Lecture 10

Topic 3

Second Law of Thermodynamics

Topics

- 3.2 Carnot cycles

Reading:

Ch 5: 5.3 – 5.9 Borgnakke & Sonntag Ed. 8

Ch 6: 6-5 – 6-11 Cengel and Boles Ed. 7

3.1 Revisiting Second Law Statements

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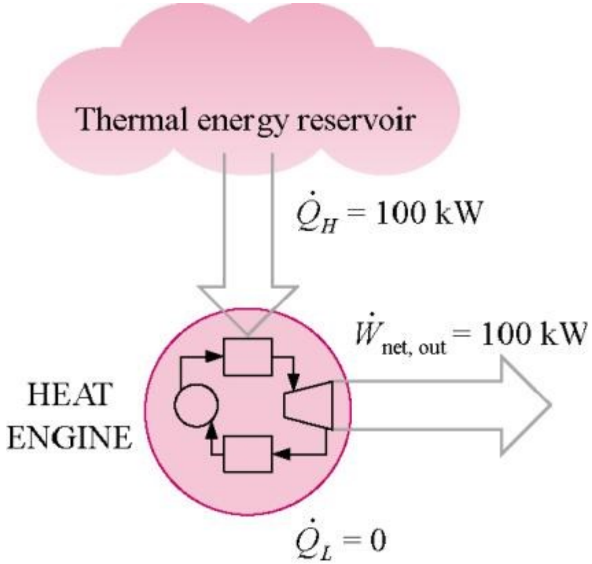
Lecture 9 takeaway

- Cannot convert HEAT energy to 100% WORK energy (Kelvin-Planck statement)
- $\eta_{TH} = \dot{W}_{net}/\dot{Q}_H < 100\%$

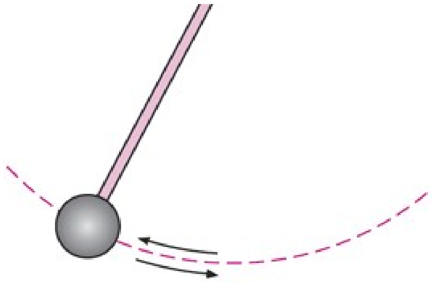


- If $\eta_{TH} < 100\%$, what is the maximum efficiency that is achievable?
- Introduction to a “reversible process”

3.2.1 Reversible and Irreversible Processes

<u>Reversible process</u>

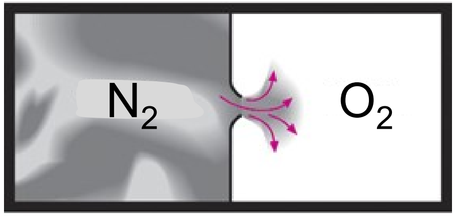
- Process that can be reversed without leaving any trace on the <u>system</u> or <u>surroundings</u>.
- Can reverse the process and will go back to original state without any disturbance



(*a*) Frictionless pendulum

<u>Irreversible process</u>

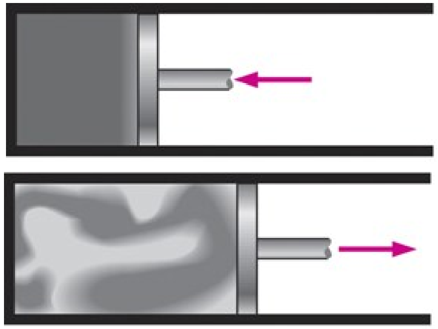
- Process that cannot go back to its original state without any change to system or surroundings
- Example:
  - Membrane separating two gases
  - Membrane bursts, mixing N_2 + O_2
  - Cannot "naturally" return components to original state



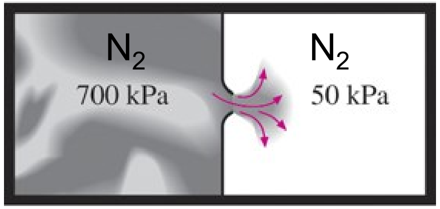
3.2.1 Reversible and Irreversible Processes

Common irreversible processes

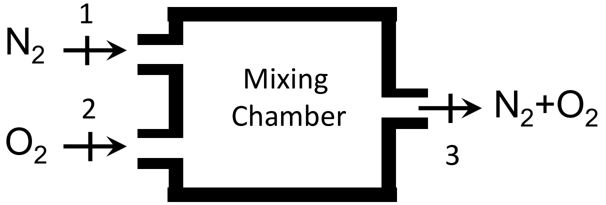
a) Fast compression / expansion
b) Unrestrained expansion
c) Friction
d) Mixing
e) Chemical reaction
f) Heat transfer at large temperature difference



