The Second Law of Thermodynamics (I)

(This slides summarize the content of Nov. 24, 2003)

- 1 Introduction to the Second Law
- 2 Temperature Reservoirs
- 3 Heat Engines

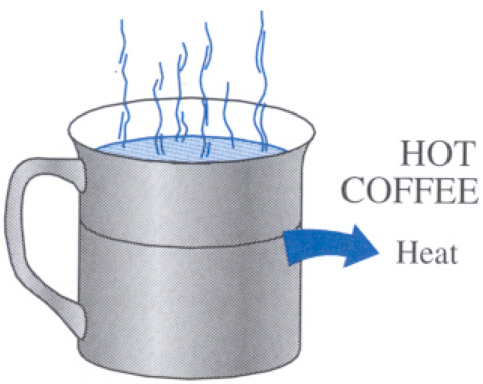
Introduction to the Second Law

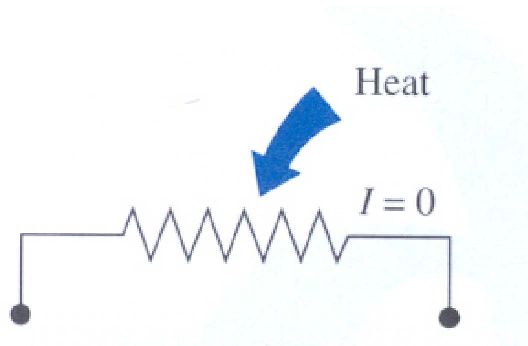
Common Processes for Explaining the Second Law

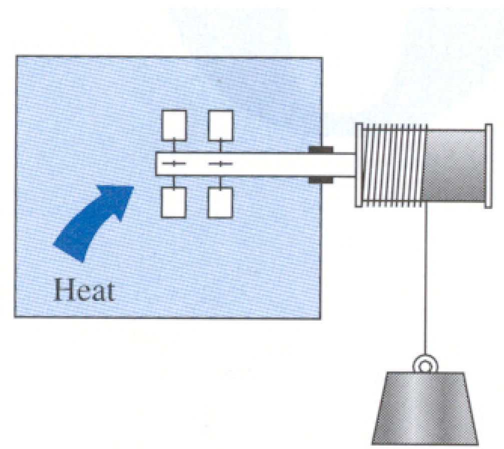
(1) A cup of hot coffee does not get hotter in a cooler room.

(2) Transferring heat to a wire will not generate electricity.

(3) Transferring heat to a paddle wheel will not cause it to rotate.







Introduction to the Second Law (continued)

- The first law of thermodynamics places no restriction on *the direction of a process*, but satisfy the first law does not ensure that that that process will actually occur. This inadequacy of the first law to identify whether a process can take place is remedied by introducing the second law of thermodynamics.

- The second law also asserts that *energy has quality as well as quantity*. More of high-temperature energy can be converted to work, and thus it has a higher quality than the same amount of energy at a lower temperature.

- The second law also can be used in determining the theoretical *limits of heat engines and refrigerators*, as well as predicting the degree of completion of chemical reactions.

Thermal Energy Reservoirs

- **In the development of the second law of thermodynamics, it is very convenient to have a hypothetical body with a relatively large thermal energy capacity that can supply or absorb finite amounts of heat without undergoing any change in temperature, such as body is called *thermal energy (heat) reservoir or temperature reservoir*.**

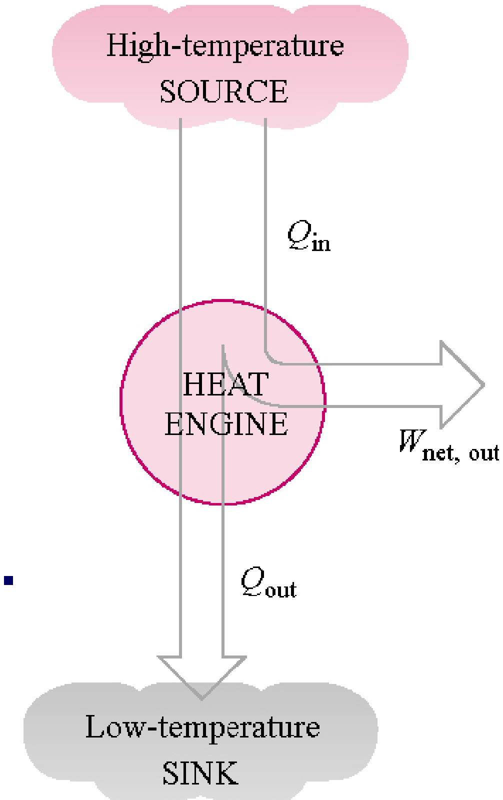
- **Examples are atmosphere, two-phase systems, and even the air in a room.**

