Thermodynamics - 1

Lecture 21

Irreversible and Reversible Processes (Ch-6)

Carnot Cycle (Ch-6)

Introduction to Entropy

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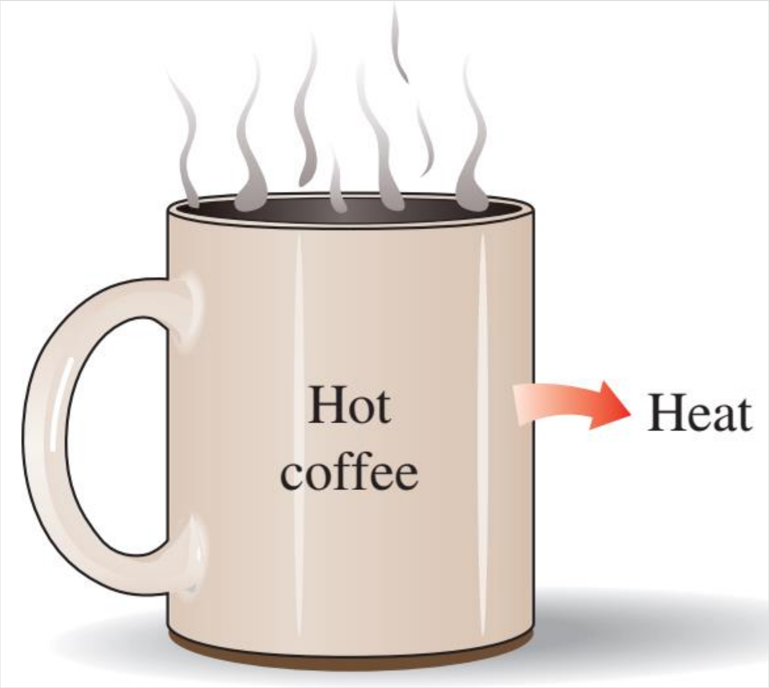
REVERSIBLE AND IRREVERSIBLE PROCESSES

Processes occur in a certain direction. Once having taken place, these process cannot reverse themselves spontaneously and restore the initial state.

A cup of hot coffee does not get hotter in a cooler room.

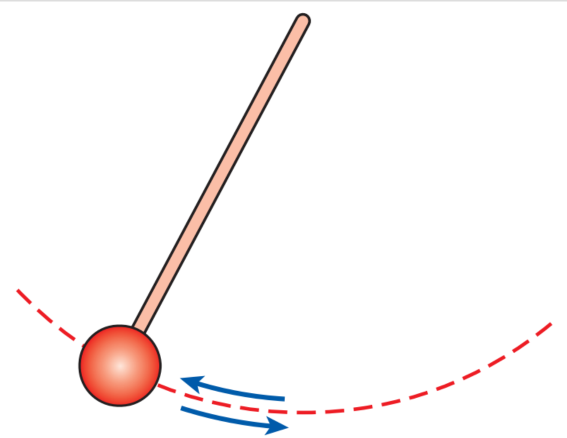


Once a cup of coffee cools, it will not heat by retrieving heat it lost from the surroundings.

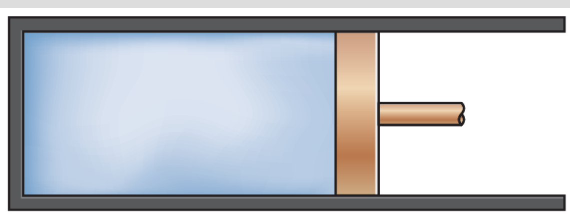
If it could, the surroundings, as well as the system (coffee) would be restored to their original condition and this would be a reversible process.

REVERSIBLE AND IRREVERSIBLE PROCESSES

Reversible process: *A process that can be reversed without leaving any trace on the surroundings.*
Irreversible process: A process that is not reversible.



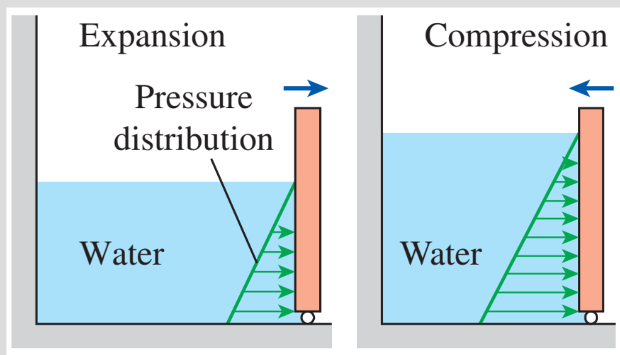
(*a*) Frictionless pendulum



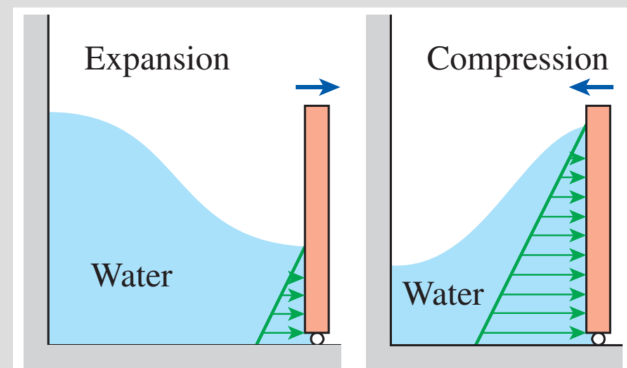
(*b*) Quasi-equilibrium expansion and compression of a gas

Two familiar reversible processes.

- All the processes occurring in nature are irreversible.
- ***Why are we interested* in reversible processes?**
- **(1)** they are easy to analyze and **(2)** they serve as idealized models (theoretical limits) to which actual processes can be compared.
- Some processes are more irreversible than others.
- We try to approximate reversible processes. **Why?**



(*a*) Slow (reversible) process

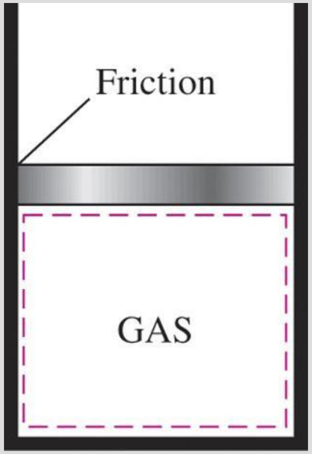


(*b*) Fast (irreversible) process

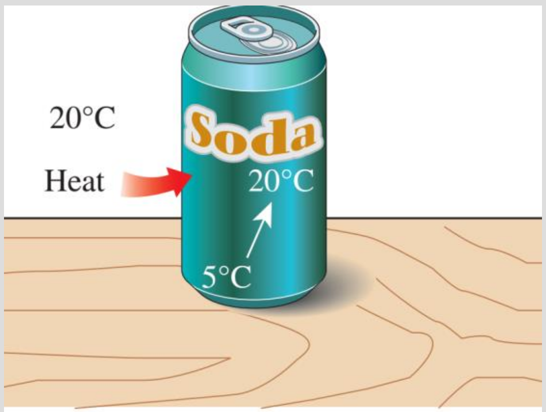
Reversible processes deliver the most and consume the least work.

Irreversibilities

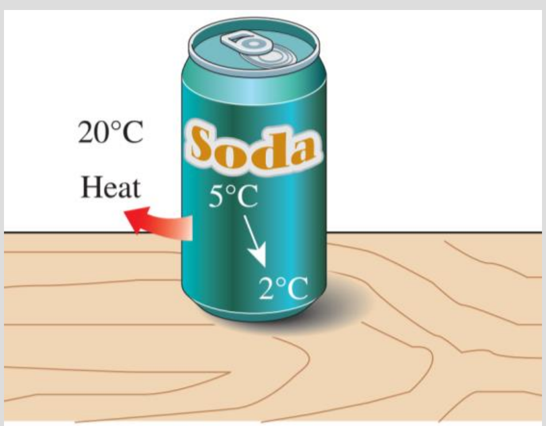
- The factors that cause a process to be irreversible are called **irreversibilities**.
- They include friction, unrestrained expansion, mixing of two fluids, heat transfer across a finite temperature difference, electric resistance, inelastic deformation of solids, and chemical reactions.
- The presence of any of these effects renders a process irreversible.



Friction renders a process irreversible.

