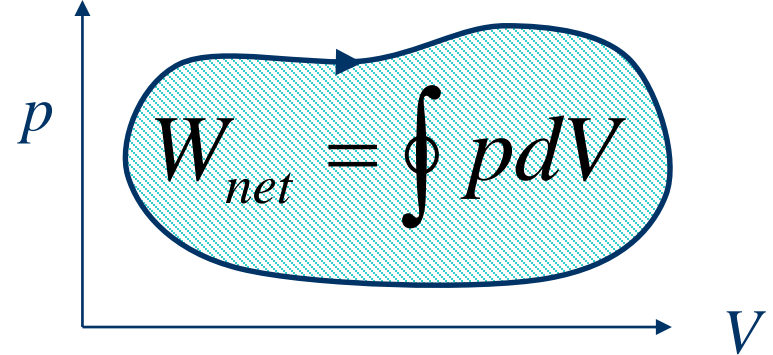


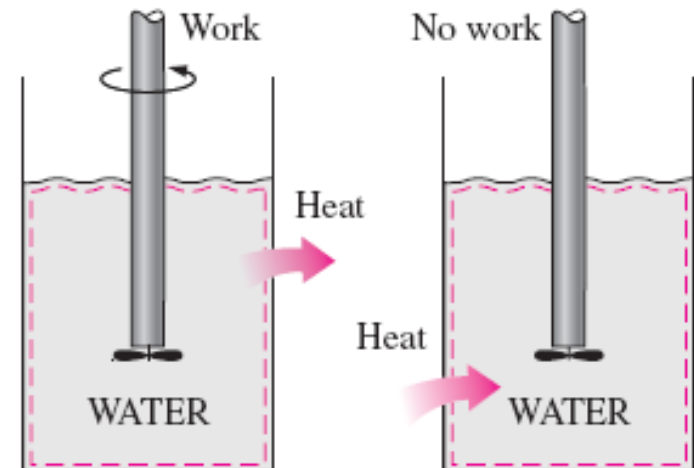
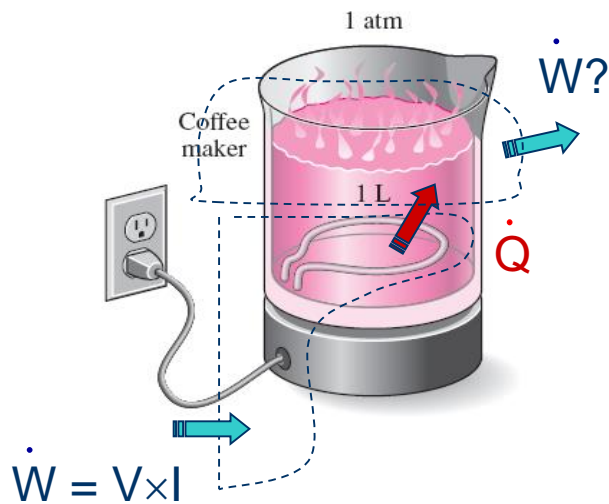
Heat Engine



- A device, which operating in a cycle, produced work from heat
- Termed the “prime mover”
 - A thermal power plant is a prime mover
- A series of processes constitute the power plant cycle
 - The working fluid undergoes change of phase alternatively
- Net heat is transferred and net work is delivered
- The Laws of Thermodynamics in energy interaction
- The goal is to design and operate a sustainable power generation system

Heat engine: how much of heat can be converted?

