Introduction to Aerospace Propulsion

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Lecture No - 14

In this lecture ...

- The Carnot cycle
- The reversed Carnot cycle
- The Carnot principles
- The thermodynamic temperature scale
- Carnot heat engine
- Quality of energy
- Carnot refrigerator and heat pump

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The Carnot cycle

- The cycle efficiency can be maximised by using reversible processes.
- Reversible cycles cannot be achieved in practice because the irreversibilities.
- Reversible cycles provide upper limits on the performance of real cycles.
- The Carnot cycle, proposed in 1824 by Sadi Carnot, is a reversible cycle.
- The theoretical heat engine that operates on the Carnot cycle is called the Carnot heat engine.

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The Carnot cycle

- The Carnot cycle consists of four reversible processes
  - Two reversible adiabatic processes
  - Two reversible isothermal processes
- It can be executed in a closed system or a steady flow mode.
- We shall consider a closed system consisting of a piston-cylinder arrangement.
- Friction and other irreversibilities are assumed to be absent.

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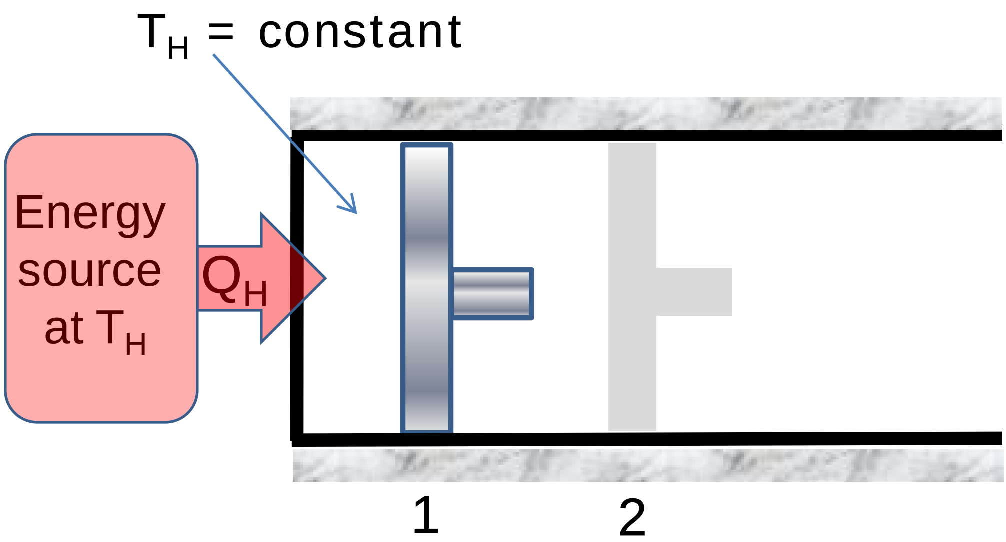
The Carnot cycle



Process 1-2

- Reversible isothermal expansion (1-2)
- Gas allowed to expand slowly.
- Infinitesimal heat transfer to keep T_H constant.
- Since temperature differential never exceeds dT, reversible isothermal process.
- Total heat transfer: Q_H

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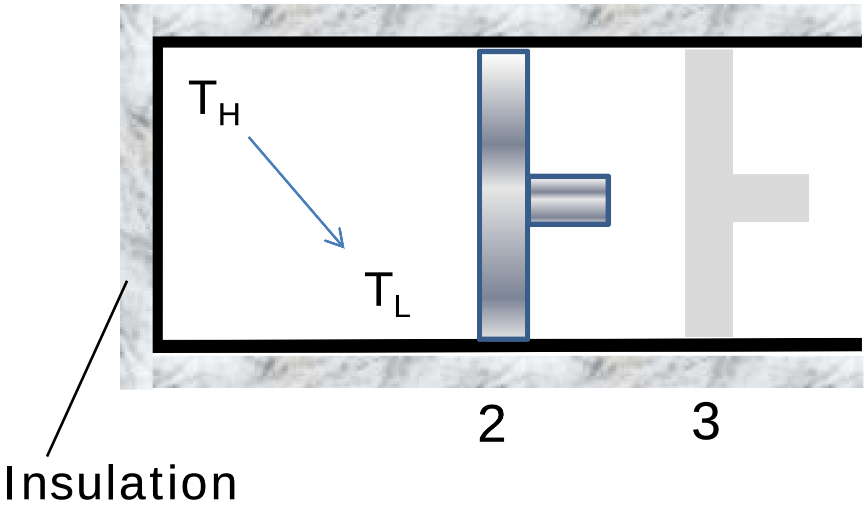
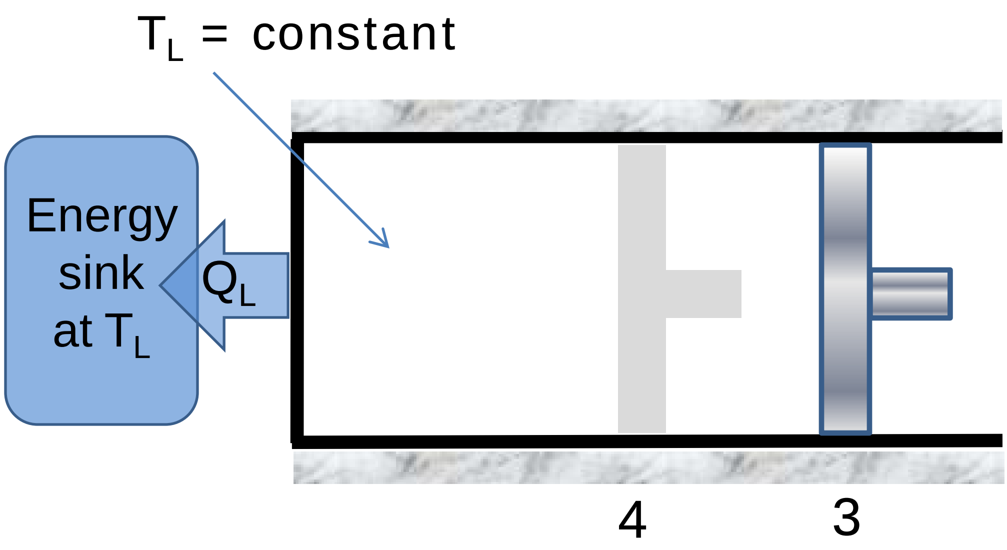
The Carnot cycle



