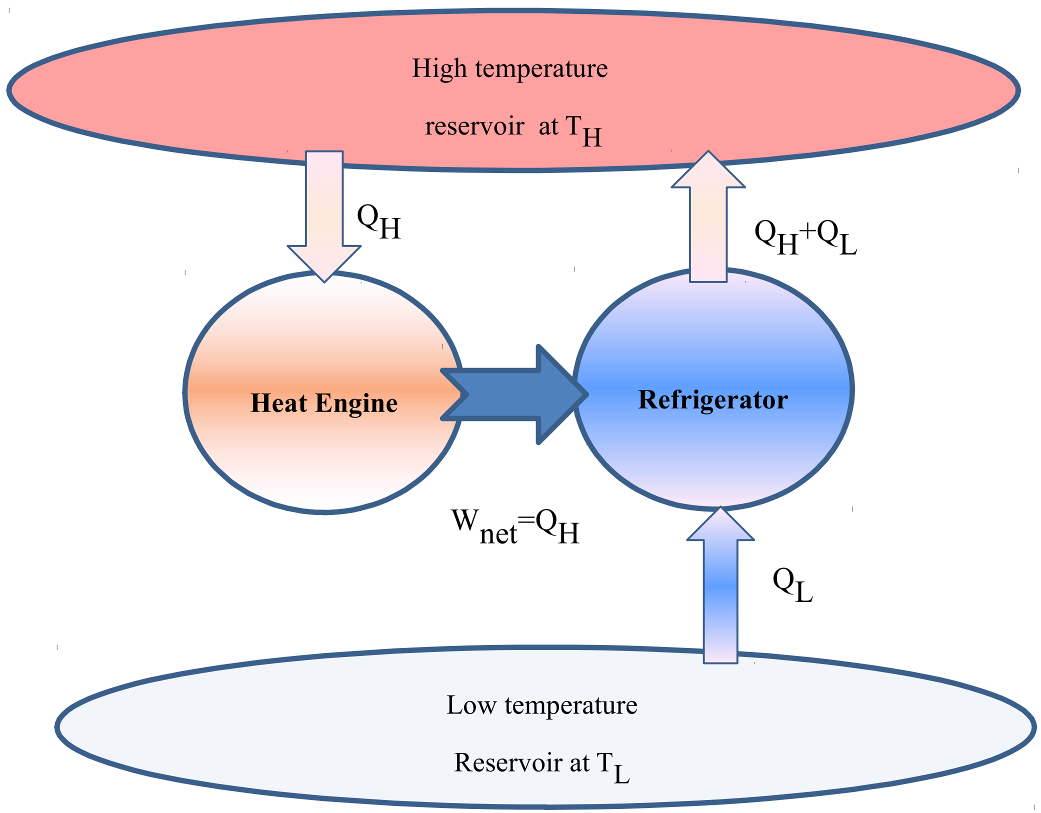
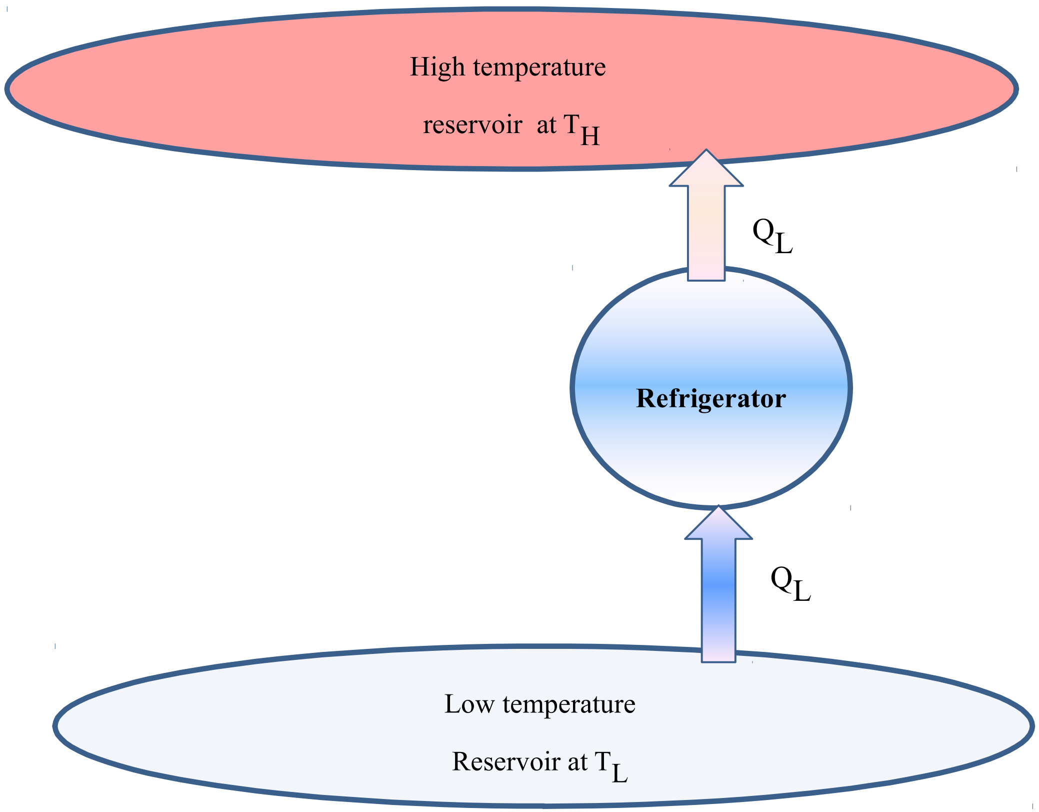
- Recap: Lecture 10: 3rd Feb 2013, 1130-1230 hrs.
  - Kelvin-Planck statement of 2nd law of thermodynamics
  - Refrigerators and heat pumps
  - Coefficient of performance
  - Clausius statement of 2nd law of thermodynamics