a) Fast compression / expansion



b) Unrestrained expansion



d) Mixing

e) Chemical Rxn

Most practical applications have irreversible processes

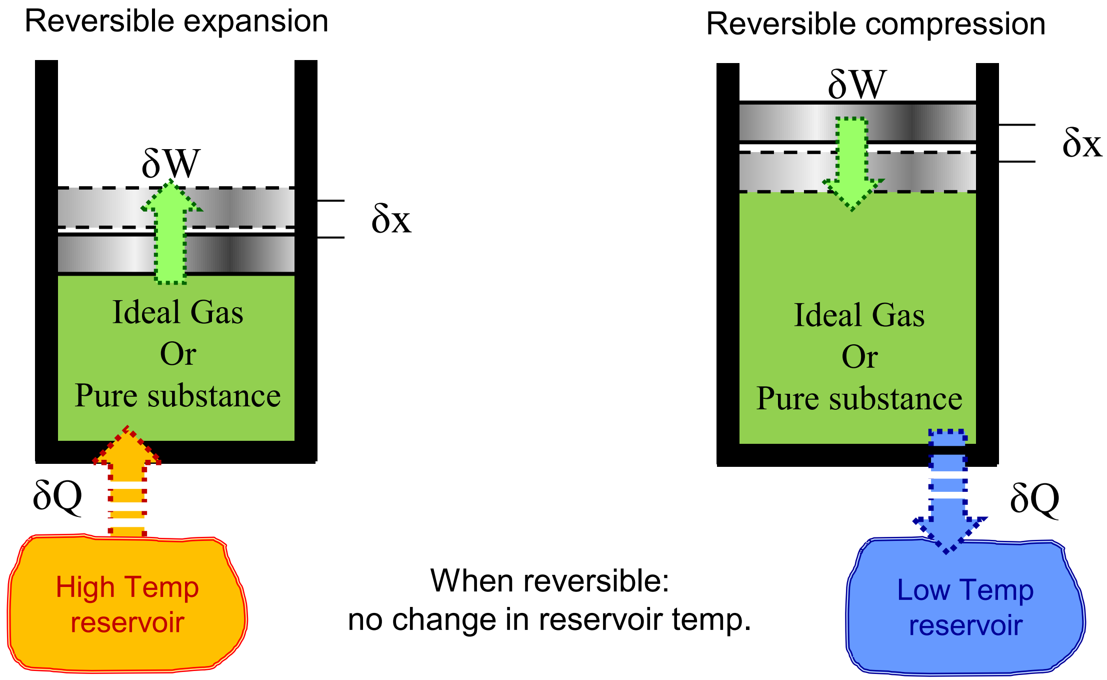
3.2.2 Reversible Processes

Why study reversible processes?

- Understand theoretical limits of real process
- Determines maximum thermal efficiency that is theoretically achievable.

Quasi-equilibrium process

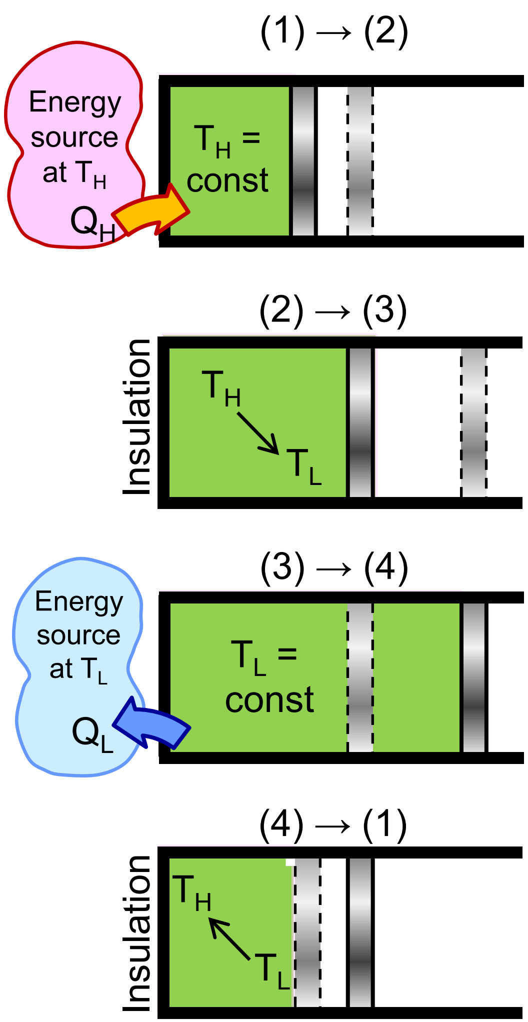
- Approximation of a reversible process
- Infinitesimal changes of δQ and δW from surroundings



When reversible:
no change in reservoir temp.

3.2.2 The Carnot Cycle

- Nicolas Sadi Carnot (1769-1832)
- Devised reversible cycle for conceptual theory (e.g. max theoretical η_{TH})



The Carnot Cycle

Process 1-2: Reversible isothermal heat addition. System remains constant at high temperature, T_H. System performs work (expansion).