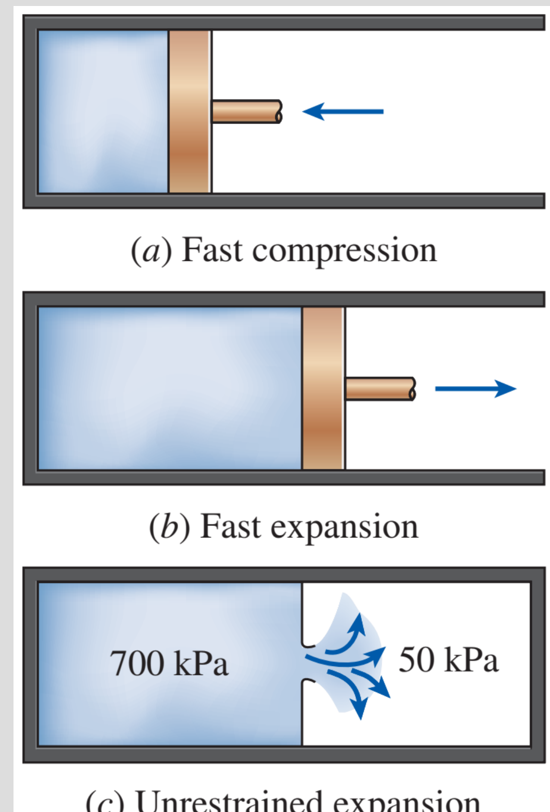


(*a*) An irreversible heat transfer process



(*b*) An impossible heat transfer process

(*a*) Heat transfer through a temperature difference is irreversible, and (*b*) the reverse process is impossible.



(*a*) Fast compression

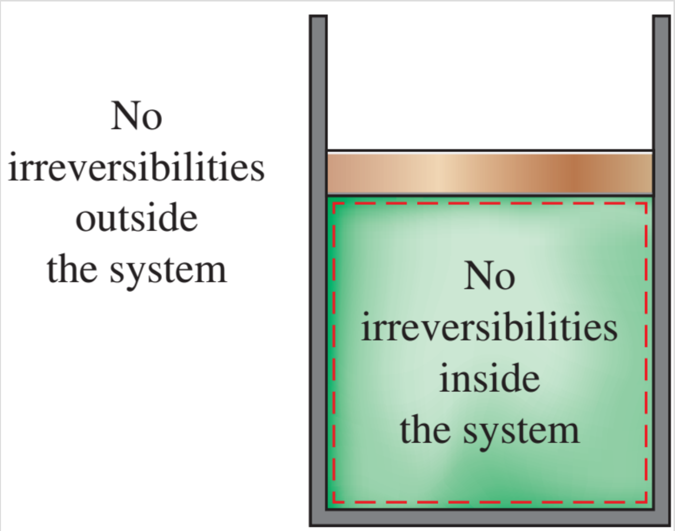
(*b*) Fast expansion

(*c*) Unrestrained expansion

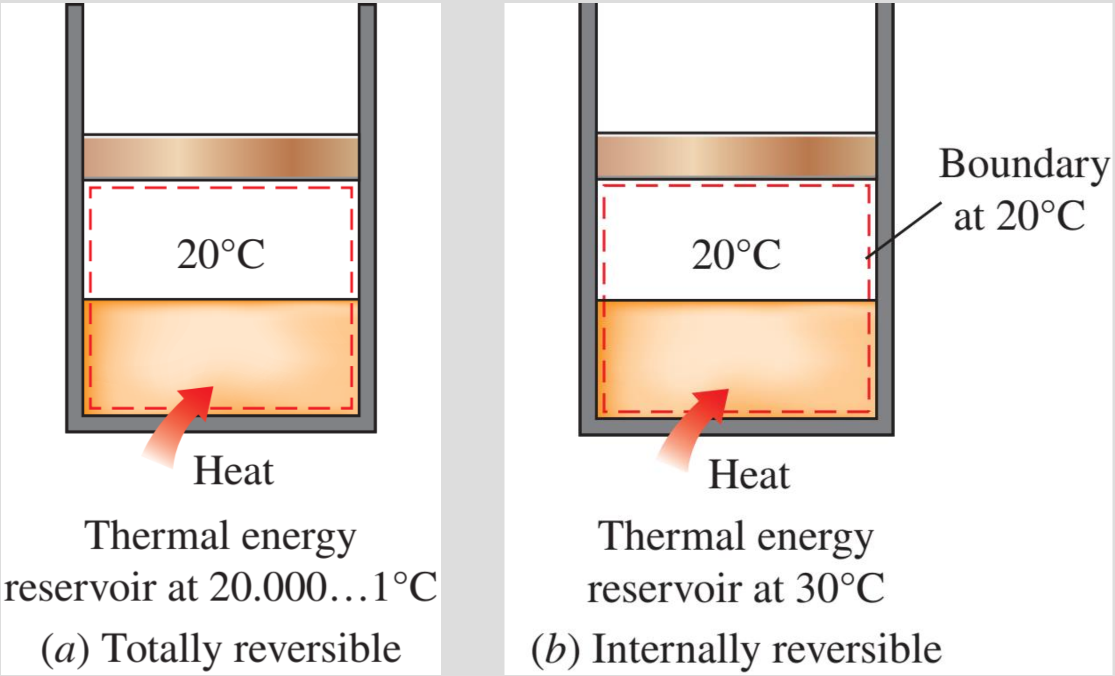
Irreversible compression and expansion processes.

INTERNALLY AND EXTERNALLY REVERSIBLE PROCESSES

- **Internally reversible process:** If no irreversibilities occur within the boundaries of the system during the process.
- **Externally reversible:** If no irreversibilities occur outside the system boundaries.
- **Totally reversible process:** It involves no irreversibilities within the system or its surroundings.
- A totally reversible process involves no heat transfer through a finite temperature difference, no nonquasi-equilibrium changes, and no friction or other dissipative effects.



A reversible process involves no internal and external irreversibilities.



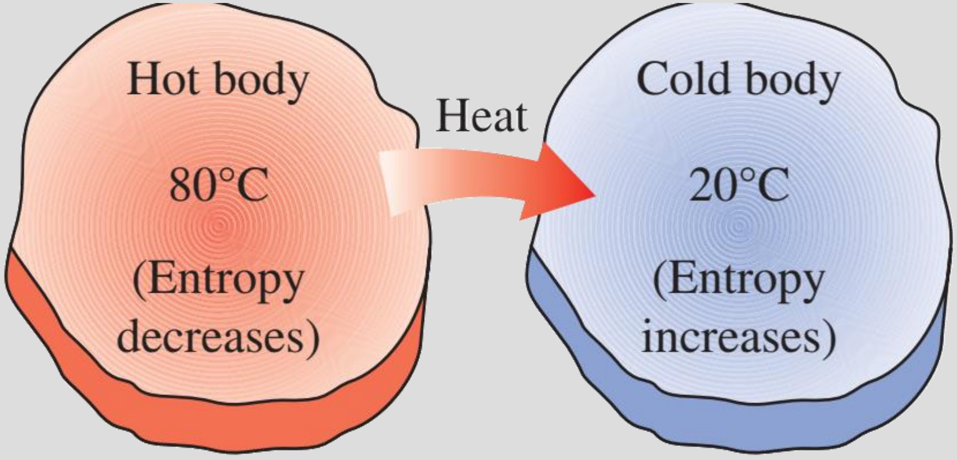
Totally and internally reversible heat transfer processes.

ENTROPY

- The **Entropy** is a measure of the amount of energy in a system that is no longer available to effect changes in that system.

- That energy becomes unavailabe not by leaving the system but by becoming irretrievalbe disordered.

