The Second Law of Thermodynamics

By

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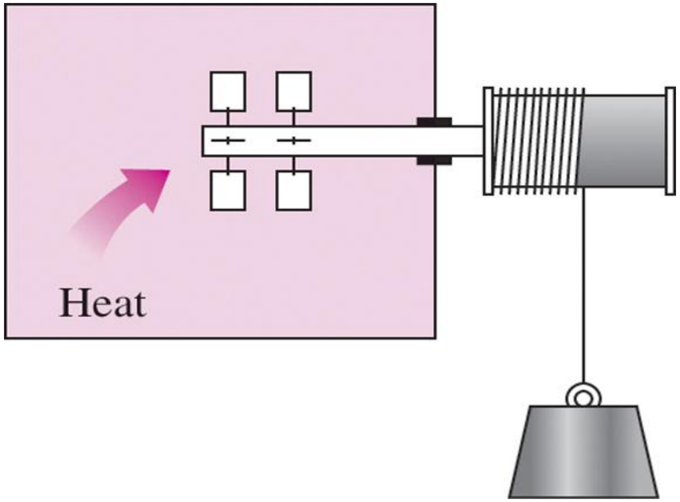
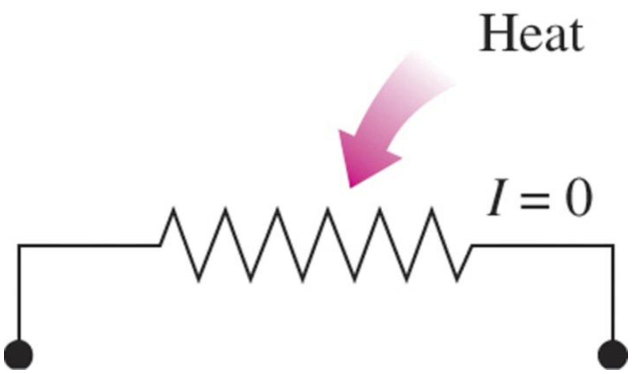
INTRODUCTION TO THE SECOND LAW

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



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

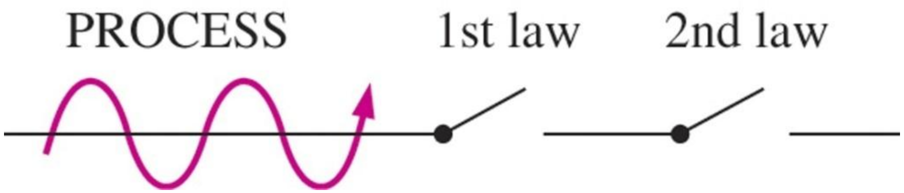


Transferring heat to a wire will not generate electricity.

These processes cannot occur even though they are not in violation of the first law.

The second law of thermodynamics - process occur in a certain direction , not in any direction. A process will not occur unless it satisfies both the first and the second law of thermodynamics.

Processes occur in a certain direction, and not in the reverse direction.

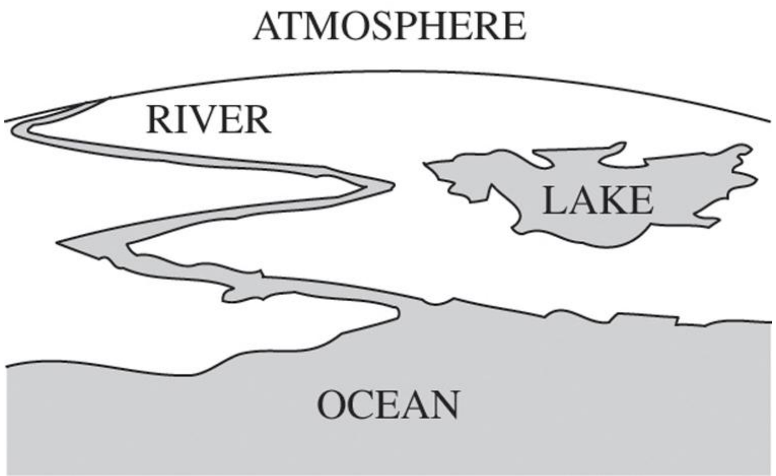


A process must satisfy both the first and second laws of thermodynamics to proceed.

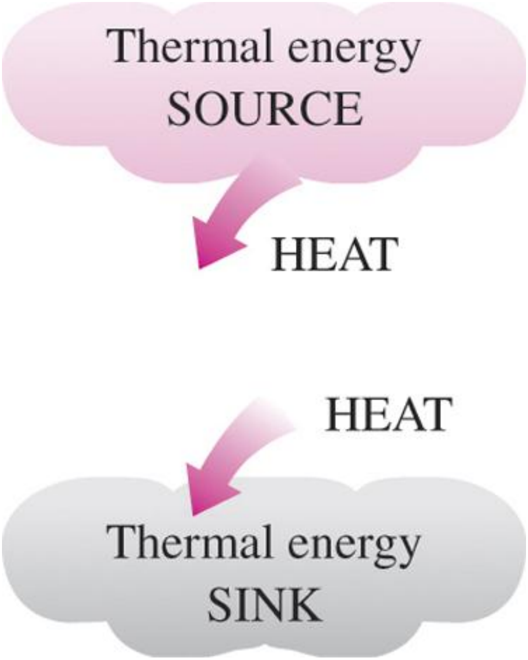
MAJOR USES OF THE SECOND LAW

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 used in determining the *theoretical limits* for the performance of commonly used engineering systems, such as heat engines and refrigerators & predicting the *degree of completion* of chemical reactions.

