

Thermodynamics: An Engineering Approach, 6th Edition
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Chapter 2

ENERGY, ENERGY TRANSFER, AND GENERAL ENERGY ANALYSIS

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.
- 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.
- Define energy conversion efficiencies.

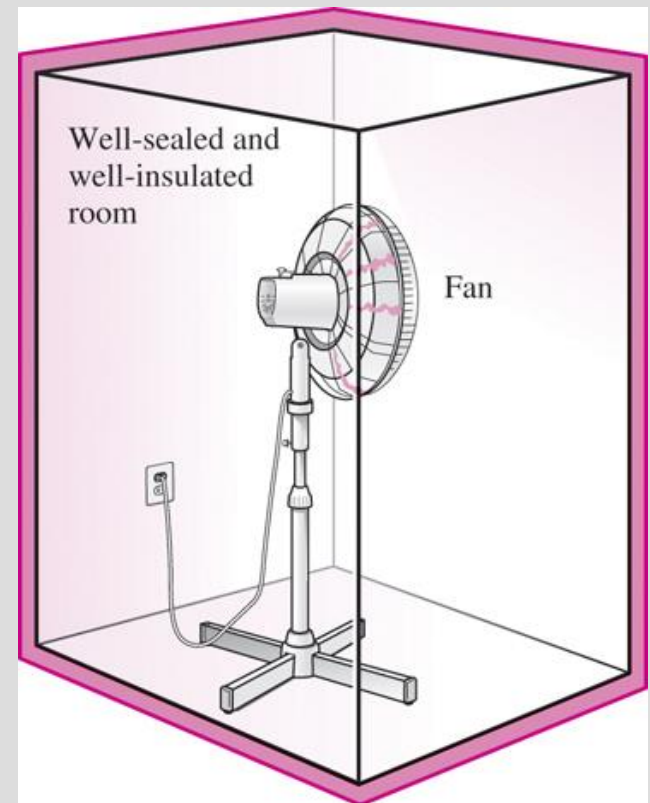
INTRODUCTION

- 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.
- As a result of the 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

- 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.
- Thermodynamics deals only with the **change** of the total energy.
- **Macroscopic forms of energy:** Those a system possesses as a whole with respect to some outside reference frame, such as kinetic and potential energies.
- **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.
- **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.



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

$$\text{KE} = m \frac{V^2}{2} \quad (\text{kJ}) \quad \text{Kinetic energy}$$

$$\text{ke} = \frac{V^2}{2} \quad (\text{kJ/kg}) \quad \text{Kinetic energy per unit mass}$$

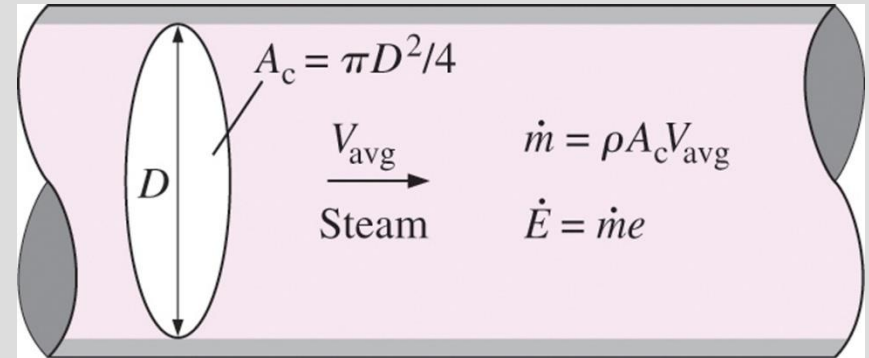
$$\text{PE} = mgz \quad (\text{kJ}) \quad \text{Potential energy}$$

$$\text{pe} = gz \quad (\text{kJ/kg}) \quad \text{Potential energy per unit mass}$$

$$E = U + \text{KE} + \text{PE} = U + m \frac{V^2}{2} + mgz \quad (\text{kJ}) \quad \text{Total energy of a system}$$

$$e = u + \text{ke} + \text{pe} = u + \frac{V^2}{2} + gz \quad (\text{kJ/kg}) \quad \text{Energy of a system per unit mass}$$

$$e = \frac{E}{m} \quad (\text{kJ/kg}) \quad \text{Total energy per unit mass}$$



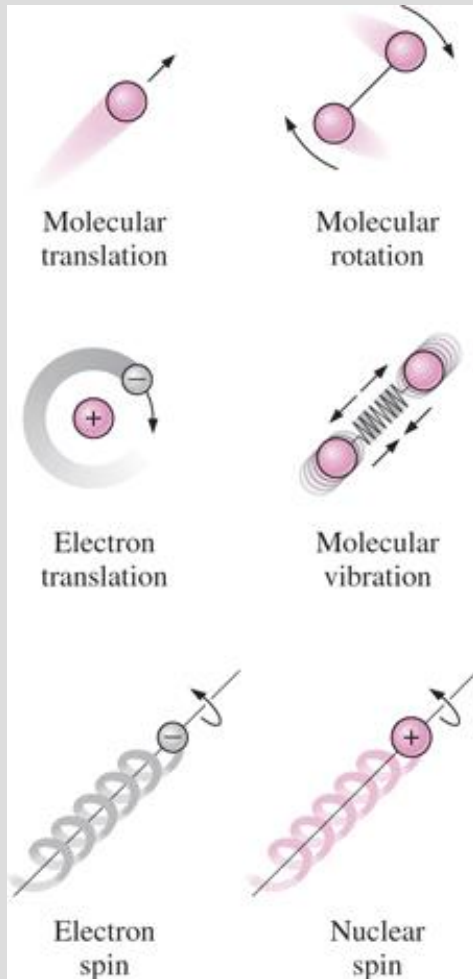
Mass flow rate

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

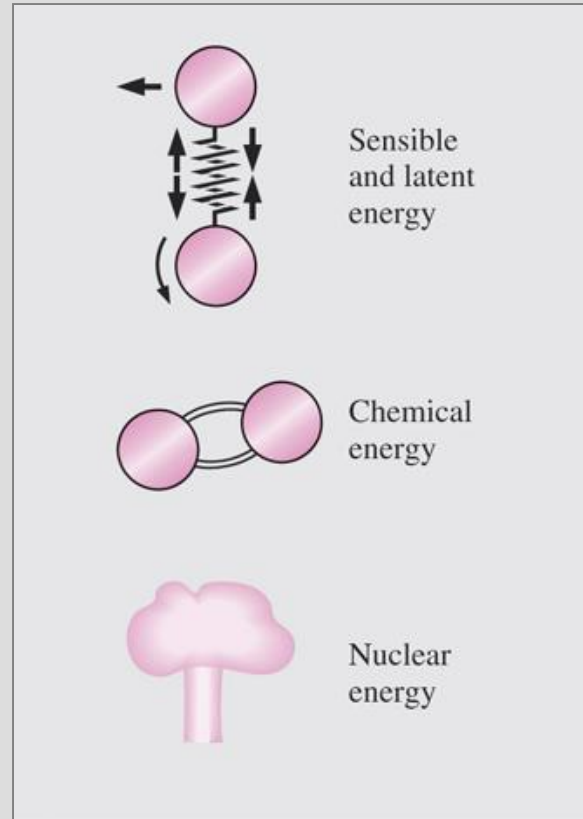
Energy flow rate

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

Some Physical Insight to Internal Energy



The various forms of microscopic energies that make up *sensible* energy.



