Thermodynamics: An Engineering Approach, 6th Edition
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Chapter 6

THE SECOND LAW OF THERMODYNAMICS

SUMMARY

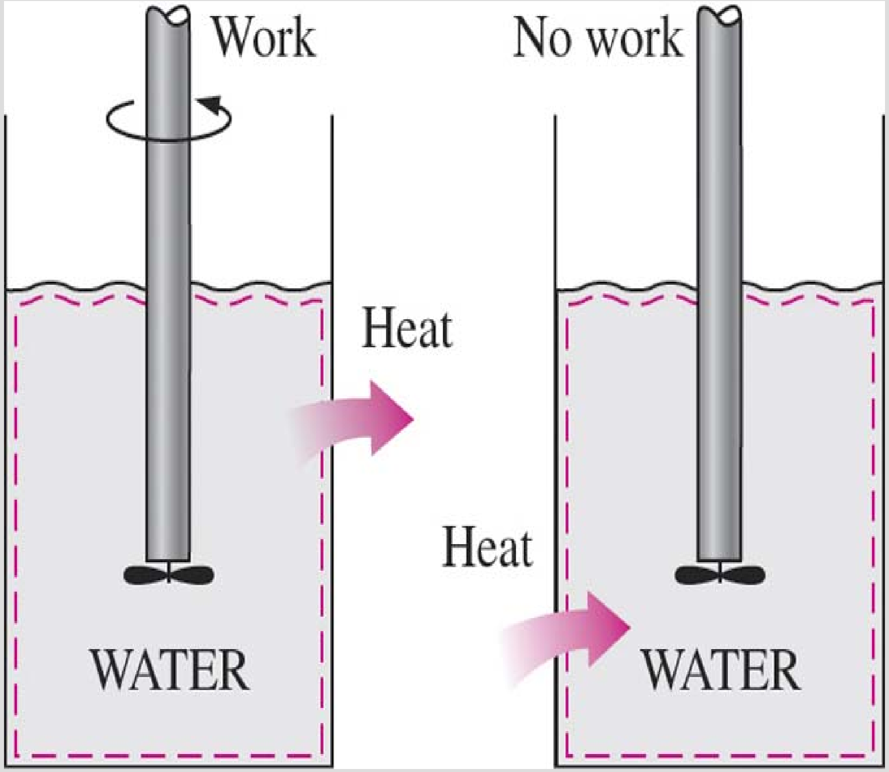
MAJOR USES OF THE SECOND LAW

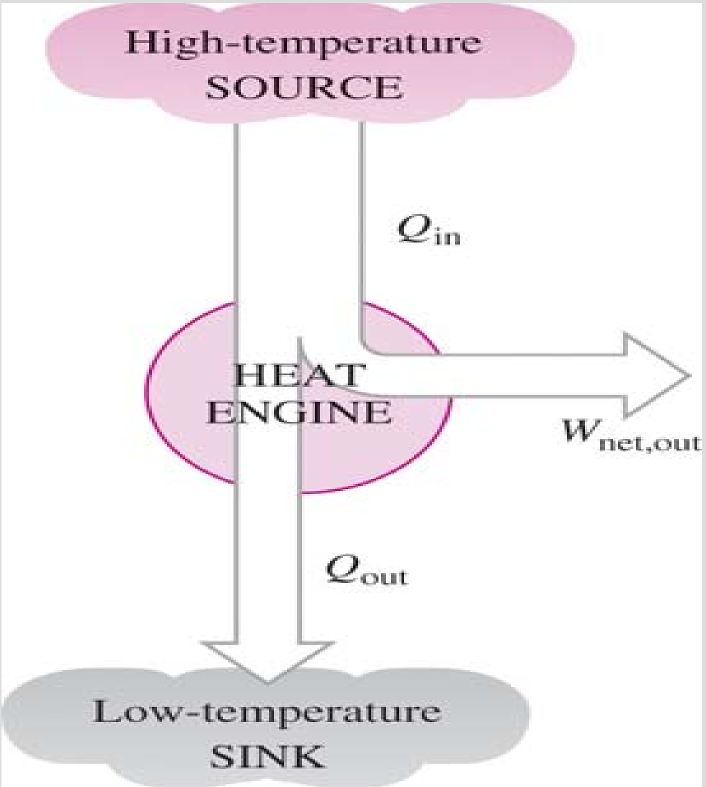
1. The second law may be used to identify the direction of processes.
2. The second law also asserts that energy has *quality* as well as *quantity*. The first law is concerned with the quantity of energy and the transformations of energy from one form to another with no regard to its quality. The second law provides the necessary means to determine the quality as well as the degree of degradation of energy during a process.
3. The second law of thermodynamics is also used in determining the *theoretical limits* for the performance of commonly used engineering systems, such as heat engines and refrigerators, as well as predicting the *degree of completion* of chemical reactions.

THERMAL ENERGY RESERVOIRS

- A hypothetical body with a relatively large *thermal energy capacity* (mass x specific heat) that can supply or absorb finite amounts of heat without undergoing any change in temperature is called a **thermal energy reservoir**, or just a reservoir.
- In practice, large bodies of water such as oceans, lakes, and rivers as well as the atmospheric air can be modeled accurately as thermal energy reservoirs because of their large thermal energy storage capabilities or thermal masses.

HEAT ENGINES





Work can always be converted to **heat** directly and completely, **but** the **reverse** is not true.

Part of the **heat** received by a heat engine is converted to **work**, while the rest is rejected to a sink.

HEAT ENGINES

The devices that convert heat to work.

1. They receive heat from a high-temperature source (solar energy, oil furnace, nuclear reactor, etc.).
2. They convert part of this heat to work (usually in the form of a rotating shaft.)
3. They reject the remaining waste heat to a low-temperature sink (the atmosphere, rivers, etc.).
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**.

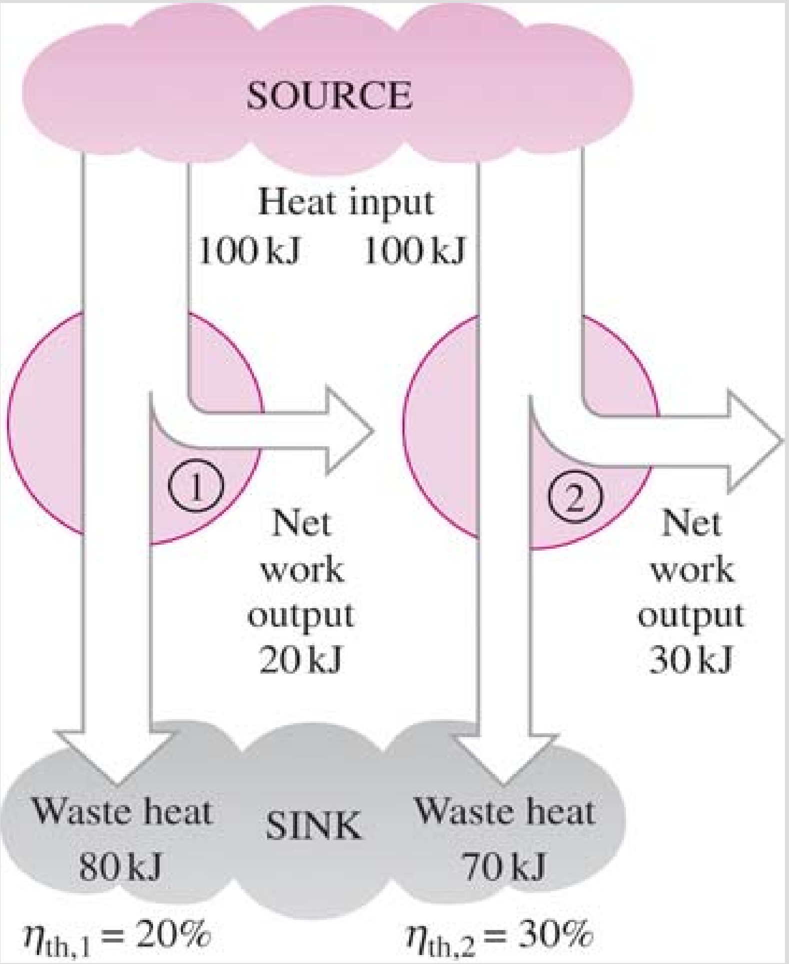
Thermal efficiency

$$\text{Thermal efficiency} = \frac{\text{Net work output}}{\text{Total heat input}}$$

$$\eta_{th} = \frac{W_{net,out}}{Q_{in}}$$

$$W_{net,out} = Q_{in} - Q_{out}$$

$$\eta_{th} = 1 - \frac{Q_{out}}{Q_{in}}$$



Some heat engines perform better than others (convert more of the heat they receive to work).