THERMAL ENERGY RESERVOIRS



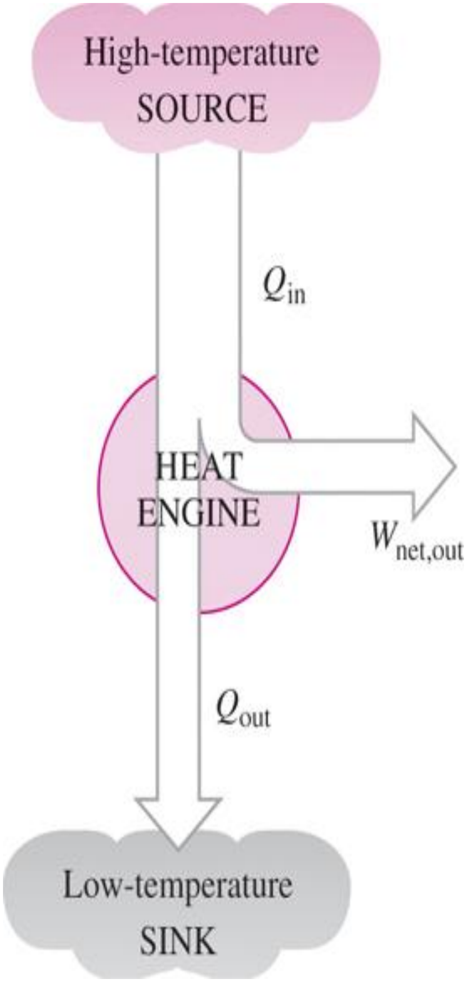
Bodies with relatively large thermal masses can be modeled as thermal energy reservoirs.



A source supplies energy in the form of heat, and a sink absorbs it.

- 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 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

