Thermodynamics: An Engineering Approach
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CHAPTER 2
ENERGY, ENERGY TRANSFER, AND GENERAL ENERGY ANALYSIS

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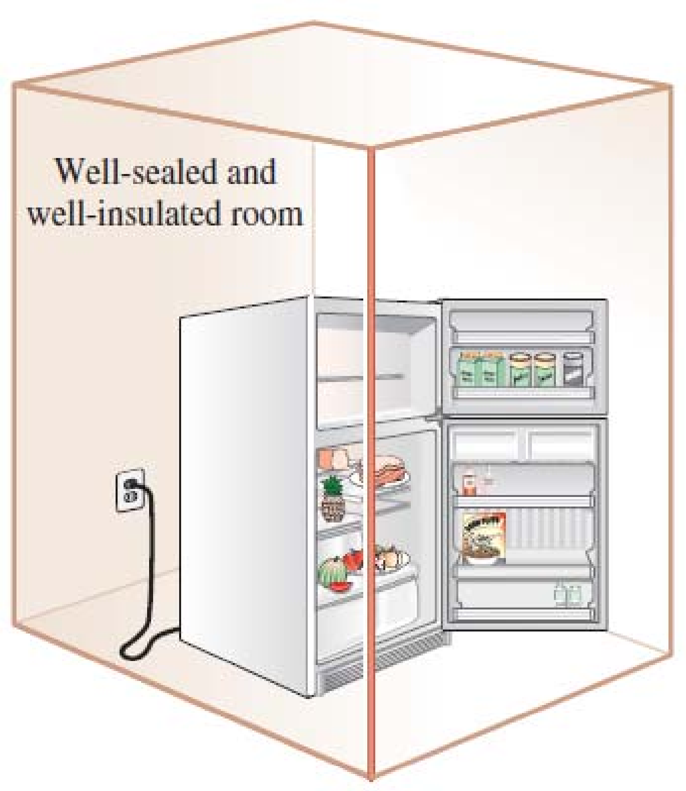
Adapted from the lecture slides by **Mehmet Kanoglu**

Objectives

- Introduce the concept of *energy* and define its various forms
- Discuss the nature of *internal energy*
- Define the concept of *heat* and the terminology associated with energy transfer by heat
- 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
- Define energy conversion efficiencies

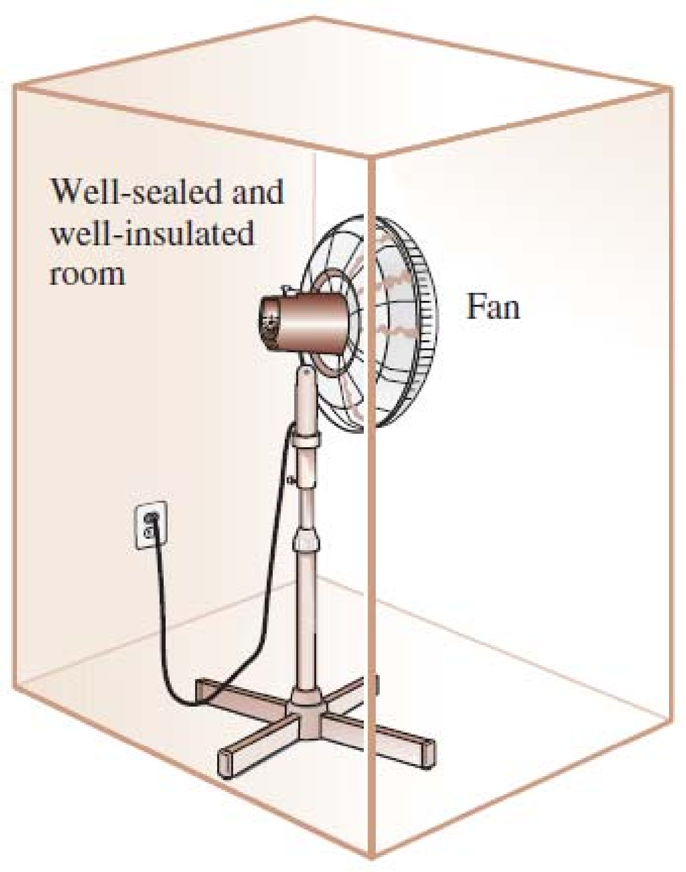
INTRODUCTION

- If we take the entire room—including the air and the refrigerator (or fan)—as the system, which is an *adiabatic closed system* since the room is well-sealed and well-insulated, the only energy interaction involved is the electrical energy crossing the system boundary and entering the room
- Due to conversion of electric energy consumed by the device to heat, the room temperature will rise



A fan running in a well-sealed and well-insulated room will raise the temperature of air in the room

A refrigerator operating with its door open in a well-sealed and well-insulated room



FORMS OF ENERGY - MACROSCOPIC

- 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
- **Macroscopic forms of energy**: Those a system possesses as a whole such as kinetic and potential energies
- **Kinetic energy, KE**: The energy that a system possesses as a result of its motion relative to some reference frame
- **Potential energy, PE:** The energy that a system possesses as a result of its elevation in a gravitational field

FIGURE 2–4
The macroscopic energy of an object changes with velocity and elevation.

FORMS OF ENERGY-MICROCOPIC

- **Microscopic forms of energy**: Those related to the molecular structure of a system and the degree of the molecular activity
- **Internal energy, *U***: The sum of all the microscopic forms of energy, such as: sensible, latent, chemical and nuclear

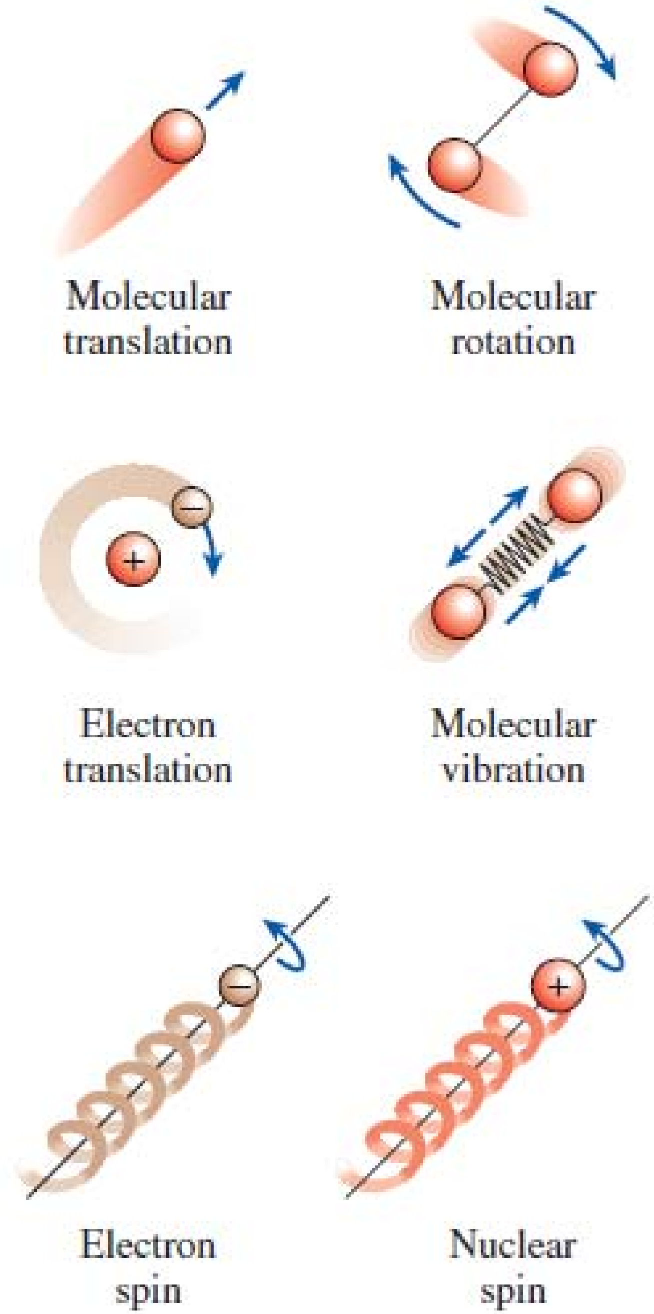


FIGURE 2–6
The various forms of microscopic energies that make up *sensible* energy.

Constituents of Internal Energy

- **Sensible energy:** The portion of the internal energy of a system associated with the kinetic energies of the molecules
- **Latent energy:** The internal energy associated with the phase of a system
- **Chemical energy:** The internal energy associated with the atomic bonds in a molecule
- **Nuclear energy:** The tremendous amount of energy associated with the strong bonds within the nucleus of the atom itself

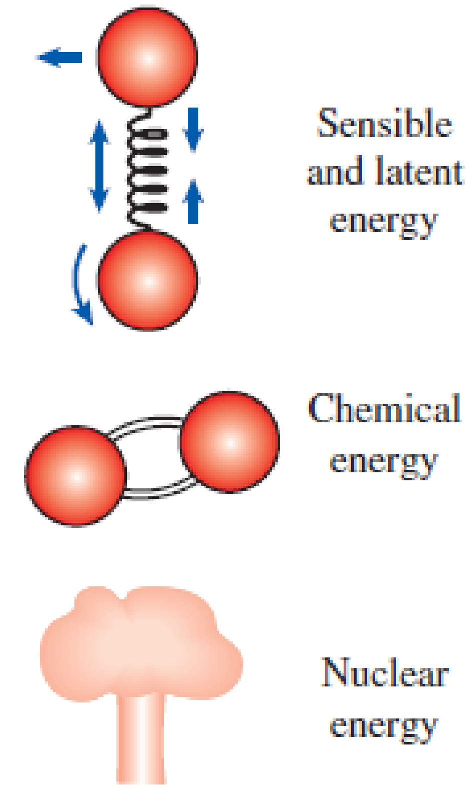


FIGURE 2–7
The internal energy of a system is the sum of all forms of the microscopic energies.

Thermal = Sensible + Latent
Internal = Sensible + Latent + Chemical + Nuclear

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

Kinetic energy (Extensive)

$$\mathrm{ke} = \frac{V^2}{2} \quad (\mathrm{kJ/kg})$$

Kinetic energy per unit mass (Intensive)

$$\mathrm{PE} = mgz \quad (\mathrm{kJ})$$

Potential energy (Extensive)

$$\mathrm{pe} = gz \quad (\mathrm{kJ/kg})$$

Potential energy per unit mass (Intensive)

- Most closed systems remain stationary during a process and thus experience no change in their kinetic and potential energies and are referred to as *stationary systems*
- We will assume a closed system to be stationary unless stated otherwise

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

Total energy of a system (Extensive)

$$e = u + \mathrm{ke} + \mathrm{pe} = u + \frac{V^2}{2} + gz \quad (\mathrm{kJ/kg})$$

Total energy of a system per unit mass (Intensive)

$$e = \frac{E}{m} \quad (\mathrm{kJ/kg})$$

Total energy per unit mass

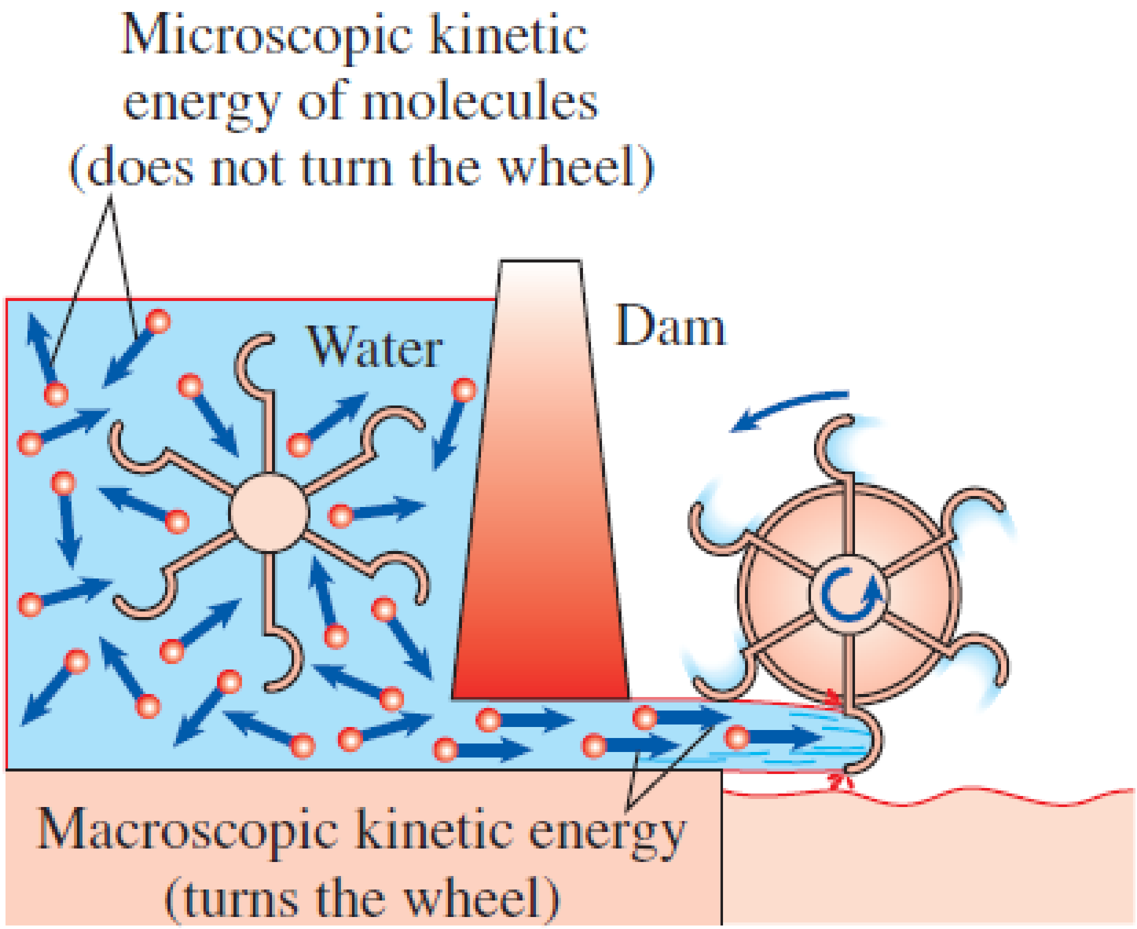


FIGURE 2–8

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

Energy Flow Rate

- *Control volumes* typically involve fluid flow for long periods of time, and it is convenient to express the energy flow associated with a fluid stream in the rate form

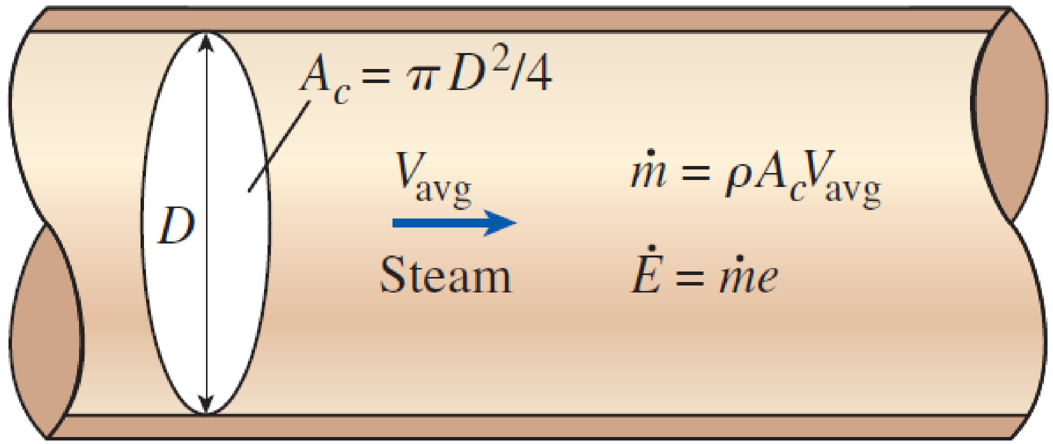


FIGURE 2–5
Mass and energy flow rates associated with the flow of steam in a pipe of inner diameter D with an average velocity of V_{avg}.

