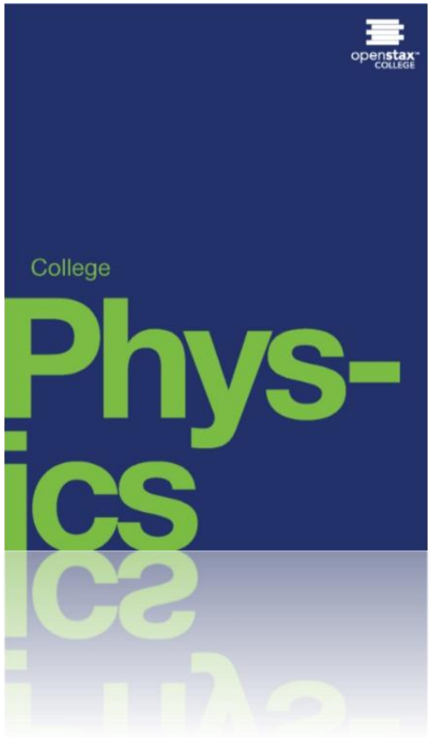
COLLEGE PHYSICS

Chapter 15 THERMODYNAMICS

PowerPoint Image Slideshow



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Contents of Chapter 15

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- Entropy and the Second Law of Thermodynamics
- Order to Disorder
- Unavailability of Energy; Heat Death

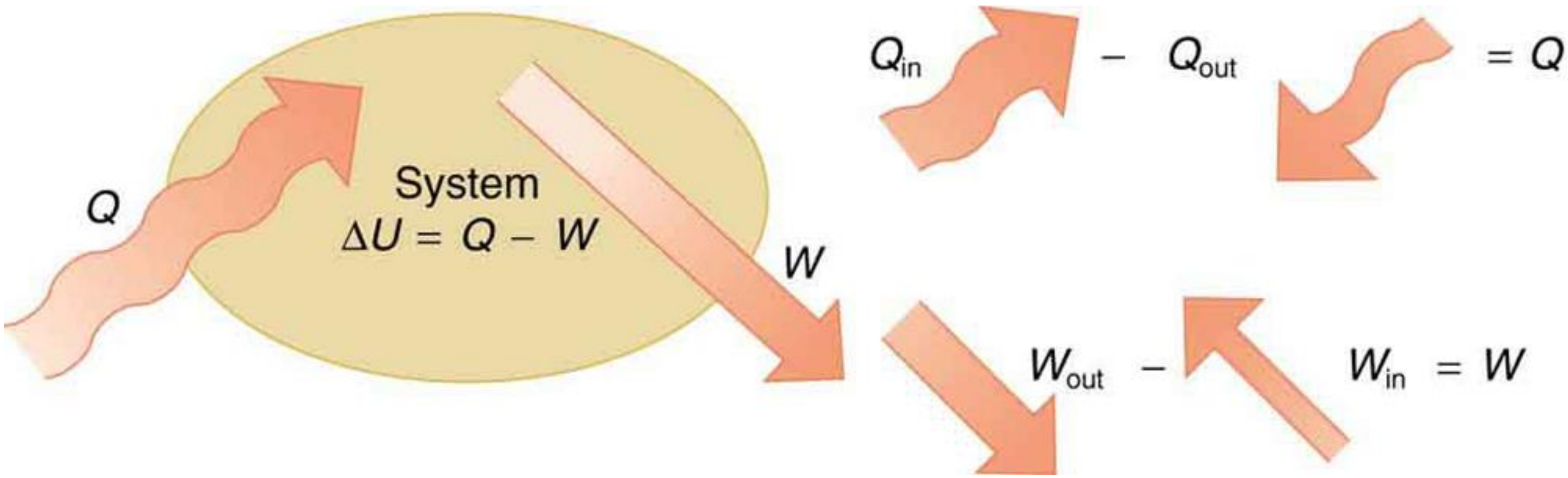
FIGURE 15.1

A steam engine uses heat transfer to do work. Tourists regularly ride this narrow-gauge steam engine train near the San Juan Skyway in Durango, Colorado, part of the National Scenic Byways Program. (credit: Dennis Adams)

FIGURE 15.2

This boiling tea kettle represents energy in motion. The water in the kettle is turning to water vapor because heat is being transferred from the stove to the kettle. As the entire system gets hotter, work is done—from the evaporation of the water to the whistling of the kettle. (credit: Gina Hamilton)

FIGURE 15.3



The first law of thermodynamics is the conservation-of-energy principle stated for a system where heat and work are the methods of transferring energy for a system in thermal equilibrium. Q represents the net heat transfer—it is the sum of all heat transfers into and out of the system. Q is positive for net heat transfer *into* the system. W is the total work done on and by the system. W is positive when more work is done *by* the system than on it. The change in the internal energy of the system, ΔU , is related to heat and work by the first law of thermodynamics, $\Delta U = Q - W$.

FIGURE 15.4

Two different processes produce the same change in a system.

(a) A total of 15.00 J of heat transfer occurs into the system, while work takes out a total of 6.00 J. The change in internal energy is $\Delta U = Q - W = 9.00\,J$.

(b) Heat transfer removes 150.00 J from the system while work puts 159.00 J into it, producing an increase of 9.00 J in internal energy.

If the system starts out in the same state in (a) and (b), it will end up in the same final state in either case—its final state is related to internal energy, not how that energy was acquired.

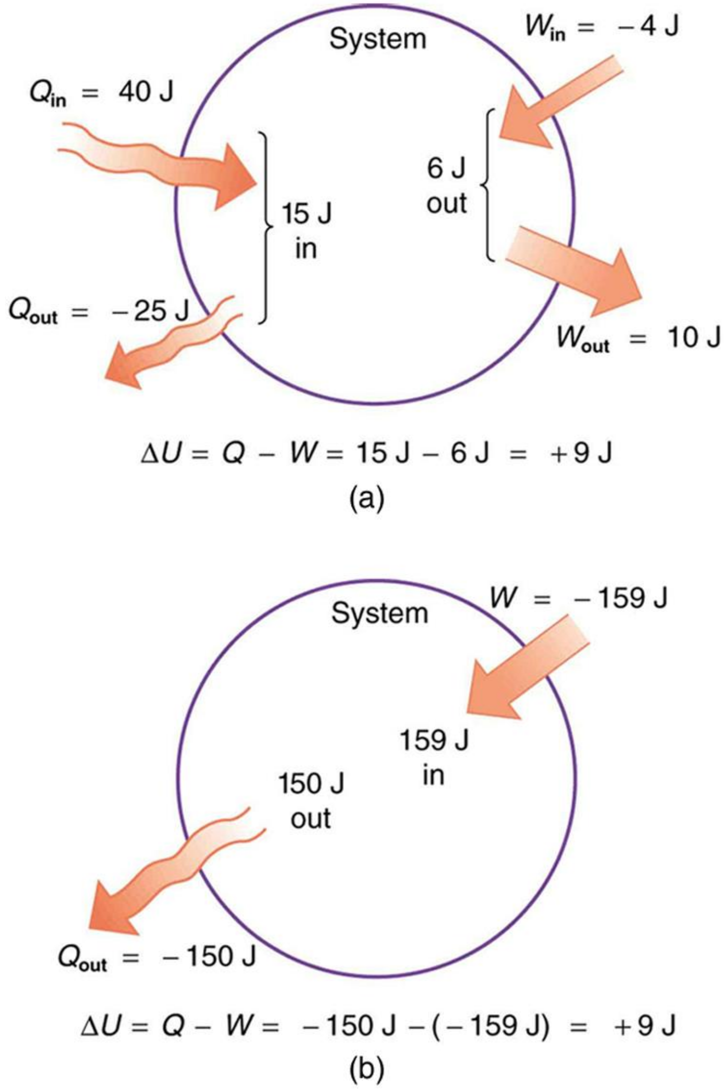
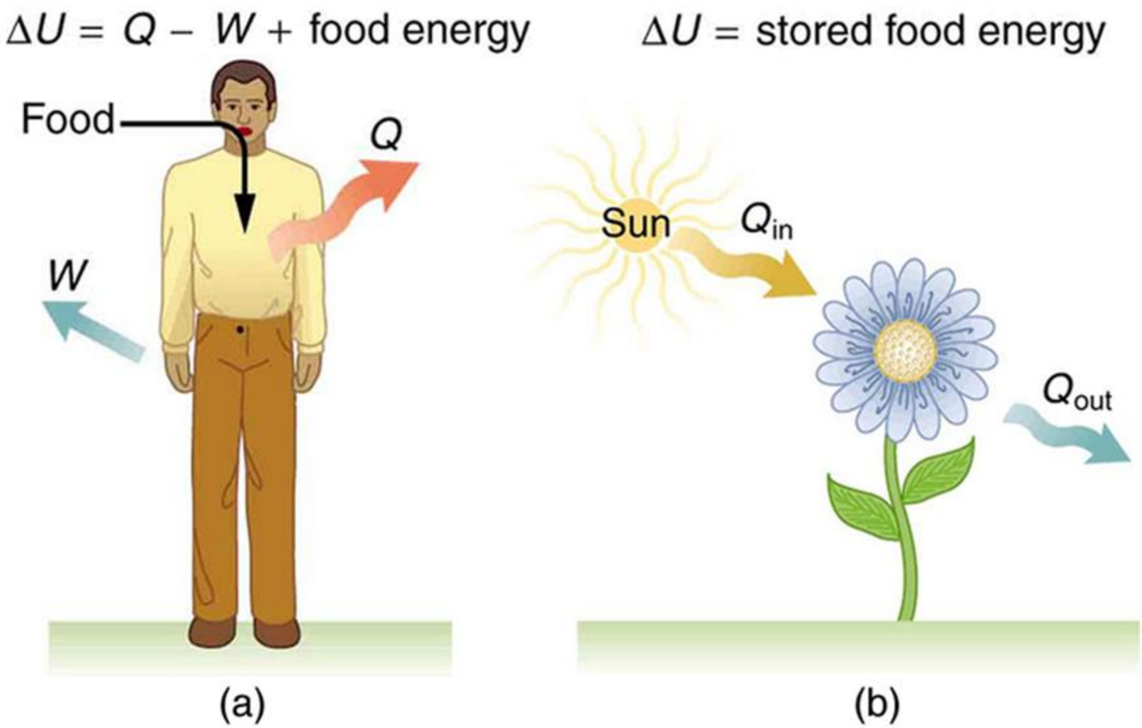


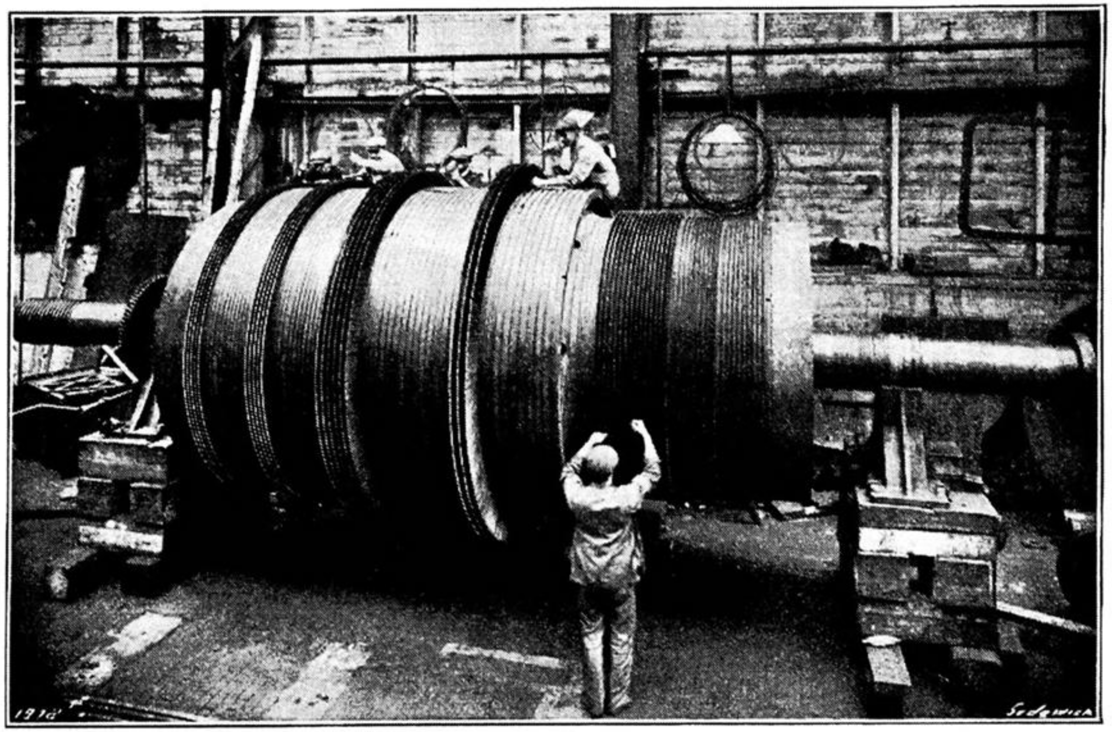
FIGURE 15.5



(a) The first law of thermodynamics applied to metabolism. Heat transferred out of the body (Q) and work done by the body (W) remove internal energy, while food intake replaces it. (Food intake may be considered as work done on the body.)

(b) Plants convert part of the radiant heat transfer in sunlight to stored chemical energy, a process called photosynthesis.

FIGURE 15.6



Beginning with the Industrial Revolution, humans have harnessed power through the use of the first law of thermodynamics, before we even understood it completely. This photo, of a steam engine at the Turbinia Works, dates from 1911, a mere 61 years after the first explicit statement of the first law of thermodynamics by Rudolph Clausius. (credit: public domain; author unknown)

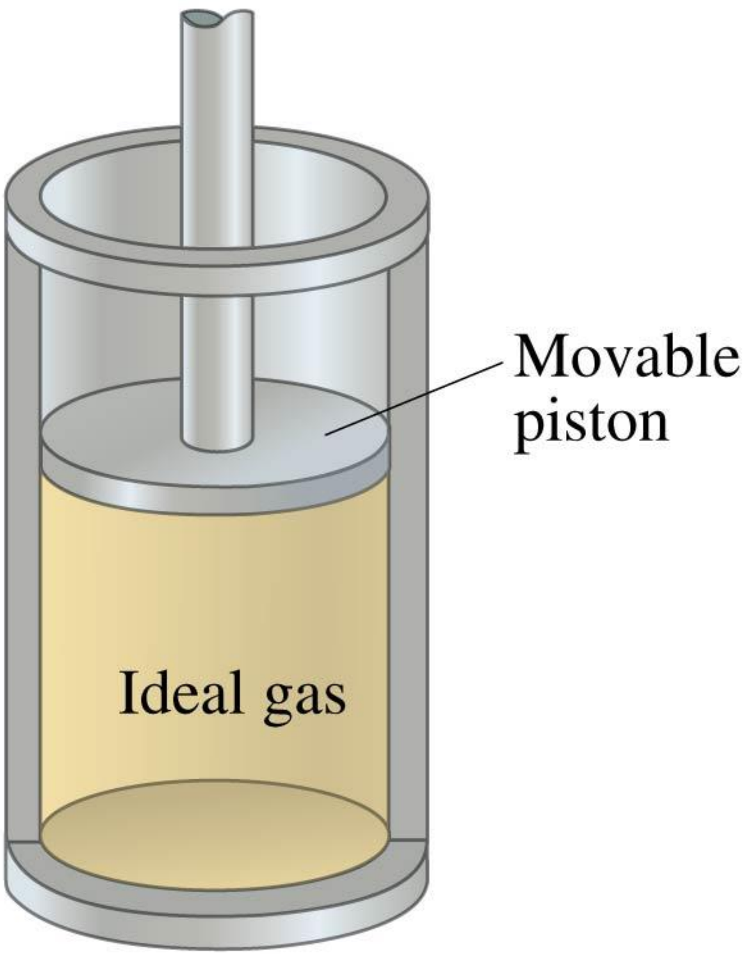
The First Law of Thermodynamics

The change in internal energy of a closed system will be equal to the energy added to the system minus the work done by the system on its surroundings.

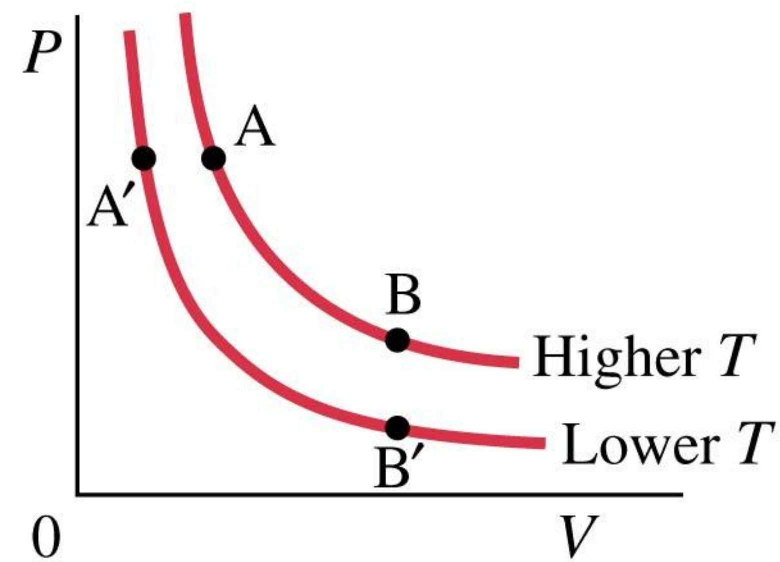
$$\Delta U = Q - W$$

This is the law of conservation of energy, written in a form useful to systems involving heat transfer.

