CAE 208 / MMAE 320: Thermodynamics

Fall 2023

November 14, 2023

Intro to second law (3) and entropy (1)

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ANNOUNCEMENTS

Announcements

- Assignment 8 was due last night. There was an issue with the submission page. It is fixed now, and the deadline is extended till tonight

- Assignment 9 is posted (2-3 days more extension is fine to submit it on Friday after the Thanksgiving)

Announcements

- How was midterm exam 2?

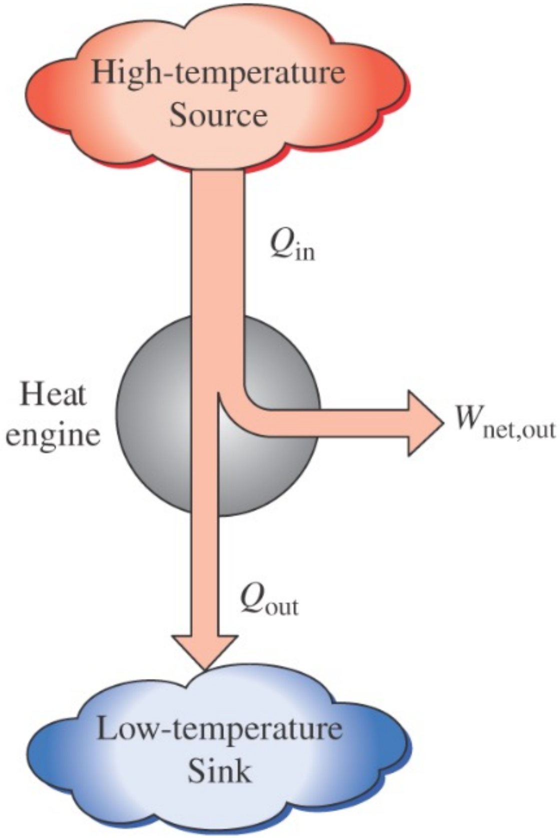
Announcements

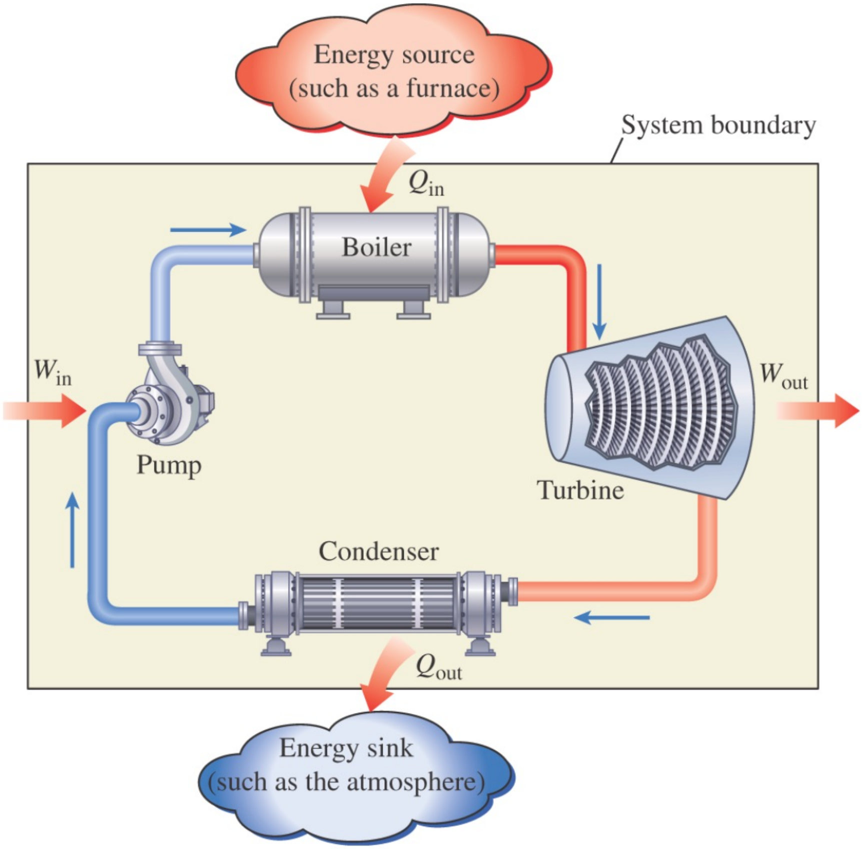
- Extra grade activity:
  - The formal write up will be posted by this Thursday
  - A group of 2 students (max 3 students for hands-on activities)
  - Submit the idea and the names by the end of next week
  - Submit the final deliverable on 12/10 (after the exams are over)
  - A few topics are:
    1. Create animations or schematic related to the topics that we cover in the course
    2. Build something small but relevant (e.g., manometer, barometer, piston–cylinder, …) – if you need to purchase things, please let me know
    3. Solve some of assignments, examples, or exam questions using a programming language (e.g., EES, Python, …). I will provide a short training video

RECAP

Recap

- Heat engines cycles are as following:





Recap

- The Second Law of Thermodynamics: Kelvin-Planck Statement:

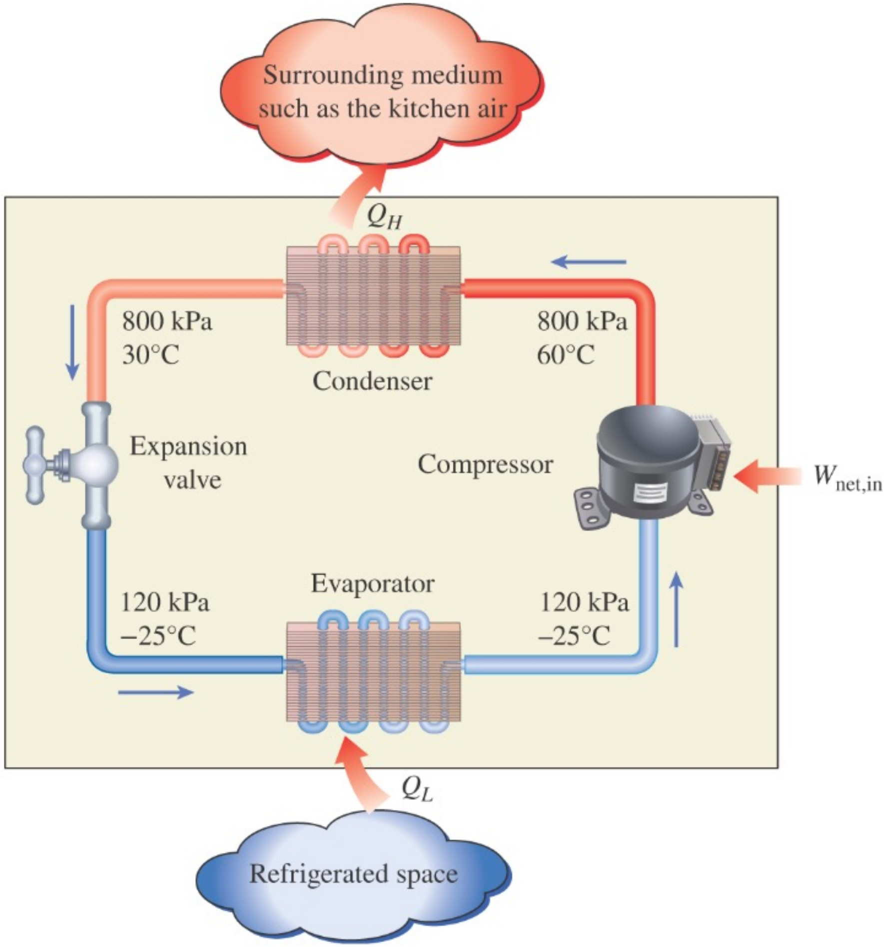
It is impossible for any device that operates on a cycle to receive heat from a single reservoir and produce a net amount of work

No heat engine can have a thermal efficiency of 100 percent

For a power plant to operate, the working fluid must exchange heat with the environment as well as the furnace

Recap

- The most frequently used refrigeration cycle is the vapor-compression refrigeration cycle

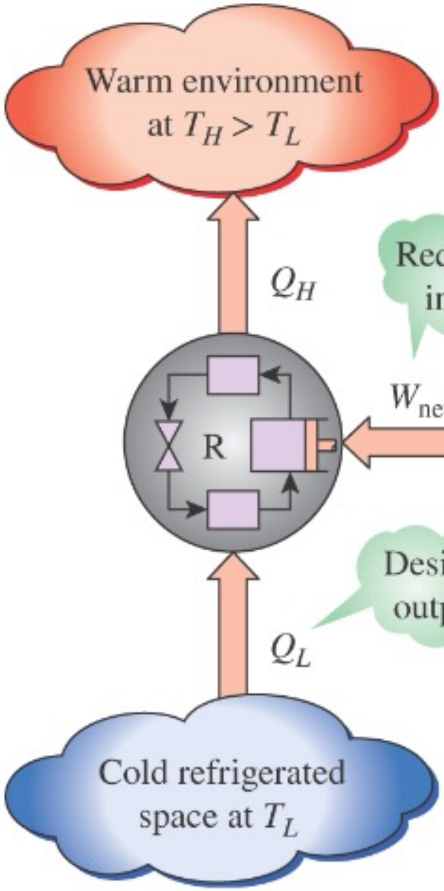


Recap

- ***Heat Pumps:*** The objective of a heat pump is to supply heat Q_H into the warmer space

$$COP_{HP} = \frac{Desired\ output}{Require\ input} = \frac{Q_H}{W_{net,in}}$$

$$COP_{HP} = \frac{Desired\ output}{Require\ input} = \frac{Q_H}{Q_H - Q_L}$$



Recap

- The Second Law of Thermodynamics: Clasius Statement

It is impossible to construct a device that operates in a cycle and produces no effect other than the transfer of heat from a lower-temperature body to a higher-temperature body.