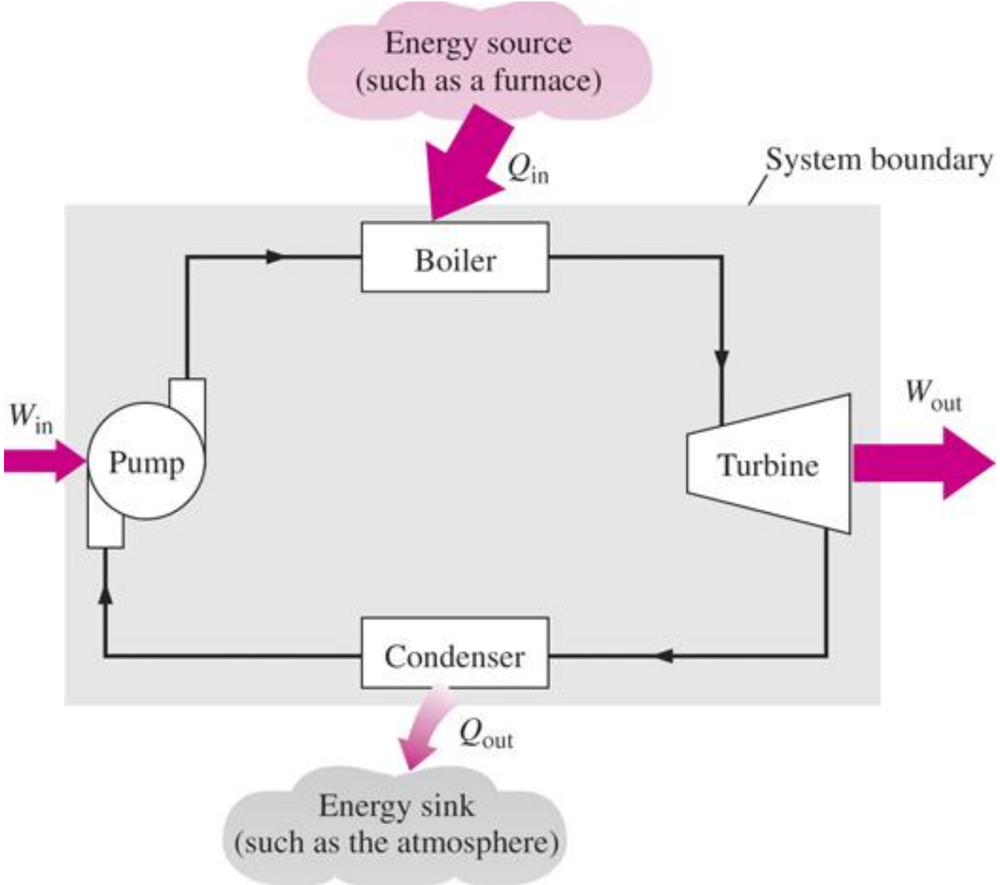


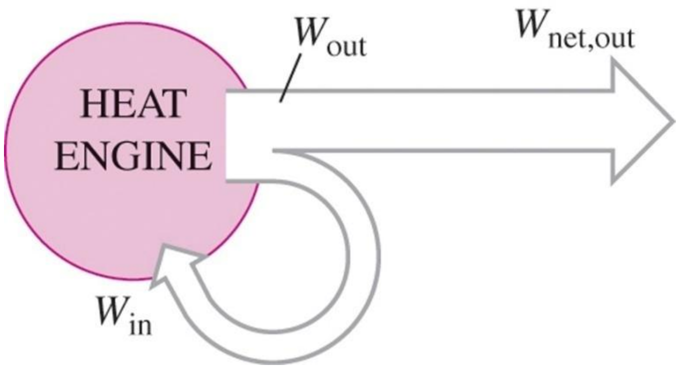
Part of the heat received by a heat engine is converted to work, while the rest is rejected to a sink.

- **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.
5. 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**.

A steam power plant





A portion of the work output of a heat engine is consumed internally to maintain continuous operation.

$$W_{net,out} = W_{out} - W_{in} \qquad (kJ)$$

$$W_{net,out} = Q_{in} - Q_{out} \qquad (kJ)$$

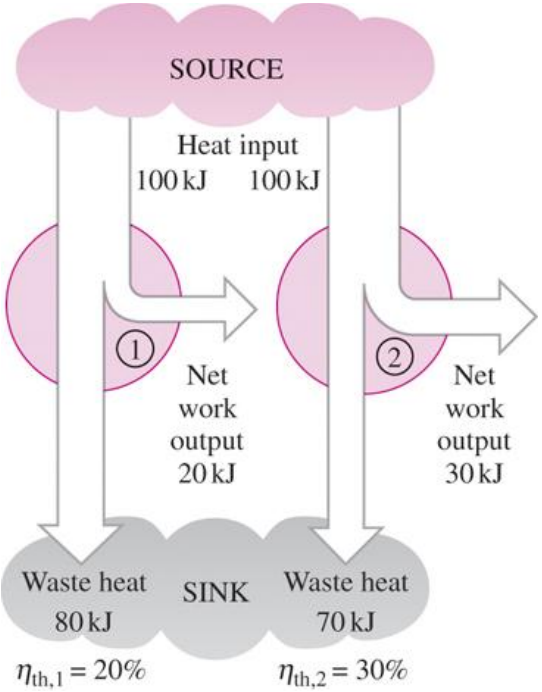
Q_{in} = amount of heat supplied to steam in boiler from a high-temperature source (furnace)

Q_{out} = amount of heat rejected from steam in condenser to a low-temperature sink (the atmosphere, a river, etc.)

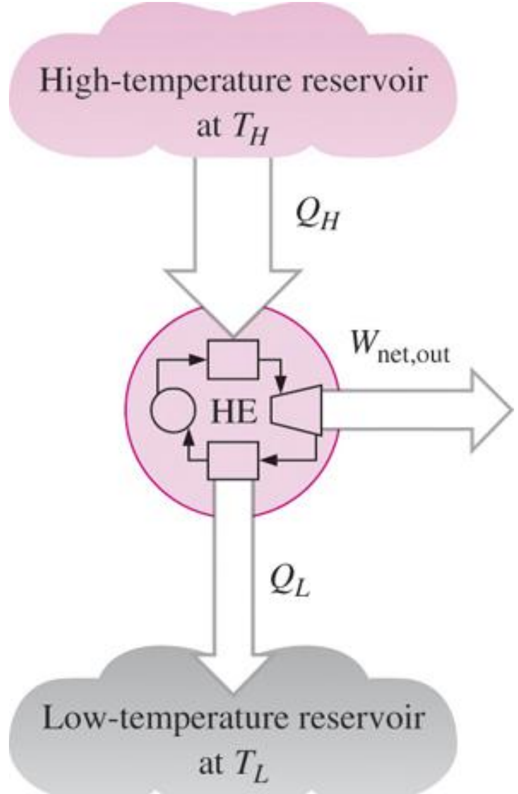
W_{out} = amount of work delivered by steam as it expands in turbine

W_{in} = amount of work required to compress water to boiler pressure

Thermal efficiency



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



$$W_{net,out} = Q_H - Q_L$$

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

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

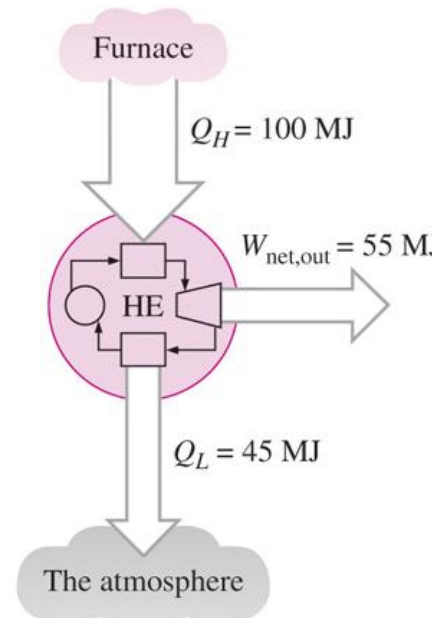
Schematic of a heat engine.