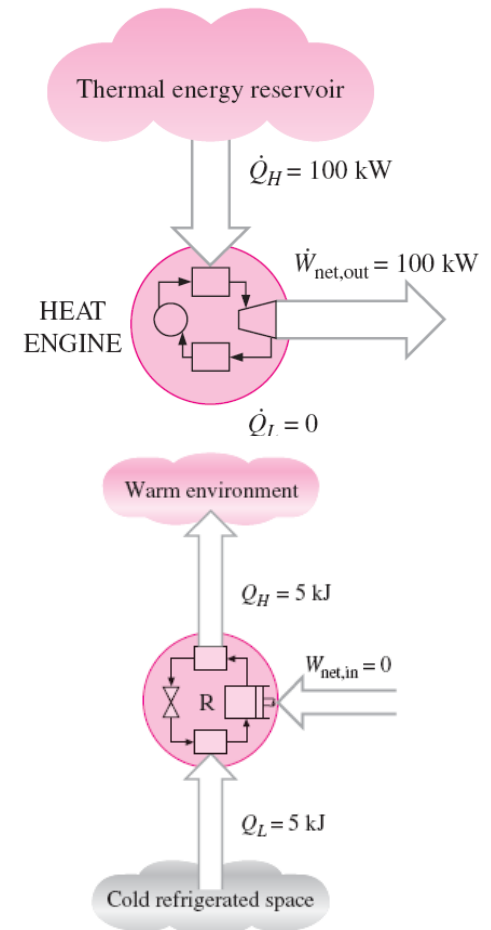
- Work can be fully converted to heat
- Can heat be fully converted to work?



The answer is **NO**

Second law of thermodynamics

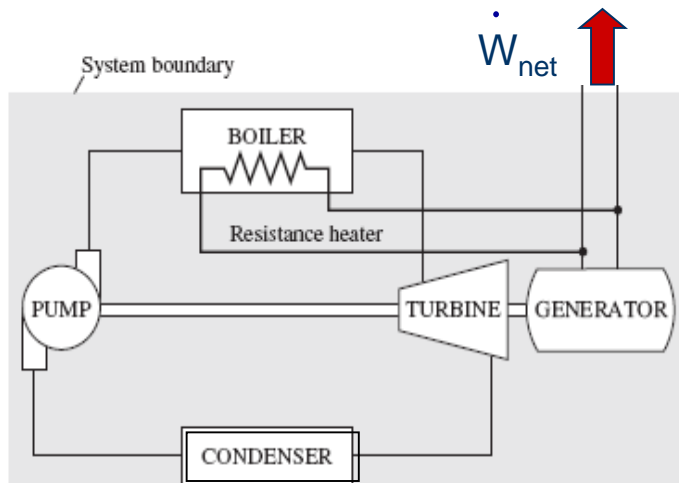
- **Kelvin Planck Statement:** It is impossible to construct a device, which, operating in a cycle, would produce no effect other than doing thermodynamic work, while exchanging heat with a single thermal reservoir.
- **Clausius Statement:** It is impossible to construct a device, which, operating in a cycle will produce no effect other than transferring heat from a low-temperature to a high-temperature thermal reservoir.



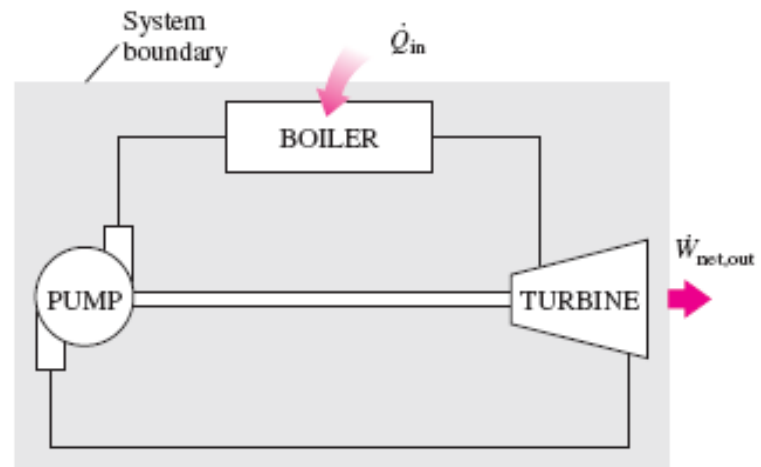
Equivalence of the two statements

- Violation of Kelvin Planck statement leads to the violation of Clausius statement
- And vice versa
- Violation of any of the two statements leads to PMM II

