Introduction to Aerospace Propulsion

Prof. Bhaskar Roy, Prof. A M Pradeep
Department of Aerospace Engineering,
IIT Bombay

Lecture No - 10

In this lecture...

- Introduction to the second law of thermodynamics
- Thermal energy reservoirs
- Heat engines
- Kelvin–Planck statement
- Refrigerators and heat pumps
- Clausius statement
- Equivalence of the two statements
- Perpetual motion machines of the second kind (PMM2)

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Second law of thermodynamics

- Need for the second law of thermodynamics
  - Limitations of the first law of thermodynamics
  - Directionality of a process
  - Quality of energy
- Examples
  - A hot object does not get hotter in a cooler room.
  - Transferring heat to a resistor will not generate electricity.

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Second law of thermodynamics

- Processes proceed in a certain direction and not in the reverse direction.
- The first law places no restriction on the direction of a process.
- This inadequacy of the first law to identify whether a process can take place or not is remedied by the second law of thermodynamics.
- A process cannot occur unless it satisfies both the first and the second laws of thermodynamics.

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Second law of thermodynamics

- The first law of thermodynamics was concerned only with the quantity of energy and its transformations.
- Second law reveals that energy has quantity as well as quality.
- Second law of thermodynamics determines theoretical limits for feasibility of a process.

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Thermal energy reservoir

- A hypothetical body with a relatively large thermal energy (mass x specific heat).
- Supply or absorb infinite amounts of heat without any change in its temperature
- Eg. Oceans, lakes, atmosphere
- A reservoir that supplies energy in the form of heat: Source
- A reservoir that absorbs energy in the form of heat: Sink

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Heat engines

- Work can be rather easily converted to heat.
- The reverse process is not easy and requires special devices: heat engines
- Receive heat from a high-temperature source (solar energy, oil furnace etc.).
- Convert part of this heat to work
- Reject the remaining waste heat to a low-temperature sink
- Operate on a cycle

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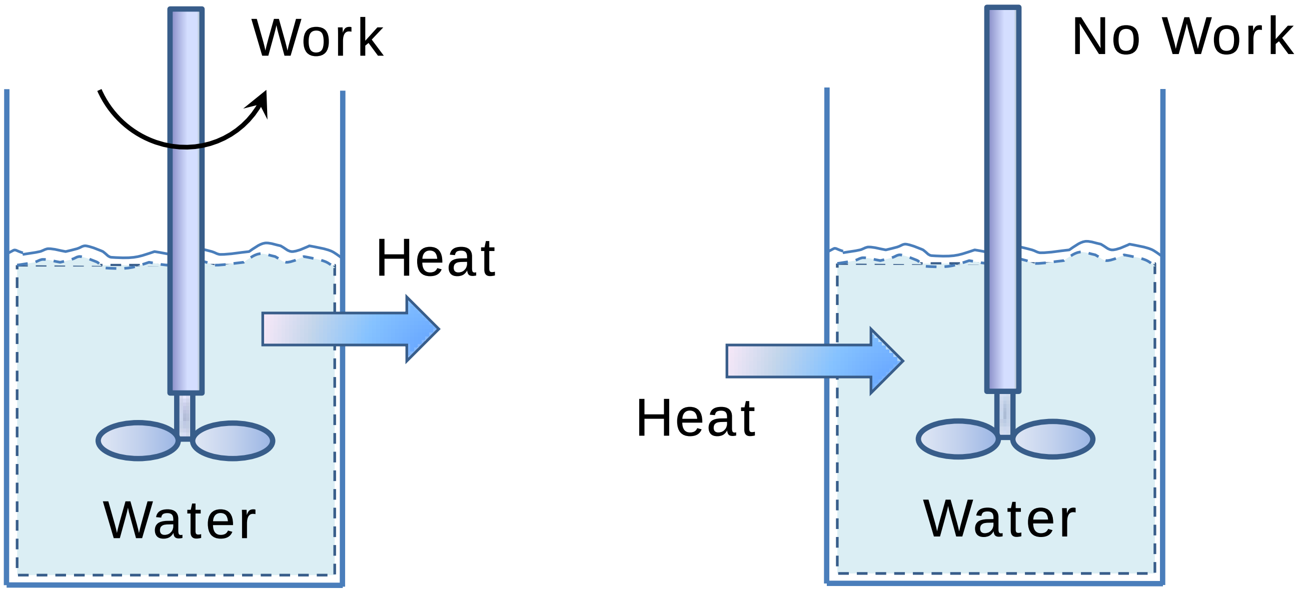
Heat engines



