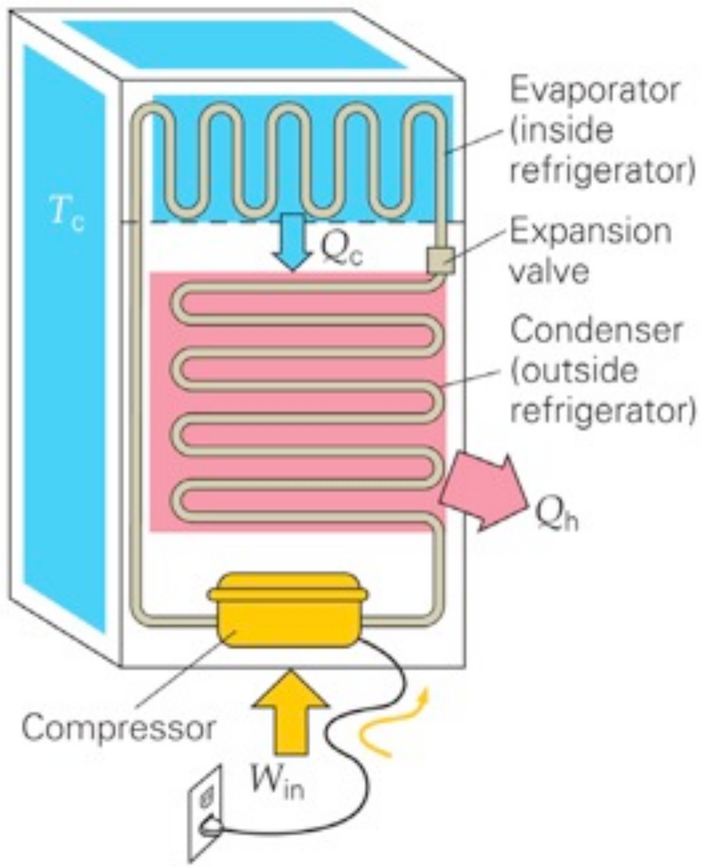
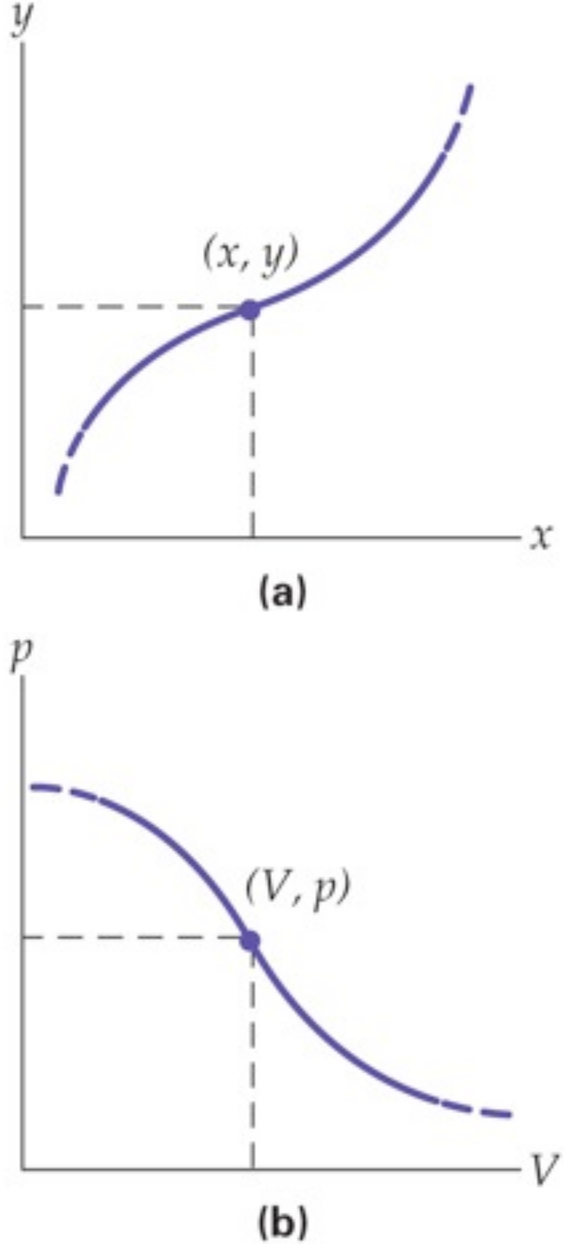
Thermodynamics

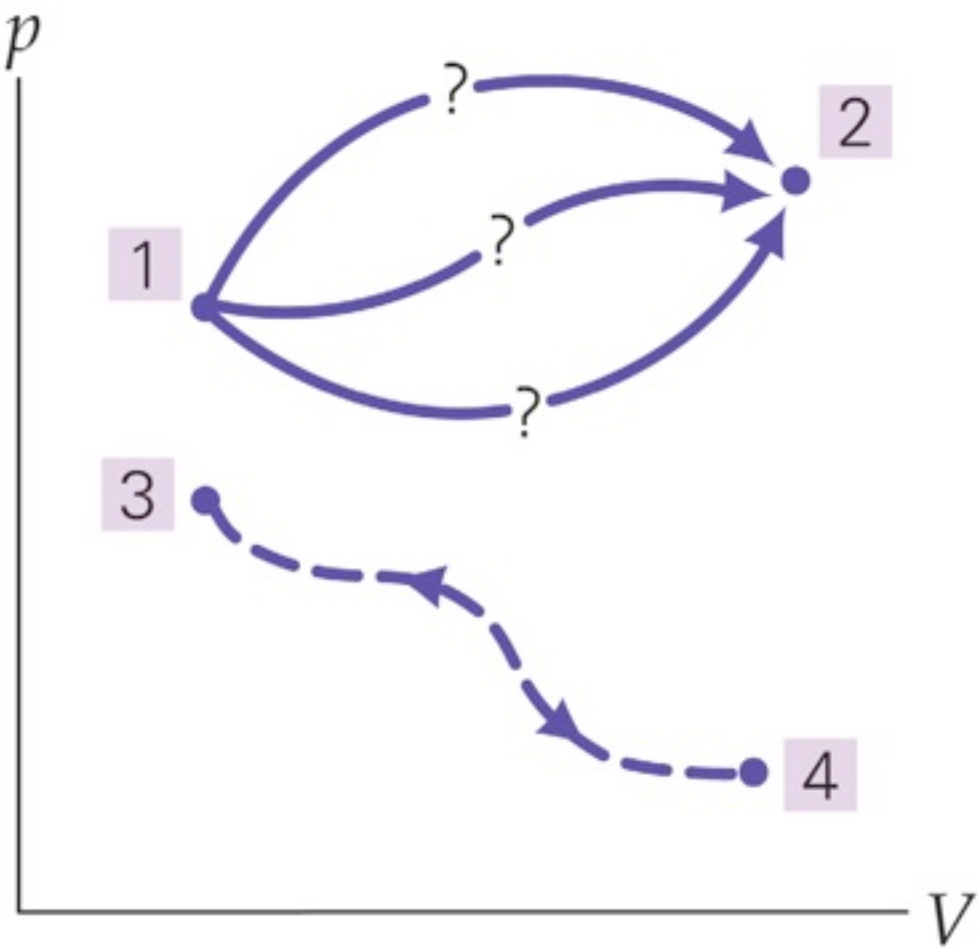


Thermodynamic Systems, States, and Processes



A thermodynamic system is described by an equation of state, such as the ideal gas law. The "location" of the state can be plotted on a p–V diagram, as at left.