Process 2-3: Reversible, adiabatic expansion. System does work as system temperature decreases from T_H to T_L.

Process 3-4: Reversible isothermal heat rejection. System remains at constant low temperature, T_L. Work is performed on system (compression).

Process 4-1: Reversible adiabatic compression. Work performed on system as system's temperature increases from T_L to T_H.

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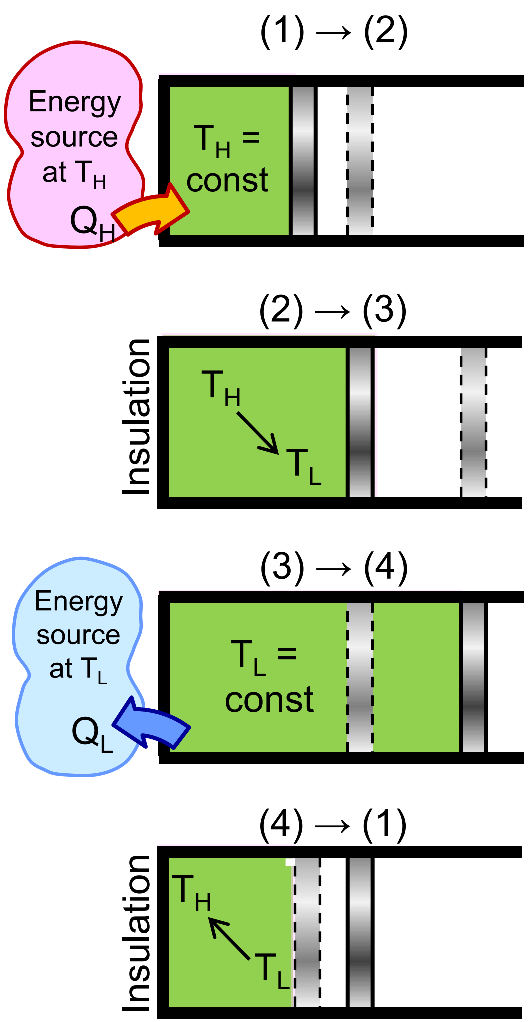
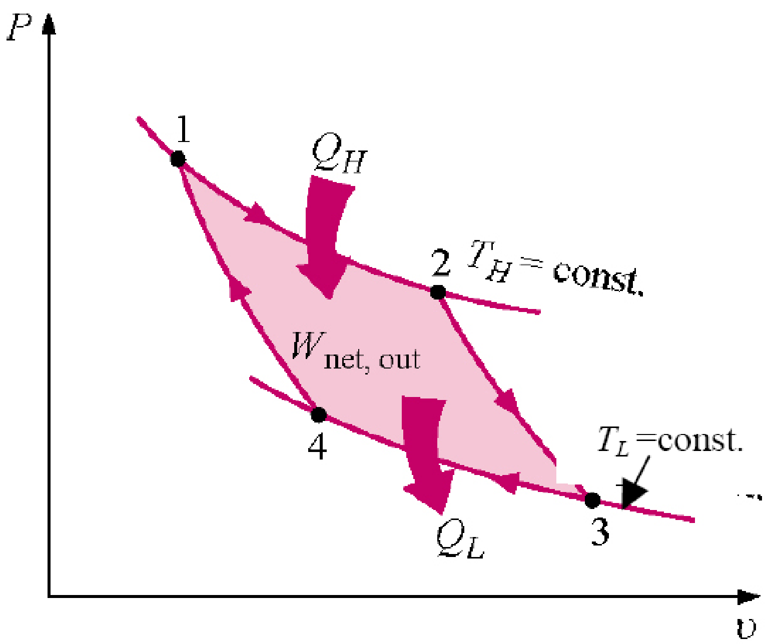