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

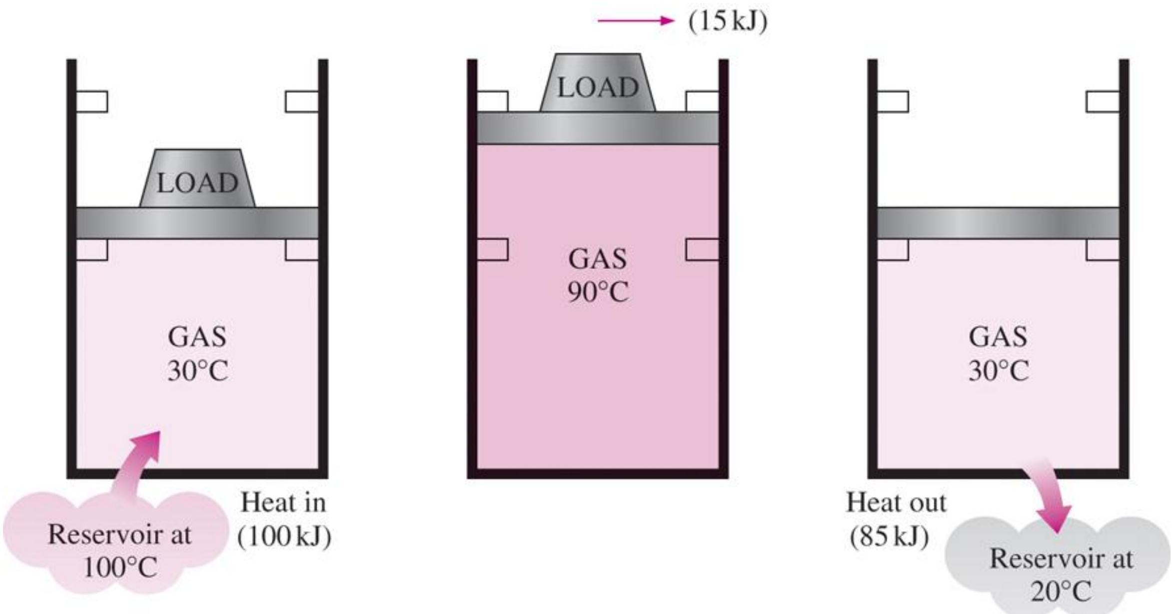
$$\eta_{th} = \frac{W_{net,out}}{Q_{in}} \longrightarrow \eta_{th} = 1 - \frac{Q_{out}}{Q_{in}}$$

Even the most efficient heat engines reject almost one-half of the energy they receive as waste heat.

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



Can we save Q_{out}?



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

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.

In a steam power plant, the condenser is the device where large quantities of waste heat is rejected to rivers, lakes, or the atmosphere.

Can we not just take the condenser out of the plant and save all that waste energy?

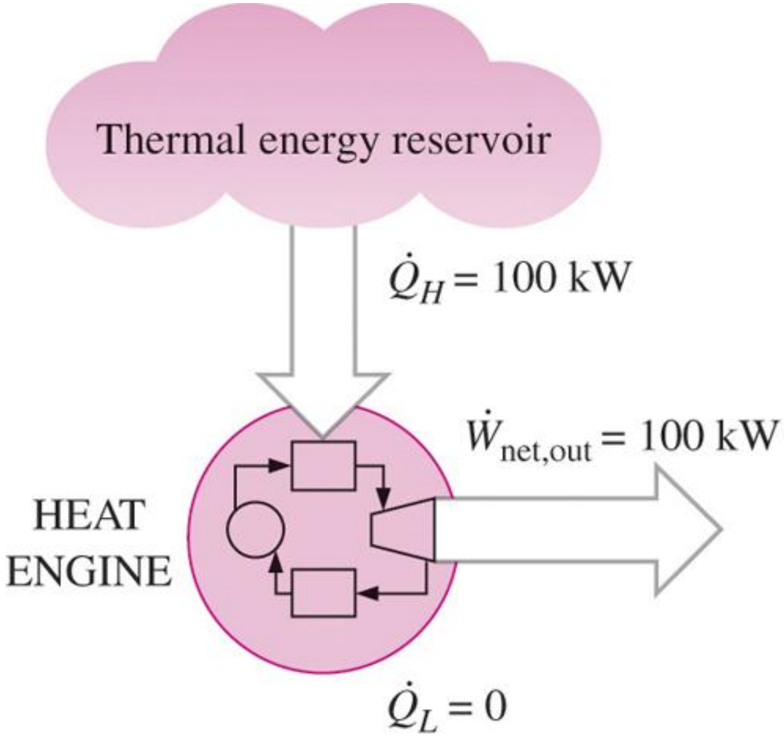
The answer is, unfortunately, a firm ***no*** for the simple reason that without a heat rejection process in a condenser, the cycle cannot be completed.