Thermodynamic Systems, States, and Processes



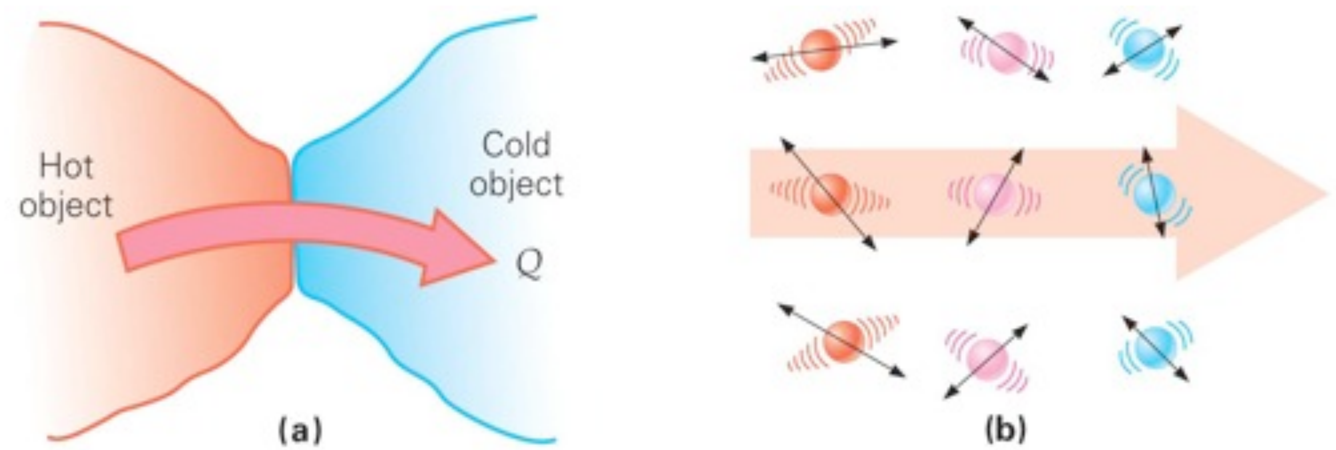
A process changes the state of a system. A process may be:
reversible (3–4) or irreversible (1–2);
if it proceeds through a sequence of equilibrium states it is reversible.

The First Law of Thermodynamics

The first law is a statement of conservation of energy in thermodynamic processes:

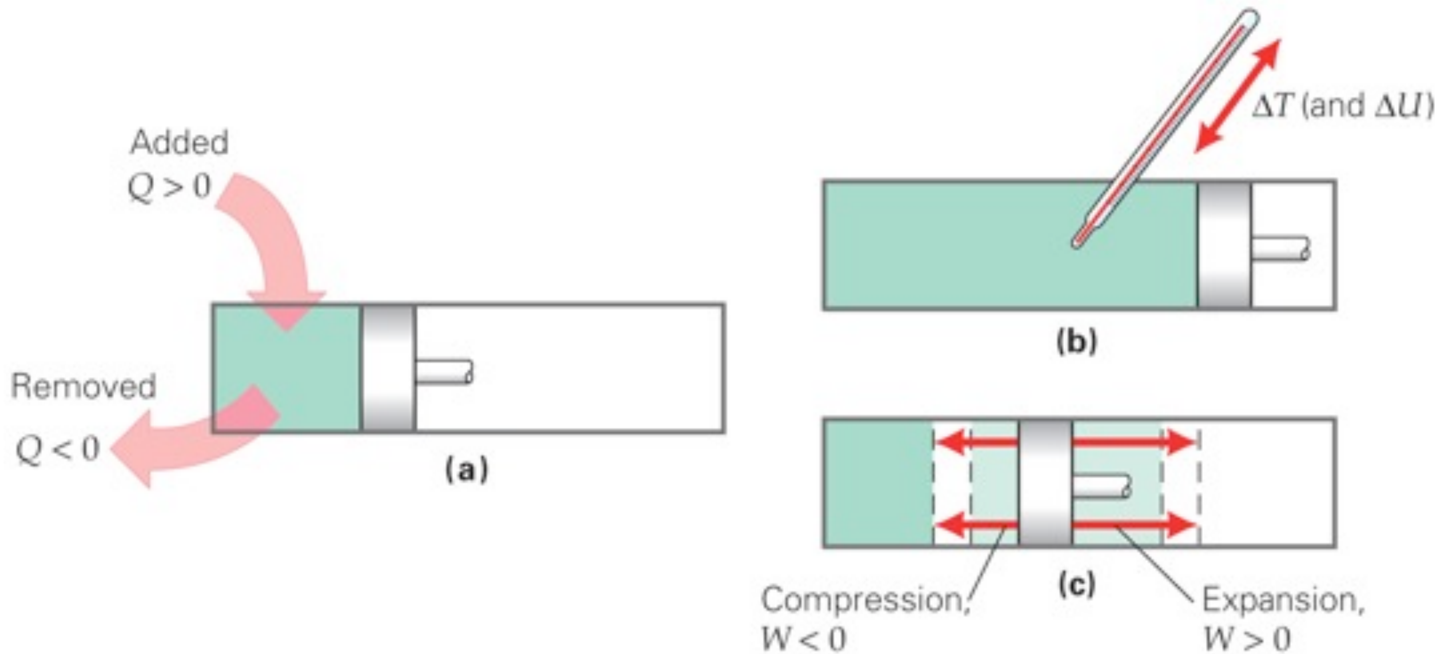
$$Q = \Delta U + W$$

Here, Q is the heat transferred, ΔU is the change in internal energy, and W is the work.

