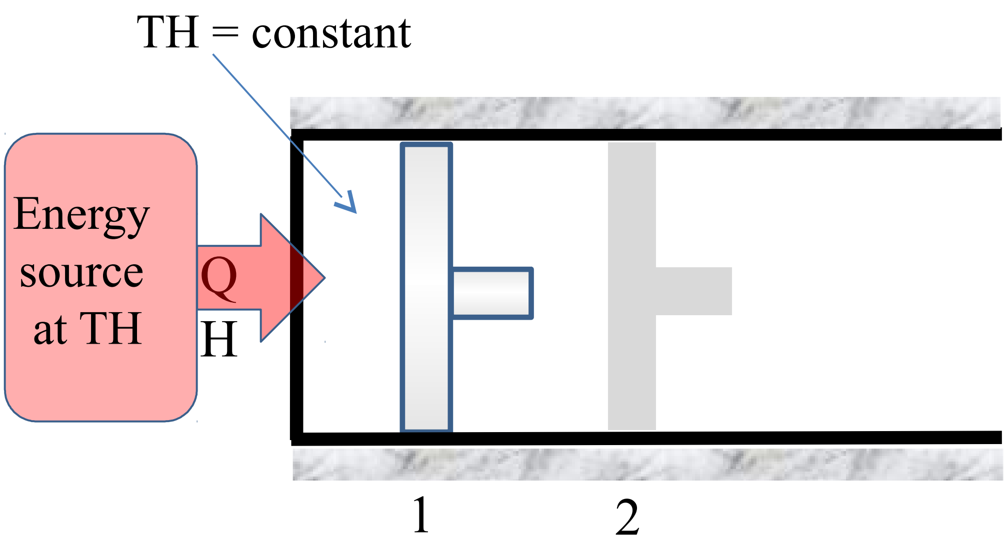
- Recap: Lecture 11: 4th Feb. 2014, 0830-0930 hrs.
  - Equivalence of Kelvin-Planck statement and the Clausius statement
  - Perpetual Motion Machines of the 2nd Kind
  - Reversible and irreversible processes
  - Causes of irreversibility
  - Internal, external and totally reversible processes
  - Carnot cycle
  - Reversed Carnot cycle

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.

