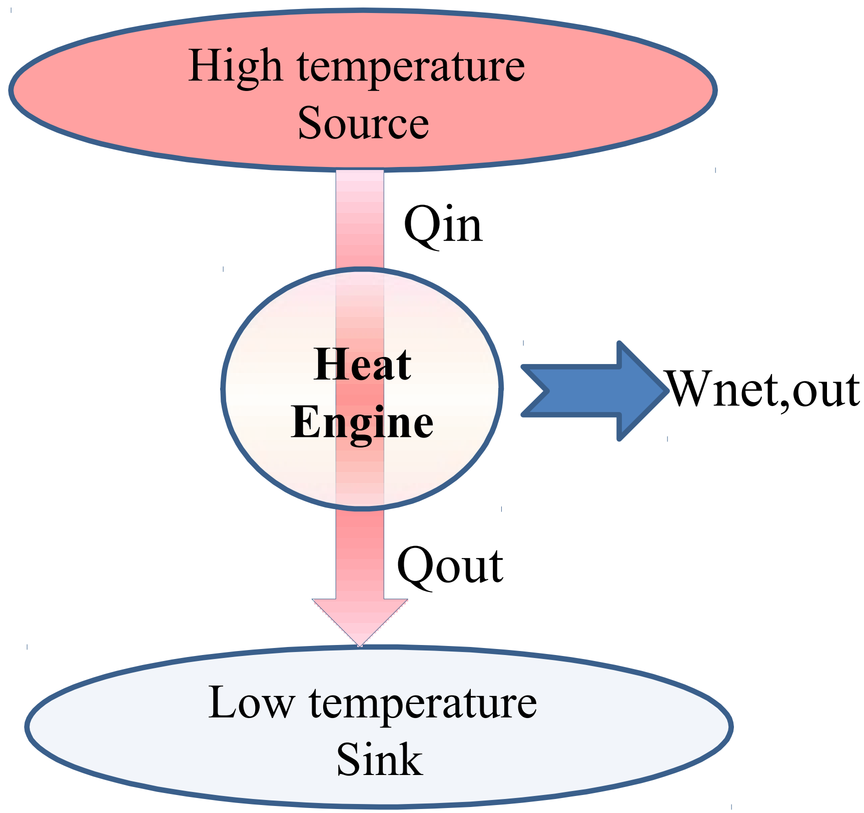
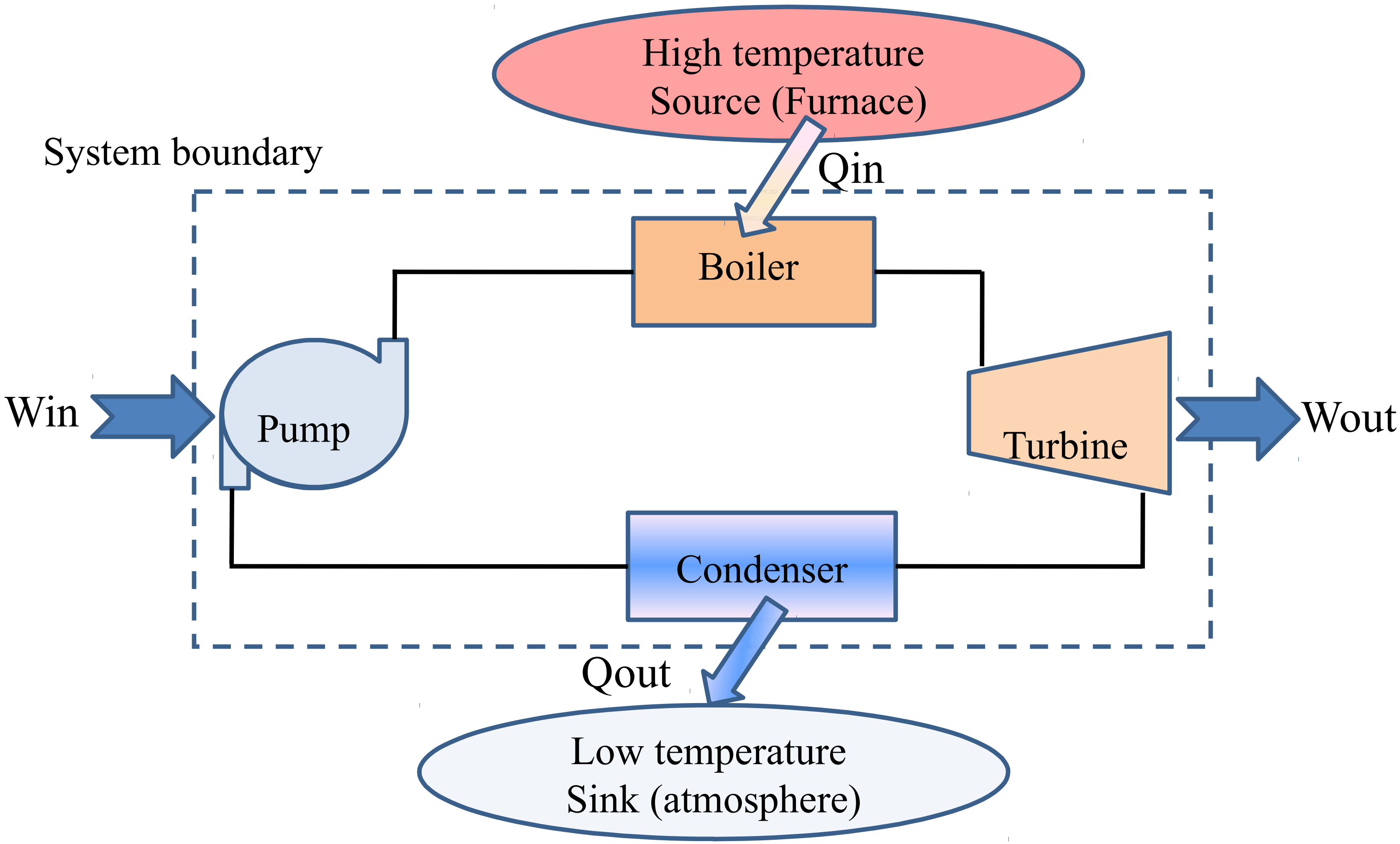
- Recap: Lecture 10: 28th January 2014, 0830-0930 hrs.
  - Energy equation Euler equation Bernoulli's equation
  - Unsteady flow processes
  - Second law of thermodynamics
  - Thermal energy reservoir, source and sink
  - Heat engines
  - Thermal efficiency