The internal energy of a system is the sum of all forms of the microscopic energies.

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.

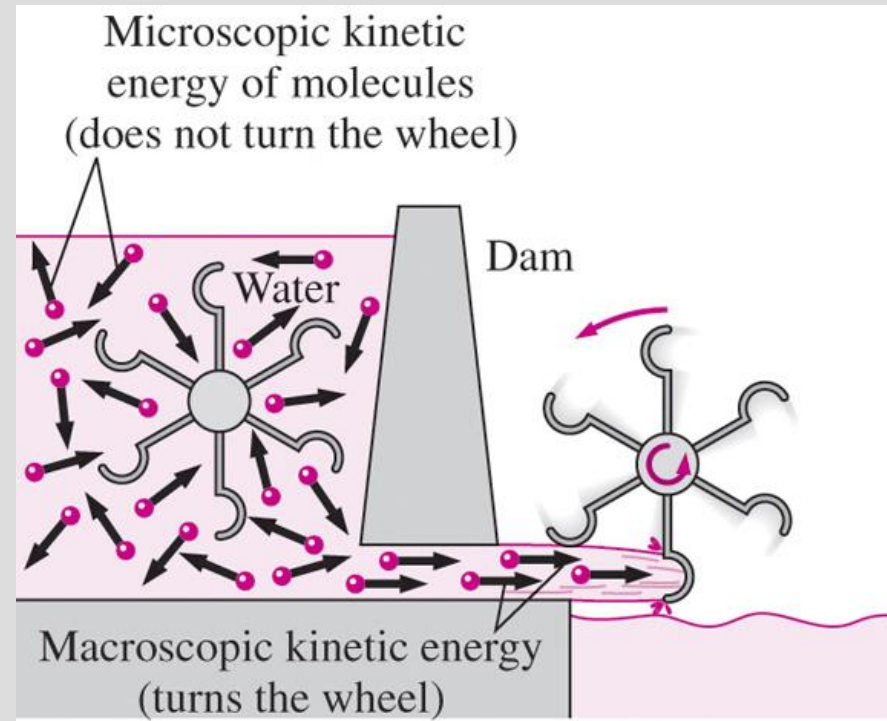
Chemical energy: The internal energy associated with the atomic bonds in a molecule.

Nuclear energy: The tremendous amount of energy associated with the strong bonds within the nucleus of the atom itself.

Thermal = Sensible + Latent

Internal = Sensible + Latent + Chemical + Nuclear

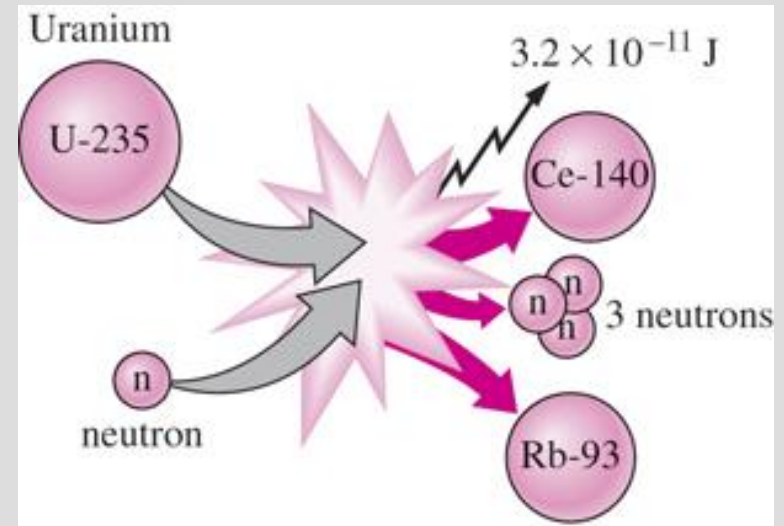
- The total energy of a system, can be *contained* or *stored* in a system, and thus can be viewed as the **static forms of energy**.
- The forms of energy not stored in a system can be viewed as the **dynamic forms of energy** or as **energy interactions**.
- The dynamic forms of energy are recognized at the system boundary as they cross it, and they represent the energy gained or lost by a system during a process.
- The only two forms of energy interactions associated with a closed system are **heat transfer** and **work**.
- **The difference between heat transfer and work:** An energy interaction is heat transfer if its driving force is a temperature difference. Otherwise it is work.



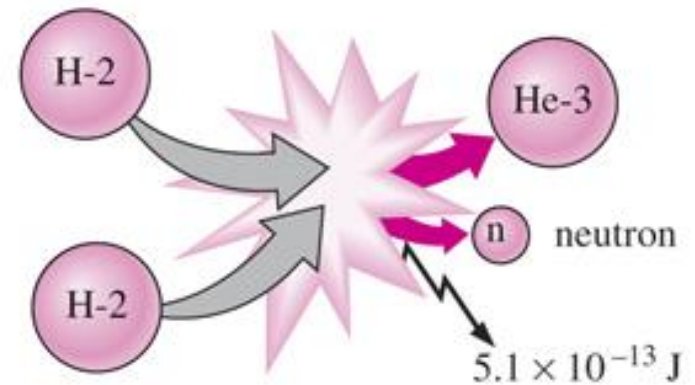
The *macroscopic* kinetic energy is an organized form of energy and is much more useful than the disorganized *microscopic* kinetic energies of the molecules.

More on Nuclear Energy

- The best known **fission** reaction involves the split of the uranium atom (the U-235 isotope) into other elements and is commonly used to generate electricity in nuclear power plants (440 of them in 2004, generating 363,000 MW worldwide), to power nuclear submarines and aircraft carriers, and even to power spacecraft as well as building nuclear bombs.
- Nuclear energy by **fusion** is released when two small nuclei combine into a larger one.
- The uncontrolled fusion reaction was achieved in the early 1950s, but all the efforts since then to achieve controlled fusion by massive lasers, powerful magnetic fields, and electric currents to generate power have failed.



(a) Fission of uranium



(b) Fusion of hydrogen

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

Mechanical Energy

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

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

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

Mechanical energy of a flowing fluid per unit mass

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

Rate of mechanical energy of a flowing fluid

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

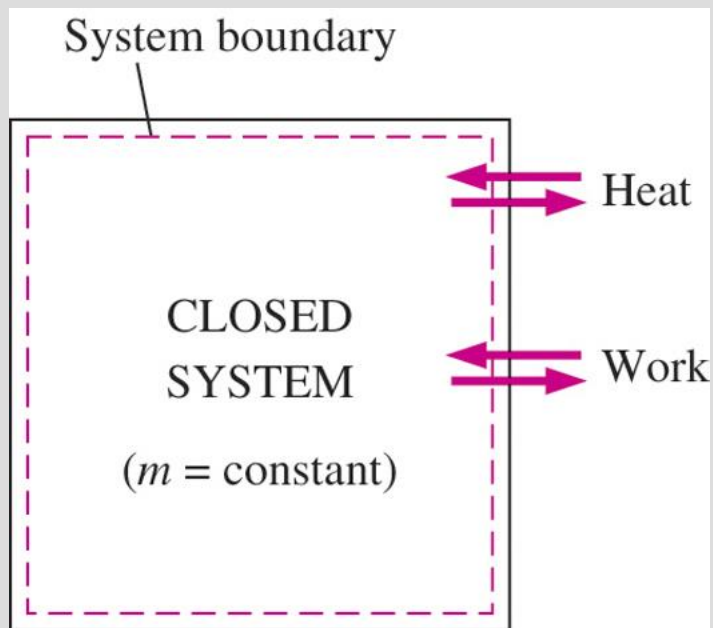
$$\Delta e_{\text{mech}} = \frac{P_2 - P_1}{\rho} + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1) \quad (\text{kJ/kg})$$