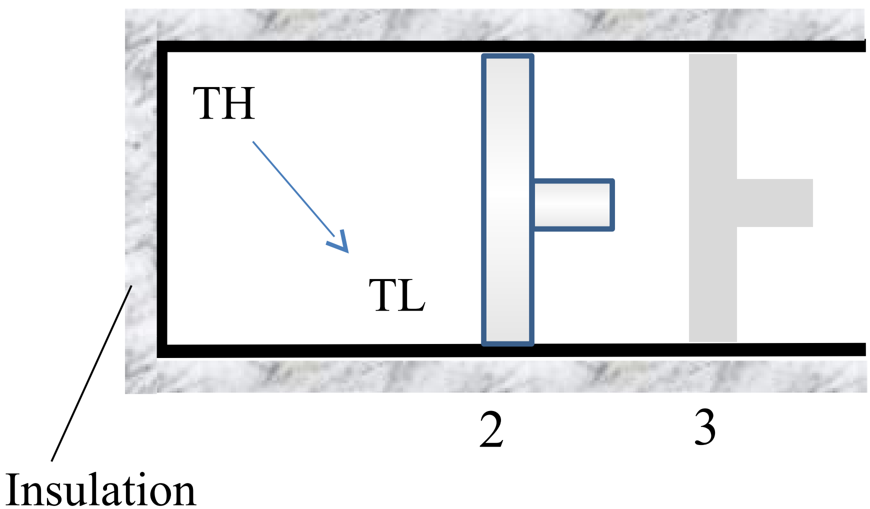
The Carnot cycle



Process 1-2

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

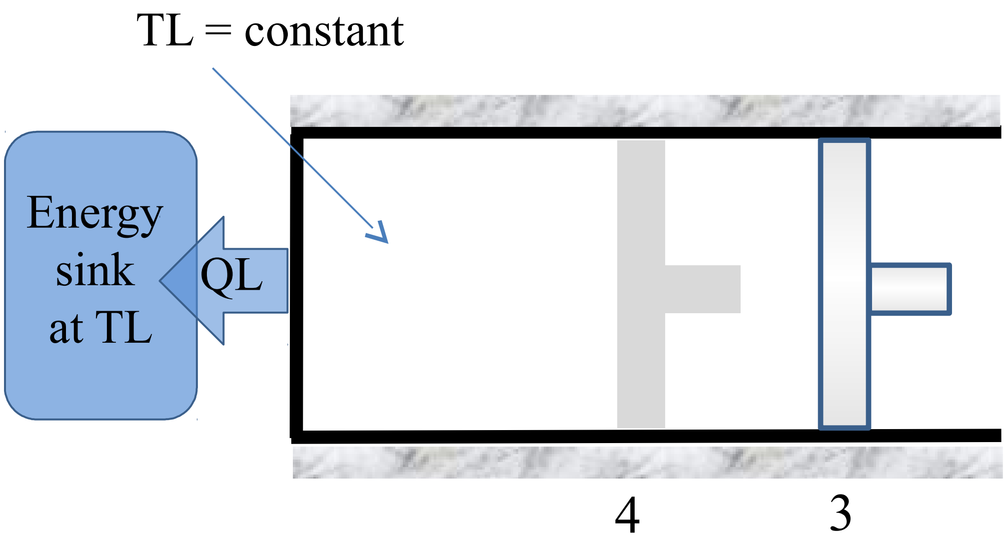
The Carnot cycle



Process 2-3

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

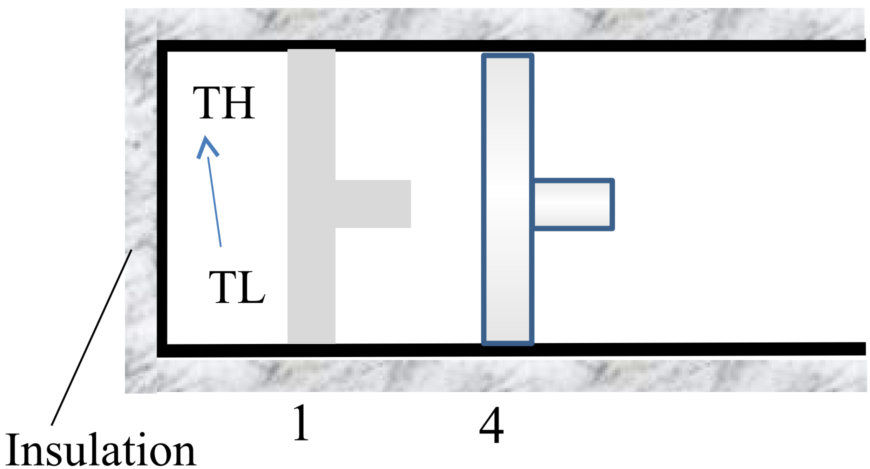
The Carnot cycle



Process 3-4

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

The Carnot cycle



Process 4-1

