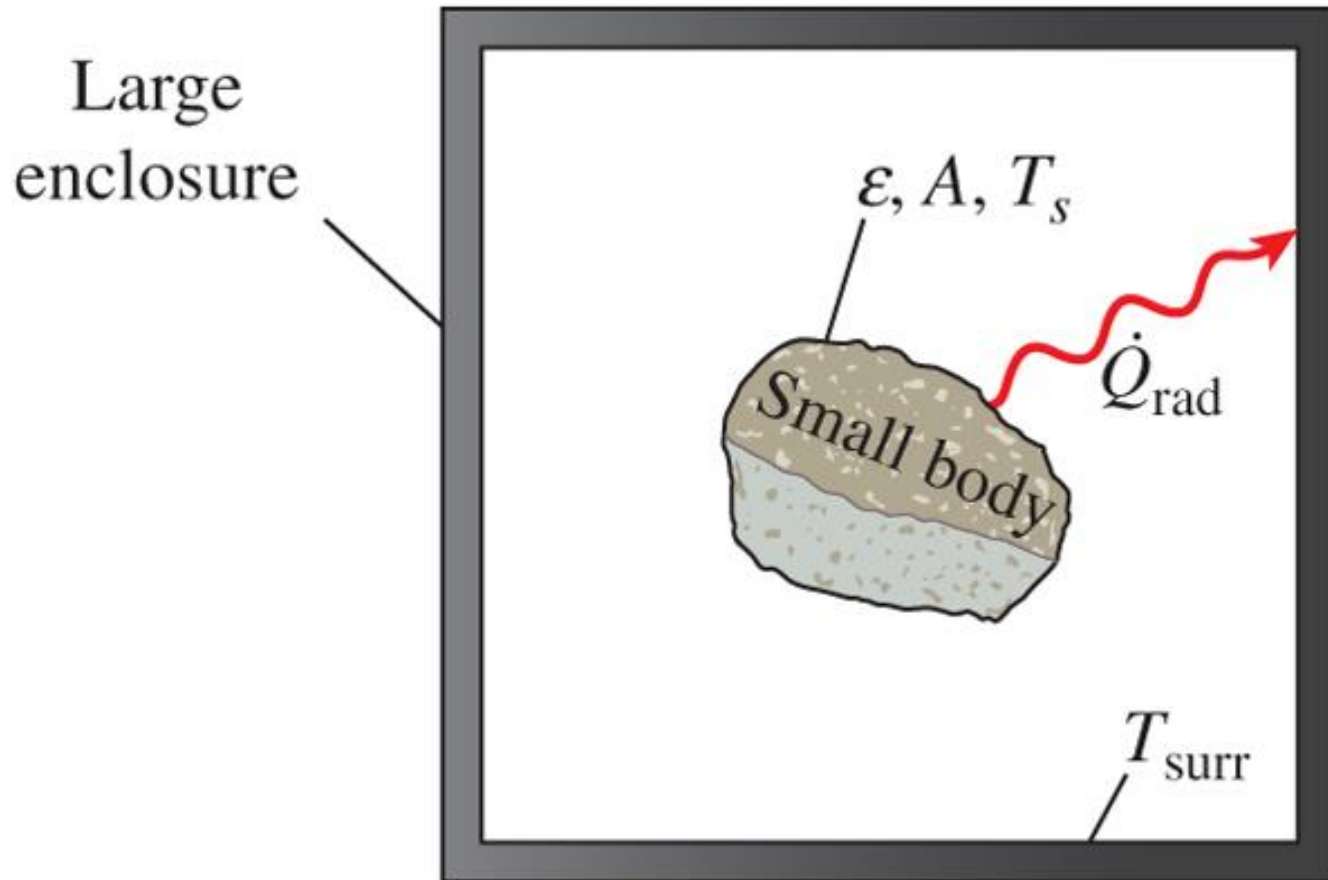
$$\dot{Q}_{emit,max} = \varepsilon \sigma A T_s^4$$