Recap

- Equivalence of the Two Statements
  - ❑ The Kelvin–Planck and the Clausius statements are equivalent in their consequences, and either statement can be used as the expression of the second law of thermodynamics
  - ❑ Any device that violates the Kelvin–Planck statement also violates the Clausius statement, and vice versa

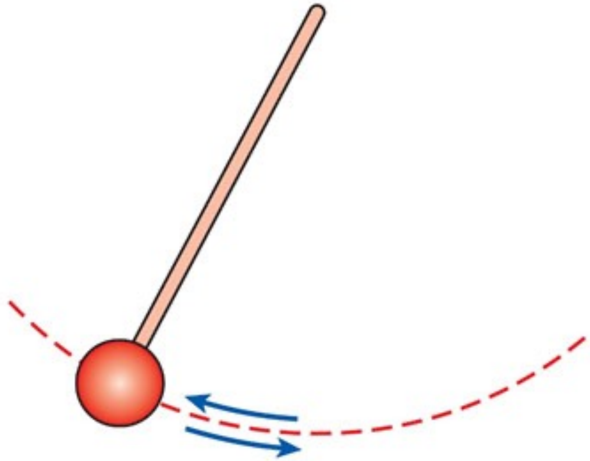
REVERSIBLE AND IRREVERSIBLE PROCESSES

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

- All the processes occurring in nature are irreversible



(*a*) Frictionless pendulum

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

Reversible and Irreversible Processes

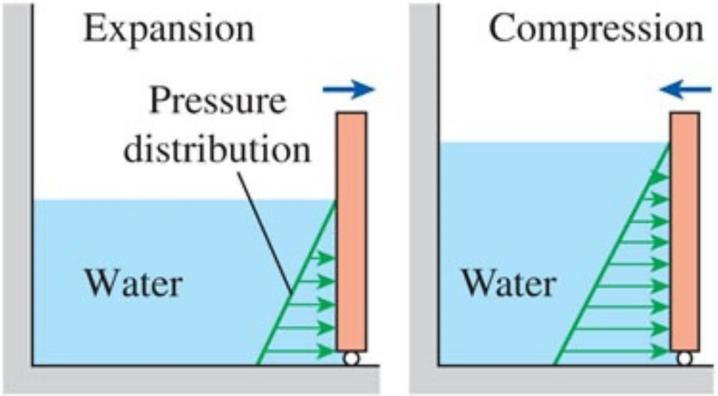
- Why are we interested in reversible processes?
  1) They are easy to analyze
  2) They serve as idealized models (theoretical limits) to which actual processes can be compared.

- Some processes are more irreversible than others

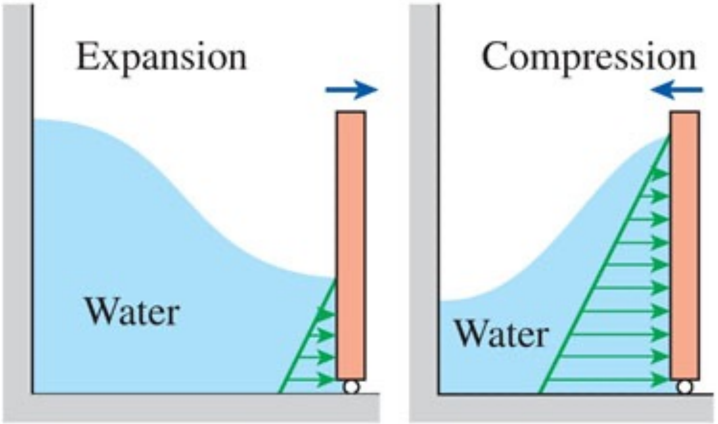
- We try to approximate reversible processes

Reversible and Irreversible Processes

- Reversible processes deliver the most and consume the least work



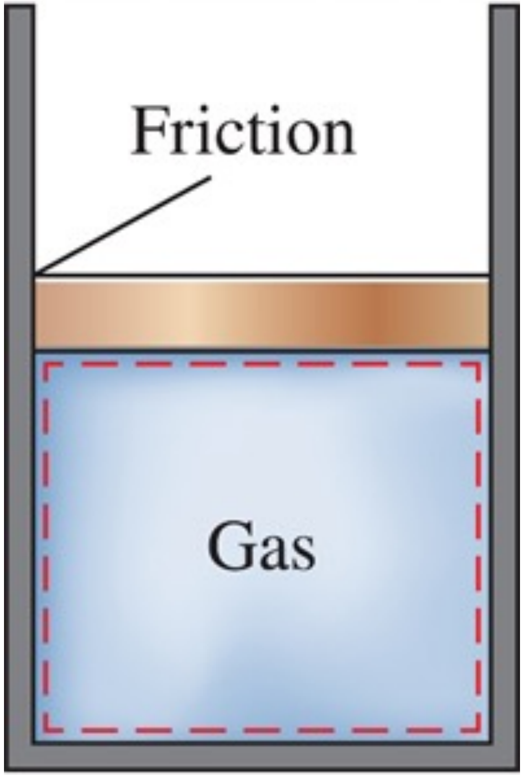
(*a*) Slow (reversible) process

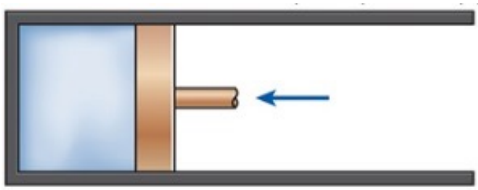


(*b*) Fast (irreversible) process

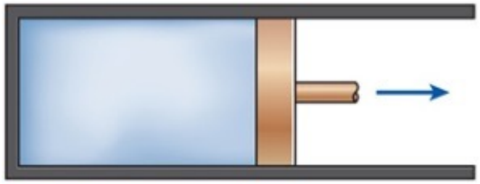
Reversible and Irreversible Processes

- The factors that cause a process to be irreversible are called irreversibilities





(*a*) Fast compression



(*b*) Fast expansion

(*c*) Unrestrained expansion

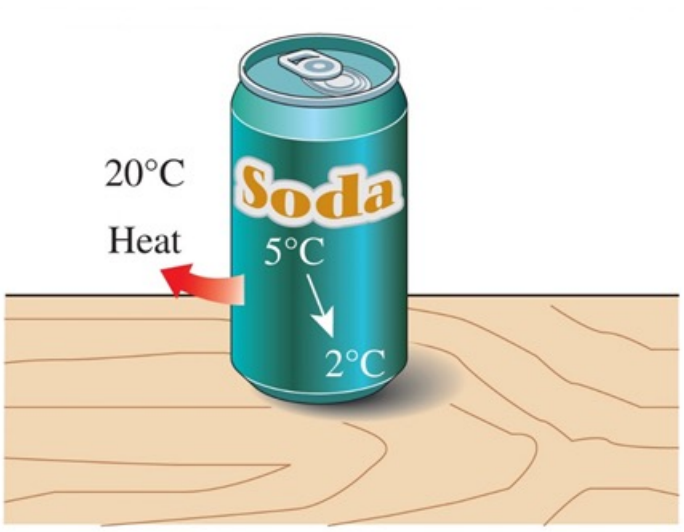
Reversible and Irreversible Processes

- Irreversibilities includes
  - ☐ Friction
  - ☐ Unrestrained expansion
  - ☐ Mixing of two fluids
  - ☐ Heat transfer across a finite temperature difference
  - ☐ Electric resistance
  - ☐ Inelastic deformation of solids
  - ☐ Chemical reactions