Work can be easily converted to heat, but the reverse does not occur naturally.

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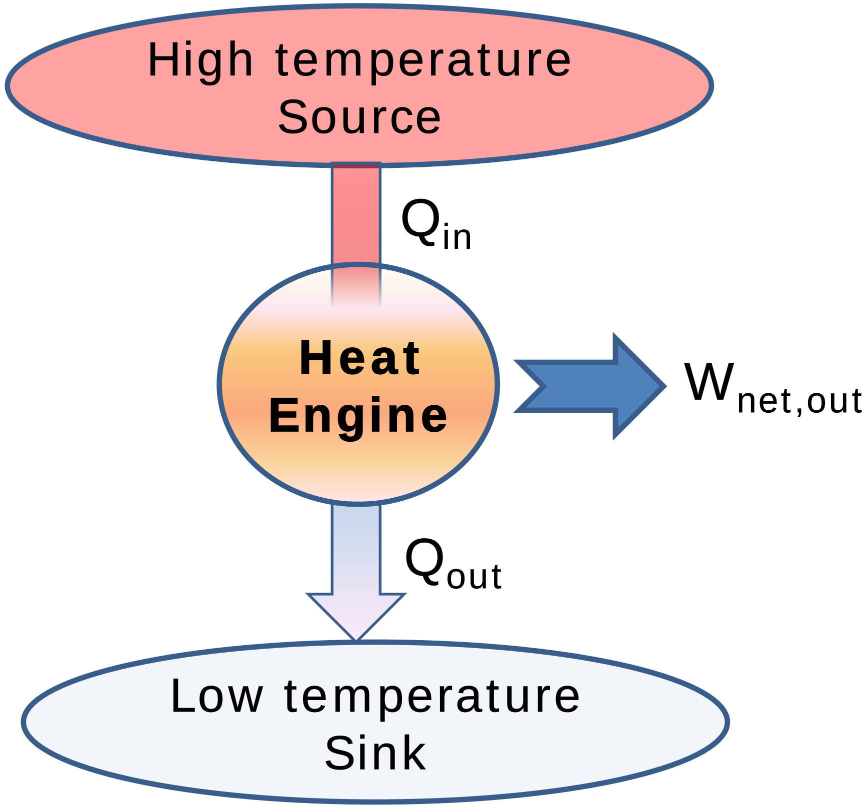
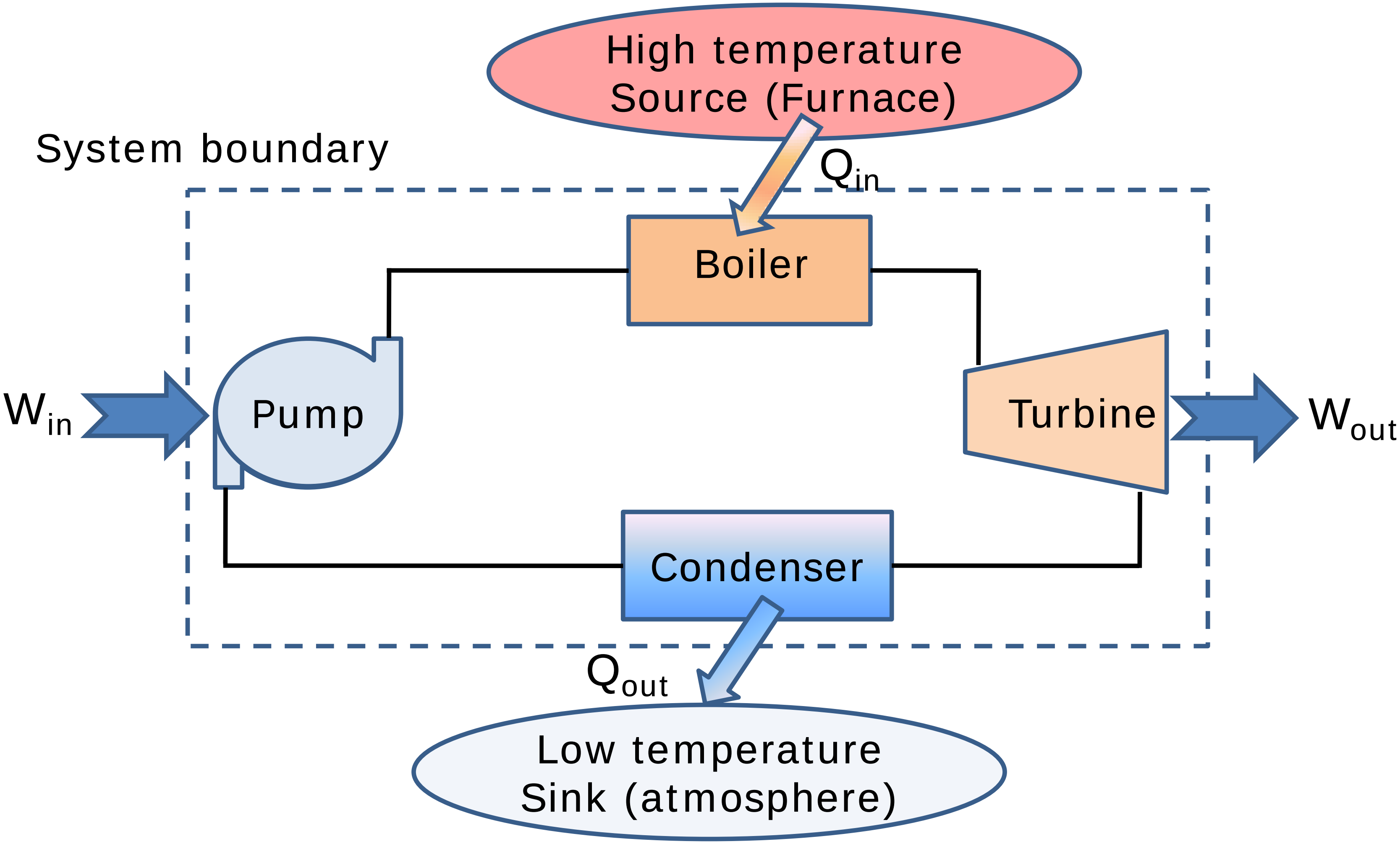
Heat engines