The Second Law of Thermodynamics: Kelvin–Planck Statement

<u>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.</u>

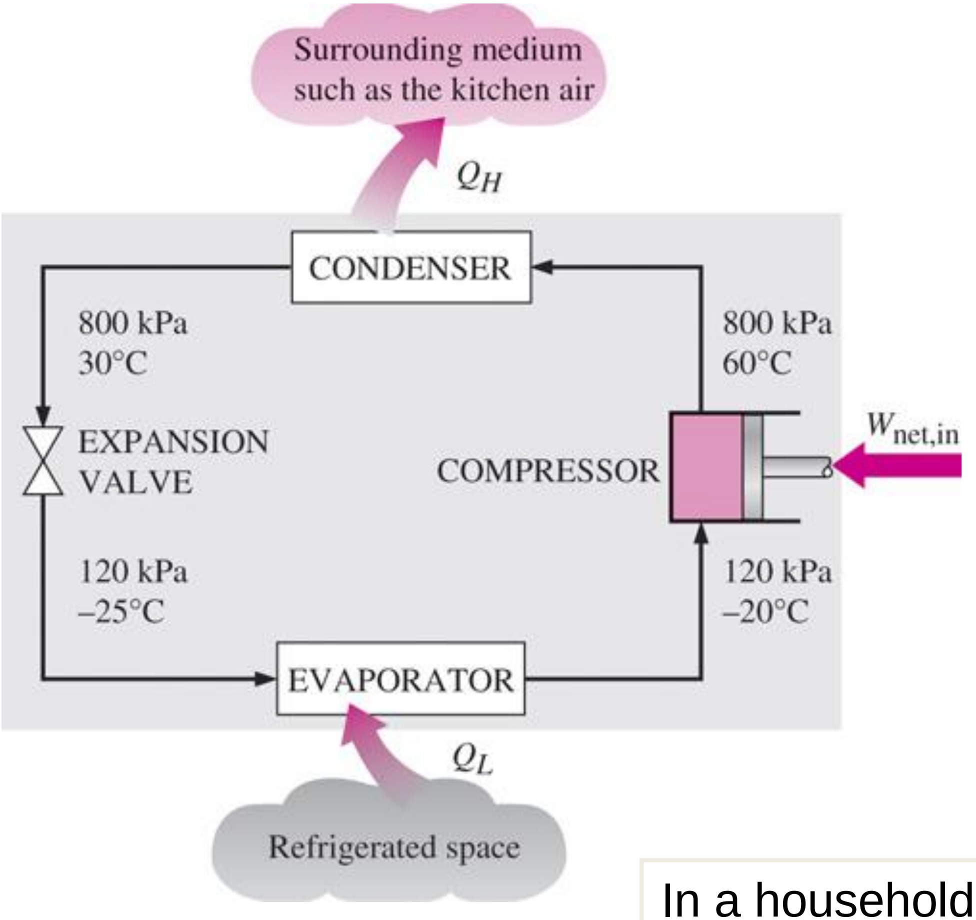
No heat engine can have a thermal efficiency of 100 percent, or as *for a power plant to operate, the working fluid must exchange heat with the environment as well as the furnace*.

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.