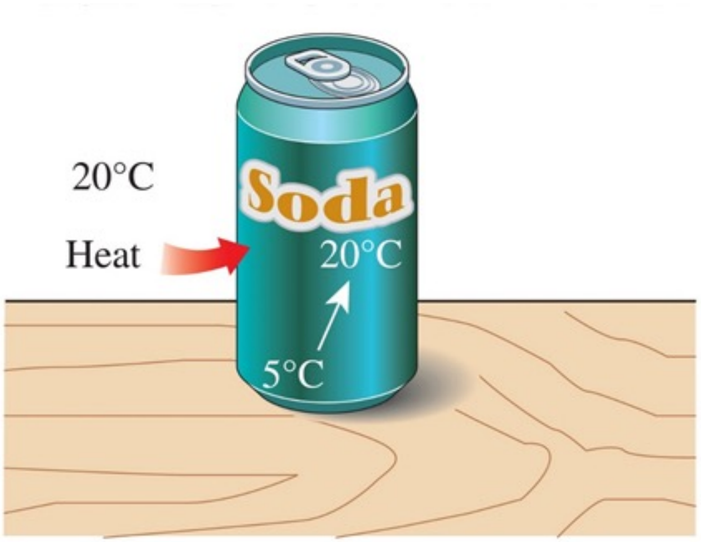
- The presence of any of these effects renders a process irreversible

Reversible and Irreversible Processes

- Heat transfer through a temperature difference is irreversible
- The reverse process is impossible



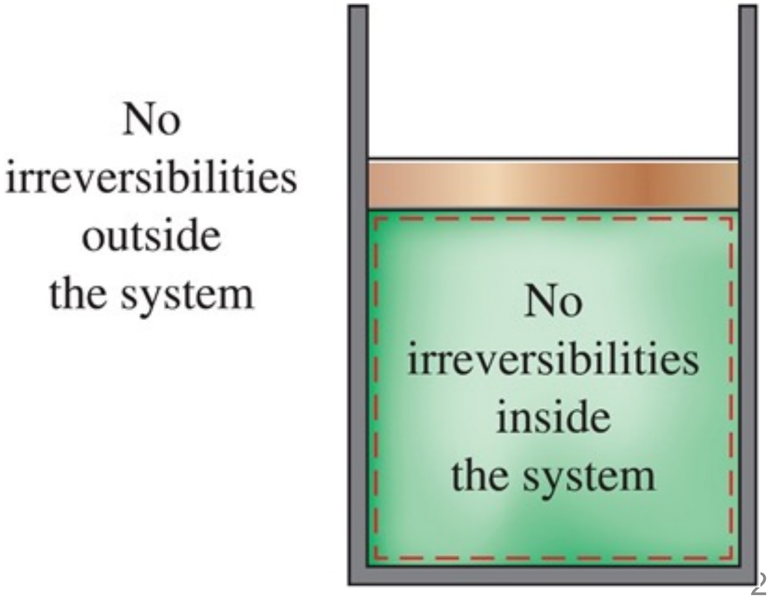
(*b*) An impossible heat transfer process



(*a*) An irreversible heat transfer process

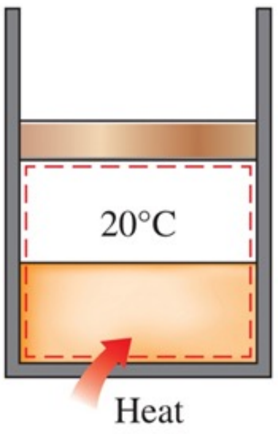
Reversible and Irreversible Processes

- Internally and Externally Reversible Processes:
  - ☐ Internally reversible process: If no irreversibilities occur within the boundaries of the system during the process (e.g., a quasi-equilibrium process)
  - ☐ Externally reversible: If no irreversibilities occur outside the system boundaries (e.g., heat transfer between reservoir and a system)

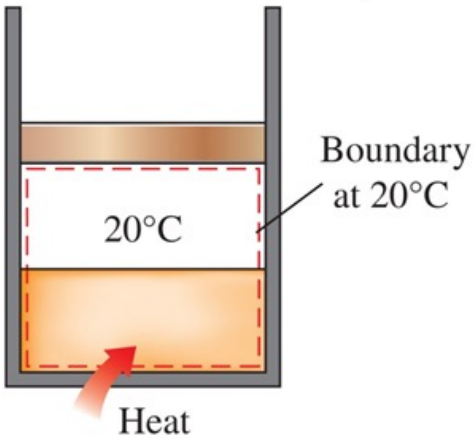


Reversible and Irreversible Processes

- Internally and Externally Reversible Processes:
  - 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*) Totally reversible

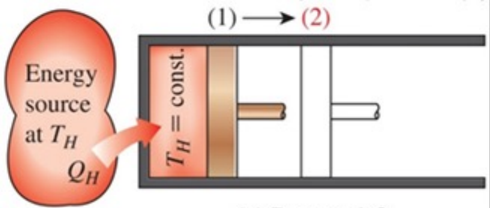


(*b*) Internally reversible

THE CARNOT CYCLE

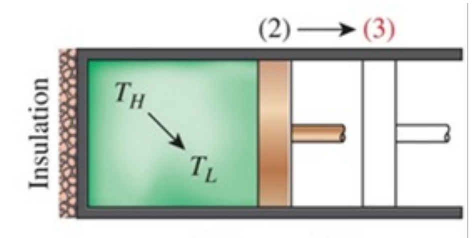
The Carnot Cycle

- Execution of the Carnot cycle in a closed system:



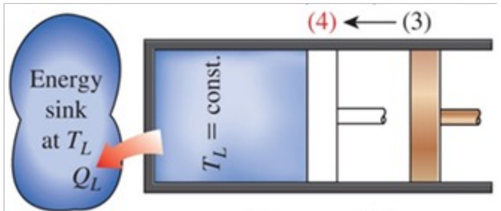
(*a*) Process 1-2

Reversible Isothermal Expansion (process 1-2, T_H = constant)



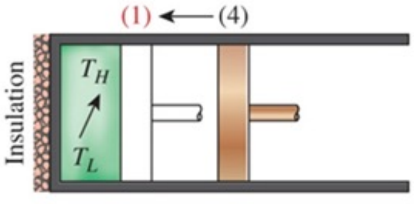
(*b*) Process 2-3

Reversible Adiabatic Expansion (process 2-3, temperature drops from T_H to T_L)



(*c*) Process 3-4

Reversible Isothermal Compression (process 3-4, T_L = constant)

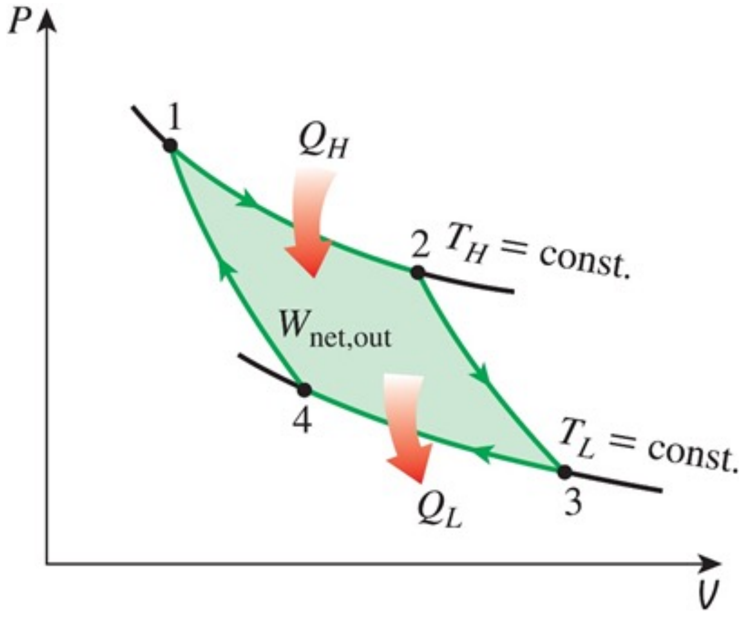


(*d*) Process 4-1

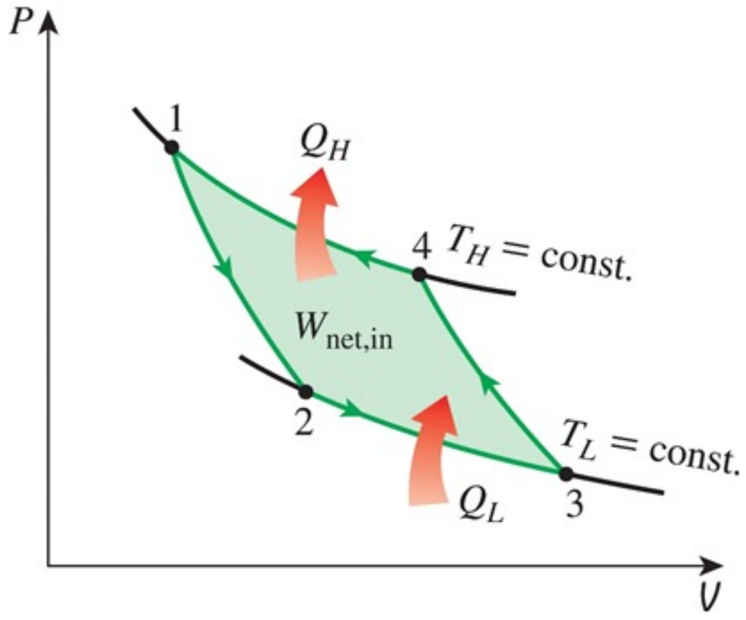
Reversible Adiabatic Compression (process 4-1, temperature rises from T_L to T_H)