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

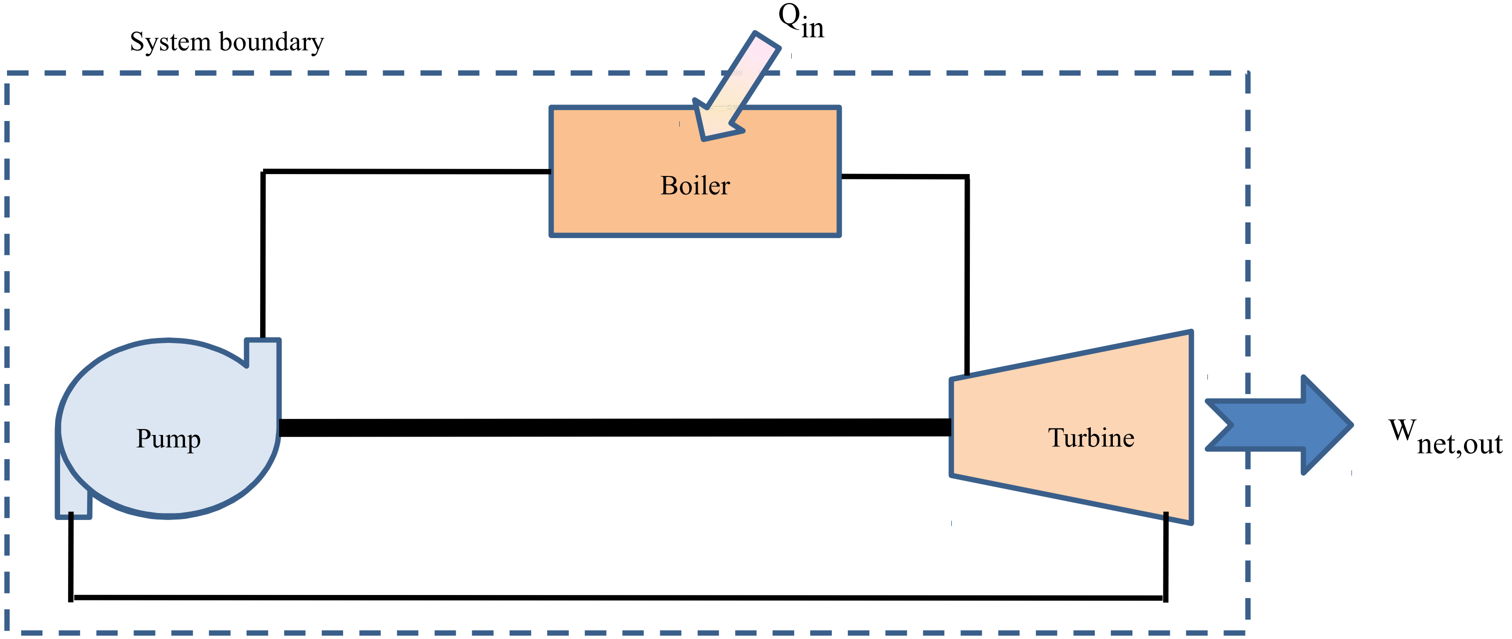


The equivalent refrigerator

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)



Reversible and irreversible processes

- 2nd law: no heat engine can have 100% efficiency
- What is the highest efficiency that an engine could have?
- Reversible process: a process that can be reversed without leaving any trace on the surroundings.
- The system and the surroundings are returned to their initial states at the end of the reverse process.