Law of increase of Entropy: Entropy of the universe is increasing all the time

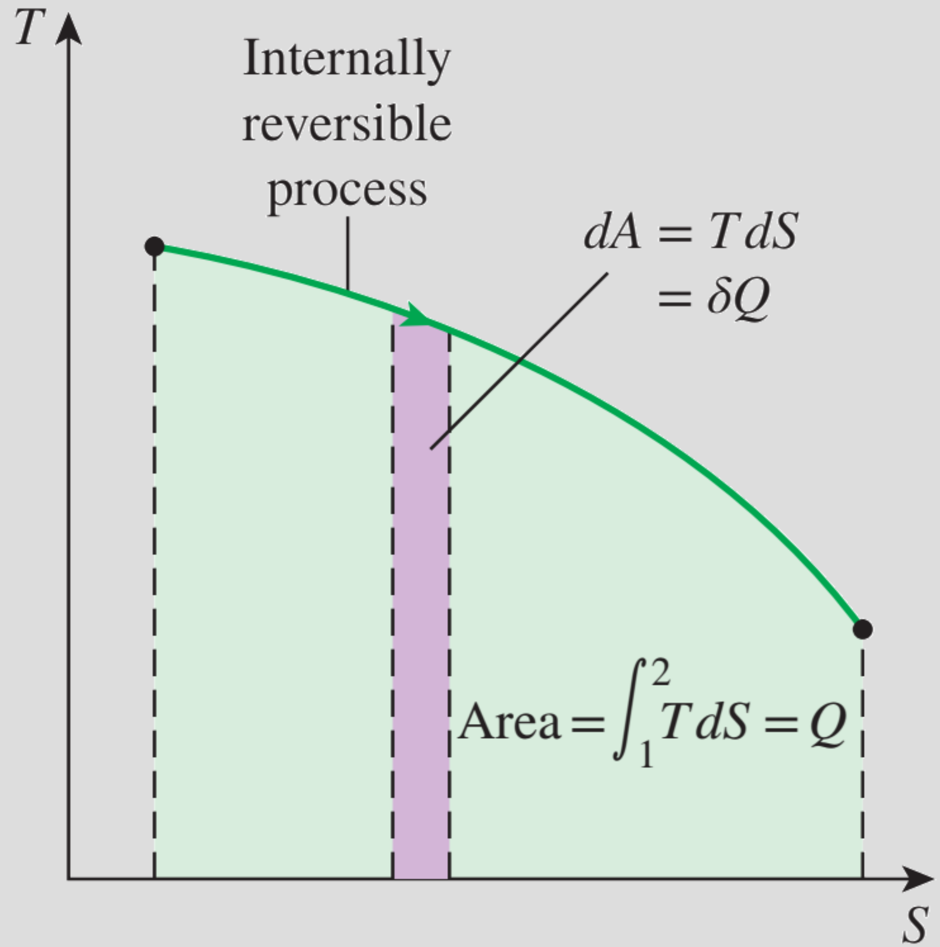


ENTROPY

The change in entropy ***(Δs)*** is equal to change in heat ***(dQ)*** divided by the absolute Temperature ***(T)*** at which heat change occurs in the system.

$$ds = \frac{dQ}{T} \qquad dQ = Tds \qquad Q = \int_1^2 Tds$$

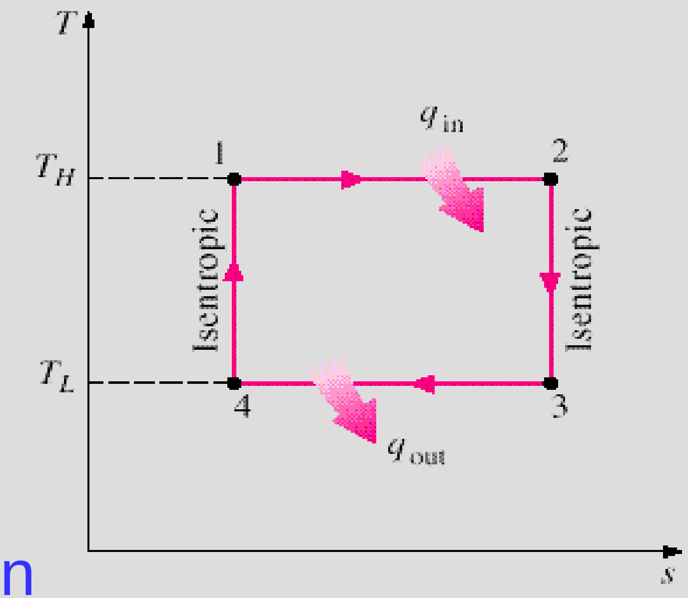
Analogous to $$W = \int_1^2 pdv$$



CARNOT CYCLE

Sadi Carnot French Engineer in 1860 proposed the most efficient thermodynamic cycle called Carnot Cycle

Carnot Cycle is the ideal cycle in which all heat is supplied at one fixed temp (T_H) and all the heat is rejected at a lower fixed temperature (T_L)



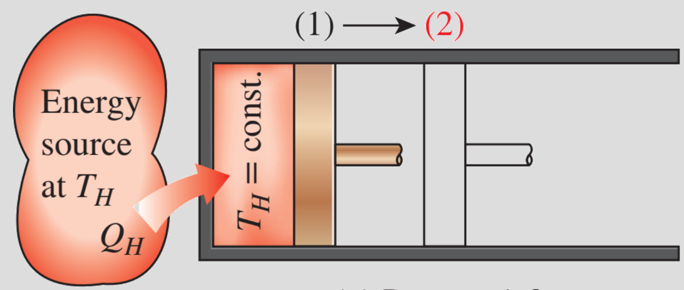
Carnot Cycle consists of 4 reversible processes. Two isothermal and two adiabatic

① Reversible Isothermal Expansion
② Reversible Adiabatic Expansion
③ Reversible Isothermal Compression
④ Reversible Adiabatic Compression

CARNOT CYCLE

Reversible Isothermal Expansion

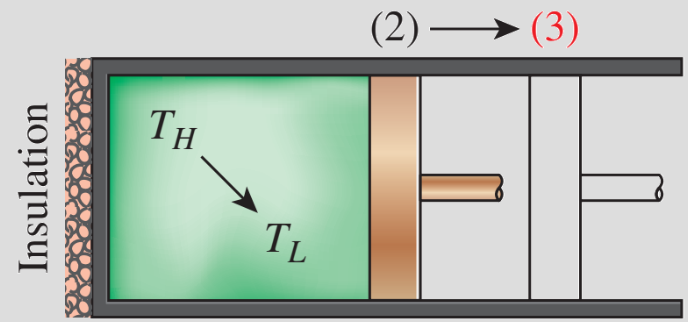
T_H is Constant, Cylinder head is in close contact with source. Gas is allowed to expand and do work. Due to expansion the temperature decrease and takes more heat from the source to keep the temperature constant



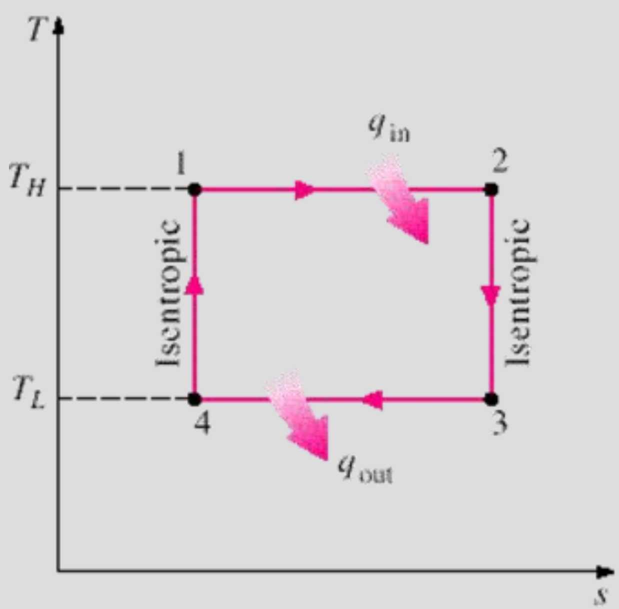
(*a*) Process 1-2

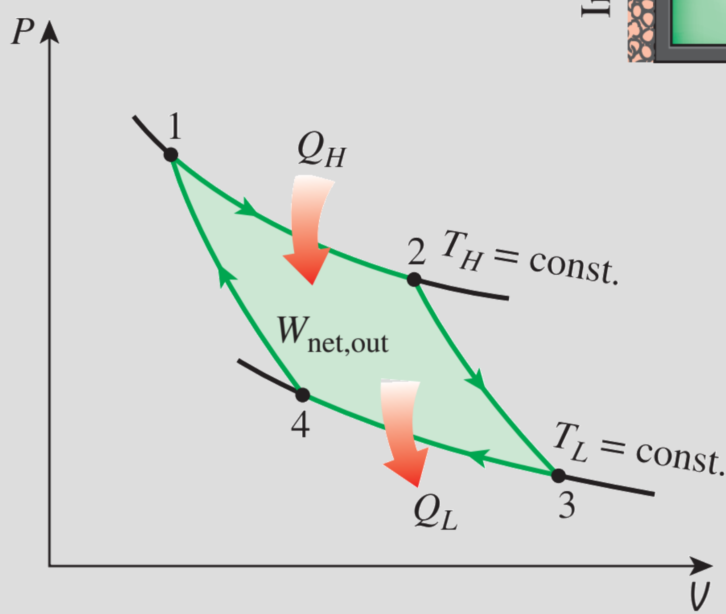
Reversible Adiabatic Expansion

The source is replaced with the insulation and the gas is allowed to expand and do work on surrounding and temperature lowers to T_L