Heat engines



Heat engines convert part of Qin to Wnet,out and reject the balance heat to the sink.

Heat engines



Heat engines

- The net work output of the heat engine

$$Wnet,out = Wout - Win \quad \text{(kJ)}$$

- The heat engine system may be considered as a closed system and hence $\Delta U=0$.

$$Wnet,out = Qin - Qout \quad \text{(kJ)}$$

Thermal efficiency

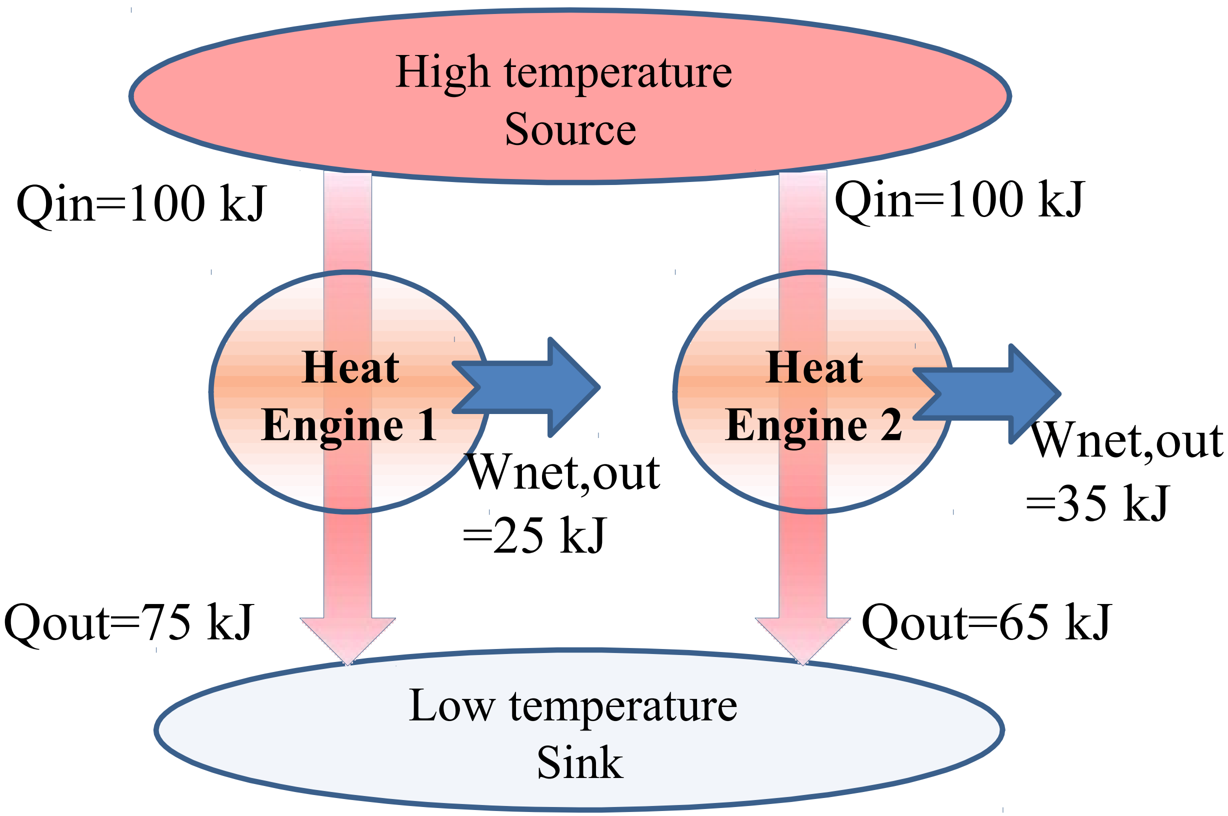
- Qout: energy "wasted" during the process
- Only part of the heat input can be converted to useful work output.
- For heat engines, thermal efficiency is defined as