Rate of mechanical energy change of a fluid during incompressible flow

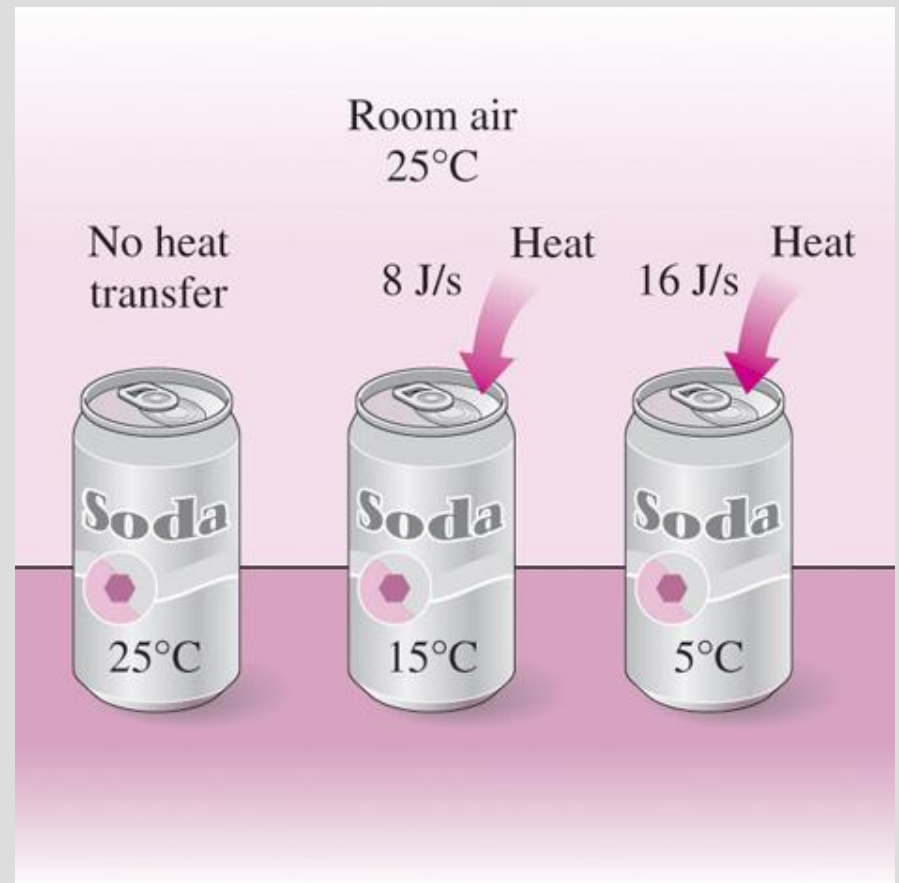
$$\Delta \dot{E}_{\text{mech}} = \dot{m}\Delta e_{\text{mech}} = \dot{m}\left(\frac{P_2 - P_1}{\rho} + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)\right) \quad (\text{kW})$$

ENERGY TRANSFER BY HEAT

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



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



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

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

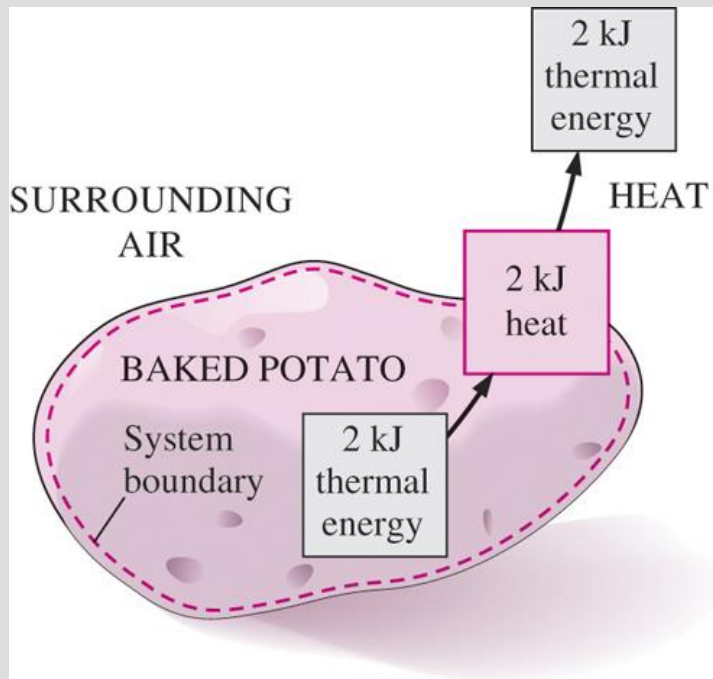
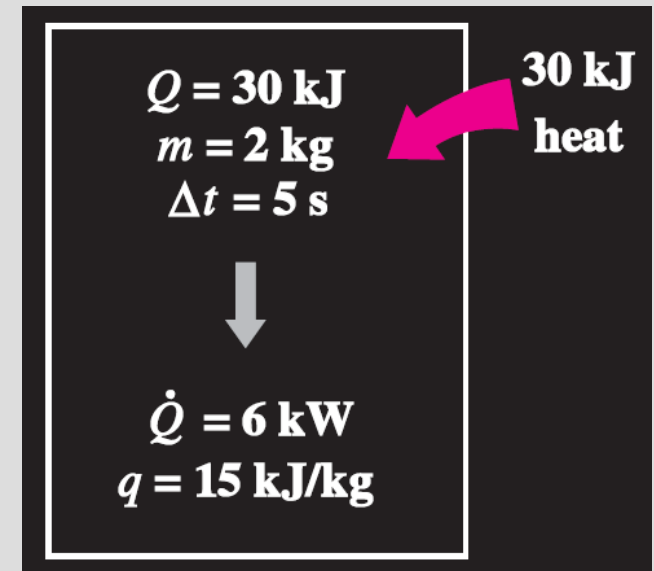
Heat transfer
per unit mass

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

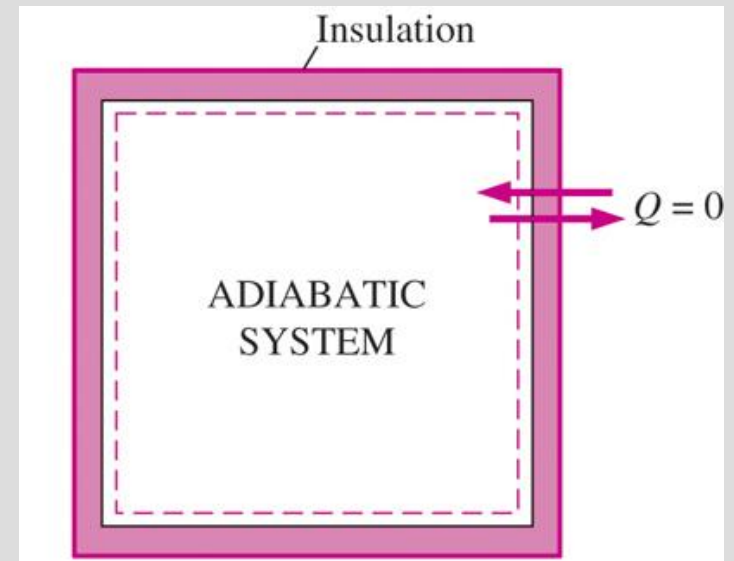
Amount of heat transfer
when heat transfer rate
is constant