(*b*) Process 2-3

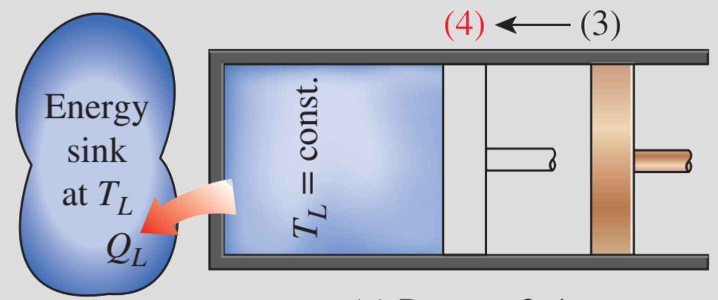




CARNOT CYCLE

Reversible Isothermal Compression

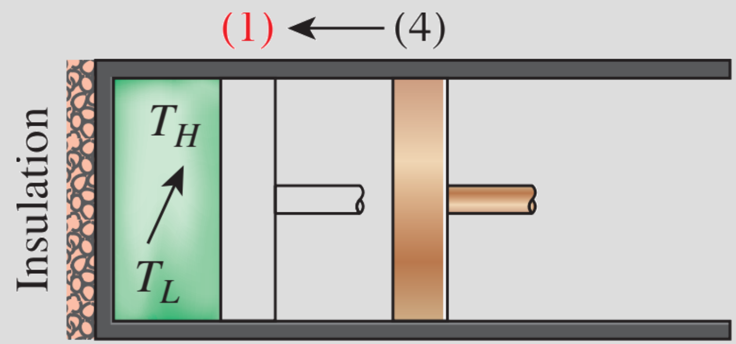
Insulation is replaced with sink at TL and the gas is compressed at constant temperature and heat is removed continuously to sink from cylinder heat



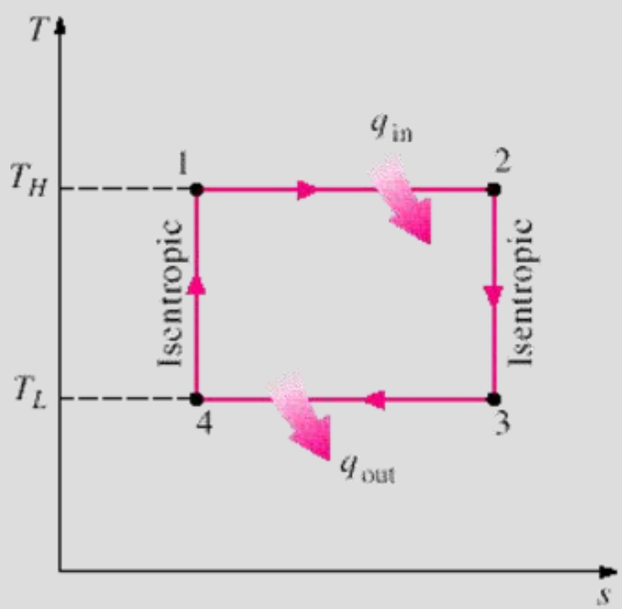
(c) Process 3-4

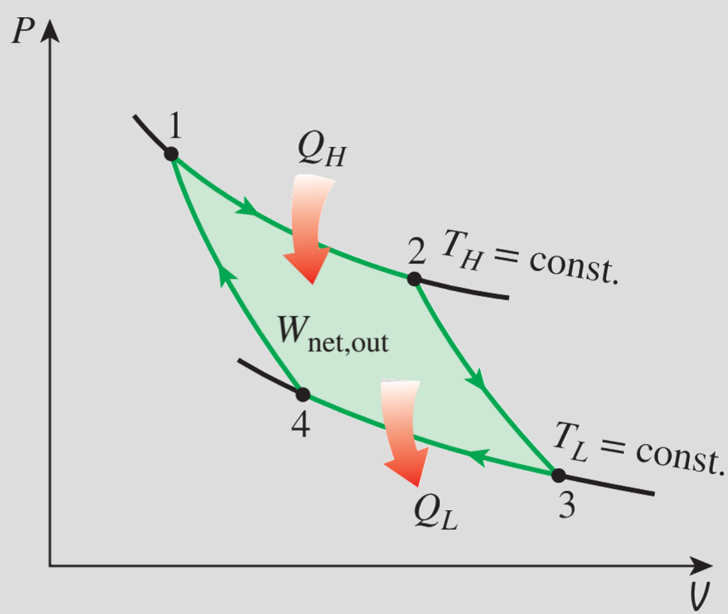
Reversible Adiabatic Compression

Sink is replaced with insulation again and gas is compressed and external work is done on the gas adiabatically and the system returns to its original initial state.



(d) Process 4-1





CARNOT CYCLE

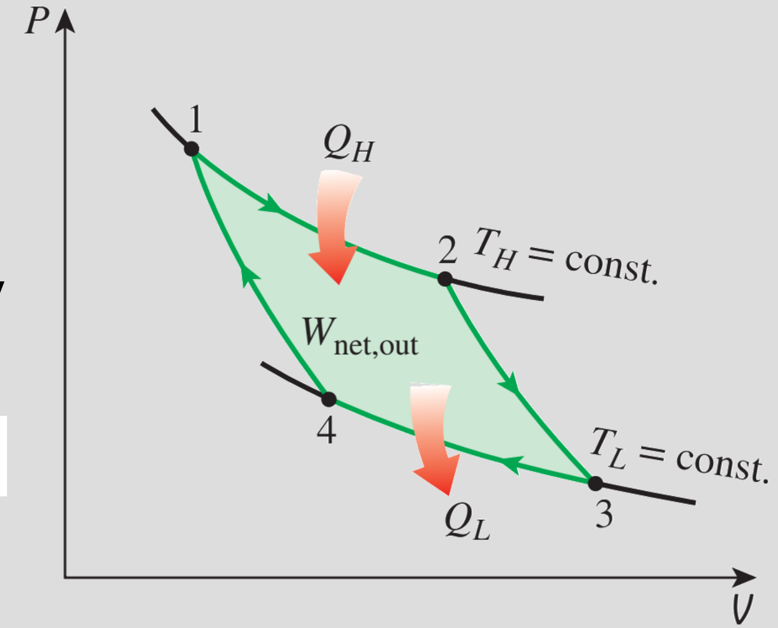
The cycle η of heat engine is given by

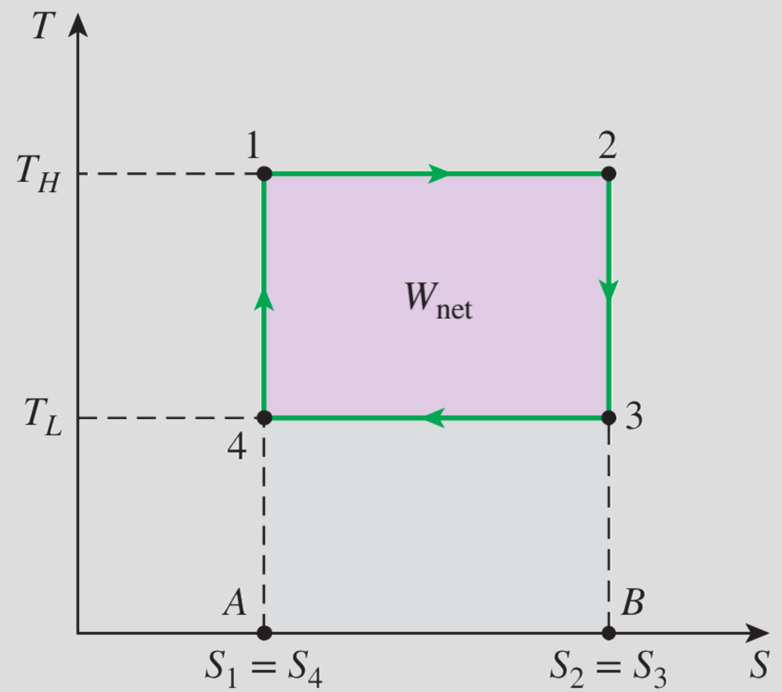
$$\eta_{th} = \frac{W_{net,out}}{Q_H}$$ *and* $$W_{net,out} = Q_H - Q_L$$