The Carnot Cycle



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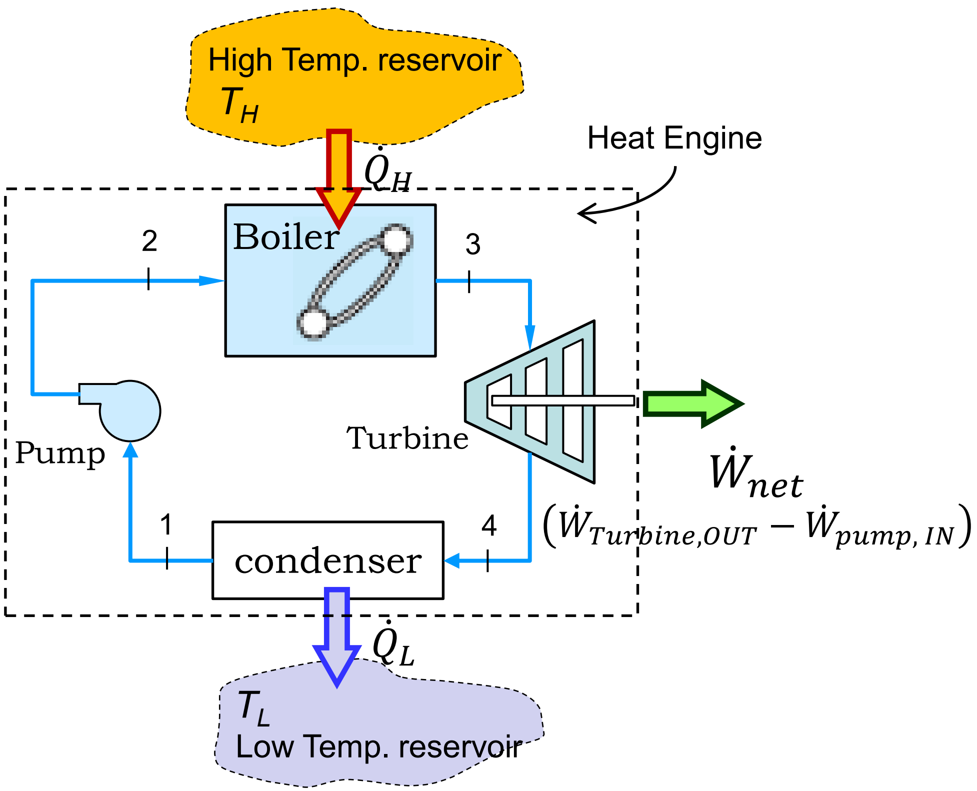
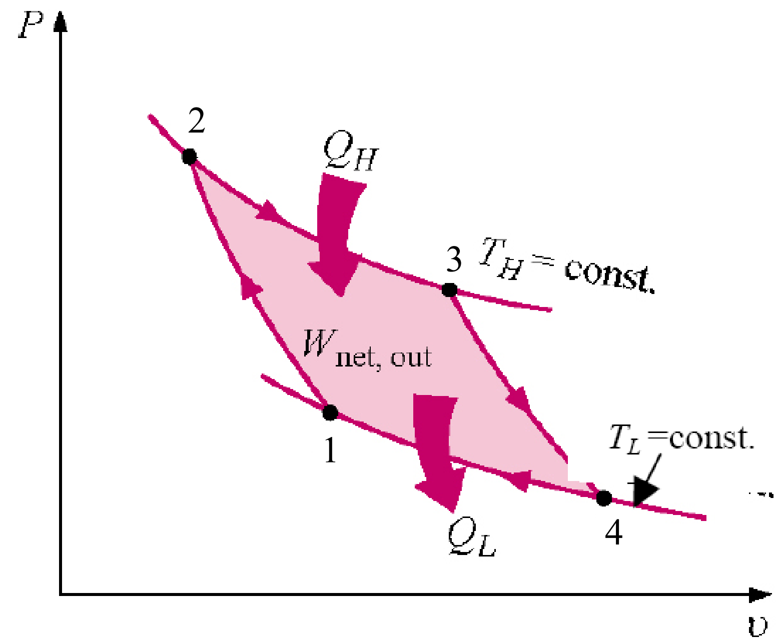
Carnot cycle applied to a heat engine (steam power plant)