Reversible and irreversible processes

- Reversible process: Net heat and work exchange between the system and surroundings (for original + reverse process) is zero.
- Why reversible processes are of interest?
- Consume least work in the case of work-consuming devices and generate maximum work in the case of work-producing devices.

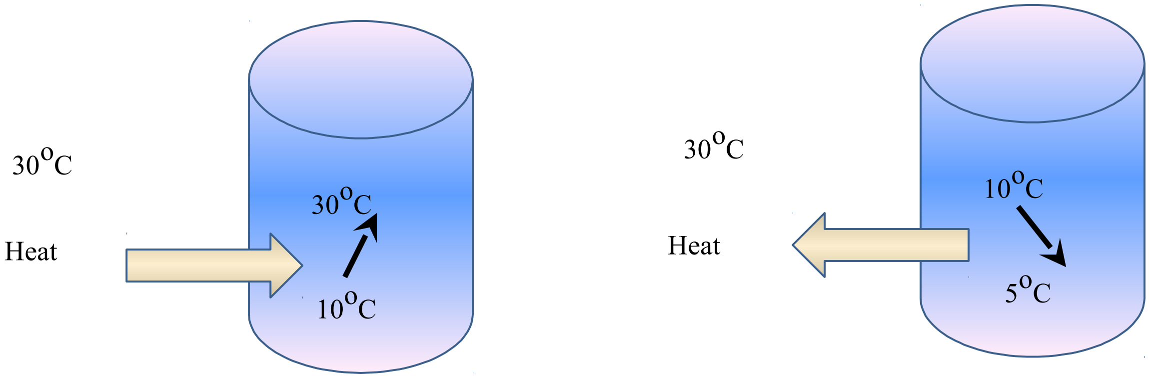
Reversible and irreversible processes

- Reversible processes serve as theoretical limits for the corresponding irreversible ones.
- Reversible processes leads to the definition of the second law efficiency for actual processes, which is the degree of approximation to the corresponding reversible processes.

Irreversibilities

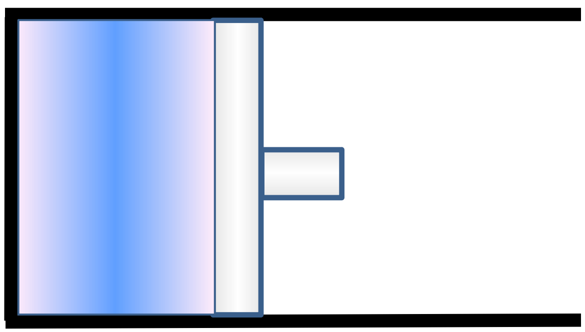
- Commonly encountered causes of irreversibilities
  - friction, unrestrained expansion, mixing of two fluids, heat transfer across a finite temperature difference, electric resistance, inelastic deformation of solids, and chemical reactions.

Irreversibilities

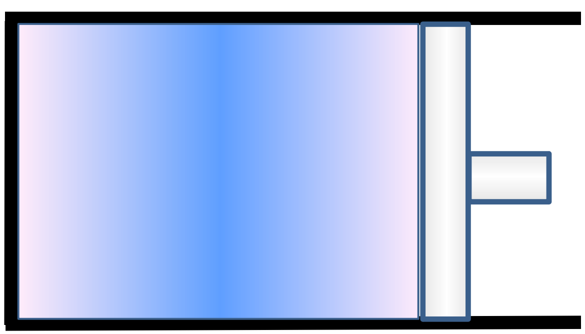


Heat transfer through a finite temperature difference is irreversible.