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

Amount of heat transfer
when heat transfer rate
changes with time



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



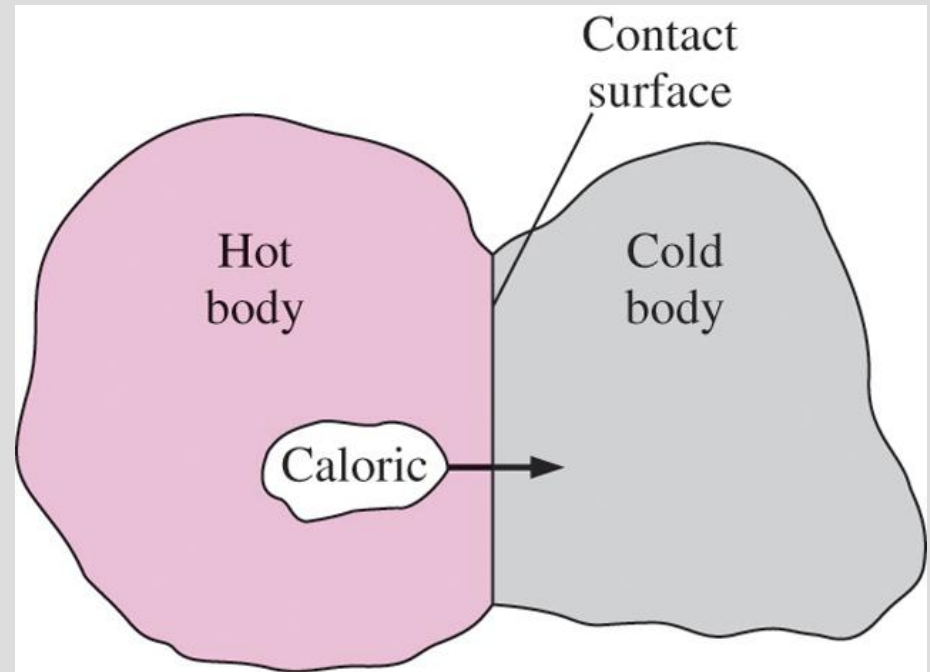
During an adiabatic process, a system
exchanges no heat with its surroundings.

Historical Background on Heat

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

Heat transfer mechanisms:

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



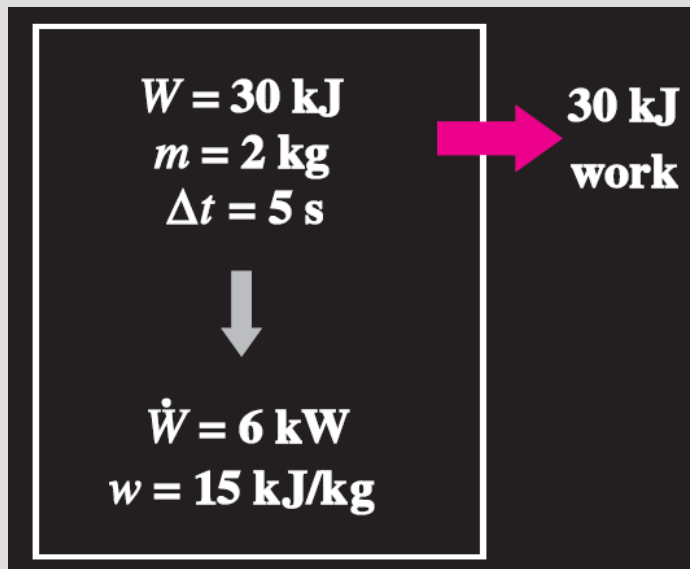
In the early nineteenth century, heat was thought to be an invisible fluid called the **caloric** that flowed from warmer bodies to the cooler ones.

ENERGY TRANSFER BY WORK

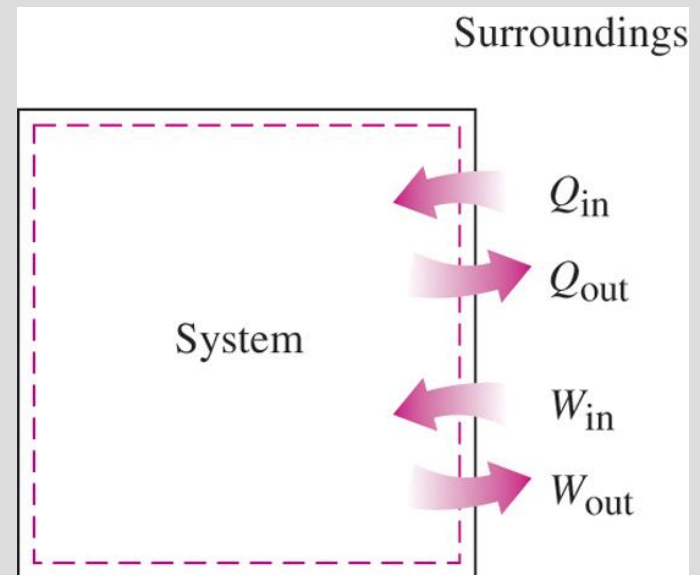
- **Work:** The energy transfer associated with a force acting through a distance.
 - ✓ **A rising piston, a rotating shaft, and an electric wire crossing the system boundaries** are all associated with work interactions
- **Formal sign convention:** *Heat transfer to a system and work done by a system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

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

Work done per unit mass



Power is the work done per unit time (kW)



Specifying the directions of heat and work.

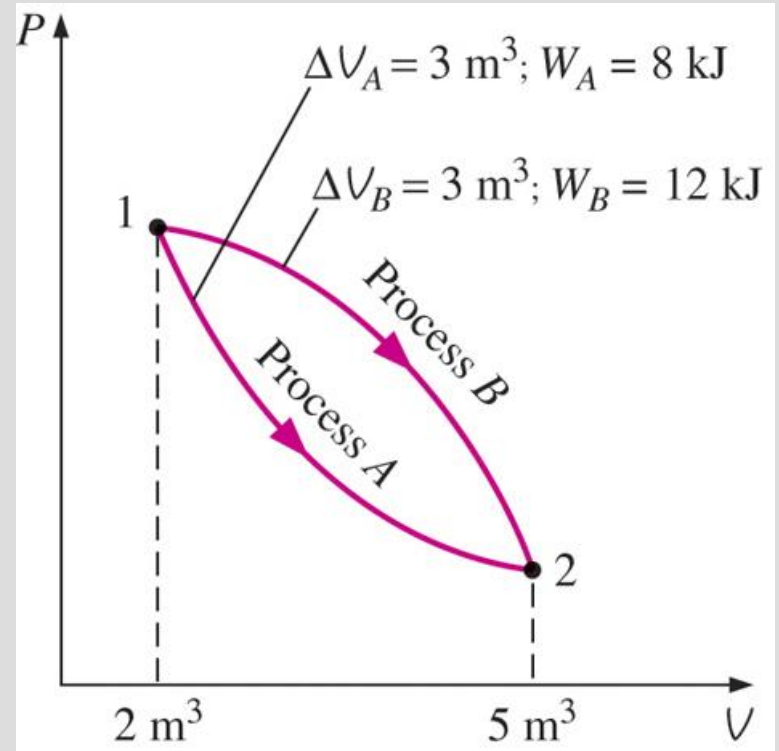
Heat vs. Work

- Both are recognized at the boundaries of a system as they cross the boundaries. That is, both heat and work are *boundary* phenomena.
- Systems possess energy, but not heat or work.
- Both are associated with a *process*, 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 (δ)