The Second Law of Thermodynamics:

Kelvin–Planck Statement

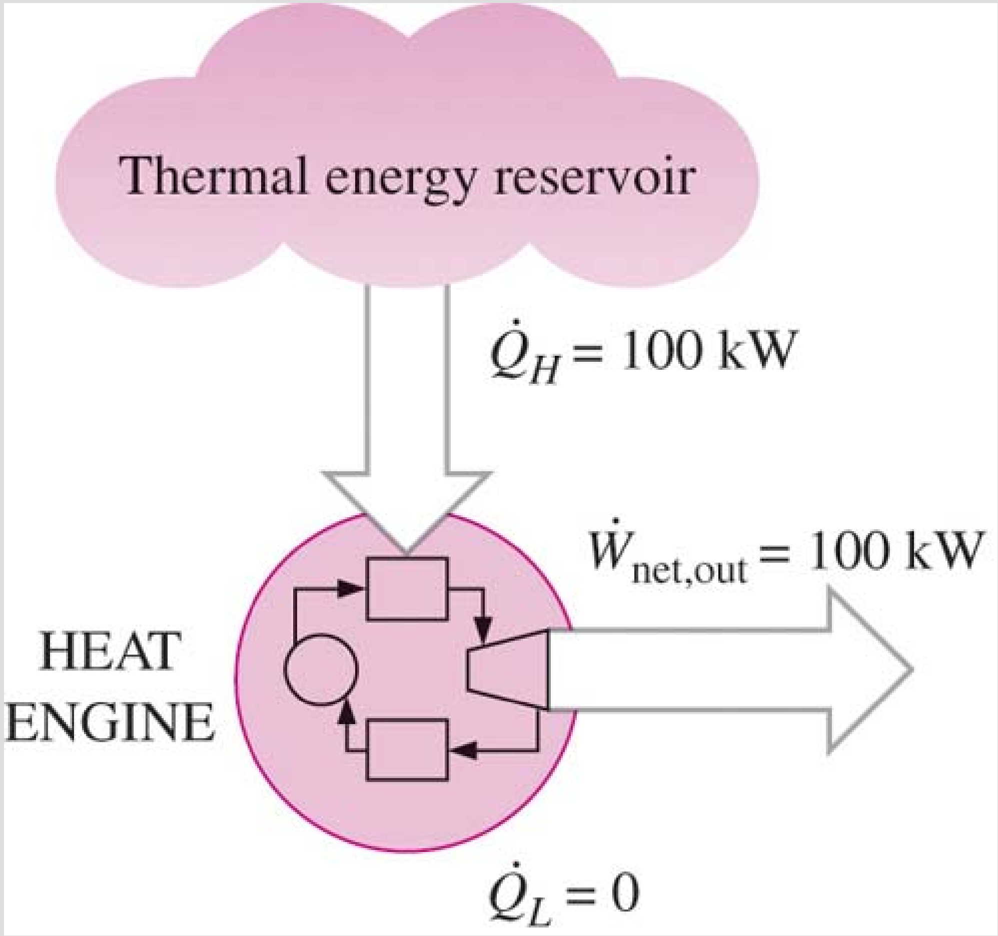
It is **impossible** for any device that operates on a **cycle** to receive **heat from a single** reservoir and **produce a net amount of work.**

No heat engine can have a ***thermal efficiency of 100 percent***, or *as for a power plant to operate, the working fluid must exchange heat with the environment as well as the furnace*.

The impossibility of having a 100% efficient heat engine is not due to friction or other dissipative effects. It is a limitation that applies to both the idealized and the actual heat engines.

The Second Law of Thermodynamics:

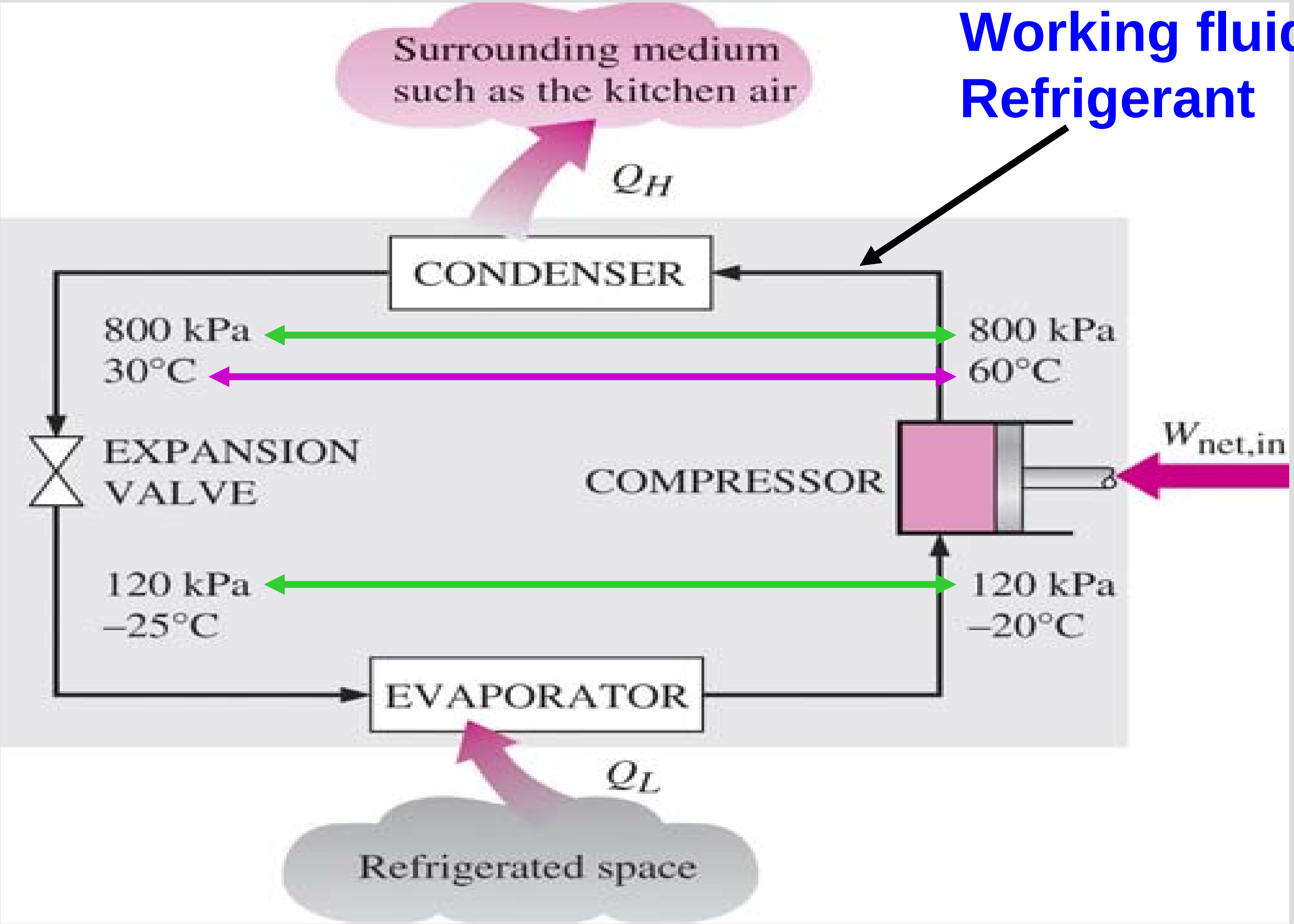
Kelvin–Planck Statement



A heat engine that violates the Kelvin–Planck statement of the second law.

REFRIGERATORS AND HEAT PUMPS

Working fluid is a Refrigerant



Basic components of a refrigeration system and typical operating conditions.

REFRIGERATORS AND HEAT PUMPS

- The transfer of heat from a low-temperature medium to a high-temperature one requires special devices called **refrigerators**.
- Refrigerators, like heat engines, are cyclic devices.
- The working fluid used in the refrigeration cycle is called a **refrigerant**.
- The most frequently used refrigeration cycle is the ***vapor-compression refrigeration cycle***.

In a household refrigerator, the **freezer compartment where heat is absorbed** by the refrigerant serves as the evaporator, and the **coils usually behind the refrigerator** where heat is dissipated to the kitchen air serve as the **condenser**.