- Emissivity,  $\varepsilon$ : material property between 0 and 1 (for blackbodies  $\varepsilon = 1$ )
- For a large surface surrounding a radiation source:

$$\dot{Q}_{rad} = \varepsilon \sigma A (T_s^4 - T_{surr}^4)$$

# Radiation

$$\dot{Q}_{rad} = \epsilon \sigma A (T_s^4 - T_{surr}^4)$$



# Example

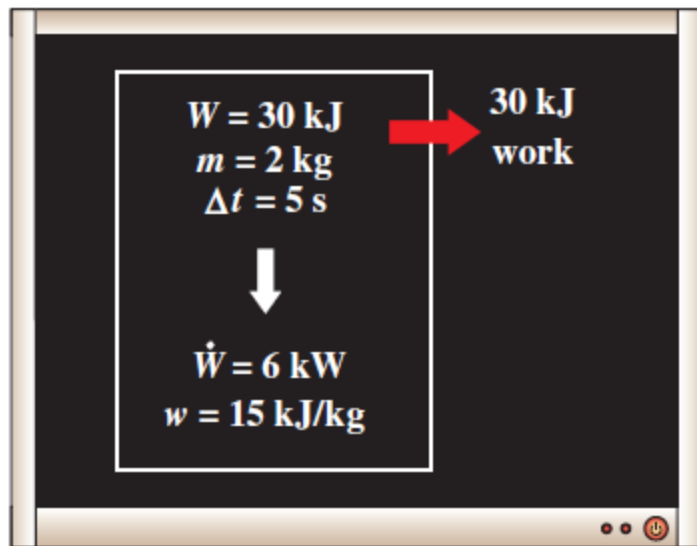
Humans can control their heat production rate and heat loss rate to maintain a nearly constant core temperature under a wide range of environmental conditions. The process is called thermoregulation. From the perspective of calculating heat transfer between a human body and its surroundings, we focus on a layer of skin and fat, with its outer surface exposed to the environment and its inner surface at a temperature slightly less than the core temperature of  $308\text{ K}$ . Consider a person with a skin/fat layer of thickness of  $3\text{ mm}$  and effective thermal conductivity of  $0.3 \frac{\text{W}}{\text{m K}}$ . The person has surface area of  $1.8\text{ m}^2$  and is dressed in a bathing suit. The emissivity of the skin is  $0.95$ . When the person is in still air at  $297\text{ K}$ , what is the skin surface temperature and rate of heat loss to the environment? Assume the convection coefficient of the air is  $2 \frac{\text{W}}{\text{m}^2\text{K}}$ . How are the surface temperature and rate of heat loss affected when the person is in water with a convection coefficient of  $200 \frac{\text{W}}{\text{m}^2\text{K}}$ ?

## Example 3



# 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.**

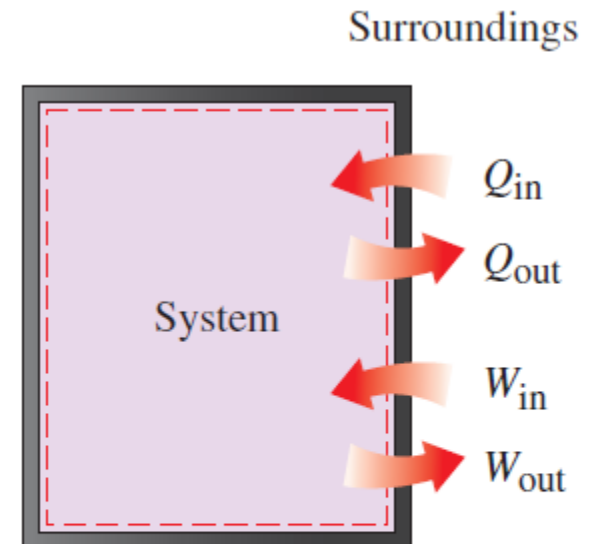


**FIGURE 2–20**

The relationships among  $w$ ,  $W$ , and  $\dot{W}$ .