Mass flow rate: $$\dot{m} = \rho \dot{V} = \rho A_c V_{avg} \quad \text{(kg/s)}$$

Energy flow rate: $$\dot{E} = \dot{m}e \quad \text{(kJ/s or kW)}$$

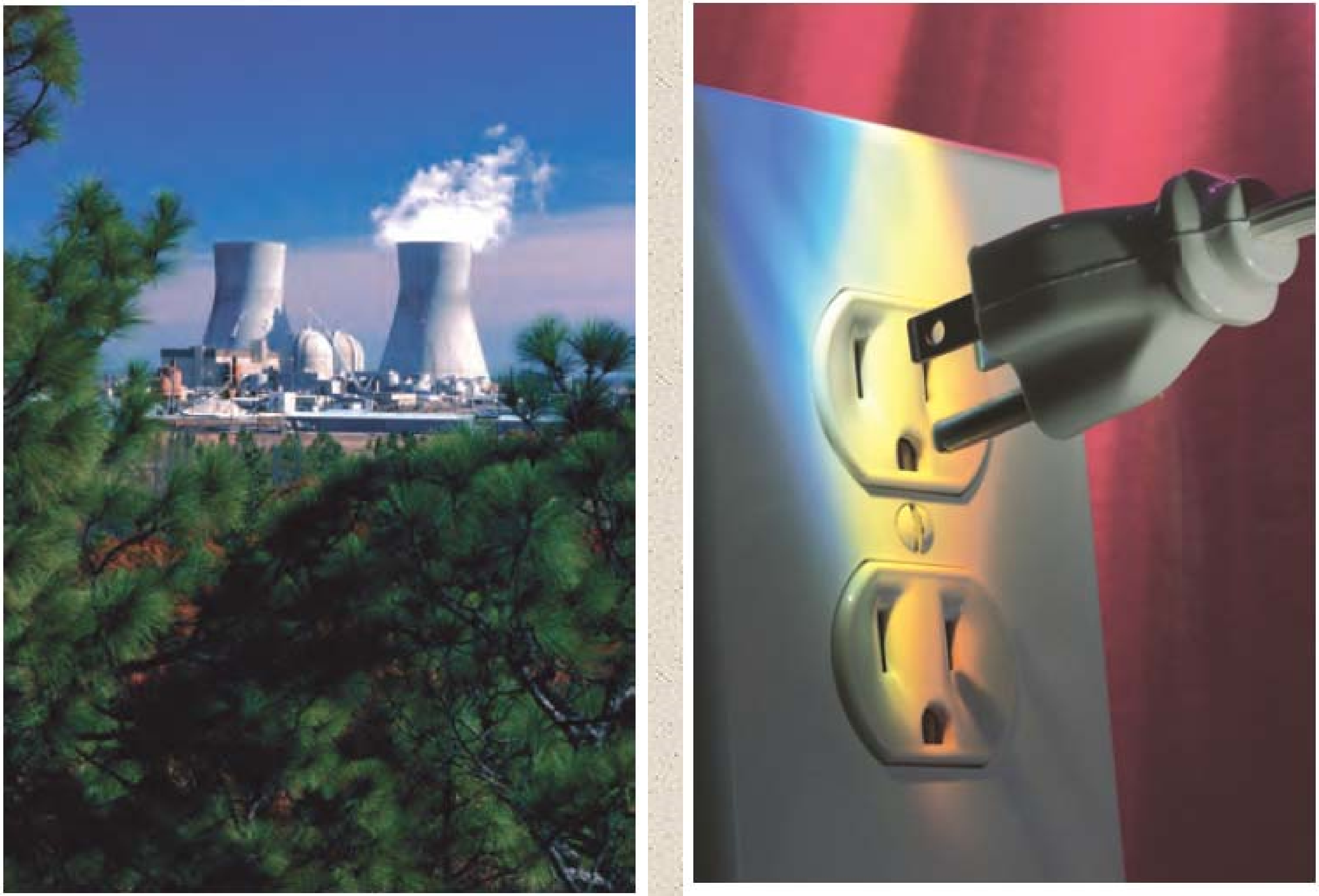


FIGURE 2–3
At least six different forms of energy are encountered in bringing power from a nuclear plant to your home: nuclear, thermal, mechanical, kinetic, magnetic, and electrical.

Heat Transfer and Work

- The total energy of a system, can be *contained* or *stored* in a system (property of 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**

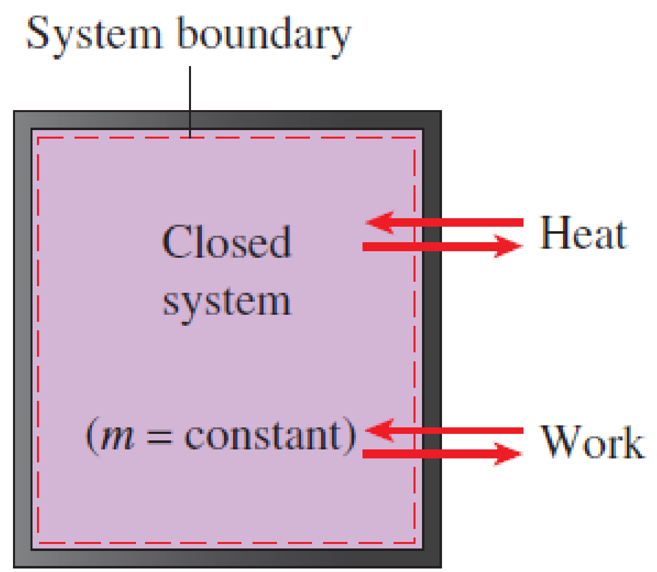


FIGURE 2–14
Energy can cross the boundaries of a closed system in the form of heat and work.

Heat and Work

- **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
- *Heat transfer and work are not properties* of a system
- In daily life, we frequently refer to the *thermal energy* as *heat*, and we talk about heat content of bodies
- In this course *"heat"* means *"heat transfer"* unless otherwise mentioned and not the thermal energy

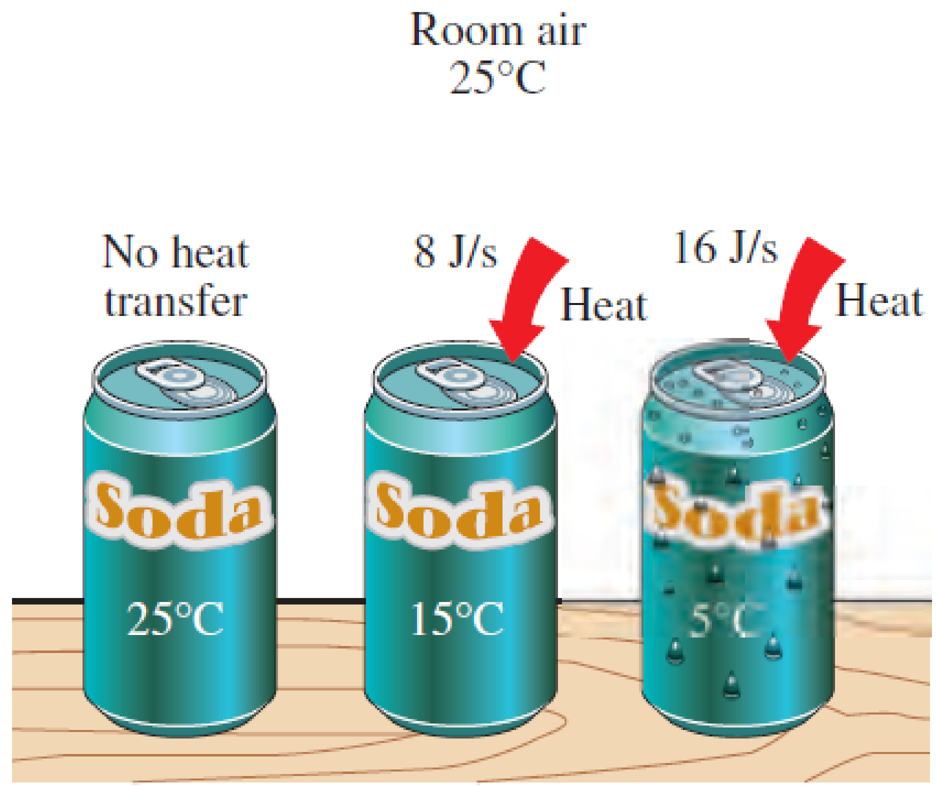
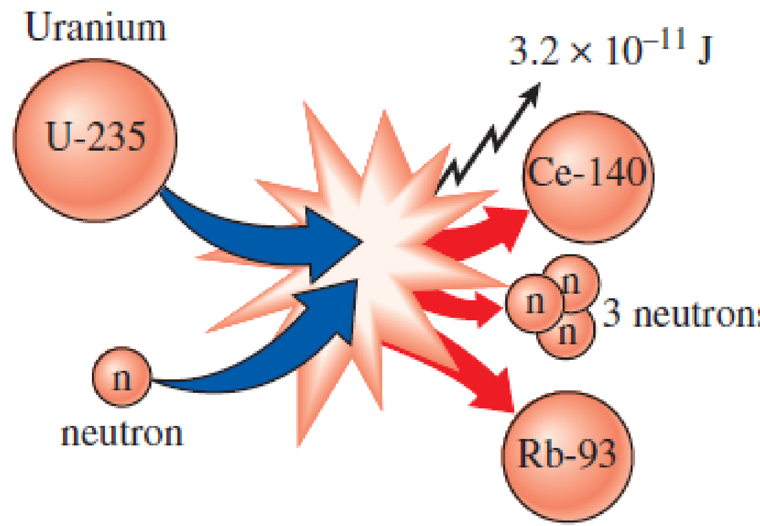


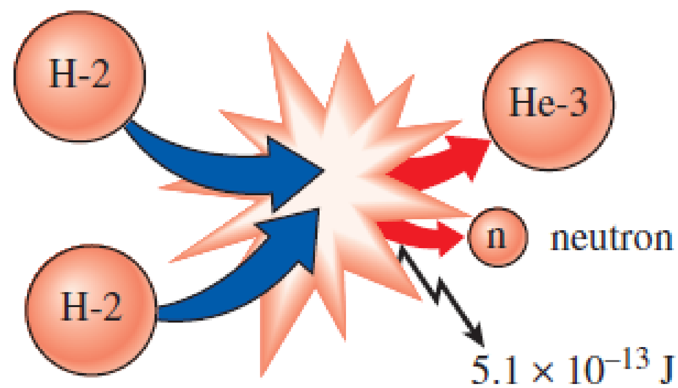
FIGURE 2–15
Temperature difference is the driving force for heat transfer. The larger the temperature difference, the higher is the rate of heat transfer.

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
- *1 kg of uranium-235* releases 6.73 × 10^{10} kJ of heat which is more than the heat released when *3000 tons of coal* are burned
- Nuclear energy by **fusion** is released when two small nuclei combine into a larger one
- The huge amount of energy radiated by the sun and other stars originates from such a fusion process



(*a*) Fission of uranium



(*b*) Fusion of hydrogen

FIGURE 2–9
The fission of uranium and the fusion of hydrogen during nuclear reactions, and the release of nuclear energy.