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

The Carnot cycle

- 1-2: A reversible isothermal process

$$Q1=U2-U1+W1-2$$

- 2-3: A reversible adiabatic process

$$0=U3-U2+W2-3$$

- 3-4: Reversible isothermal process

$$Q2=U4-U3-W3-4$$

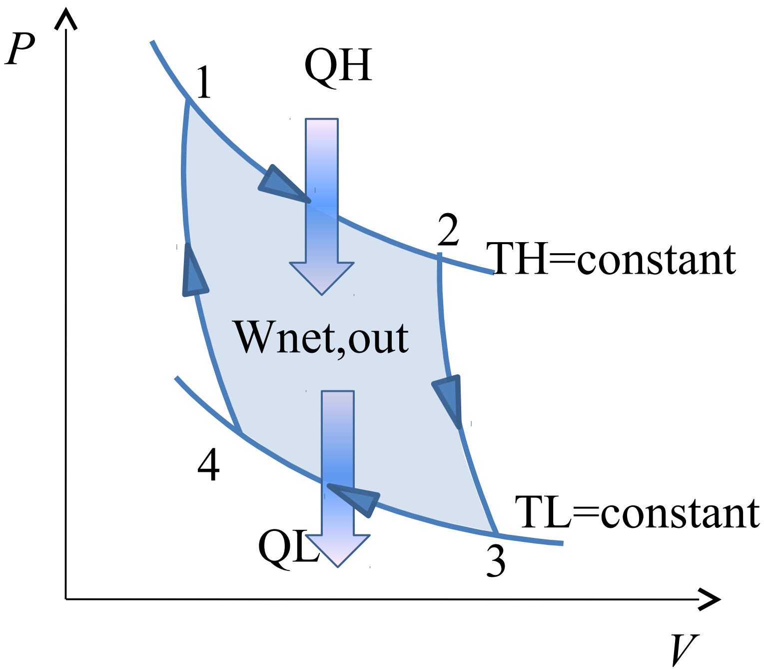
- 4-1: Reversible adiabatic process

$$0=U1-U4-W4-1$$

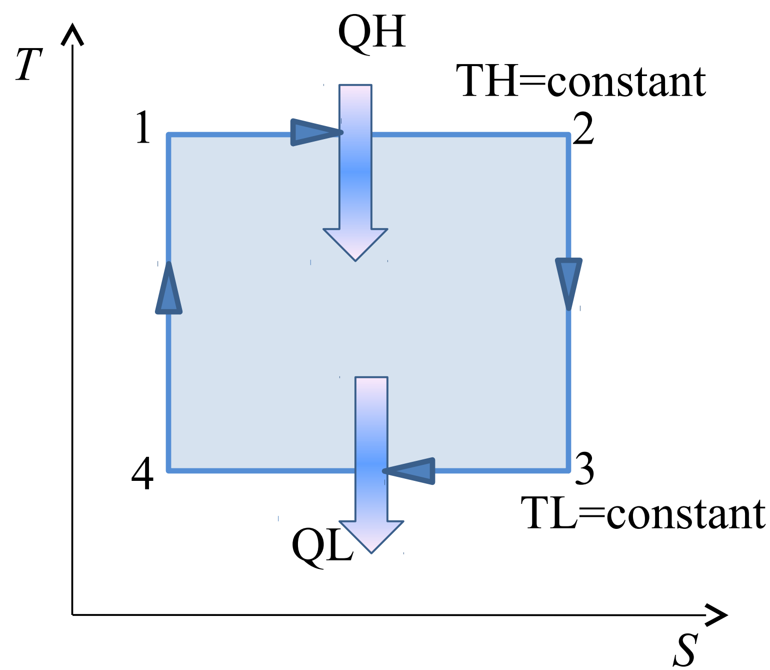
$$Q1-Q2=W1-2+W2-3-(W3-4+W4-1)$$