- **A reservoir that supplies energy in the form of heat is called a *source*, and one that absorbs energy in the form of heat is called a *sink*.**

Heat Engines

Devices (figure at right) that converts heat into work is called ***heat engines***, which can be characterized by the following:

1. They receive heat from high-temperature source.
2. They convert part of this heat to work.
3. They reject the remaining waste heat to a low-temperature sink.
4. They operate on a cycle.



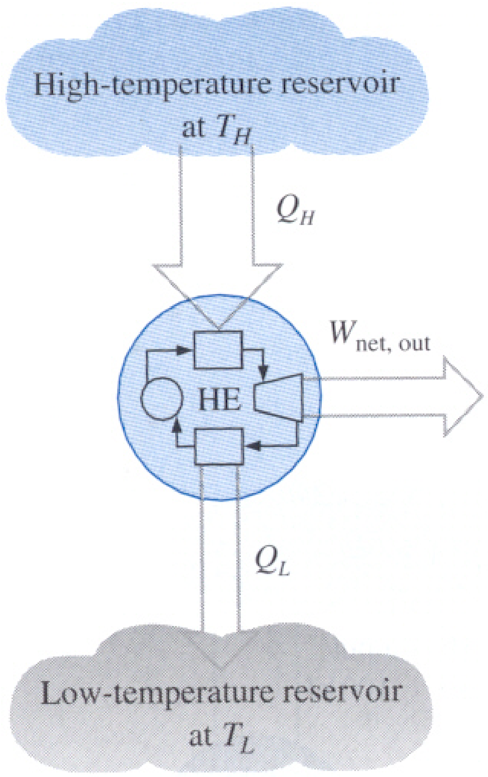
Heat engines and other cyclic devices usually involve a fluid to and from which heat is transferred while undergoing a cycle. This fluid is called the ***working fluid***.

Thermal Efficiency

The fraction of the heat input that is converted to net work output is a measure of the performance of a heat engine and is called the thermal efficiency η_{th}.

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

$$\eta_{th} = \frac{\text{Net work output}}{\text{Total heat input}} = \frac{W_{net,out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}}$$