Work done  
per unit mass

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



**FIGURE 2–21**

Specifying the directions  
of heat and work.

# Heat vs. Work

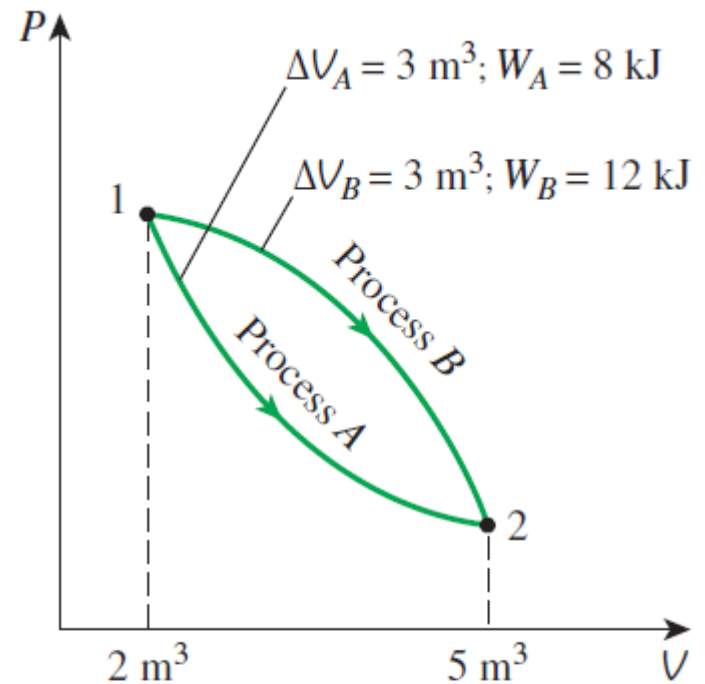
- Both are recognized at the boundaries of a system as they cross the boundaries. That is, both heat and work are *boundary* phenomena.
- Systems possess energy, but not heat or work.
- Both are associated with a *process*, not a state.
- Unlike properties, heat or work has no meaning at a state.
- Both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

Properties are point functions  
have exact differentials ( $d$ ).

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

Path functions  
have inexact  
differentials ( $\delta$ )

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



**FIGURE 2-22**

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

# Electrical Work

Electrical work

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

Electrical power

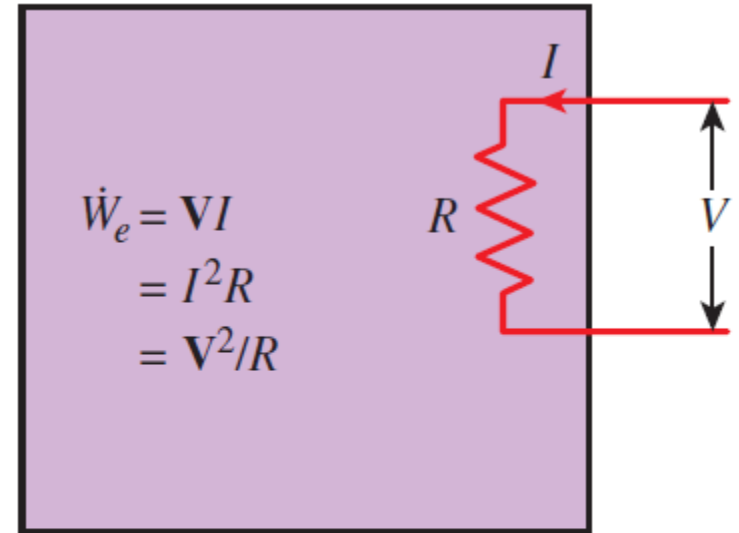
$$\dot{W}_e = \mathbf{V}I \quad (\text{W})$$