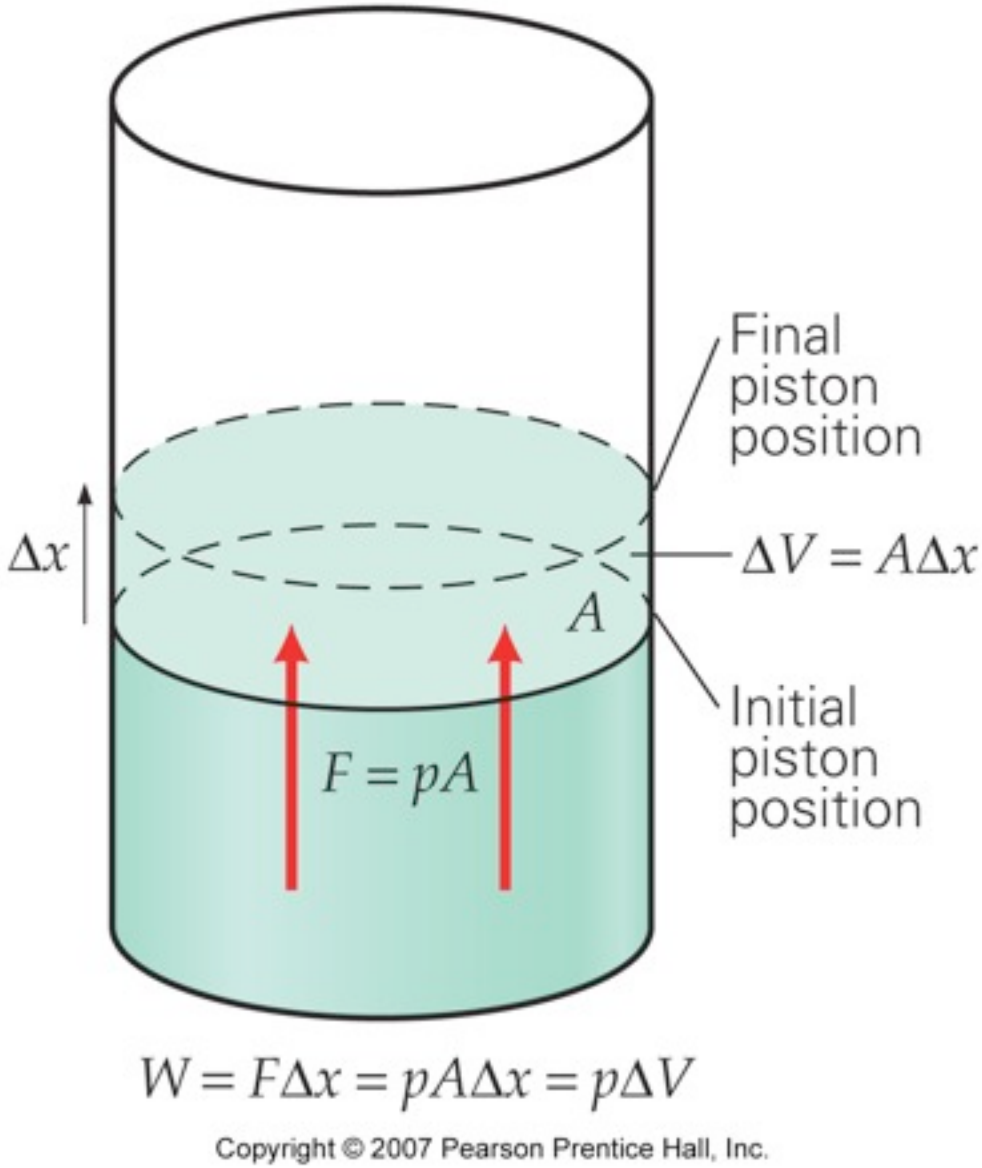


The First Law of Thermodynamics

It is important to get the signs of Q, ΔU, and W correct. The diagram below illustrates the sign conventions.



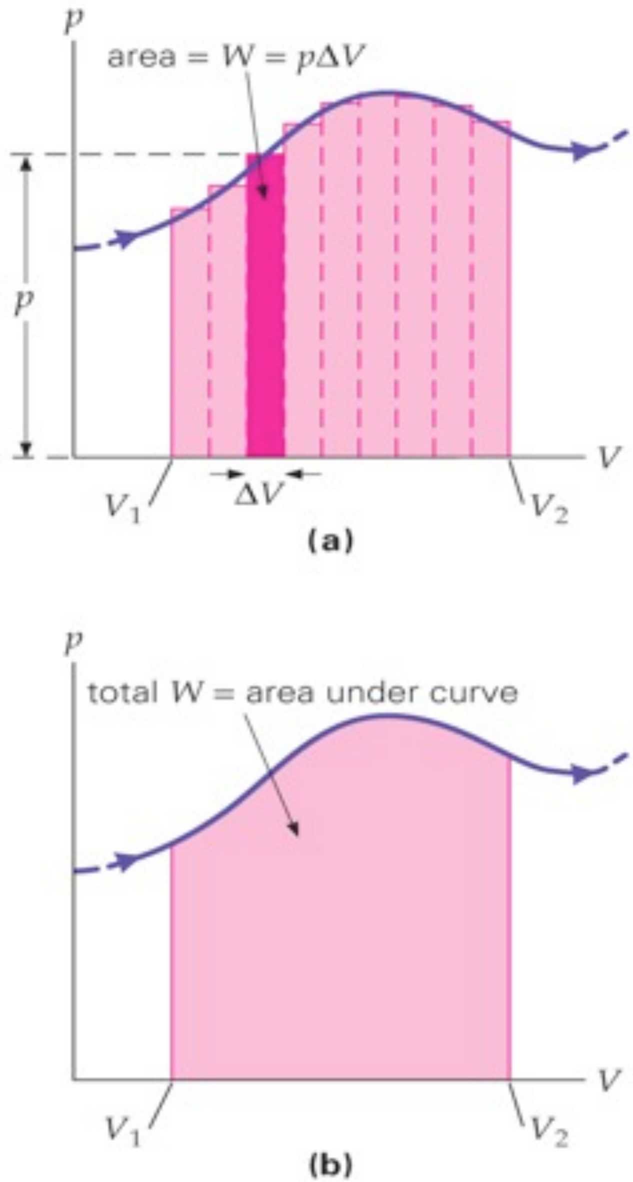
The First Law of Thermodynamics



It can be shown that the work done in expanding a gas is given by:

$$W = p\Delta V$$

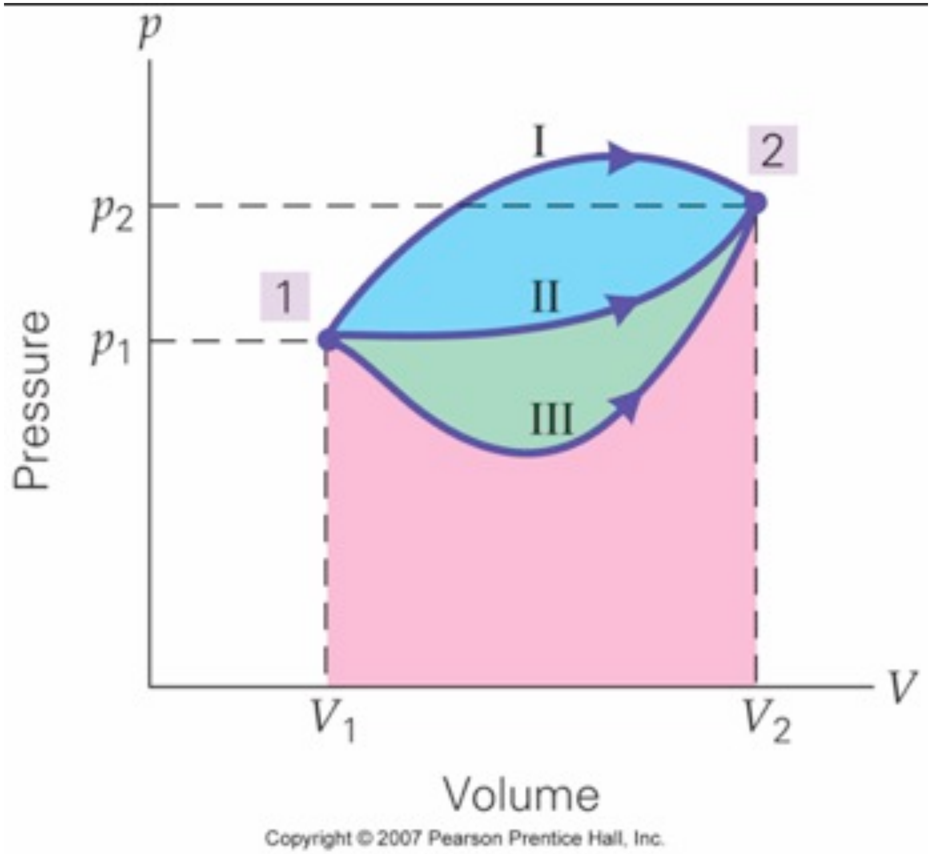
The First Law of Thermodynamics



Generalizing, we see that:

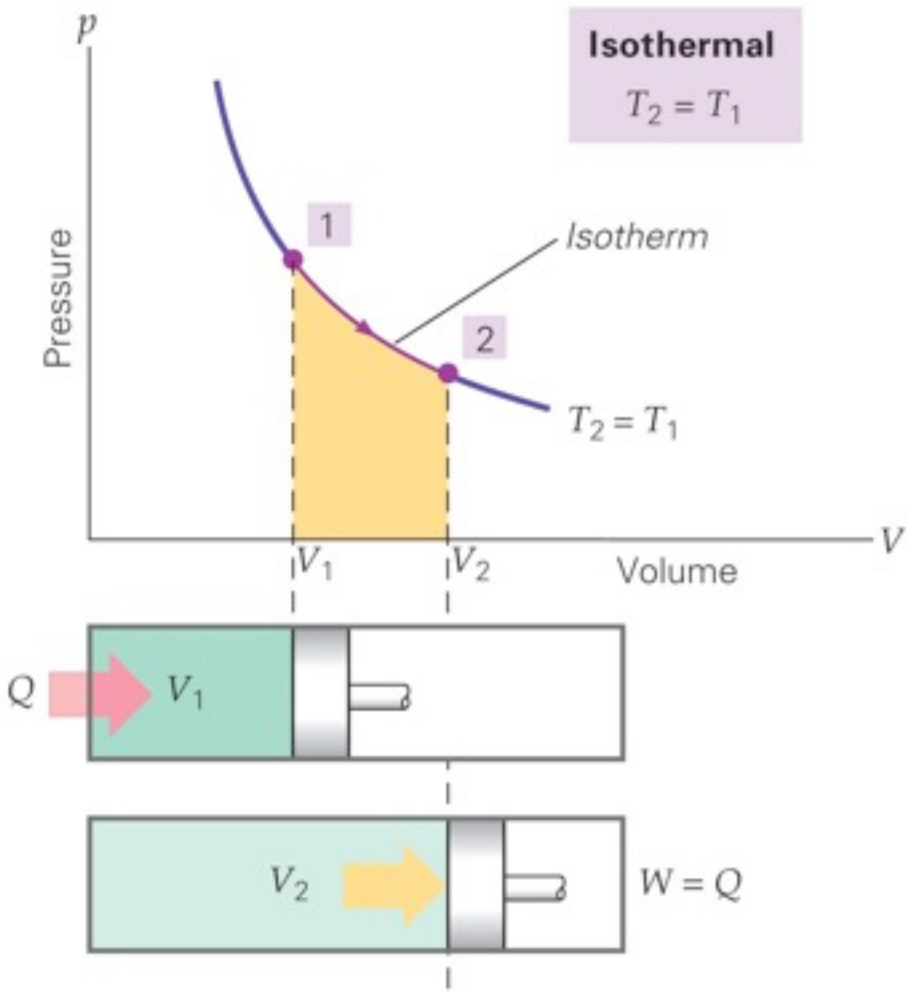
The work done by a system is equal to the area under the process curve on a p–V diagram.

The First Law of Thermodynamics



The heat transferred and the work done both depend on the path taken from state 1 to state 2; the change in internal energy depends only on the end points.

Thermodynamic Processes for an Ideal Gas



An isothermal process is one in which the temperature does not change.

Thermodynamic Processes for an Ideal Gas

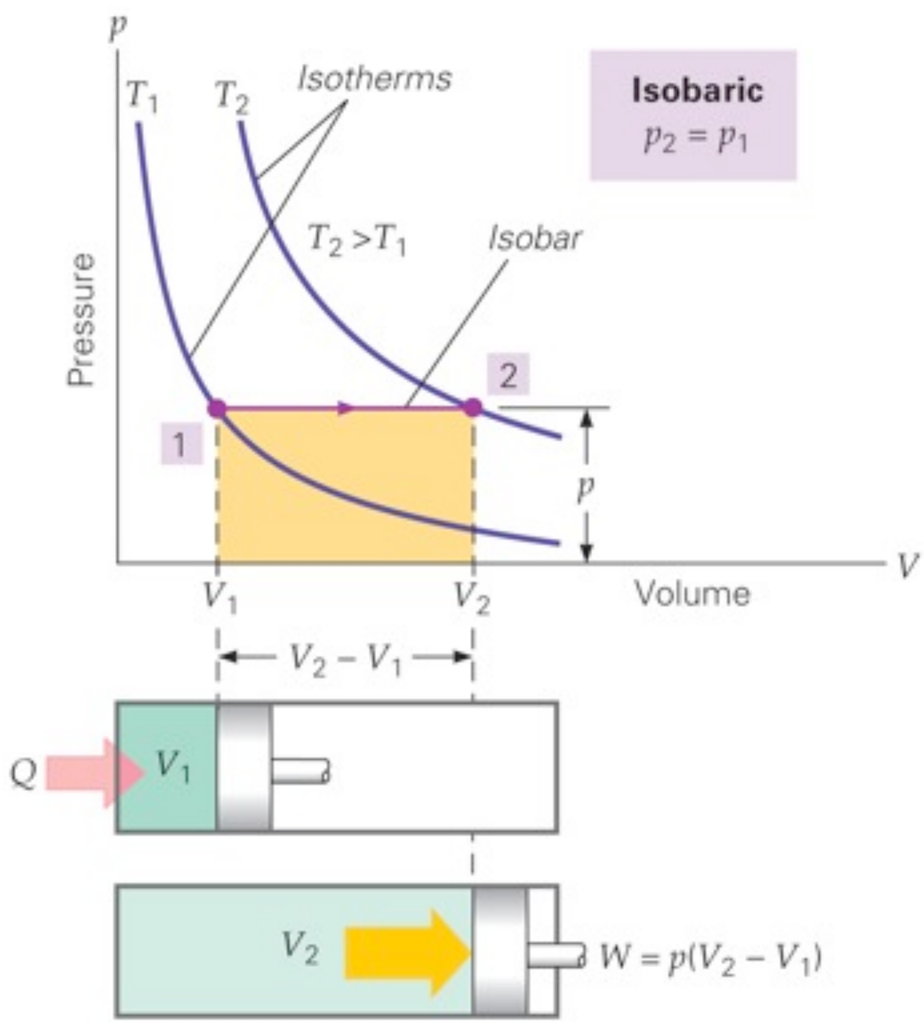
The first law of thermodynamics gives:

$$Q = W$$

The work done is:

$$W_{\text{isothermal}} = nRT \ln\left(\frac{V_2}{V_1}\right)$$

Thermodynamic Processes for an Ideal Gas



An isobaric process is one in which the pressure does not change.