Mechanical Energy

- Some systems do not involve the *conversion of nuclear, chemical and thermal energies*, also they do not involve heat transfer in any significant amount, and they *operate essentially at constant temperature*
- Such systems can be analyzed *conveniently* by considering the *mechanical forms of energy* only and the *frictional effects* that cause the mechanical energy to be lost (i.e. to be *converted to thermal 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
- Thermal energy is not mechanical energy since it cannot be converted to work directly and completely (second law of thermodynamics)
- *Kinetic and potential energies* are the familiar forms of mechanical energy

Flow Energy

- A pump transfers mechanical energy to a fluid by raising its pressure, and a turbine extracts mechanical energy from a fluid by dropping its pressure
- Therefore, the pressure of a flowing fluid is also associated with its mechanical energy
- Note that *pressure itself in not a form of energy* but a pressure force acting on a fluid through a distance produces work (Pv or P/ρ), called *flow work*
- It is *convenient* to view *flow work* as part of the energy of a flowing fluid and call it *flow energy*

- Mechanical energy = Flow energy + Kinetic Energy + Potential energy

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

Mechanical energy of a flowing fluid per unit mass

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

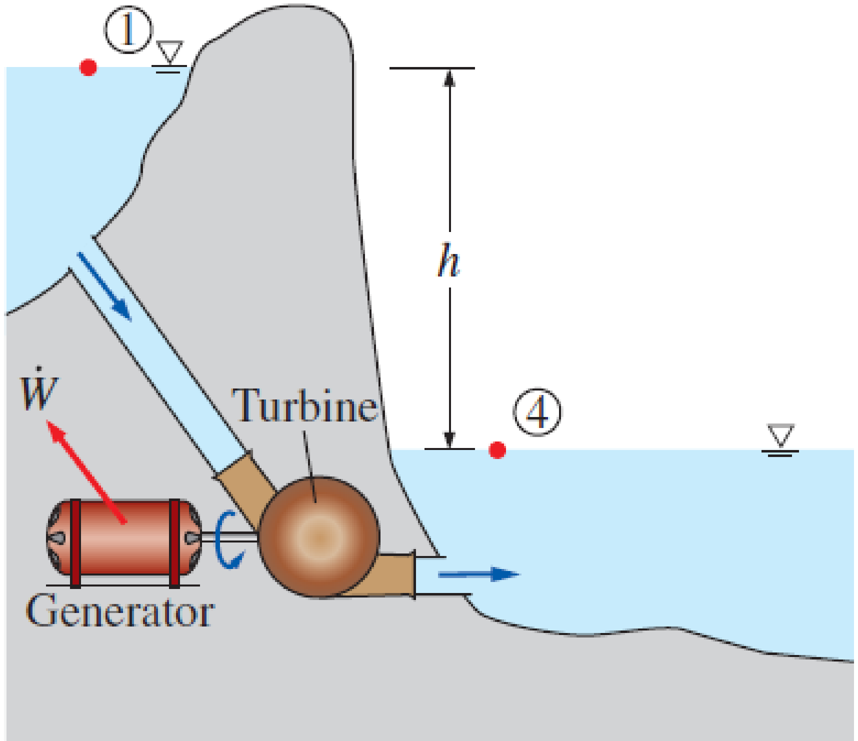
Rate of mechanical energy of a flowing fluid

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

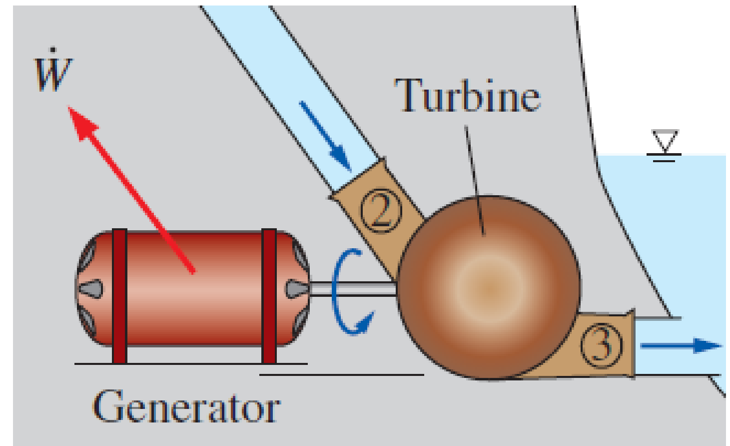
$$\Delta \dot{E}_{\text{mech}} = \dot{m}\Delta e_{\text{mech}} = \dot{m}\left(\frac{P_2 - P_1}{\rho} + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)\right) \qquad \text{(kW)}$$



$$\dot{W}_{\max} = \dot{m}\,\Delta e_{\text{mech}} = \dot{m}g(z_1 - z_4) = \dot{m}gh$$

since $P_1 \approx P_4 = P_{\text{atm}}$ and $V_1 = V_4 \approx 0$

(a)



$$\dot{W}_{\max} = \dot{m}\,\Delta e_{\text{mech}} = \dot{m}\frac{P_2 - P_3}{\rho} = \dot{m}\frac{\Delta P}{\rho}$$

since $V_2 \approx V_3$ and $z_2 = z_3$

(b)

FIGURE 2–12

Mechanical energy is illustrated by an ideal hydraulic turbine coupled with an ideal generator. In the absence of irreversible losses, the maximum produced power is proportional to (a) the change in water surface elevation from the upstream to the downstream reservoir or (b) (close-up view) the drop in water pressure from just upstream to just downstream of the turbine.

- P/ρ term actually represents *flow work* but is included in mechanical energy for *convenience* and we refer to it here as the *flow energy*

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*

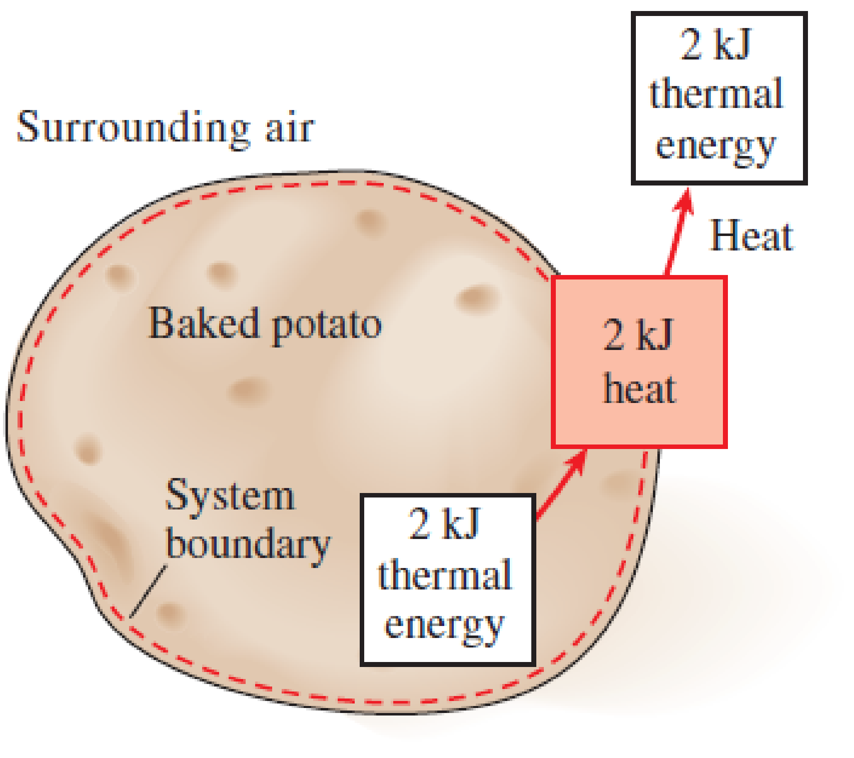


FIGURE 2–16
Energy is recognized as heat transfer only as it crosses the system boundary.

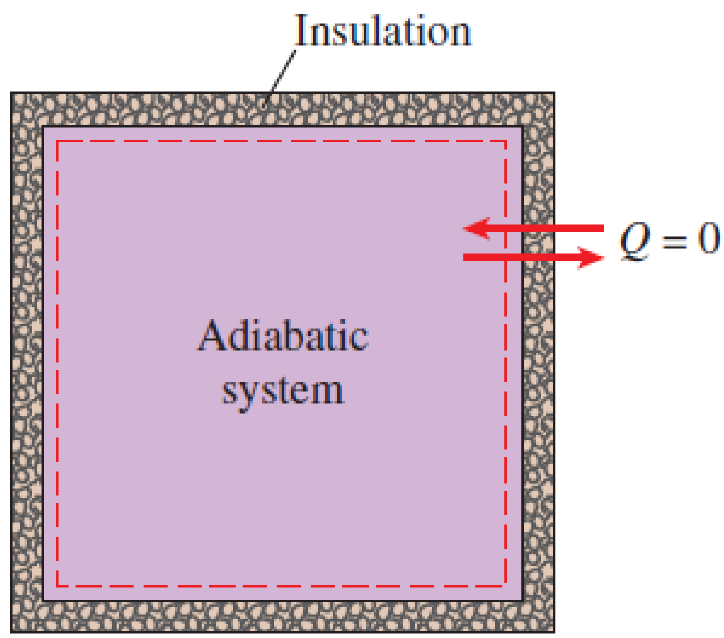


FIGURE 2–17
During an adiabatic process, a system exchanges no heat with its surroundings.

ENERGY TRANSFER BY HEAT

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

Heat transfer per unit mass (of closed system)

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

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

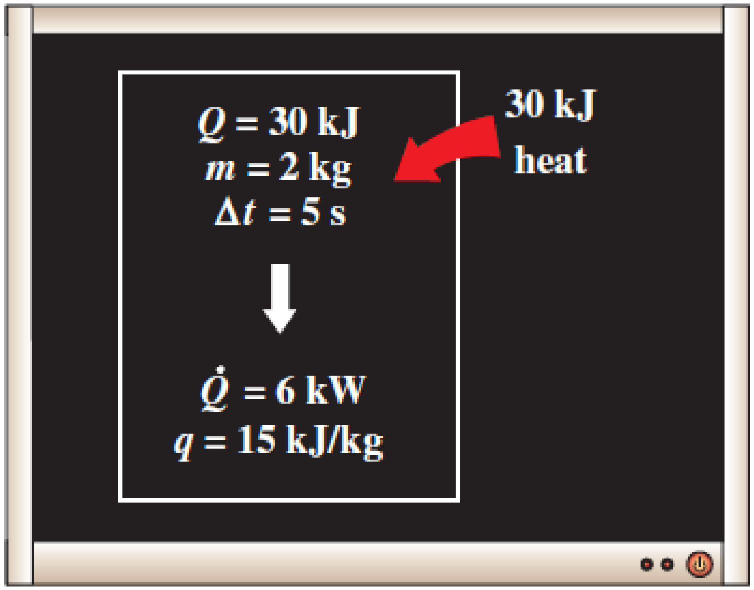


FIGURE 2–18
The relationships among q, Q, and $\dot{Q}$.

Historical Background on Heat

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

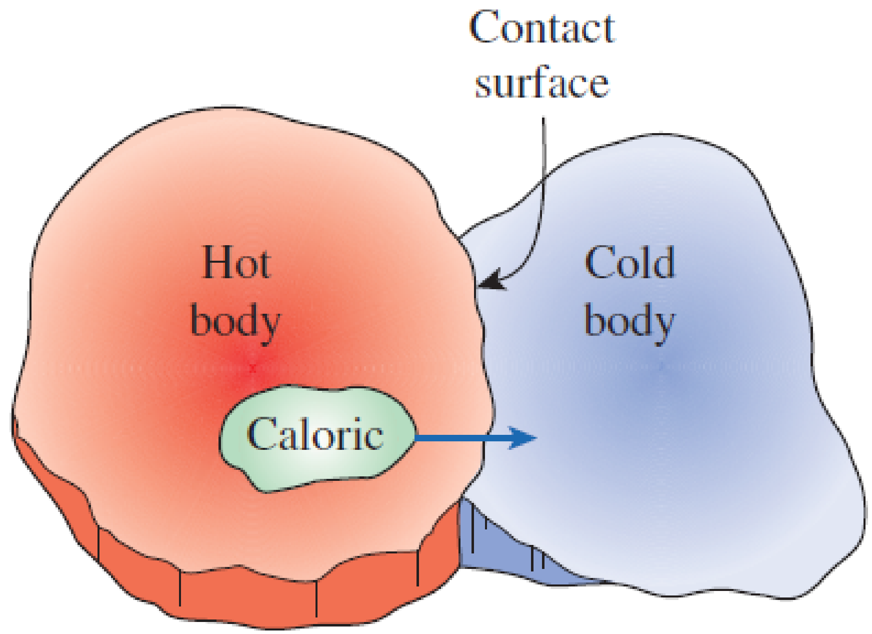
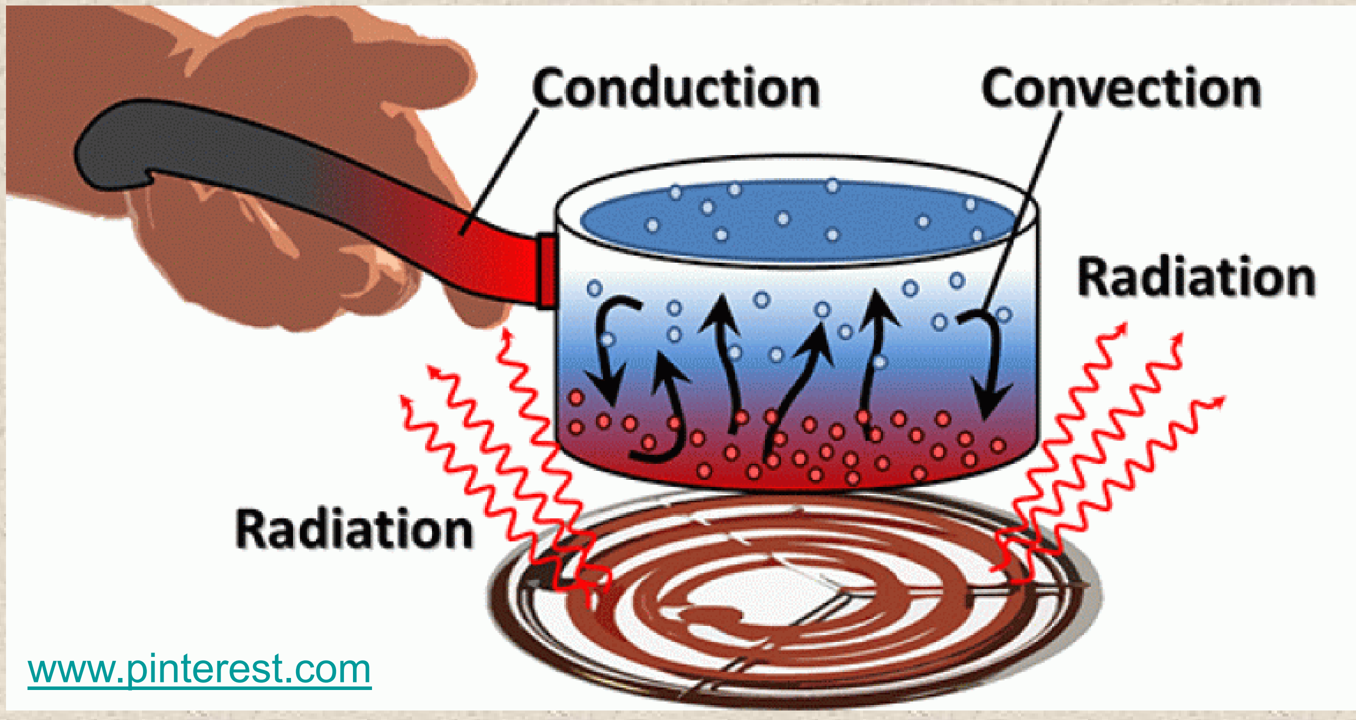


FIGURE 2–19
In the early nineteenth century, heat was thought to be an invisible fluid called the *caloric* that flowed from warmer bodies to the cooler ones.