Heat engines convert part of Q_{in} to $W_{net,out}$ and reject the balance heat to the sink.

Heat engines



Heat engines

- The net work output of the heat engine

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

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

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

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Thermal efficiency

- Q_{out}: 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

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

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

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

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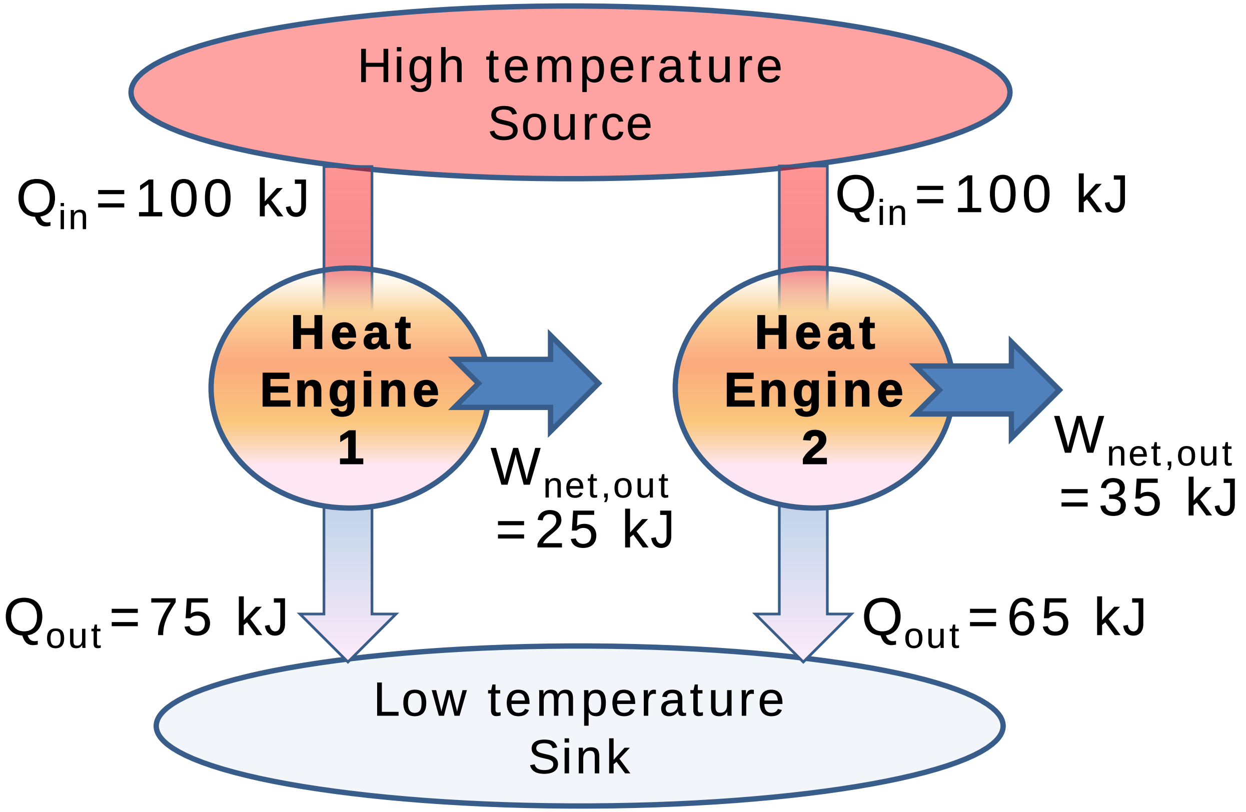
Thermal efficiency



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

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

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%

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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 percent.

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Kelvin-Planck statement

- The impossibility of having a 100 percent 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

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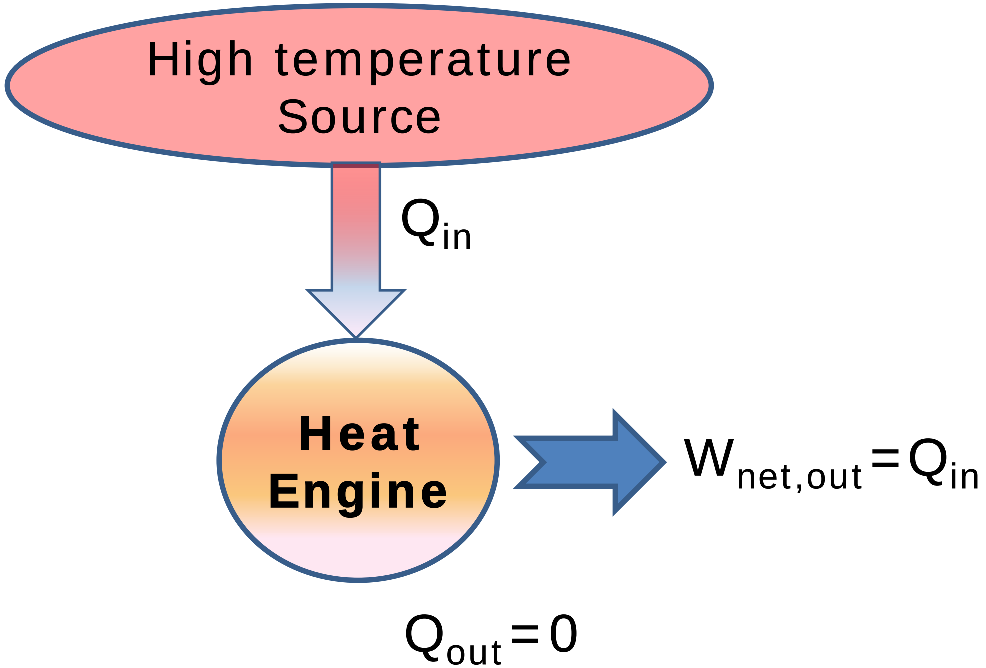
Heat engines