Thermodynamic Processes for an Ideal Gas

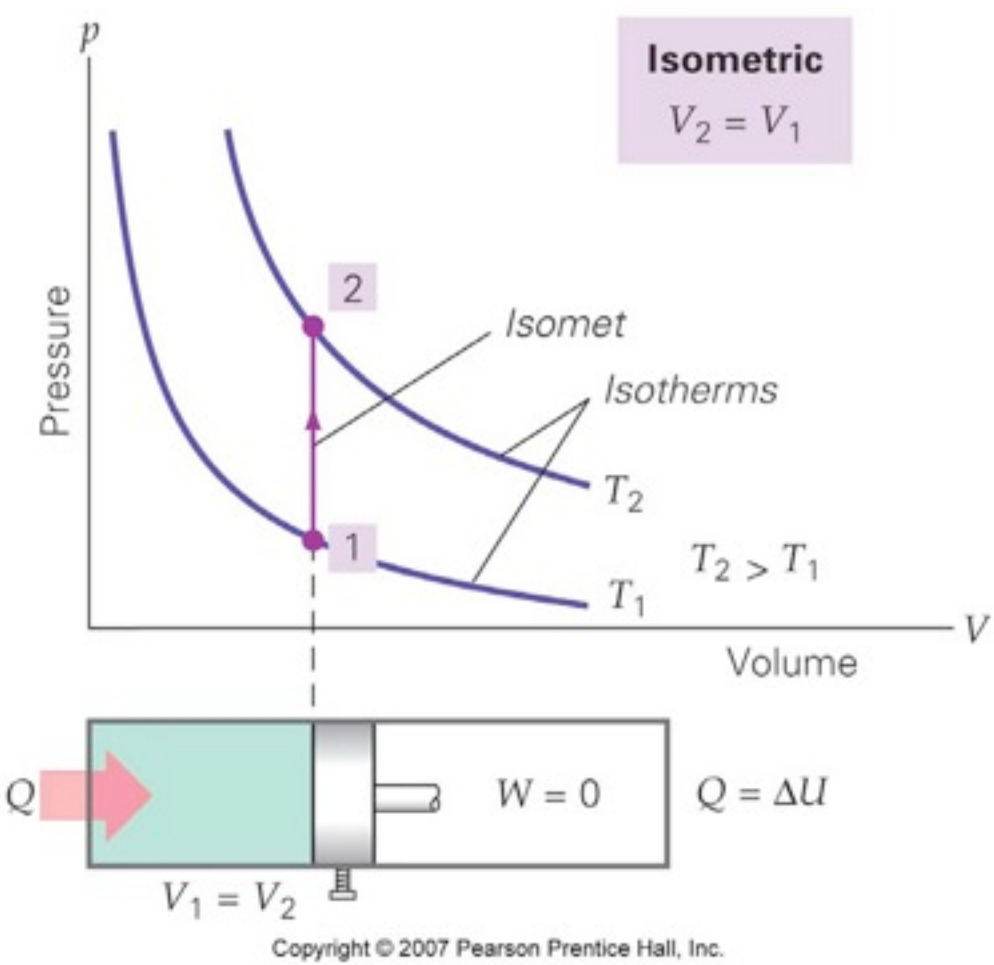
The first law of thermodynamics gives:

$$Q = \Delta U + W = \Delta U + p\Delta V$$

The work done is:

$$W_{\text{isobaric}} = p(V_2 - V_1) = p\Delta V$$

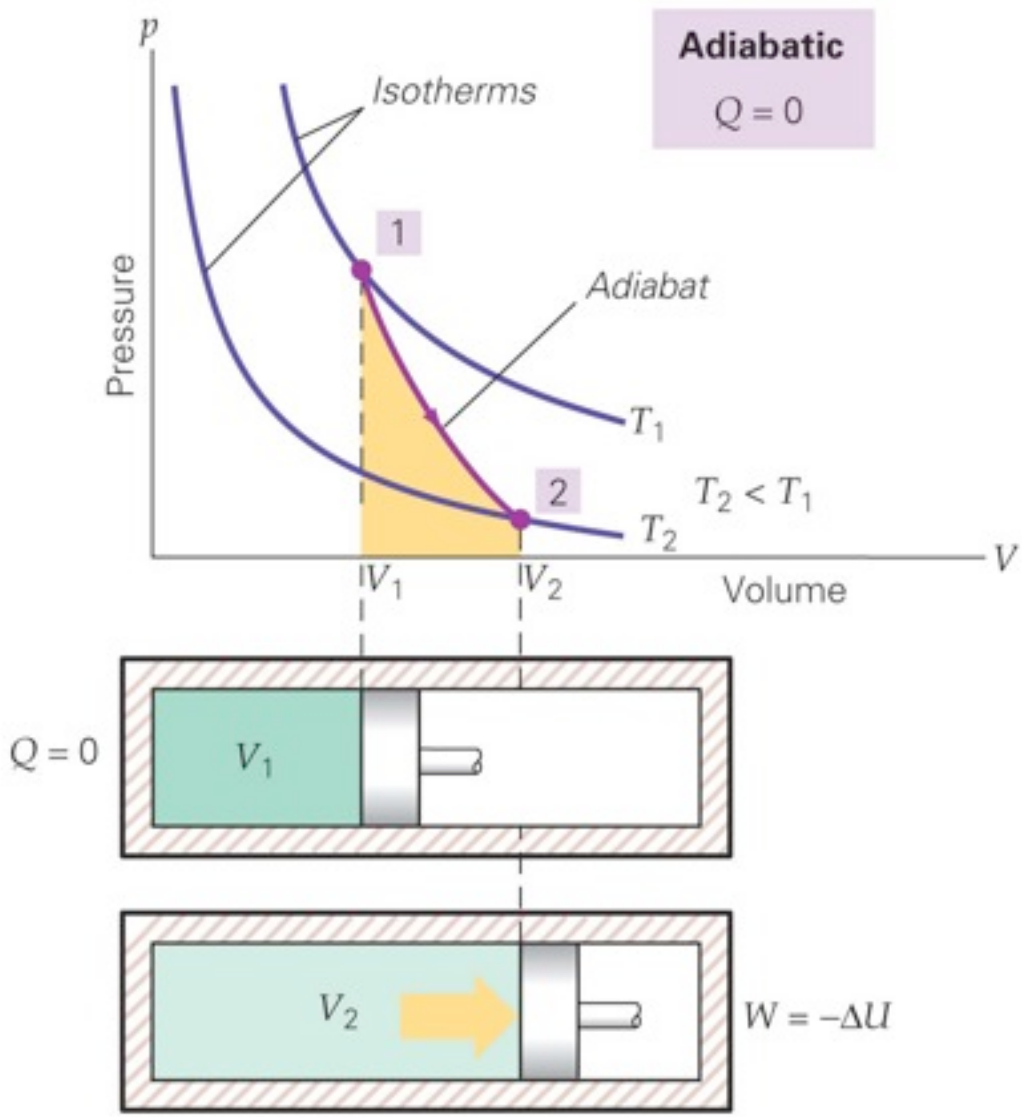
Thermodynamic Processes for an Ideal Gas



An isometric process is one in which the volume is constant.
In this case, no work is done, so

$$Q = \Delta U$$

Thermodynamic Processes for an Ideal Gas



An adiabatic process is one where there is no heat transfer.

Thermodynamic Processes for an Ideal Gas

In this case,

$$\Delta U = -W$$

And

$$W_{\text{adiabatic}} = \frac{p_1 V_1 - p_2 V_2}{\gamma - 1}$$

where

$$\gamma = c_{\text{p}}/c_{\text{v}}$$

Thermodynamic Processes for an Ideal Gas

TABLE 12.1 Important Thermodynamic Processes

Process	*Characteristic*	*Result*	*The First Law of Thermodynamics*
Isothermal	$T = \text{constant}$	$\Delta U = 0$	$Q = W$
Isobaric	$p = \text{constant}$	$W = p\Delta V$	$Q = \Delta U + p\Delta V$
Isometric	$V = \text{constant}$	$W = 0$	$Q = \Delta U$
Adiabatic	$Q = 0$		$\Delta U = -W$

As a final summary for these thermodynamic processes, their characteristics and consequences are listed in Table 12.1.

The Second Law of Thermodynamics and Entropy

The second law of thermodynamics:

1. In a thermal cycle, heat energy cannot be completely transformed into mechanical work.

2. It is impossible to construct an operational perpetual-motion machine.

3. It's impossible for any process to have as its sole result the transfer of heat from a cooler to a hotter body

The Second Law of Thermodynamics and Entropy

Another statement of the second law of thermodynamics:
All naturally occurring processes move toward a state of greater disorder or disarray.

It is a lot easier to break things than it is to put them back together again!

The Second Law of Thermodynamics and Entropy

What is entropy?
We cannot measure it directly, only changes in it.

Entropy:
–Is a measure of disorder
–Is increasing in the universe
–Is a measure of a system's ability to do useful work

Determines the direction of time

$$\Delta S = \frac{Q}{T}$$ *(change in entropy at constant temperature)*

The Second Law of Thermodynamics and Entropy

The entropy of an isolated system never decreases. The universe is the ultimate isolated system; therefore, the total energy of the universe increases during every natural process.