When potential difference  
and current change with time

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

When potential difference  
and current remain constant

$$W_e = \mathbf{V}I \, \Delta t \quad (\text{kJ})$$



**FIGURE 2–27**

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

# MECHANICAL FORMS OF WORK

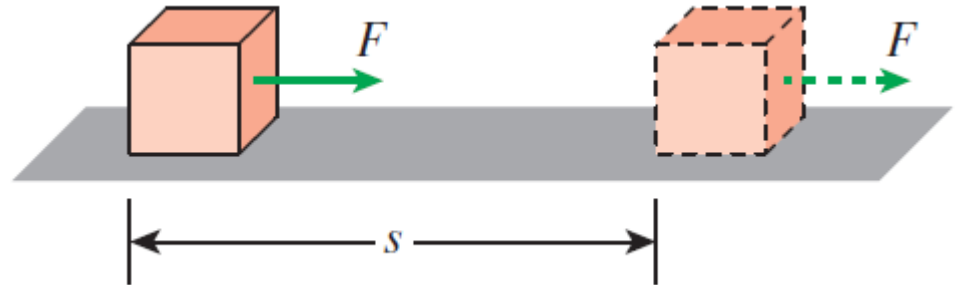
- There are two requirements for a work interaction between a system and its surroundings to exist:
  - there must be a **force** acting on the boundary.
  - the boundary must **move**.

Work = Force × Distance

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

When force is not constant

$$W = \int_1^2 F \, ds \quad (\text{kJ})$$



**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  $T$

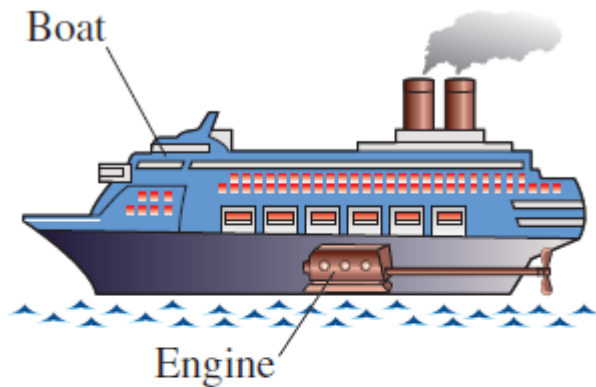
$$T = Fr \rightarrow F = \frac{T}{r}$$

This force acts through a distance  $s$   $s = (2\pi r)n$

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

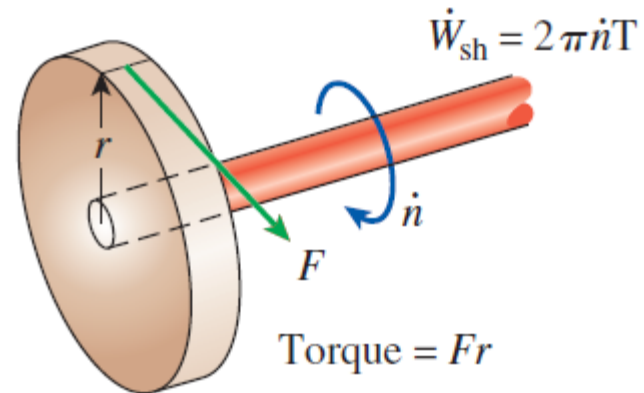
The power transmitted through the shaft is the shaft work done per unit time

$$\dot{W}_{sh} = 2\pi nT \quad (\text{kW})$$



**FIGURE 2–29**

Energy transmission through rotating shafts is commonly encountered in practice.



**FIGURE 2–30**

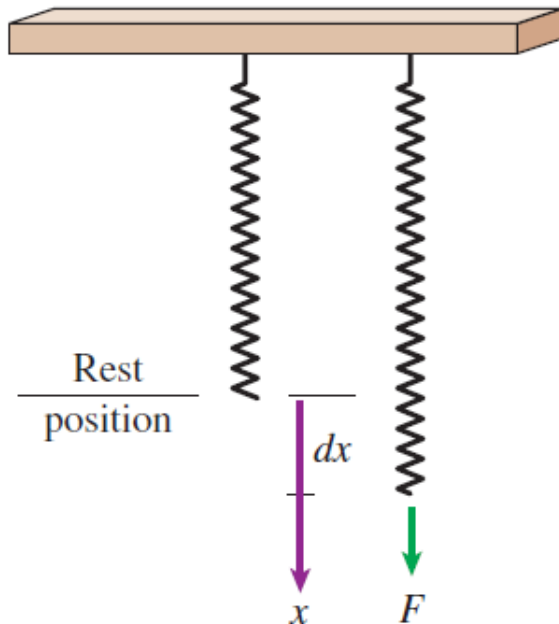
Shaft work is proportional to the torque applied and the number of revolutions of the shaft.