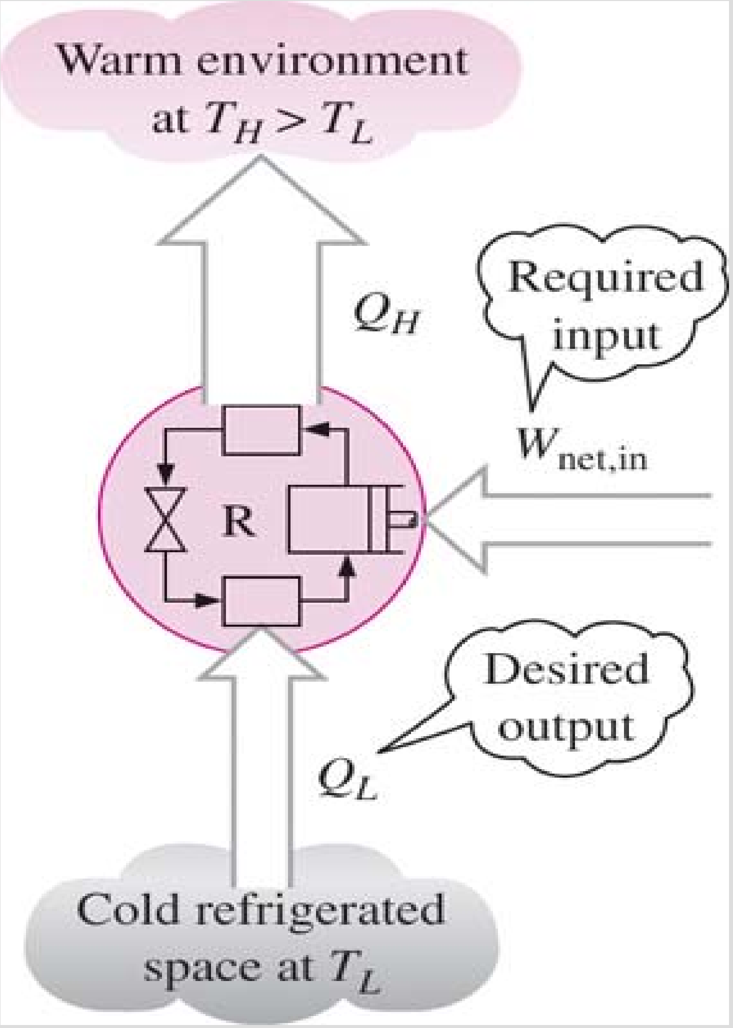
Coefficient of Performance (COP)

The objective of a refrigerator is to remove heat (Q_L) from the refrigerated space.

$$\text{COP}_R = \frac{\text{Desired output}}{\text{Required input}} = \frac{Q_L}{W_{\text{net,in}}}$$

$$W_{\text{net,in}} = Q_H - Q_L \qquad \text{(kJ)}$$

$$\text{COP}_R = \frac{Q_L}{Q_H - Q_L} = \frac{1}{Q_H/Q_L - 1}$$



The objective of a refrigerator is to remove Q_L from the cooled space.

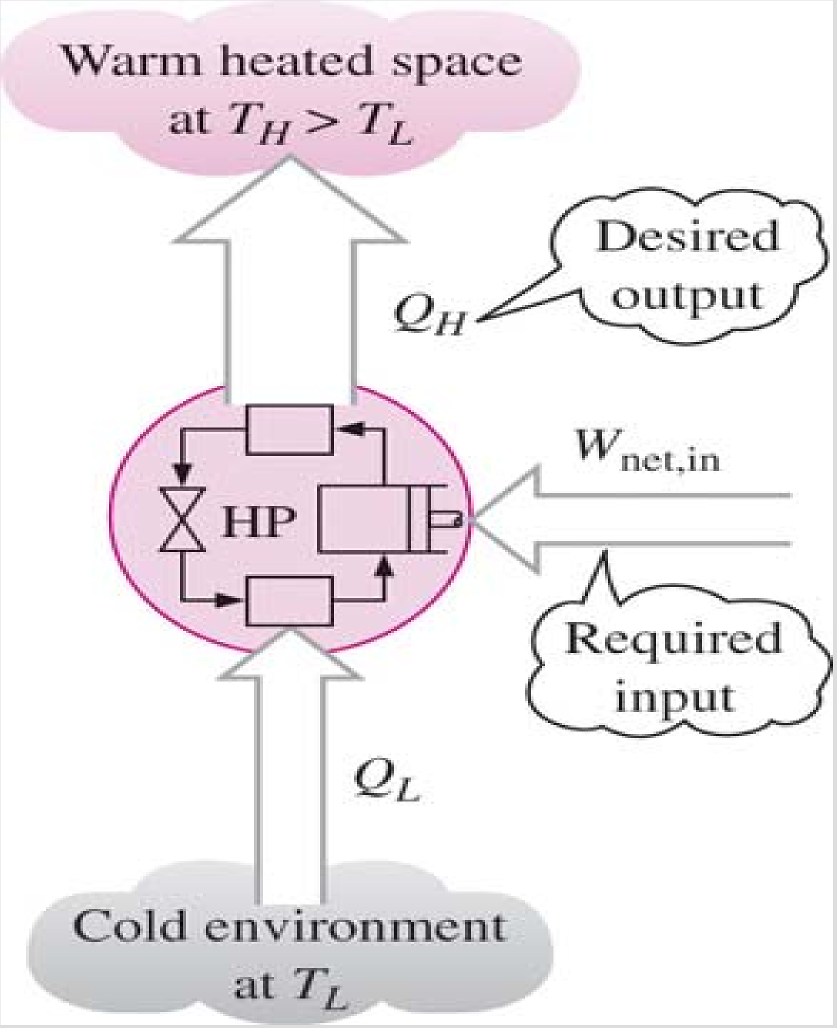
Heat Pumps

$$\mathrm{COP_{HP}} = \frac{\text{Desired output}}{\text{Required input}} = \frac{Q_H}{W_{\mathrm{net,in}}}$$

$$\mathrm{COP_{HP}} = \frac{Q_H}{Q_H - Q_L} = \frac{1}{1 - Q_L/Q_H}$$

$$\mathrm{COP_{HP}} = \mathrm{COP_R} + 1$$

For fixed values of Q_L and Q_H



The objective of a heat pump is to supply heat Q_H into the warmer space.

The Second Law of Thermodynamics:

Clasius Statement

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.

It states that a refrigerator cannot operate unless its compressor is driven by an external power source, such as an electric motor.

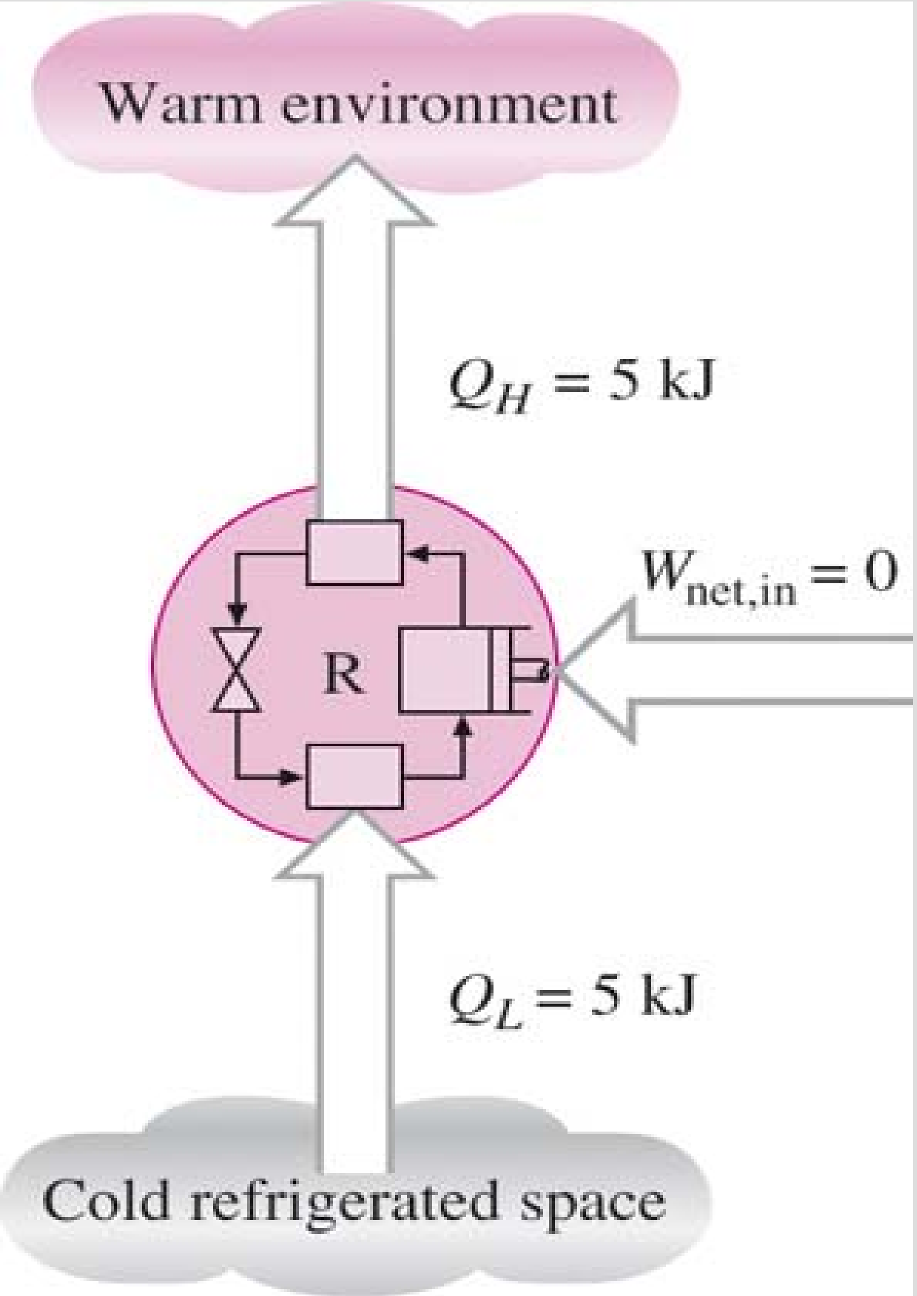
This way, the net effect on the surroundings involves the consumption of some energy in the form of work, in addition to the transfer of heat from a colder body to a warmer one.