Thermodynamic Processes and the First Law



An isothermal process is one where the temperature does not change.



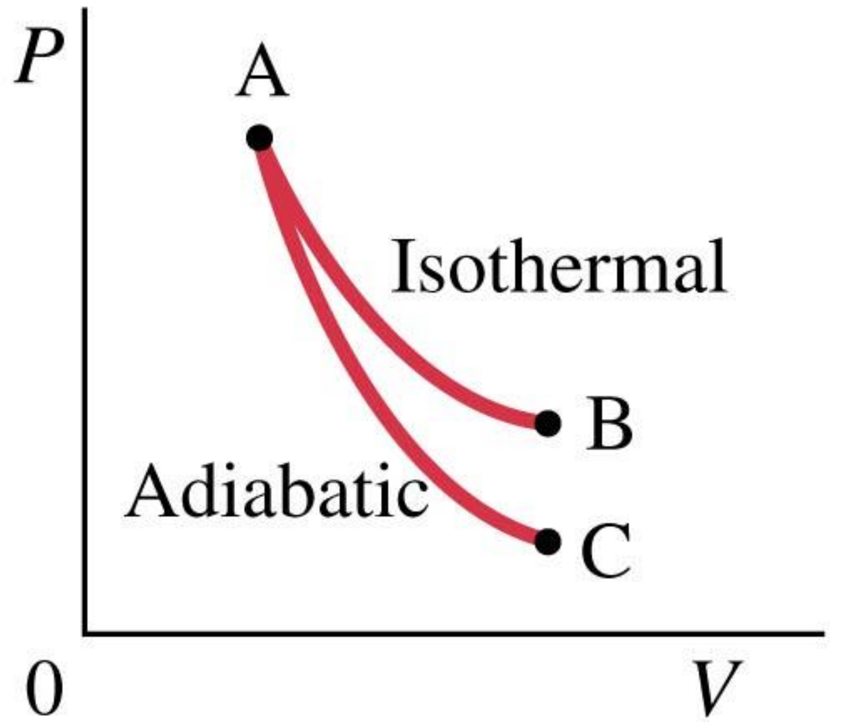
Thermodynamic Processes and the First Law

In order for an isothermal process to take place, we assume the system is in contact with a heat reservoir.

In general, we assume that the system remains in equilibrium throughout all processes.

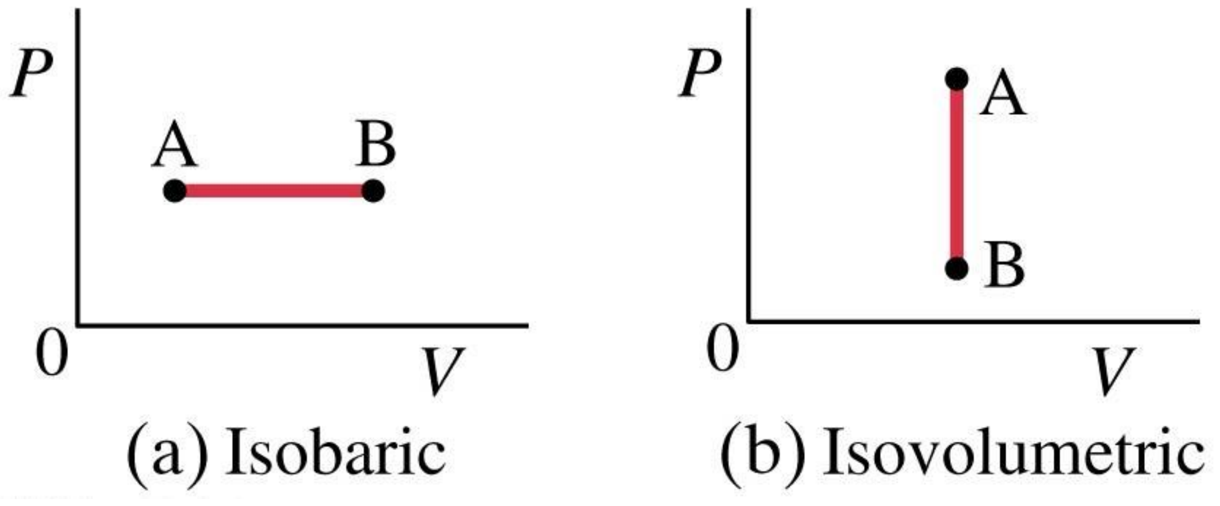
Thermodynamic Processes and the First Law

An adiabatic process is one where there is no heat flow into or out of the system.



Thermodynamic Processes and the First Law

An isobaric process (a) occurs at constant pressure; an isovolumetric one (b) at constant volume.



Thermodynamic Processes and the First Law

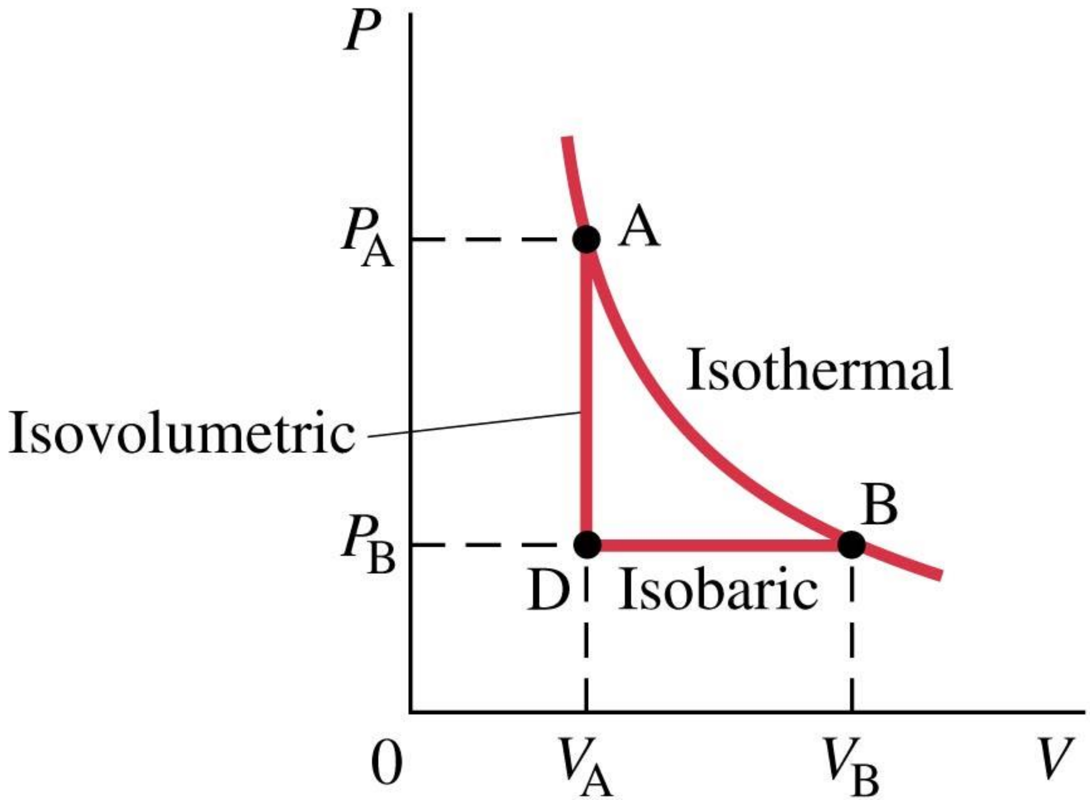
If the pressure is constant, the work done is the pressure multiplied by the change in volume:

$W = P \Delta V$ - [constant pressure]

In an isovolumetric process, the volume does not change, so the work done is zero.

Thermodynamic Processes and the First Law

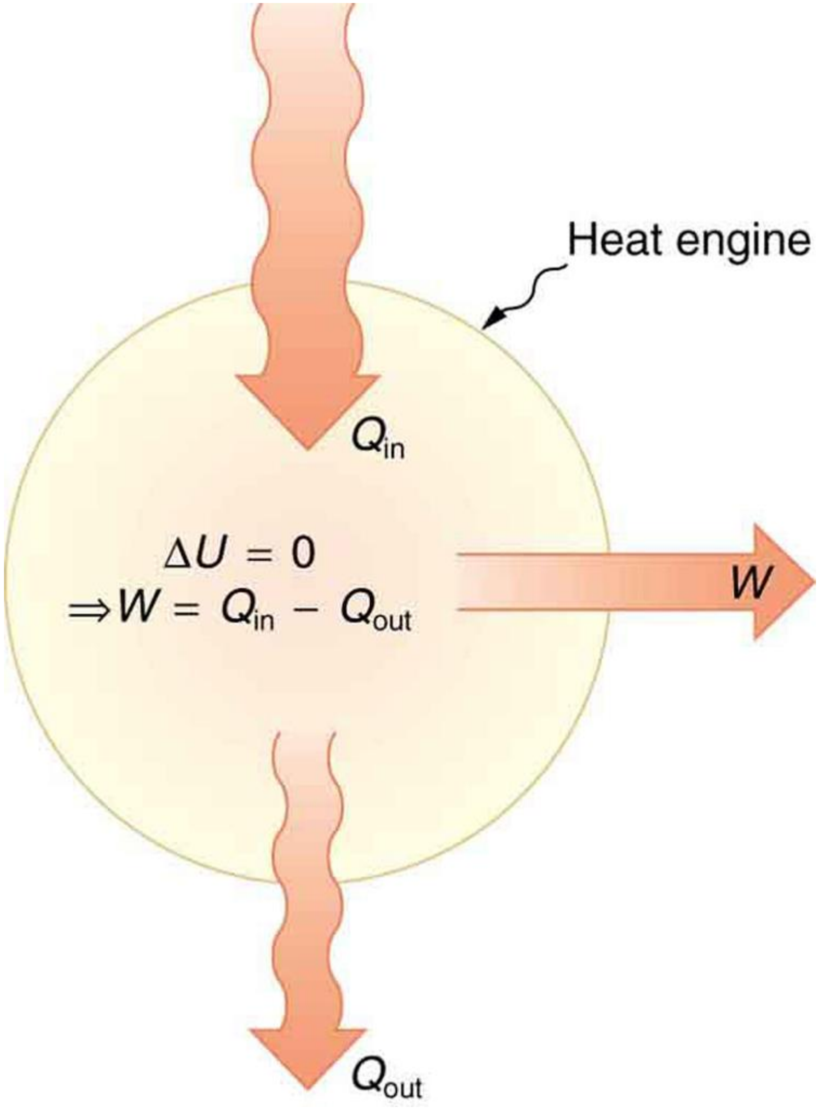
For processes where the pressure varies, the work done is the area under the P-V curve.



Thermodynamic Processes and the First Law

Process	What is constant:	The first law, $\Delta U = Q - W$, predicts:
Isothermal	T = constant	$\Delta T = 0$ makes $\Delta U = 0$, so $Q = W$
Isobaric	P = constant	$Q = \Delta U + W = \Delta U + P\,\Delta V$
Isovolumetric	V = constant	$\Delta V = 0$ makes $W = 0$, so $Q = \Delta U$
Adiabatic	$Q = 0$	$\Delta U = -W$

FIGURE 15.7



Schematic representation of a heat engine, governed, of course, by the first law of thermodynamics. It is impossible to devise a system where $Q_{out} = 0$, that is, in which no heat transfer occurs to the environment.

FIGURE 15.8

(a) Heat transfer to the gas in a cylinder increases the internal energy of the gas, creating higher pressure and temperature.

(b) The force exerted on the movable cylinder does work as the gas expands. Gas pressure and temperature decrease when it expands, indicating that the gas's internal energy has been decreased by doing work.

(c) Heat transfer to the environment further reduces pressure in the gas so that the piston can be more easily returned to its starting position.

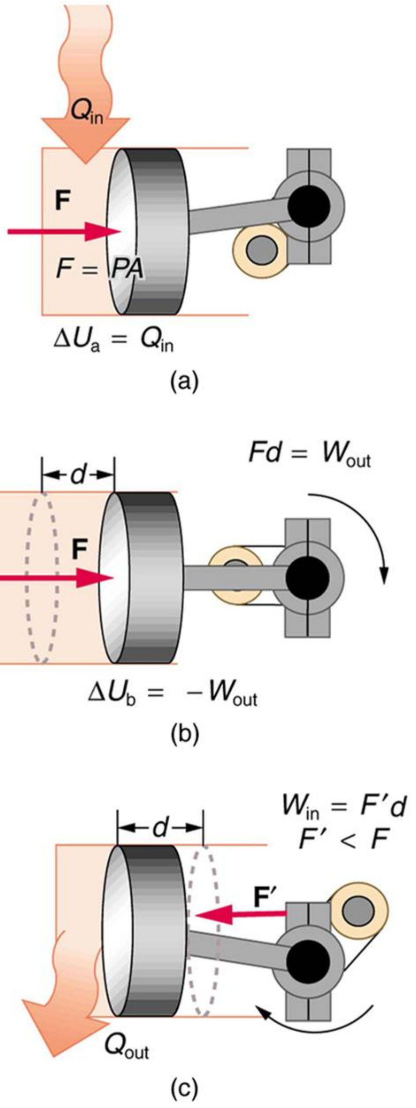
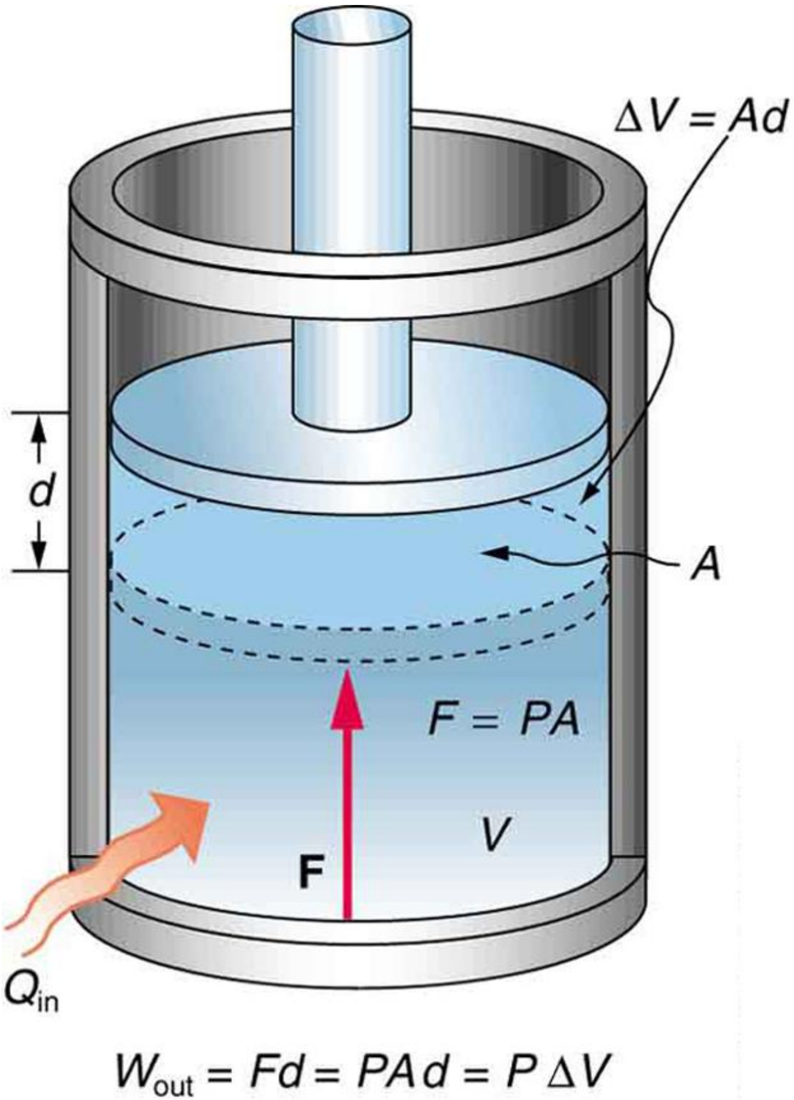
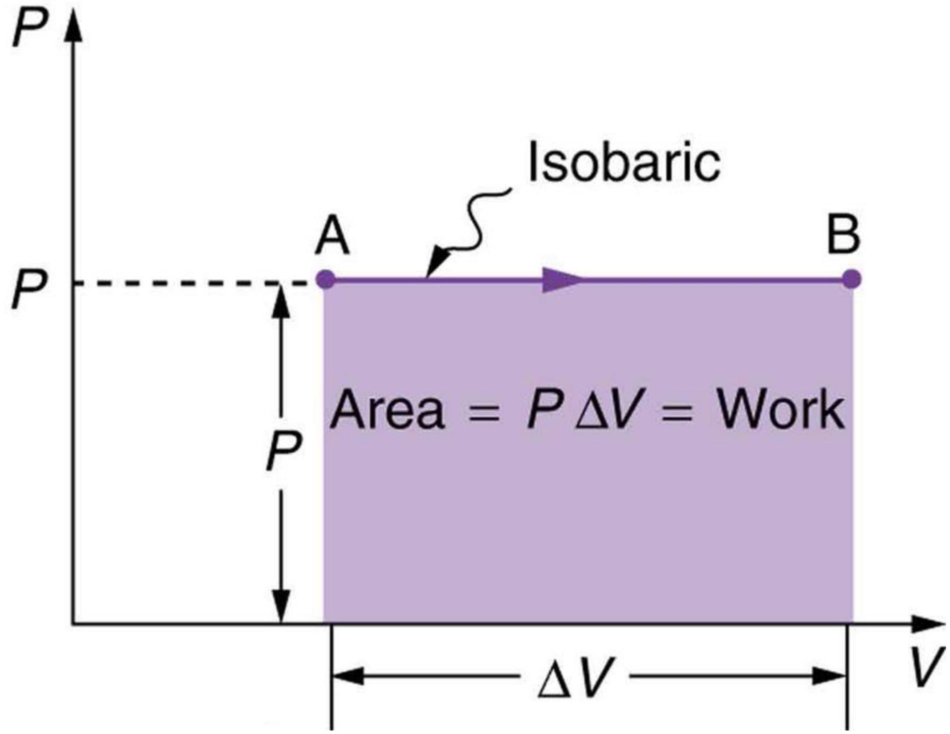


FIGURE 15.9



An isobaric expansion of a gas requires heat transfer to keep the pressure constant. Since pressure is constant, the work done is $P\Delta V$.