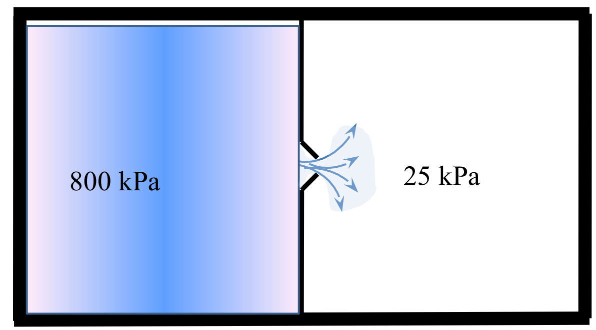
Irreversibilities



Fast compression



Fast expansion



Unrestrained expansion

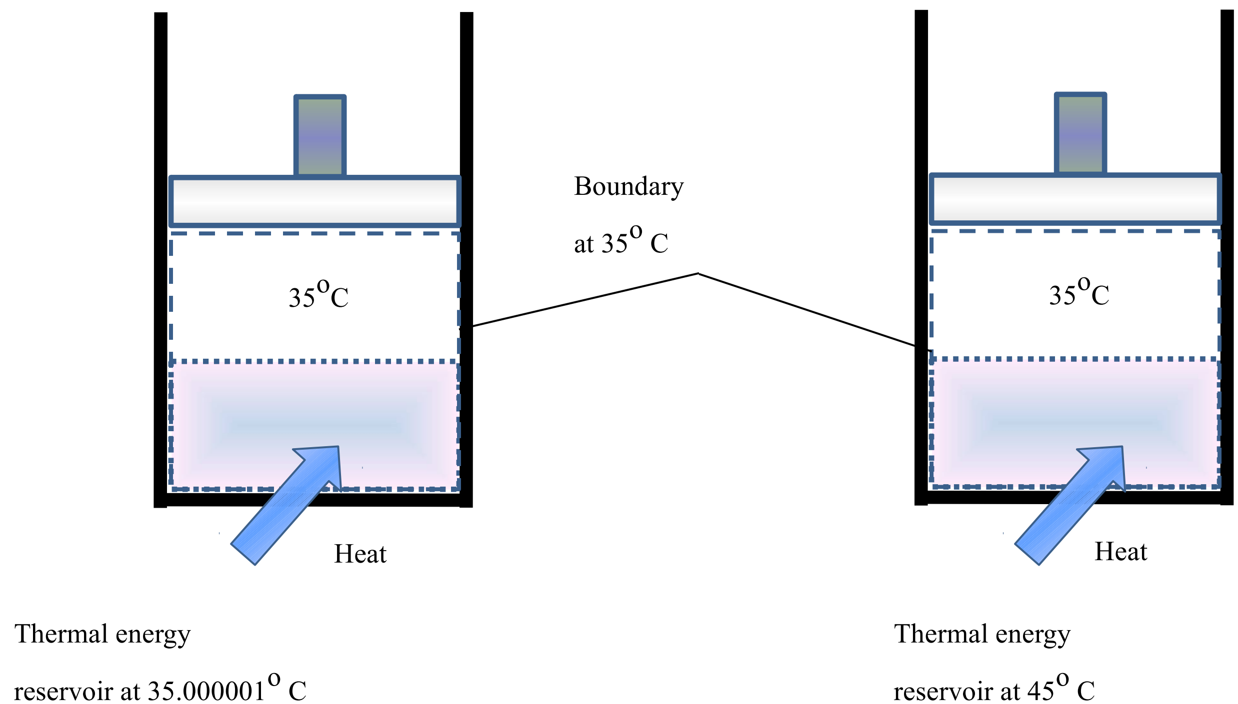
Internally and Externally Reversible Processes

- Internally reversible process
  - if no irreversibilities occur within the boundaries of the system during the process.
  - the paths of the forward and reverse processes coincide for an internally reversible process

Internally and Externally Reversible Processes

- Externally reversible process
  - no irreversibilities occur outside the system boundaries during the process.
  - Heat transfer between a reservoir and a system is an externally reversible process if the outer surface of the system is at the temperature of the reservoir.
- Totally reversible or reversible
  - no irreversibilities within the system or its surroundings.