To date, no experiment has been conducted that contradicts the second law, and this should be taken as sufficient proof of its validity.

The Second Law of Thermodynamics:

Clasius Statement

A refrigerator that violates the Clausius statement of the second law.



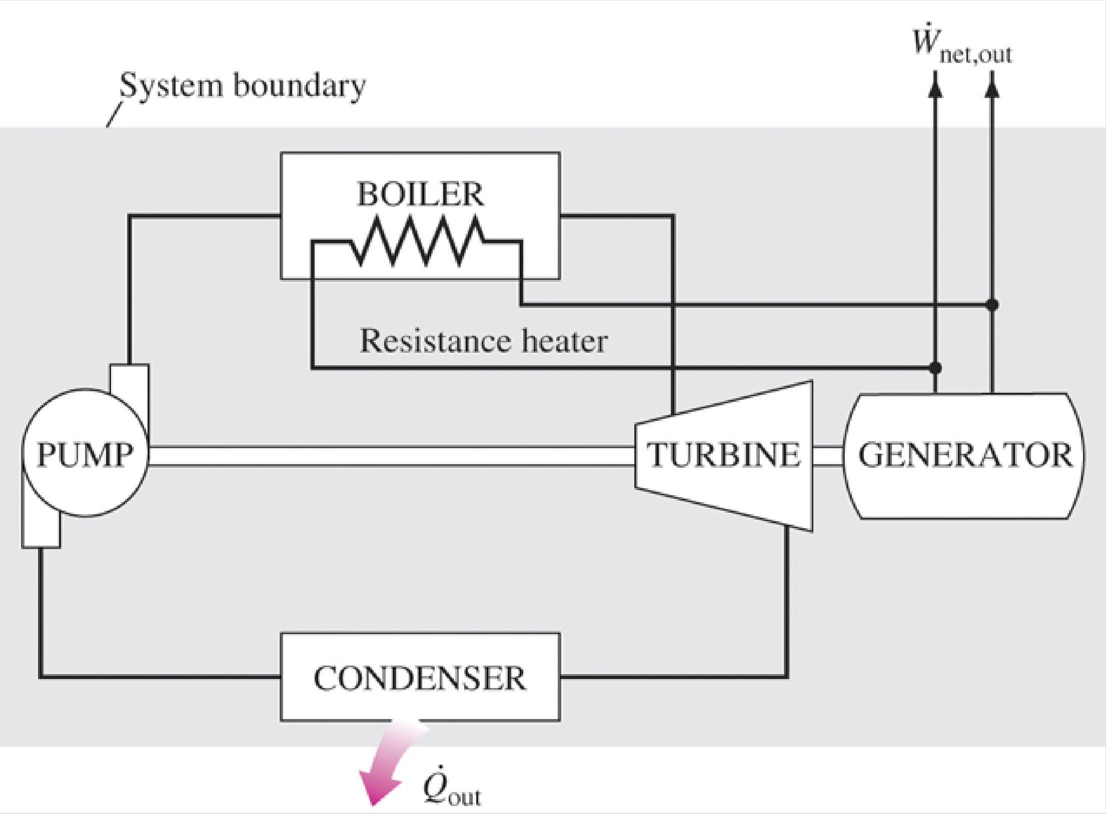
Equivalence of the Two Statements

The Kelvin–Planck and the Clausius statements are equivalent in their consequences, and either statement can be used as the expression of the second law of thermodynamics.

Any device that violates the Kelvin–Planck statement also violates the Clausius statement, and vice versa.

PERPETUAL-MOTION MACHINES

Perpetual-motion machine: Any device that violates the first or the second law.

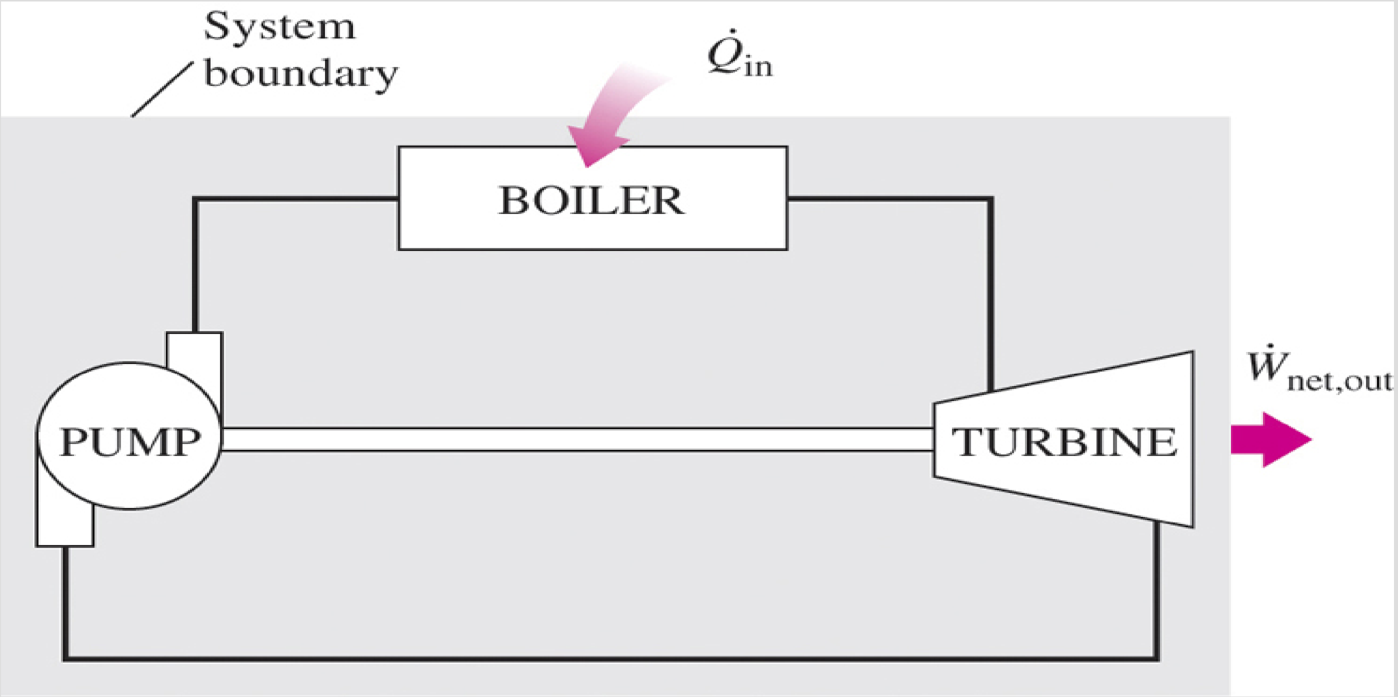


A perpetual-motion machine that violates the first law (PMM1).

A device that violates the first law (by *creating* energy) is called a PMM1.

PERPETUAL-MOTION MACHINES

A device that violates the second law is called a PMM2.



A perpetual-motion machine that violates the second law of thermodynamics (PMM2).

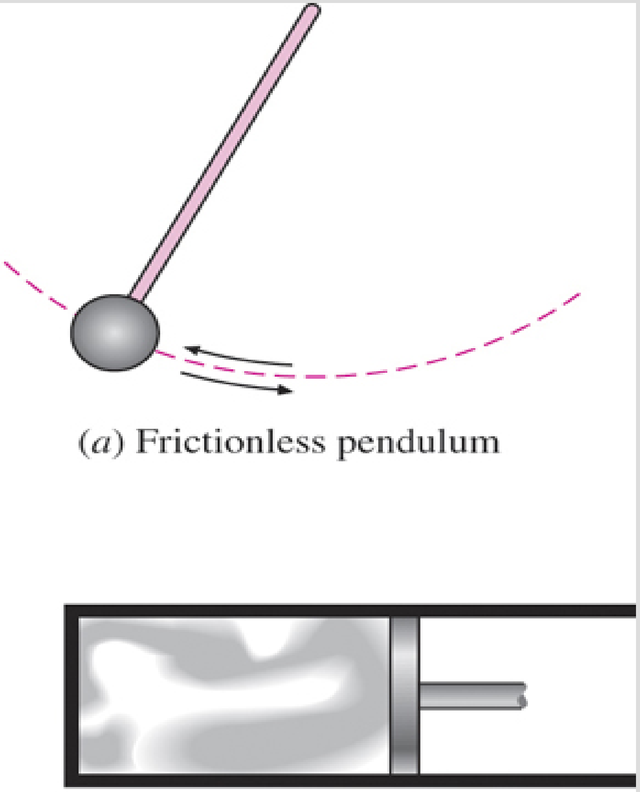
Despite numerous attempts, no perpetual-motion machine is known to have worked. *If something sounds too good to be true, it probably is*.