The heat supplied to the cycle,
Q_H = area 12BA1 = $T_H(s_B - s_A)$

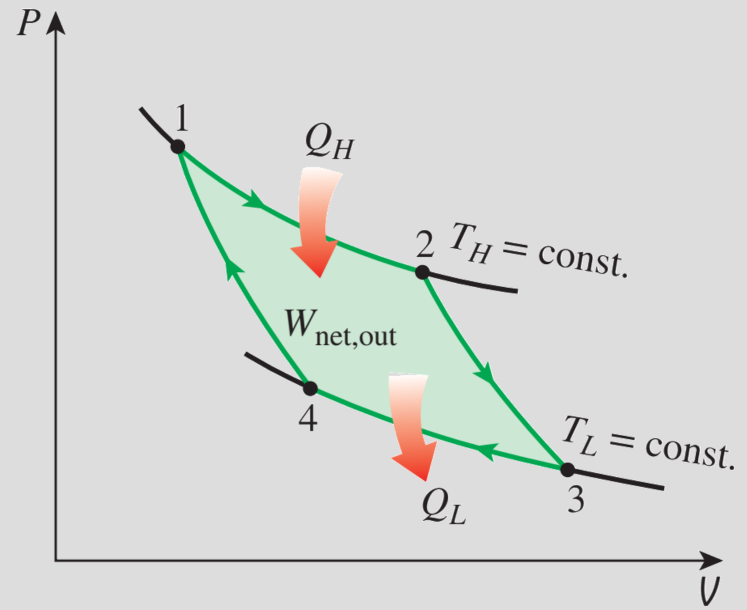
The heat rejected from the cycle,
Q_L = area 43BA4 = $T_L(s_B - s_A)$

So,
$W_{netout} = T_H - T_L(s_B - s_A)$





CARNOT CYCLE

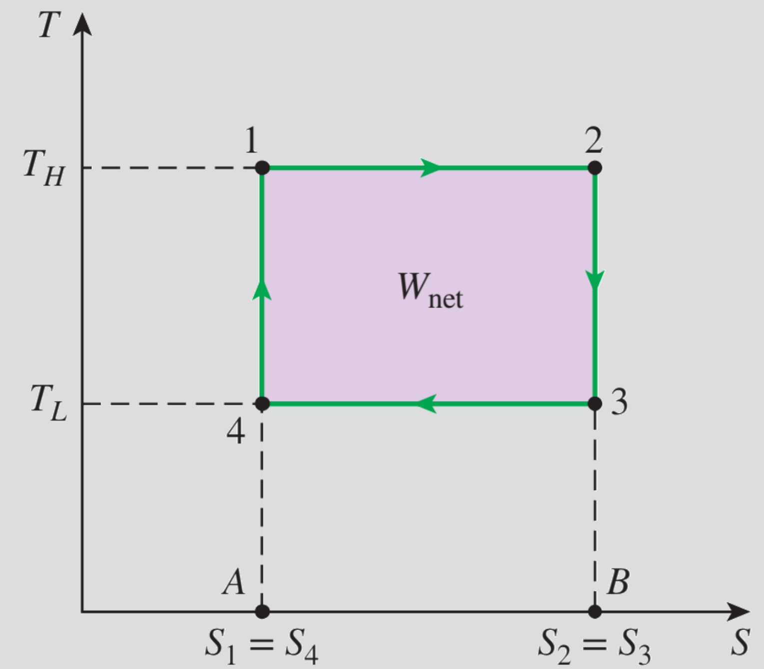


Hence η_{Carnot} = Carnot Cycle Eff. given by

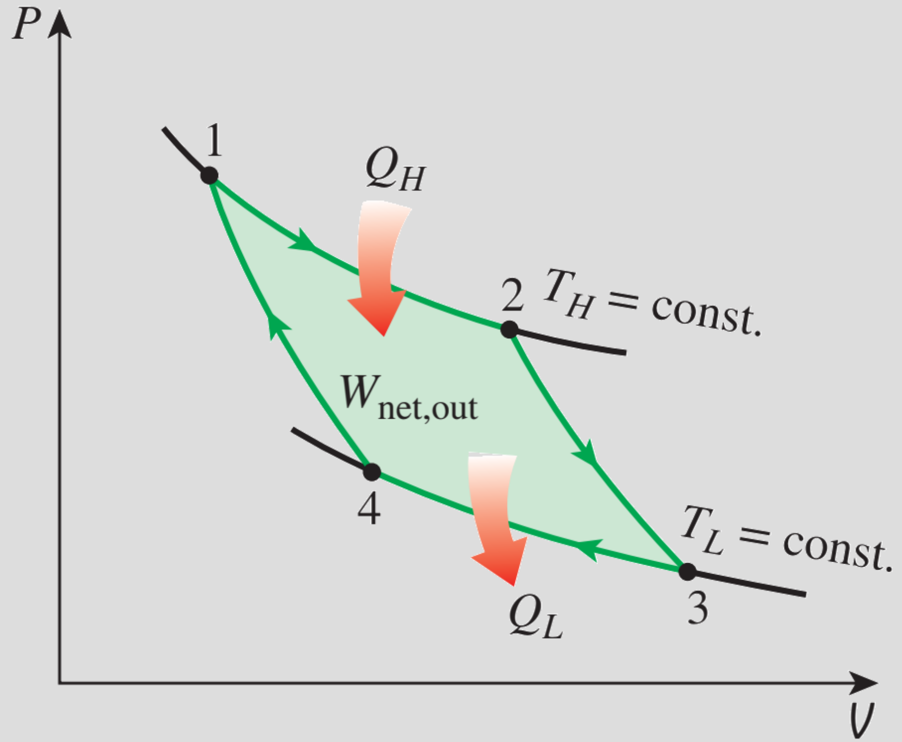
$$\eta_{\text{th}} = \frac{W_{\text{net,out}}}{Q_H} \quad \textbf{\textit{and}} \quad W_{\text{net,out}} = Q_H - Q_L$$

$$\eta_{\text{Carnot}} = T_H - T_L(s_B - s_A)/T_H(s_B - s_A)$$

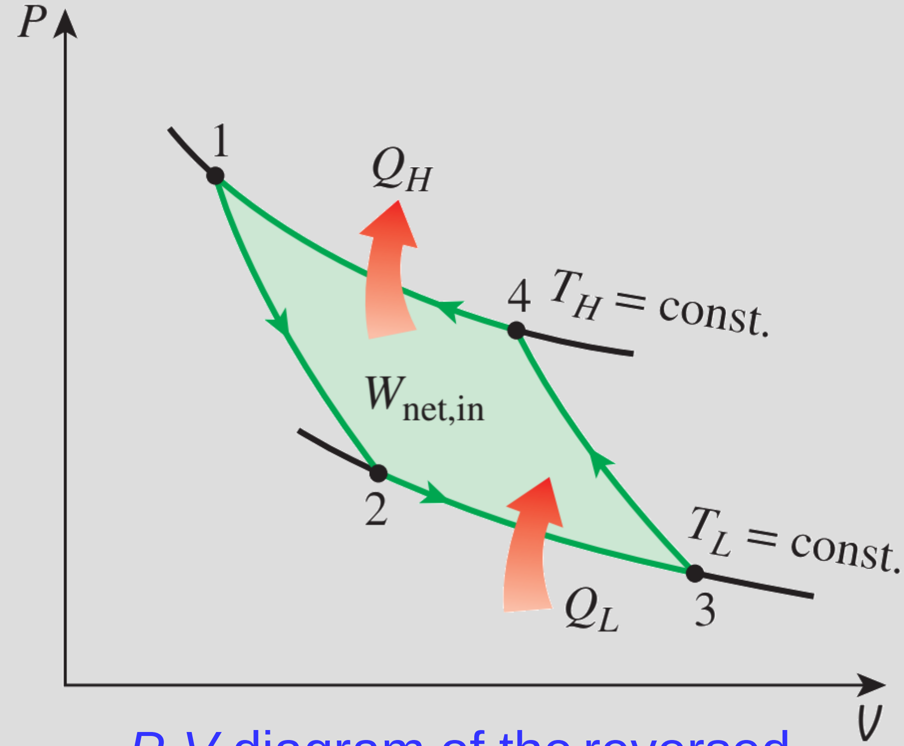
$$\eta_{\text{Carnot}} = 1 - T_L / T_H$$



If sink is kept at constant Temp (T_L), upper temperature (T_H) must be made as high as possible to get the maximum η



P-V diagram of the Carnot cycle.