A violation of the Kelvin-Planck statement as there is no Q_{out}, which means $\eta_{th} = 100\%$

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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

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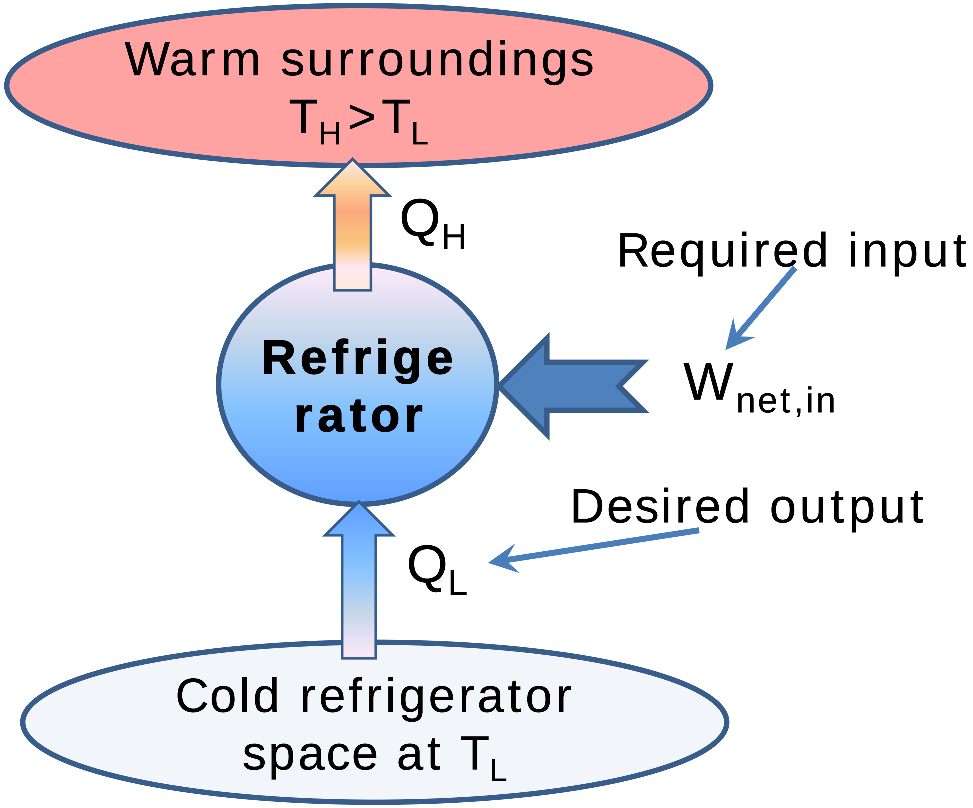
Refrigerator