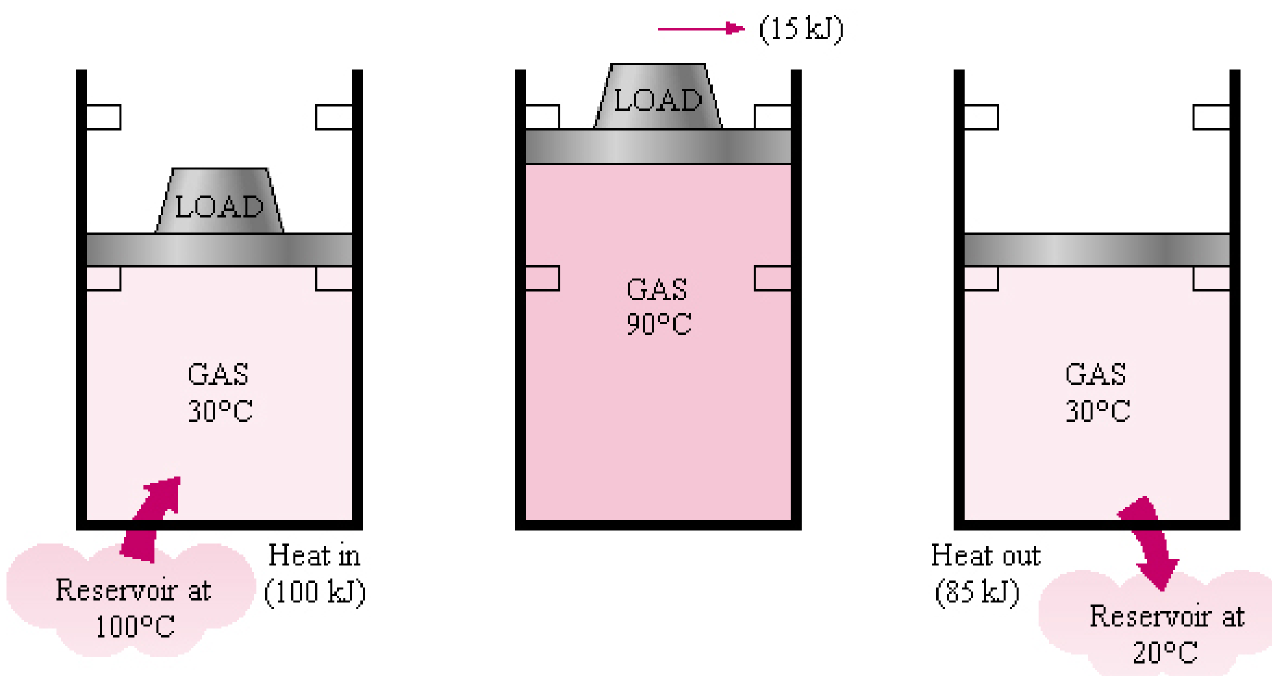


The thermal efficiencies of work-producing devices are relatively low. 25% for ordinary spark-iginition automobile engines; 40% for diesel engines; and 60% for large combined gas-steam power plants.

Can we save Q_{out}?

Every heat engine must waste some energy by transferring it to a low-temperature reservoir in order to complete the cycle, even under idealized conditions. It requires at least two reservoirs for continuous operation.

A heat- engine cycle cannot be completed without *rejecting* some heat to a low temperature sink.



The Second Law of Thermodynamics: Kelvin-Plank Statement

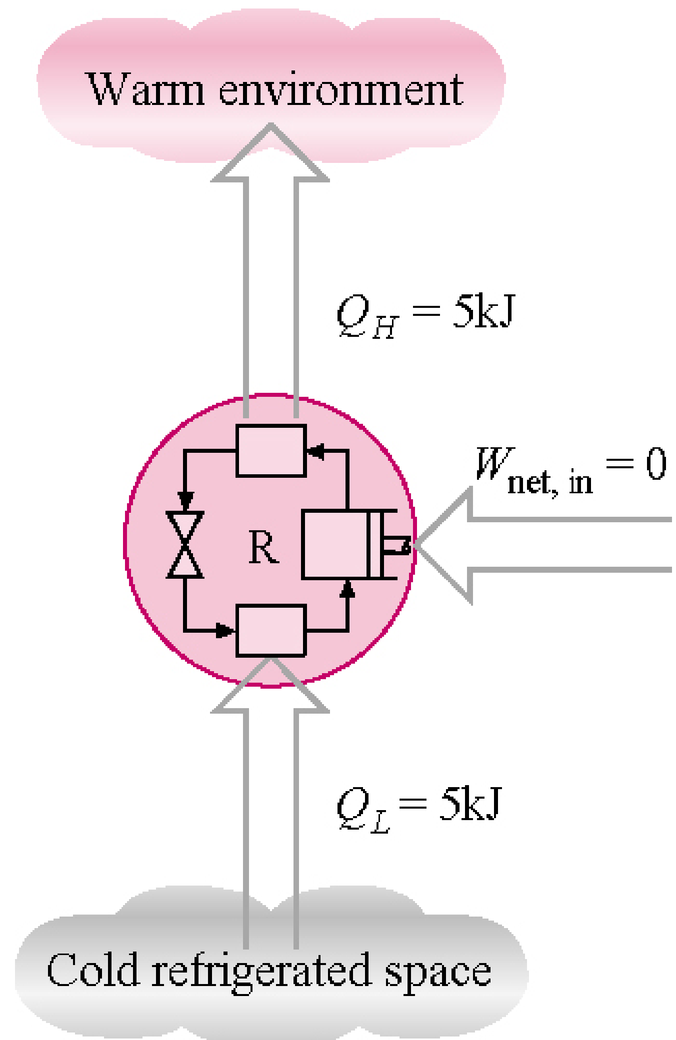
It is impossible for any device that operates on a cycle to receive heat from a single reservoir and produce a net amount of work.

It implies that: *No heat engine can have a thermal efficiency of 100%*.