FIGURE 15.10

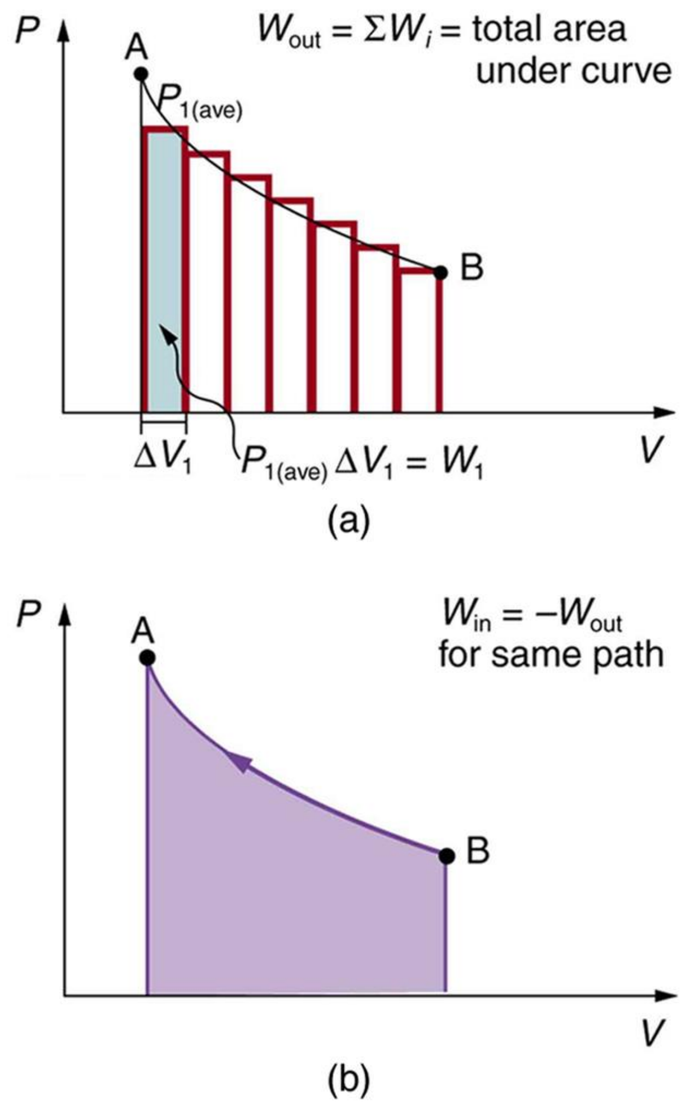


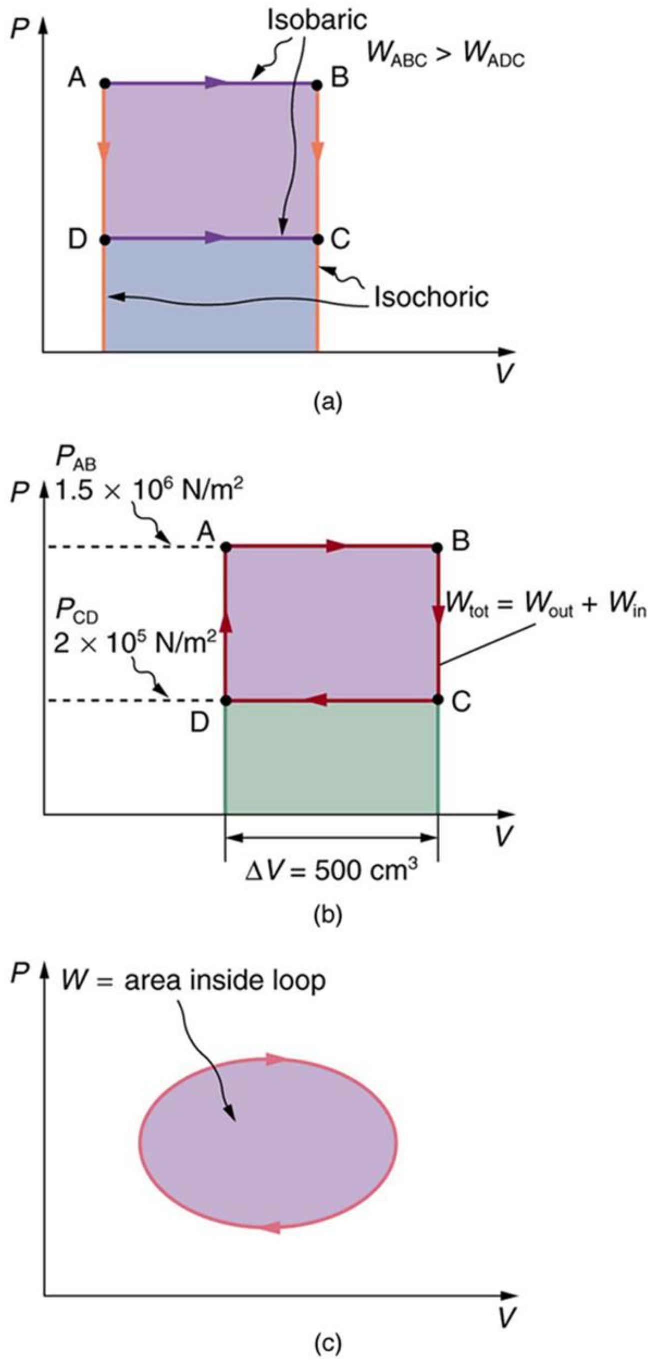
A graph of pressure versus volume for a constant-pressure, or isobaric process, such as the one shown in **Figure**. The area under the curve equals the work done by the gas, since $W = P\Delta V$.

FIGURE 15.11

(a) A *PV* diagram in which pressure varies as well as volume. The work done for each interval is its average pressure times the change in volume, or the area under the curve over that interval. Thus the total area under the curve equals the total work done.

(b) Work must be done on the system to follow the reverse path. This is interpreted as a negative area under the curve.





(a) The work done in going from A to C depends on path. The work is greater for the path ABC than for the path ADC, because the former is at higher pressure. In both cases, the work done is the area under the path. This area is greater for path ABC.

(b) The total work done in the cyclical process ABCDA is the area inside the loop, since the negative area below CD subtracts out, leaving just the area inside the rectangle. (The values given for the pressures and the change in volume are intended for use in the example below.)

(c) The area inside any closed loop is the work done in the cyclical process. If the loop is traversed in a clockwise direction, W is positive—it is work done on the outside environment. If the loop is traveled in a counter-clockwise direction, W is negative—it is work that is done to the system.

FIGURE 15.13

(a) The upper curve is an isothermal process ($\Delta T = 0$), whereas the lower curve is an adiabatic process ($Q = 0$). Both start from the same point A, but the isothermal process does more work than the adiabatic because heat transfer into the gas takes place to keep its temperature constant. This keeps the pressure higher all along the isothermal path than along the adiabatic path, producing more work. The adiabatic path thus ends up with a lower pressure and temperature at point C, even though the final volume is the same as for the isothermal process.

(b) The cycle ABCA produces a net work output.

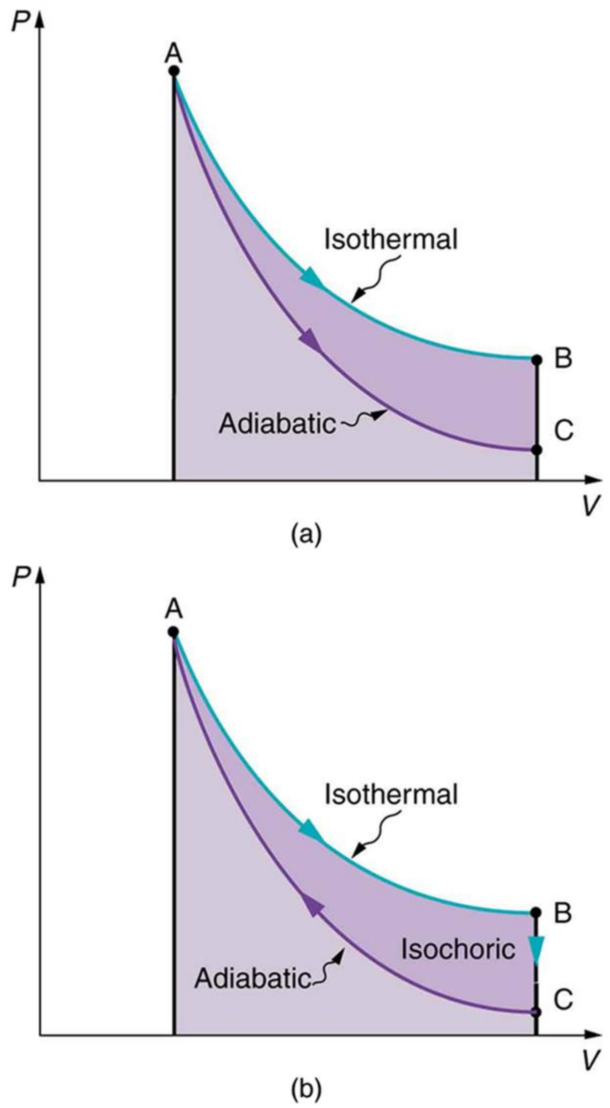
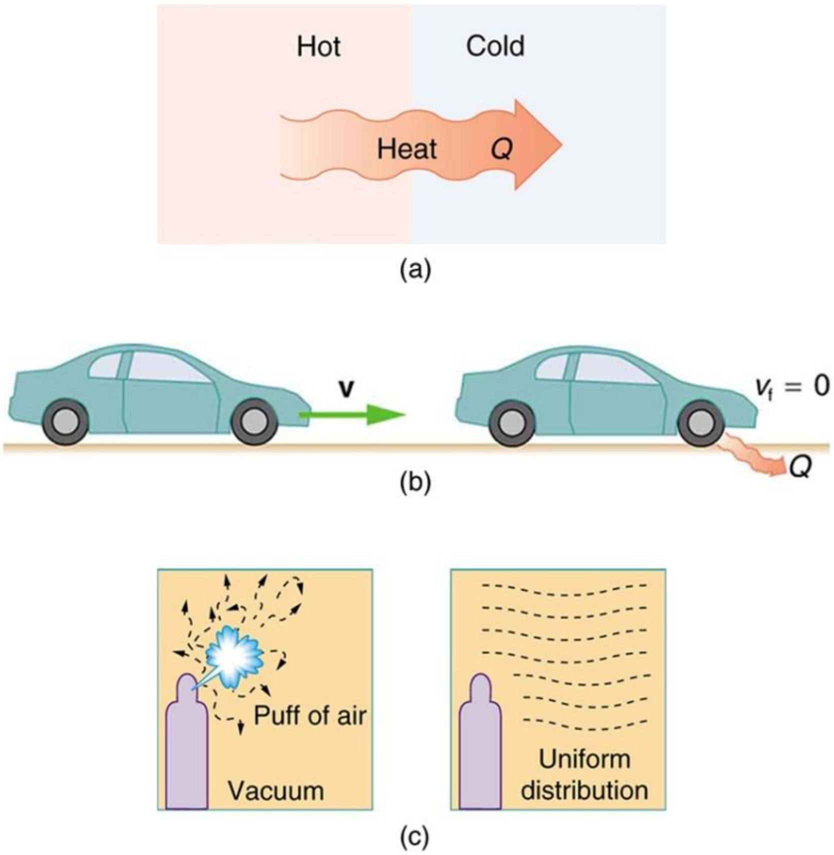


FIGURE 15.15

These ice floes melt during the Arctic summer. Some of them refreeze in the winter, but the second law of thermodynamics predicts that it would be extremely unlikely for the water molecules contained in these particular floes to reform the distinctive alligator-like shape they formed when the picture was taken in the summer of 2009. (credit: Patrick Kelley, U.S. Coast Guard, U.S. Geological Survey)

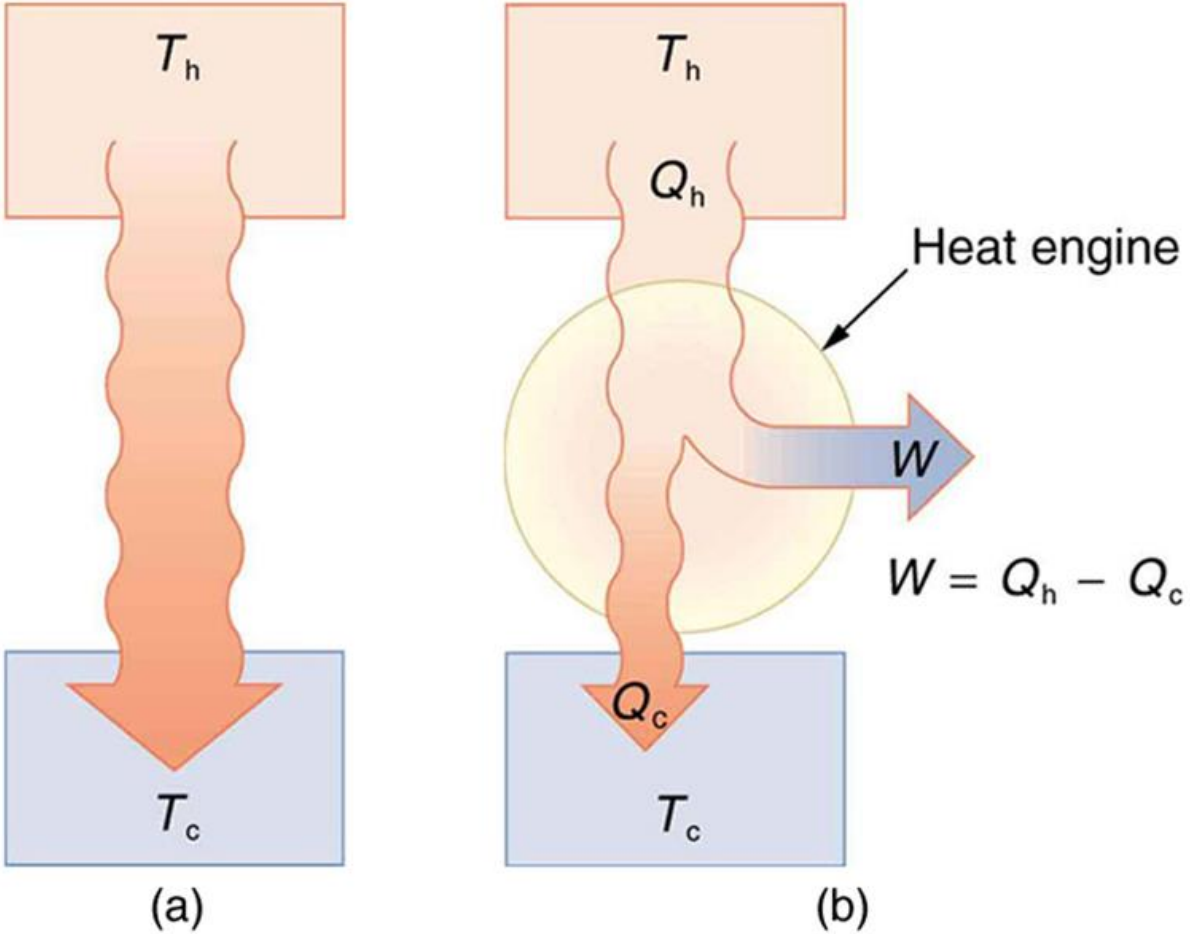


Examples of one-way processes in nature.

(a) Heat transfer occurs spontaneously from hot to cold and not from cold to hot.