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)



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
  - ✓ If the energy crossing the boundary of a closed system is not heat, it must be work

Work done per unit mass (of closed system)

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

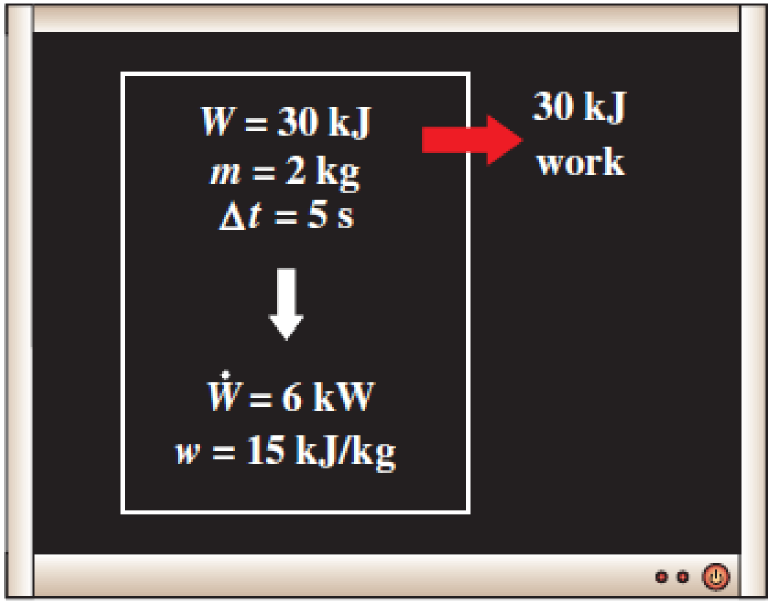


FIGURE 2–20
The relationships among w, W, and $\dot{W}$.

SIGN CONVENTION

- Heat and work are *directional quantities*, and thus the complete description of a heat or work interaction requires specification of both the *magnitude* and *direction*
- **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 course*

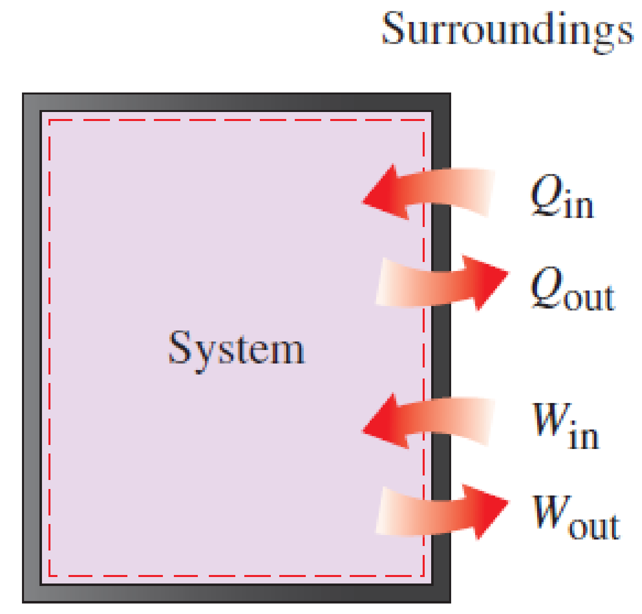
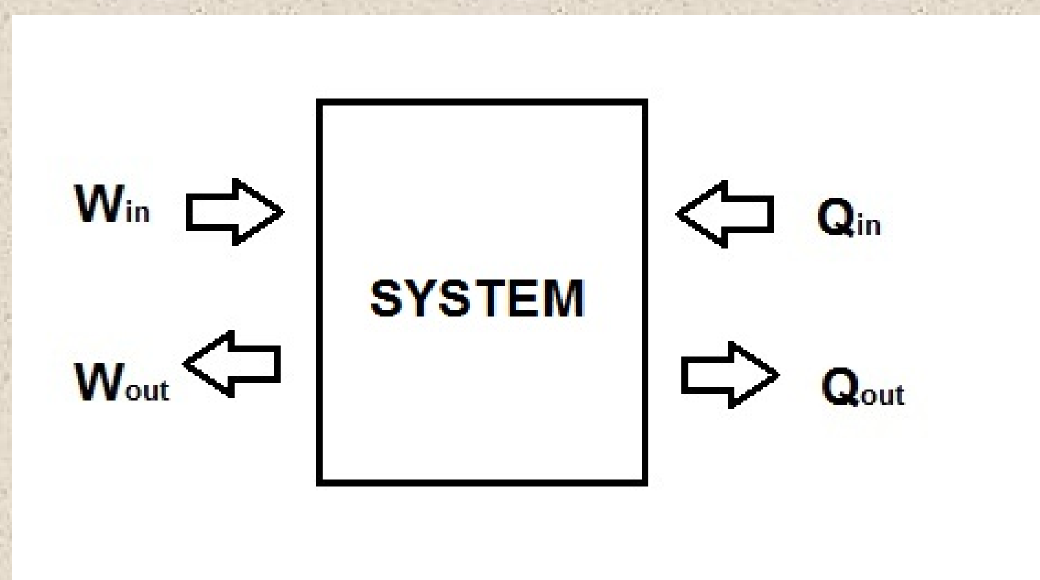


FIGURE 2–21
Specifying the directions of heat and work.

Heat vs. Work as boundary phenomena

- Both are *recognized at the boundaries* of a system as they cross the boundaries
- That is, both heat and work are *boundary* phenomena
- *System possess energy, but not heat or work*
- Both heat and work are associated with a *process*, not a state
- Unlike properties, heat or work has no meaning at a state



Heat and Work as path functions

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

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

Path functions have inexact differentials (δ)

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

Properties are point functions have exact differentials (d)

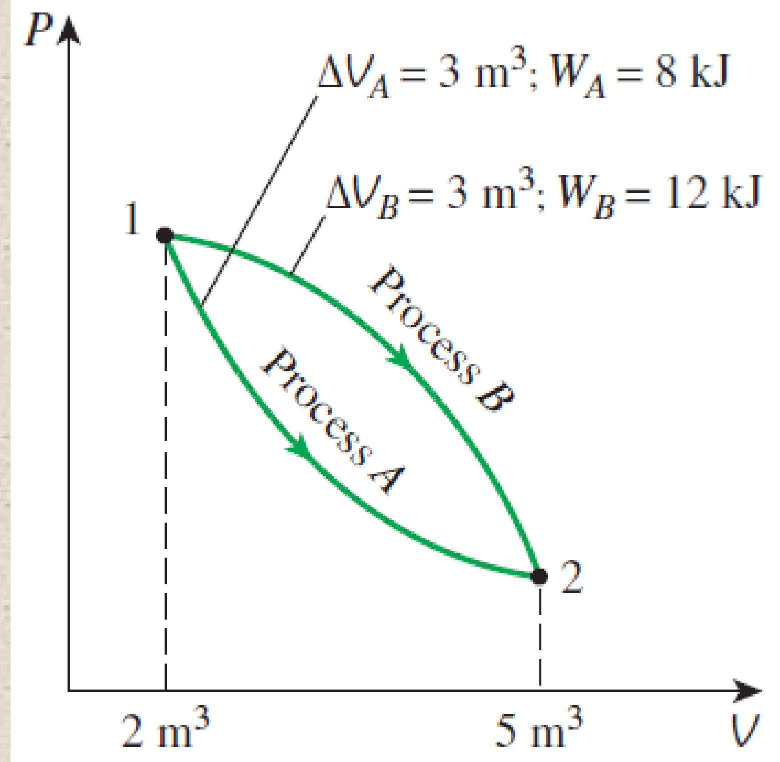


FIGURE 2–22

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

Electrical Work

Electrical work

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

N coulombs of electric charge move through potential difference V

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

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

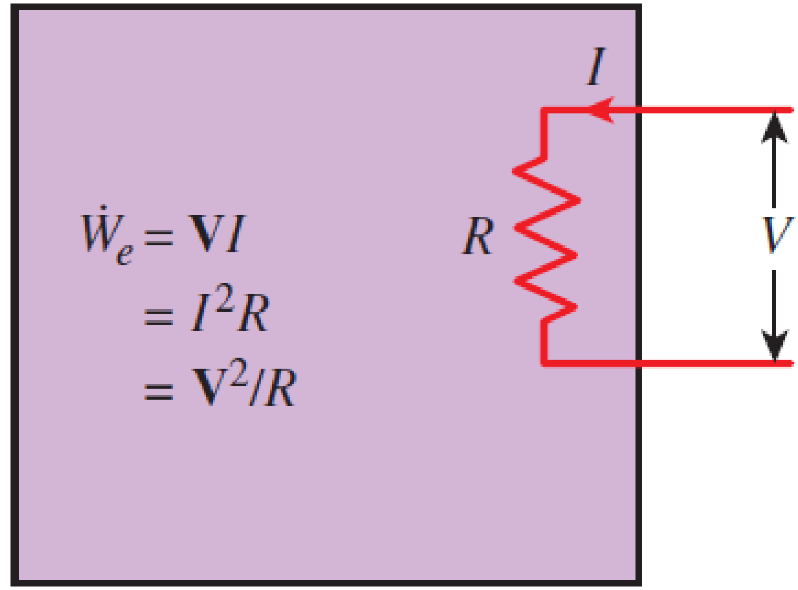


FIGURE 2–27

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

- Electrons crossing the system boundary do electrical work

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

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

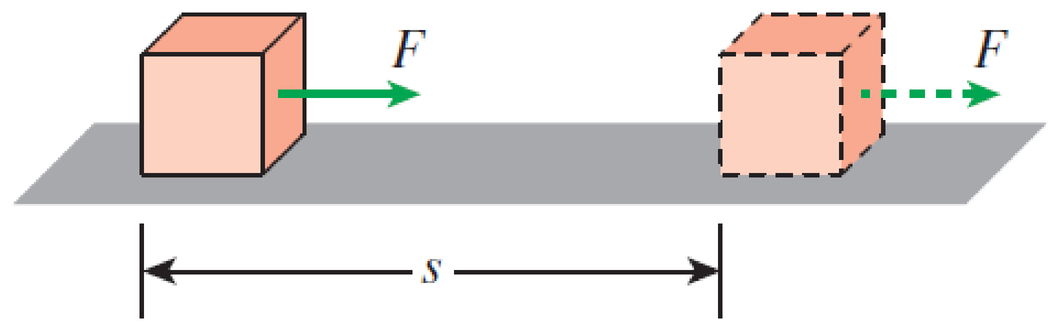


FIGURE 2–28
The work done is proportional to the force applied (F) and the distance traveled (s).

Shaft Work

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

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

This force acts through a distance s

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

Shaft work

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

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

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

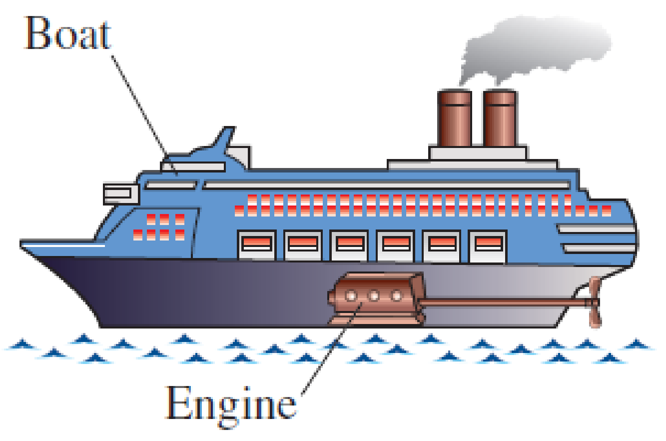


FIGURE 2–29
Energy transmission through rotating shafts is commonly encountered in practice.

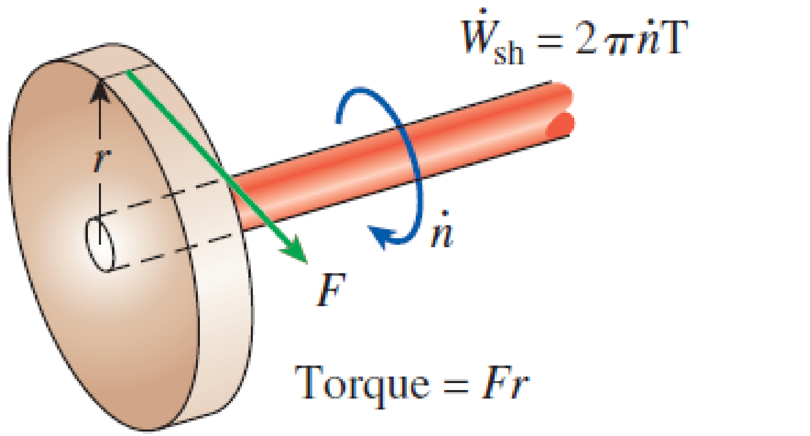


FIGURE 2–30
Shaft work is proportional to the torque applied and the number of revolutions of the shaft.

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)

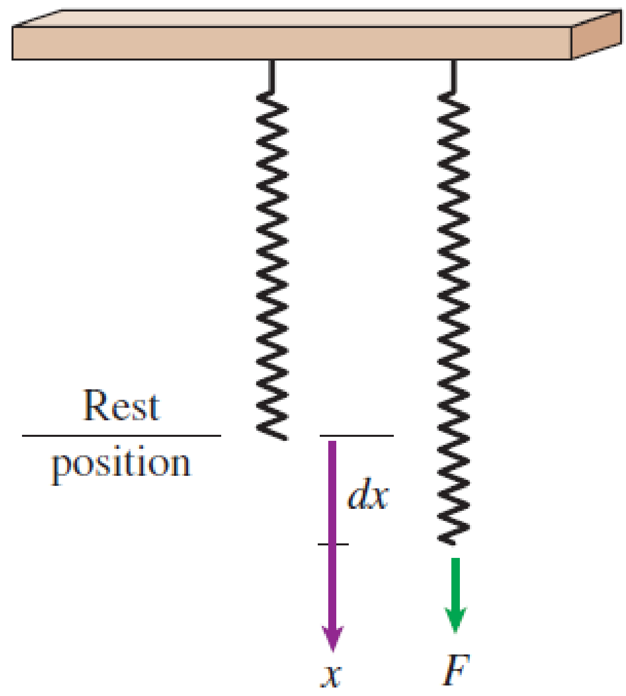


FIGURE 2–32
Elongation of a spring under the influence of a force.