The Carnot Cycle



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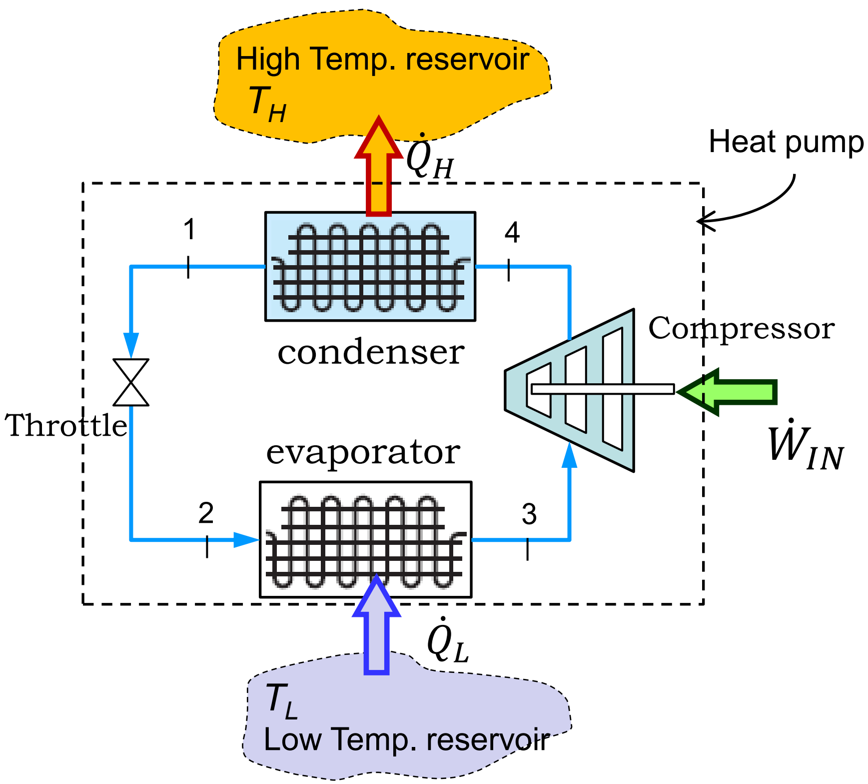
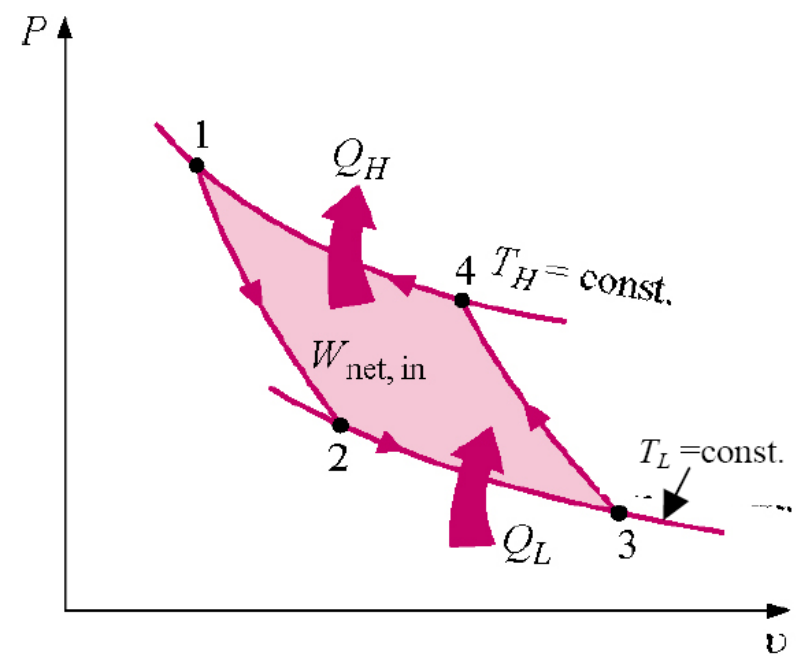
Carnot cycle applied to a heat pump / refrigeration cycle



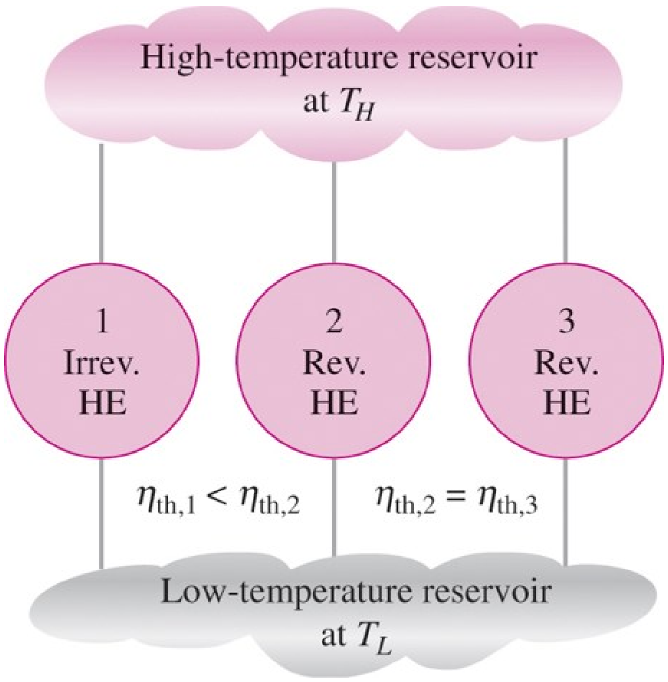
The Carnot Cycle



3.2.3 Carnot Cycle Efficiency

Propositions regarding Carnot Cycle Efficiency

- Consider the heat engines operating between temperature reservoirs $T_H > T_L$
    1. Irreversible
    2. Reversible
    3. Reversible



a) Efficiency of the irreversible heat engine is less than that of the reversible heat engine
- $\eta_{th,\, irreversible} < \eta_{th,\, reversible}$
- $\eta_{th,\, reversible} = \eta_{th,\, Carnot}$
- Maximum efficiency: $\eta_{th,\, Carnot}$