REVERSIBLE AND IRREVERSIBLE PROCESSES

Reversible process: *A process that can be reversed without leaving any trace on the surroundings.*

Irreversible process: A process that is not reversible.

Two familiar reversible processes.



(*a*) Frictionless pendulum

(*b*) Quasi-equilibrium expansion and compression of a gas

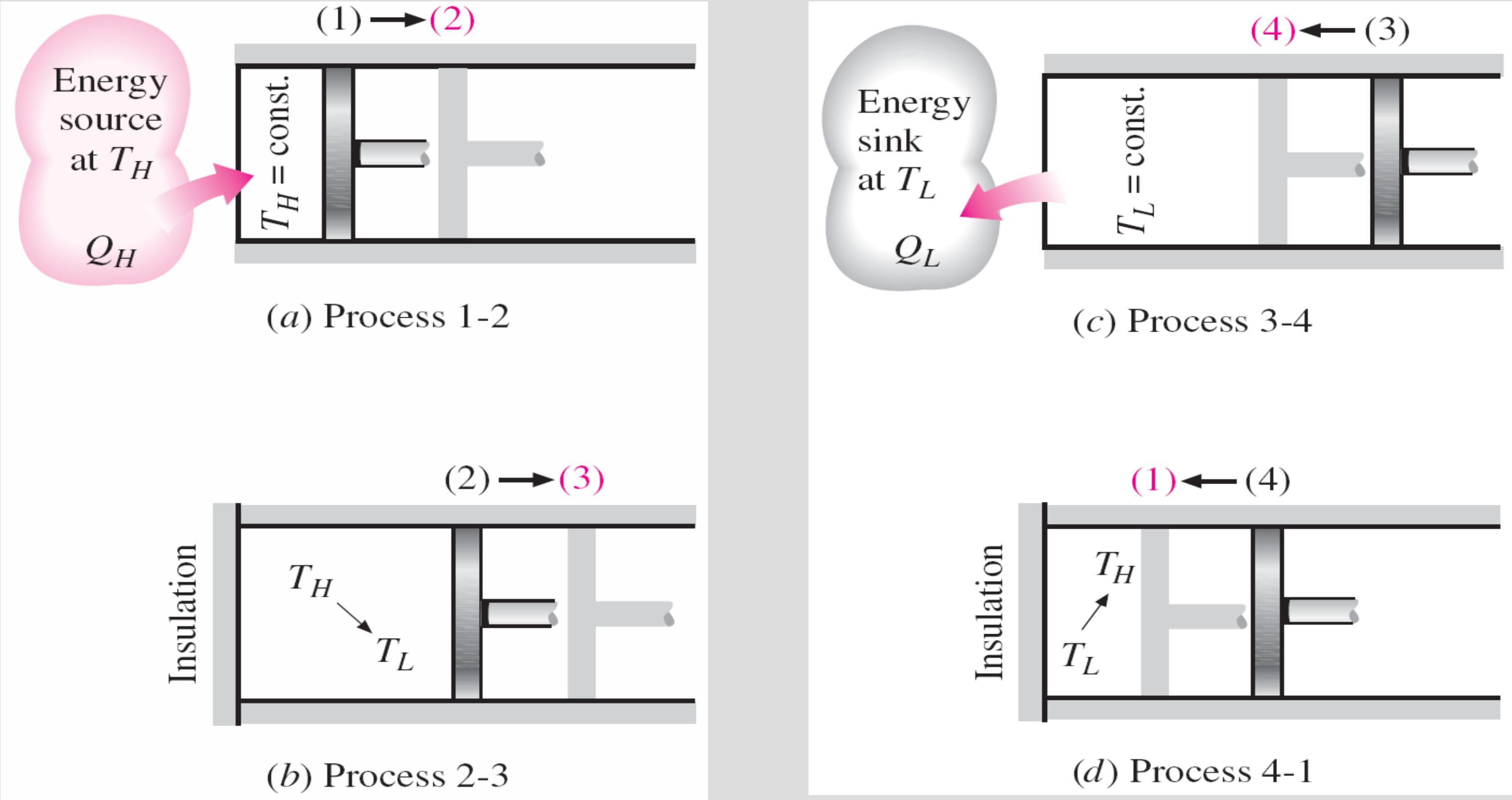
IRREVERSIBILITIES

- The factors that cause a process to be irreversible are called **Irreversibilities**.
- They include friction, unrestrained expansion, mixing of two fluids, heat transfer across a finite temperature difference, electric resistance, inelastic deformation of solids, and chemical reactions.
- The presence of any of these effects renders a process irreversible.

Internally and Externally Reversible Processes

- **Internally reversible process:** If no irreversibilities occur within the boundaries of the system during the process.
- **Externally reversible:** If no irreversibilities occur outside the system boundaries.
- **Totally reversible process:** It involves no irreversibilities within the system or its surroundings.
- 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

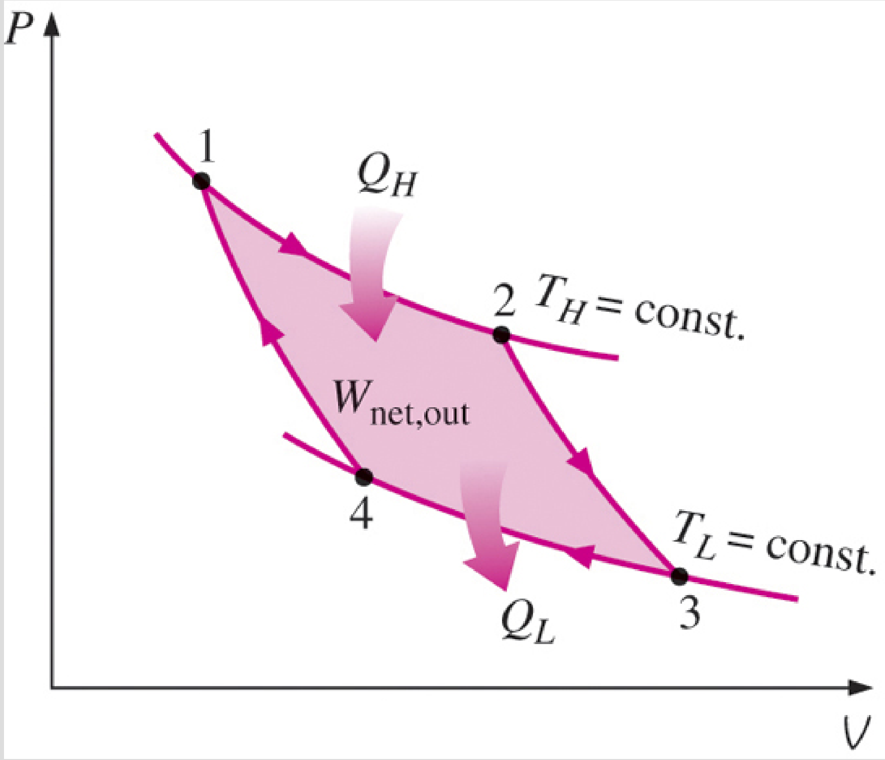


Reversible Isothermal Expansion (process 1-2, T_H = constant)