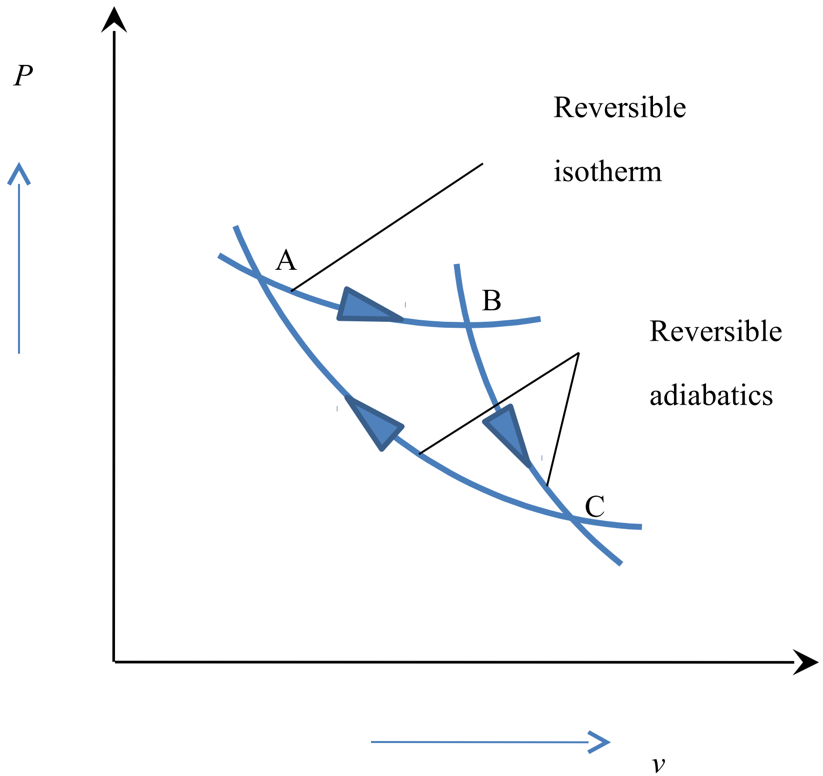
Internally and Externally Reversible Processes



(a) Totally reversible

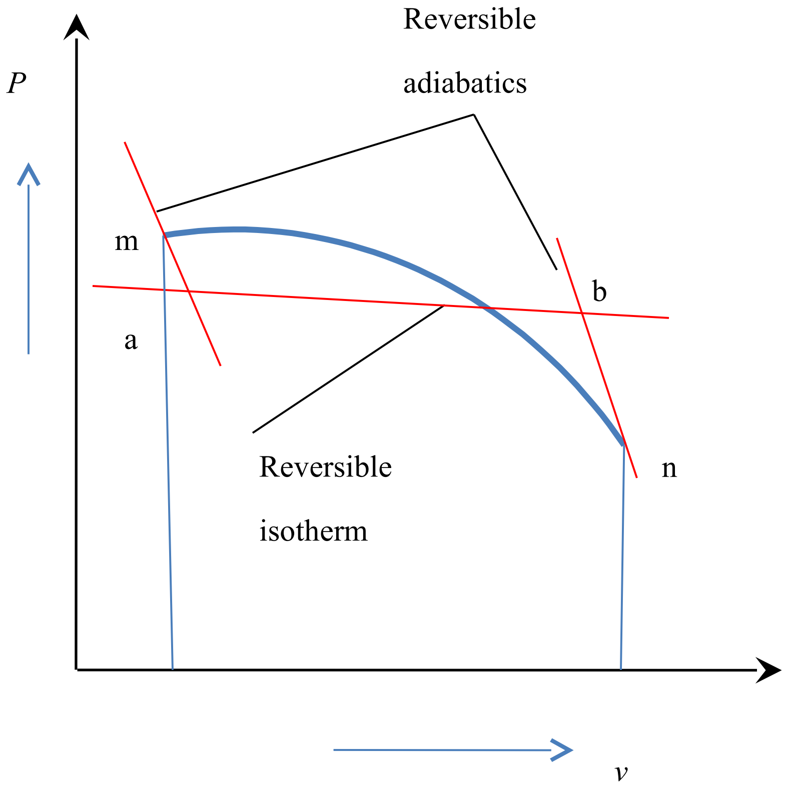
(b) Internally reversible

Reversible adiabatics



- Two reversible adiabatic paths cannot intersect
- Through one point, only one reversible adiabatic can pass
- Violation of Kelvin-Planck statement

Reversible adiabatics



<u>Process m-n</u>

$$Q_{m\text{-}n} = U_n - U_m + W_{mn}$$

<u>Process m-a-b-n</u>

$$Q_{m\text{-}a\text{-}b\text{-}n} = U_n - U_m + W_{m\text{-}a\text{-}b\text{-}n}$$

Since, $W_{m\text{-}a\text{-}b\text{-}n} = W_{mn}$

$$Q_{m\text{-}n} = Q_{m\text{-}a\text{-}b\text{-}n}$$

$$= Q_{m\text{-}a} + Q_{a\text{-}b} + Q_{b\text{-}n}$$

Since $Q_{m\text{-}a} = 0,\ Q_{b\text{-}n} = 0$

$$Q_{m\text{-}n} = Q_{a\text{-}b}$$

Reversible path can be substituted by two reversible adiabatics and a reversible isotherm