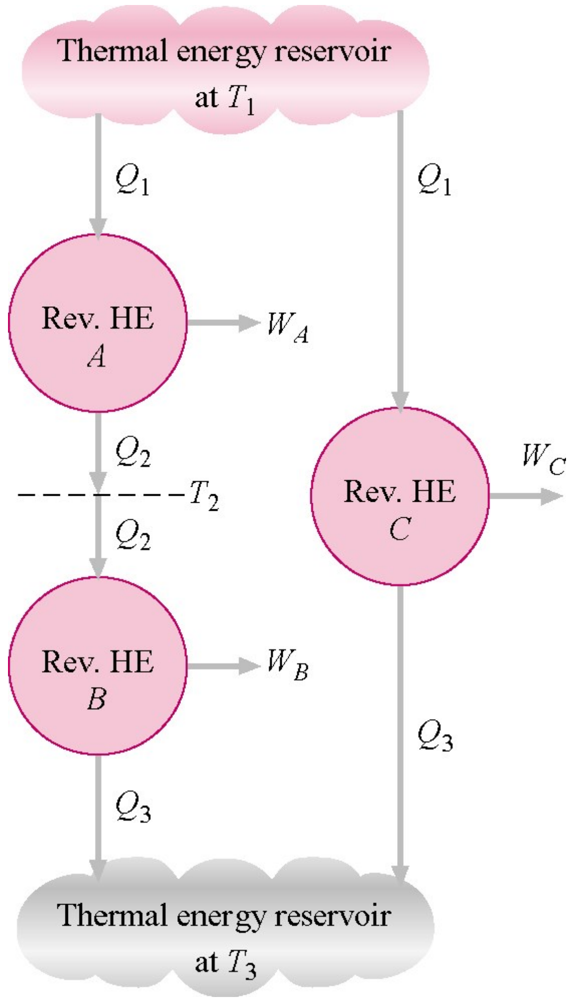
b) Reversible heat engines will have the same efficiency
- $\eta_{th,Carnot} = 1 - \frac{Q_L}{Q_H} \rightarrow \eta_{th,Carnot} = 1 - f(T_H, T_L)$
- $\eta_{th,Carnot}$ is a function of temperature

3.2.4 Thermodynamic Temperature Scale

- Consider reversible heat engines *A, B, C*
  a) Engines A and C supplied with Q_1 from reservoir T_1
  b) Engines B and C reject Q_3 to reservoir T_3
  c) Engine A rejects Q_2 to reservoir T_2
  d) Q_2 supplied to Engine B from reservoir T_2

- Engine A+B will have the same efficiency as engine C

- Thermal efficiency: $\eta_{th} = W/Q_{IN} = (Q_{IN} - Q_{out})/Q_{IN}$
  - $\eta_{th,\,A} = 1 - Q_2/Q_1 \quad \& \quad Q_2/Q_1 = \psi(T_1, T_2)$
  - $\eta_{th,\,B} = 1 - Q_3/Q_2 \quad \& \quad Q_3/Q_2 = \psi(T_2, T_3)$
  - $\eta_{th,\,C} = 1 - Q_3/Q_1 \quad \& \quad Q_3/Q_1 = \psi(T_1, T_3)$
  - ψ is a functional relationship



3.2.4 Thermodynamic Temperature Scale

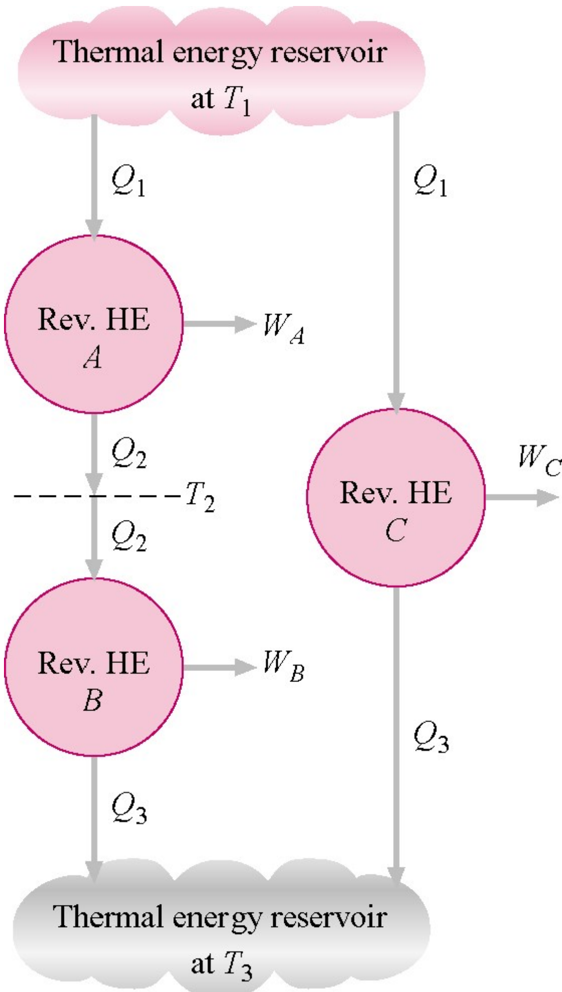
- Functional relations of the three Carnot cycles:

$$\frac{Q_1}{Q_2} = \psi(T_1, T_2) \qquad \frac{Q_2}{Q_3} = \psi(T_2, T_3) \qquad \frac{Q_1}{Q_3} = \psi(T_1, T_3)$$