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

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

$$(\text{since } \mathrm{W}_{\text{net,out}} = Q_{in} - Q_{out})$$

Thermal efficiency



$$\eta_{th1} = \frac{25}{100} = 0.25$$

$$\eta_{th2} = \frac{35}{100} = 0.35$$

All heat engines do not perform the same way.

Thermal efficiency

- Even the most efficient heat engines reject a huge fraction of the input energy.
- Thermal efficiency of common heat engines
  - Automobile engines: 20-25%
  - Aero engines: 25-30%
  - Gas turbine power plants: 40%
  - Combined cycle power plants: 60%

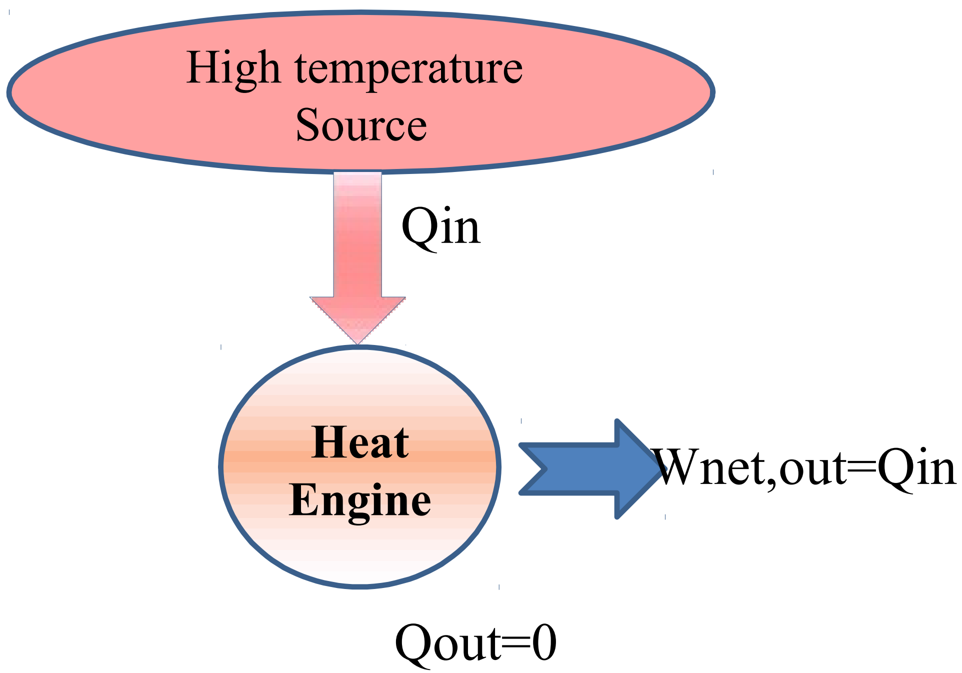
Kelvin-Planck statement

- 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.
- That is, a heat engine must exchange heat with a low-temperature sink as well as a high-temperature source to keep operating.
- No heat engine can have a thermal efficiency of 100 %.