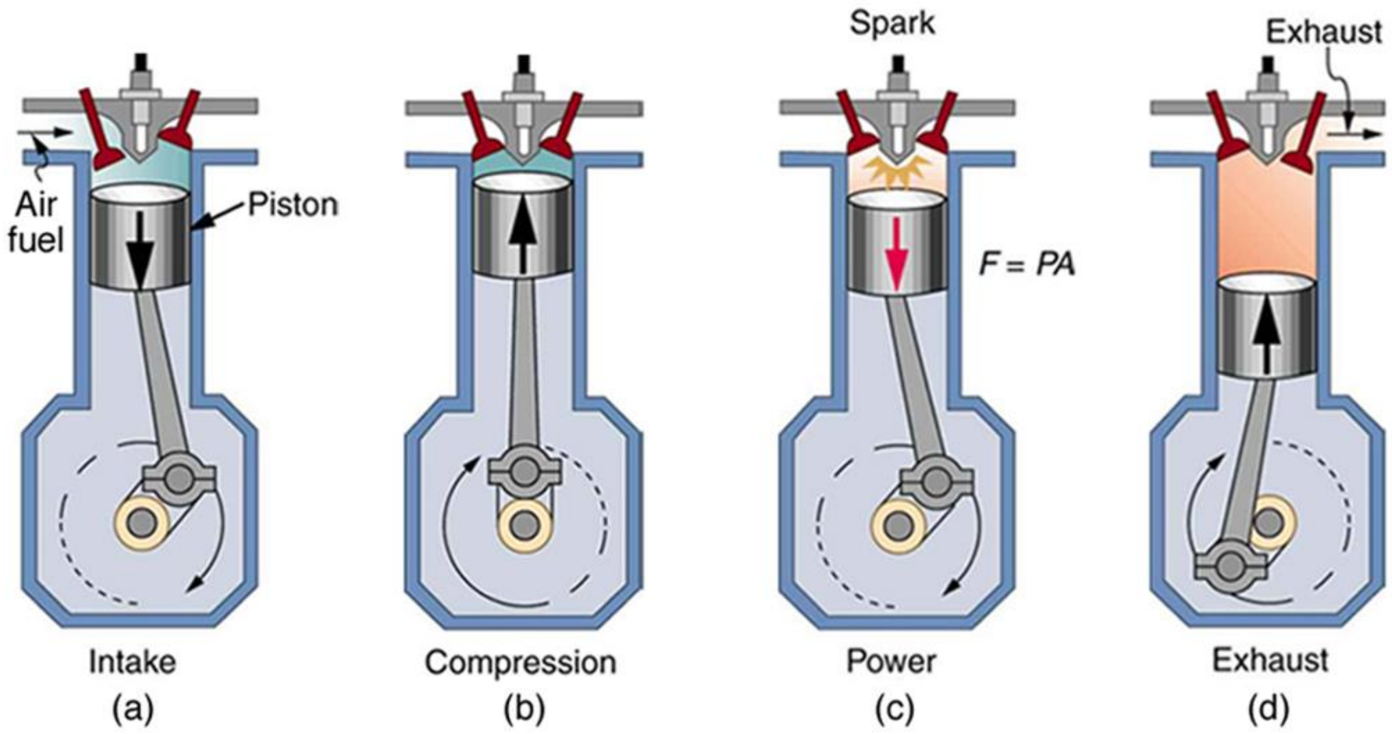
(b) The brakes of this car convert its kinetic energy to heat transfer to the environment. The reverse process is impossible.

(c) The burst of gas let into this vacuum chamber quickly expands to uniformly fill every part of the chamber. The random motions of the gas molecules will never return them to the corner.

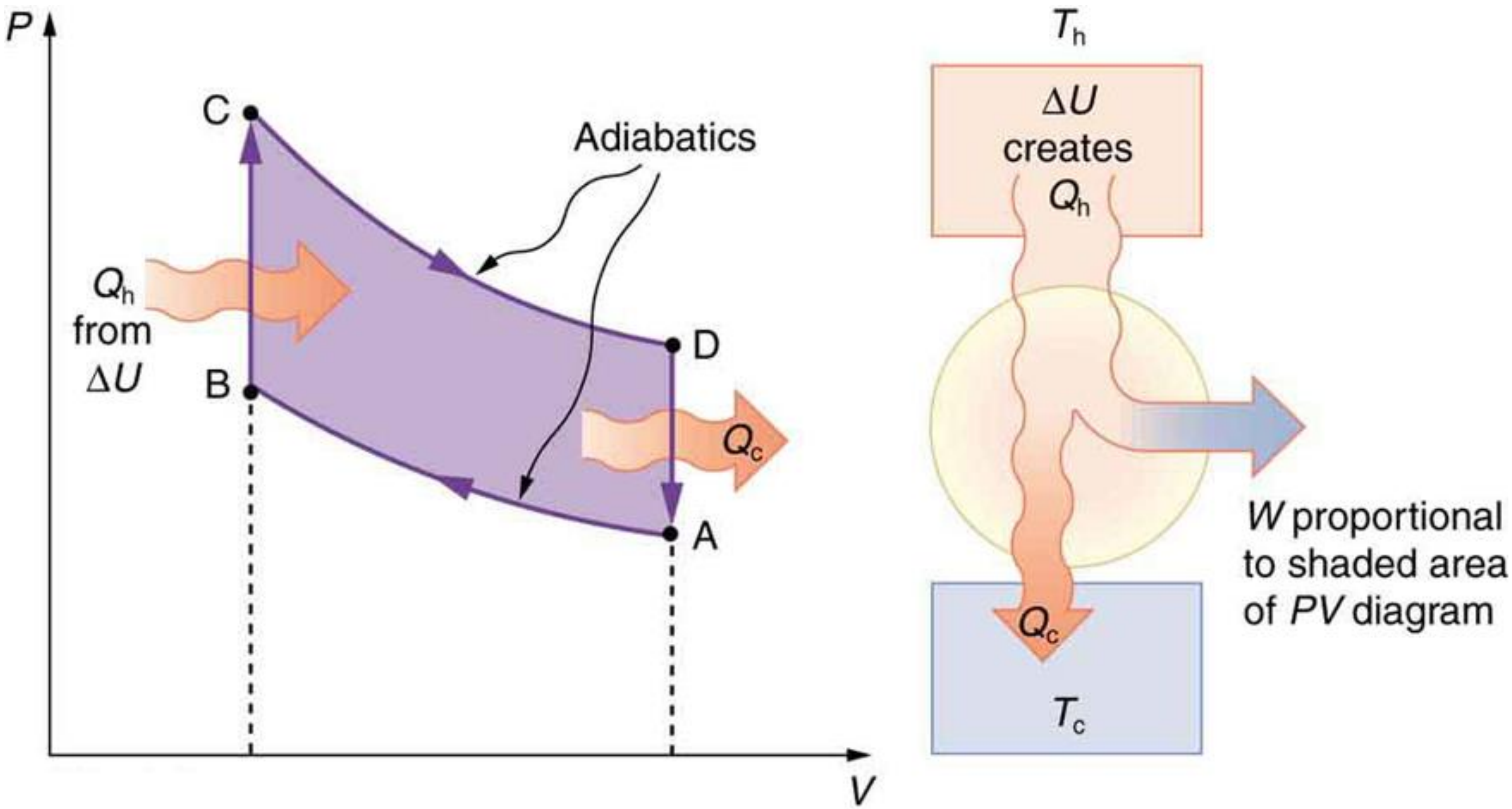


(a) Heat transfer occurs spontaneously from a hot object to a cold one, consistent with the second law of thermodynamics.

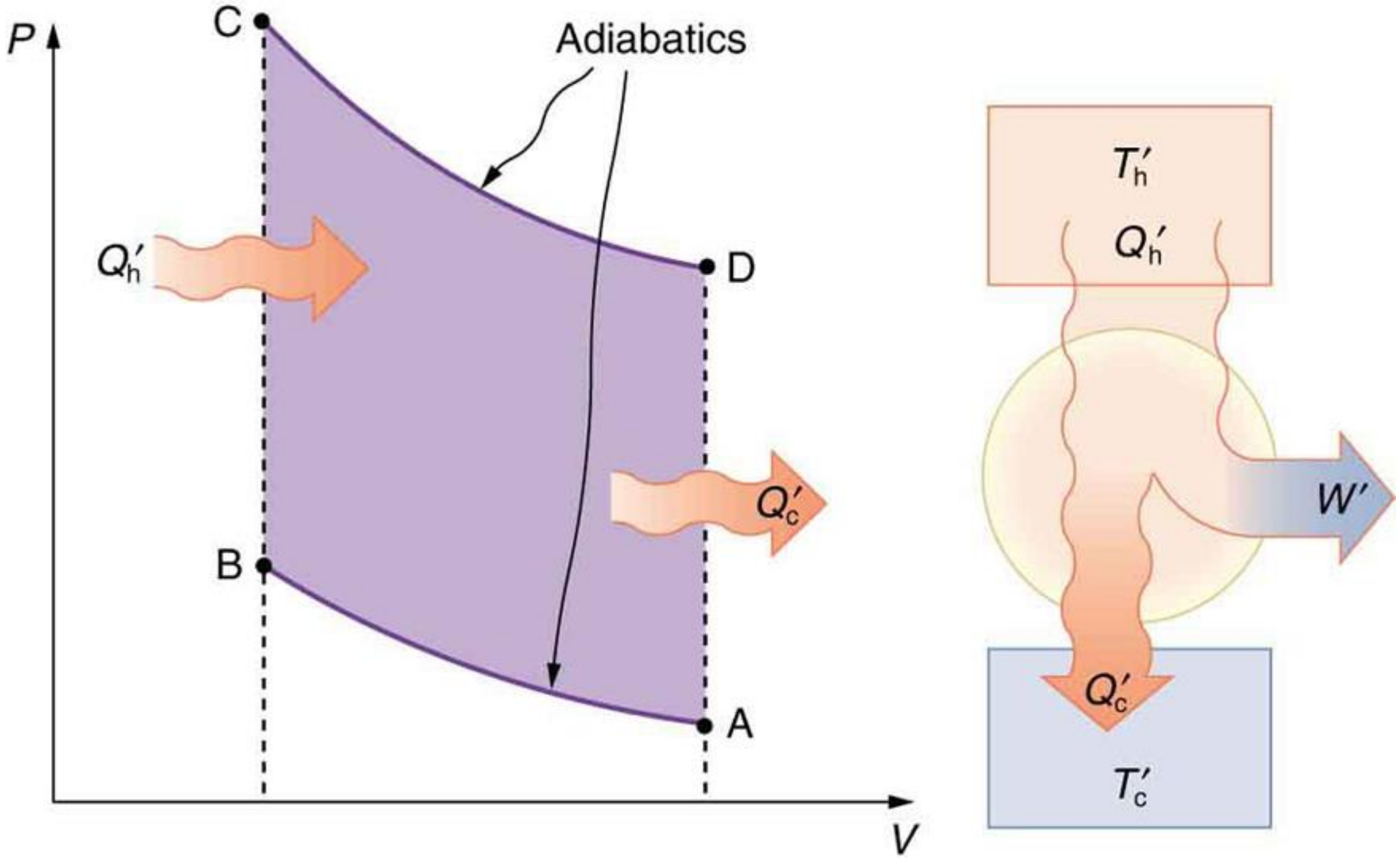
(b) A heat engine, represented here by a circle, uses part of the heat transfer to do work. The hot and cold objects are called the hot and cold reservoirs. Q_h is the heat transfer out of the hot reservoir, W is the work output, and Q_c is the heat transfer into the cold reservoir.



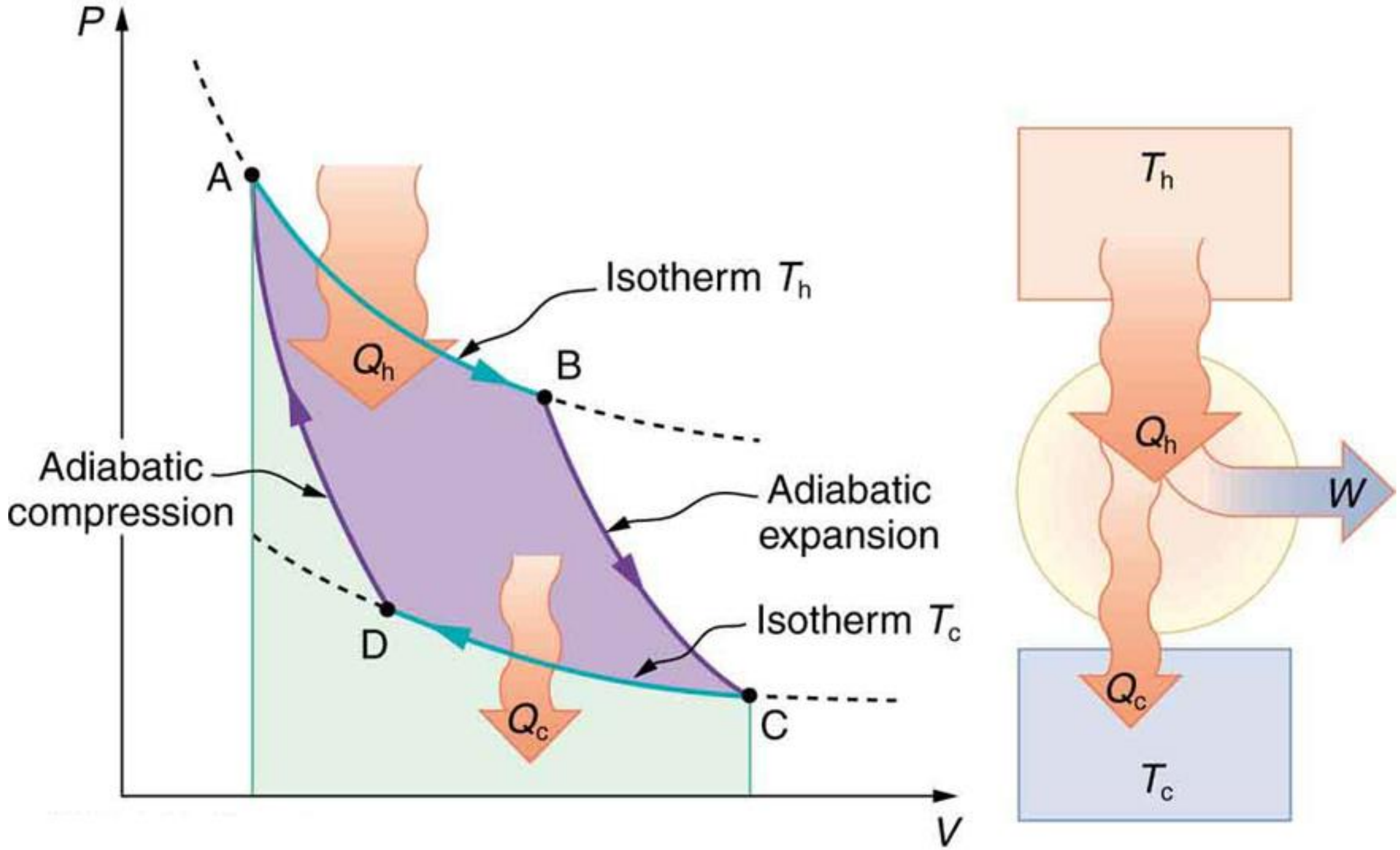
In the four-stroke internal combustion gasoline engine, heat transfer into work takes place in the cyclical process shown here. The piston is connected to a rotating crankshaft, which both takes work out of and does work on the gas in the cylinder. (a) Air is mixed with fuel during the intake stroke. (b) During the compression stroke, the air-fuel mixture is rapidly compressed in a nearly adiabatic process, as the piston rises with the valves closed. Work is done on the gas. (c) The power stroke has two distinct parts. First, the air-fuel mixture is ignited, converting chemical potential energy into thermal energy almost instantaneously, which leads to a great increase in pressure. Then the piston descends, and the gas does work by exerting a force through a distance in a nearly adiabatic process. (d) The exhaust stroke expels the hot gas to prepare the engine for another cycle, starting again with the intake stroke.