- Take: $\frac{Q_1}{Q_3} = \frac{Q_1}{Q_2} \times \frac{Q_2}{Q_3} \rightarrow \psi(T_1, T_3) = \psi(T_1, T_2) \times \psi(T_2, T_3)$
- Left hand side is independent of T_2
- Right hand side must also be independent of T_2
- The function, ψ, must be such that

$$\psi(T_1, T_2) = \frac{f(T_1)}{f(T_2)} \qquad \psi(T_2, T_3) = \frac{f(T_2)}{f(T_3)}$$

- Thus, $\psi(T_1, T_3) = \frac{f(T_1)}{f(T_2)} \times \frac{f(T_2)}{f(T_3)} = \frac{f(T_1)}{f(T_3)}$
- $\frac{Q_1}{Q_3} = \psi(T_1, T_3) = \frac{f(T_1)}{f(T_3)}$

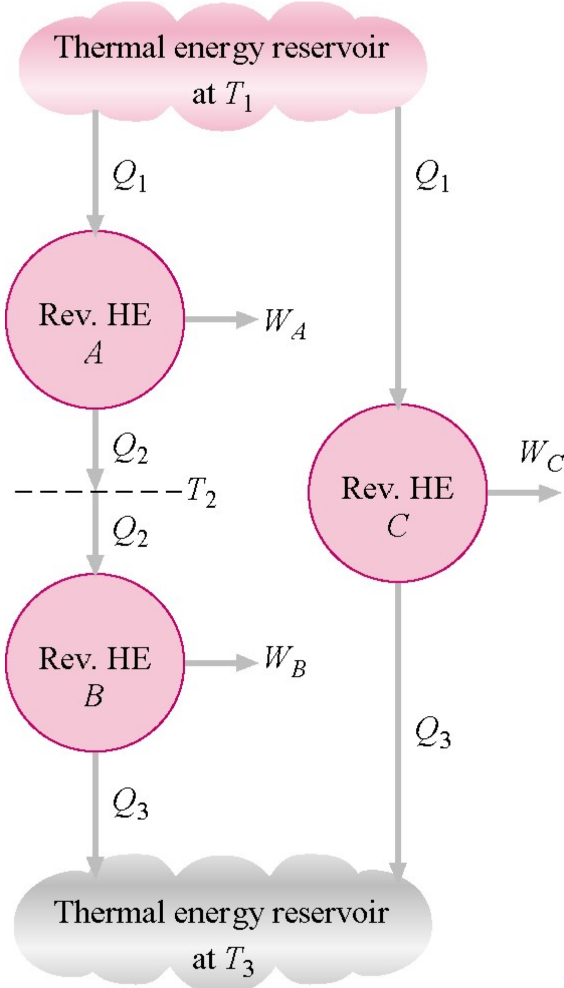


3.2.4 Thermodynamic Temperature Scale

- General form
  - $\frac{Q_1}{Q_3} = \psi(T_1, T_3) = \frac{f(T_1)}{f(T_3)}$

- Simplest form of f is the absolute temperature, $f(T)$=T.

$$\frac{Q_1}{Q_3} = \frac{(T_1)}{(T_3)} \quad \text{or more generally} \quad \frac{Q_H}{Q_L} = \frac{(T_H)}{(T_L)}$$



The Carnot thermal efficiency becomes

$$\eta_{th,rev} = 1 - \frac{Q_3}{Q_1} \longrightarrow 1 - \frac{T_3}{T_1}$$

more generally $\eta_{th,rev} = 1 - \frac{Q_L}{Q_H} \longrightarrow 1 - \frac{T_L}{T_H}$