$\Sigma Qnet= \Sigma Wnet$ for the cycle

The Carnot cycle



P-V diagram of Carnot cycle

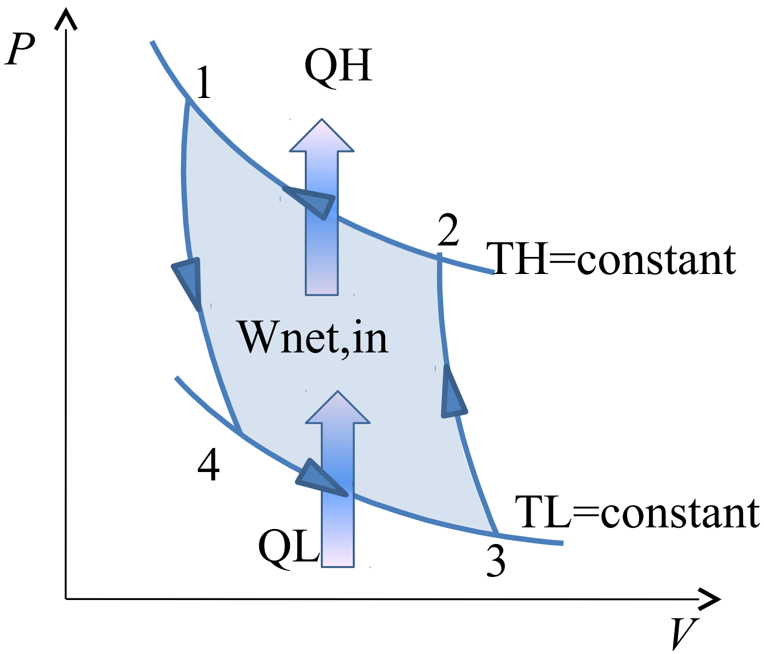


T-S diagram of Carnot cycle

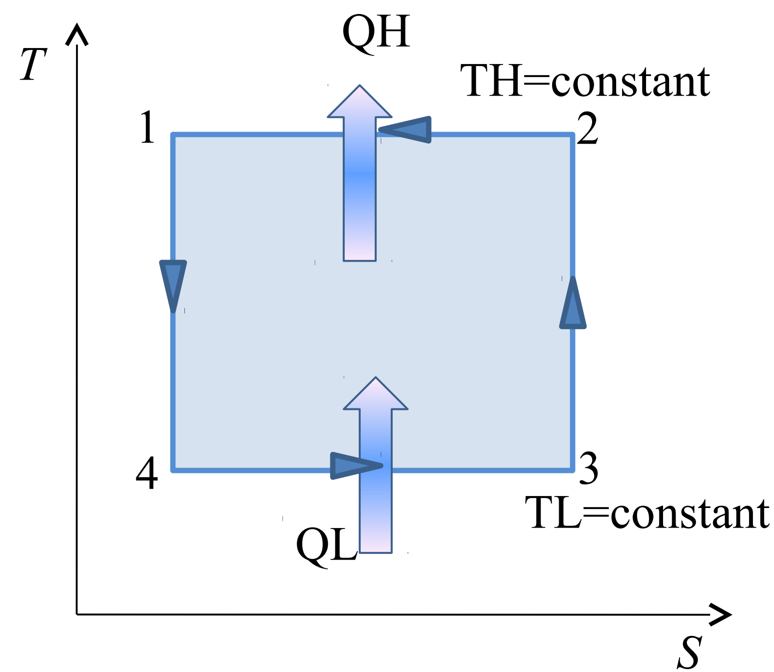
The Reversed Carnot cycle

- 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.
- *QL* : heat absorbed from the low temperature reservoir
- *QH* : heat rejected to the high temperature reservoir
- *Wnet,in*: Net work input required