The 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



P-V diagram of the Carnot cycle

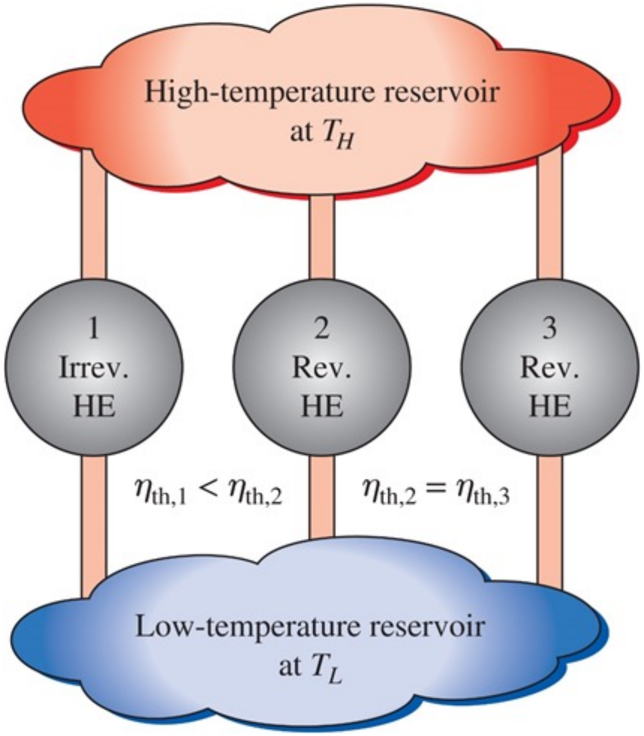


P-V diagram of the reversed Carnot cycle

THE CARNOT PRINCIPLES

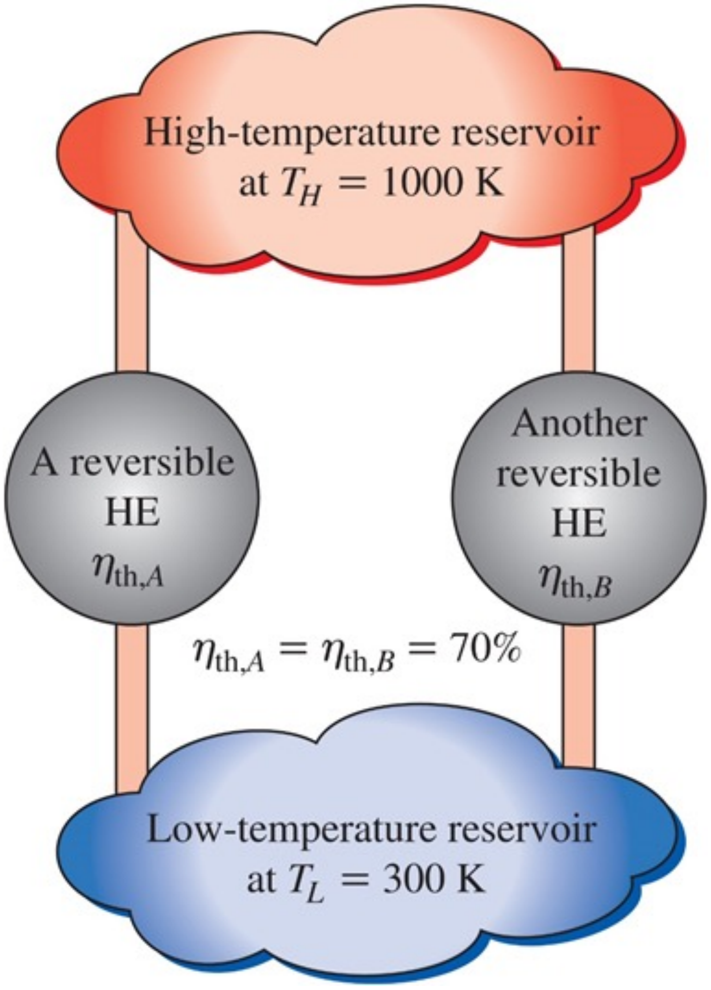
The Carnot Principles

- Two main 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



The Carnot Principles

- All reversible heat engines operating between the same two reservoirs have the same efficiency (the second Carnot principle)

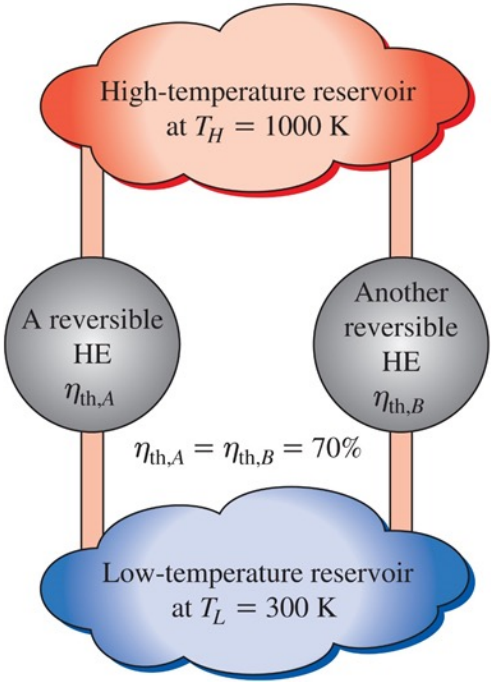


THE THERMODYNAMIC TEMPERATURE SCALE

The Thermodynamic Temperature Scale

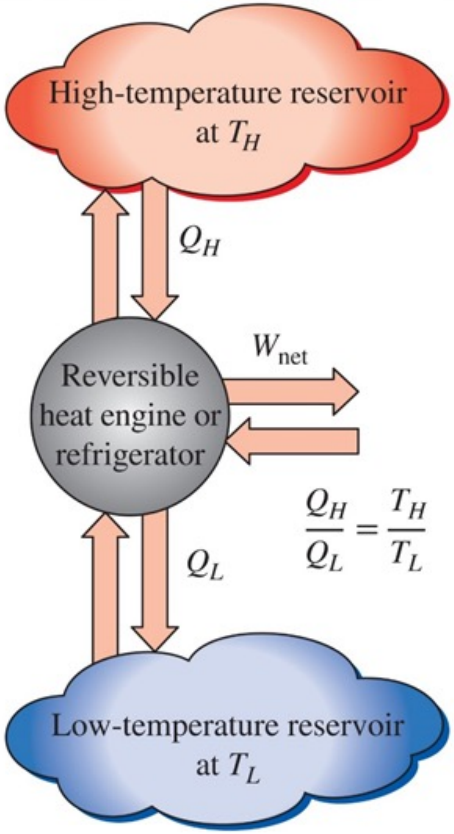
- A temperature scale that is independent of the properties of the substances that are used to measure temperature is called a thermodynamic temperature scale

- Such a temperature scale offers great conveniences in thermodynamic calculations



The Thermodynamic Temperature Scale

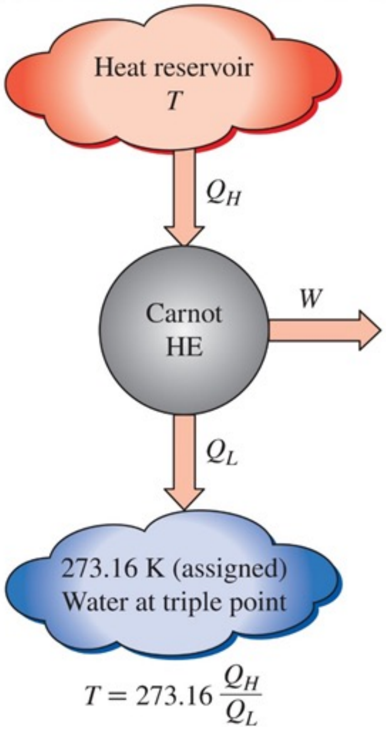
- This temperature scale is called the Kelvin scale, and the temperatures on this scale are called absolute temperatures
  - ❑ For reversible cycles, the heat transfer ratio Q_H/Q_L can be replaced by the absolute temperature ratio T_H/T_L



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

The Thermodynamic Temperature Scale

- This temperature scale is called the Kelvin scale, and the temperatures on this scale are called absolute temperatures
  - ❑ A conceptual experimental setup to determine thermodynamic temperatures on the Kelvin scale by measuring heat transfers Q_H and Q_L.