Process 2-3

- Reversible adiabatic expansion (2-3)
- Insulation at the cylinder head
- Temperature drops from T_H to T_L
- Gas expands and does work
- Process is therefore reversible and adiabatic.

The Carnot cycle



Process 3-4

- Reversible isothermal compression (3-4)
- Insulation removed
- T_L is constant
- Infinitesimal heat transfer to the sink at T_L
- Temperature differential never exceeds dT, reversible isothermal process
- Total heat transfer: Q_L

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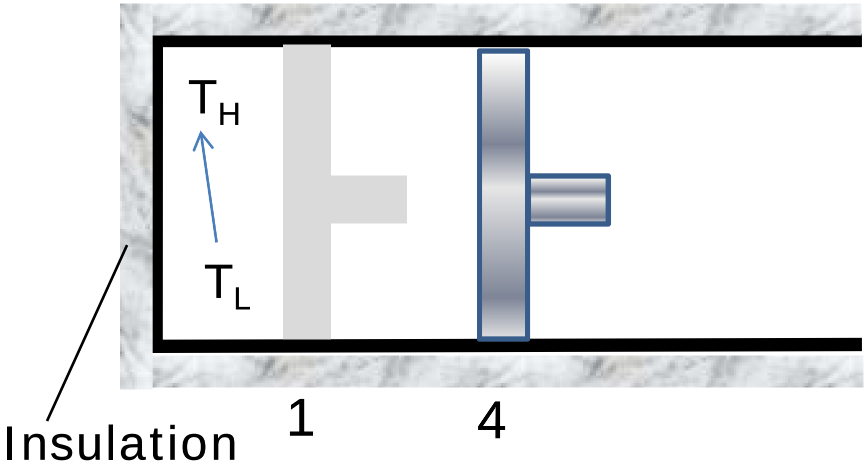
The Carnot cycle



Process 4-1

- Reversible adiabatic compression (4-1)
- Temperature rises from T_L to T_H
- Insulation put back
- The gas is compressed in a reversible manner.
- The temperature rises from T_L to T_H