Kelvin-Planck statement

- 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.
- Maximum value of thermal efficiency depends on the reservoir temperatures

Heat engines

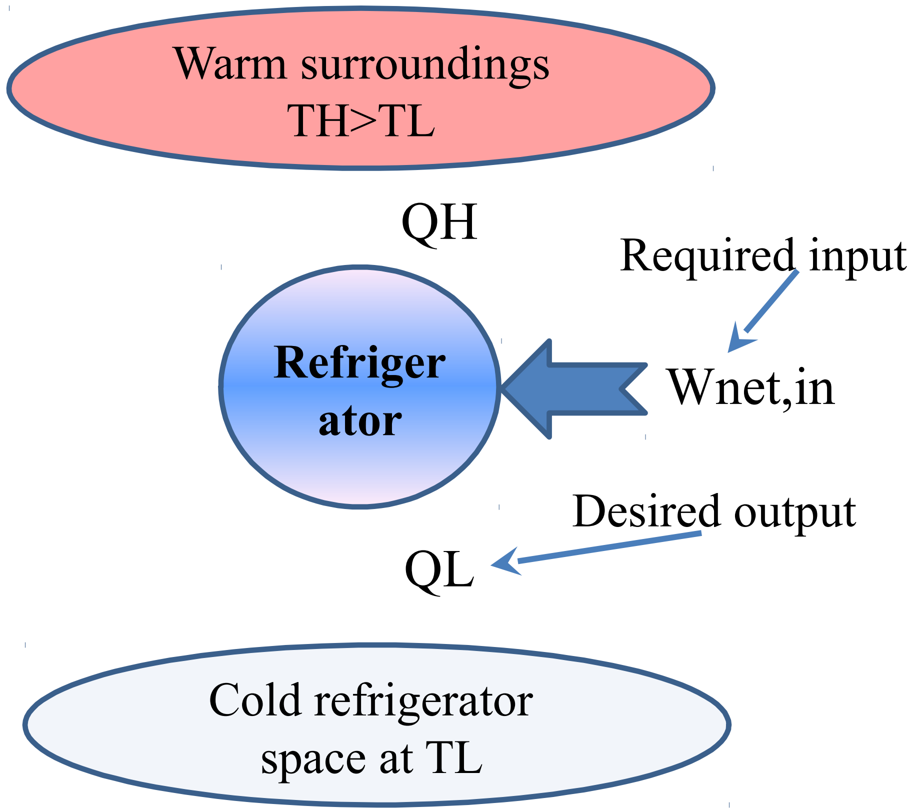


A violation of the Kelvin-Planck statement as there is no Qout, which means ηth=100%

Refrigerators and heat pumps

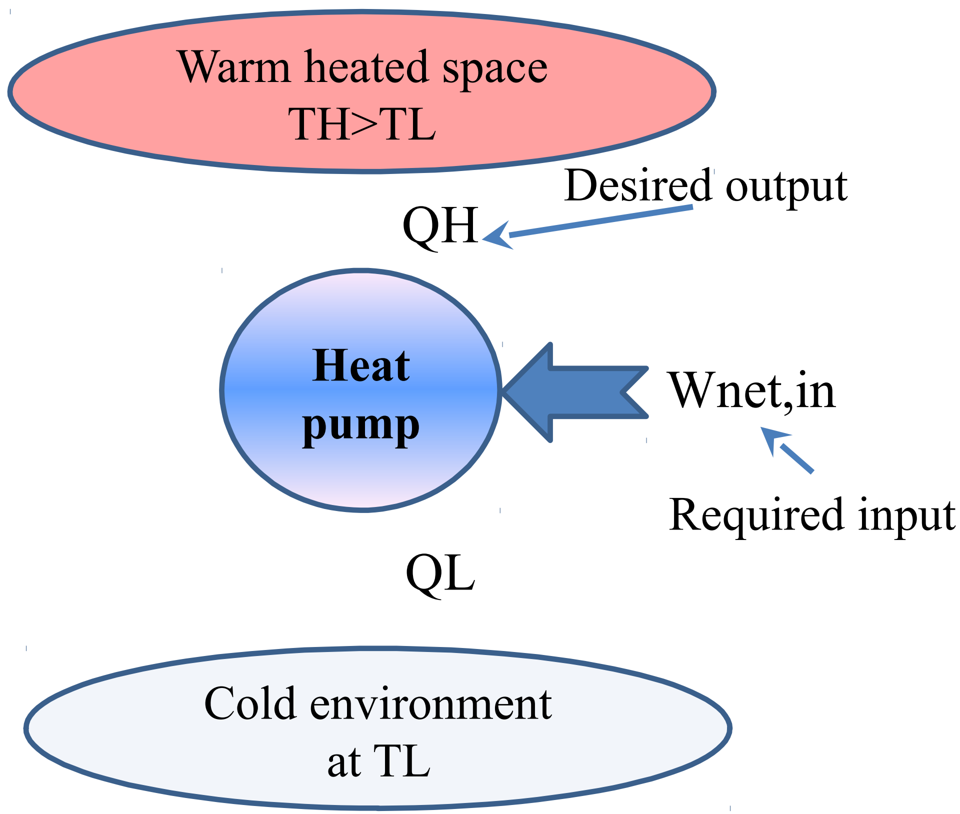
- Refrigerators and heat pumps transfer heat from a low temperature medium to a high temperature one.
- Both of these devices operate on the same cycle, but differ in their objectives.
- Refrigerator: maintains the refrigerated space at a low temperature by removing heat from it.
- Heat pump: maintains a heated space at a high temperature