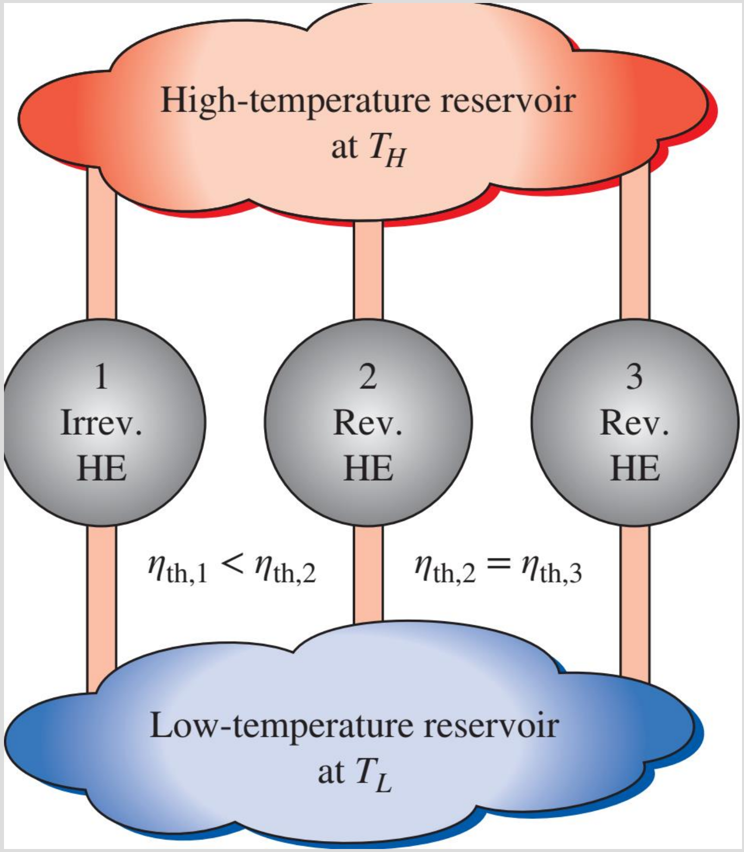


P-V diagram of the reversed Carnot cycle.

The Reversed Carnot Cycle

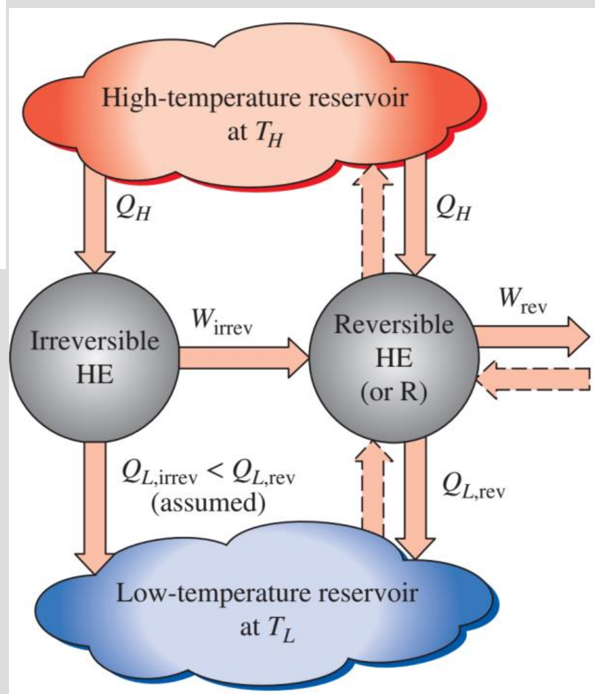
- The Carnot heat-engine cycle is a totally reversible cycle.
- Therefore, all the processes that comprise it can be *reversed*, in which case it becomes the **Carnot refrigeration cycle**.

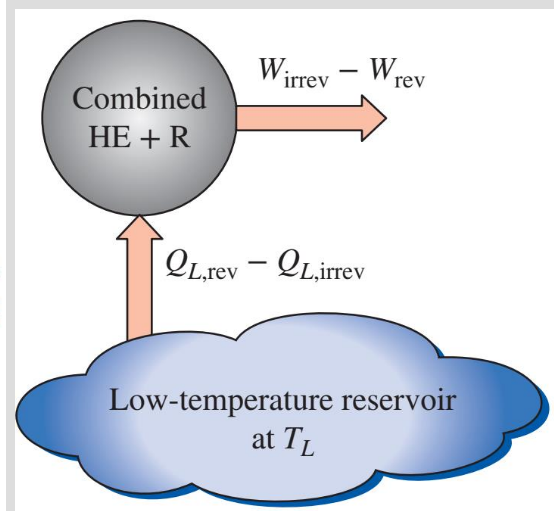
THE CARNOT PRINCIPLES



1. The efficiency of an irreversible heat engine is always less than the efficiency of a reversible one operating between the same two reservoirs.

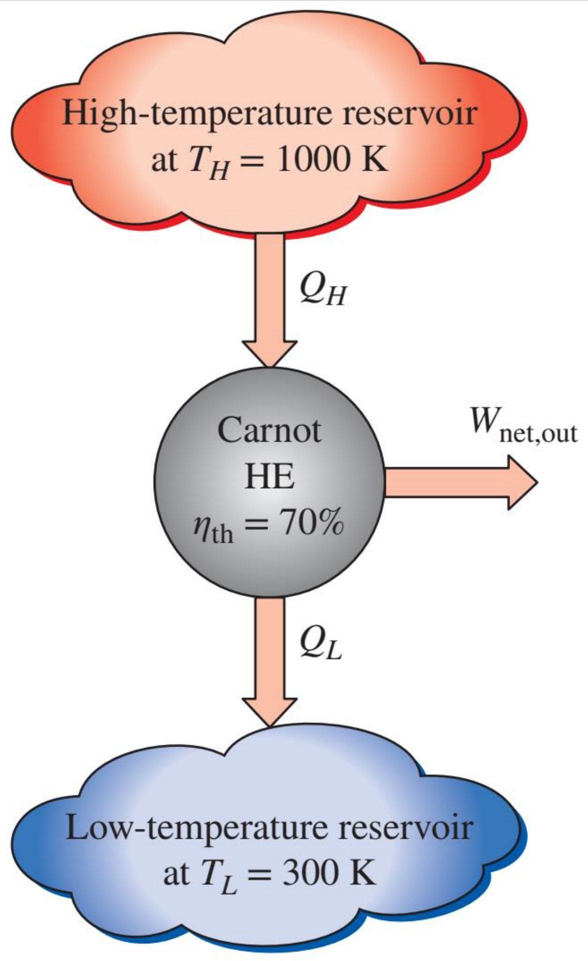
2. The efficiencies of all reversible heat engines operating between the same two reservoirs are the same.