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

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

MECHANICAL FORMS OF WORK

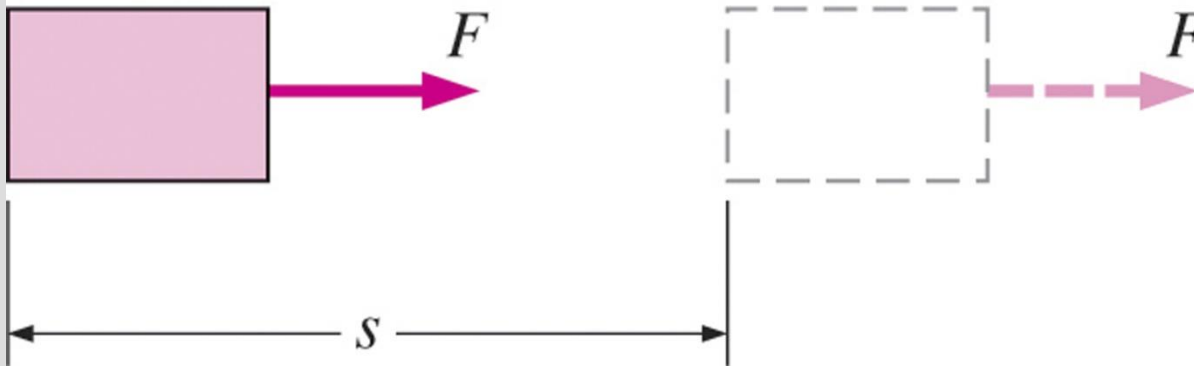
- There are two requirements for a work interaction between a system and its surroundings to exist:
 - ✓ there must be a **force** acting on the boundary.
 - ✓ the boundary must **move**.

Work = Force × Distance

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

When force is not constant

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



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



If there is no movement, no work is done.

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

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

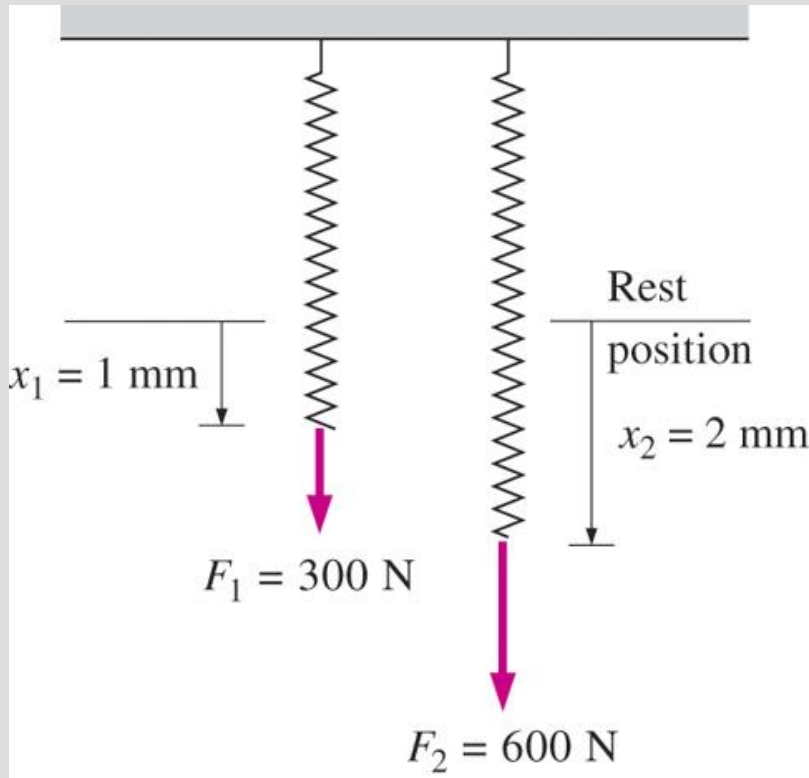
For linear elastic springs, the displacement x is proportional to the force applied

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

Substituting and integrating yield

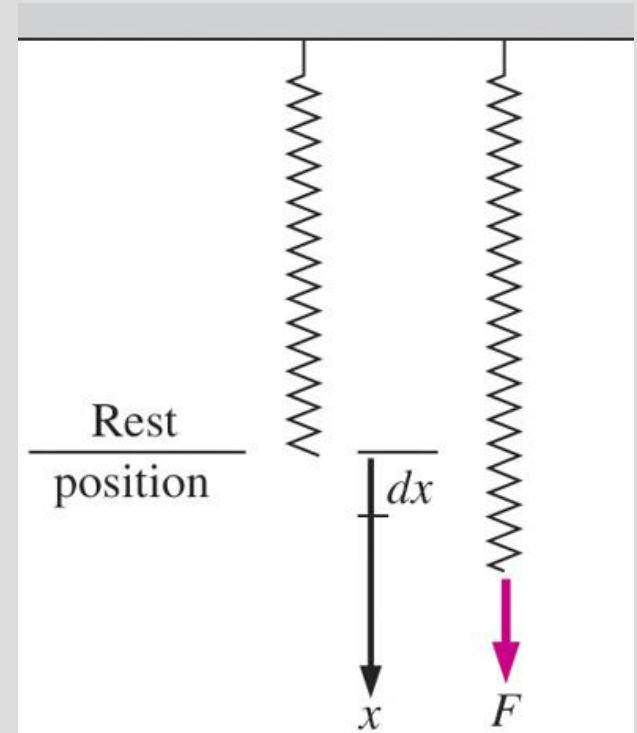
$$W_{\text{spring}} = \frac{1}{2}k(x_2^2 - x_1^2) \quad (\text{kJ})$$

x_1 and x_2 : the initial and the final displacements



Elongation
of a spring
under the
influence of
a force.

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



Work Done to Raise or to Accelerate a Body

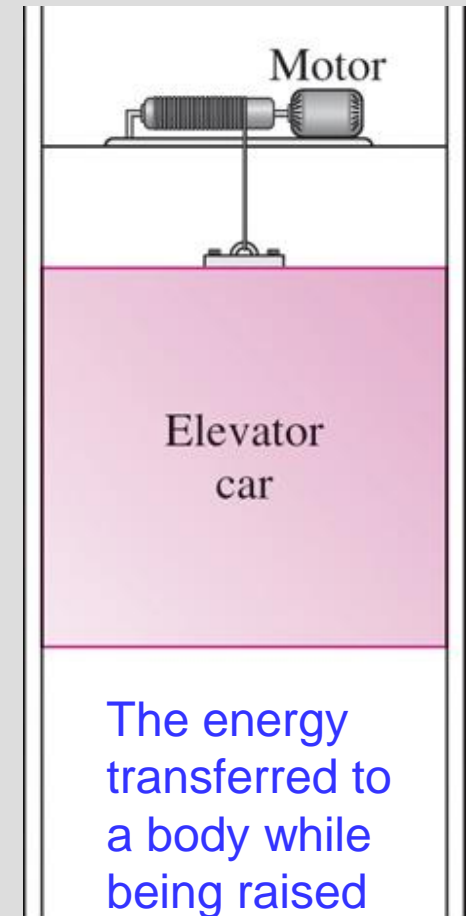
1. The work transfer needed to raise a body is equal to the change in the potential energy of the body.
2. The work transfer needed to accelerate a body is equal to the change in the kinetic energy of the body.