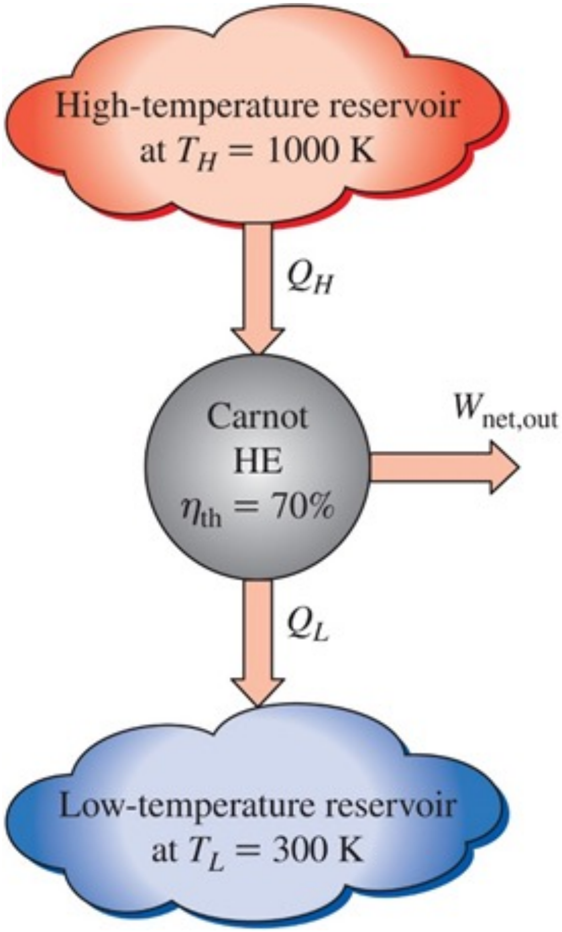


$$T = 273.16 \frac{Q_H}{Q_L}$$

THE CARNOT HEAT ENGINE

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



The Carnot Heat Engine

- Any heat engine:

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

- Any Carnot heat engine:

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

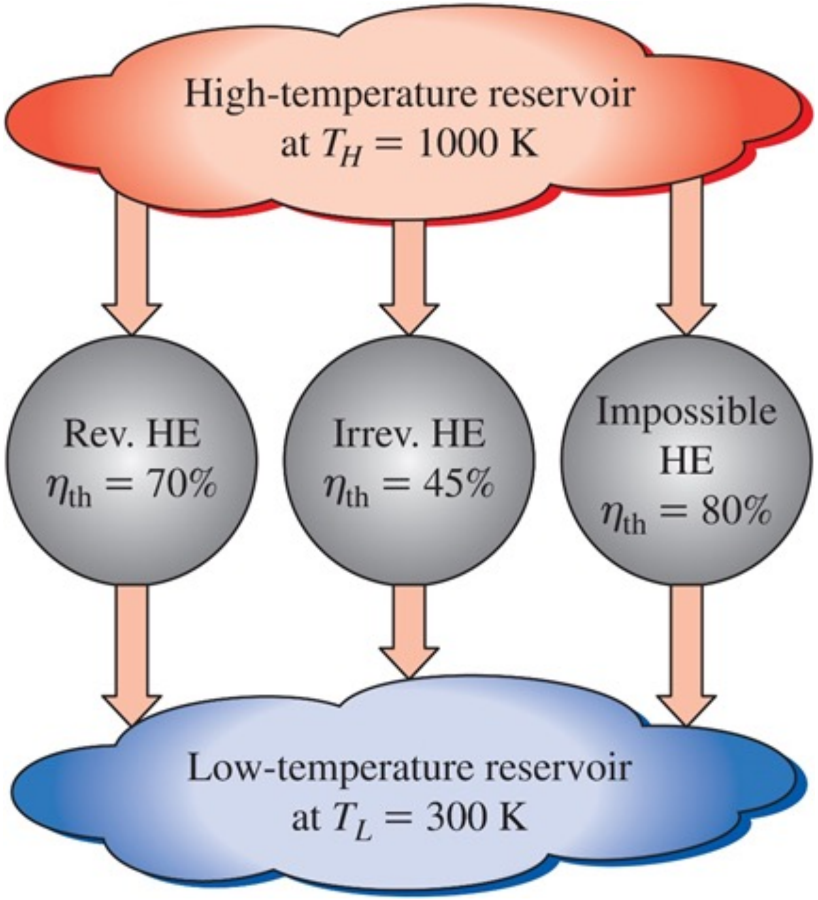
The Carnot Heat Engine

- We can say:

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

The Carnot Heat Engine

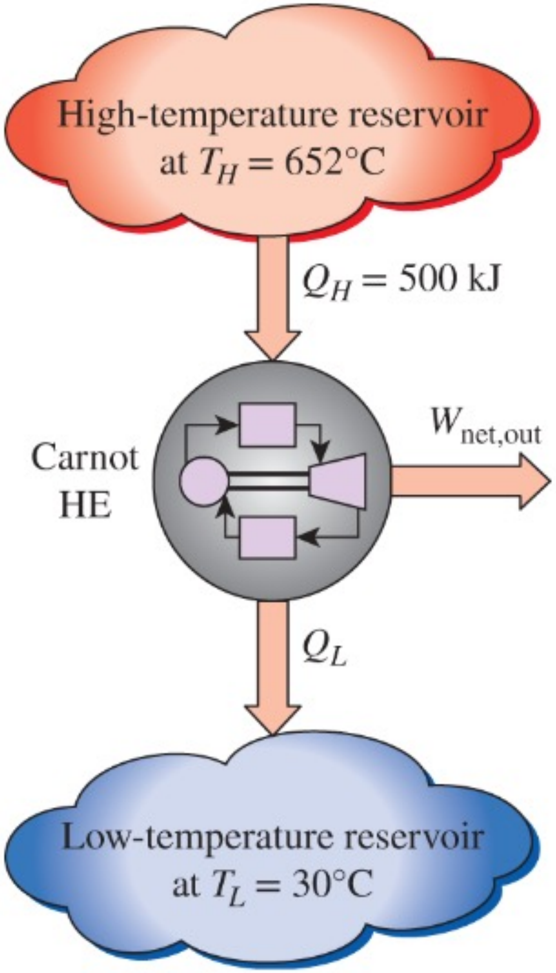
- No heat engine can have a higher efficiency than a reversible heat engine operating between the same high- and low-temperature reservoirs



CLASS ACTIVITY

Class Activity

- A Carnot heat engine 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) A thermal efficiency of this Carnot engine
  b) The amount of heat rejected to the sink per cycle



Class Activity

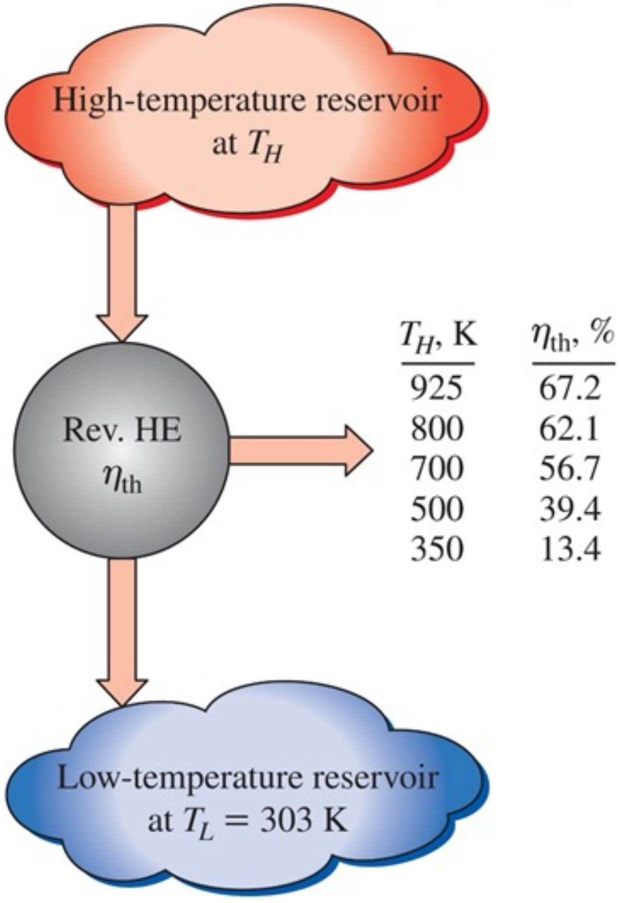
- Solution:

$$\eta_{th,rev} = 1 - \frac{T_L}{T_H} = 1 - \frac{30 + 273}{652 + 273} = 0.672$$

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

The Carnot Heat Engine

- The quality of Energy: The fraction of heat that can be converted to work as a function of source temperature (for T_L = 303 K).