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

REFRIGERATORS AND HEAT PUMPS

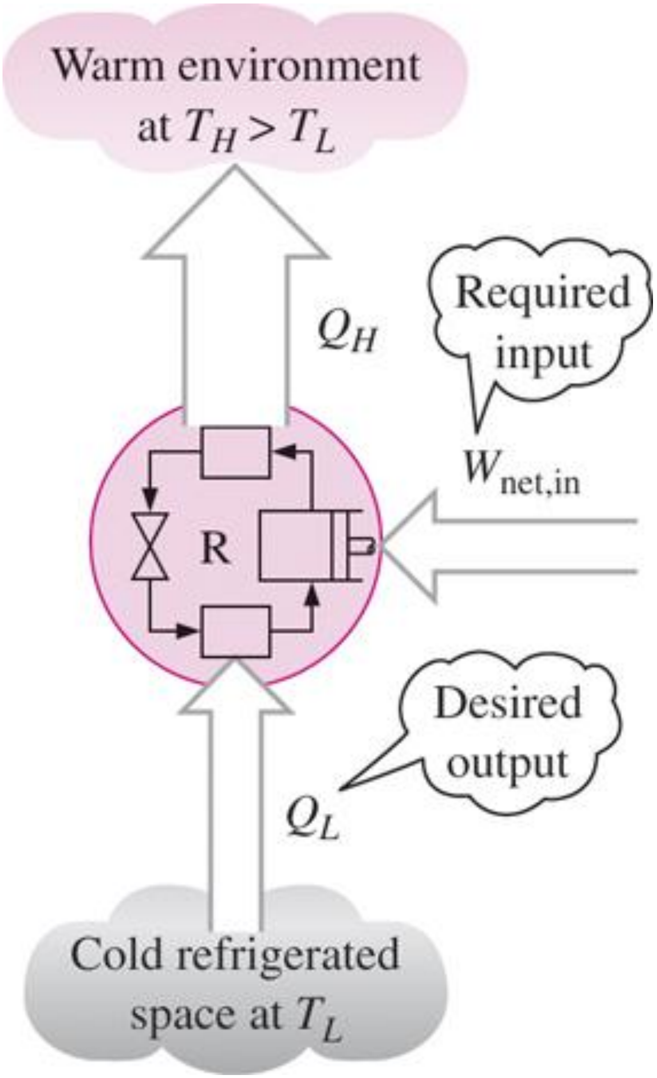


Basic components of a refrigeration system and typical operating conditions.

- 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



The *efficiency* of a refrigerator is expressed in terms of the **coefficient of performance** (COP).

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

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

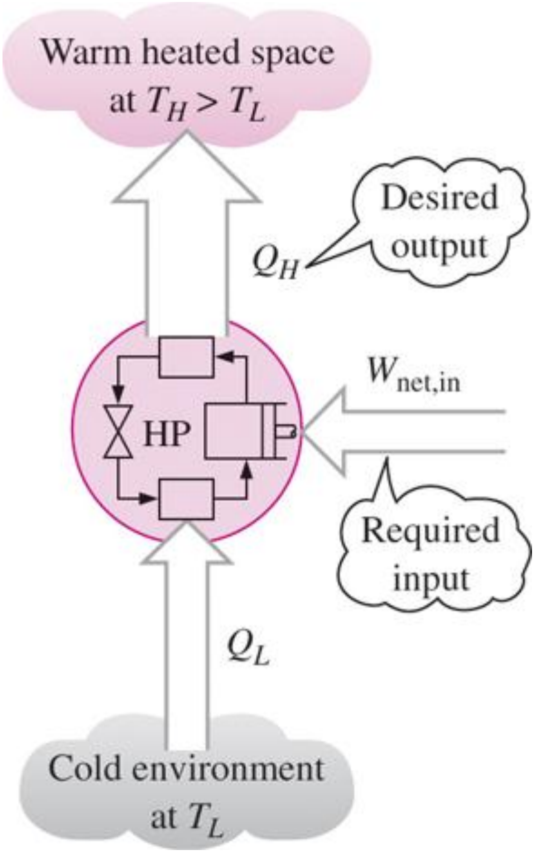
$$W_{\text{net,in}} = Q_H - Q_L \qquad (\text{kJ})$$

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

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

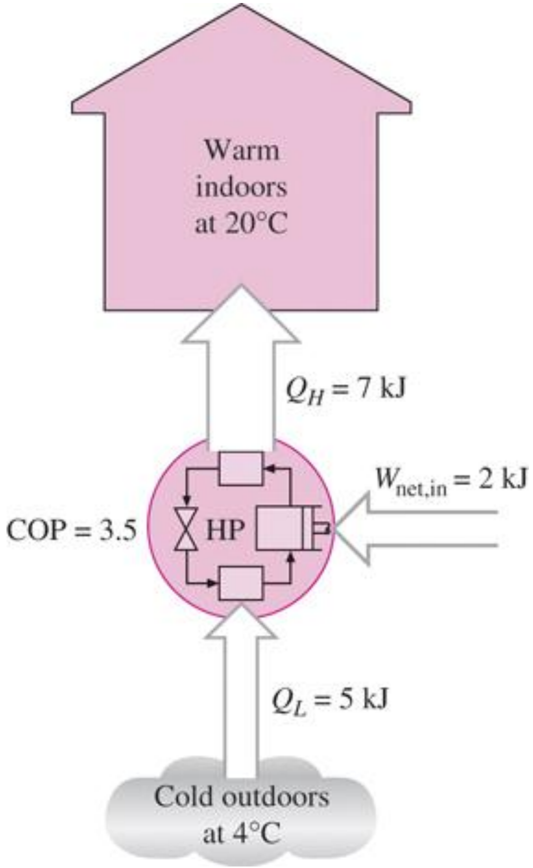
Can the value of $\mathrm{COP_R}$ be greater than unity?

Heat Pumps



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

The work supplied to a heat pump is used to extract energy from the cold outdoors and carry it into the warm indoors.