There are processes during which the entropy does not change; however, during any process the entropy of the universe can only increase or remain constant.

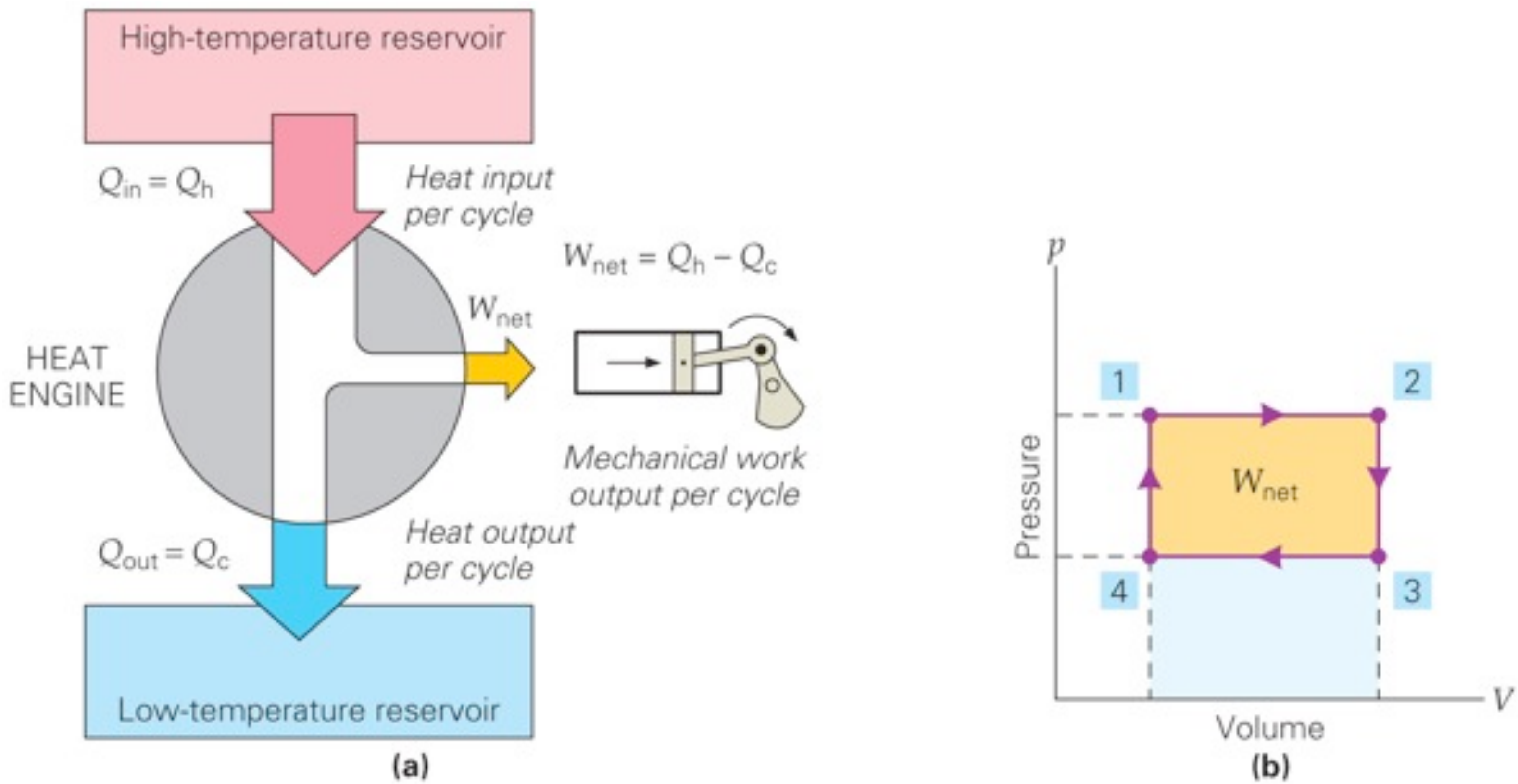
$$\Delta S \geq 0$$

Heat Engines and Thermal Pumps

A heat engine converts heat energy into work. According to the second law of thermodynamics, however, it cannot convert *all* of the heat energy supplied to it into work.
Basic heat engine: hot reservoir, cold reservoir, and a machine to convert heat energy into work.

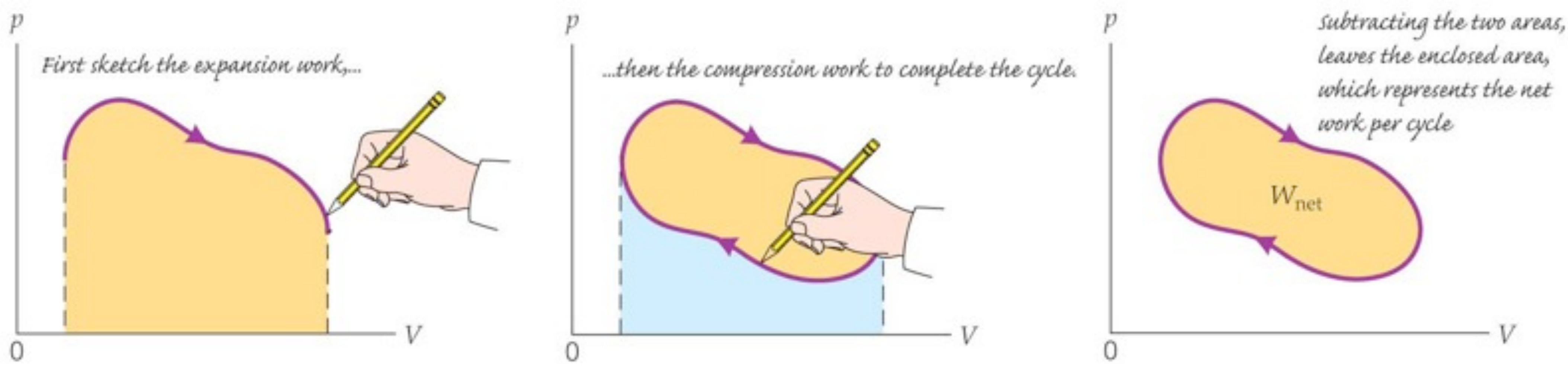
Heat Engines and Thermal Pumps

This is a simplified diagram of a heat engine, along with its thermal cycle.



Heat Engines and Thermal Pumps

An important quantity characterizing a heat engine is the net work it does when going through an entire cycle.