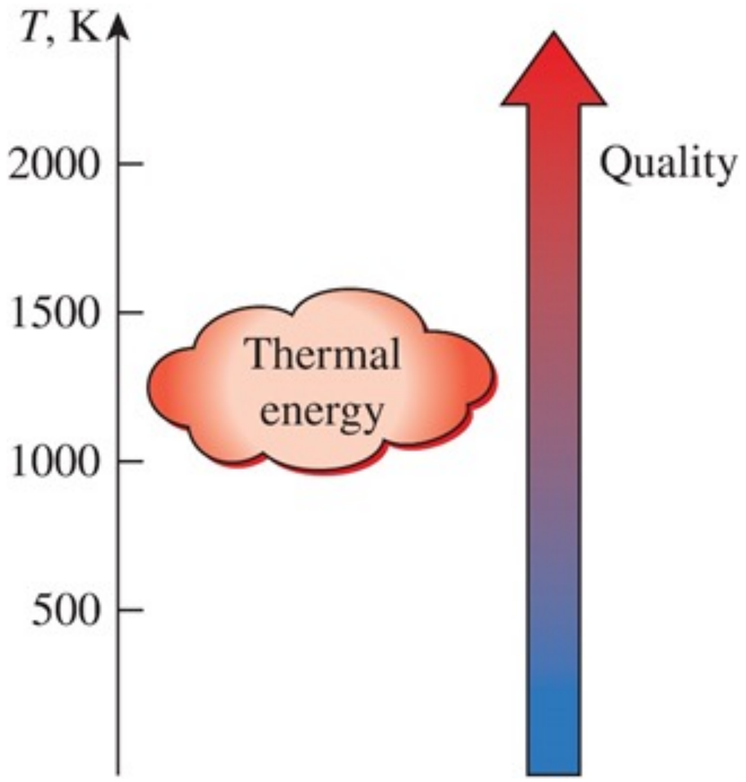


T_H, K	η_{th}, %
925	67.2
800	62.1
700	56.7
500	39.4
350	13.4

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

The Carnot Heat Engine

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



THE CARNOT REFRIGERATOR AND HEAT PUMP

The Carnot Refrigerator and Heat Pump

- For any refrigerator or heat pump:

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

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

The Carnot Refrigerator and Heat Pump

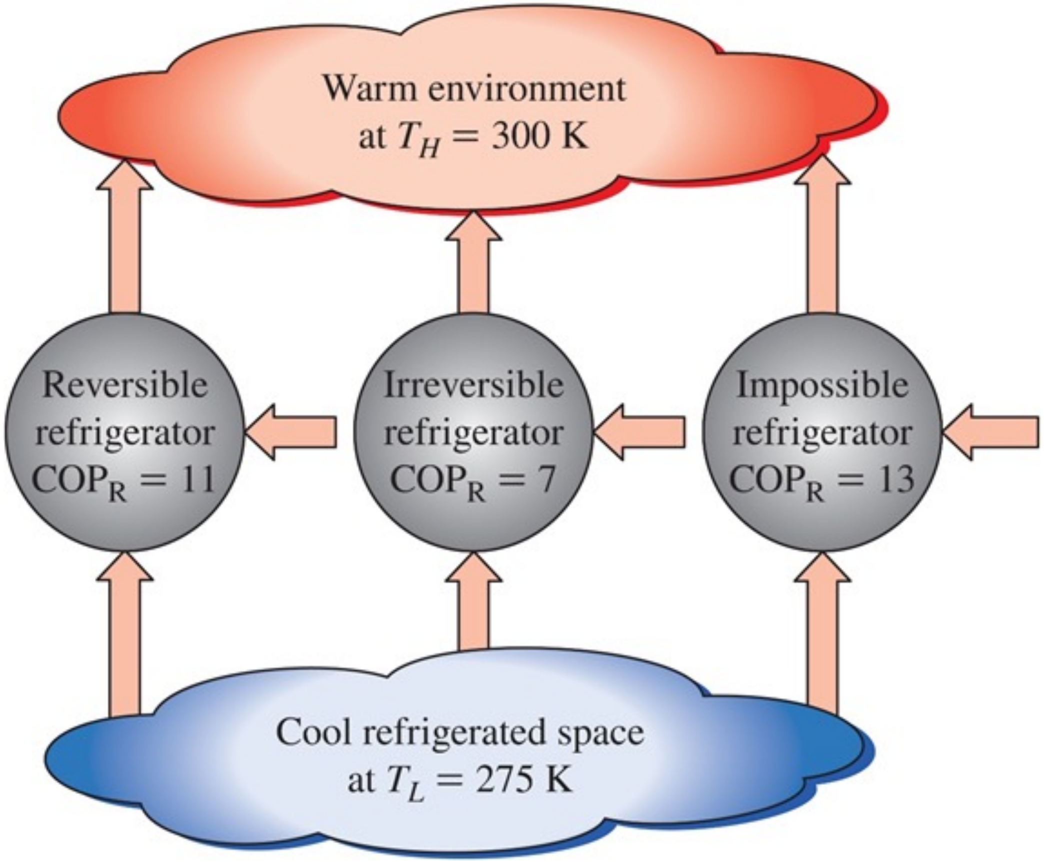
- For any refrigerator or heat pump:

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

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

The Carnot Refrigerator and Heat Pump

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



The Carnot Refrigerator and Heat Pump

- The COP of a reversible refrigerator or heat pump is the maximum theoretical value for the specified temperature limits
- Actual refrigerators or heat pumps may approach these values as their designs are improved, but they can never reach them

$$COP_R = \begin{cases} < COP_{R,rev} & irreversible\ refrigerator \\ = COP_{R,rev} & reversible\ refrigerator \\ > COP_{R,rev} & impossible\ refrigerator \end{cases}$$

The Carnot Refrigerator and Heat Pump

- The COPs of both the refrigerators and the heat pumps decrease as T_L decreases
- That is, it requires more work to absorb heat from lower-temperature media.

$$COP_{HP} = \begin{cases} < COP_{HP,rev} & \text{irreversible heat pump} \\ = COP_{HP,rev} & \text{reversible heat pump} \\ > COP_{HP,rev} & \text{impossible heat pump} \end{cases}$$

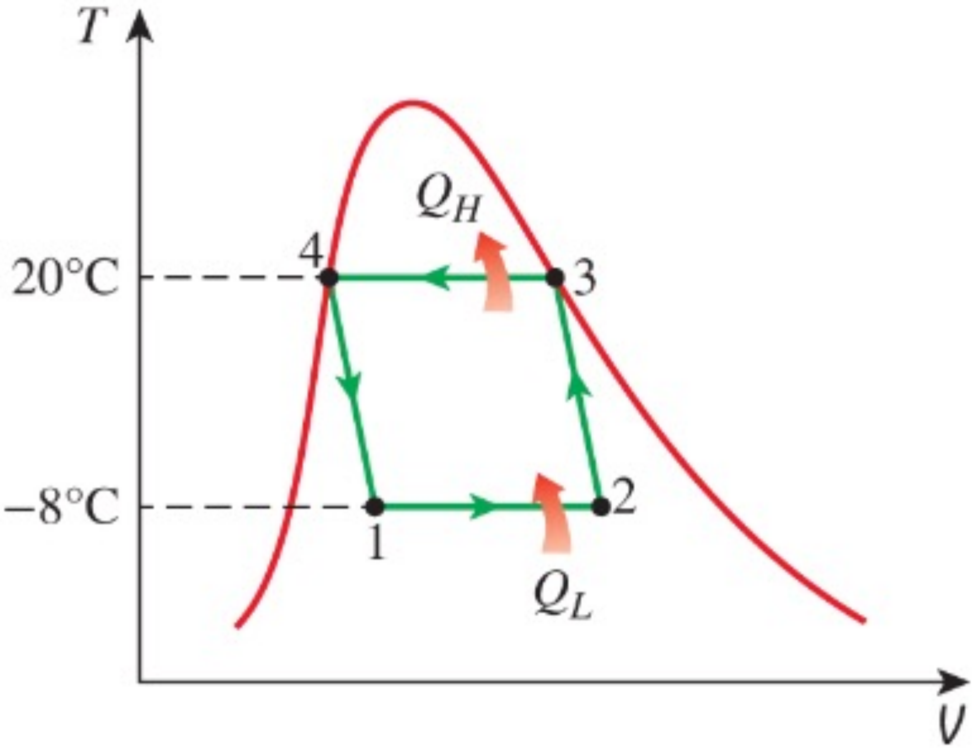
CLASS ACTIVITY

Class Activity

- A Carnot refrigeration cycle is executed in a closed system in the saturated liquid-vapor mixture region using 0.8 kg of refrigerant 134-a as the working fluid. The maximum and the minimum temperatures in the cycle are 20 and -8 °C, respectively. It is known that the refrigerant is saturated at the end of the hat rejection process, and the net work input to the cycle is 15 kJ. Determine the fraction of the mass of the refrigerant that vaporizes during the heat addition process and the pressure at the end of the rejection process.