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

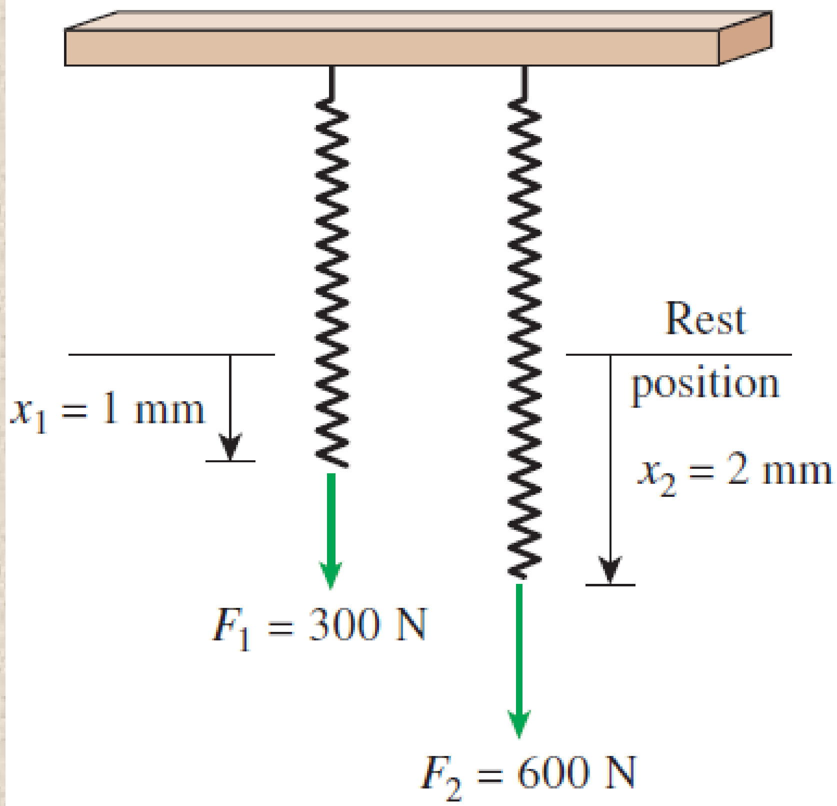


FIGURE 2–33
The displacement of a linear spring doubles when the force is doubled.

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

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

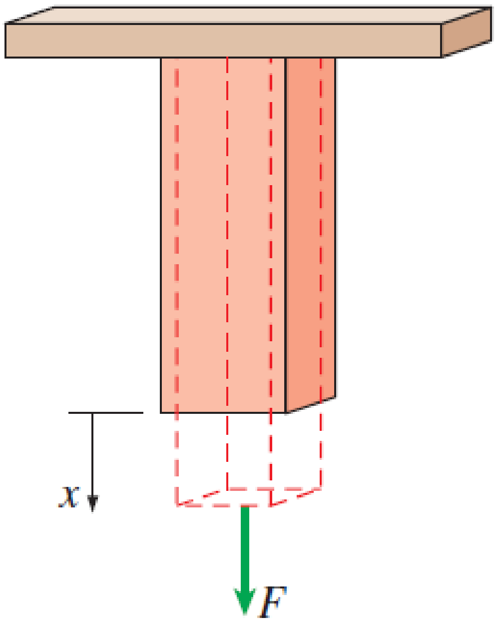


FIGURE 2–34
Solid bars behave as springs under the influence of a force.

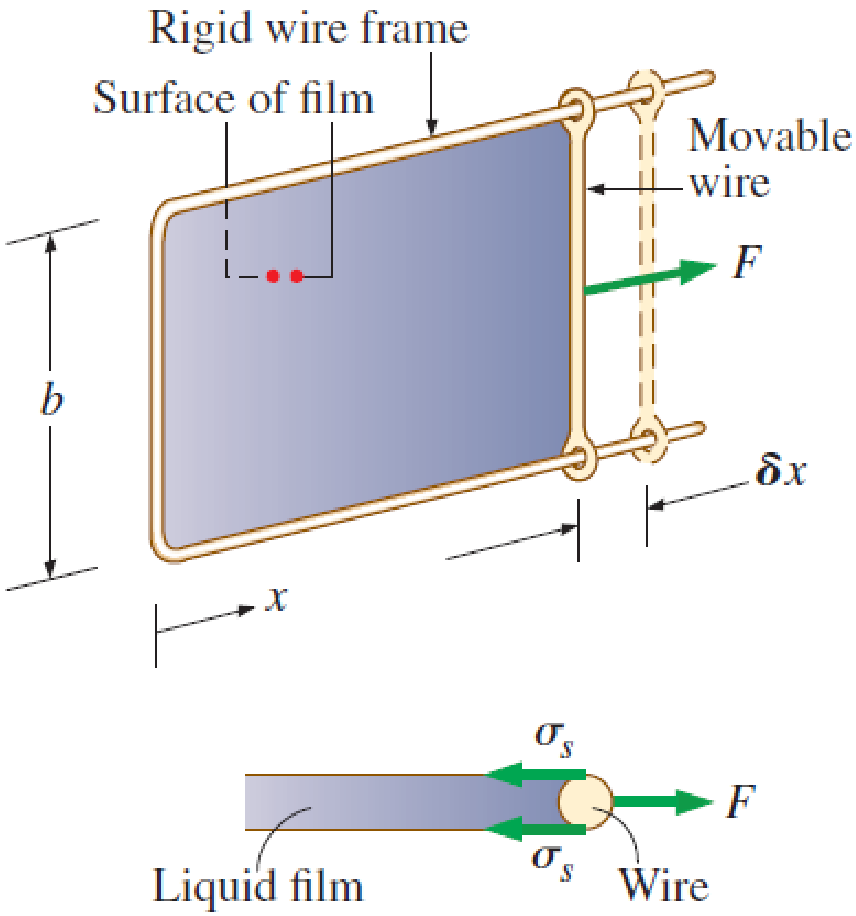


FIGURE 2–35
Stretching a liquid film with a U-shaped wire, and the forces acting on the movable wire of length b.

Work Done to Raise or to Accelerate a Body

- The work transfer needed to raise a body is equal to the *change in the potential energy* of the body
- The work transfer needed to accelerate a body is equal to the *change in the kinetic energy* of the body

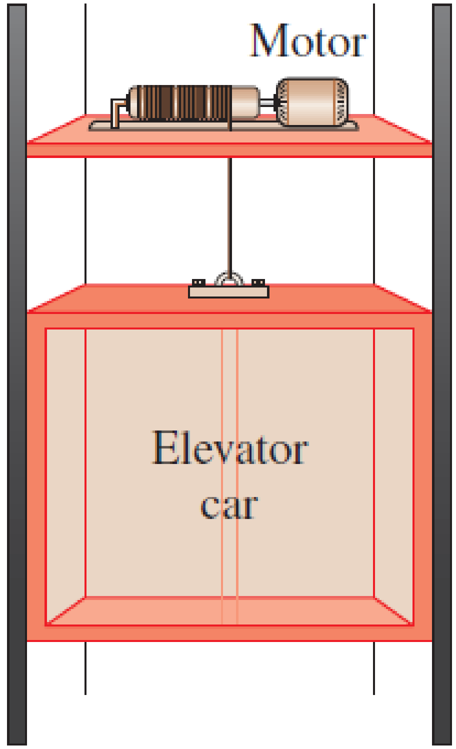


FIGURE 2–36
The energy transferred to a body while being raised is equal to the change in its potential energy.

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*

THE FIRST LAW OF THERMODYNAMICS

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

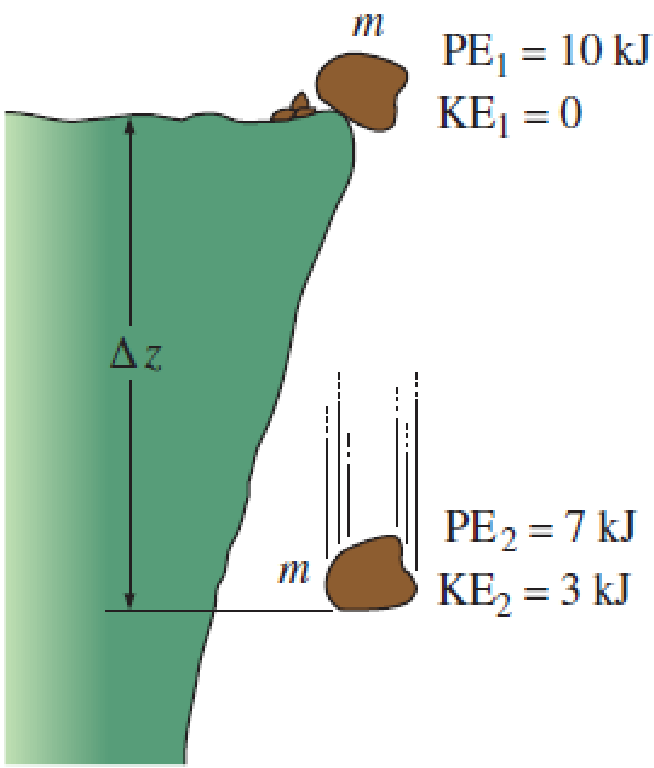


FIGURE 2–39
Energy cannot be created or destroyed; it can only change forms.

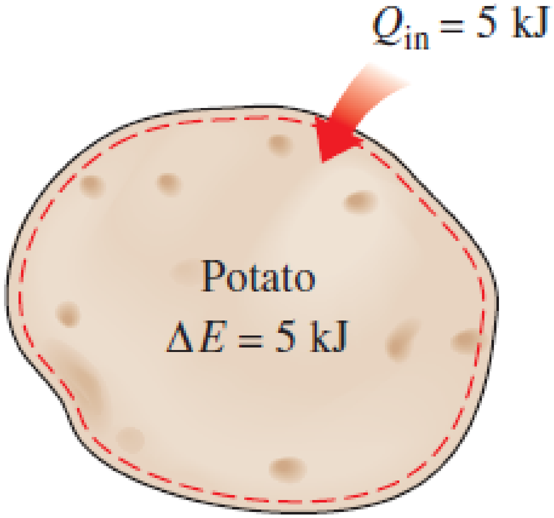


FIGURE 2–40
The increase in the energy of a potato in an oven is equal to the amount of heat transferred to it.

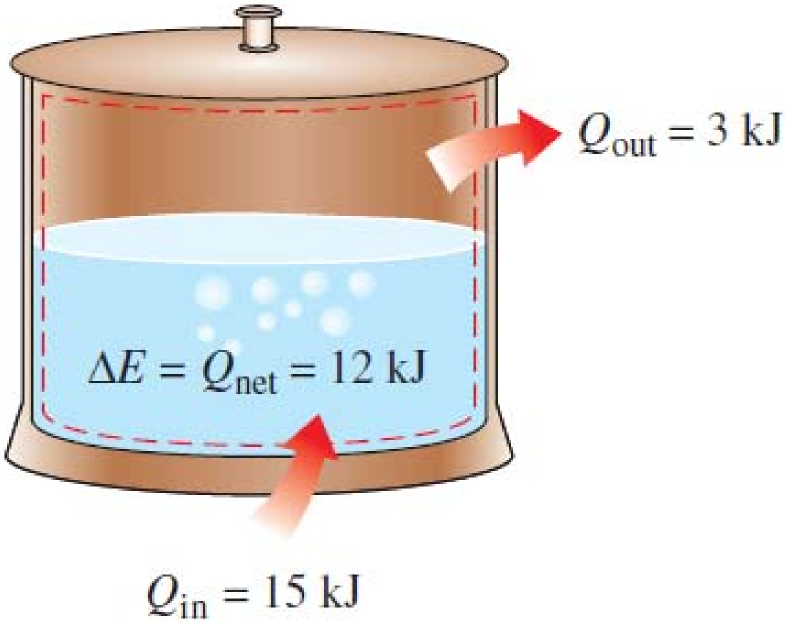


FIGURE 2–41
In the absence of any work interactions, the energy change of a system is equal to the net heat transfer.

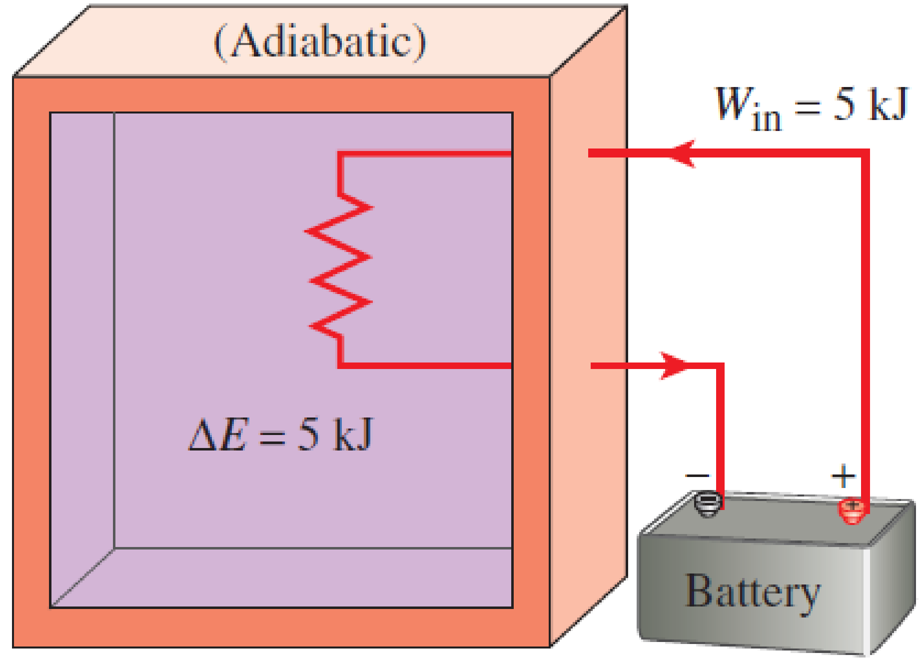


FIGURE 2–42
The work (electrical) done on an adiabatic system is equal to the increase in the energy of the system.