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

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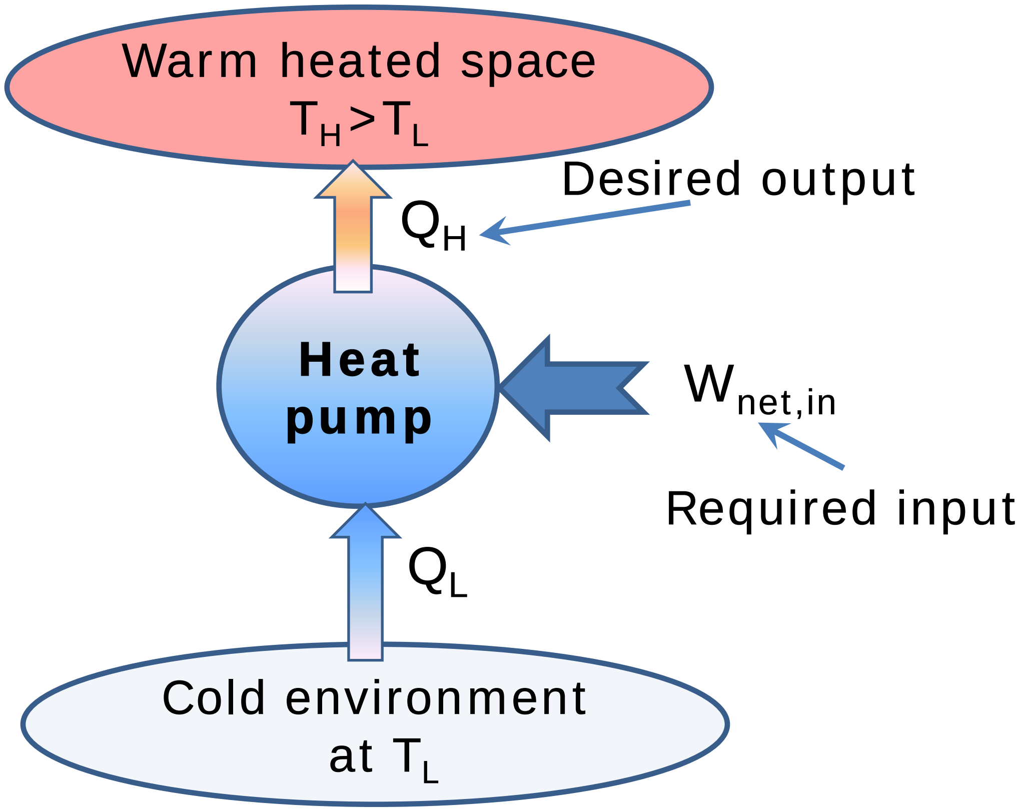
Heat pump



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

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

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Coefficient of performance

- $COP_{HP} = COP_R + 1$
- Hence, COP_{HP} will be always > unity
- COP_R can also be > unity (but not always)
- Amount of heat removed from the refrigerated space can be greater than the amount of work input.

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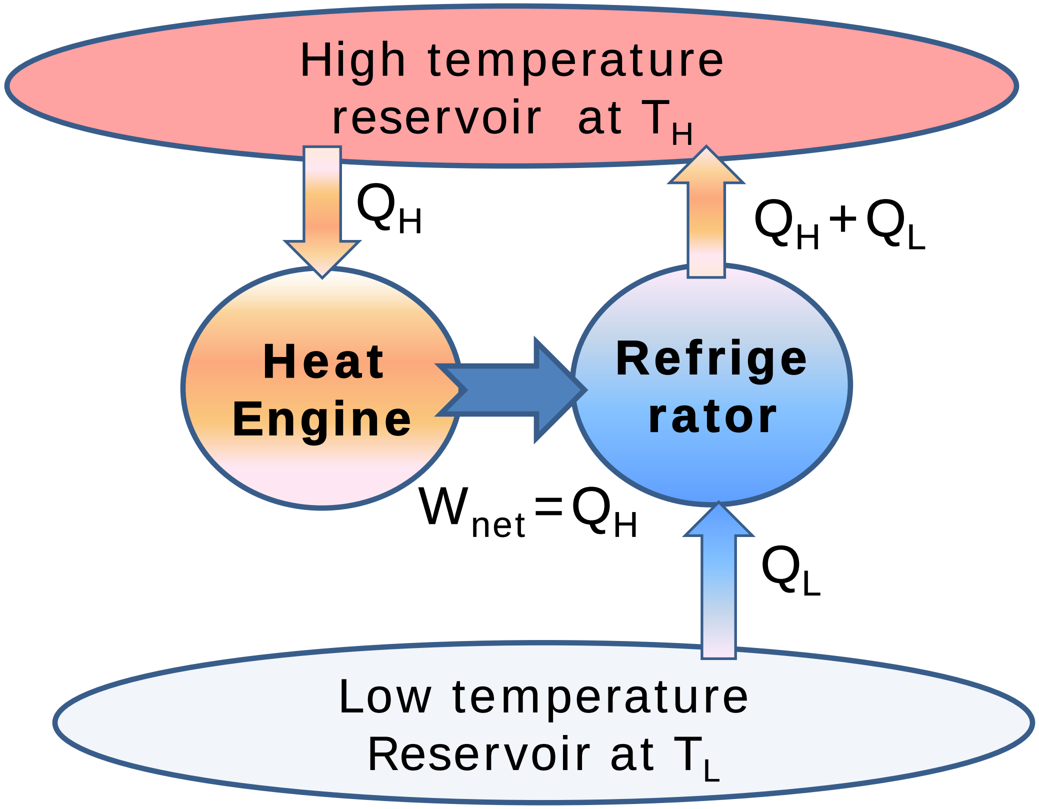
Clausius statement