Class Activity

- Solution:



Class Activity

- Solution:

$$COP_R = \frac{1}{\frac{T_H}{T_L} - 1} = \frac{1}{\frac{20 + 273}{-8 + 273} - 1} = 9.464$$

$$Q_L = COP_R \times W_{in} = (9.464)(15\ kJ) = 142\ kJ \quad (The\ amount\ of\ cooling)$$

$$Q_l = m_{eva} h_{fg\ @\ -8\ ^{\circ}C} = \frac{142\ kJ}{204.59\,\frac{kJ}{kg}} = 0.694\ kg \quad (Table\ A - 11)$$

Class Activity

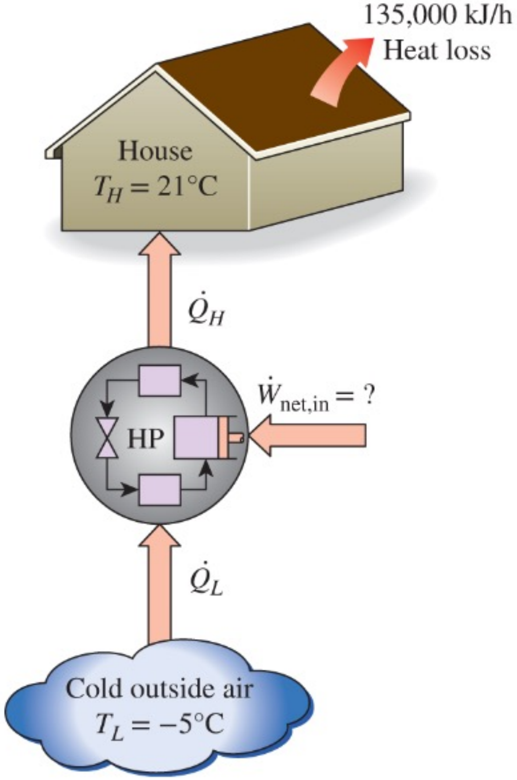
- Solution:

$$Mass\ Fraction = \frac{m_{evap}}{m_{total}} = \frac{0.694\ kg}{0.8\ kg} = 0.868$$

$$P_4 = P_{sat\ @\ 20°C} = 572.1\ kPa$$

Class Activity

- A heat pump is to be used during the winter. The house is to be maintained at 21 °C at all times. The house is estimated to be losing heat at a rate of 135,000 kJ/h when the outside temperature drops to -5 °C. Determine the minimum power required to drive this heat pump.

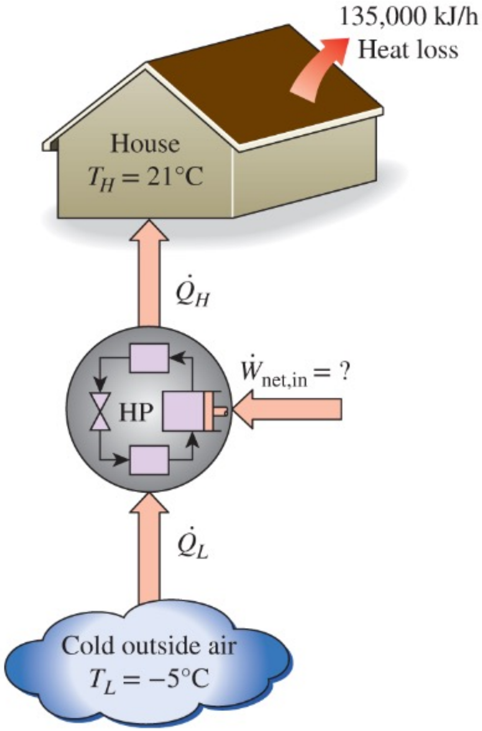


Class Activity

- Solution:

$$COP_{HP,rev} = \frac{1}{1 - T_L/T_H} = \frac{1}{1 - \frac{-5+273}{21+273}} = 11.3$$

$$\dot{W}_{net,in} = \frac{\dot{Q}_H}{COP_{HP}} = \frac{37.5\ kW}{11.3} = 3.32\ kW$$



ENTROPY

Entropy

- Objectives of Chapter 8:
  - ☐ Apply the second law of thermodynamics to processes
  - ☐ Define a new property called entropy to quantify the second-law effects
  - ☐ Establish the increase of entropy principle
  - ☐ Calculate the entropy changes that take place during processes for pure substances, incompressible substances, and ideal gases
  - ☐ Examine a special class of idealized processes, called isentropic processes, and develop the property relations for these processes
  - ☐ Derive the reversible steady-flow work relations
  - ☐ Develop the isentropic efficiencies for various steady-flow devices
  - ☐ Introduce and apply the entropy balance to various systems

Entropy

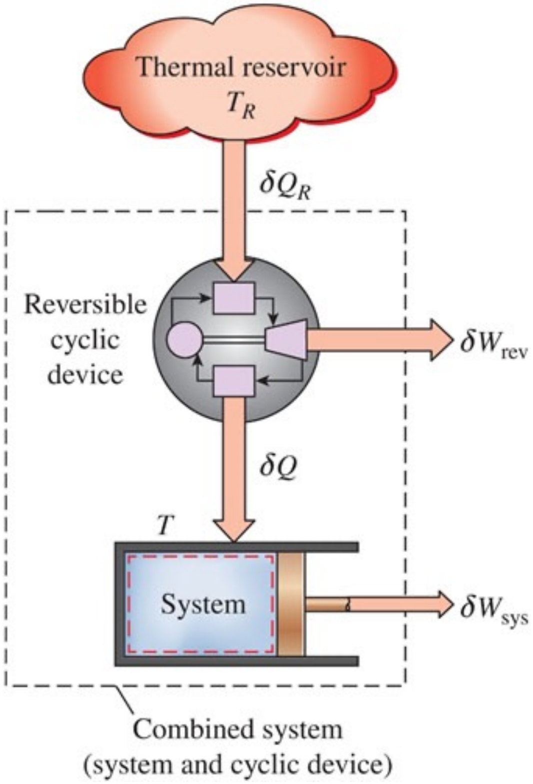
- While the first law of thermodynamics deals with the property “energy” and “the conservation of it”, the second law leads to the definition of a new property called “entropy”

- Entropy is somewhat an abstract property, and it is difficult to give a physical description of it without considering the microscopic state of the system

- Entropy is best understood and appreciated by studying *its uses in commonly encountered engineering processes*, and this is what we intend to do

Entropy

- The equality in the Clausius inequality holds for totally or just internally reversible cycles and the inequality for the irreversible ones



$$\oint \frac{\delta Q}{T} \leq 0$$

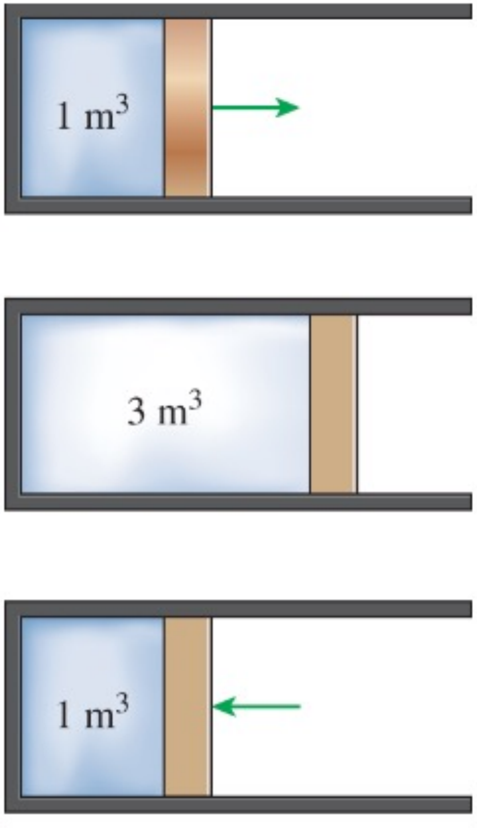
Entropy

- The equality in the Clausius inequality holds for totally or jut internally reversible cycles and the inequality for the irreversible ones

$$\left(\oint \frac{\delta Q}{T}\right)_{int,rev} = 0$$

Entropy

- Let's try to find out more about entropy with looking at work in a cycle:



$$\oint dV = ?$$

$$\oint dV = \Delta V_{cycle} = 0$$

$How\ about\ \delta W?$

Entropy

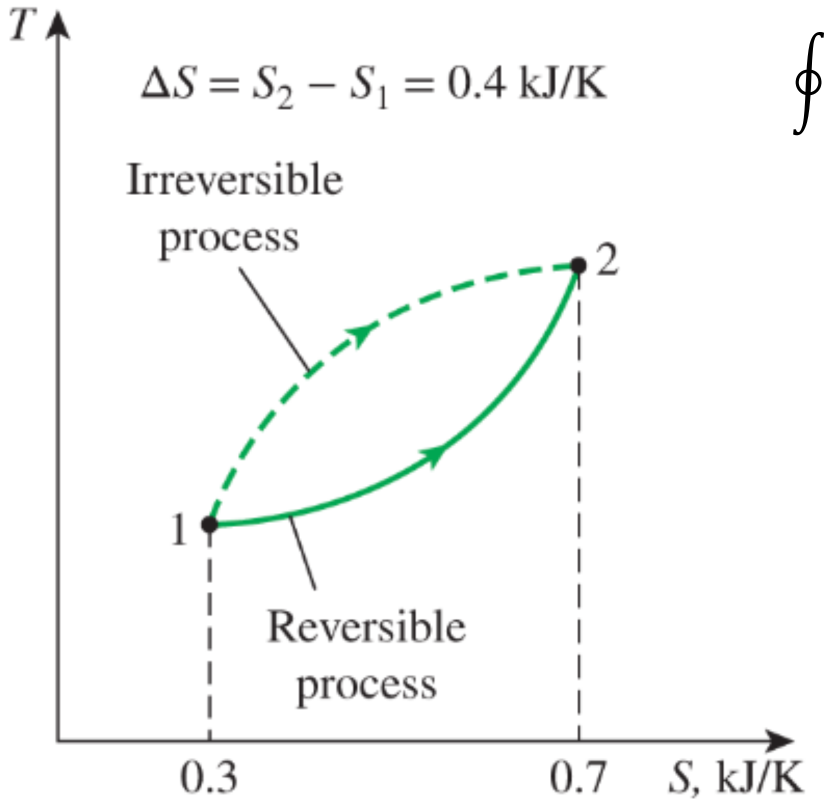
- Let’s try to find out more about entropy with looking into a cycle:

$$dS = \oint \frac{\delta Q}{T} \qquad (\frac{kJ}{K})$$

$$\Delta S = S_2 - S_1 = \int_1^2 \left(\frac{\delta Q}{T}\right)_{int,rev}$$

Entropy

- Pay attention to reversible and irreversible integration:



$$\oint \frac{\delta Q}{T} = if\ internally\ reversible = S$$

Entropy

- A special case: *Internally reversible isothermal* heat transfer processes:

$$\Delta S = \int_1^2 \left(\frac{\delta Q}{T}\right)_{int,rev} = \int_1^2 \left(\frac{\delta Q}{T_0}\right)_{int,rev} = \frac{1}{T_0}\int_1^2 \delta Q_{int,rev}$$

$$\Delta S_{isothermal} = \frac{Q}{T_0} \qquad \left(\frac{kJ}{K}\right)$$

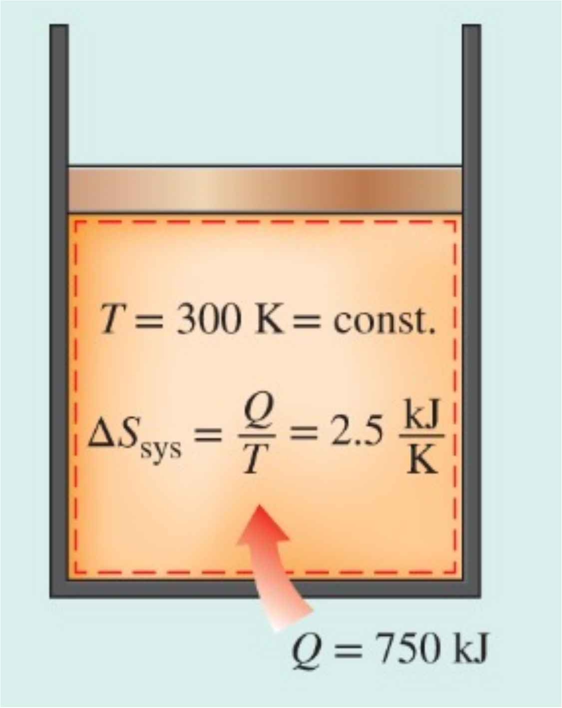
(A reservoir can absorb or supply heat indefinitely at a constant temperature)

Class Activity

- A piston-cylinder device contains a liquid-vapor mixture of water at 300 K. During a constant pressure process, 750 kJ of heat is transferred to the water. As a result of the liquid in the cylinder vaporizes. Determine the entropy change of water during this process.

Class Activity

- Solution:

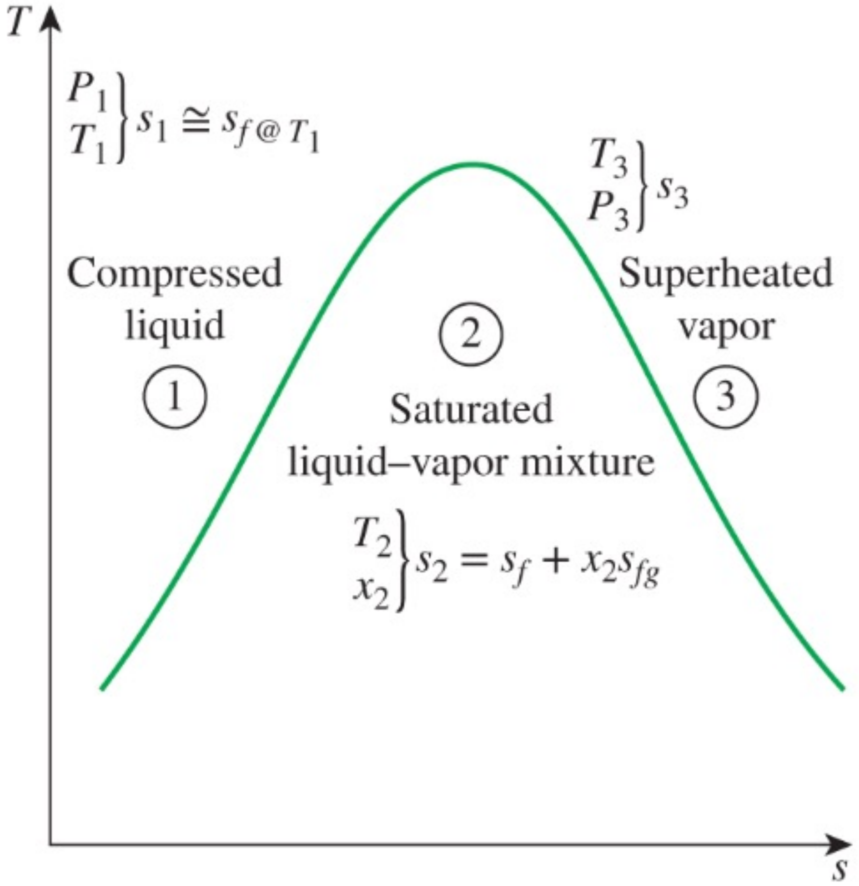


$$\Delta S_{isothermal} = \frac{Q}{T_0} \qquad \left(\frac{kJ}{K}\right)$$

$$\Delta S = \frac{750\ kJ}{300\ K} = 2.5\,\frac{kJ}{K}$$

Entropy Change of Pure Substances

- Entropy is a property:



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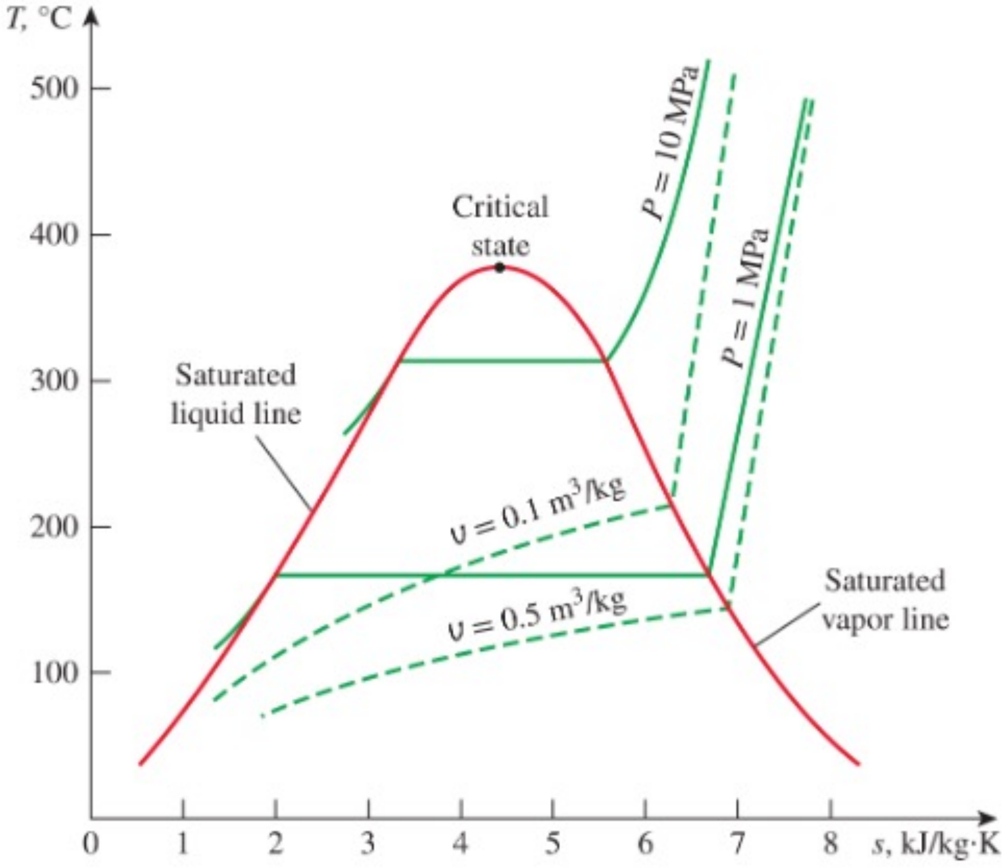

Entropy Change of Pure Substances

- For a closed system (m = constant), during a process we have:

$$\Delta S = m\Delta s = m(s_2 - s_1)$$