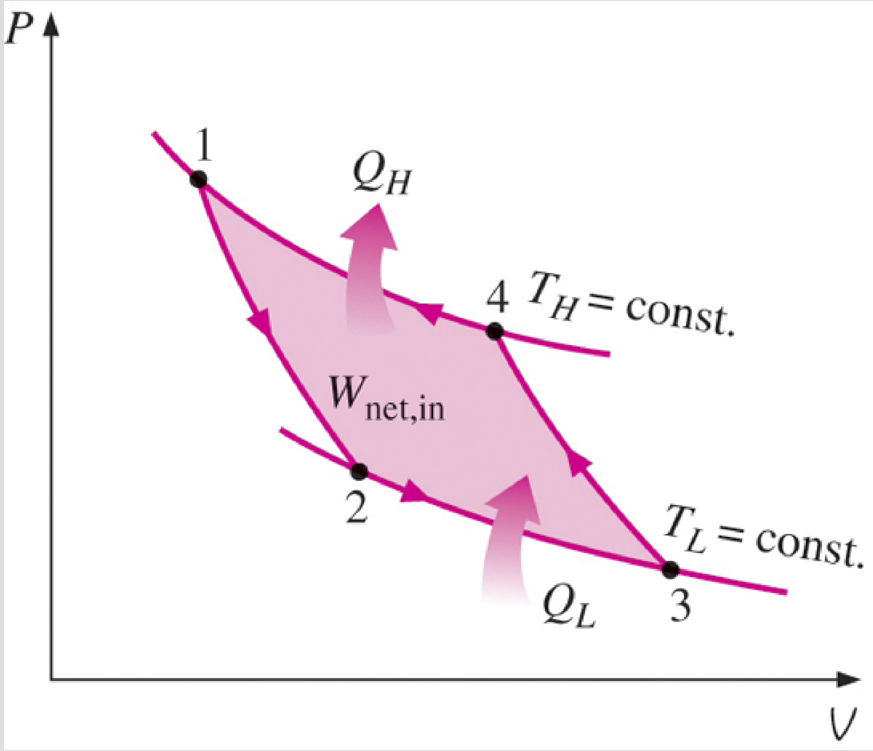
Reversible Adiabatic Expansion (process 2-3, temperature drops from T_H to T_L)

Reversible Isothermal Compression (process 3-4, T_L = constant)

Reversible Adiabatic Compression (process 4-1, temperature rises from T_L to T_H)



P-V **diagram of the Carnot cycle.**



P-V **diagram of the reversed Carnot cycle.**

The Reversed Carnot Cycle

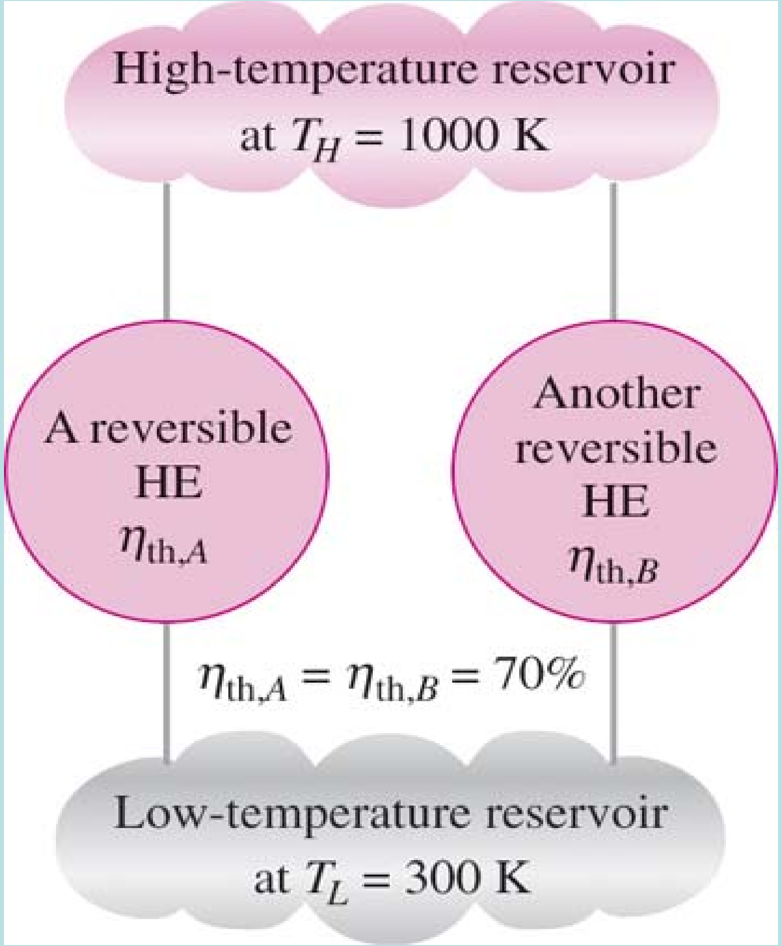
The Carnot heat-engine cycle is a totally reversible cycle.

Therefore, all the processes that comprise it can be *reversed*, in which case it becomes the **Carnot refrigeration cycle.**

THE CARNOT PRINCIPLES

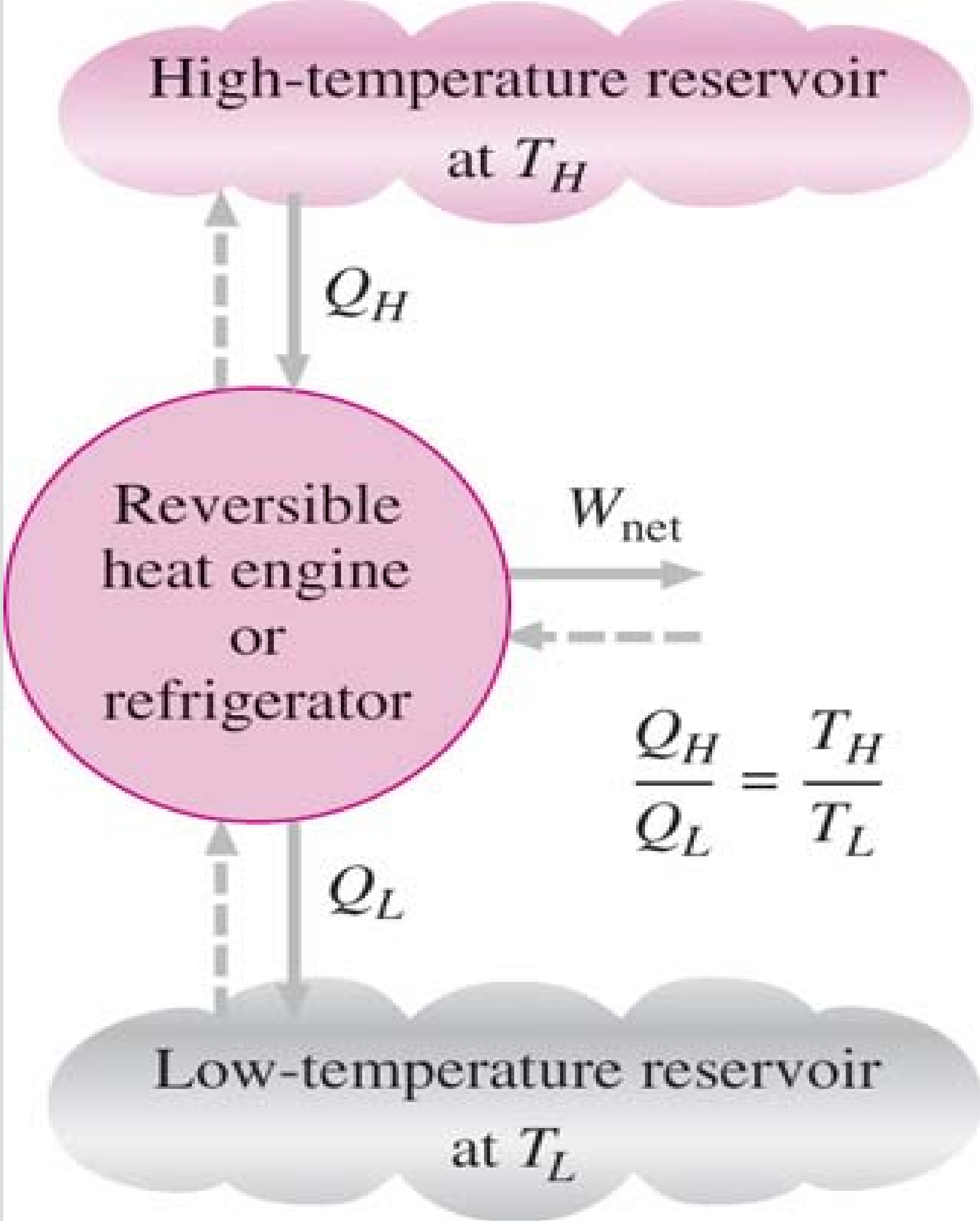
1. The efficiency of an irreversible heat engine is always less than the efficiency of a reversible one operating between the same two reservoirs.

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



All reversible heat engines operating between the same two reservoirs have the same efficiency.

For reversible cycles, the heat transfer ratio Q_H/Q_L can be replaced by the absolute temperature ratio T_H/T_L.