- 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 $\eta_{th}=100\%$

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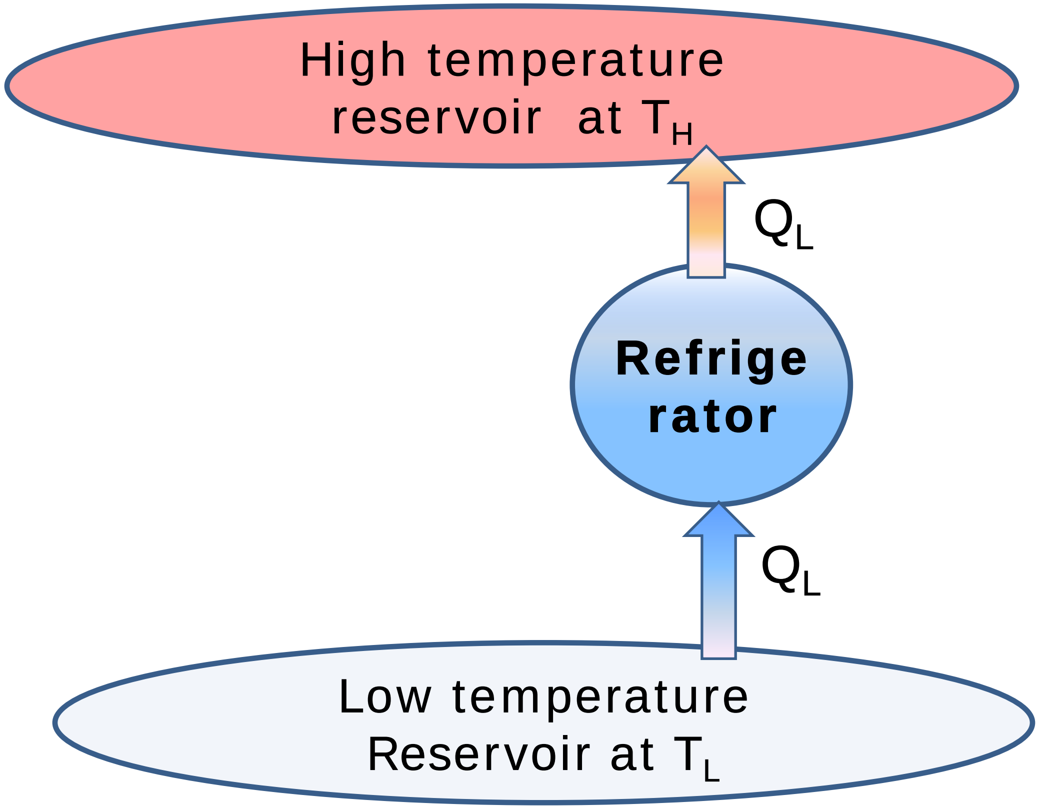
Equivalence of the Kelvin-Planck and the Clausius statement



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.