Note that the *impossibility* of having a 100% efficient heat engine is a limitation that applies to both idealized and the actual heat engines.

The second Law of Thermodynamics: Clausius Statement

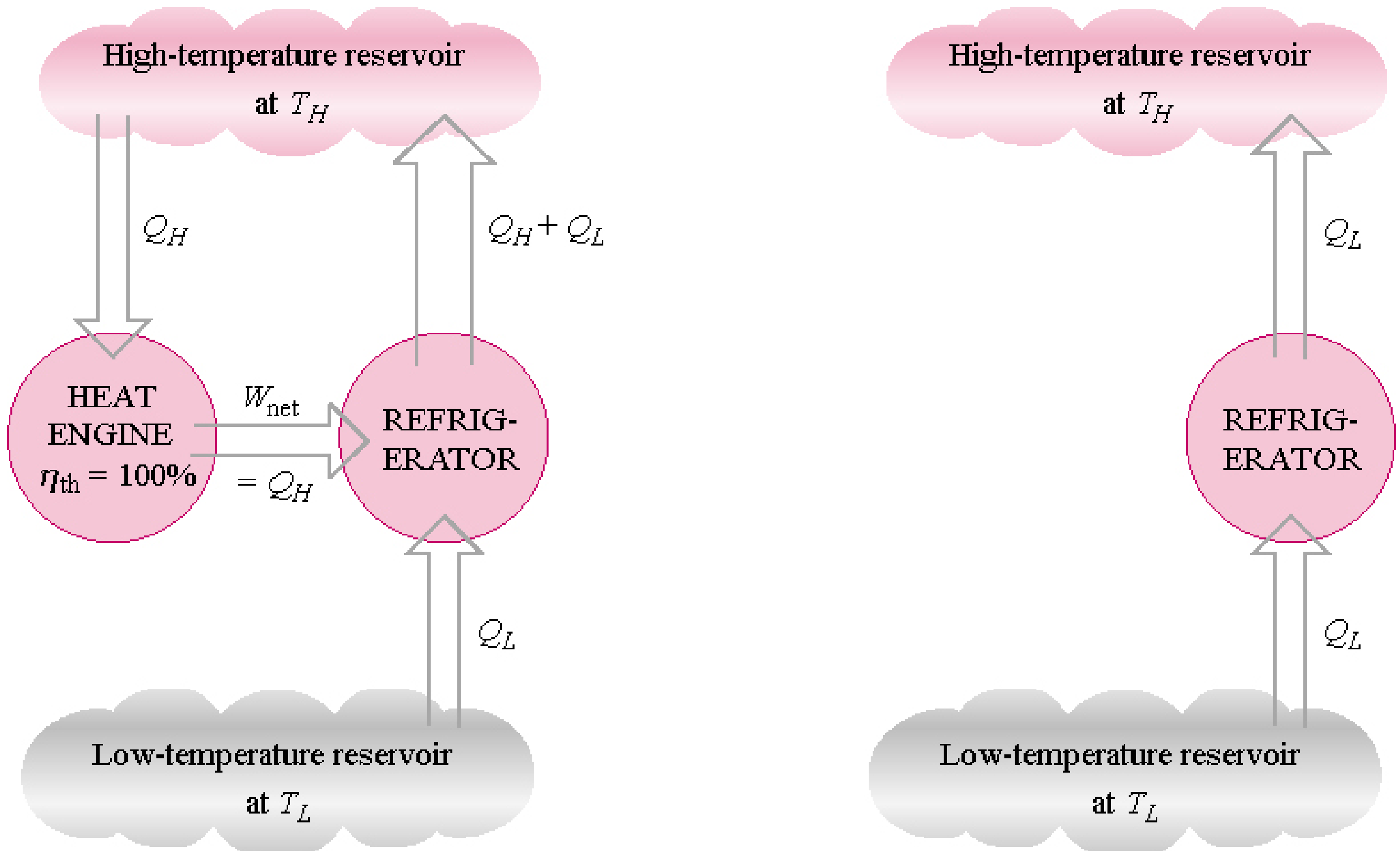
There are two classical statements of the second law – the Kelvin-Plank statement, which is related to heat engines, and the Clausius statement, which is related to refrigerators or heat pumps. The *Clausius statement* is expressed as follows:



It is impossible to construct a device that operates in a cycle and produces no effect other than the transfer of heat from a lower-temperature body to a higher-temperature body.