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The Carnot cycle

- 1-2: A reversible isothermal process

$$Q_1 = U_2 - U_1 + W_{1-2}$$

- 2-3: A reversible adiabatic process

$$0 = U_3 - U_2 + W_{2-3}$$

- 3-4: Reversible isothermal process

$$Q_2 = U_4 - U_3 - W_{3-4}$$

- 4-1: Reversible adiabatic process

$$0 = U_1 - U_4 - W_{4-1}$$

$$Q_1 - Q_2 = W_{1-2} + W_{2-3} - (W_{3-4} + W_{4-1})$$

$\Sigma Q_{net} = \Sigma W_{net}$ for the cycle

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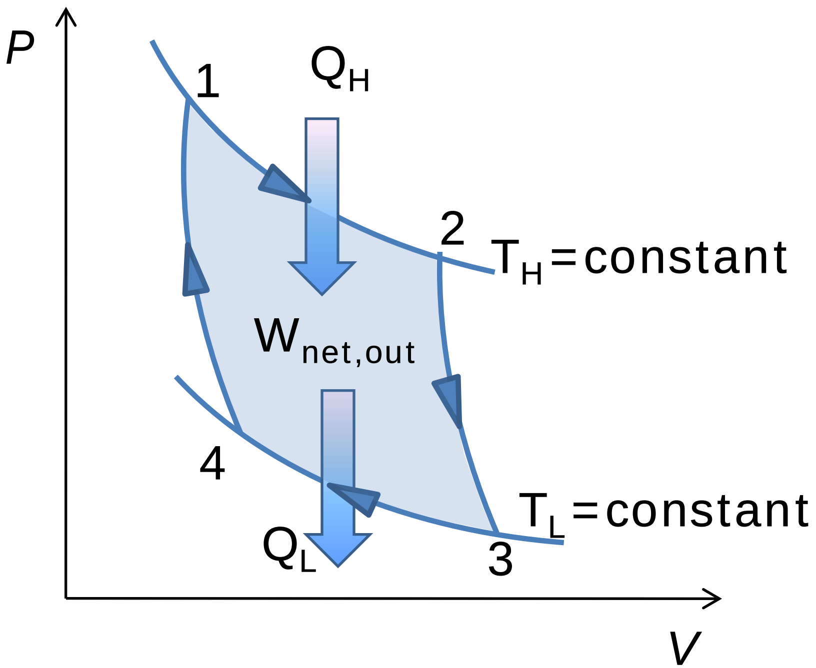
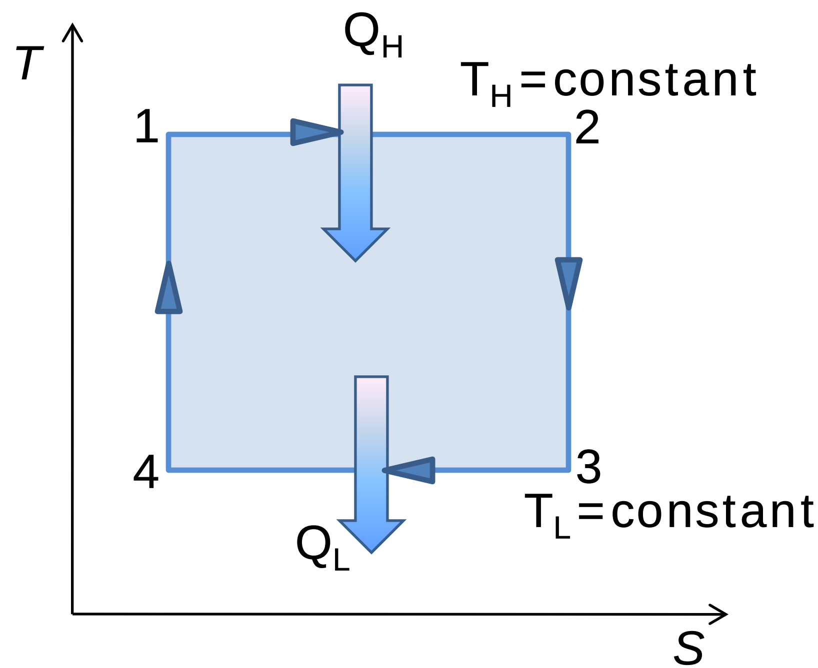
The Carnot cycle



P-*V* diagram of Carnot cycle



T-*S* diagram of Carnot cycle

The Reversed Carnot cycle

- The Carnot cycle comprises of reversible processes.
- So all the processes can be reversed.
- This is like a Carnot Refrigeration cycle.
- The cycle remains same, but the directions of heat and work interactions are reversed.
- Q_L : heat absorbed from the low temperature reservoir
- Q_H : heat rejected to the high temperature reservoir
- $W_{net,in}$: Net work input required

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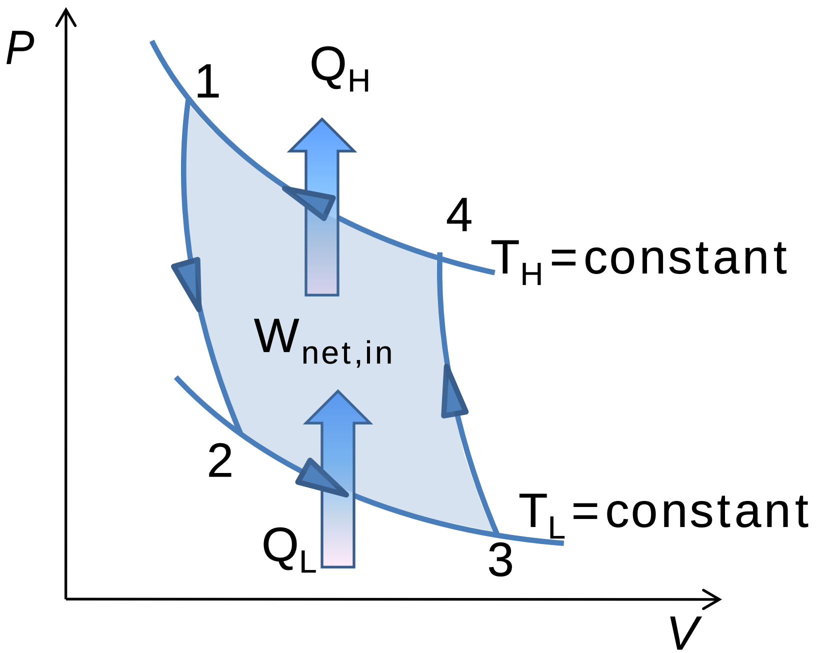
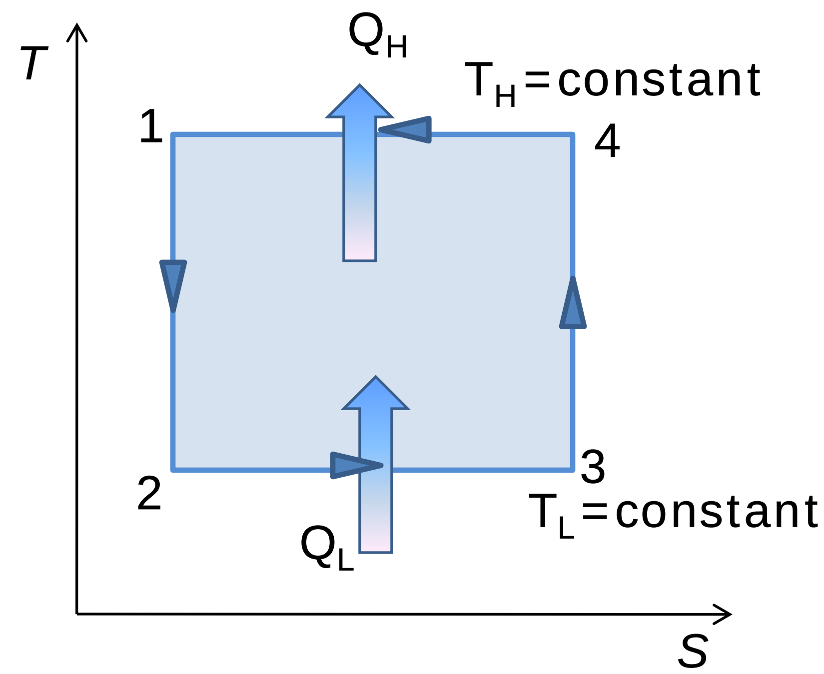
The Reversed Carnot cycle