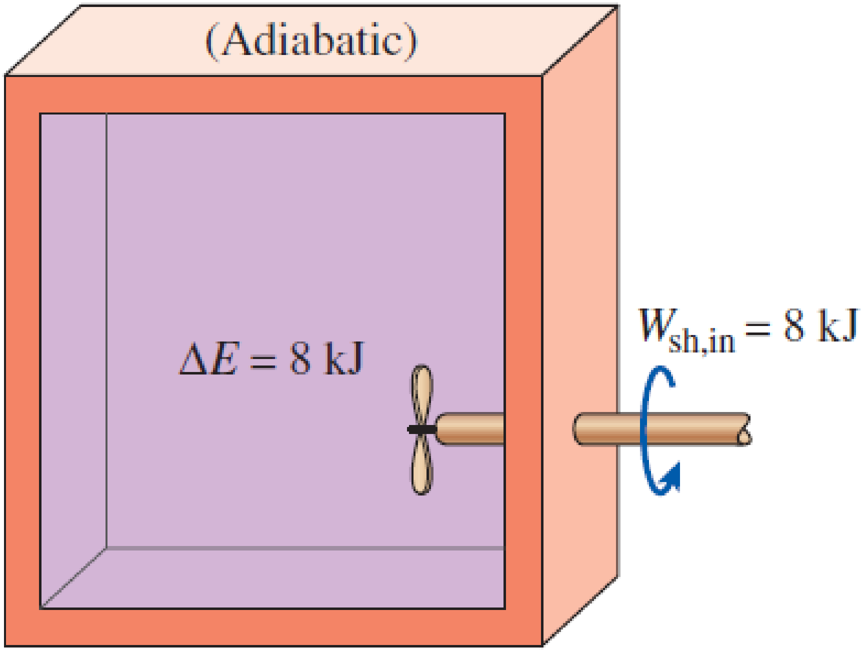


FIGURE 2–43
The work (shaft) done on an adiabatic system is equal to the increase in the energy of the system.

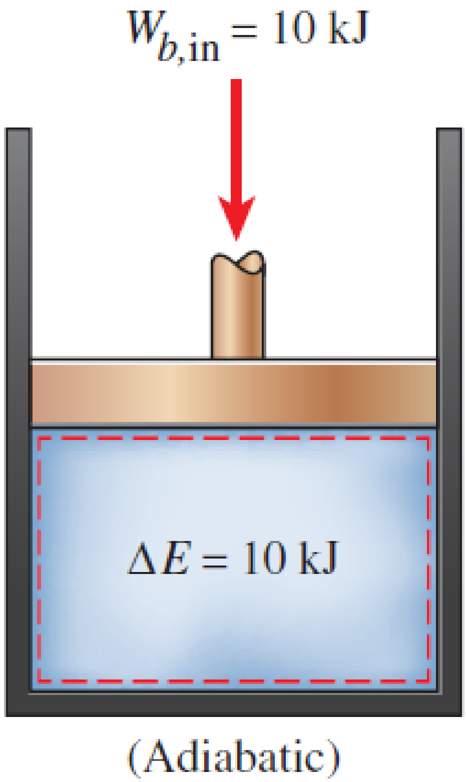


FIGURE 2–44
The work (boundary) done on an adiabatic system is equal to the increase in the energy of the system.

Energy Balance

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

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

- 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
- Energy balance is applicable to any kind of system (open or closed) undergoing any kind of process (equilibrium or non-equilibrium)

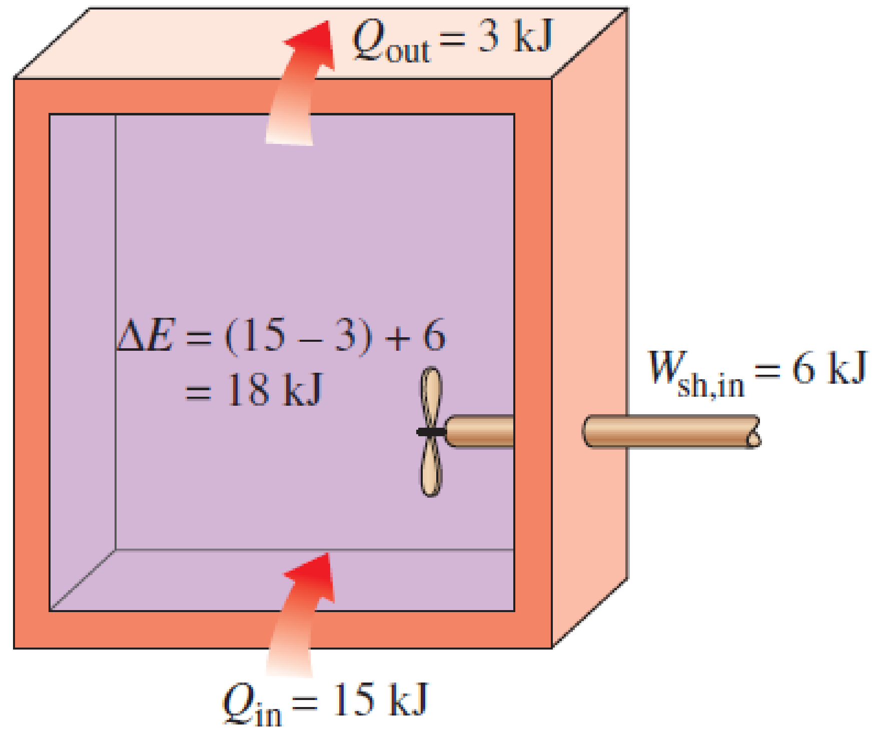


FIGURE 2–45
The energy change of a system during a process is equal to the *net* work and heat transfer between the system and its surroundings.

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

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

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

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

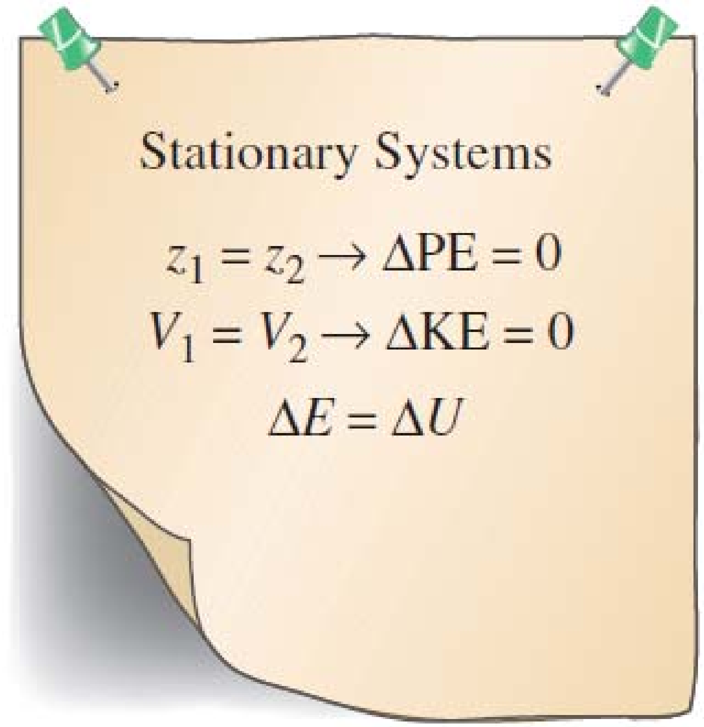


FIGURE 2–46

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

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

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

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

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

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

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

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

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

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

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

Energy Balance for a Closed System Working in a Cycle

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

- A closed system involves only *heat transfer* and *work* as mechanisms of energy transfer

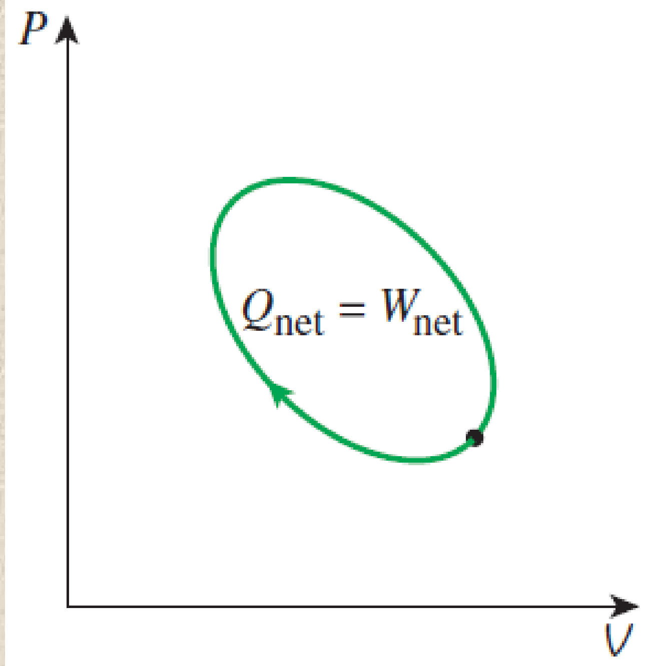


FIGURE 2–48
For a cycle $\Delta E = 0$, thus $Q = W$.

Energy Balance for Control Volume

Mechanisms of energy transfer:

- Heat transfer
- Work transfer
- **Mass flow**

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

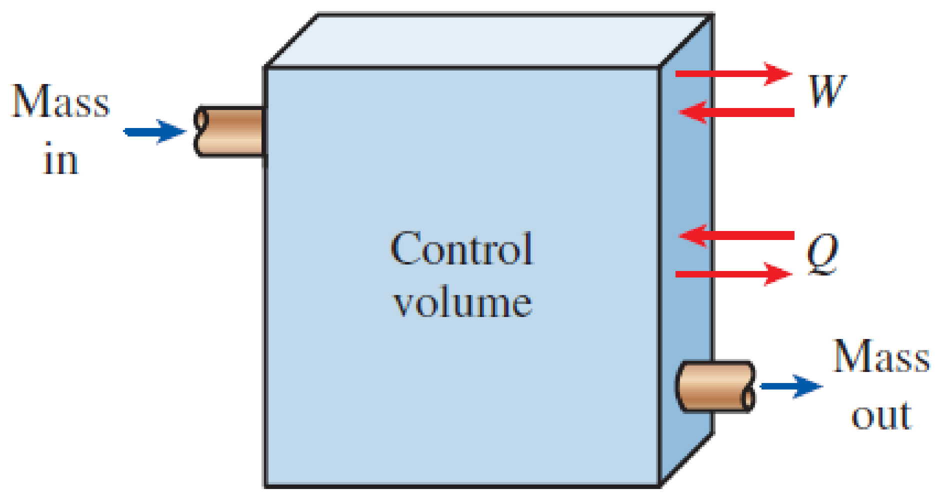


FIGURE 2–47

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

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

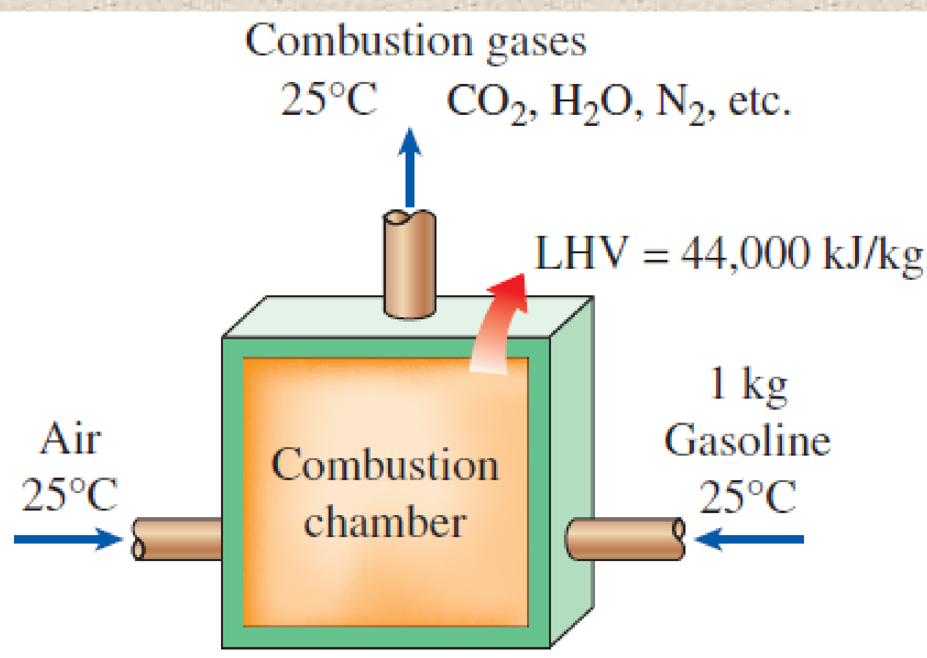


FIGURE 2–54
The definition of the heating value of gasoline.

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

Overall efficiency ($\eta_{overall}$) of a power plant: net electrical work power output to the rate of fuel energy input

- **Generator:** A device that converts mechanical energy to electrical energy
- **Generator efficiency ($\eta_{generator}$):** The ratio of the electrical power output to the mechanical power input
- **Thermal efficiency of a power plant ($\eta_{thermal}$):** The ratio of the net shaft work output of the turbine to the rate of fuel energy input

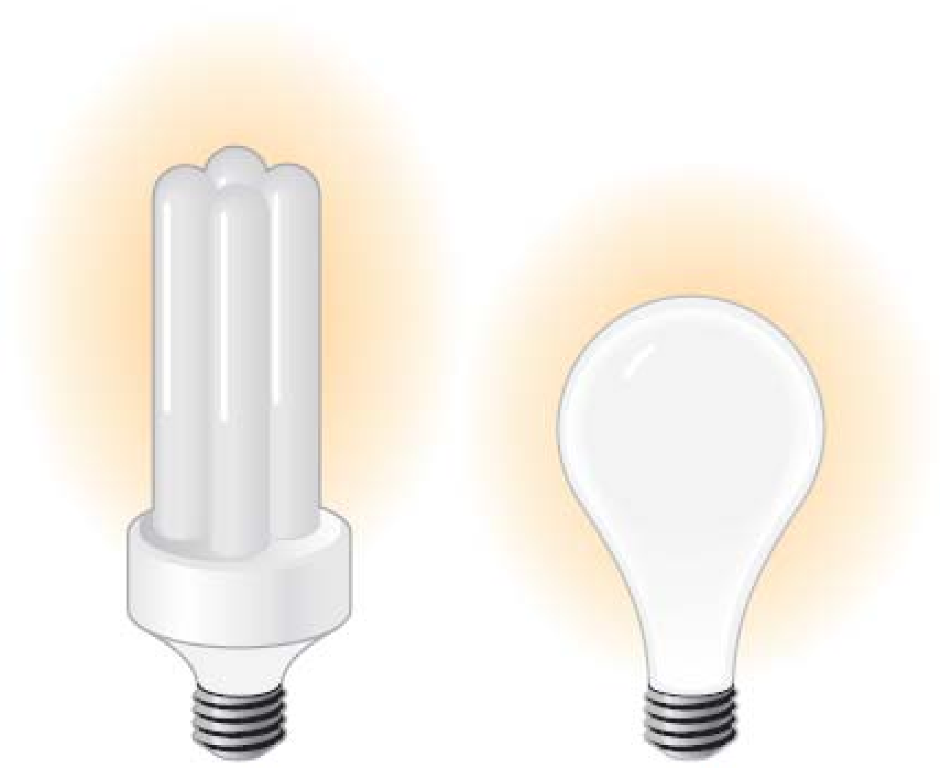


FIGURE 2–55
A 15-W compact fluorescent lamp provides as much light as a 60-W incandescent lamp.