Equivalence of the Two Statements

Proof that the violation of the Kelvin-Planck statement leads to the violation of the Clausius Statement.



(*a*) A refrigerator which is powered by a 100% efficient heat engine

(*b*) The equivalent refrigerator

Perpetual-Motion Machines

A device that violates the first law of thermodynamics (by creating energy) is called a perpetual-motion machine of the first kind (*PMM1*). *No energy input to but output from the system*.

A device that violates the second law of thermodynamics is called a perpetual-motion machine of the second kind (*PMM2*).

Reversible and Irreversible Processes

A ***reversible process*** is defined as a process that can be reversed without leaving any trace on the surroundings.

Reversible processes can be viewed as theoretical limits for the corresponding irreversible ones. The more closely we approximate a reversible process, the more work delivered by a work-producing device or the less work required by a work-consuming device.

The concept of reversible processes leads to the definition of the second-law efficiency for actual processes, which is the degree of approximation to the corresponding reversible process.

Irreversibilities

The factors that cause a process to be irreversible are called irreversibilities. They include:

- **friction**
- **unstrained expansion**
- **mixing of two gases**
- **heat transfer across a finite temperature difference**
- **flow of electric current through an electric resistance**
- **inelastic deformation of solids**
- **chemical reactions.**

Totally Reversible

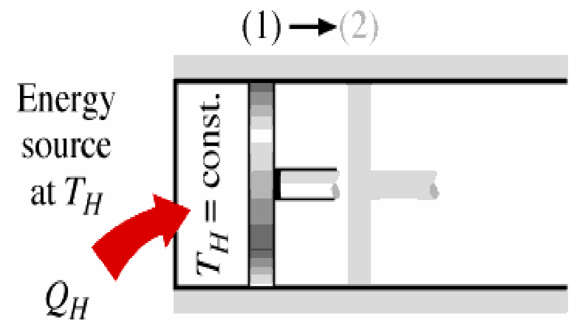
A process is called totally reversible, or simply reversible, if it involves no irreversibilities within the system (internally reversible) or its surroundings (externally reversible). A totally reversible process involves no heat transfer through a finite temperature difference, no non-quasi-equilibrium changes, and no friction or other dissipative effects.

The Carnot Cycle

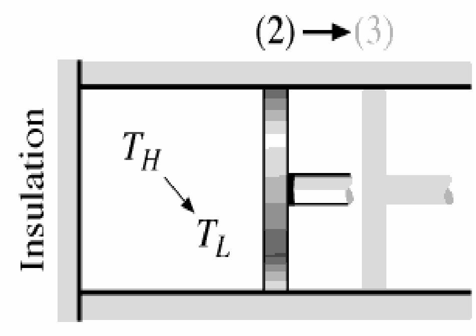
The best known reversible cycle is the Carnot cycle, first proposed in 1824 by French engineer Sadi Carnot. The four reversible processes that make up the Carnot cycle are as follows:

***Reversible Isothermal Expansion*:**
Temperature remains at T_H, the amount of total heat transferred to the gas during this isothermal process is Q_H.

***Reversible Adiabatic Expansion*:**
Temperature drops from T_H to T_L, the process is reversible as well as adiabatic.



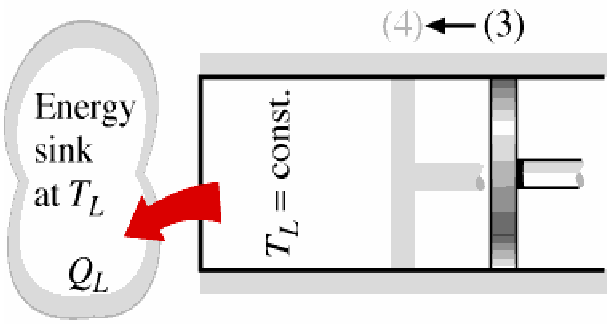
(a) Process 1-2



(b) Process 2-3

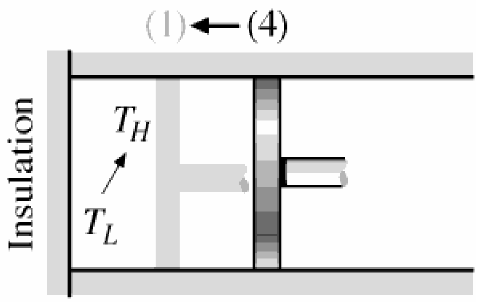
The Carnot Cycle (continued)