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

$$F = kx \quad (\text{kN}) \quad k: \text{spring constant (kN/m)}$$



**FIGURE 2–32**

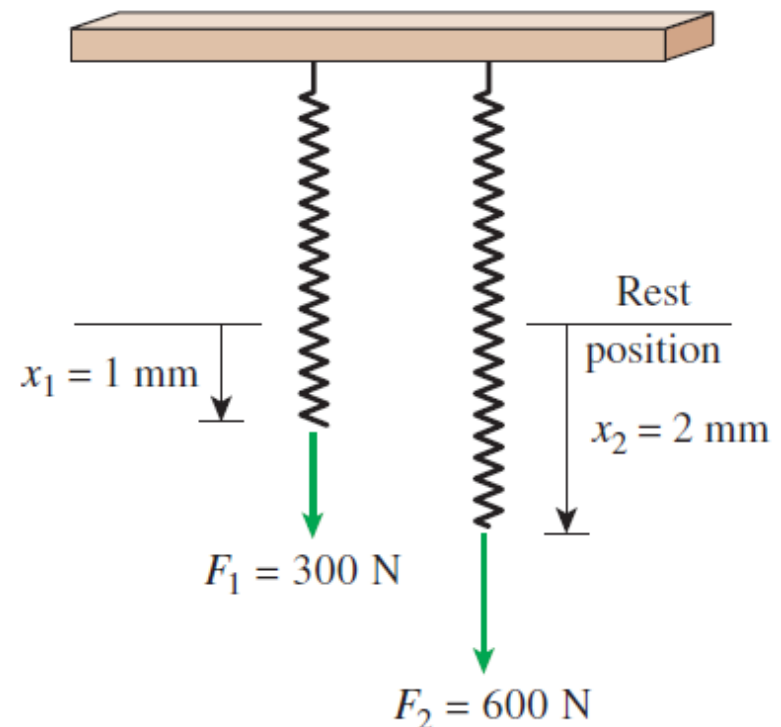
Elongation of a spring under the influence of a force.

# Spring Work

Substituting and integrating yield

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

$x_1$  and  $x_2$ : the initial and the final displacements



**FIGURE 2–33**

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

# Example

Determine the energy necessary to stretch a spring (with a spring constant of 200 lbf/in) 4 inches. Express your answer in Btu.