TABLE 2–1

The efficacy of different lighting systems

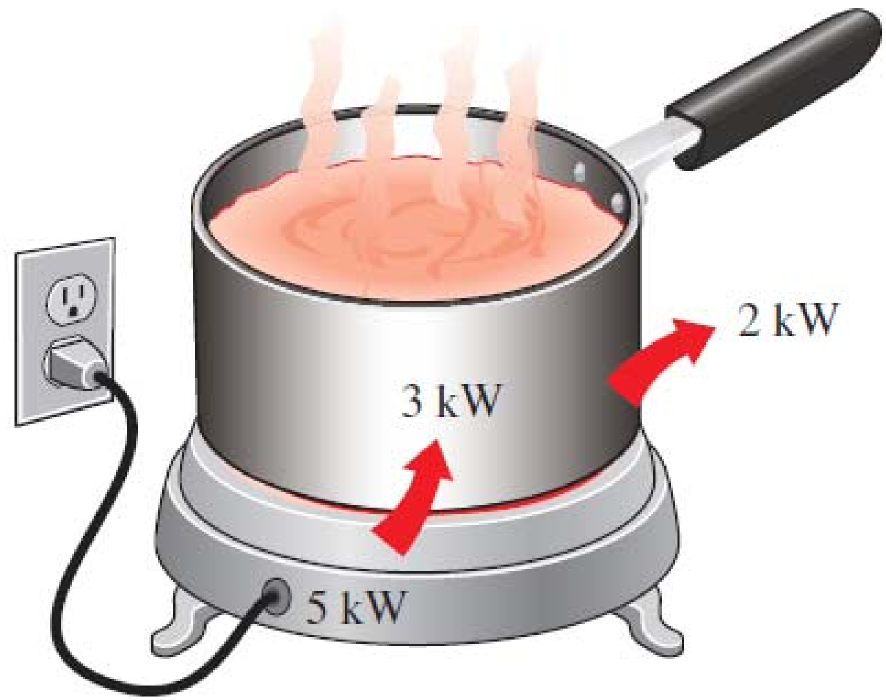
Type of lighting	Efficacy, lumens/W
Combustion	
Candle	0.3
Kerosene lamp	1–2
Incandescent	
Ordinary	6–20
Halogen	15–35
Fluorescent	
Compact	40–87
Tube	60–120
High-intensity discharge	
Mercury vapor	40–60
Metal halide	65–118
High-pressure sodium	85–140
Low-pressure sodium	70–200
Solid-State	
LED	20–160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

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

The lumen (symbol: lm) is the SI derived unit of luminous flux, a measure of the total quantity of *visible light* emitted by a source per unit of time. Luminous flux differs from power (radiant flux) in that radiant flux includes all electromagnetic waves emitted, while luminous flux is weighted according to a model (a "luminosity function") of the human eye's sensitivity to various wavelengths.

*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.

- Using energy-efficient appliances conserve energy.
- It helps the **environment** by reducing the amount of pollutants emitted to the atmosphere during the combustion of fuel.
- The combustion of fuel produces
  - carbon dioxide, causes global warming
  - nitrogen oxides and hydrocarbons, cause smog
  - carbon monoxide, toxic
  - sulfur dioxide, causes acid rain



$$\text{Efficiency} = \frac{\text{Energy utilized}}{\text{Energy supplied to appliance}}$$

$$= \frac{3\text{ kWh}}{5\text{ kWh}} = 0.60$$

FIGURE 2–56

The efficiency of a cooking appliance represents the fraction of the energy supplied to the appliance that is transferred to the food.

TABLE 2–2

Energy costs of cooking a casserole with different appliances*

[From J. T. Amann, A. Wilson, and K. Ackerly, *Consumer Guide to Home Energy Savings*, 9th ed., American Council for an Energy-Efficient Economy, Washington, D.C., 2007, p. 163.]

Cooking appliance	Cooking temperature	Cooking time	Energy used	Cost of energy
Electric oven	350°F (177°C)	1 h	2.0 kWh	\$0.19
Convection oven (elect.)	325°F (163°C)	45 min	1.39 kWh	\$0.13
Gas oven	350°F (177°C)	1 h	0.112 therm	\$0.13
Frying pan	420°F (216°C)	1 h	0.9 kWh	\$0.09
Toaster oven	425°F (218°C)	50 min	0.95 kWh	\$0.09
Crockpot	200°F (93°C)	7 h	0.7 kWh	\$0.07
Microwave oven	"High"	15 min	0.36 kWh	\$0.03

*Assumes a unit cost of \$0.095/kWh for electricity and \$1.20/therm for gas.

Efficiencies of Mechanical and Electrical Devices

Mechanical efficiency

$$\eta_{\text{mech}} = \frac{\text{Mechanical energy output}}{\text{Mechanical energy input}} = \frac{E_{\text{mech,out}}}{E_{\text{mech,in}}} = 1 - \frac{E_{\text{mech,loss}}}{E_{\text{mech,in}}}$$

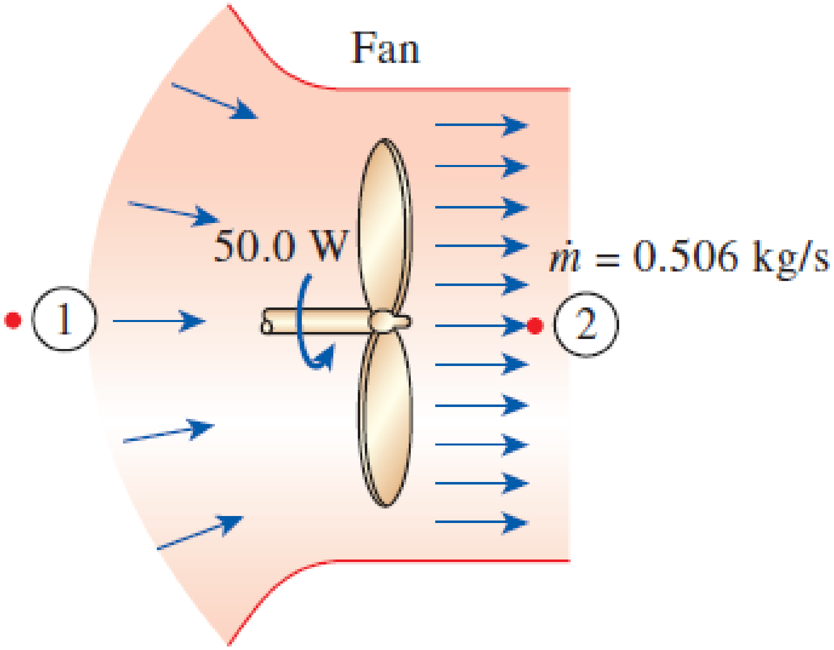
- The effectiveness of the conversion process between the mechanical work supplied or extracted and the mechanical energy of the fluid is expressed by the **pump efficiency** and **turbine efficiency**

$$\eta_{\text{pump}} = \frac{\text{Mechanical energy increase of the fluid}}{\text{Mechanical energy input}} = \frac{\Delta \dot{E}_{\text{mech,fluid}}}{\dot{W}_{\text{shaft,in}}} = \frac{\dot{W}_{\text{pump},u}}{\dot{W}_{\text{pump}}}$$

$$\Delta \dot{E}_{\text{mech,fluid}} = \dot{E}_{\text{mech,out}} - \dot{E}_{\text{mech,in}}$$

$$\eta_{\text{turbine}} = \frac{\text{Mechanical energy output}}{\text{Mechanical energy decrease of the fluid}} = \frac{\dot{W}_{\text{shaft,out}}}{|\Delta \dot{E}_{\text{mech,fluid}}|} = \frac{\dot{W}_{\text{turbine}}}{\dot{W}_{\text{turbine},e}}$$

$$|\Delta \dot{E}_{\text{mech,fluid}}| = \dot{E}_{\text{mech,in}} - \dot{E}_{\text{mech,out}}$$



$V_1 \approx 0$, $V_2 = 12.1$ m/s
$z_1 = z_2$
$P_1 \approx P_{atm}$ and $P_2 \approx P_{atm}$

$$\eta_{mech,\ fan} = \frac{\Delta \dot{E}_{mech,\ fluid}}{\dot{W}_{shaft,\ in}} = \frac{\dot{m}V_2^2/2}{\dot{W}_{shaft,\ in}}$$

$$= \frac{(0.506 \text{ kg/s})(12.1 \text{ m/s})^2/2}{50.0 \text{ W}}$$

$$= 0.741$$

FIGURE 2–58
The mechanical efficiency of a fan is the ratio of the rate of increase of the mechanical energy of air to the mechanical power input.

Efficiencies of Mechanical and Electrical Devices

Motor efficiency

$$\eta_{\text{motor}} = \frac{\text{Mechanical power output}}{\text{Electric power input}} = \frac{\dot{W}_{\text{shaft,out}}}{\dot{W}_{\text{elect,in}}}$$

Generator efficiency

$$\eta_{\text{generator}} = \frac{\text{Electric power output}}{\text{Mechanical power input}} = \frac{\dot{W}_{\text{elect,out}}}{\dot{W}_{\text{shaft,in}}}$$

Pump-Motor overall efficiency

$$\eta_{\text{pump-motor}} = \eta_{\text{pump}}\eta_{\text{motor}} = \frac{\dot{W}_{\text{pump},u}}{\dot{W}_{\text{elect,in}}} = \frac{\Delta\dot{E}_{\text{mech,fluid}}}{\dot{W}_{\text{elect,in}}}$$

Turbine-Generator overall efficiency

$$\eta_{\text{turbine-gen}} = \eta_{\text{turbine}}\eta_{\text{generator}} = \frac{\dot{W}_{\text{elect,out}}}{\dot{W}_{\text{turbine},e}} = \frac{\dot{W}_{\text{elect,out}}}{|\Delta\dot{E}_{\text{mech,fluid}}|}$$

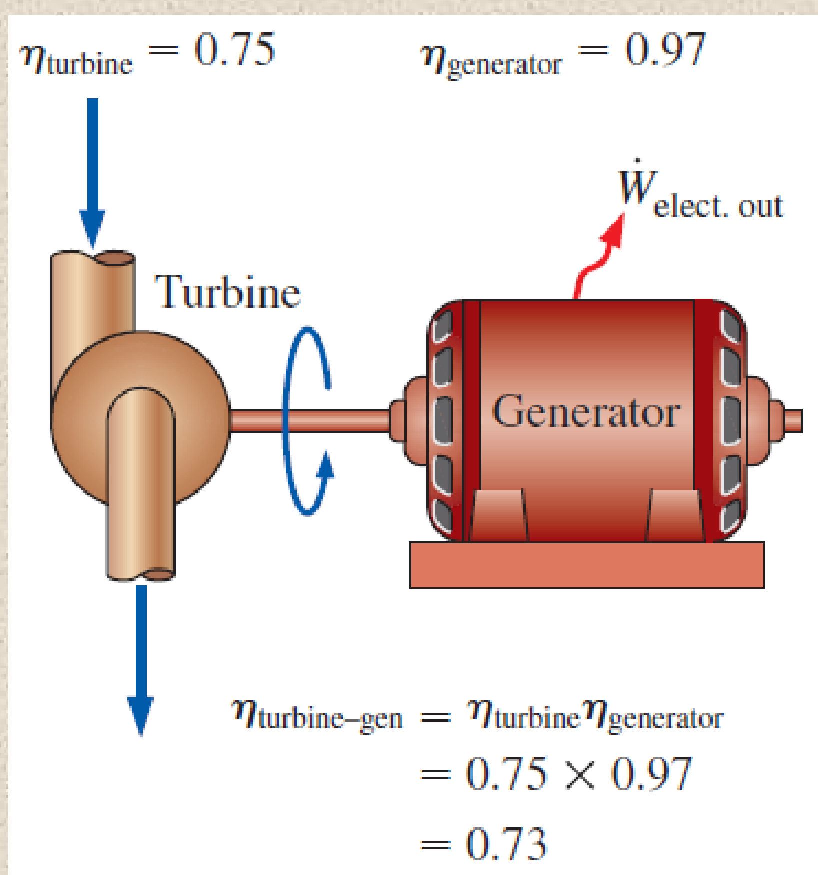


FIGURE 2–59

The overall efficiency of a turbine–generator is the product of the efficiency of the turbine and the efficiency of the generator, and represents the fraction of the mechanical power of the fluid converted to electrical power.

ENERGY AND ENVIRONMENT

- The conversion of energy from one form to another often affects the environment and the air we breathe in many ways, and thus the study of energy is not complete without considering its impact on the environment
- Pollutants emitted during the combustion of fossil fuels are responsible for **smog, acid rain**, and **global warming**
- The environmental pollution has reached such high levels that it became a serious threat to **vegetation, wild life**, and **human health**

FIGURE 2–62
Energy conversion processes are often accompanied by environmental pollution.

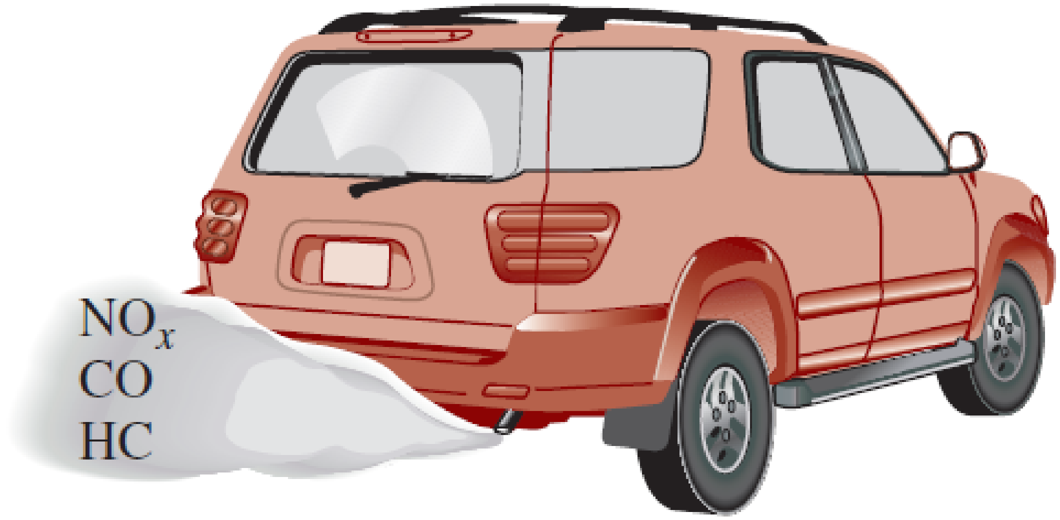


FIGURE 2–63
Motor vehicles are the largest source of air pollution.