P-V diagram of Reversed Carnot cycle



T-S diagram of Reversed Carnot cycle

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The Carnot principles

- There are theoretical limits to the operation of all cyclic devices (2nd law of thermodynamics).
- Carnot principles:
  - Efficiency of an irreversible heat engine is always less than that of a reversible engine operating between the same reservoirs.
  - Efficiencies of all reversible heat engines operating between the same reservoirs are the same.

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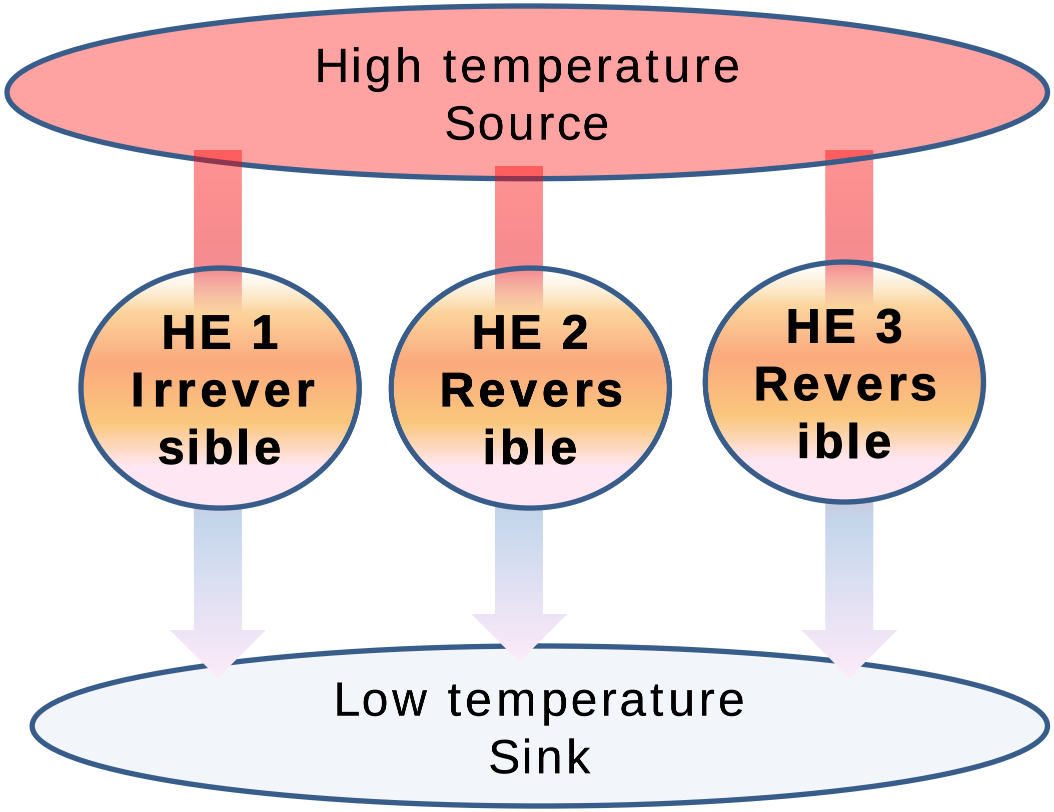
The Carnot principles