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*.

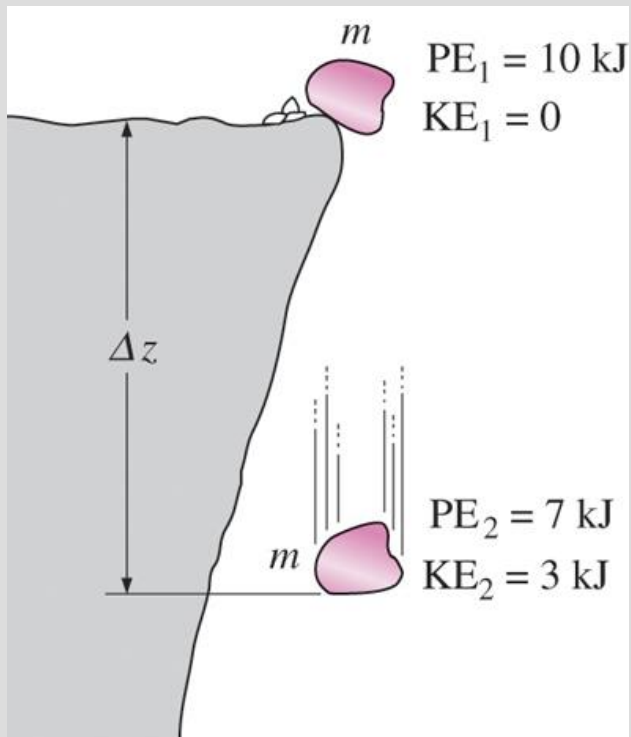
Electrical polarization work: The generalized force is the *electric field strength* and the generalized displacement is the *polarization of the medium*.



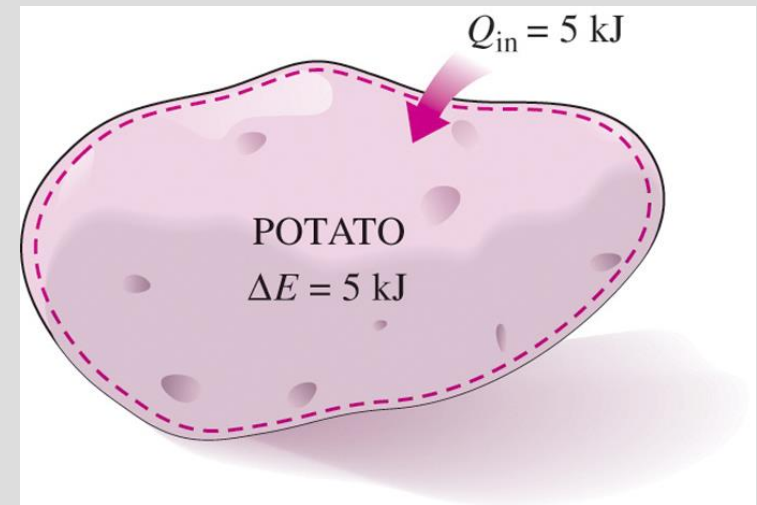
The energy transferred to a body while being raised is equal to the change in its potential energy.

THE FIRST LAW OF THERMODYNAMICS

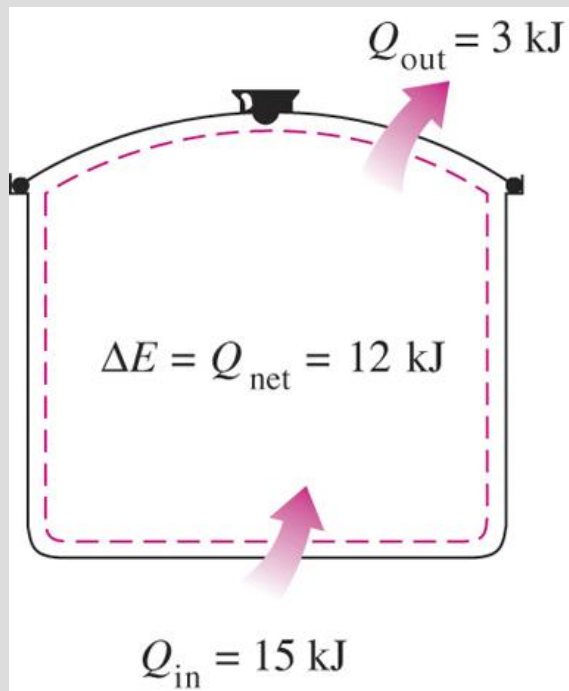
- The *first law of thermodynamics (the conservation of energy principle)* provides a sound basis for studying the relationships among the various forms of energy and energy interactions.
- The first law states that *energy can be neither created nor destroyed during a process; it can only change forms.*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



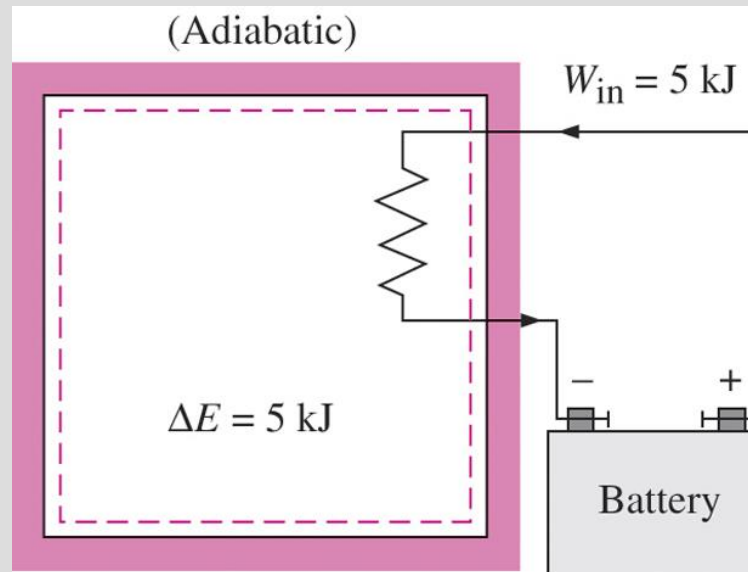
Energy cannot be created or destroyed; it can only change forms.