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

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

$$\text{COP}_{\text{HP}} = \text{COP}_{\text{R}} + 1$$

- Most heat pumps in operation today have a seasonally averaged COP of 2 to 3.
- Most existing heat pumps use the cold outside air as the heat source in winter (*air-source* HP).
- In cold climates their efficiency drops considerably when temperatures are below the freezing point.
- In such cases, *geothermal* (*ground-source*) HP that use the ground as the heat source can be used.
- Such heat pumps are more expensive to install, but they are also more efficient.
- **Air conditioners** are basically refrigerators whose refrigerated space is a room or a building instead of the food compartment.
- The COP of a refrigerator decreases with decreasing refrigeration temperature.
- Therefore, it is not economical to refrigerate to a lower temperature than needed.

Energy efficiency rating (EER): The amount of heat removed from the cooled space in Btu's for 1 Wh (watthour) of electricity consumed.

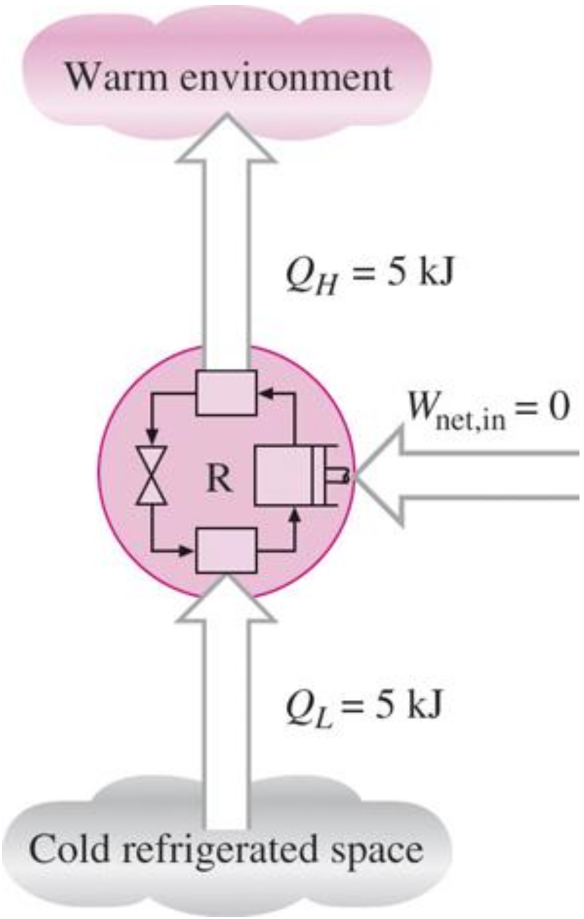
The Second Law of Thermodynamics: Clasius Statement

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.

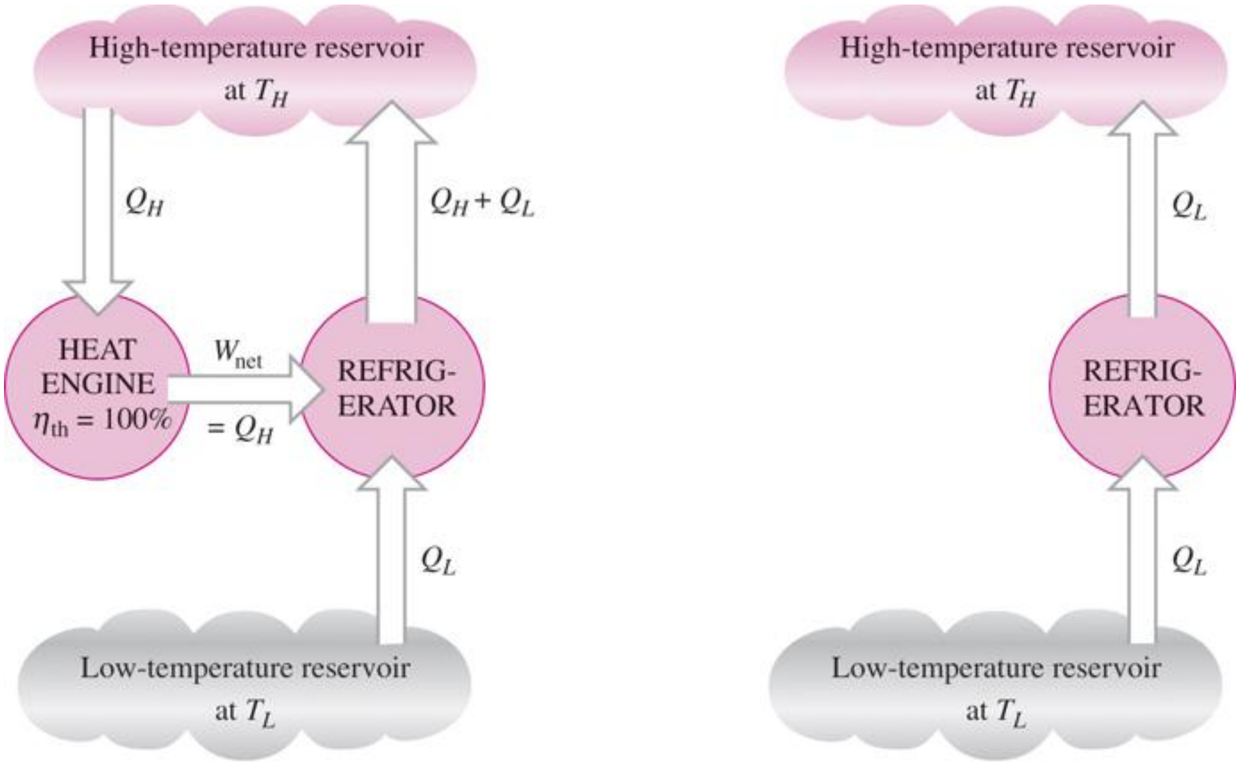
This way, the net effect on the surroundings involves the consumption of some energy in the form of work, in addition to the transfer of heat from a colder body to a warmer one.