Refrigerator



Refrigerator removes heat from a cooled space and rejects heat to the ambient.

Heat pump



Heat pump supplies heat to a heated space.

Coefficient of performance

- The efficiency of a refrigerator is expressed in terms of the coefficient of performance, denoted by COP.
- COP is expressed as:

$$COP = \frac{\text{Desired effect}}{\text{Required input}}$$

$$\text{Required input} = W_{net,in} = Q_H - Q_L$$

Coefficient of performance

For a refrigerator, the desired effect is Q_L

Hence, $COP_R = \dfrac{Q_L}{Q_H - Q_L}$

Similarly, for a heat pump, the desired effect is Q_H

$$COP_{HP} = \frac{Q_H}{Q_H - Q_L}$$

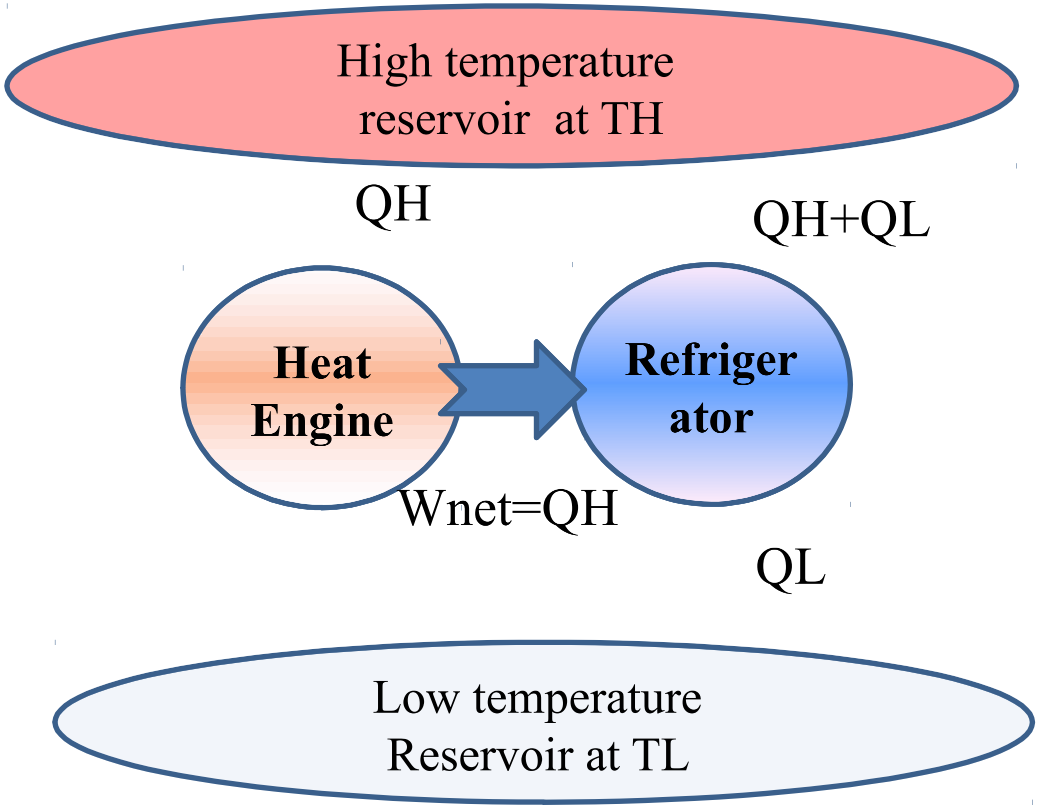
Coefficient of performance

- COPHP = COPR + 1
- Hence, COPHP will be always > unity
- COPR can also be > unity (but not always)
- Amount of heat removed from the refrigerated space can be greater than the amount of work input.

Clausius statement

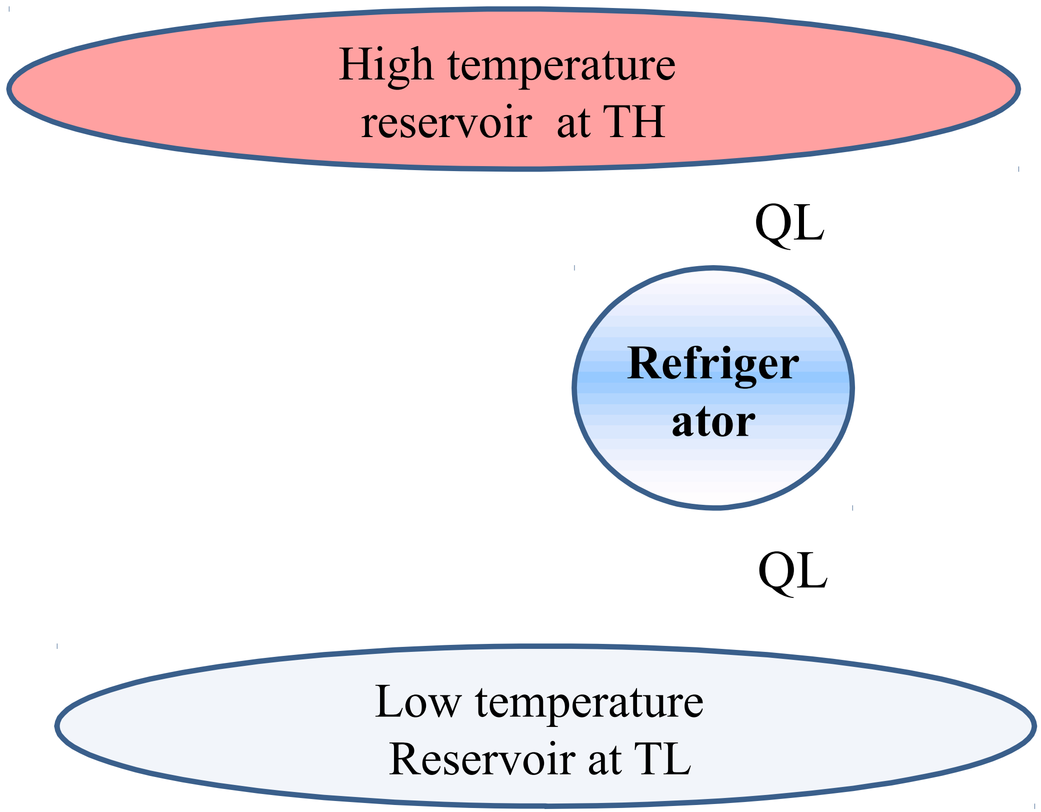
- It is impossible to construct a device that operates in a cycle and produces no effect other than the transfer of heat from a lower-temperature body to a higher-temperature body.
- Refrigerators and heat pumps do not violate the Clausius statement as they operate with a work input.
- Both the Kelvin–Planck and the Clausius statements are negative statements, and hence cannot be proved.

Equivalence of the Kelvin-Planck and the Clausius statement



A refrigerator that works using a heat engine with $\eta_{th}=100\%$

Equivalence of the Kelvin-Planck and the Clausius statement



The equivalent refrigerator

Perpetual motion machines of the second kind (PMM2)

- Any device that violates the second law is called a perpetual-motion machine of the second kind (PMM2).
- Such a device will
  - Either generate work by exchanging heat with a single reservoir
  - Or transfer heat from a low temperature reservoir to a higher temperature one without any work input.

Perpetual motion machine of the second kind (PMM2)