The Reversed Carnot cycle



P-V diagram of Reversed Carnot cycle

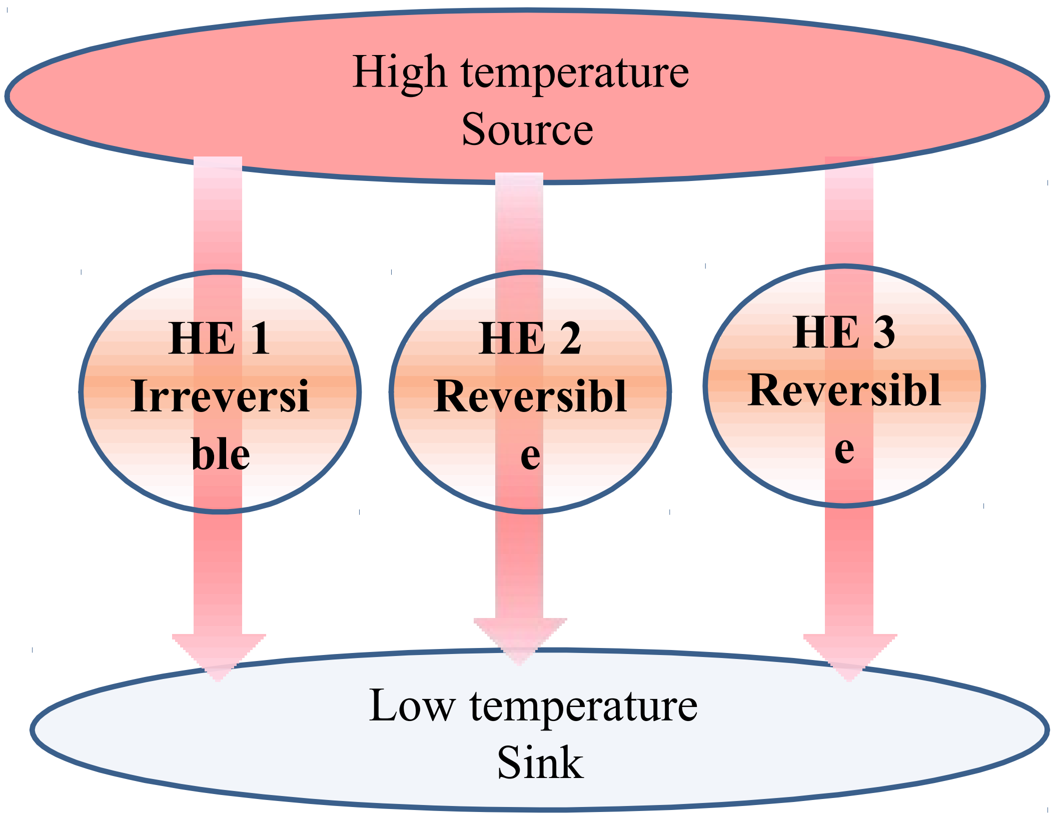


T-S diagram of Reversed Carnot cycle

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.