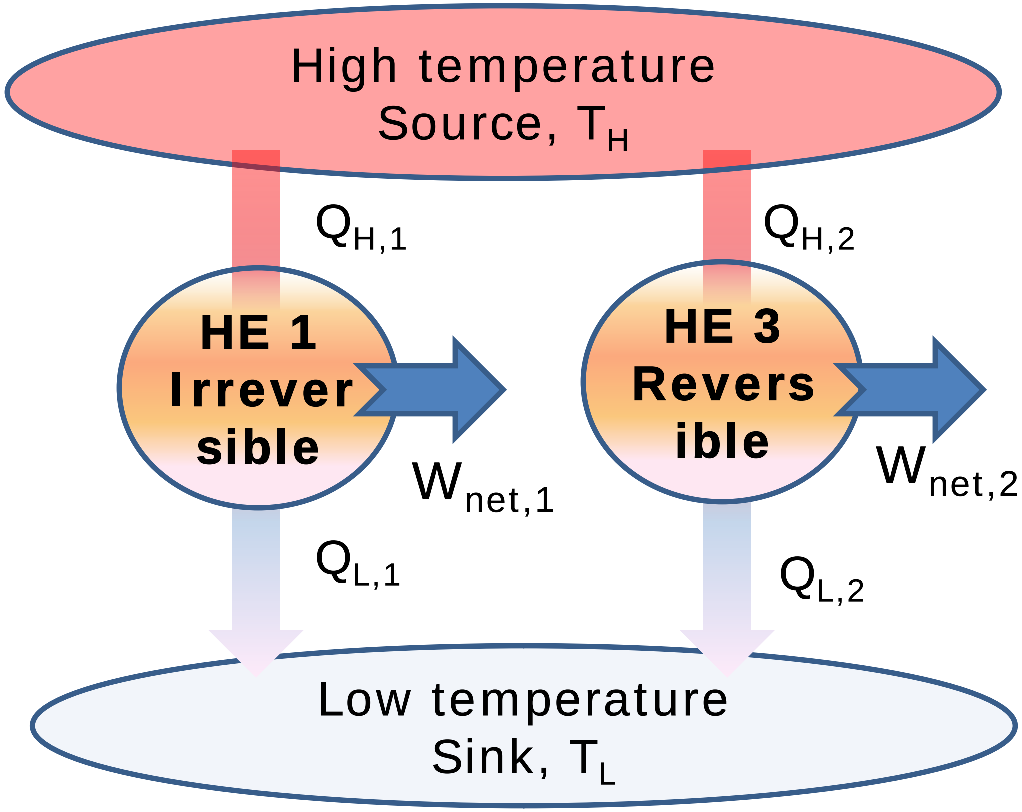


$$\eta_{th,1} < \eta_{th,2}$$

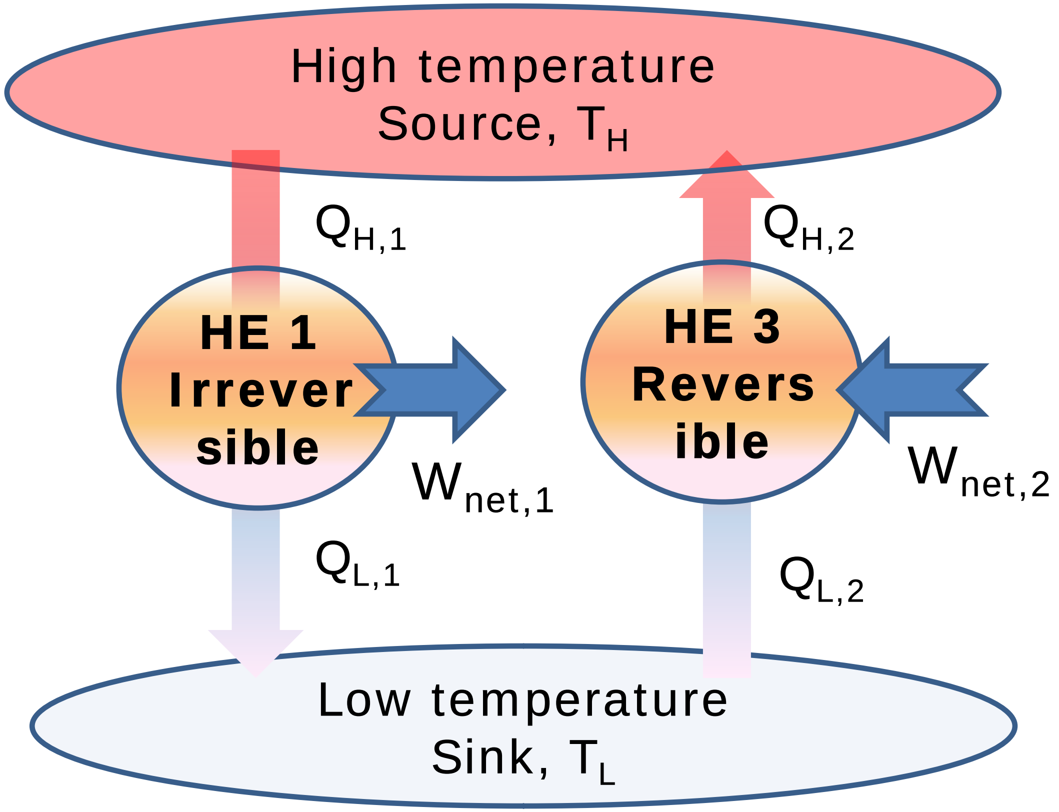
$$\eta_{th,1} < \eta_{th,3}$$

$$\eta_{th,2} = \eta_{th,3}$$

Proof of the Carnot principles



Proof of the Carnot principles



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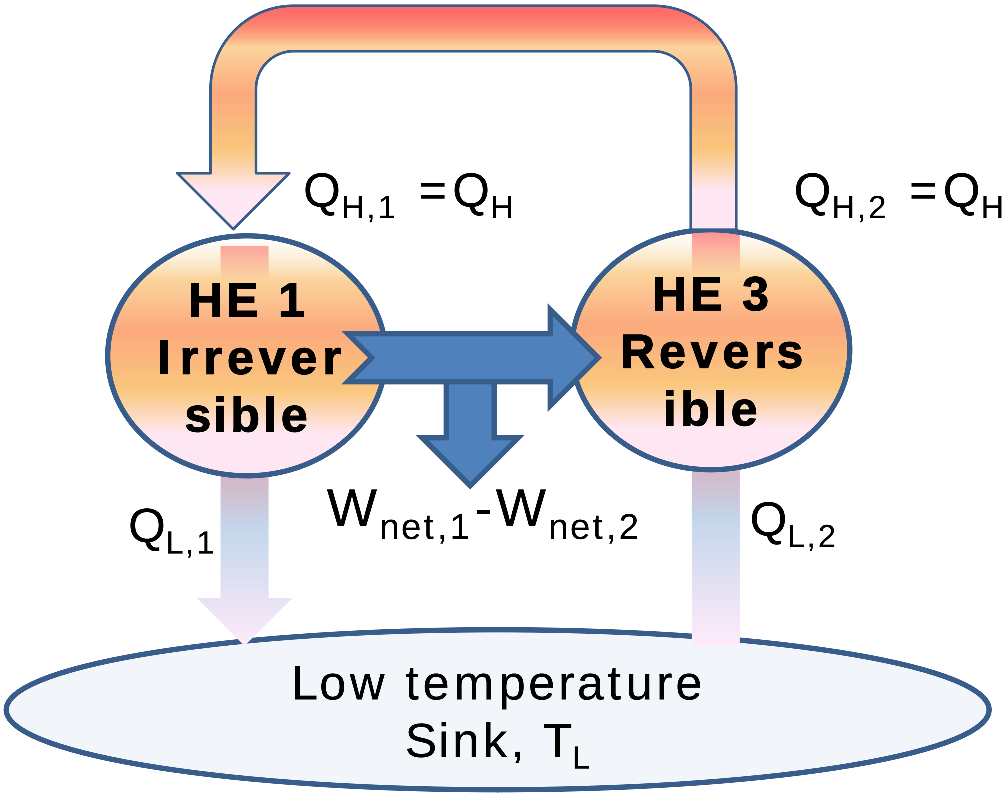
Proof of the Carnot principles



The combined heat engine cycle generates a net work output while interacting with a single reservoir, violating the Kelvin-Planck statement.

The thermodynamic temperature scale