***Reversible Isothermal Compression*:** **Temperature remains at T_L, a reversible heat transfer process, the amount of total heat transferred to the gas during this isothermal process is Q_L.**



(c) Process 3-4

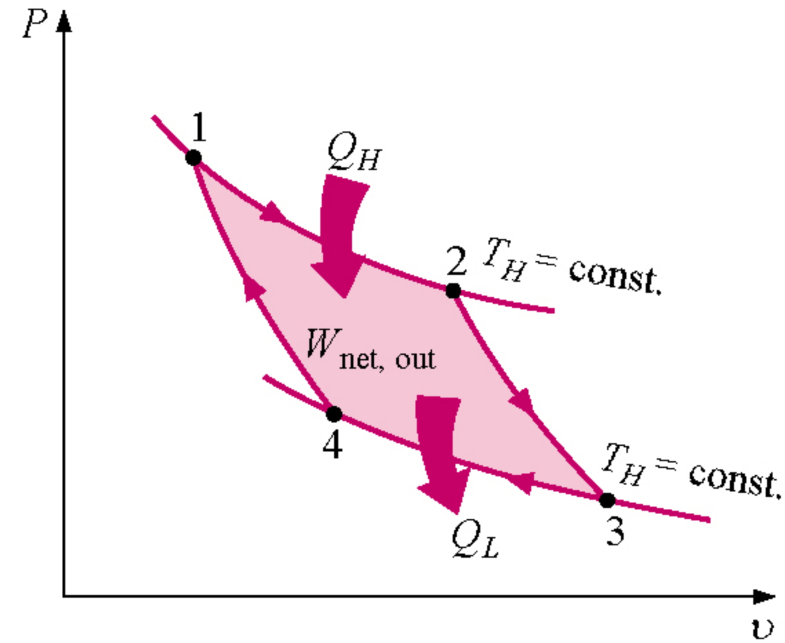
***Reversible Adiabatic Compression*:** **Temperature rises from T_L to T_H, the process is reversible as well as adiabatic compression process, which completes the cycle.**



(d) Process 4-1

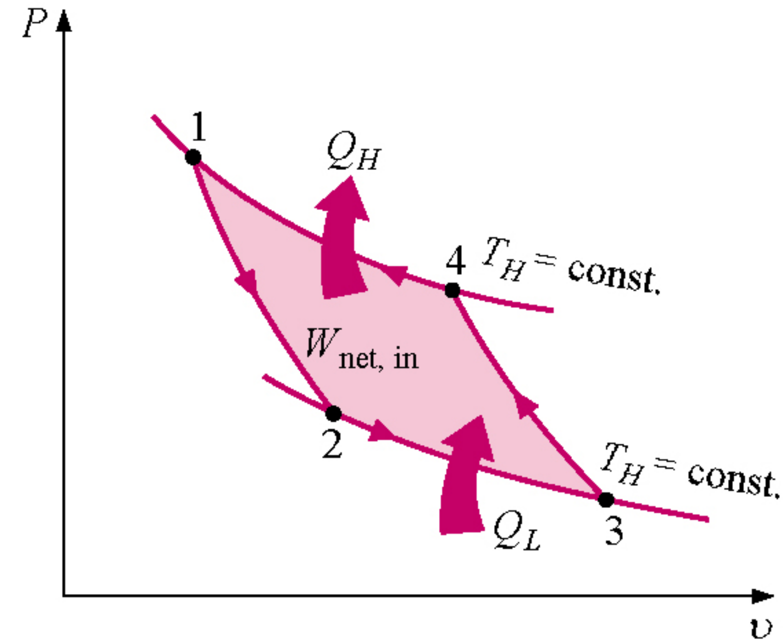
P-υ Diagram of Carnot Cycle

The P-υ diagram of Carnot cycle is shown in the figure at right.



Area under curve 1-2-3 corresponds to the work done by the gas, area under curve 3-4-1 corresponds to the work done on the gas.