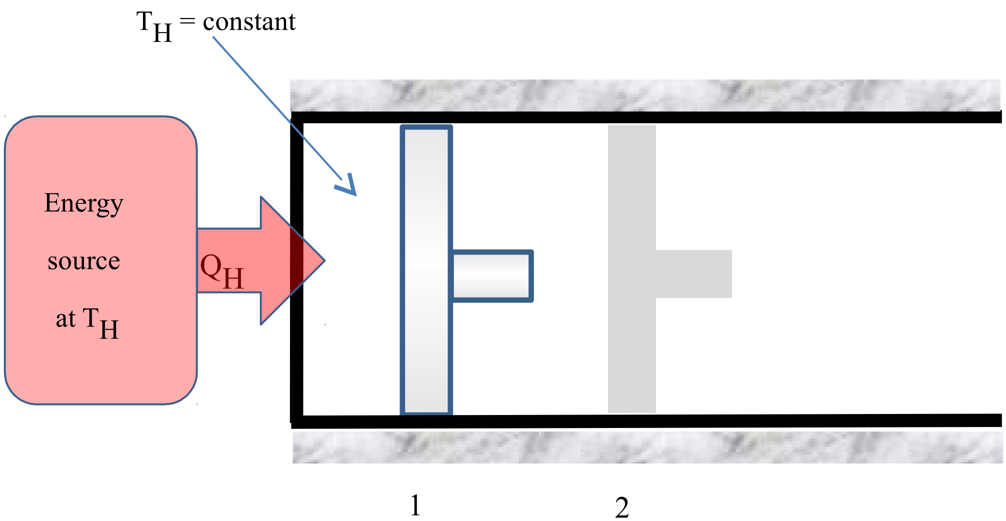
The Carnot cycle

- 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.

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.