- A temperature scale that is independent of the properties of the substances that are used to measure temperature.
- 2^{nd} Carnot principle: all reversible heat engines have the same thermal efficiency when operating between the same two reservoirs.
- The efficiency of a reversible engine is independent of the working fluid employed and its properties, or the type of reversible engine used.

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The thermodynamic temperature scale

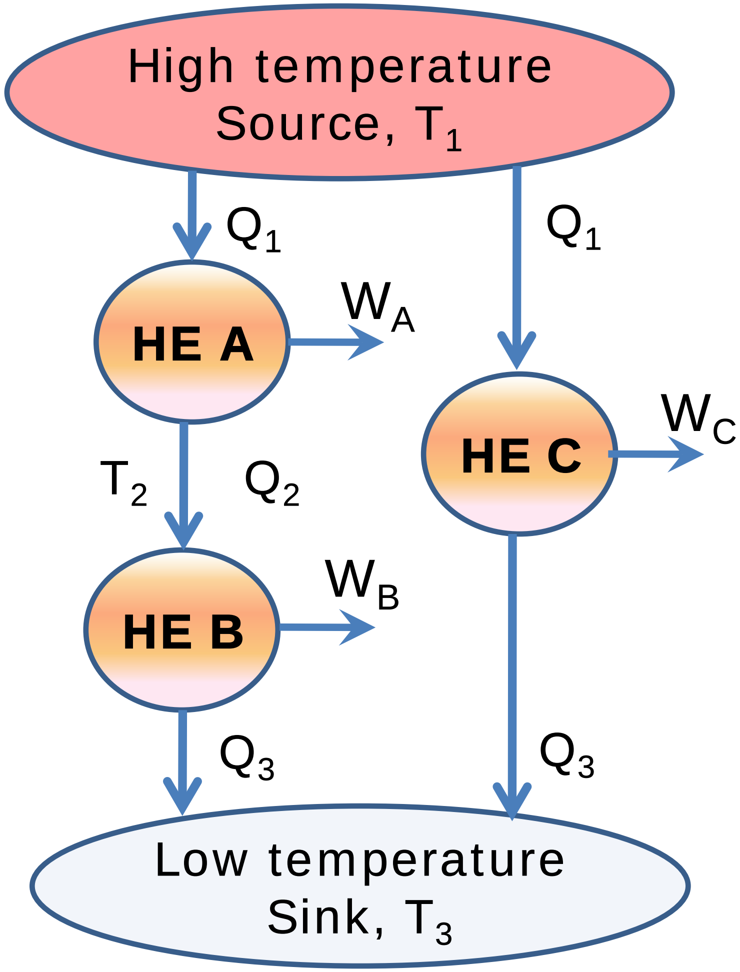
- A temperature scale that is independent of the properties of the substances that are used to measure temperature.