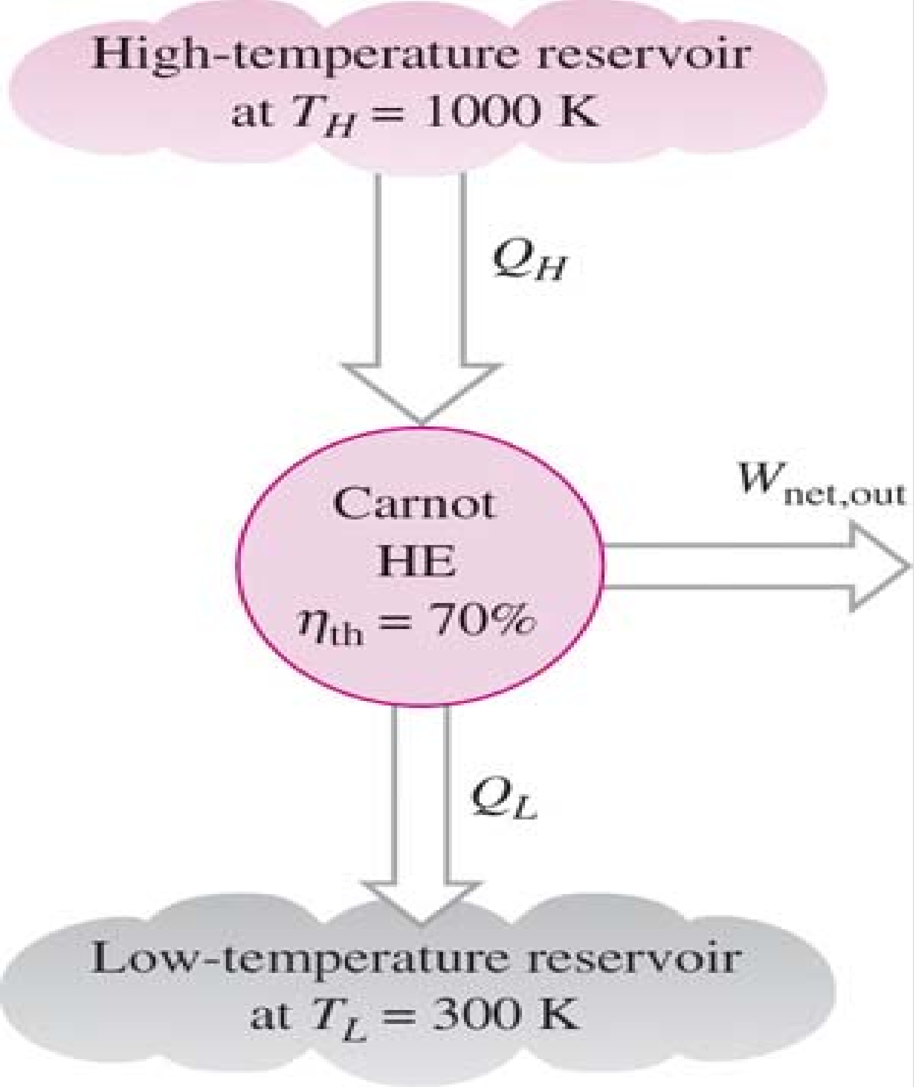


Any heat engine

$$\eta_{th} = 1 - \frac{Q_L}{Q_H}$$

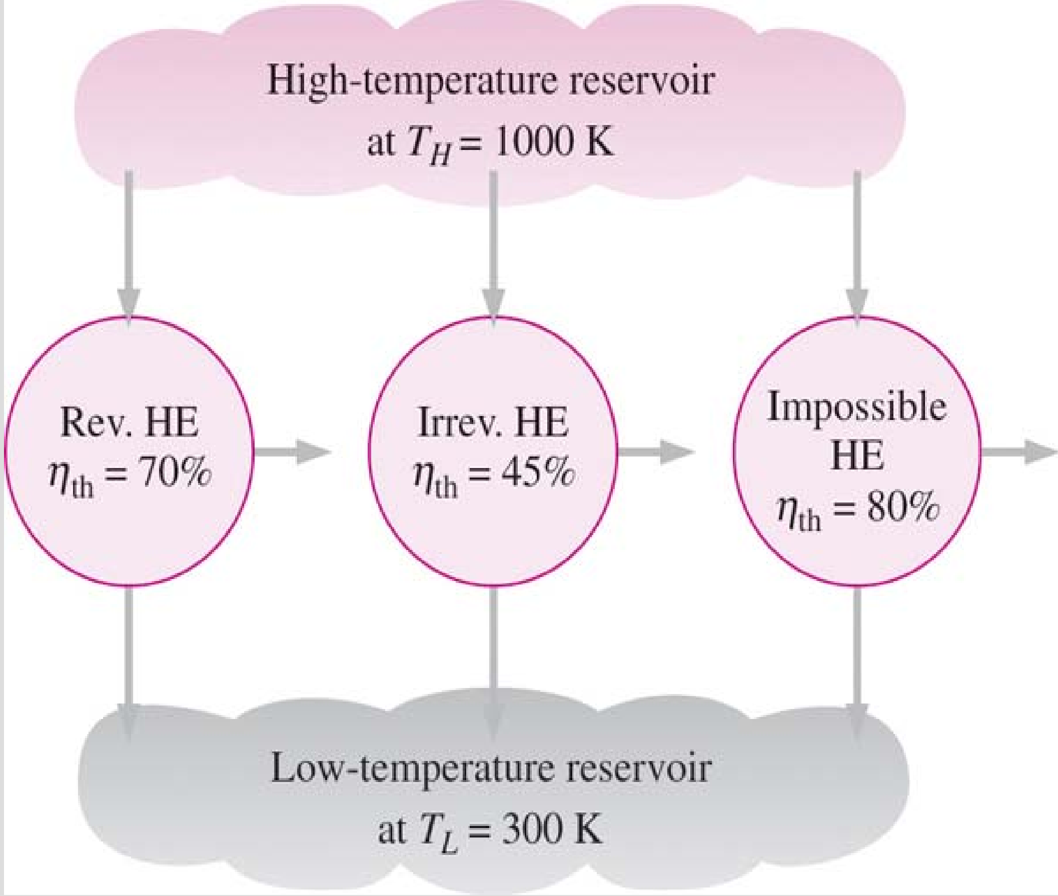
Carnot heat engine

$$\eta_{th,rev} = 1 - \frac{T_L}{T_H}$$



The Carnot heat engine is the most efficient of all heat engines operating between the same high- and low-temperature reservoirs.

No heat engine can have a higher efficiency than a reversible heat engine operating between the same high- and low-temperature reservoirs.

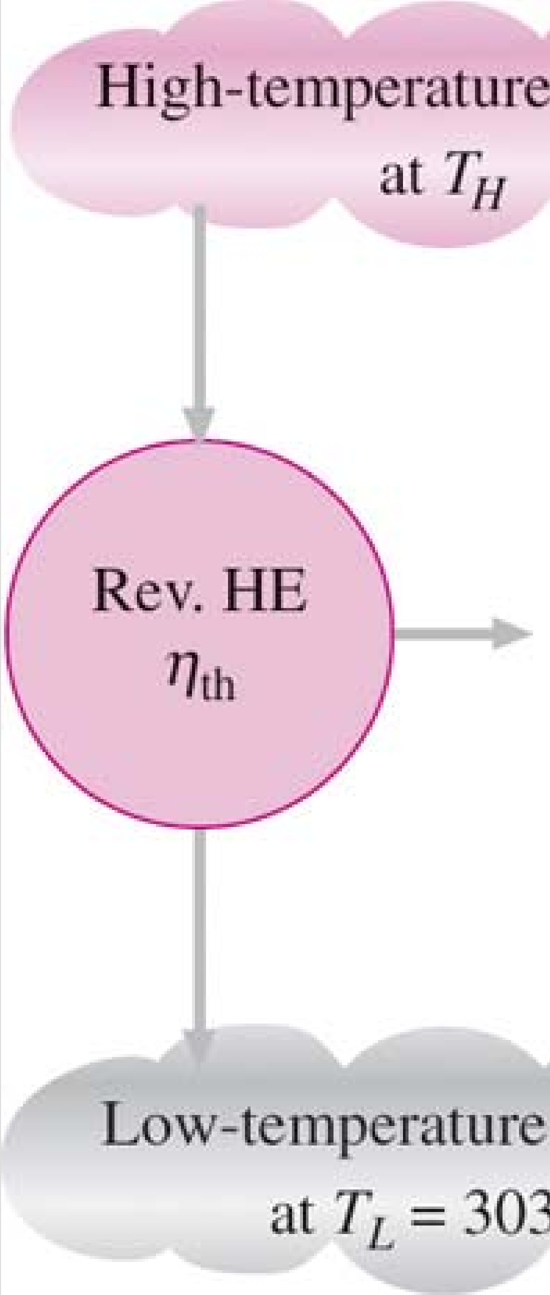


$$\eta_{th}\begin{cases} < \eta_{th,rev} & \text{irreversible heat engine} \\ = \eta_{th,rev} & \text{reversible heat engine} \\ > \eta_{th,rev} & \text{impossible heat engine} \end{cases}$$