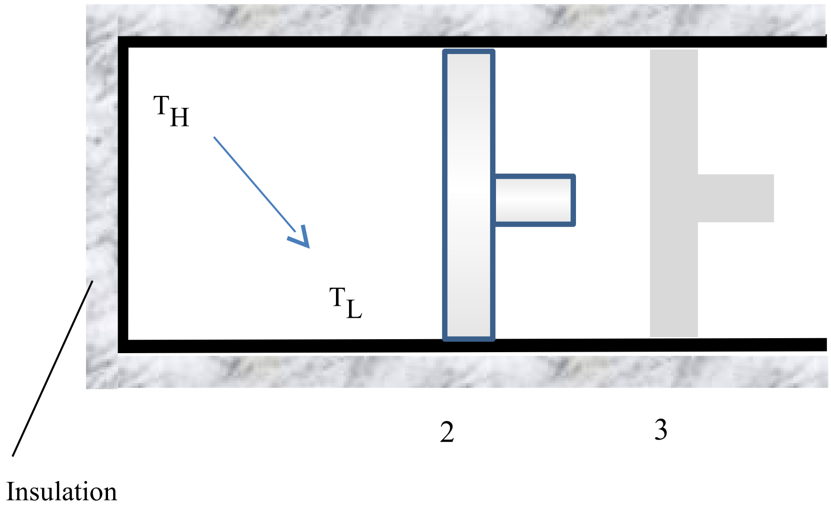
The Carnot cycle



Process 1-2

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

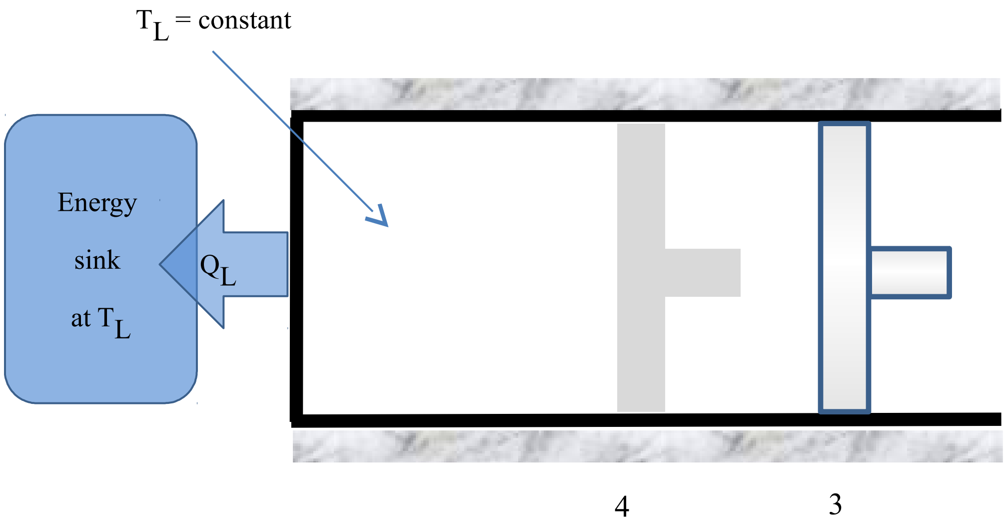
The Carnot cycle



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.