The Reversed Carnot Cycle

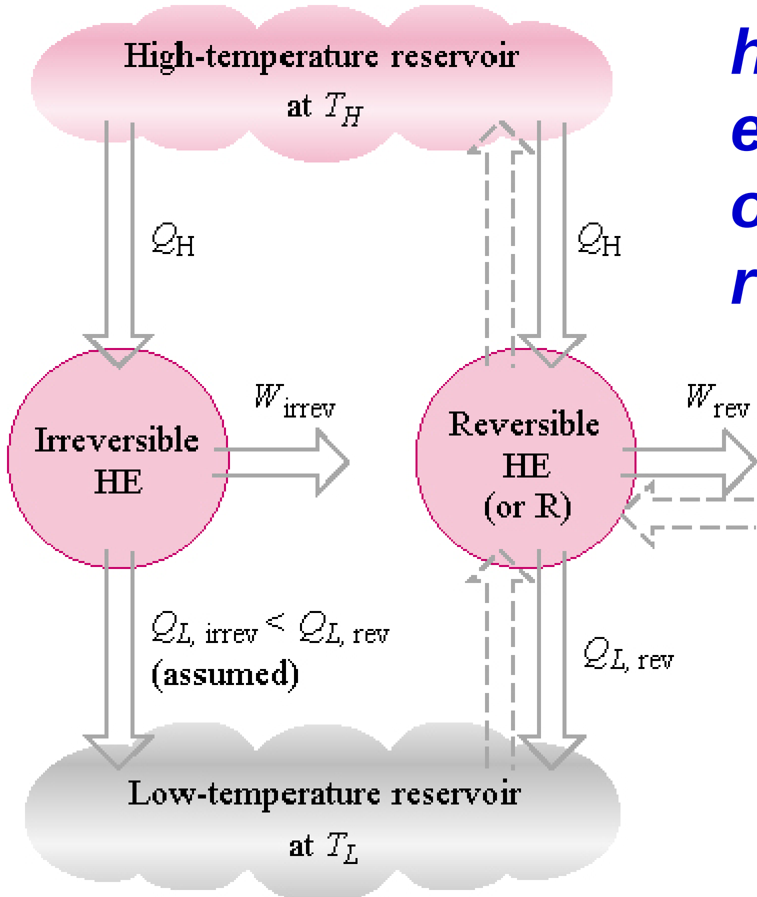


The Carnot heat-engine cycle is a totally reversible cycle. Therefore, all the processes that comprise it can be reversed, in which case it becomes the refrigeration cycle.

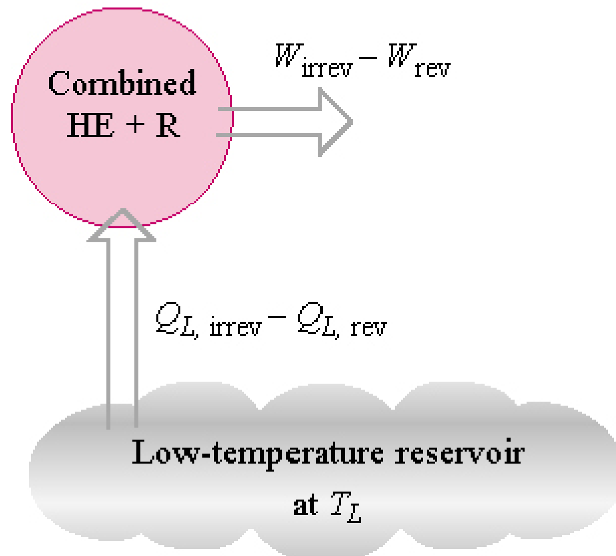
The P-υ diagram of the reversed Carnot cycle is the same as the one given for Carnot cycle, except that the direction of the processes are reversed, as shown in figure at right. Heat in the amount of Q_L is absorbed from the low-temperature reservoir, heat in the amount of Q_H is rejected to a high-temperature reservoir, and a work input of $W_{net,in}$ is required to accomplish all this.

The Carnot Principles

1. ***The efficiency of an irreversible heat engine is always less than the efficiency of a reversible one operating between the same two reservoirs.***



(*a*) A reversible and an irreversible heat engine operating between the same two reservoirs (the reversible heat engine is then reversed to run as a refrigerator)



(*b*) The equivalent combined system

The Carnot Principles
(continued)

2. *The efficiencies of all reversible heat engines operating between the same two reservoirs are the same.*