Heat Engines and Thermal Pumps

Thermal efficiency of a heat engine:

$$\varepsilon = \frac{\text{net work out}}{\text{heat in}} = \frac{W_{\text{net}}}{Q_{\text{in}}}$$

For an ideal gas heat engine,

$$\varepsilon = \frac{W_{\text{net}}}{Q_{\text{h}}} = \frac{Q_{\text{h}} - Q_{\text{c}}}{Q_{\text{h}}} = 1 - \frac{Q_{\text{c}}}{Q_{\text{h}}}$$

Heat Engines and Thermal Pumps

Yet another restatement of the second law of thermodynamics:

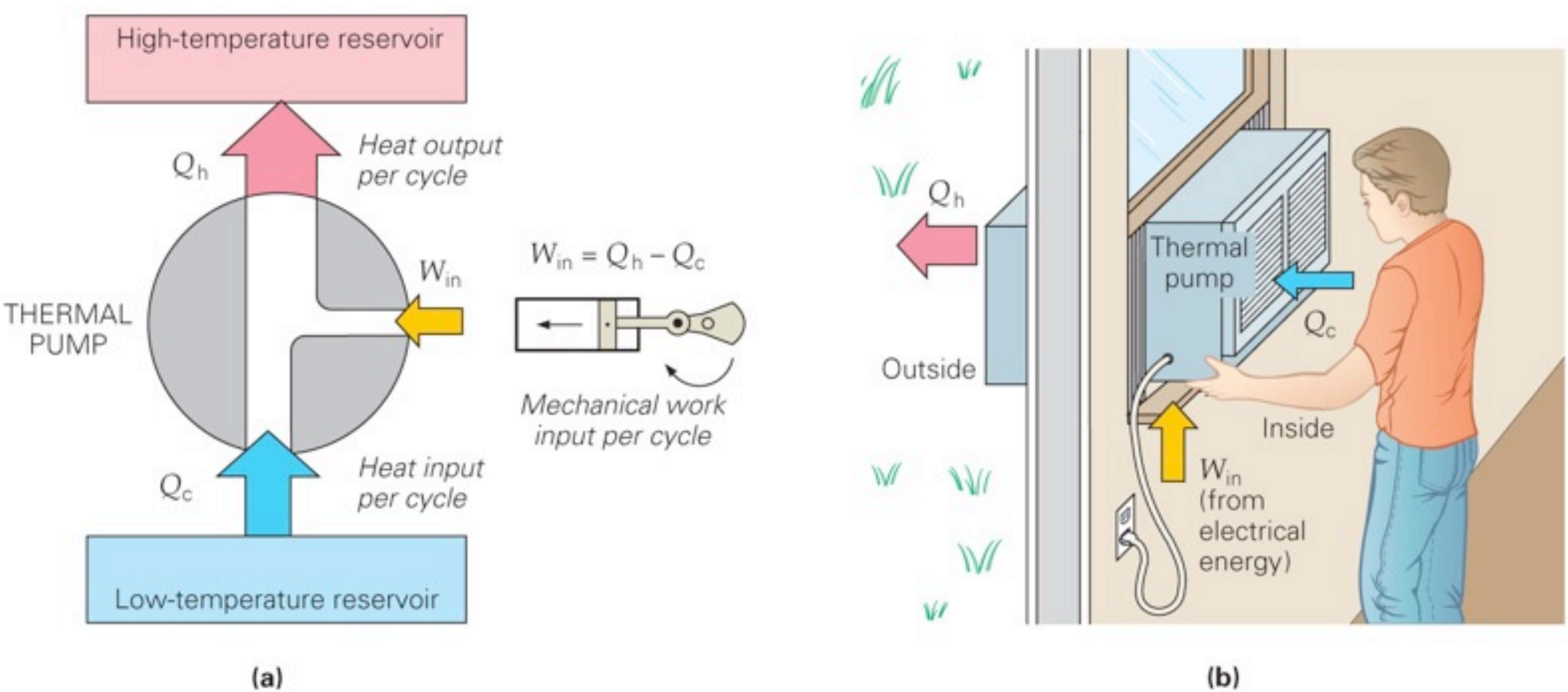
No cyclic heat engine can convert its heat input completely to work.

Heat Engines and Thermal Pumps

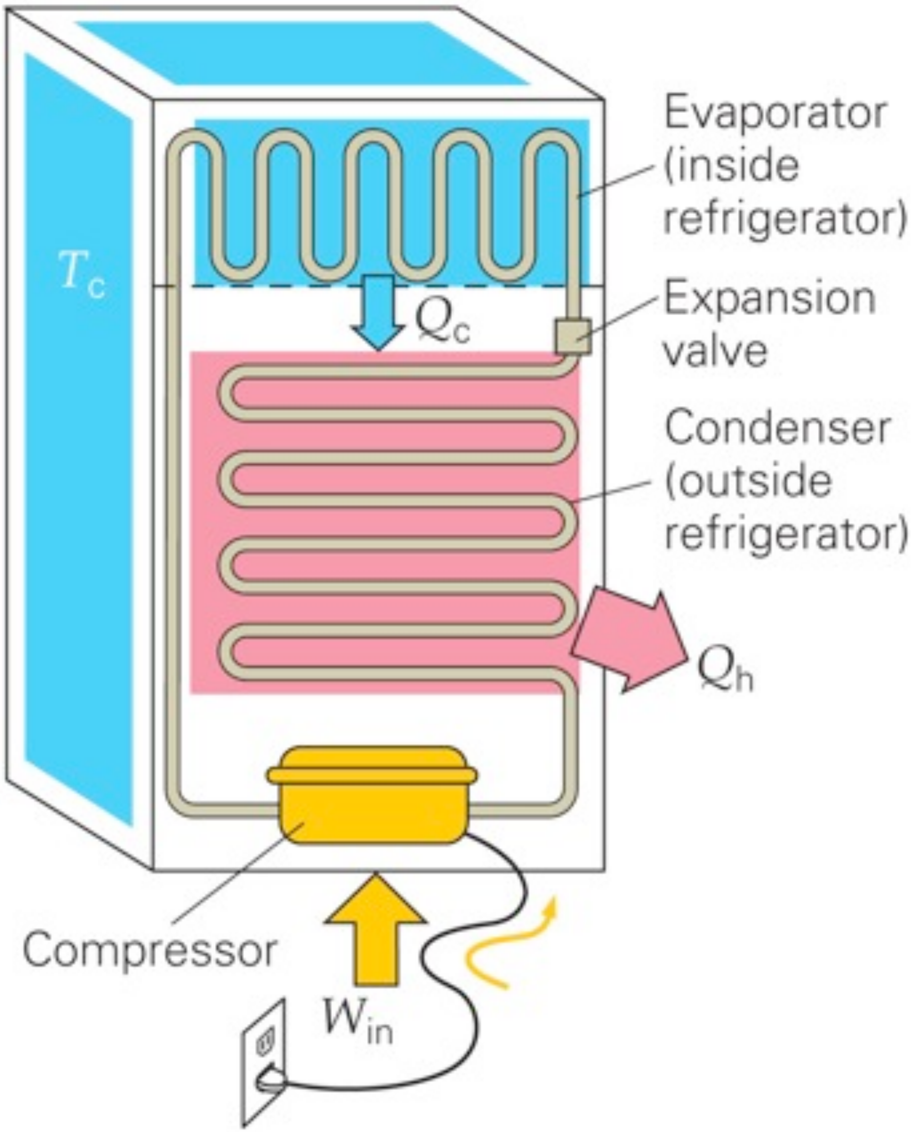
A thermal pump is the opposite of a heat engine: it transfers heat energy from a cold reservoir to a hot one.
As this will not happen spontaneously, work must be done on the pump as well.
Examples of thermal pumps: refrigerator, air conditioner

Heat Engines and Thermal Pumps

An air conditioner removes heat from the house and exhausts it outside, where it is hotter.



Heat Engines and Thermal Pumps



A refrigerator does the same thing, except the warm air is exhausted into the kitchen.

Heat Engines and Thermal Pumps

The purpose of a refrigerator or air conditioner is to keep a cool place cool; we describe such a device by its coefficient of performance (COP).

$$\mathrm{COP}_{\mathrm{ref}} = \frac{Q_{\mathrm{c}}}{W_{\mathrm{in}}} = \frac{Q_{\mathrm{c}}}{Q_{\mathrm{h}} - Q_{\mathrm{c}}}$$

Typical COPs are in the range of 3–5; this is the ratio of the heat removed to the work done to remove it.