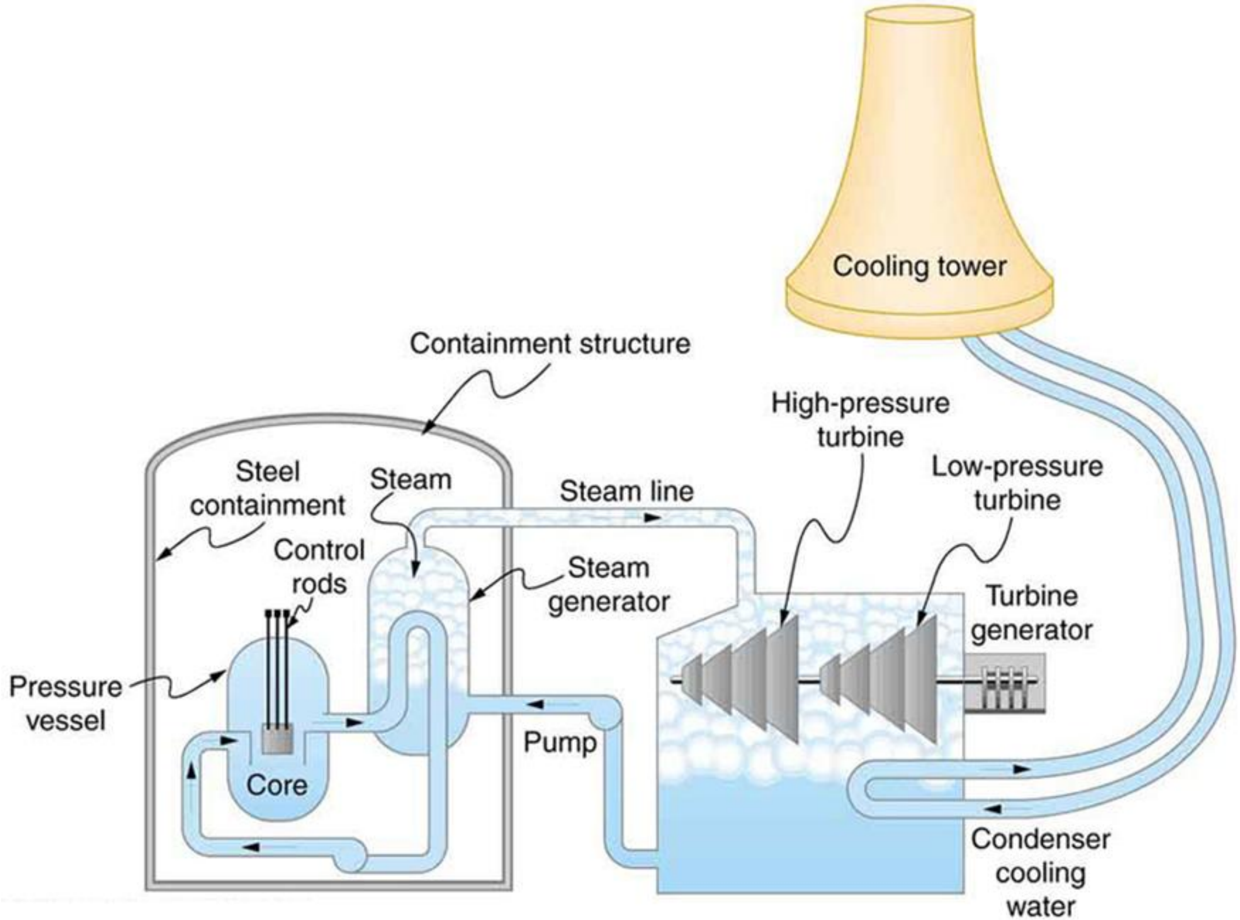
PV diagram for a simplified Otto cycle, analogous to that employed in an internal combustion engine. Point A corresponds to the start of the compression stroke of an internal combustion engine. Paths AB and CD are adiabatic and correspond to the compression and power strokes of an internal combustion engine, respectively. Paths BC and DA are isochoric and accomplish similar results to the ignition and exhaust-intake portions, respectively, of the internal combustion engine's cycle. Work is done on the gas along path AB, but more work is done by the gas along path CD, so that there is a net work output.



This Otto cycle produces a greater work output than the one in previous **Figure**, because the starting temperature of path CD is higher and the starting temperature of path AB is lower. The area inside the loop is greater, corresponding to greater net work output.



PV diagram for a Carnot cycle, employing only reversible isothermal and adiabatic processes. Heat transfer Q_h occurs into the working substance during the isothermal path AB, which takes place at constant temperature T_h . Heat transfer Q_c occurs out of the working substance during the isothermal path CD, which takes place at constant temperature T_c . The net work output W equals the area inside the path ABCDA. Also shown is a schematic of a Carnot engine operating between hot and cold reservoirs at temperatures T_h and T_c . Any heat engine using reversible processes and operating between these two temperatures will have the same maximum efficiency as the Carnot engine.



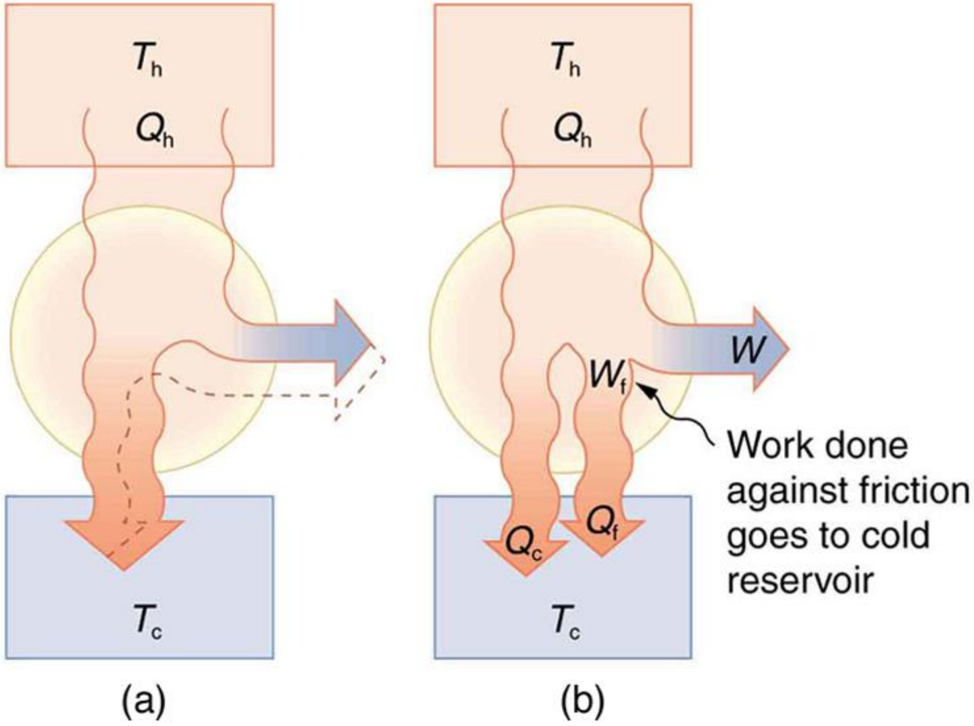
Schematic diagram of a pressurized water nuclear reactor and the steam turbines that convert work into electrical energy. Heat exchange is used to generate steam, in part to avoid contamination of the generators with radioactivity. Two turbines are used because this is less expensive than operating a single generator that produces the same amount of electrical energy. The steam is condensed to liquid before being returned to the heat exchanger, to keep exit steam pressure low and aid the flow of steam through the turbines (equivalent to using a lower-temperature cold reservoir). The considerable energy associated with condensation must be dissipated into the local environment; in this example, a cooling tower is used so there is no direct heat transfer to an aquatic environment. (Note that the water going to the cooling tower does not come into contact with the steam flowing over the turbines.)


(a)


(b)

(a) A nuclear power station (credit: BlatantWorld.com) and

(b) a coal-fired power station. Both have cooling towers in which water evaporates into the environment, representing Q_c. The nuclear reactor, which supplies Q_h , is housed inside the dome-shaped containment buildings.



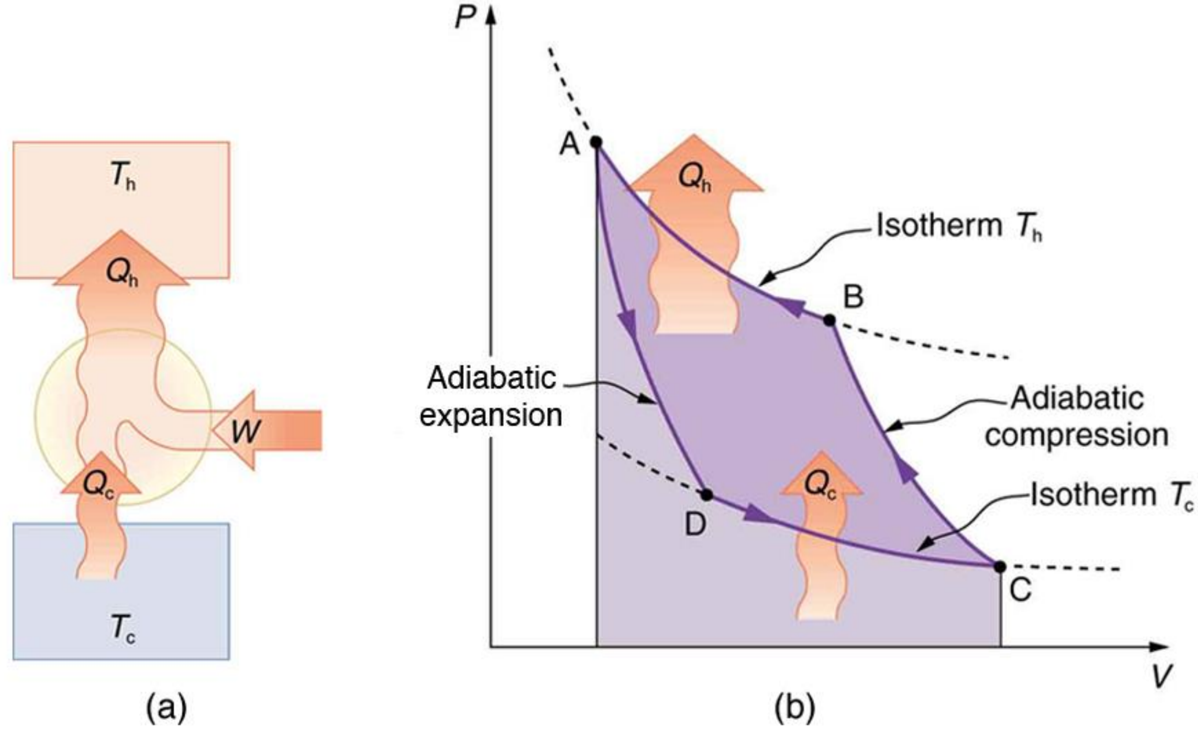
Real heat engines are less efficient than Carnot engines.

(a) Real engines use irreversible processes, reducing the heat transfer to work. Solid lines represent the actual process; the dashed lines are what a Carnot engine would do between the same two reservoirs.

(b) Friction and other dissipative processes in the output mechanisms of a heat engine convert some of its work output into heat transfer to the environment.

FIGURE 15.26

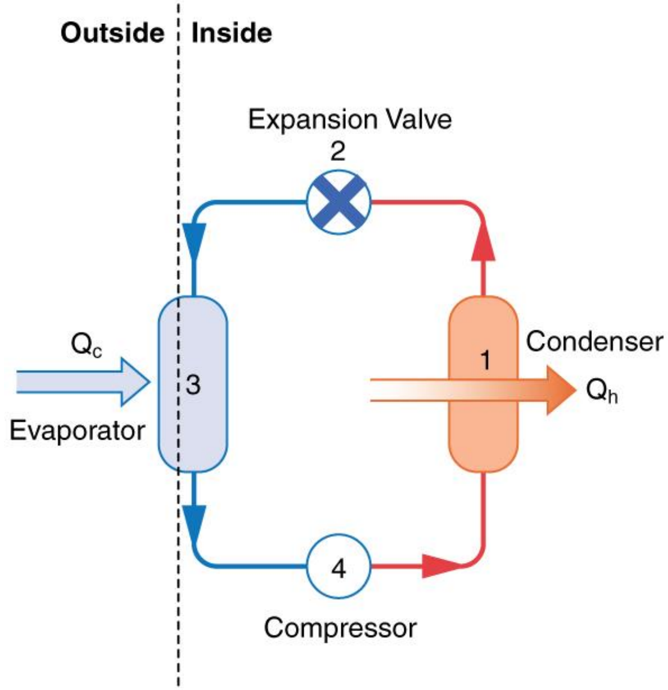
Almost every home contains a refrigerator. Most people don’t realize they are also sharing their homes with a heat pump.



Heat pumps, air conditioners, and refrigerators are heat engines operated backward. The one shown here is based on a Carnot (reversible) engine.

(a) Schematic diagram showing heat transfer from a cold reservoir to a warm reservoir with a heat pump. The directions of $\boldsymbol{W}$, Q_h , and Q_c are opposite what they would be in a heat engine.

(b) ***PV*** diagram for a Carnot cycle similar to that in **Figure** but reversed, following path ADCBA. The area inside the loop is negative, meaning there is a net work input. There is heat transfer Q_c into the system from a cold reservoir along path DC, and heat transfer Q_h out of the system into a hot reservoir along path BA.



A simple heat pump has four basic components: (1) condenser, (2) expansion valve, (3) evaporator, and (4) compressor. In the heating mode, heat transfer Q_c occurs to the working fluid in the evaporator (3) from the colder outdoor air, turning it into a gas. The electrically driven compressor (4) increases the temperature and pressure of the gas and forces it into the condenser coils (1) inside the heated space. Because the temperature of the gas is higher than the temperature in the room, heat transfer from the gas to the room occurs as the gas condenses to a liquid. The working fluid is then cooled as it flows back through an expansion valve (2) to the outdoor evaporator coils.

FIGURE 15.29

When a real heat engine is run backward, some of the intended work input (W) goes into heat transfer before it gets into the heat engine, thereby reducing its coefficient of performance COP_{hp} . In this figure, W' represents the portion of W that goes into the heat pump, while the remainder of W is lost in the form of frictional heat (Q_f) to the cold reservoir. If all of ***W*** had gone into the heat pump, then Q_h would have been greater. The best heat pump uses adiabatic and isothermal processes, since, in theory, there would be no dissipative processes to reduce the heat transfer to the hot reservoir.

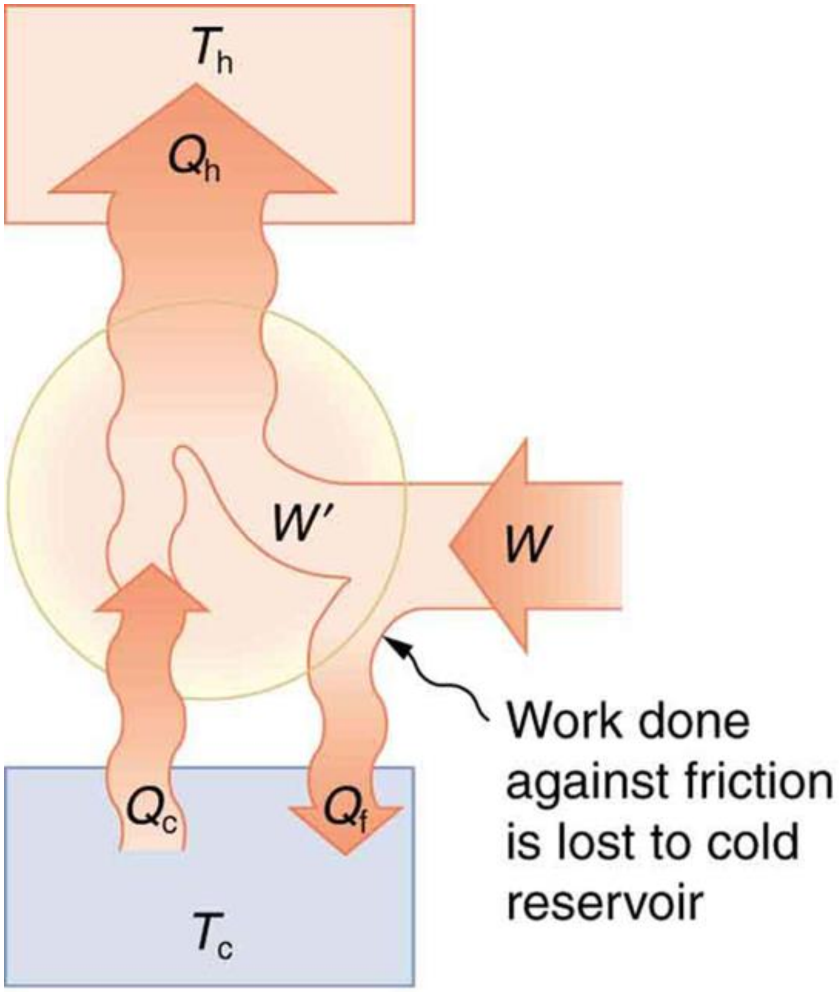
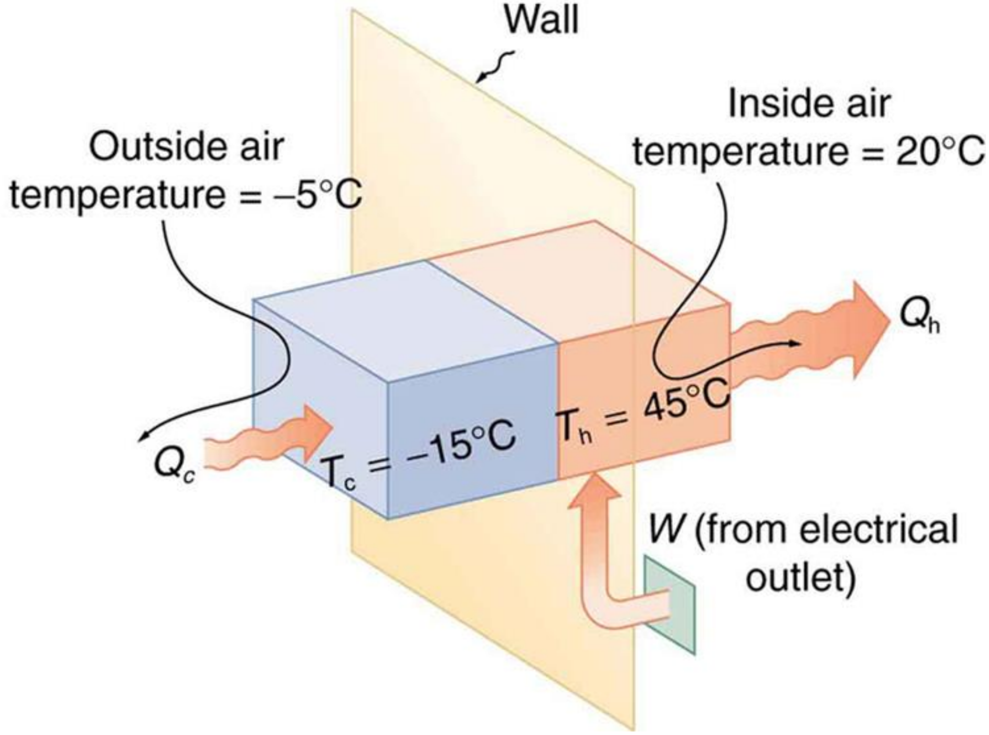
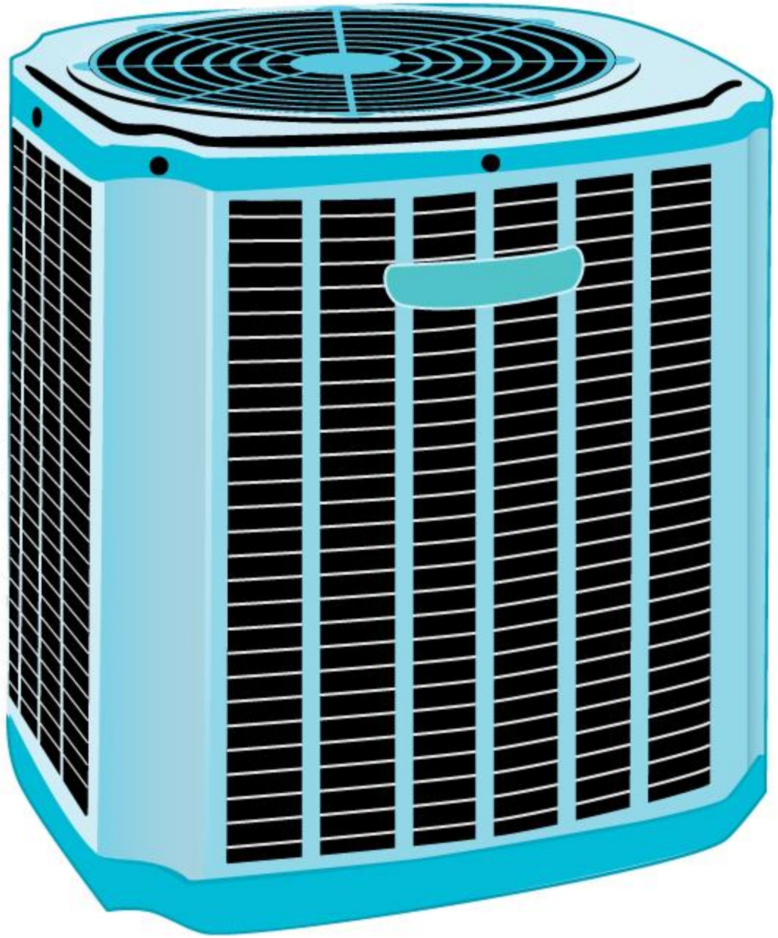