The Quality of Energy

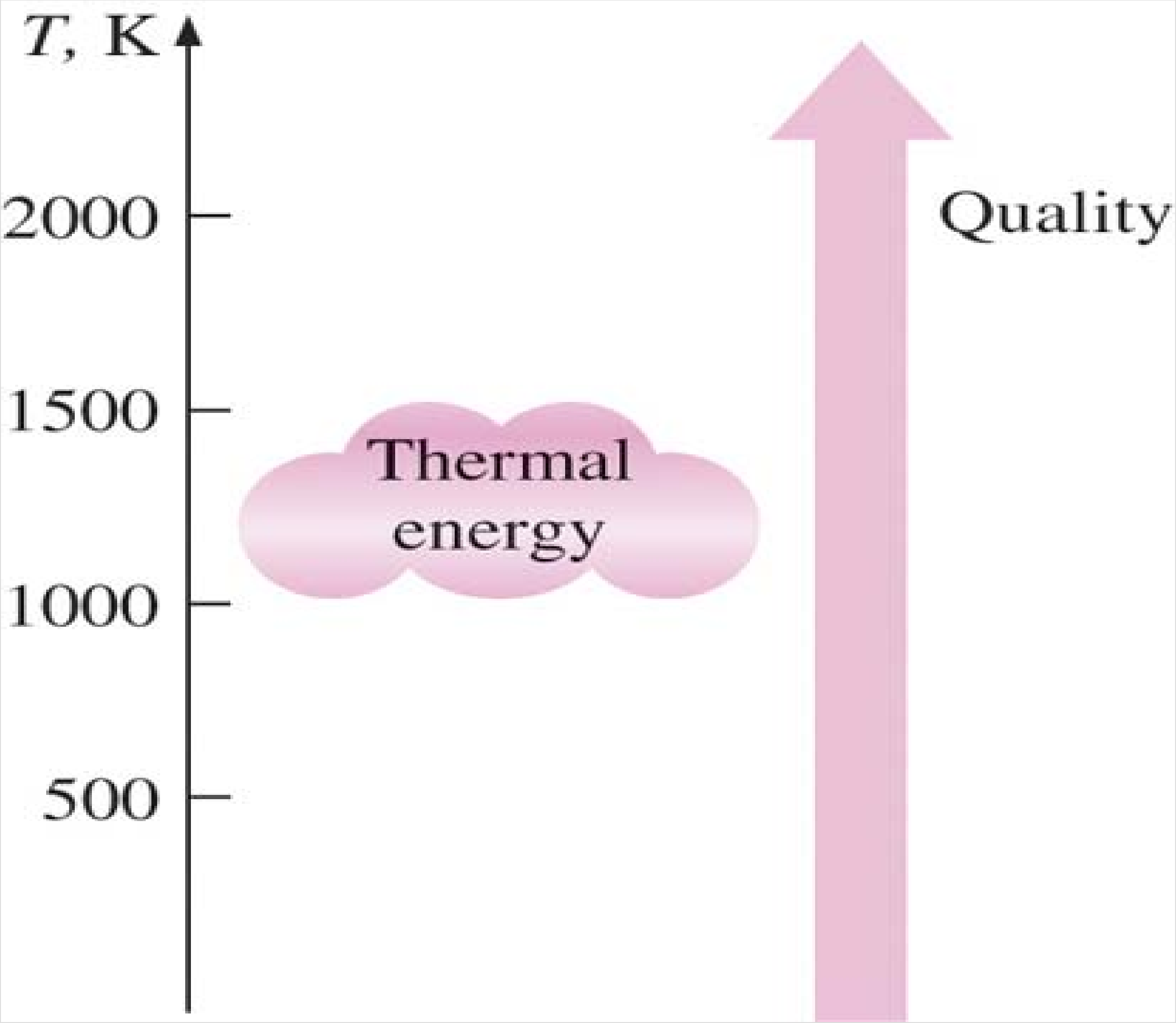
$$\eta_{th,rev} = 1 - \frac{T_L}{T_H}$$

The fraction of heat that can be converted to work as a function of source temperature.



T_H, K	η_{th}, %
925	67.2
800	62.1
700	56.7
500	39.4
350	13.4

The Quality of Energy



The higher the temperature of the thermal energy, the higher its quality.

THE CARNOT REFRIGERATOR AND HEAT PUMP

Any refrigerator or heat pump

$$\mathrm{COP}_{\mathrm{HP}} = \frac{1}{1 - Q_L/Q_H}$$

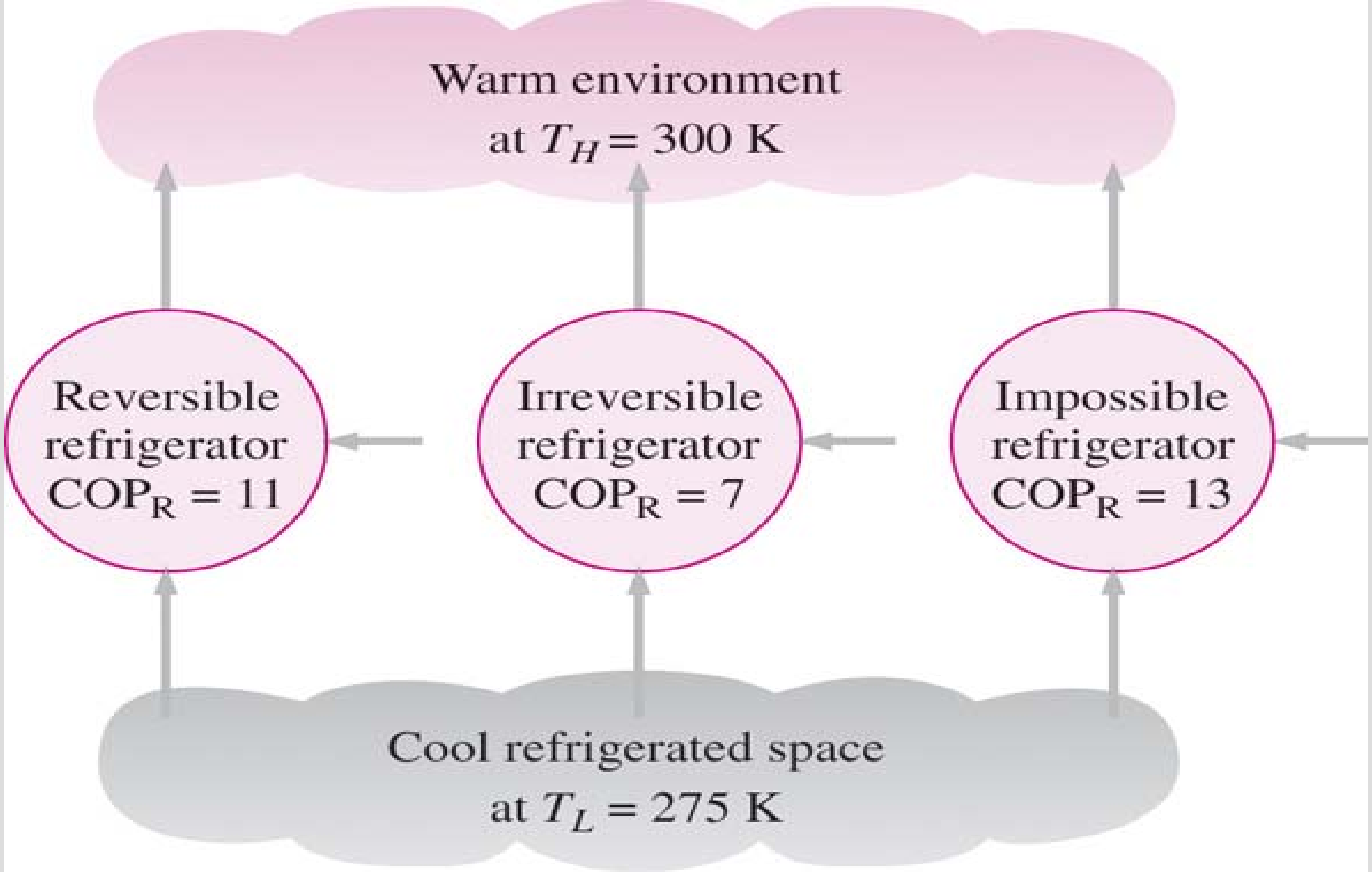
$$\mathrm{COP}_{\mathrm{R}} = \frac{1}{Q_H/Q_L - 1}$$

Carnot refrigerator or heat pump

$$\mathrm{COP}_{\mathrm{R,rev}} = \frac{1}{T_H/T_L - 1}$$

$$\mathrm{COP}_{\mathrm{HP,rev}} = \frac{1}{1 - T_L/T_H}$$

THE CARNOT REFRIGERATOR AND HEAT PUMP



No refrigerator can have a higher COP than a reversible refrigerator operating between the same temperature limits.

<u>THE END</u>