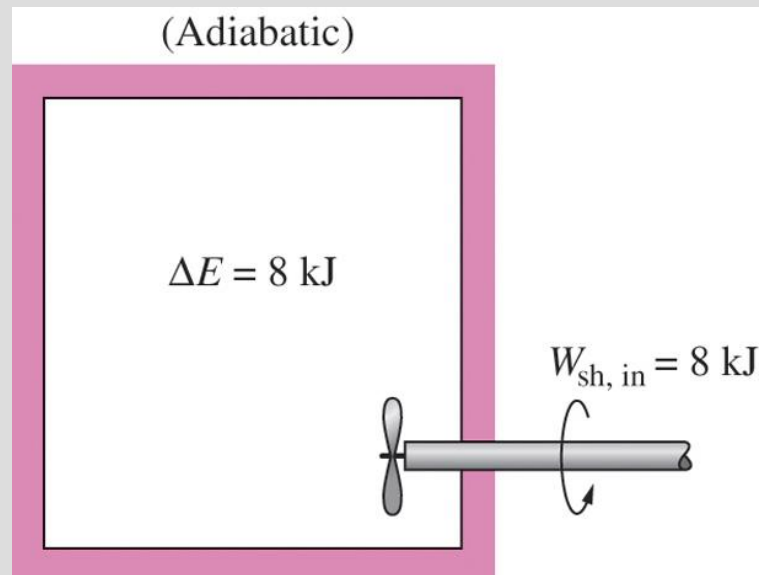
The increase in the energy of a potato in an oven is equal to the amount of heat transferred to it.



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



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



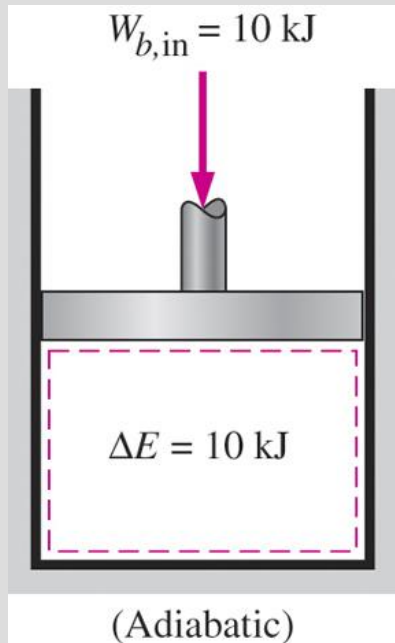
The work (shaft) done on an adiabatic system is equal to the increase in the energy of the system.

Energy Balance

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

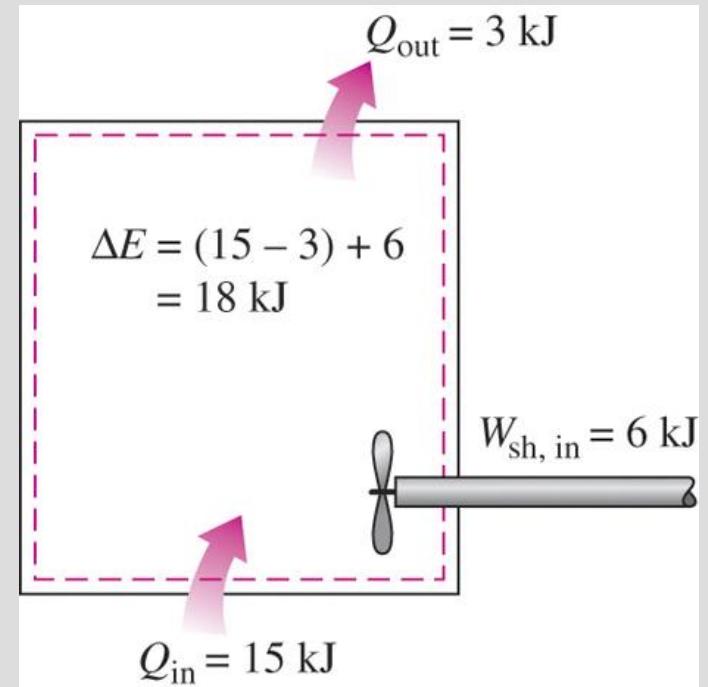
$$\left(\begin{array}{c} \text{Total energy} \\ \text{entering the system} \end{array} \right) - \left(\begin{array}{c} \text{Total energy} \\ \text{leaving the system} \end{array} \right) = \left(\begin{array}{c} \text{Change in the total} \\ \text{energy of the system} \end{array} \right)$$

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



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

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



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

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

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

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

Stationary Systems

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

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

$$\Delta E = \Delta U$$

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

- Heat transfer
- Work transfer
- Mass flow

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

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

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

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

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

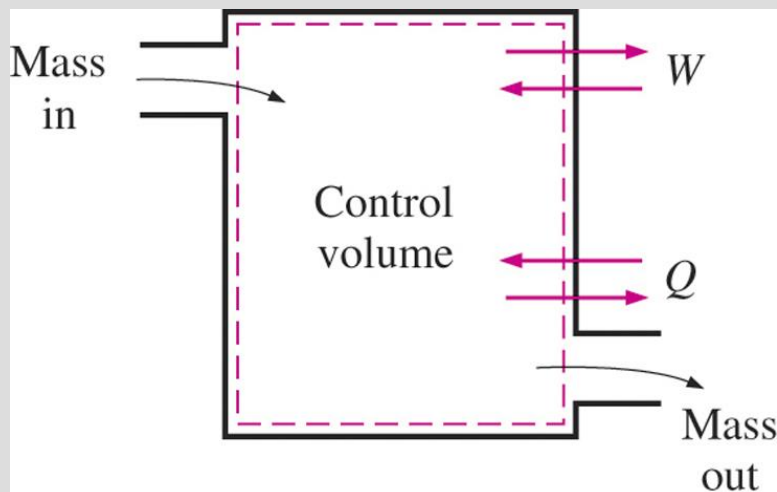
$$\delta E_{in} - \delta E_{out} = dE_{system} \quad \delta e_{in} - \delta e_{out} = de_{system}$$

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

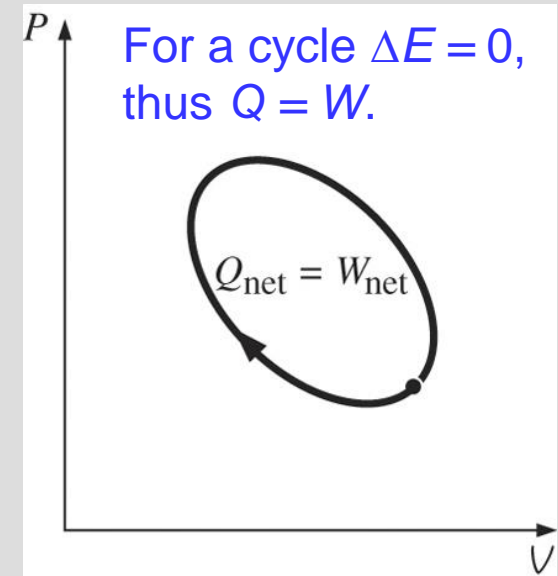
$$Q = \dot{Q} \Delta t \quad (\text{kJ})$$

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

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

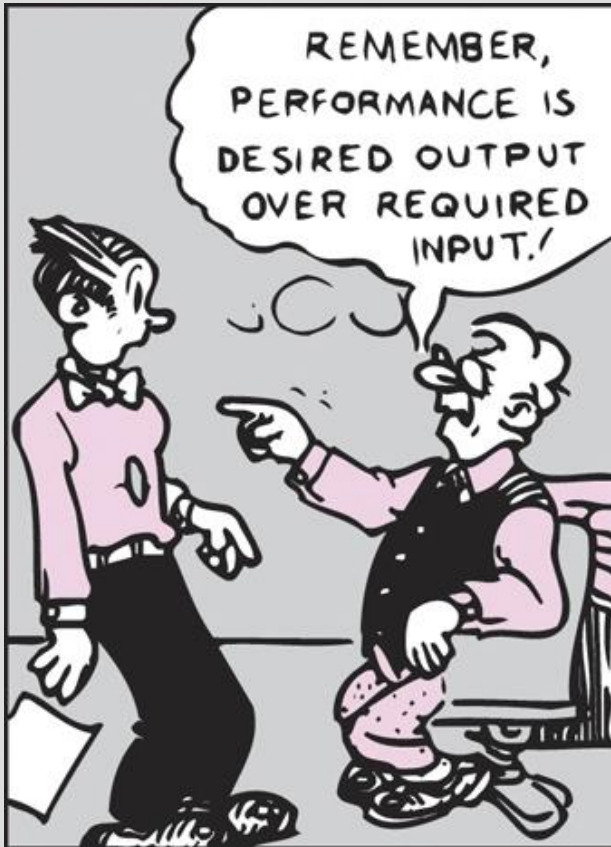


The energy content of a control volume can be changed by mass flow as well as heat and work interactions.