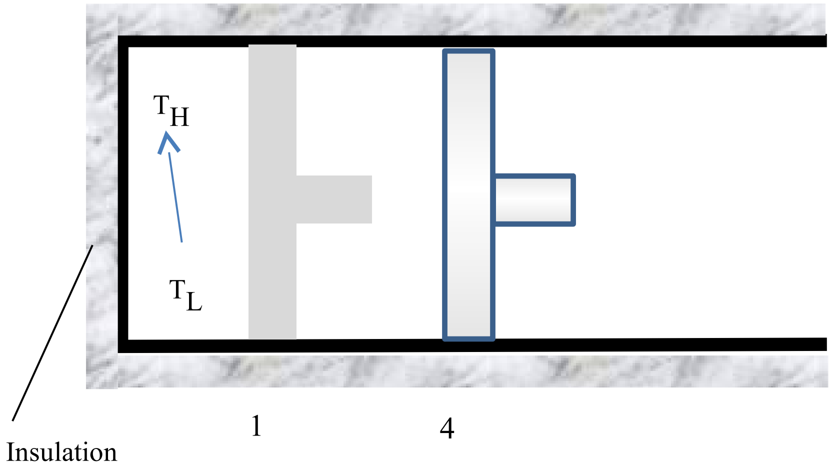
The Carnot cycle



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

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

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

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

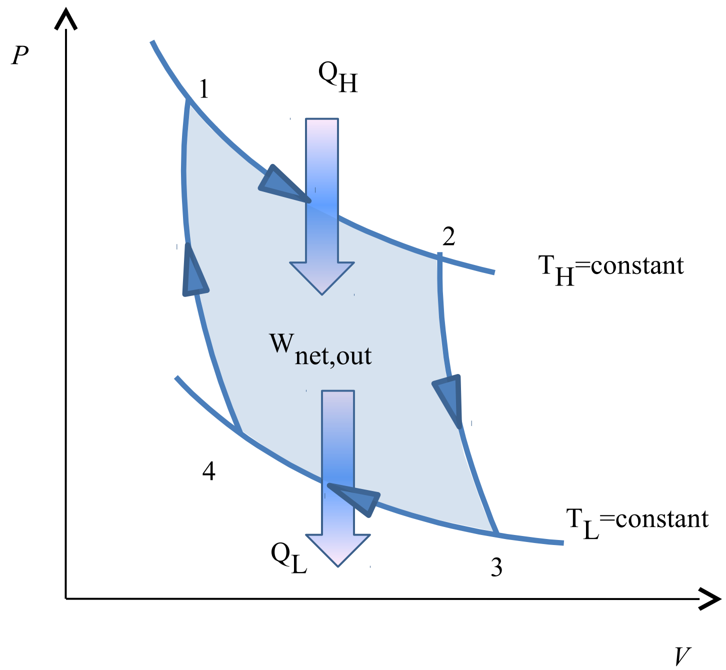
- 4-1: Reversible adiabatic process

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

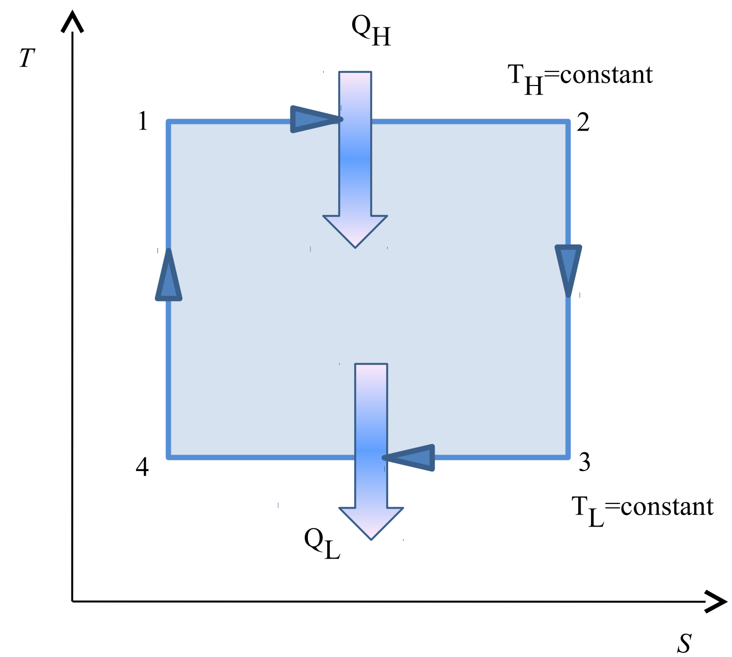
$$Q_1-Q_2=W_{1-2}+W_{2-3}-(W_{3-4}+W_{4-1})$$

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

The Carnot cycle



P-V diagram of Carnot cycle

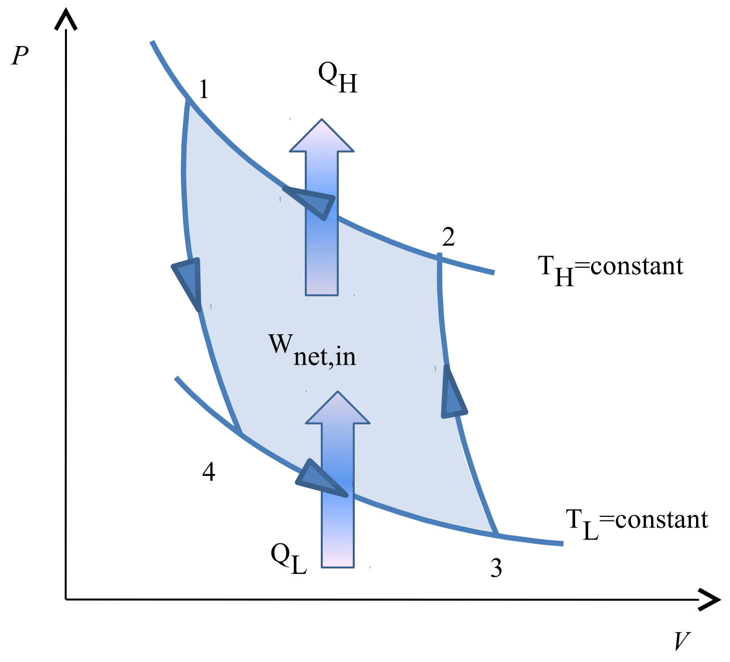


T-S diagram of Carnot cycle

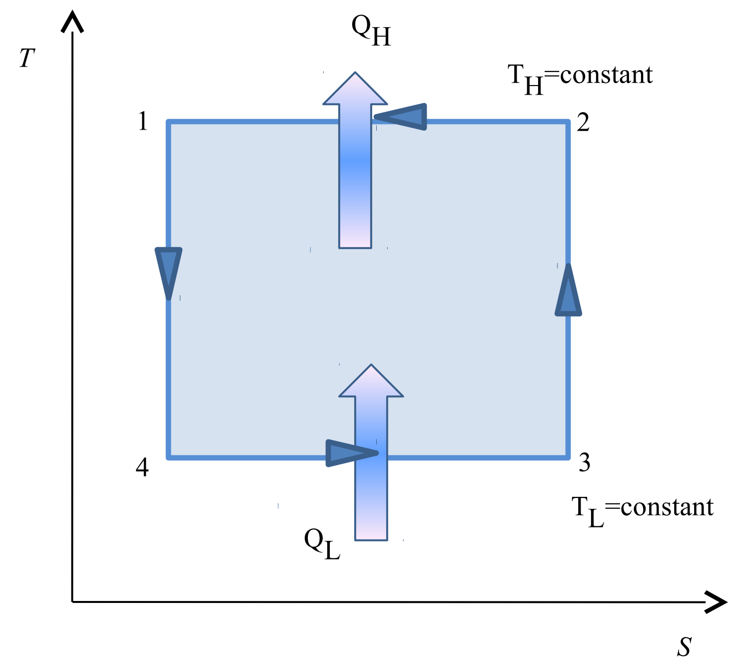
The Reversed Carnot cycle

- 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

The Reversed Carnot cycle



P-V diagram of Reversed Carnot cycle



T-S diagram of Reversed Carnot cycle