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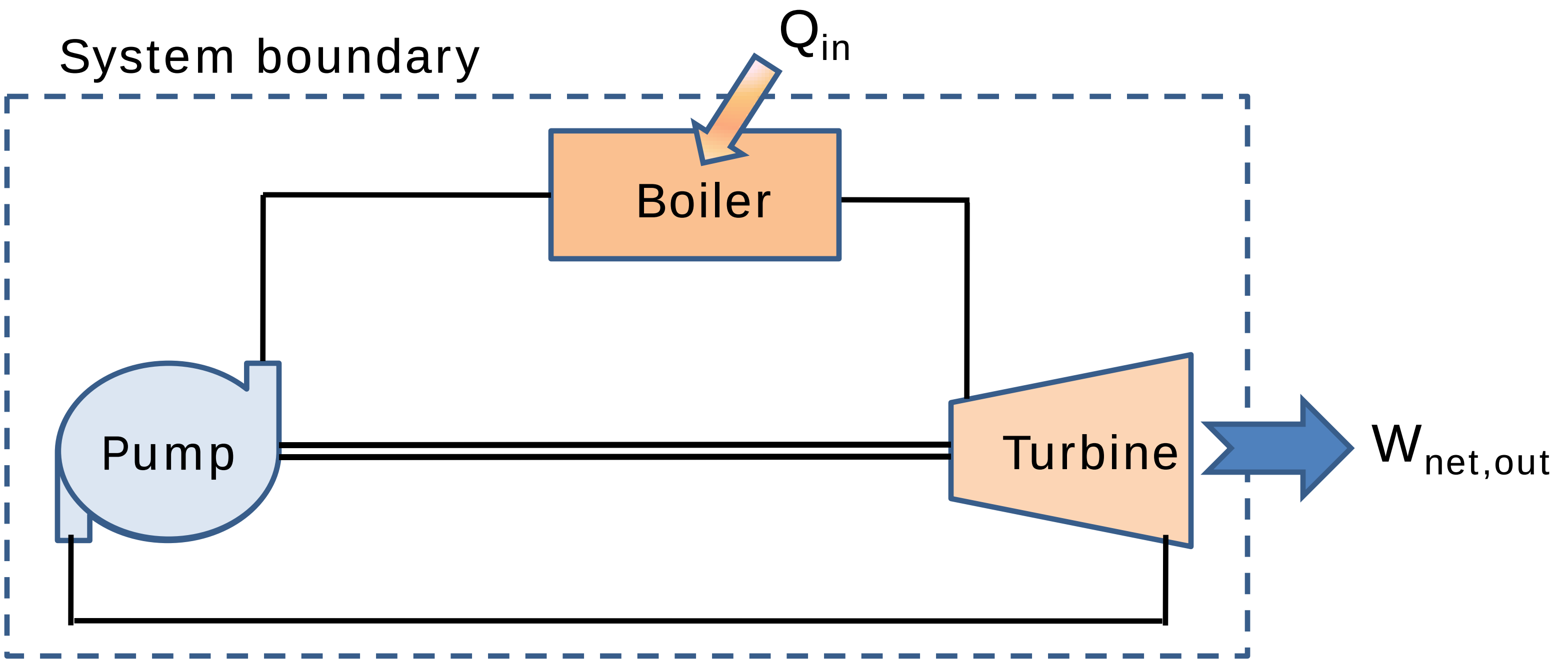
Perpetual motion machine of the second kind (PMM2)



Recap of this lecture

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In the next lecture ...

- Reversible and Irreversible Processes
- Irreversibilities
- Internally and Externally Reversible Processes
- Entropy
- Clausius theorem and inequality
- Property of entropy
- Temperature-entropy plots
- Isentropic processes

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