FIGURE 15.30

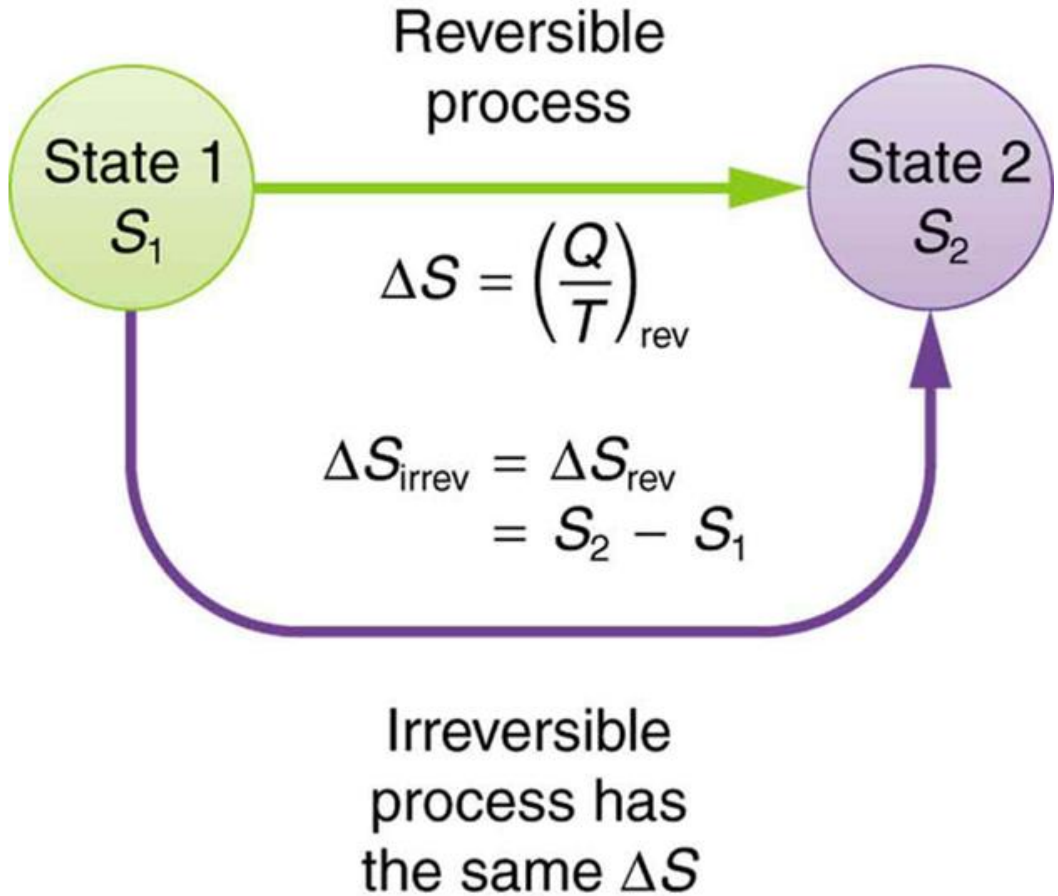


Heat transfer from the outside to the inside, along with work done to run the pump, takes place in the heat pump of the example above. Note that the cold temperature produced by the heat pump is lower than the outside temperature, so that heat transfer into the working fluid occurs. The pump's compressor produces a temperature greater than the indoor temperature in order for heat transfer into the house to occur.

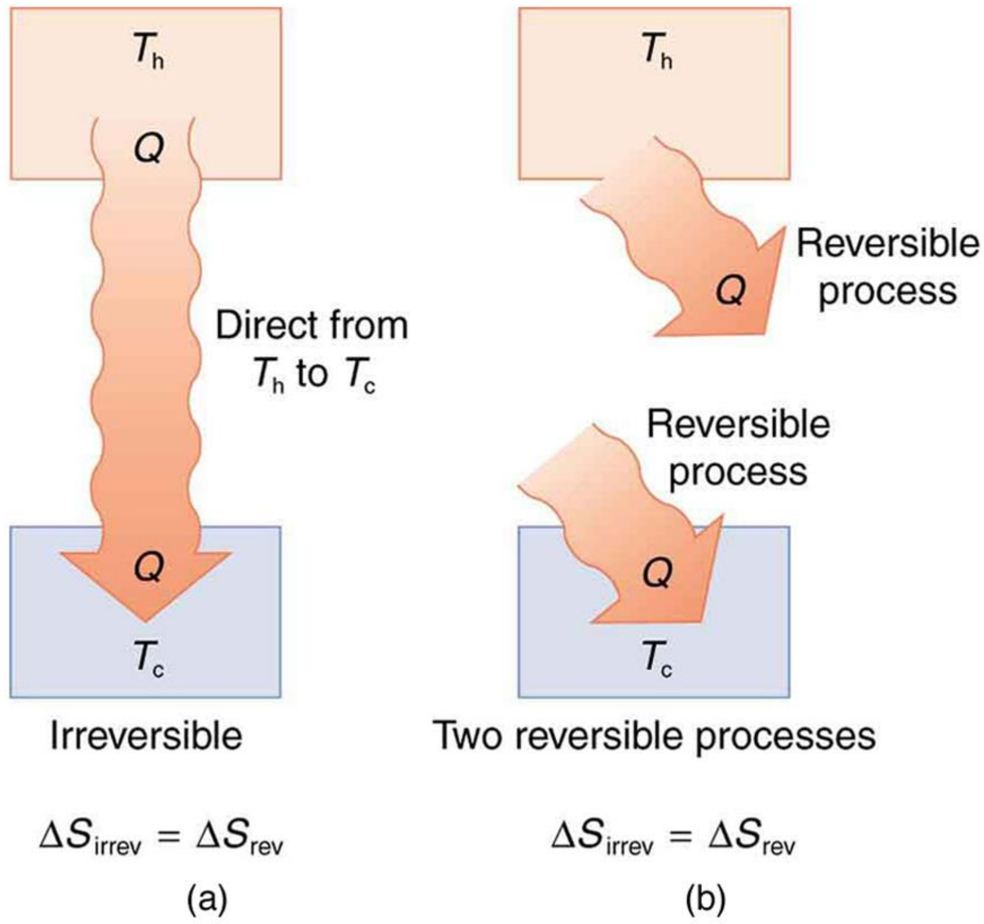


In hot weather, heat transfer occurs from air inside the room to air outside, cooling the room. In cool weather, heat transfer occurs from air outside to air inside, warming the room. This switching is achieved by reversing the direction of flow of the working fluid.

The ice in this drink is slowly melting. Eventually the liquid will reach thermal equilibrium, as predicted by the second law of thermodynamics.

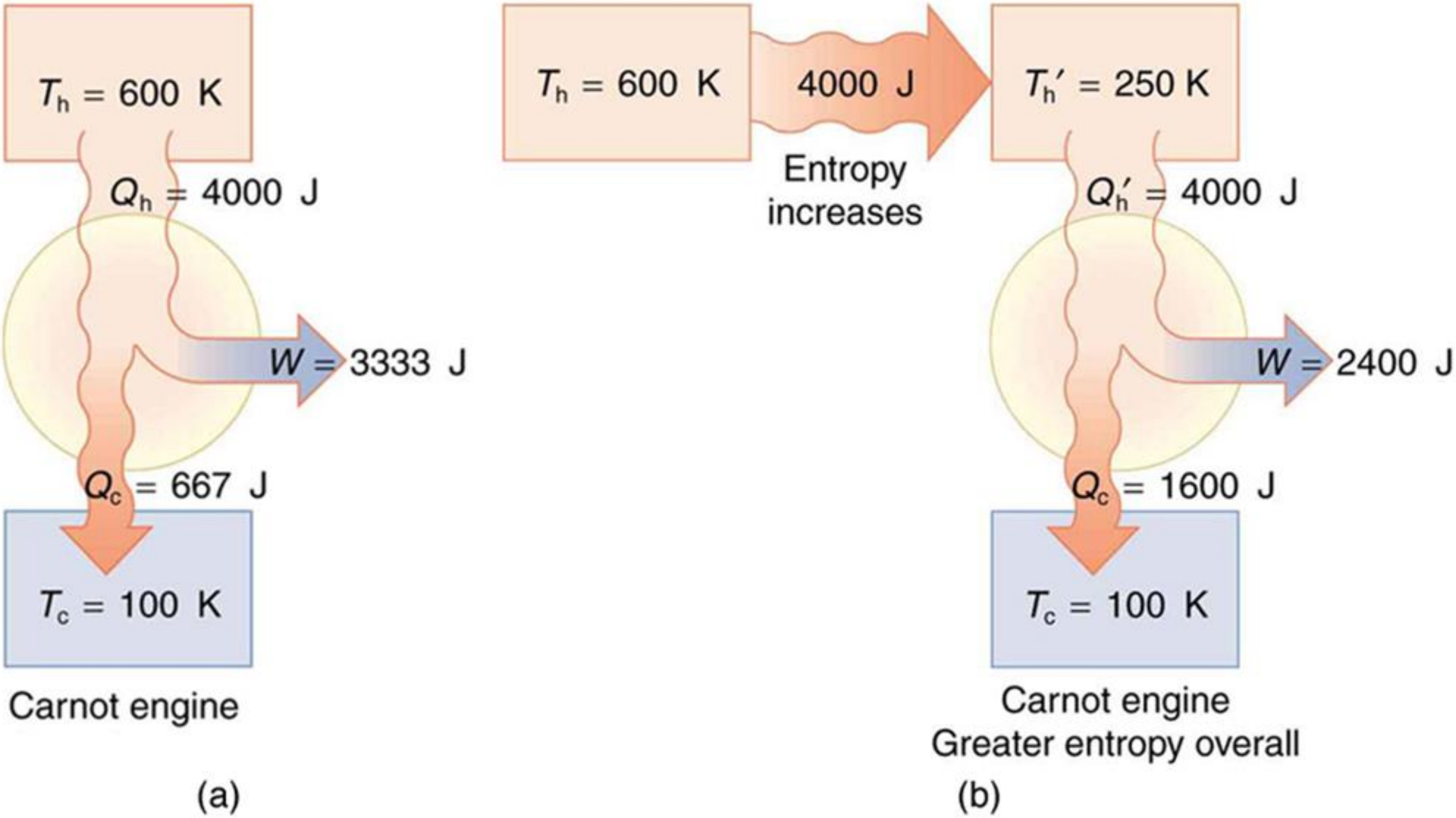


When a system goes from state 1 to state 2, its entropy changes by the same amount ΔS, whether a hypothetical reversible path is followed or a real irreversible path is taken.



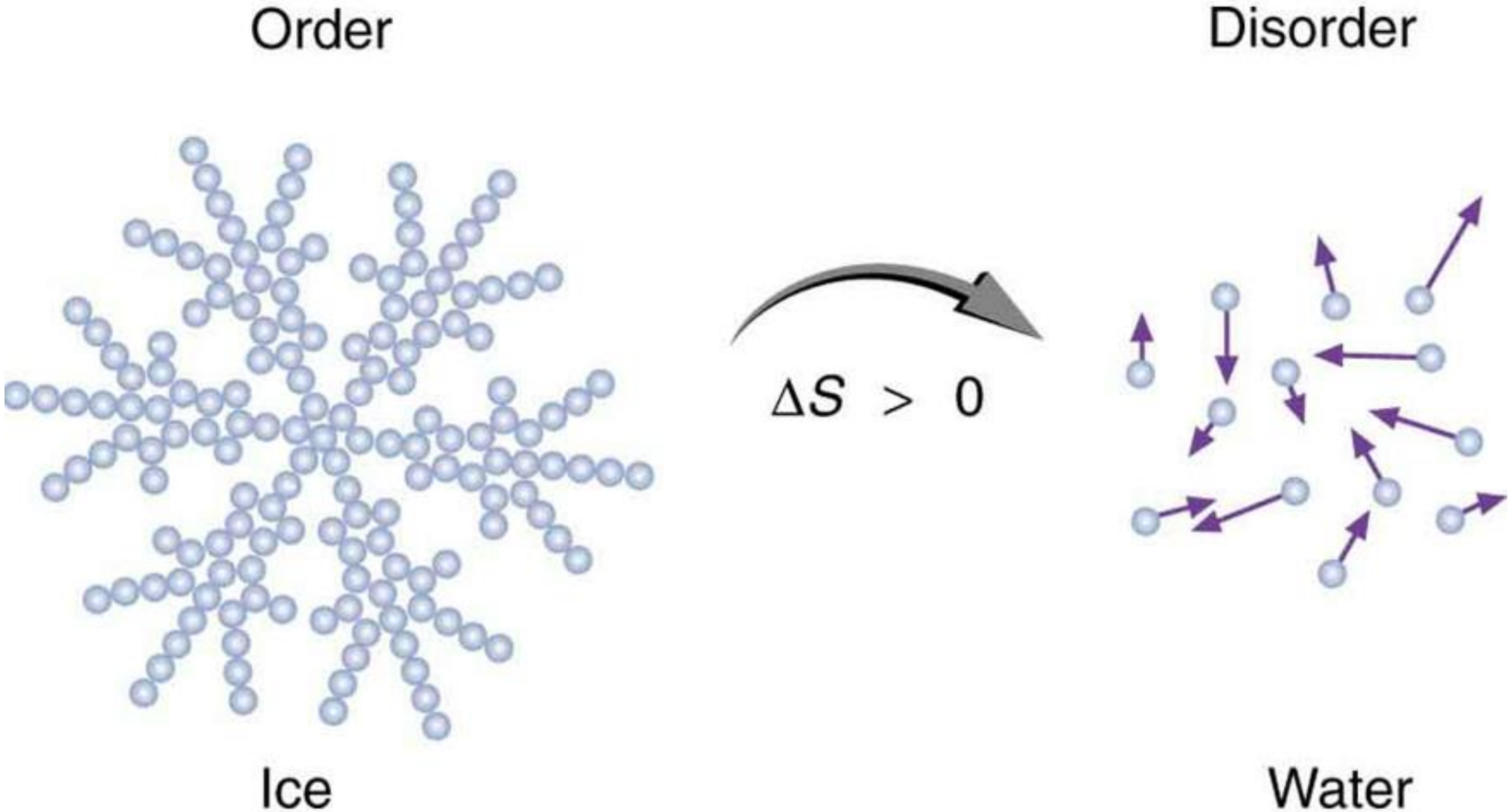
(a) Heat transfer from a hot object to a cold one is an irreversible process that produces an overall increase in entropy.

(b) The same final state and, thus, the same change in entropy is achieved for the objects if reversible heat transfer processes occur between the two objects whose temperatures are the same as the temperatures of the corresponding objects in the irreversible process.