$$\eta_{th,rev} = f(T_H, T_L)$$

$$\text{Since } \eta_{th} = 1 - Q_L / Q_H, \quad \frac{Q_H}{Q_L} = f(T_H, T_L)$$

- We shall consider three reversible engines to derive an expression for $f(T_H, T_L)$.

The thermodynamic temperature scale



The thermodynamic temperature scale

Consider three reversible heat engines : A, B and C

$$\frac{Q_1}{Q_2} = f(T_1, T_2), \quad \frac{Q_2}{Q_3} = f(T_2, T_3), \quad \frac{Q_1}{Q_3} = f(T_1, T_3)$$

Since, $\dfrac{Q_1}{Q_3} = \dfrac{Q_1}{Q_2} \cdot \dfrac{Q_2}{Q_3}$,

Therefore, $f(T_1, T_3) = f(T_1, T_2) \cdot f(T_2, T_3)$

Since the LHS of the above equation depends only on T_1 and T_3, the RHS must be independent of T_2

The thermodynamic temperature scale

- For this to be true,

$$f(T_1,T_2)=\frac{\phi(T_1)}{\phi(T_2)},\quad f(T_2,T_3)=\frac{\phi(T_2)}{\phi(T_3)}$$

$$\text{Hence, }\frac{Q_1}{Q_3}=f(T_1,T_3)=\frac{\phi(T_1)}{\phi(T_3)}$$

- In general, for a reversible engine,

$$\frac{Q_H}{Q_L}=\frac{\phi(T_H)}{\phi(T_L)}$$

The thermodynamic temperature scale

- Lord Kelvin proposed $\phi(T)=T$ to define a thermodynamic scale as

$$\left(\frac{Q_H}{Q_L}\right)_{rev}=\frac{T_H}{T_L}$$

- This is called the Kelvin scale and the temperatures on this scale are called absolute temperatures.
- For reversible cycles, the heat transfer ratio can be replaced by the absolute temperature ratio.

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The thermodynamic temperature scale

- On the Kelvin scale, the triple point of water was assigned a value of 273.16 K.
- Therefore the magnitude of Kevin is defined 1/273.16 K of the interval between absolute zero and the triple point of water.
- Since reversible engines are not practical, other methods like constant volume ideal gas thermometers are used for defining temperature scales.

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The Carnot heat engine

- A hypothetical engine that operates on the Carnot cycle.
- We know that $\eta_{th} = 1 - \frac{Q_L}{Q_H}$
- Since the Carnot heat engine is reversible,

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

- This is known as the Carnot efficiency and is the highest efficiency that a heat engine can have while operating between T_H and T_L (the temperatures are in Kelvin).

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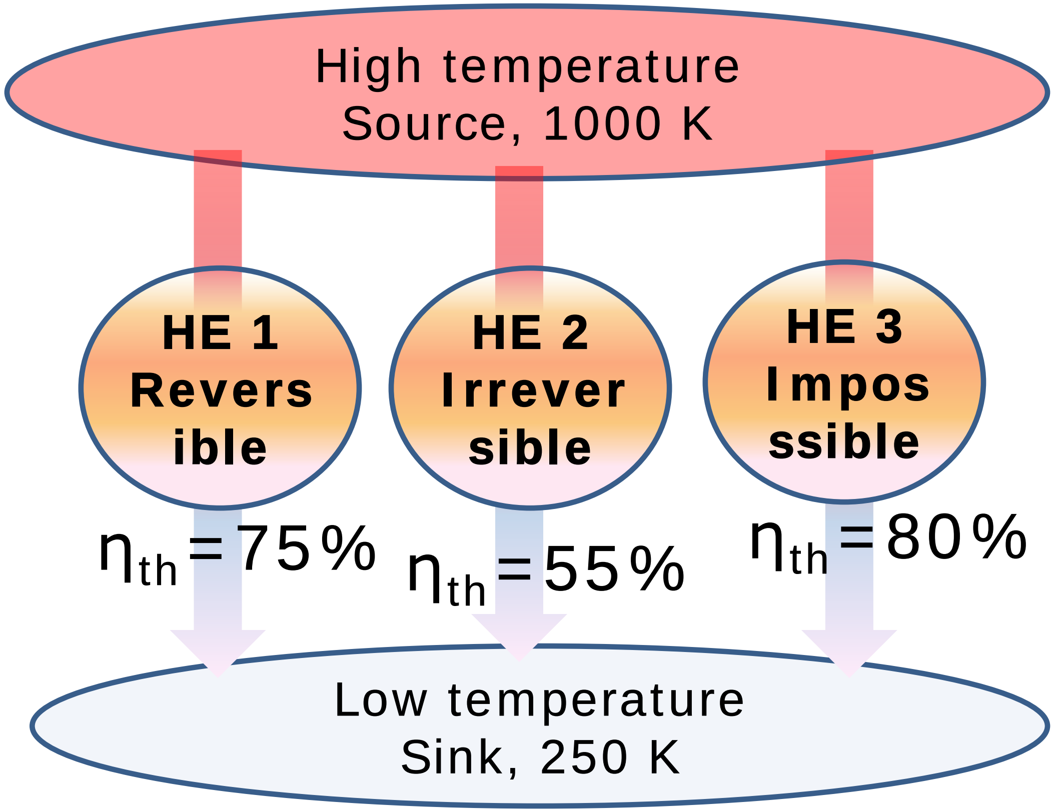
The Carnot heat engine