The Carnot principles

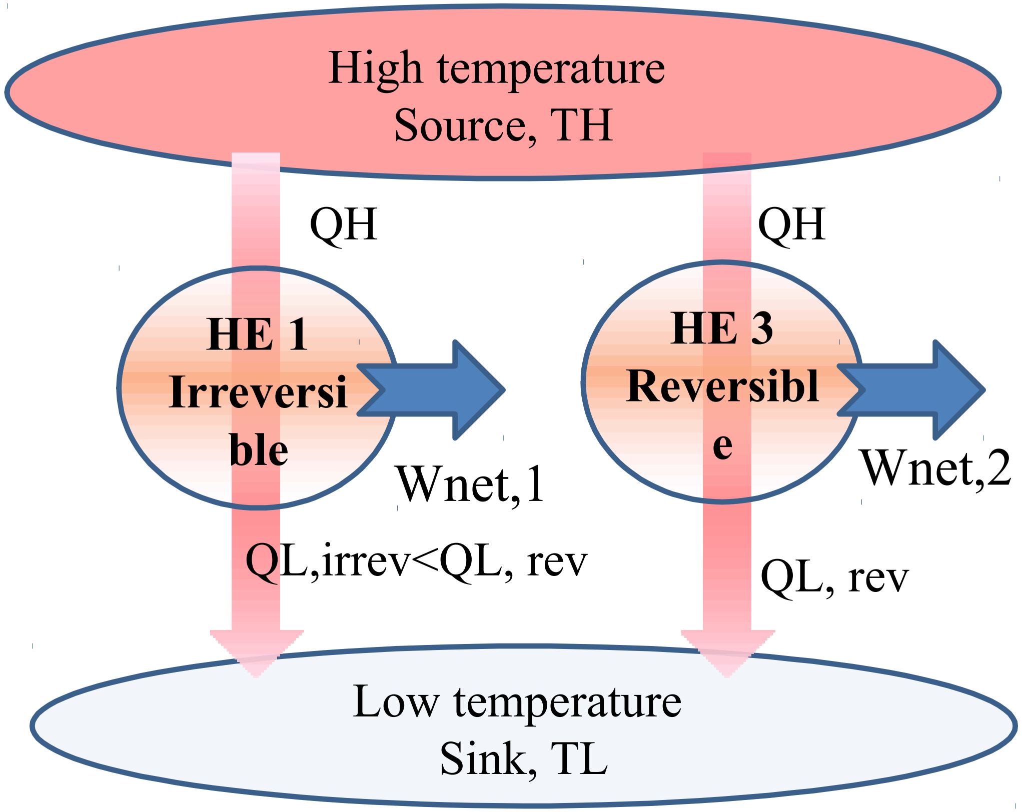


$$\eta_{th,1} < \eta_{th,2}$$

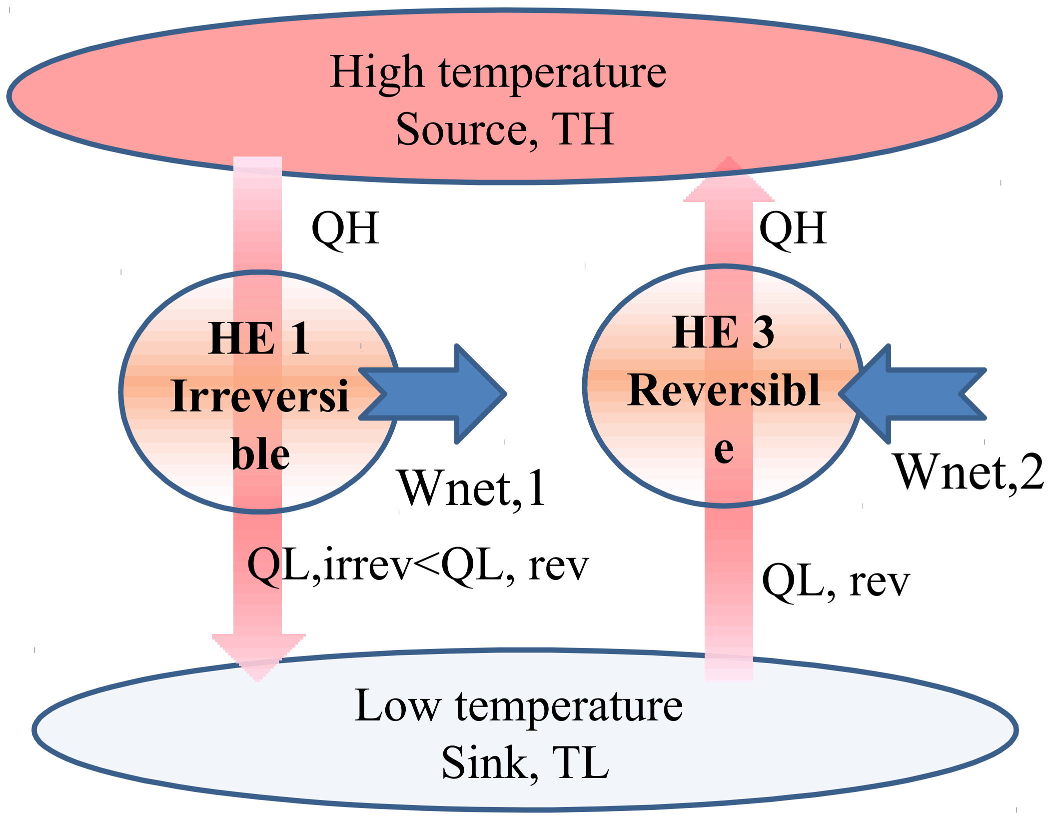
$$\eta_{th,1} < \eta_{th,3}$$

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

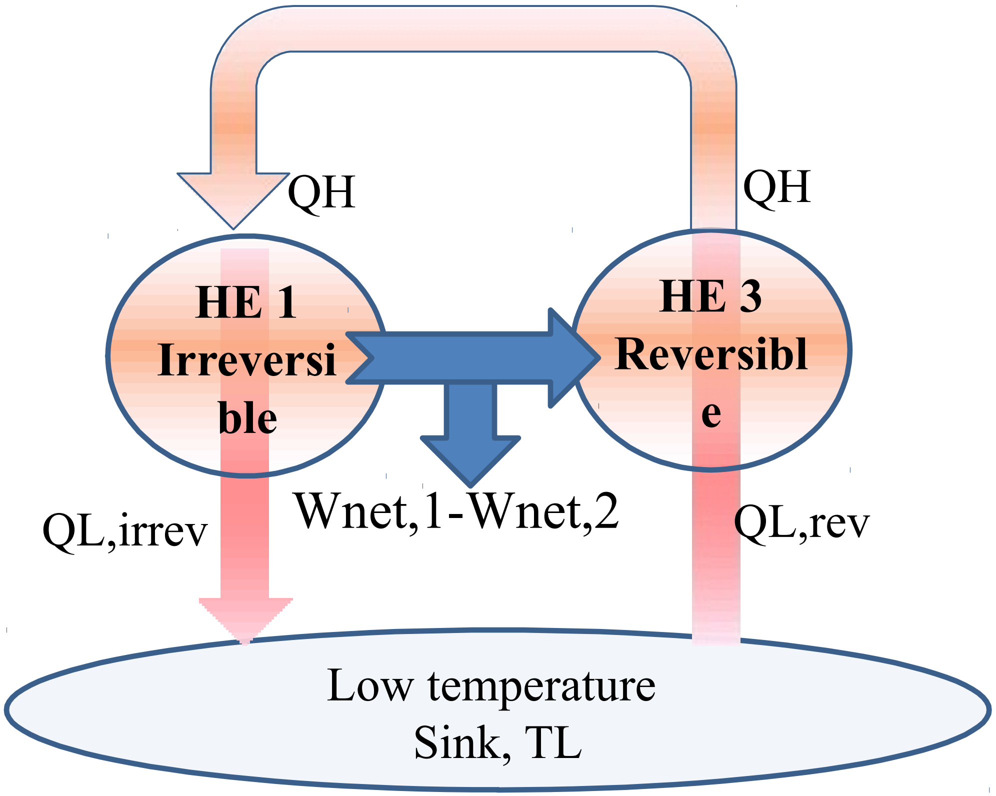
Proof of the Carnot principles



Proof of the Carnot principles



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.
- 2nd 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.

The thermodynamic temperature scale

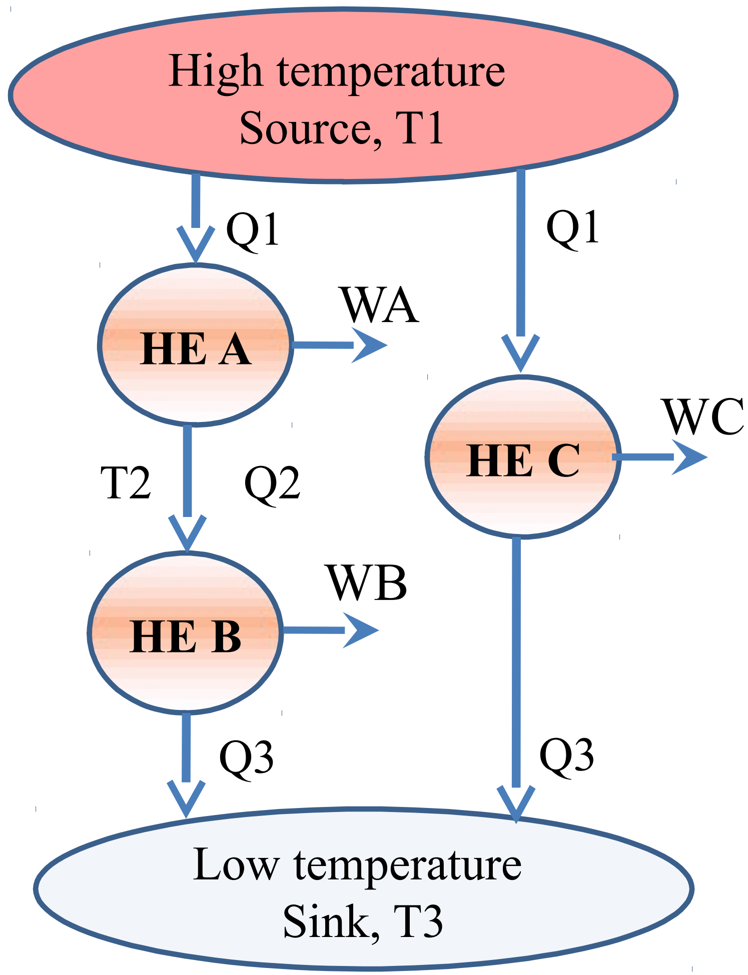
- A temperature scale that is independent of the properties of the substances that are used to measure temperature.

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

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

- We shall consider three reversible engines to derive an expression for *f(TH,TL)*.

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 *T1* and *T3*, the RHS must be independent of *T2*

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.

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 Kelvin 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.