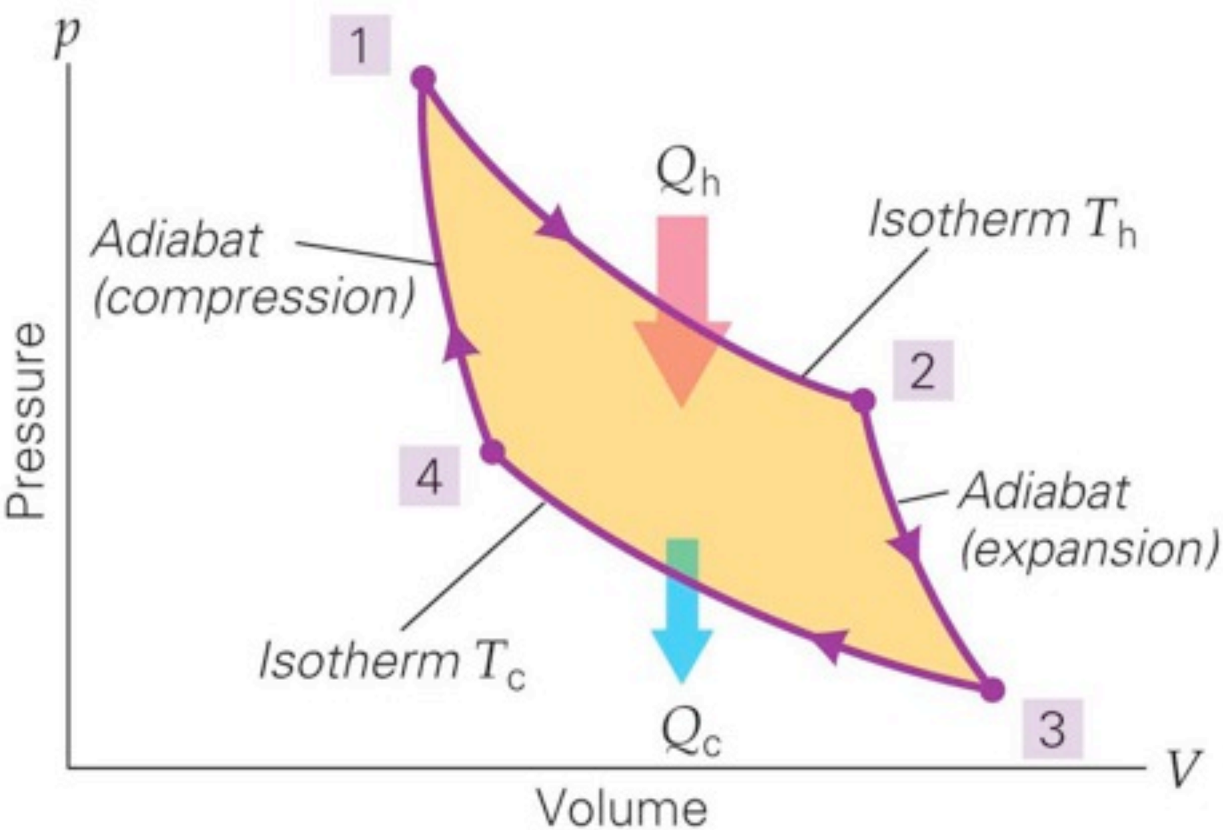
Heat Engines and Thermal Pumps

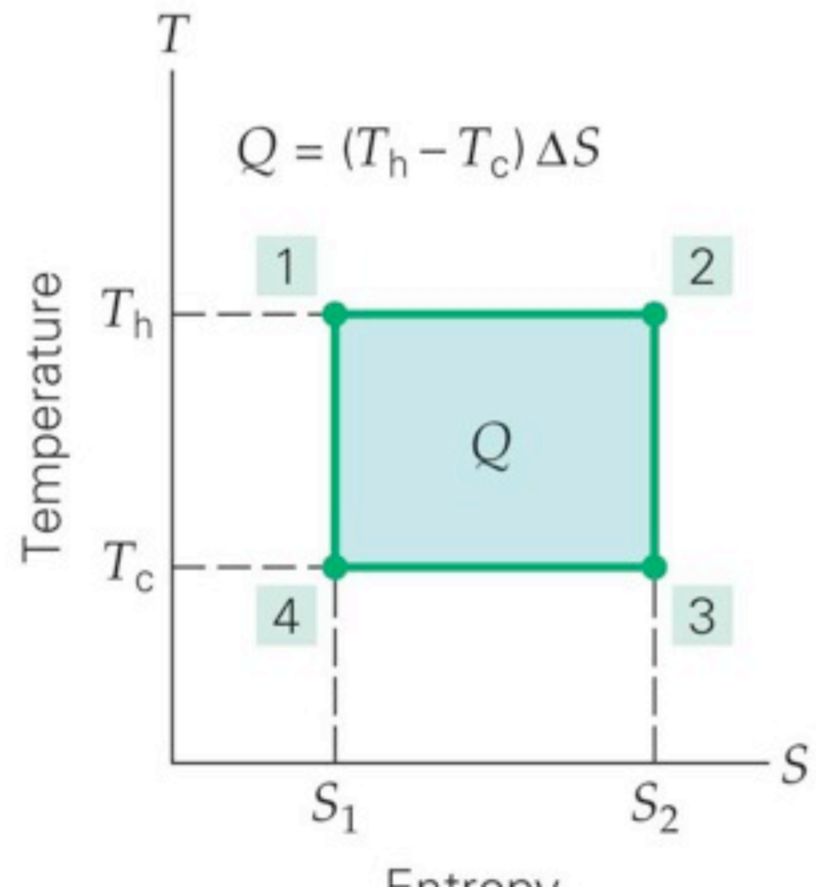
Heat pumps can also be used to warm cool places, such as a house in winter. The fundamental operation is the same—heat is taken from a cool place and sent to a warm one—but now the point is to keep the house warm, not to keep the outside cold. There is a different COP that describes how well a heat engine is doing this:

$$\mathrm{COP_{hp}} = \frac{Q_h}{W_{in}} = \frac{Q_h}{Q_h - Q_c}$$

The Carnot Cycle and Ideal Heat Engines

The Carnot cycle consists of two isotherms and two adiabats.





The Carnot Cycle and Ideal Heat Engines

An ideal Carnot engine—with perfect isotherms and adiabats—has the maximum efficiency a heat engine can have.

$$\varepsilon_C = 1 - \frac{T_c}{T_h}$$

This leads to the third law of thermodynamics:

It is impossible to reach absolute zero in a finite number of thermal processes.

Summary

First law of thermodynamics is conservation of energy:

$$Q = \Delta U + W$$

Thermodynamic processes: isothermal, isobaric, isometric, adiabatic

Work done:

$$W_{\text{isothermal}} = nRT \ln\left(\frac{V_2}{V_1}\right)$$

$$W_{\text{isobaric}} = p(V_2 - V_1) = p\Delta V$$

$$W_{\text{adiabatic}} = \frac{p_1 V_1 - p_2 V_2}{\gamma - 1}$$

Summary

Second law of thermodynamics specifies the direction a spontaneous interaction can take. Entropy is a measure of disorder:

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

During any kind of process, the entropy of the universe can only stay the same or increase.

Summary

A heat engine converts heat energy into work.
Efficiency:

$$\varepsilon = \frac{W_{\text{net}}}{Q_{\text{h}}} = \frac{Q_{\text{h}} - Q_{\text{c}}}{Q_{\text{h}}} = 1 - \frac{Q_{\text{c}}}{Q_{\text{h}}}$$

A thermal pump extracts heat from a cold reservoir and transfers it to a hot one.
A Carnot engine has the highest efficiency possible:

$$\varepsilon_{\text{C}} = 1 - \frac{T_{\text{c}}}{T_{\text{h}}}$$