Smog (Smoke + Fog)

- **Smog**: Made up mostly of ground-level ozone (O_3), but it also contains carbon monoxide (CO), particulate matter such as soot and dust, volatile organic compounds (VOCs)
- **Hydrocarbons** and **nitrogen oxides** react in the presence of sunlight on hot calm days to form ground-level ozone
- **Ozone** irritates eyes and damages the air sacs in the lungs, causes shortness of breath, wheezing, fatigue, headaches, and nausea, and asthma
- The other serious pollutant in smog is **carbon monoxide**, which is a colorless, odorless, poisonous gas
- It deprives the body's organs from getting enough oxygen by binding with the red blood cells that carry oxygen
- Suspended particulate matter such as dust and soot are emitted by vehicles and industrial facilities. Such particles irritate the eyes and the lungs

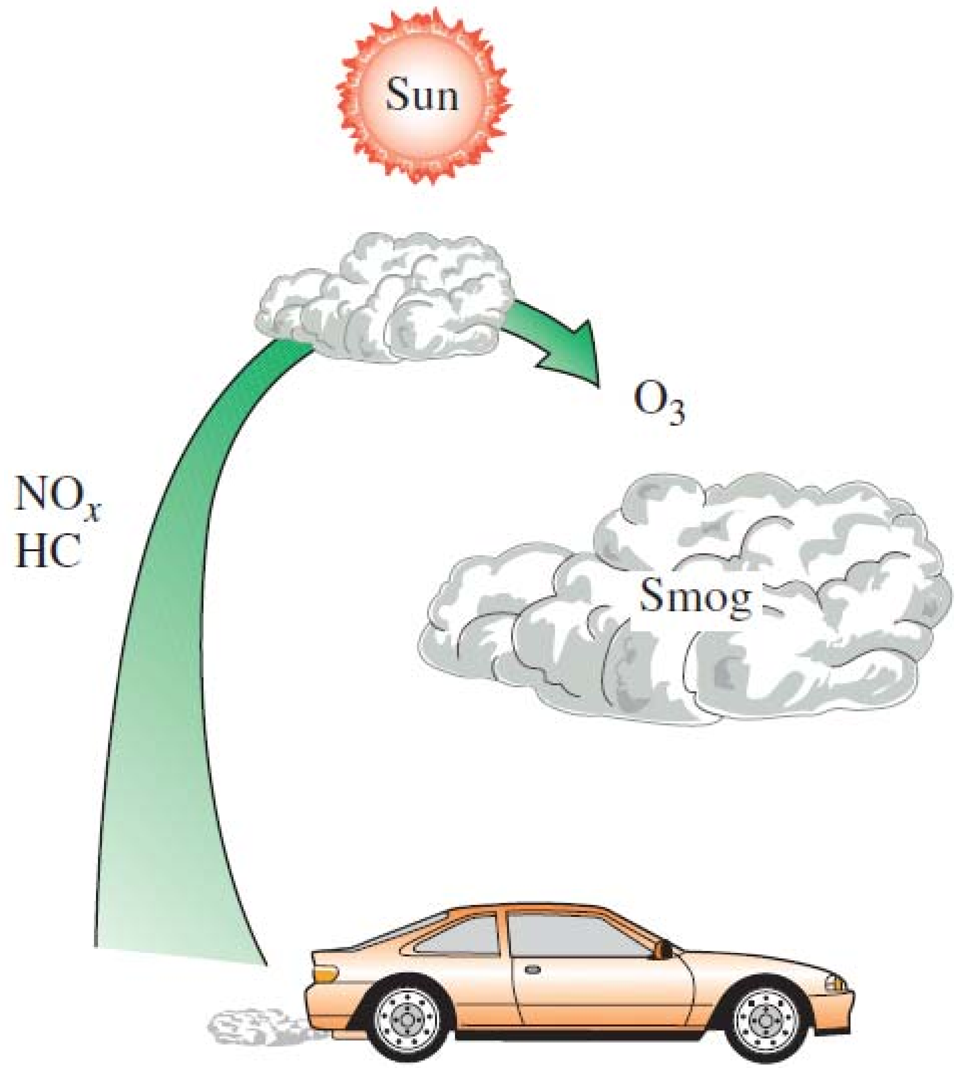


FIGURE 2–64
Ground-level ozone, which is the primary component of smog, forms when HC and NO_x react in the presence of sunlight in hot calm days.

Acid Rain

- The sulfur in the fuel reacts with oxygen to form sulfur dioxide (SO_2), which is an air pollutant
- The main source of SO_2 is the electric power plants that burn high-sulfur coal
- Motor vehicles also contribute to SO_2 emissions since gasoline and diesel fuel also contain small amounts of sulfur
- The sulfur oxides and nitric oxides react with water vapor and other chemicals high in the atmosphere in the presence of sunlight to form *sulfuric* and *nitric acids*
- The acids formed usually dissolve in the suspended water droplets in clouds or fog
- These acid-laden droplets, which can be as acidic as lemon juice, are washed from the air on to the soil by rain or snow. This is known as **acid rain**

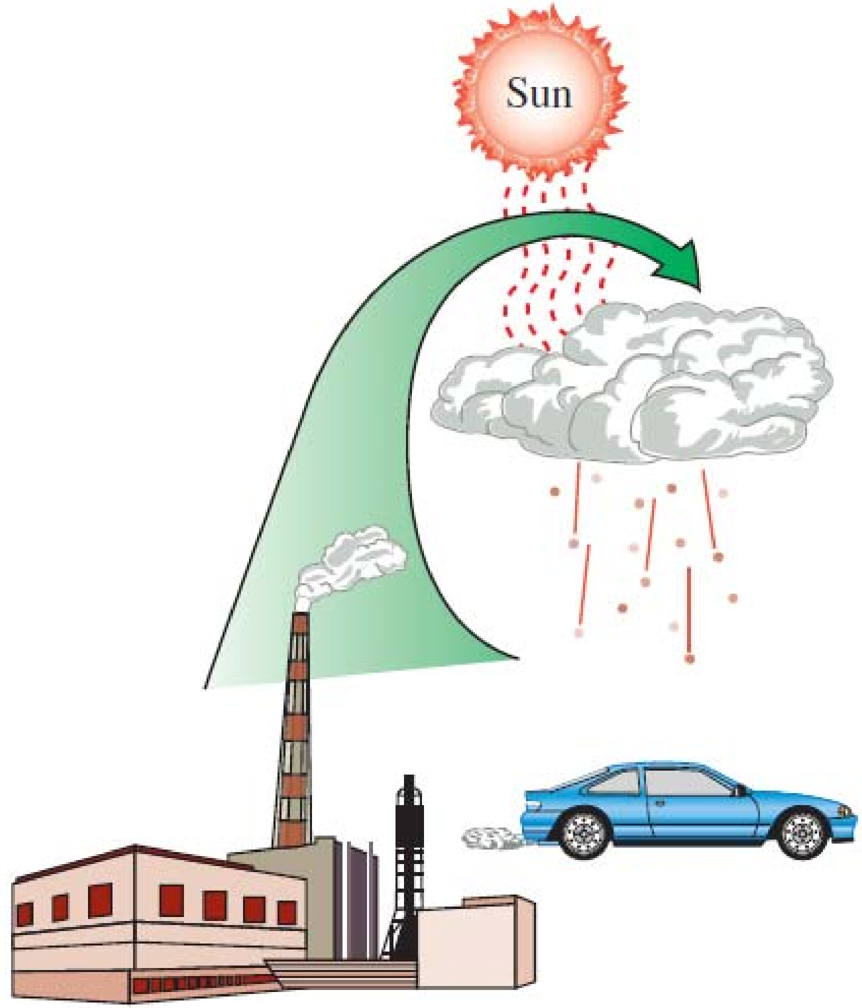


FIGURE 2–65

Sulfuric acid and nitric acid are formed when sulfur oxides and nitric oxides react with water vapor and other chemicals high in the atmosphere in the presence of sunlight.

The Greenhouse Effect: Global Warming and Climate Change

- **Greenhouse effect**: Glass allows the solar radiation to enter freely but blocks the infrared radiation emitted by the interior surfaces. This causes a rise in the interior temperature as a result of the thermal energy buildup in a space (i.e., car).
- **Carbon dioxide (CO_2),** water vapor, and trace amounts of some other gases such as methane and nitrogen oxides act like a blanket and keep the earth warm by blocking the heat radiated from the earth
- These gases are called "**greenhouse gases**," with CO_2 being the primary component

The Greenhouse Effect: Global Warming and Climate Change

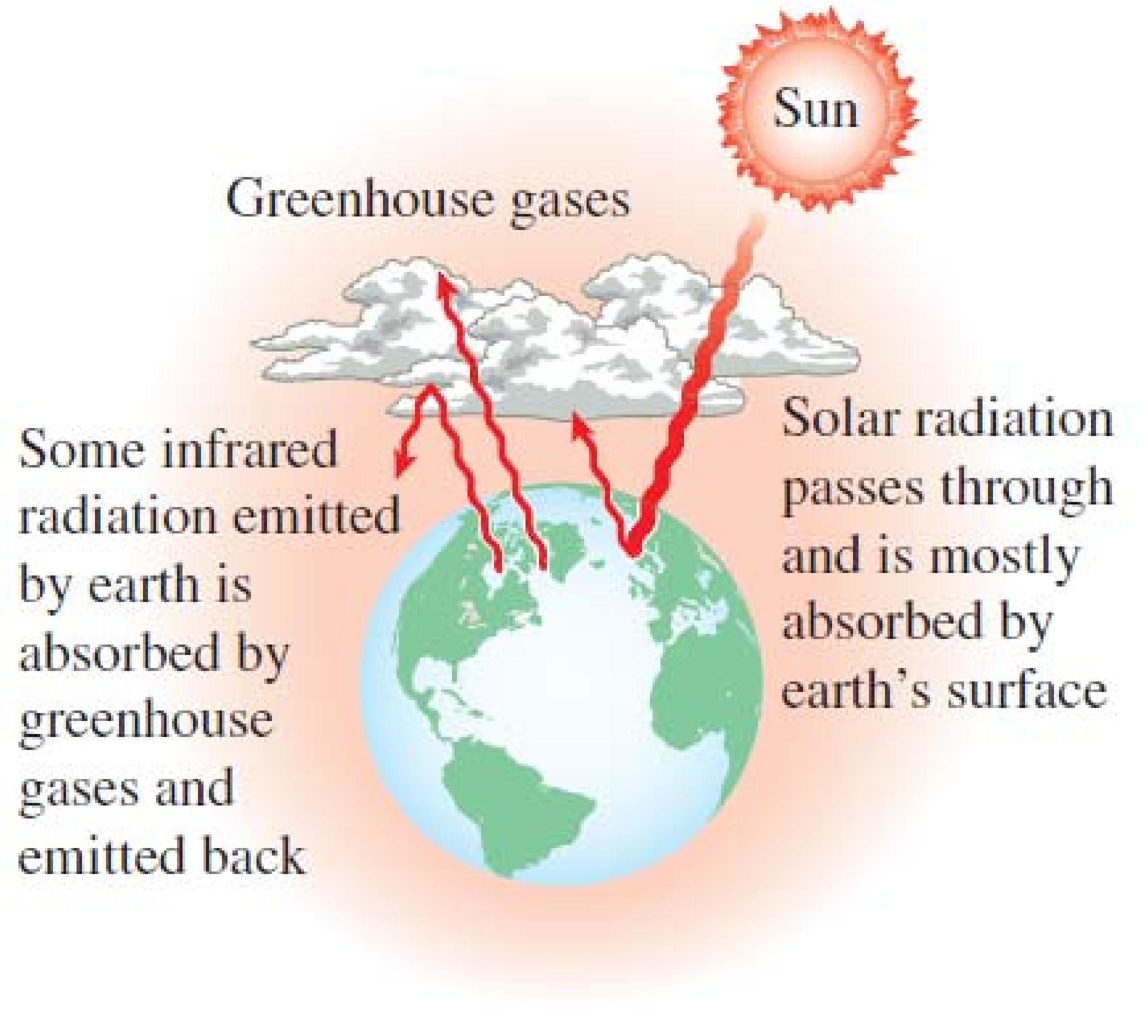


FIGURE 2–66
The greenhouse effect on earth.

- CO_2 is produced by the burning of fossil fuels such as **coal**, **oil**, **and natural gas**.

- **A 1995 report**: The earth has already warmed about **0.5 °C** during the last century, and they estimate that the earth's temperature will rise another **2 °C** by the year 2100
- A rise of this magnitude can cause **severe changes in weather patterns** with storms and heavy rains and flooding at some parts and drought in others, major floods due to the melting of ice at the poles, loss of wetlands and coastal areas due to rising sea levels, and other negative results
  - Improved energy efficiency,
  - energy conservation,
  - using renewable energy sources
  - help minimize global warming

FIGURE 2–67
The average car produces several times its weight in CO_2 every year (it is driven 13,500 miles a year, consumes 600 gallons of gasoline, and produces 20 lbm of CO_2 per gallon).

FIGURE 2–68
Renewable energies such as wind are called "green energy" since they emit no pollutants or greenhouse gases.

Summary

- Forms of energy
  - ✓ Macroscopic = kinetic + potential
  - ✓ Microscopic = Internal energy (sensible + latent + chemical + nuclear)
- 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)
- Energy conversion efficiencies
  - ✓ Efficiencies of mechanical and electrical devices (turbines, pumps)
- Energy and environment
  - ✓ Ozone and smog
  - ✓ Acid rain
  - ✓ The Greenhouse effect: Global warming and climate change