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.



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

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

Type	Efficiency
Gas, conventional	55%
Gas, high-efficiency	62%
Electric, conventional	90%
Electric, high-efficiency	94%

The definition of performance is not limited to thermodynamics only.

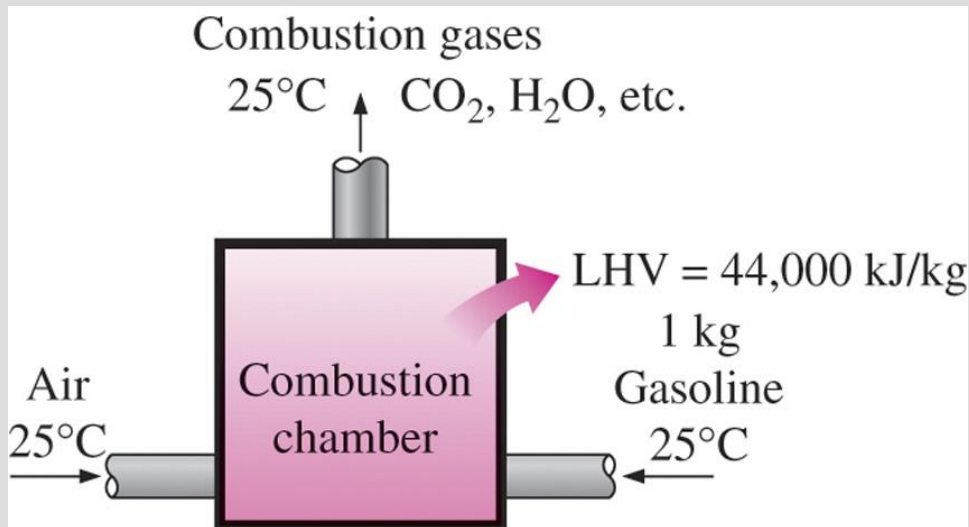


$$\eta_{\text{combustion}} = \frac{Q}{\text{HV}} = \frac{\text{Amount of heat released during combustion}}{\text{Heating value of the fuel burned}}$$

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.



The definition of the heating value of gasoline.

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

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

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

Overall efficiency of a power plant

TABLE 2–1

The efficacy of different lighting systems

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

Lighting efficacy:

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

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

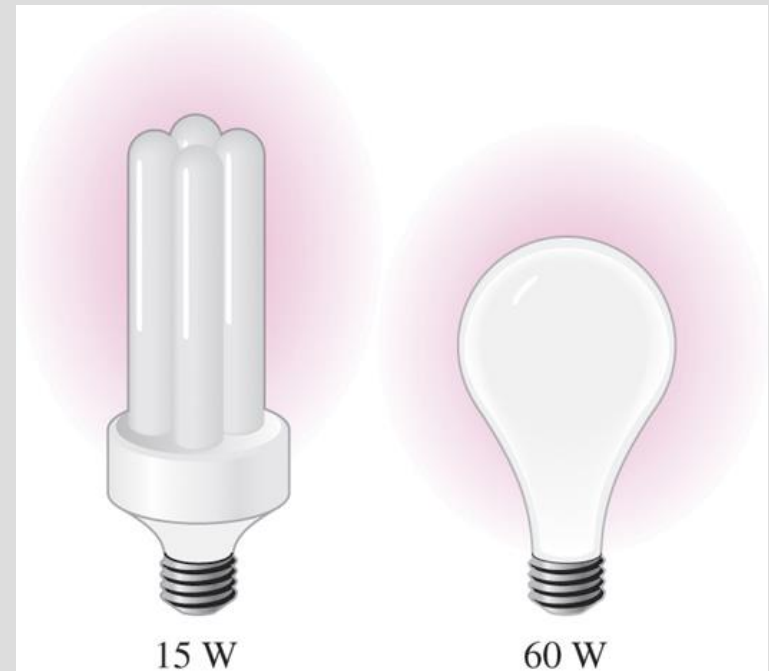


TABLE 2-2

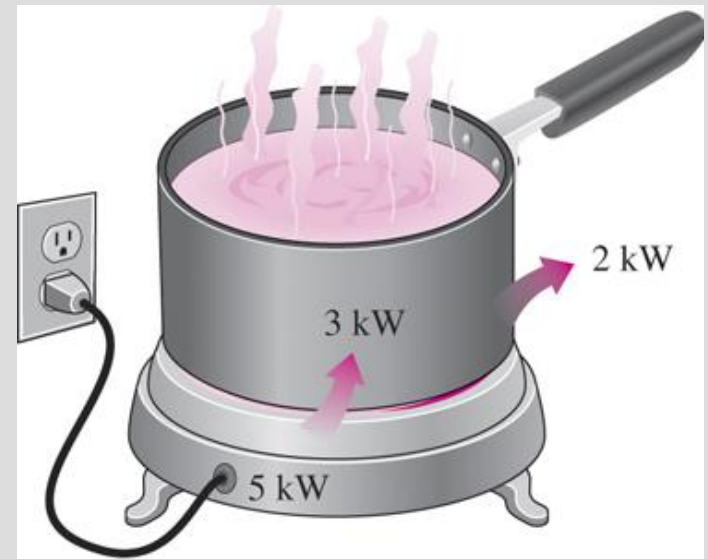
Energy costs of cooking a casserole with different appliances*

[From A. Wilson and J. Morril, *Consumer Guide to Home Energy Savings*, Washington, DC: American Council for an Energy-Efficient Economy, 1996, p. 192.]

Cooking appliance	Cooking temperature	Cooking time	Energy used	Cost of energy
Electric oven	350°F (177°C)	1 h	2.0 kWh	\$0.16
Convection oven (elect.)	325°F (163°C)	45 min	1.39 kWh	\$0.11
Gas oven	350°F (177°C)	1 h	0.112 therm	\$0.07
Frying pan	420°F (216°C)	1 h	0.9 kWh	\$0.07
Toaster oven	425°F (218°C)	50 min	0.95 kWh	\$0.08
Electric slow cooker	200°F (93°C)	7 h	0.7 kWh	\$0.06
Microwave oven	"High"	15 min	0.36 kWh	\$0.03

*Assumes a unit cost of \$0.08/kWh for electricity and \$0.60/therm for gas.

- 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.



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

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

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

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)