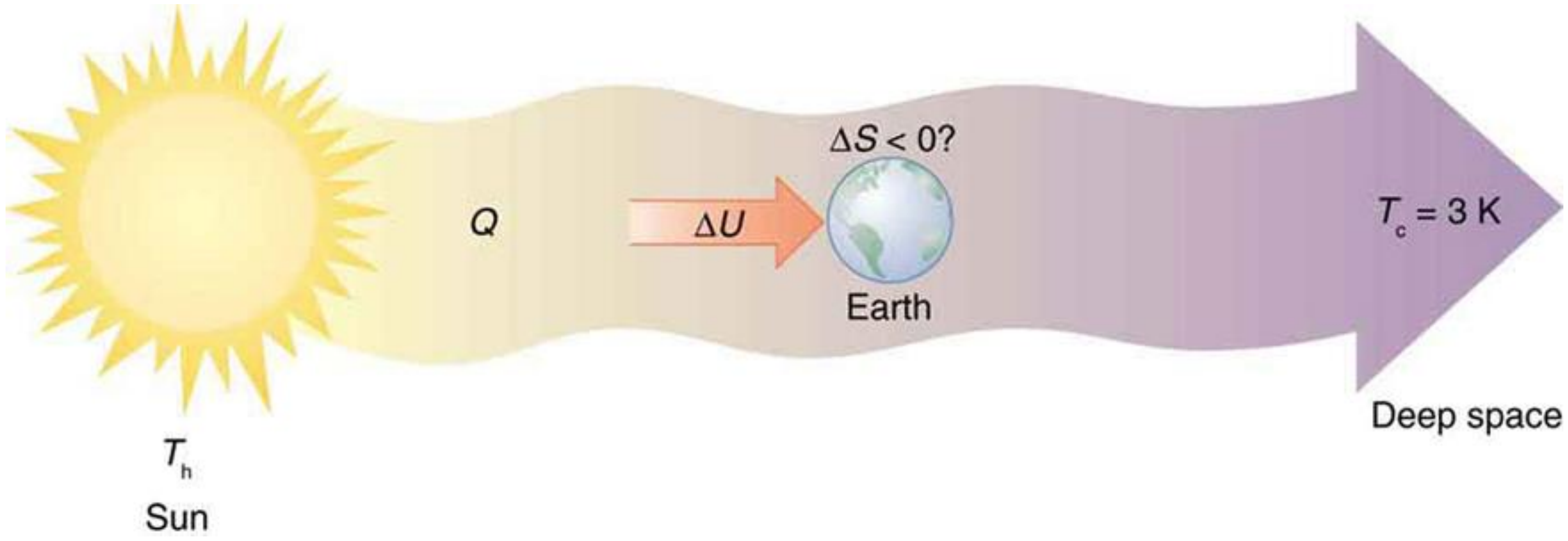
(a) A Carnot engine working at between 600 K and 100 K has 4000 J of heat transfer and performs 3333 J of work.

(b) The 4000 J of heat transfer occurs first irreversibly to a 250 K reservoir and then goes into a Carnot engine. The increase in entropy caused by the heat transfer to a colder reservoir results in a smaller work output of 2400 J. There is a permanent loss of 933 J of energy for the purpose of doing work.



When ice melts, it becomes more disordered and less structured. The systematic arrangement of molecules in a crystal structure is replaced by a more random and less orderly movement of molecules without fixed locations or orientations. Its entropy increases because heat transfer occurs into it. Entropy is a measure of disorder.

FIGURE 15.37



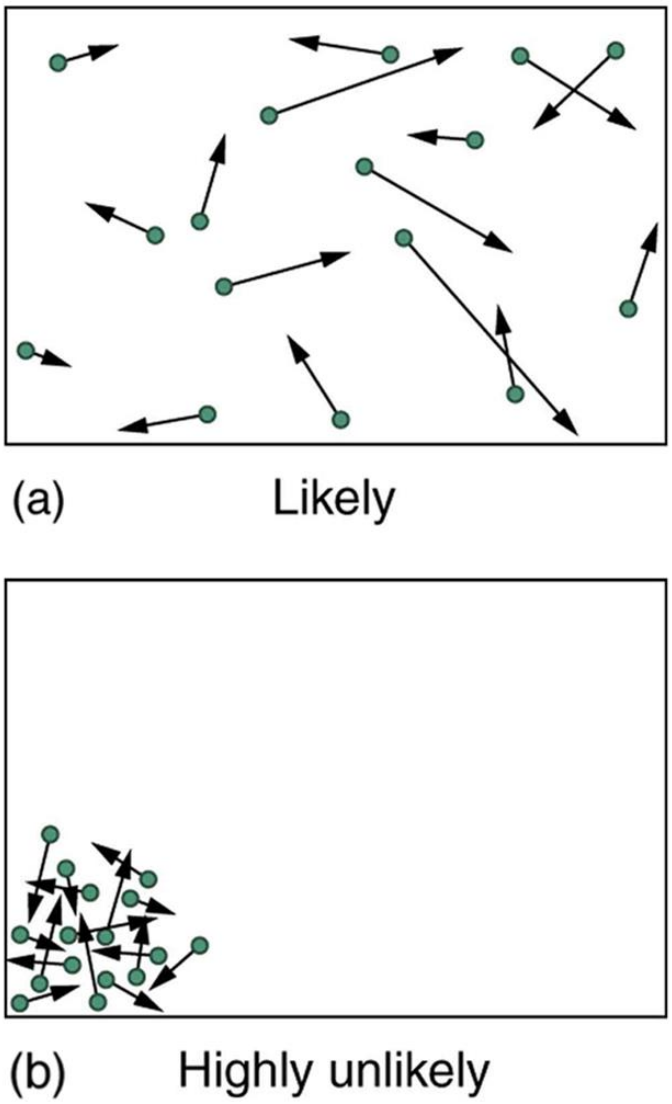
Earth's entropy may decrease in the process of intercepting a small part of the heat transfer from the Sun into deep space. Entropy for the entire process increases greatly while Earth becomes more structured with living systems and stored energy in various forms.

FIGURE 15.38

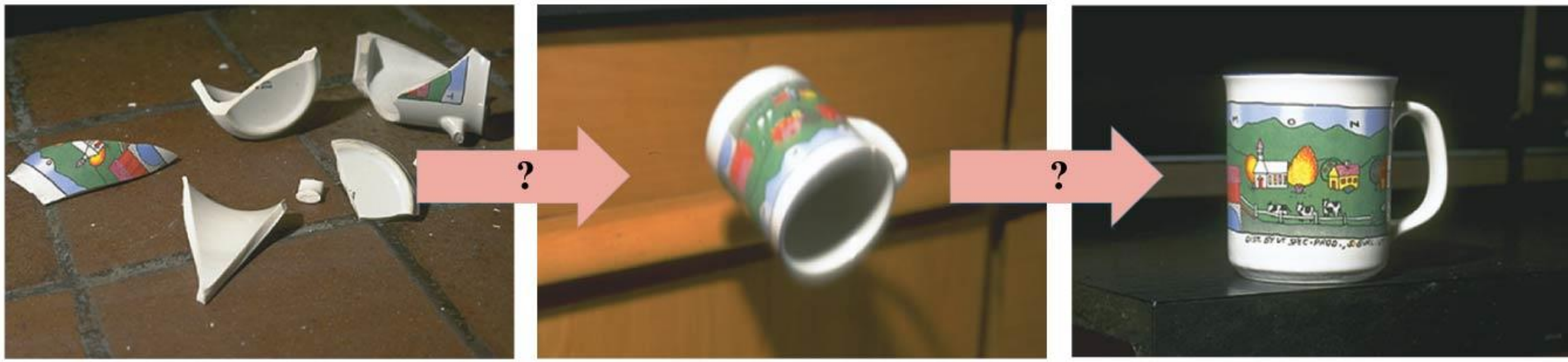
When you toss a coin a large number of times, heads and tails tend to come up in roughly equal numbers. Why doesn’t heads come up 100, 90, or even 80% of the time? (credit: Jon Sullivan, PDPhoto.org)

(a) The ordinary state of gas in a container is a disorderly, random distribution of atoms or molecules with a Maxwell-Boltzmann distribution of speeds. It is so unlikely that these atoms or molecules would ever end up in one corner of the container that it might as well be impossible.

(b) With energy transfer, the gas can be forced into one corner and its entropy greatly reduced. But left alone, it will spontaneously increase its entropy and return to the normal conditions, because they are immensely more likely.



The Second Law of Thermodynamics – Introduction



(a) Initial state. (b) Later: cup reassembles and rises up. (c) Later still: cup lands on table.

The absence of the process illustrated above indicates that conservation of energy is not the whole story. If it were, movies run backwards would look perfectly normal to us!

The Second Law of Thermodynamics – Introduction

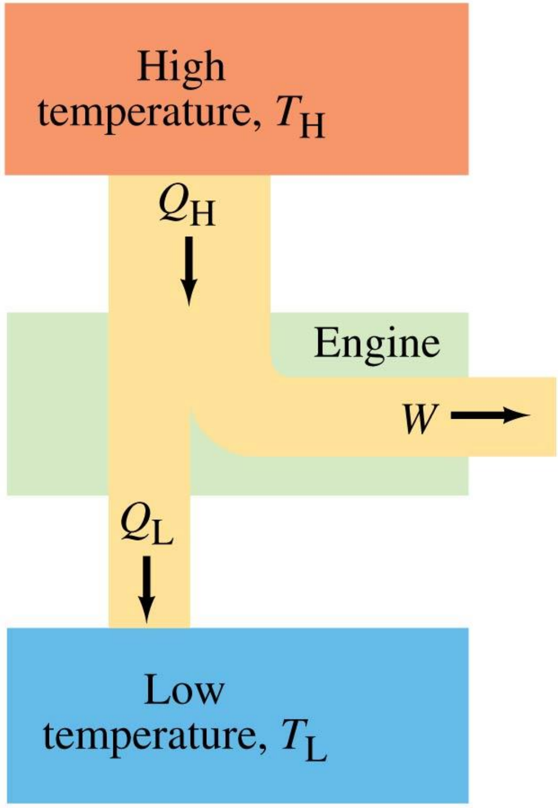
The second law of thermodynamics is a statement about which processes occur and which do not. There are many ways to state the second law; here is one:

Heat can flow spontaneously from a hot object to a cold object; it will not flow spontaneously from a cold object to a hot object.

Heat Engines

It is easy to produce thermal energy using work, but how does one produce work using thermal energy?

This is a heat engine; mechanical energy can be obtained from thermal energy only when heat can flow from a higher temperature to a lower temperature.



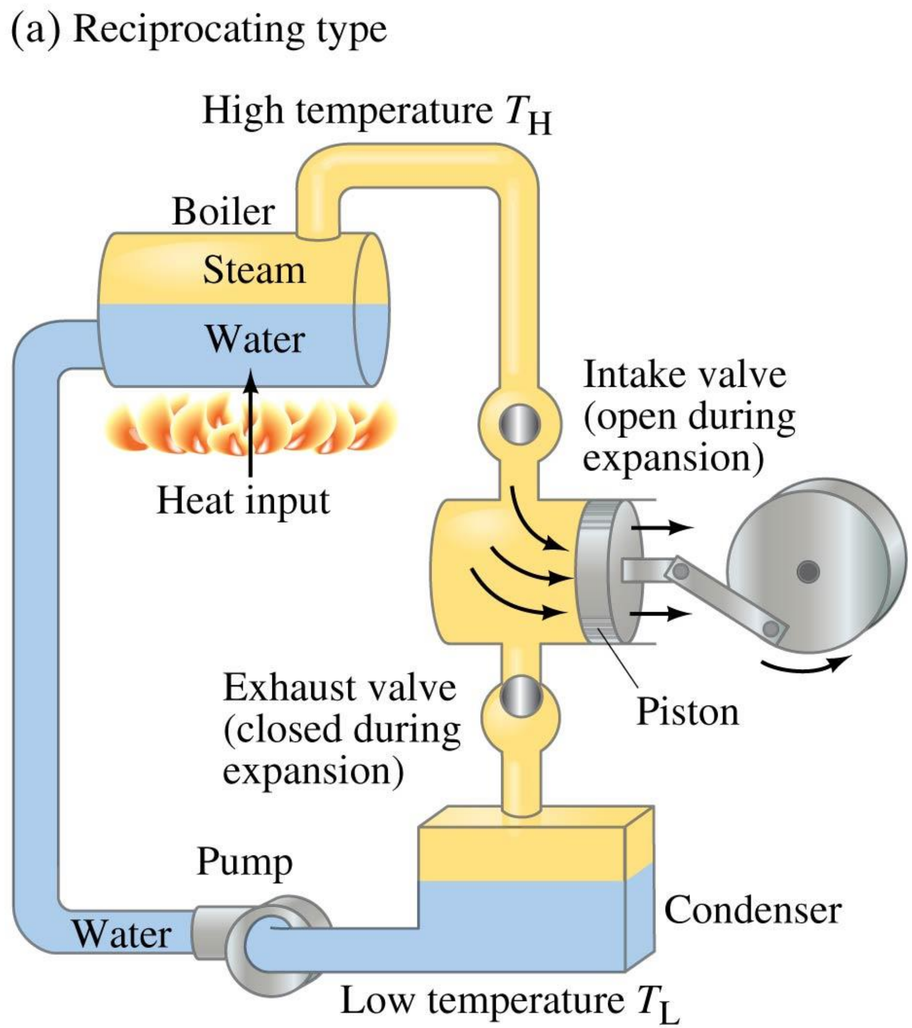
Heat Engines

We will discuss only engines that run in a repeating cycle; the change in internal energy over a cycle is zero, as the system returns to its initial state.

The high temperature reservoir transfers an amount of heat Q_H to the engine, where part of it is transformed into work W and the rest, Q_L, is exhausted to the lower temperature reservoir. Note that all three of these quantities are positive.

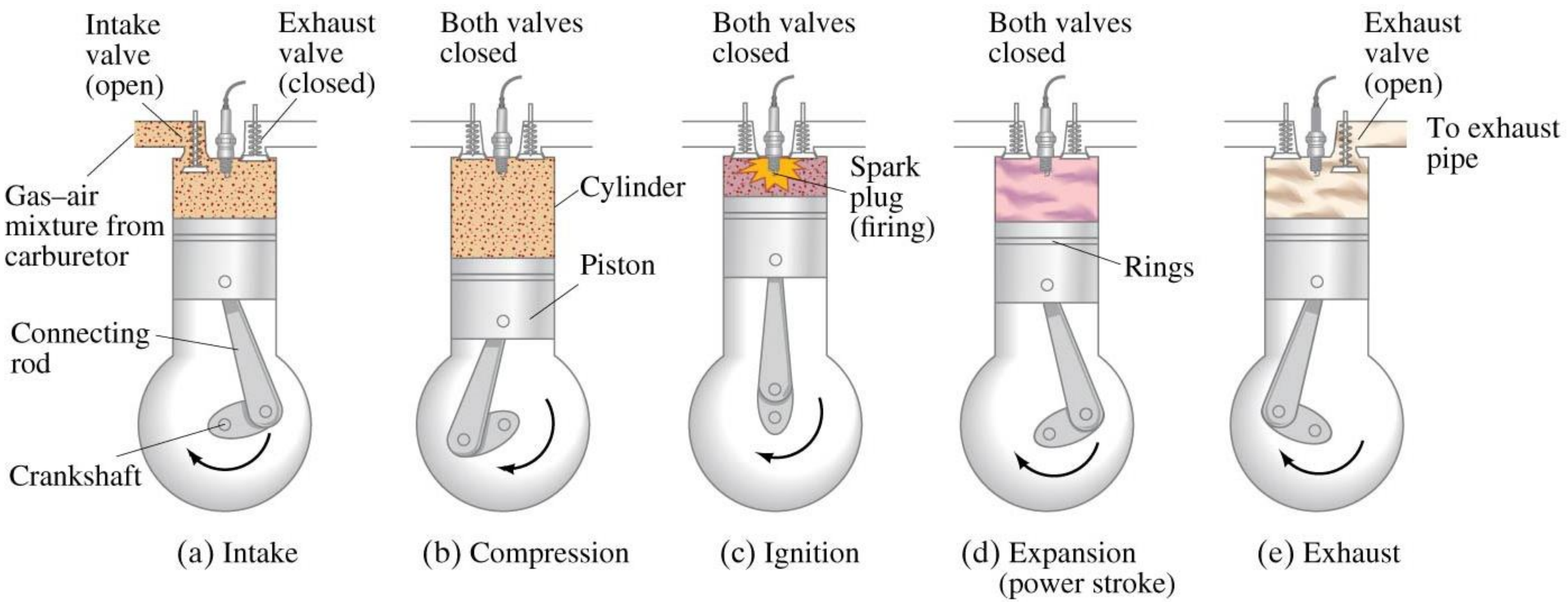
Heat Engines

A steam engine is one type of heat engine.



Heat Engines

The internal combustion engine is a type of heat engine as well.



Heat Engines

Why does a heat engine need a temperature difference?

Otherwise the work done on the system in one part of the cycle will be equal to the work done by the system in another part, and the net work will be zero.