Q's become T's

3.2.4 Thermodynamic Temperature Scale

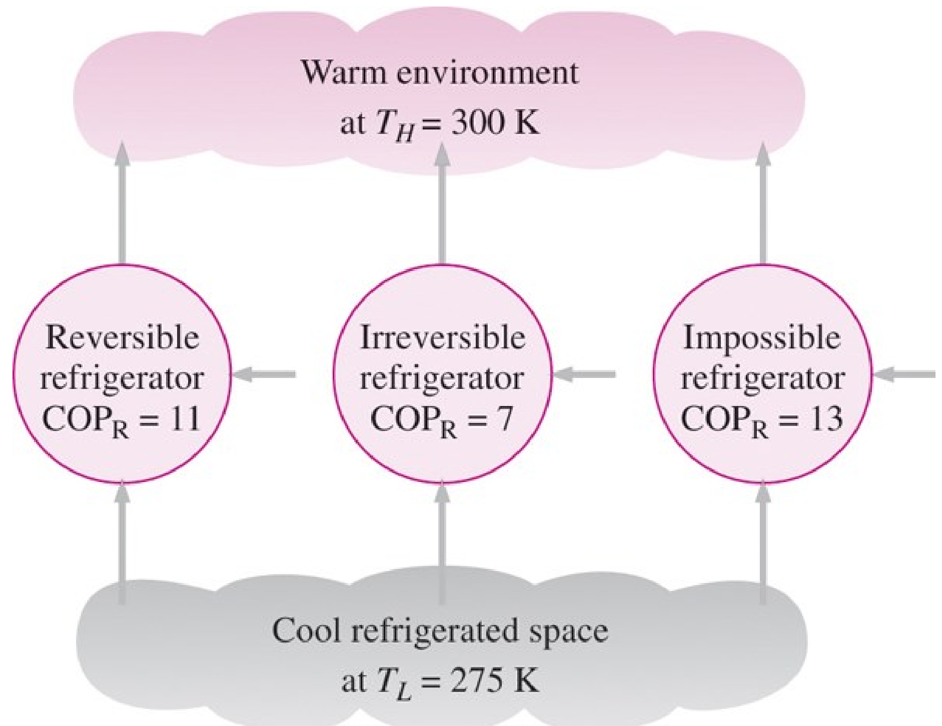
- Relationships of η_{th} for heat engines:

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

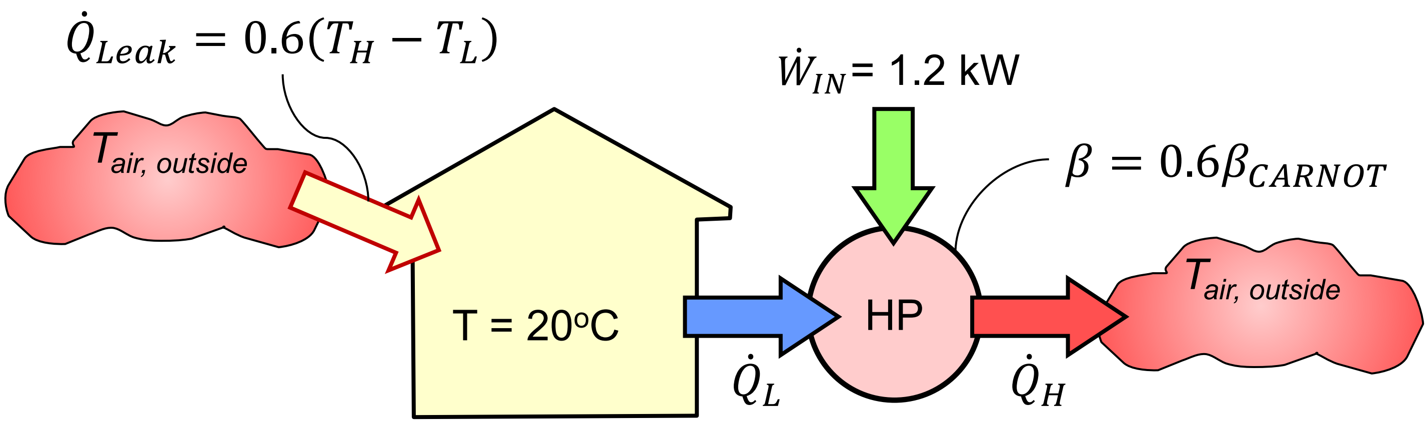
- Remember for Carnot
  - Temperature is in absolute units (Kelvin)
  - $\eta_{th,Carnot} = 1 - \dfrac{Q_L}{Q_H} \longrightarrow 1 - \dfrac{T_L}{T_H}$

Heat Pump and Refrigeration

- $COP_{HP} = \beta' = \dfrac{Q_H}{Q_H - Q_L} \underbrace{=}_{Carnot} \dfrac{T_H}{T_H - T_L}$
- $COP_{REF} = \beta = \dfrac{Q_L}{Q_H - Q_L} \underbrace{=}_{Carnot} \dfrac{T_L}{T_H - T_L}$
- $COP_{Carnot} > COP_{real}$



Example 3.2:
An air conditioner maintains a house at T_L = 20°C with a maximum power input of $\dot{W}_{IN}$ = 1.2 kW. Hot outside air leaks into the house as $\dot{Q}_{leak} = 0.6(T_H - T_L)\ [kW]$. The refrigeration COP is $\beta = 0.6\beta_{CARNOT}$. Find the maximum outside temperature, T_H, for which the air conditioner until provides sufficient cooling.



Ans: 311.9 K or 38.8°C

Extra:

a) Determine the cooling capacity of the air conditioner in kW.

b) If the heat pump operated on the Carnot cycle, how much would $\dot{W}_{IN}$ decrease to maintain the same cooling capacity?

Ans: (a) $\dot{Q}_L = 11.25\ kW$, (b) $\dot{W}_{in} = 0.72 kW$; decrease by ~ 40%