**Useful Information:**     1 Btu = 778.169 lbf · ft

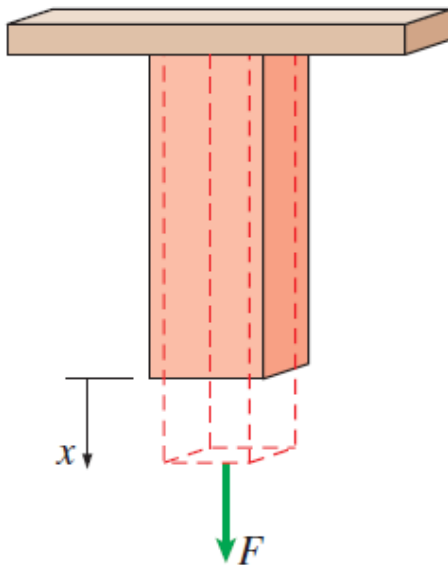
Example 4

## Work Associated with the Stretching of a Liquid Film

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

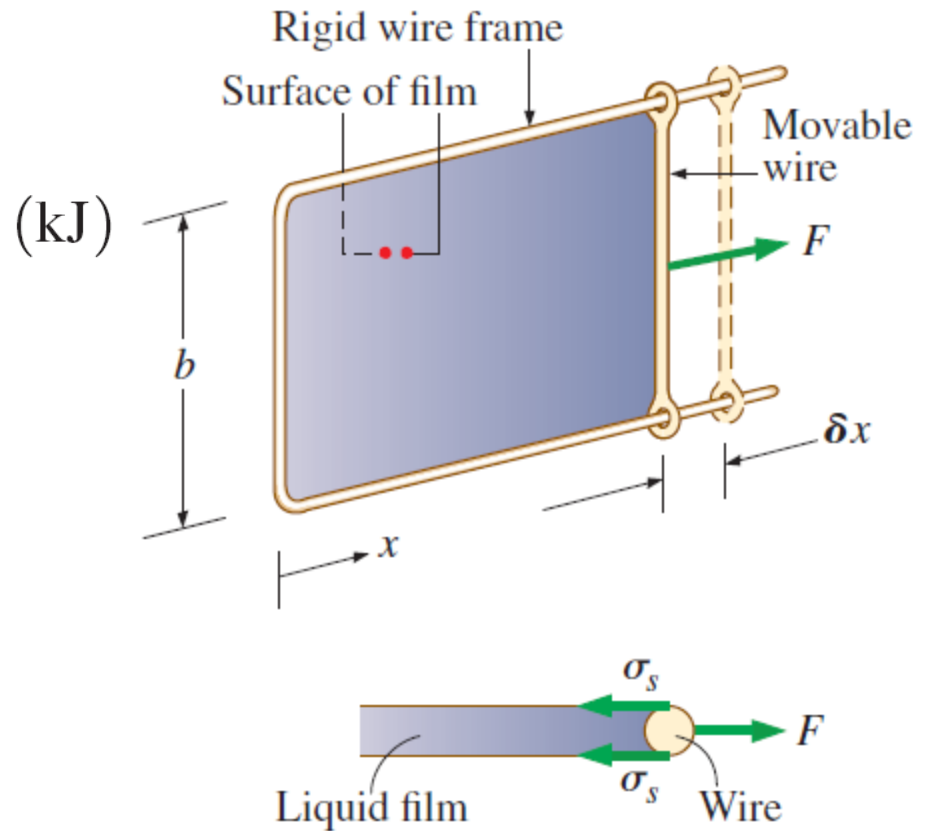
### Work Done on Elastic Solid Bars

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



**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

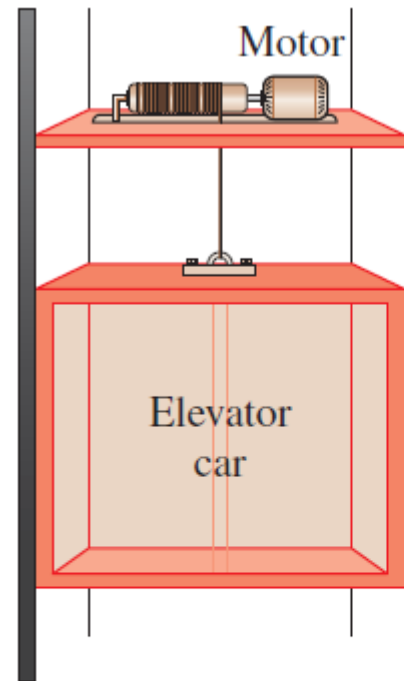
1. The work transfer needed to raise a body is equal to the change in the potential energy of the body.
2. The work transfer needed to accelerate a body is equal to the change in the kinetic energy of the body.

## 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*.

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



**FIGURE 2–36**

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

# Summary

- Systems and control volumes
- Processes and cycles
  - The steady-flow process
- Energy transfer by heat
- Energy transfer by work
- Mechanical forms of work
- The first law of thermodynamics
  - Energy balance
  - Energy change of a system
  - Mechanisms of energy transfer (heat, work, mass flow)