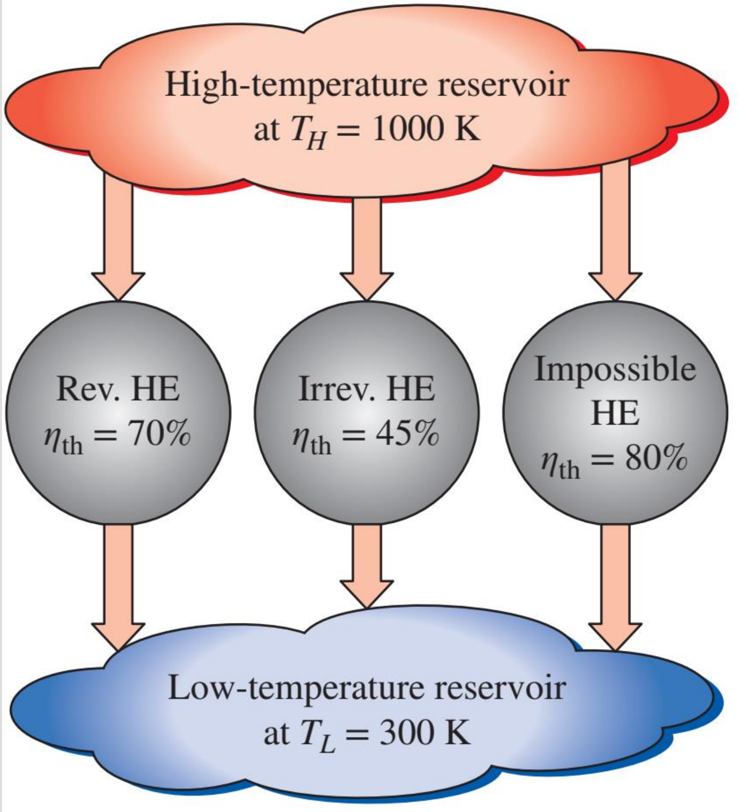


(*b*) The equivalent combined system

THE CARNOT HEAT ENGINE



The Carnot heat engine is the most efficient of all heat engines operating between the same high- and low-temperature reservoirs.



No heat engine can have a higher efficiency than a reversible heat engine operating between the same high- and low-temperature reservoirs.

Any heat engine

$$\eta_{th} = 1 - \frac{Q_L}{Q_H}$$

Carnot heat engine

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

$$\eta_{th} \begin{cases} < \eta_{th,rev} & \text{irreversible heat engine} \\ = \eta_{th,rev} & \text{reversible heat engine} \\ > \eta_{th,rev} & \text{impossible heat engine} \end{cases}$$

Example 6-5:

EXAMPLE 6–5 Analysis of a Carnot Heat Engine

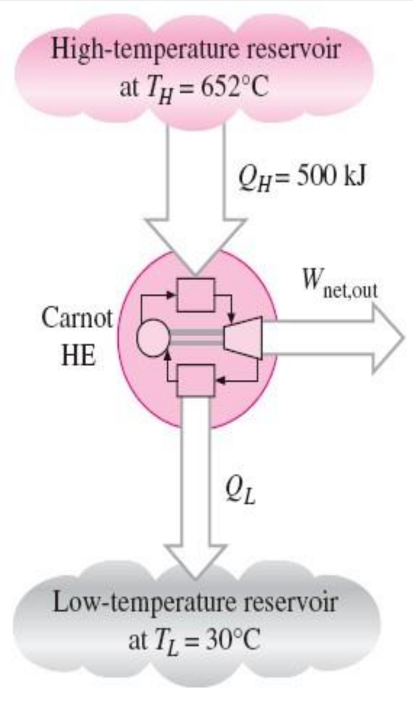
A Carnot heat engine, shown in Fig. 6–48, receives 500 kJ of heat per cycle from a high-temperature source at 652°C and rejects heat to a low-temperature sink at 30°C. Determine (*a*) the thermal efficiency of this Carnot engine and (*b*) the amount of heat rejected to the sink per cycle.

Analysis (*a*) The Carnot heat engine is a reversible heat engine, and so its efficiency can be determined from Eq. 6–18 to be

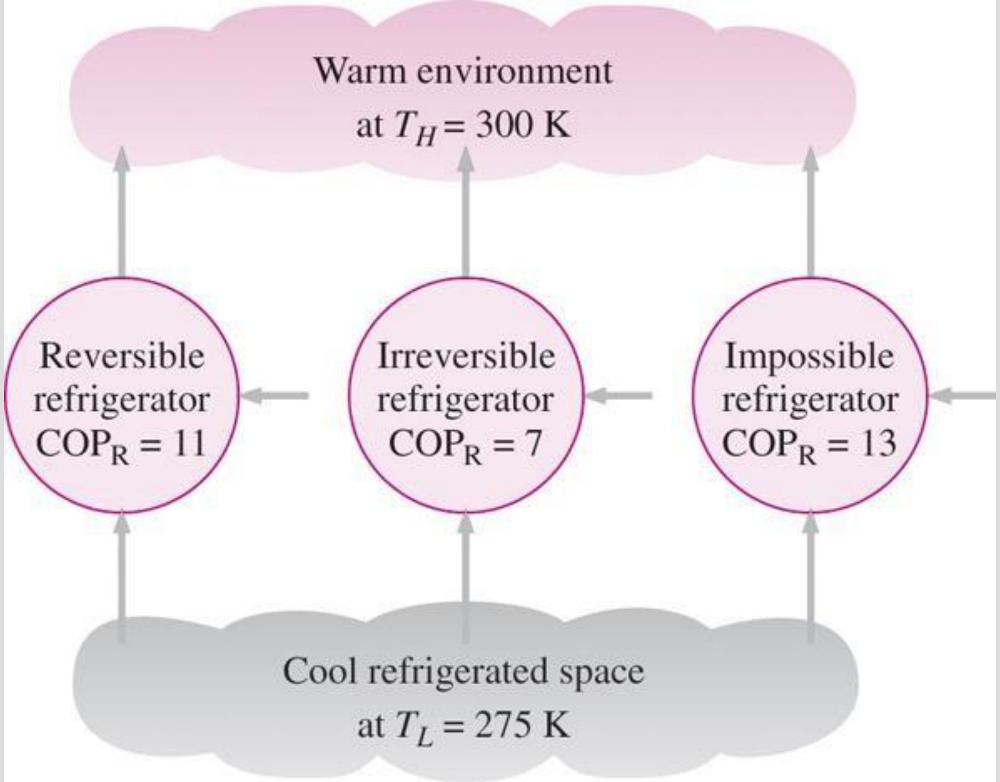
$$\eta_{\text{th},C} = \eta_{\text{th,rev}} = 1 - \frac{T_L}{T_H} = 1 - \frac{(30 + 273)\text{ K}}{(652 + 273)\text{ K}} = \mathbf{0.672}$$

(*b*) The amount of heat rejected Q_L by this reversible heat engine is easily determined from Eq. 6–16 to be

$$Q_{L,\text{rev}} = \frac{T_L}{T_H} Q_{H,\text{rev}} = \frac{(30 + 273)\text{ K}}{(652 + 273)\text{ K}} (500\text{ kJ}) = \mathbf{164\ kJ}$$



THE CARNOT REFRIGERATOR AND HEAT PUMP



No refrigerator can have a higher COP than a reversible refrigerator operating between the same temperature limits.

Any refrigerator or heat pump

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

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

Carnot refrigerator or heat pump

$$COP_{HP,rev} = \frac{1}{1 - T_L/T_H}$$

$$COP_{R,rev} = \frac{1}{T_H/T_L - 1}$$

Example 6-6:

EXAMPLE 6–6 **A Questionable Claim for a Refrigerator**

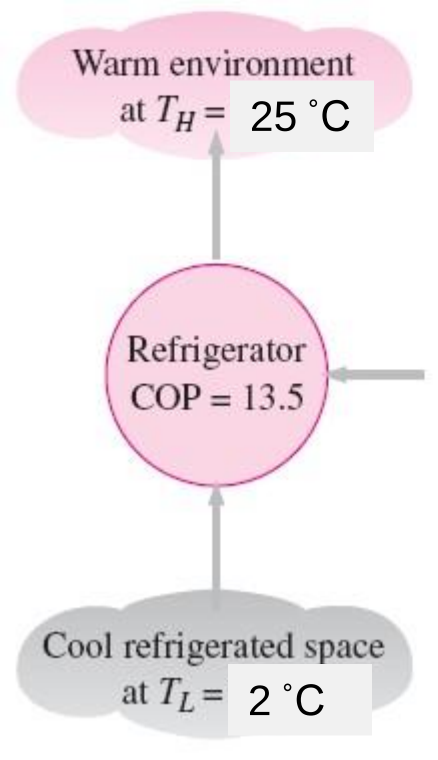
An inventor claims to have developed a refrigerator that maintains the refrigerated space at 2 °C while operating in a room where the temperature is 25 °C and that has a COP of 13.5. Is this claim reasonable?