Heat Engines

The efficiency of the heat engine is the ratio of the work done to the heat input:

$$e = \frac{W}{Q_{\mathrm{H}}}.$$

Using conservation of energy to eliminate W, we find:

$$e = \frac{W}{Q_{\mathrm{H}}} = \frac{Q_{\mathrm{H}} - Q_{\mathrm{L}}}{Q_{\mathrm{H}}}$$

or

$$e = 1 - \frac{Q_{\mathrm{L}}}{Q_{\mathrm{H}}}.$$

Heat Engines

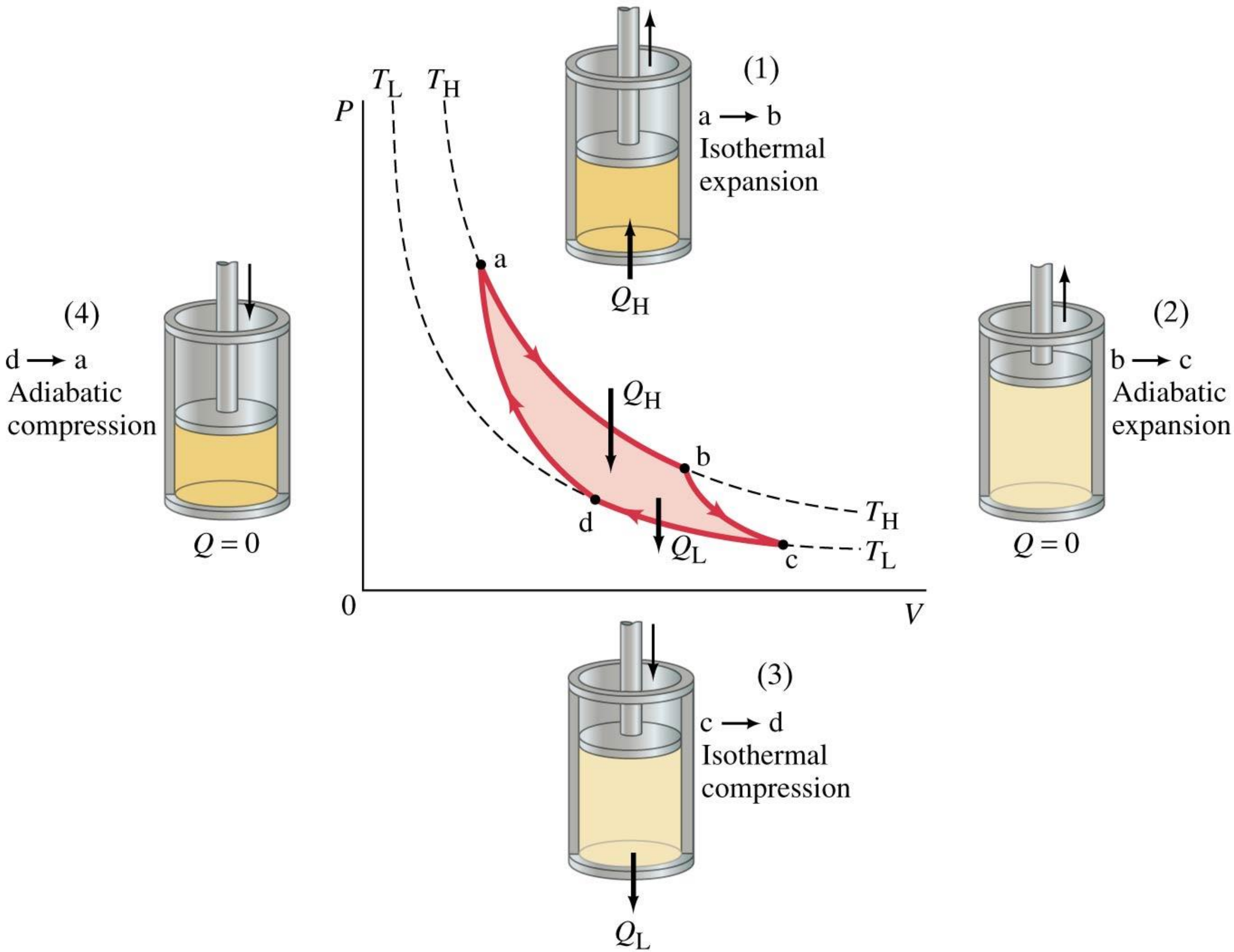
The Carnot engine was created to examine the efficiency of a heat engine. It is idealized, as it has no friction. Each leg of its cycle is reversible.

The Carnot cycle consists of:

- Isothermal expansion
- Adiabatic expansion
- Isothermal compression
- Adiabatic compression

An example is on the next slide.

Heat Engines



Heat Engines

For an ideal reversible engine, the efficiency can be written in terms of the temperature:

$$e_{\text{ideal}} = \frac{T_H - T_L}{T_H} = 1 - \frac{T_L}{T_H}. \qquad \left[\begin{array}{c}\text{Carnot (ideal)}\\ \text{efficiency}\end{array}\right]$$

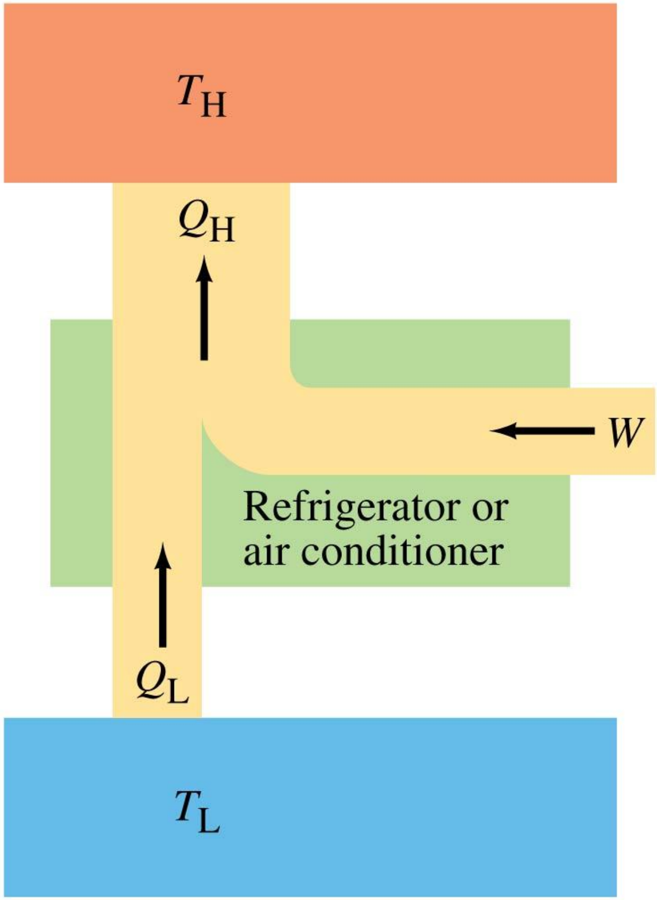
From this we see that 100% efficiency can be achieved only if the cold reservoir is at absolute zero, which is impossible.

Real engines have some frictional losses; the best achieve 60-80% of the Carnot value of efficiency.

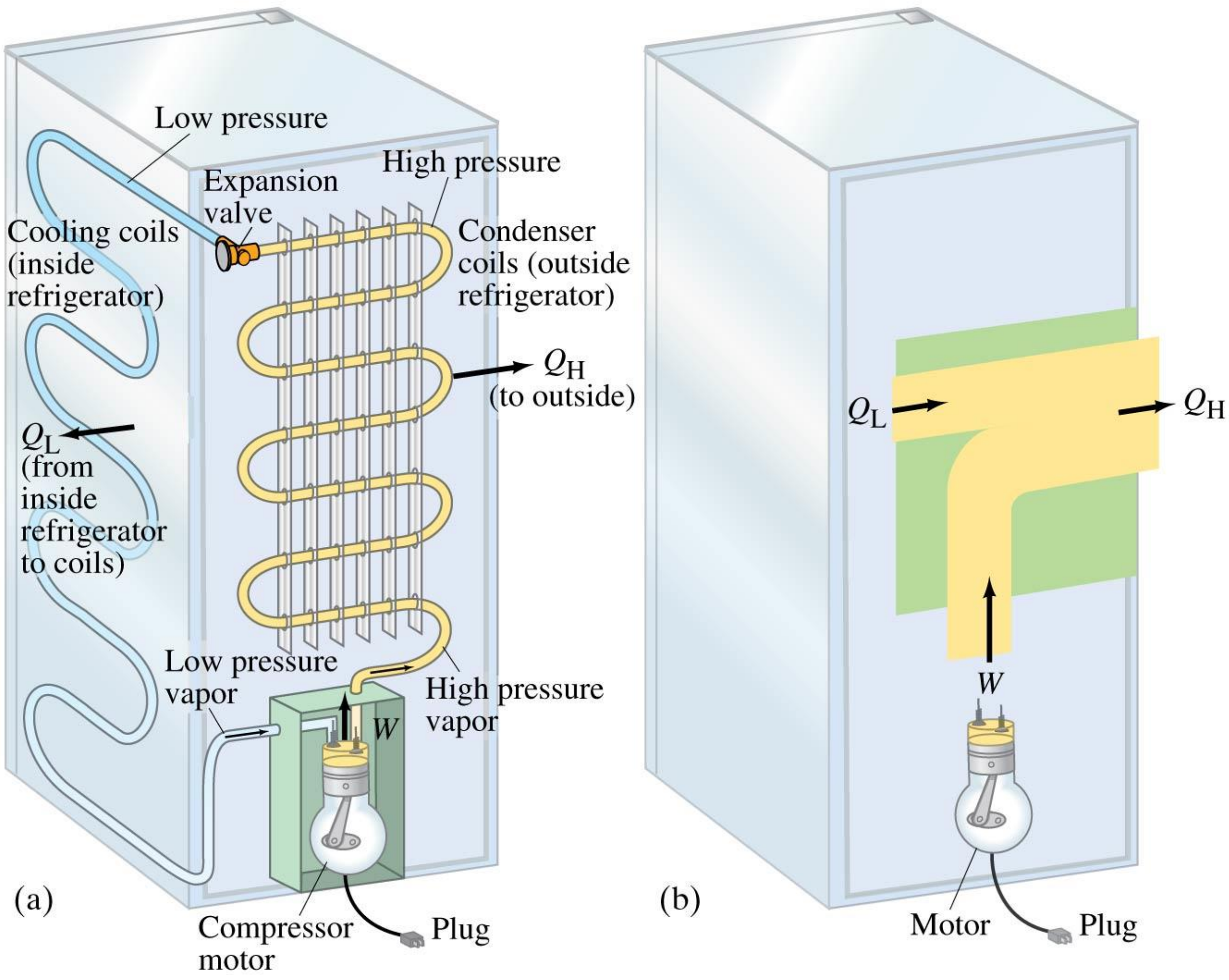
Refrigerators, Air Conditioners, and Heat Pumps

These appliances can be thought of as heat engines operating in reverse.

By doing work, heat is extracted from the cold reservoir and exhausted to the hot reservoir.



Refrigerators, Air Conditioners, and Heat Pumps



Refrigerators, Air Conditioners, and Heat Pumps

Refrigerator performance is measured by the coefficient of performance (COP):

$$\mathrm{COP} = \frac{Q_L}{W}. \qquad \left[\begin{array}{l}\text{refrigerator and}\\ \text{air conditioner}\end{array}\right]$$

Substituting:

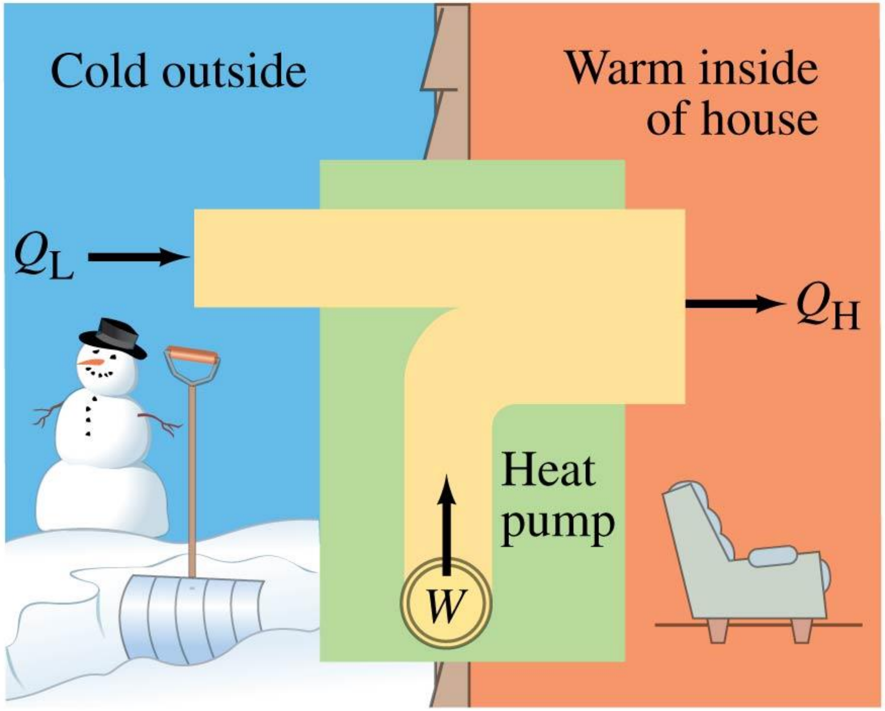
$$\mathrm{COP} = \frac{Q_L}{W} = \frac{Q_L}{Q_H - Q_L}. \qquad \left[\begin{array}{l}\text{refrigerator and}\\ \text{air conditioner}\end{array}\right]$$

$$\mathrm{COP}_{\text{ideal}} = \frac{T_L}{T_H - T_L}, \qquad \left[\begin{array}{l}\text{refrigerator and}\\ \text{air conditioner}\end{array}\right]$$

Refrigerators, Air Conditioners, and Heat Pumps

A heat pump can heat a house in the winter:

$$\mathrm{COP} = \frac{Q_\mathrm{H}}{W}. \qquad \text{[heat pump]}$$



Entropy and the Second Law of Thermodynamics

Definition of the change in entropy *S* when an amount of heat *Q* is added:

$$\Delta S = \frac{Q}{T},$$

Another statement of the second law of thermodynamics:

The total entropy of an isolated system never decreases.

Order to Disorder

Entropy is a measure of the disorder of a system.
This gives us yet another statement of the second law:

Natural processes tend to move toward a state of greater disorder.

Example: If you put milk and sugar in your coffee and stir it, you wind up with coffee that is uniformly milky and sweet. No amount of stirring will get the milk and sugar to come back out of solution.

Order to Disorder

Another example: when a tornado hits a building, there is major damage. You never see a tornado approach a pile of rubble and leave a building behind when it passes.

Thermal equilibrium is a similar process—the uniform final state has more disorder than the separate temperatures in the initial state.

Order to Disorder

Growth of an individual, and evolution of a species, are both processes of increasing order. Do they violate the second law of thermodynamics?

No! These are not isolated systems. Energy comes into them in the form of food, sunlight, and air, and energy also leaves them.

The second law of thermodynamics is the one that defines the arrow of time—processes will occur that are not reversible, and movies that run backward will look silly.

Unavailability of Energy; Heat Death

Another consequence of the second law:

In any natural process, some energy becomes unavailable to do useful work.

If we look at the universe as a whole, it seems inevitable that, as more and more energy is converted to unavailable forms, the ability to do work anywhere will gradually vanish. This is called the heat death of the universe.

Summary of Chapter 15

- First law of thermodynamics:

$$\Delta U = Q - W$$

- Isothermal process: temperature is constant.
- Adiabatic process: no heat is exchanged.
- Work done by gas at constant pressure:

$$W = P\,\Delta V. \qquad \text{[constant pressure]}$$

- Heat engine changes heat into useful work; needs temperature difference.

$$e = \frac{W}{Q_{\mathrm{H}}}.$$

- Efficiency of a heat engine:

$$e = \frac{W}{Q_{\mathrm{H}}} = \frac{Q_{\mathrm{H}} - Q_{\mathrm{L}}}{Q_{\mathrm{H}}}$$

or

$$e = 1 - \frac{Q_{\mathrm{L}}}{Q_{\mathrm{H}}}.$$

Summary of Chapter 15

- Upper limit on efficiency:

$$e_{\text{ideal}} = \frac{T_{\text{H}} - T_{\text{L}}}{T_{\text{H}}} = 1 - \frac{T_{\text{L}}}{T_{\text{H}}}. \qquad \begin{bmatrix}\text{Carnot (ideal)}\\ \text{efficiency}\end{bmatrix}$$

- Refrigerators and air conditioners do work to extract heat from a cooler region and send it to a warmer region:

$$\text{COP} = \frac{Q_{\text{L}}}{W}. \qquad \begin{bmatrix}\text{refrigerator and}\\ \text{air conditioner}\end{bmatrix}$$

- A heat pump is similar:

$$\text{COP} = \frac{Q_{\text{H}}}{W}. \qquad [\text{heat pump}]$$

Summary of Chapter 15

- Second law of thermodynamics:
    - heat flows spontaneously from a hot object to a cold one, but not the reverse
    - a given amount of heat cannot be changed entirely to work
    - natural processes tend to increase entropy.
- Change in entropy: $\Delta S = \frac{Q}{T},$
- Entropy is a measure of disorder.
- As time goes on, less and less energy is available to do useful work.