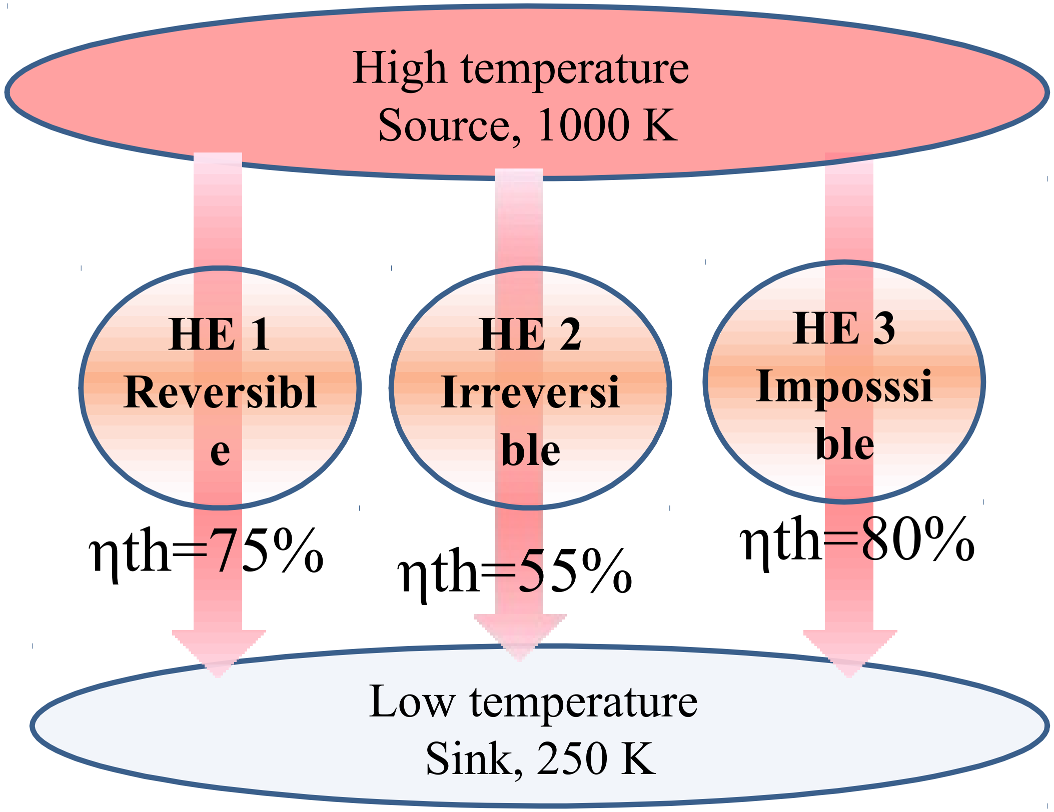
The Carnot heat engine

- 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 *TH* and *TL* (the temperatures are in Kelvin).

The Carnot heat engine



ηth<ηth,rev
Irreversible heat engine

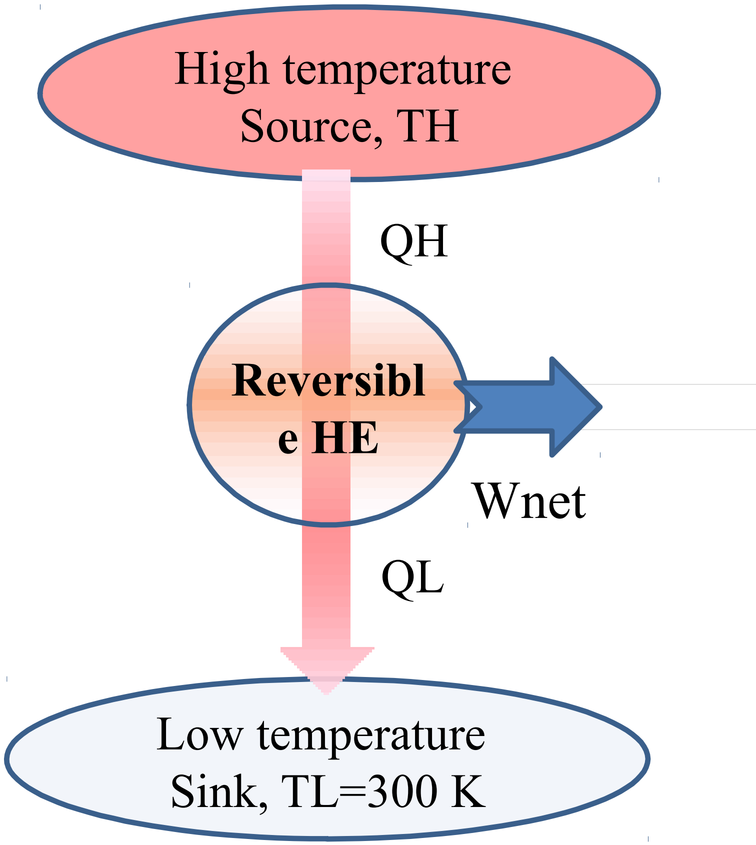
ηth=ηth,rev Reversible heat engine

ηth>ηth,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.

Quality of energy



TH, K	ηth, %
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.