Analysis The performance of this refrigerator (shown in Fig. 6–52) can be evaluated by comparing it with a reversible refrigerator operating between the same temperature limits:

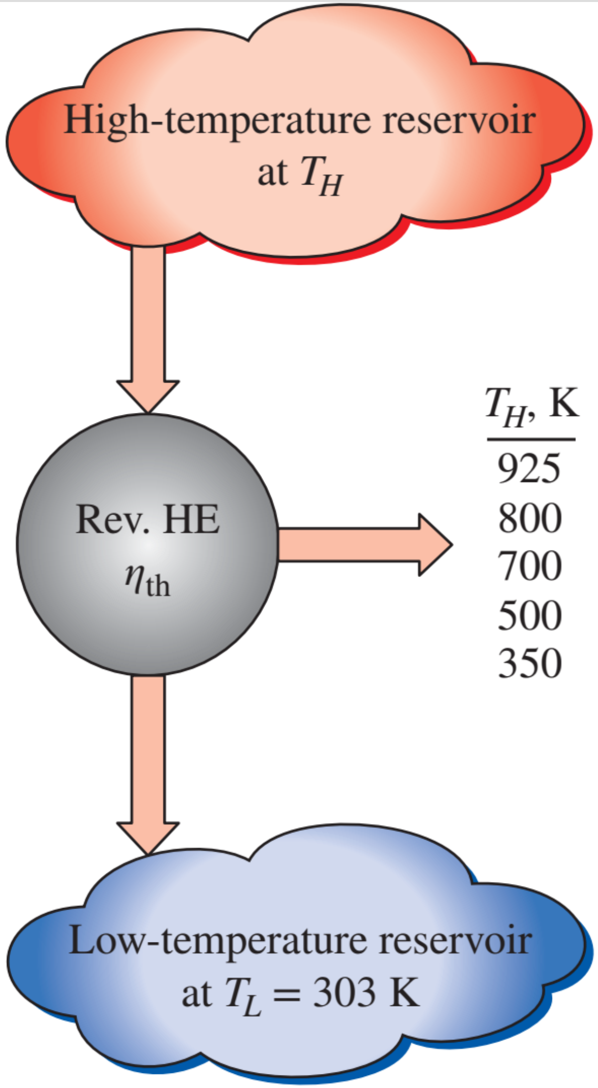
$$\mathrm{COP}_{\mathrm{R,max}} = \mathrm{COP}_{\mathrm{R,rev}} = \frac{1}{T_H/T_L - 1}$$

$$= \frac{1}{(75 + 460\ \mathrm{R})/(35 + 460\ \mathrm{R}) - 1} = 12.4$$

the claim is *false*.



THE QUALITY OF ENERGY

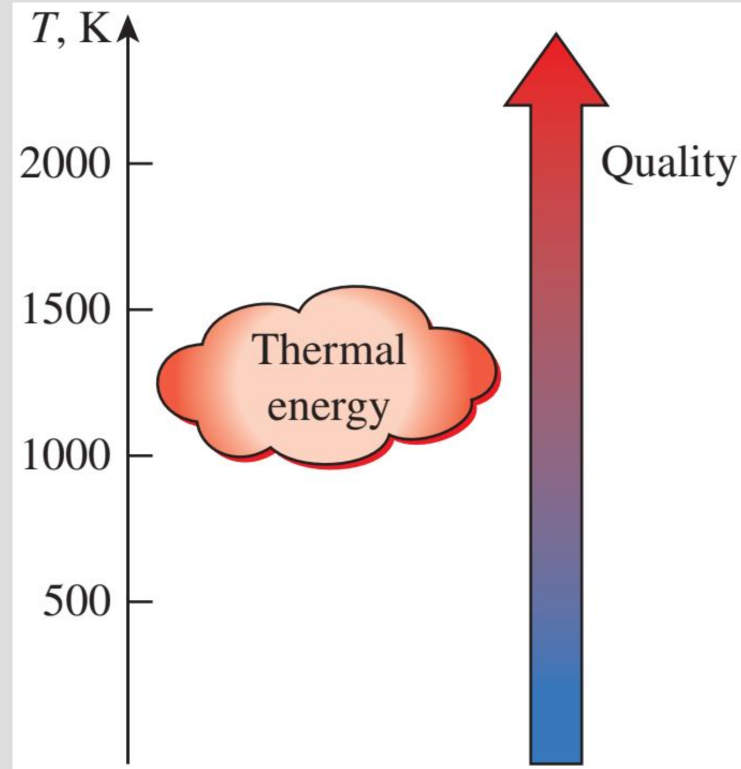


T_H, K	η_{th}, %
925	67.2
800	62.1
700	56.7
500	39.4
350	13.4

The fraction of heat that can be converted to work as a function of source temperature.

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

Can we use °C unit for temperature here?



The higher the temperature of the thermal energy, the higher its quality.

How do you increase the thermal efficiency of a Carnot heat engine? How about for actual heat engines?

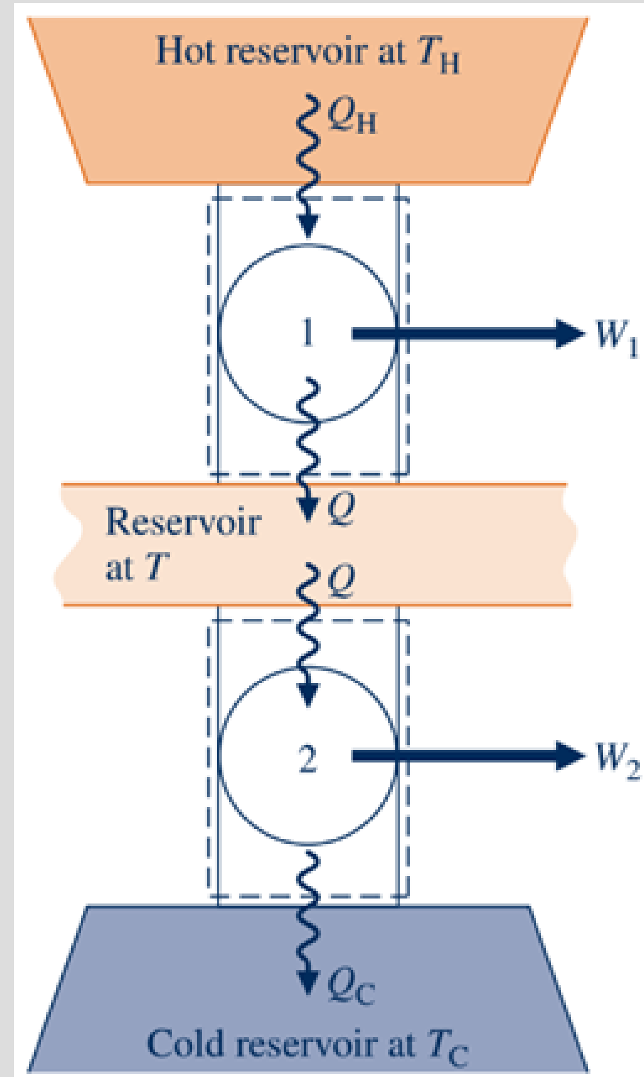
Problem:

Figure shows two power cycles, denoted 1 and 2, operating in series, together with three thermal reservoirs. The energy transfer by heat into cycle 2 is equal in magnitude to the energy transfer by heat from cycle 1. All energy transfers are positive in the directions of the arrows.

(a) Determine an expression for the thermal efficiency of an overall cycle consisting of cycles 1 and 2 expressed in terms of their individual thermal efficiencies.

(b) If cycles 1 and 2 are each reversible, use the result of part (a) to obtain an expression for the thermal efficiency of the overall cycle in terms of the temperatures of the three reservoirs, T_H, T, and T_C, as required. Comment.

(c) If cycles 1 and 2 are each reversible and have the same thermal efficiency, obtain an expression for the intermediate temperature T in terms of T_H and T_C.



Summary

- Introduction to the second law
- Thermal energy reservoirs
- Heat engines
  - ✓ Thermal efficiency
  - ✓ The 2nd law: Kelvin-Planck statement
- Refrigerators and heat pumps
  - ✓ Coefficient of performance (COP)
  - ✓ The 2nd law: Clasius statement
- Perpetual motion machines
- Reversible and irreversible processes
  - ✓ Irreversibilities, Internally and externally reversible processes
- The Carnot cycle
  - ✓ The reversed Carnot cycle
- The Carnot principles
- The Carnot heat engine
  - ✓ The quality of energy
- The Carnot refrigerator and heat pump