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



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

Equivalence of the Two Statements



(*a*) A refrigerator that is powered by a 100 percent efficient heat engine

(*b*) The equivalent refrigerator

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

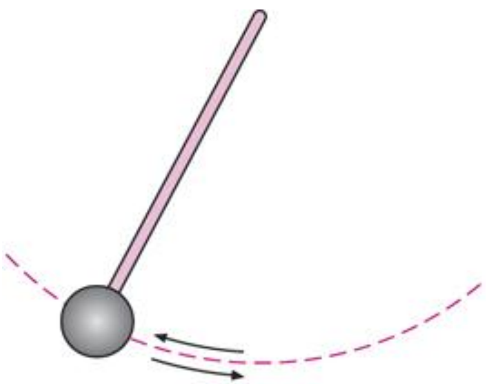
The Kelvin–Planck and the Clausius statements are equivalent in their consequences, and either statement can be used as the expression of the second law of thermodynamics.

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

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.



(*a*) Frictionless pendulum

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

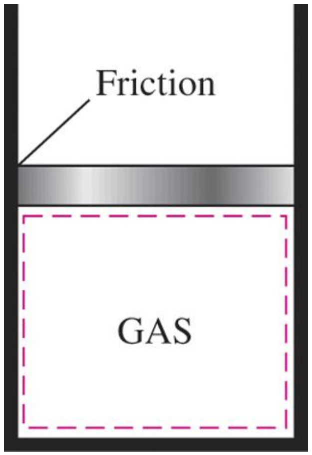
Two familiar reversible processes.

- All the processes occurring in nature are irreversible.
- ***Why are we interested* in reversible processes?**
- **(1)** they are easy to analyze and **(2)** they serve as idealized models (theoretical limits) to which actual processes can be compared.
- Some processes are more irreversible than others.
- We try to approximate reversible processes. **Why?**

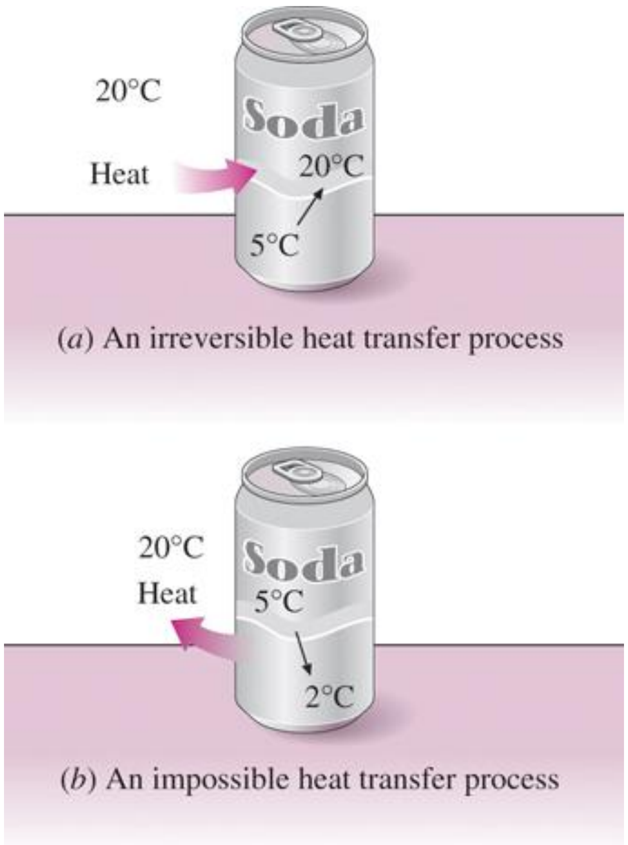
Reversible processes deliver the most and consume the least work.

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.



Friction renders a process irreversible.



(*a*) An irreversible heat transfer process

(*b*) An impossible heat transfer process

(a) Heat transfer through a temperature difference is irreversible
(b) the reverse process is impossible.