$\eta_{th} < \eta_{th,rev}$
Irreversible heat engine

$\eta_{th} = \eta_{th,rev}$
Reversible heat engine

$\eta_{th} > \eta_{th,rev}$
Impossible heat engine

The Carnot heat engine

- The efficiency of a Carnot heat engine increases as T_H is increased, or as T_L is decreased.
- The thermal efficiency of actual heat engines can be maximized by supplying heat to the engine at the highest possible temperature and rejecting heat from the engine at the lowest possible temperature.

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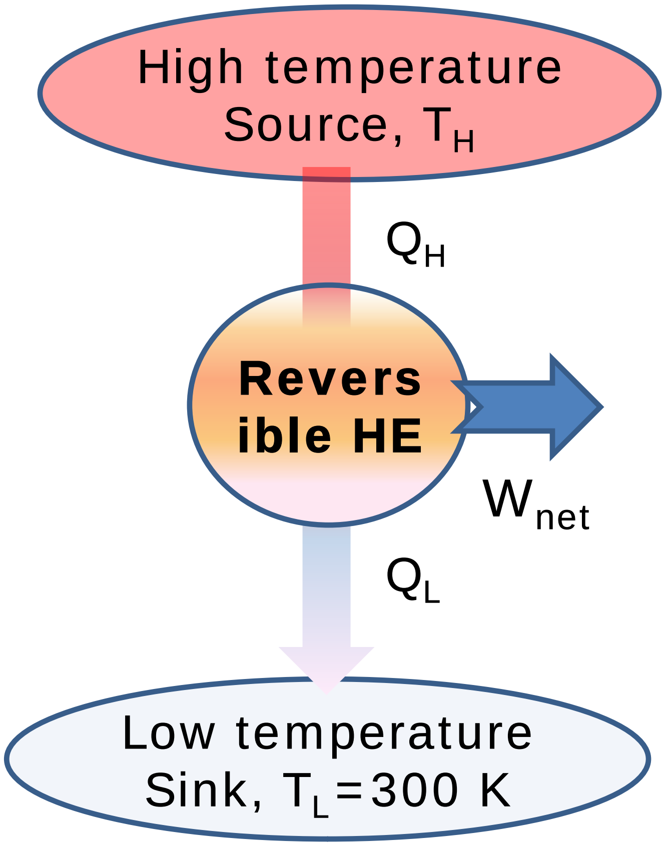
Quality of energy



T_H, K	η_{th}, %
1000	70
700	57.1
500	40
400	25
350	14.3

Quality of energy

- Energy has quality as well as quantity.
- More of the high-temperature thermal energy can be converted to work.
- The higher the temperature, the higher the quality of the energy.
- Work is a high quality form of energy than heat since 100 percent of work can be converted to heat, but only a fraction of heat can be converted to work.

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Carnot refrigerator and heat pump

- Operates on a reversed Carnot cycle.
- The coefficients of performance are:

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

$$or, \quad COP_R = \frac{1}{T_H / T_L - 1} \qquad COP_{HP} = \frac{1}{1 - T_L / T_H}$$

- These are the highest coefficients of performance that a refrigerator or a heat pump operating between the temperature limits of T_L and T_H can have.

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Carnot refrigerator and heat pump

$$COP_{R/HP}\begin{cases} < COP_{R/HP,\ reversible} & \text{Irreversible} \\ = COP_{R/HP,\ reversible} & \text{Reversible} \\ > COP_{R/HP,\ reversible} & \text{Impossible} \end{cases}$$

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In the next lecture ...

- Exergy: A Measure of Work Potential
- Reversible Work and Irreversibility
- Second-Law Efficiency
- Exergy Change of a System
- The Decrease of Exergy Principle and Exergy Destruction
- Exergy Balance

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