Perpetual motion machine



PMM-I

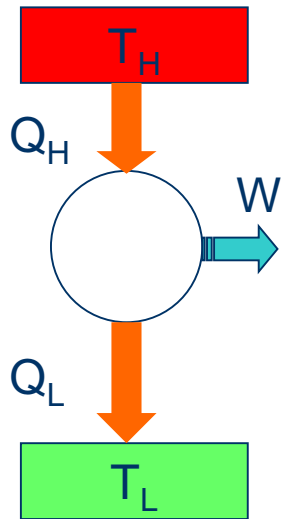


PMM-II

We should be careful that our heat engine designs does not lead to PMM-I or PMM-II

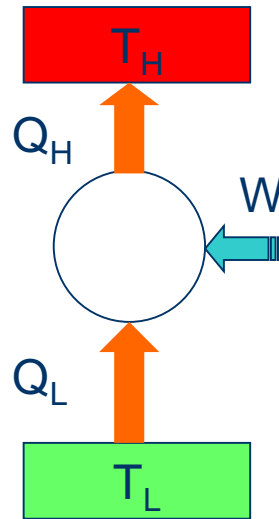
Heat Engine, Heat Pump and Refrigerator

Heat Engine



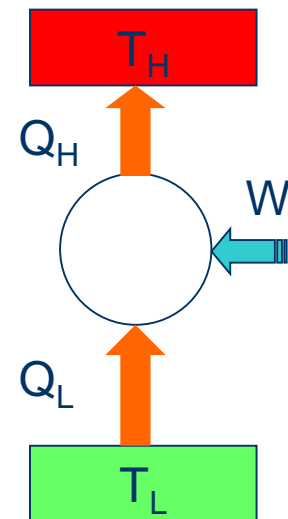
$$\begin{aligned}\eta &= W/Q_H \\ &= (Q_H - Q_L)/Q_H \\ &= 1 - Q_L/Q_H\end{aligned}$$

Heat Pump



$$\begin{aligned}\text{COP}_{\text{HP}} &= Q_H / W \\ &= Q_H / (Q_H - Q_L)\end{aligned}$$

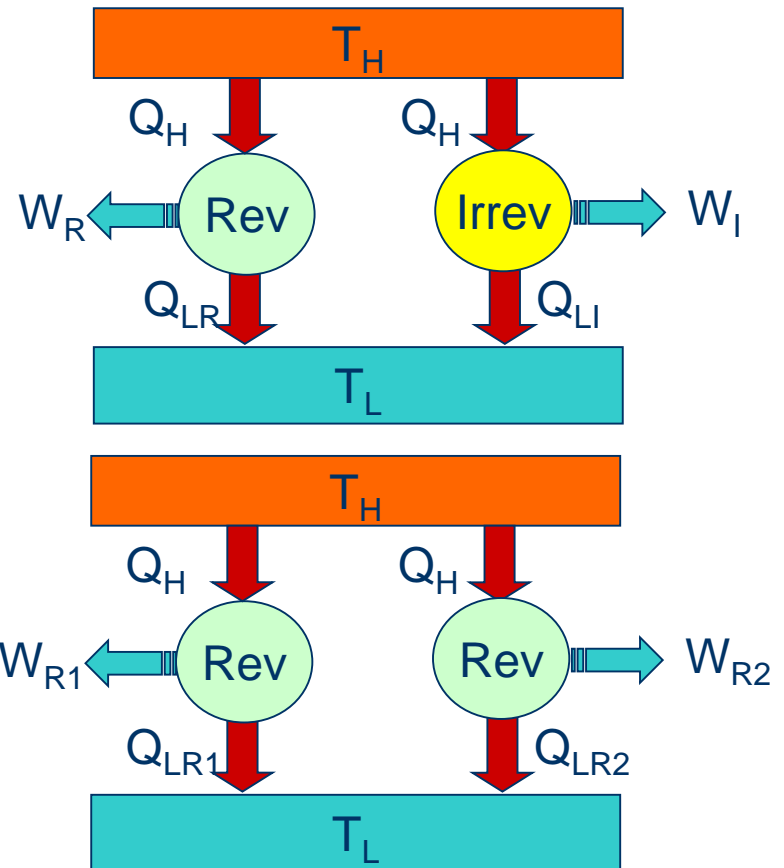
Refrigerator



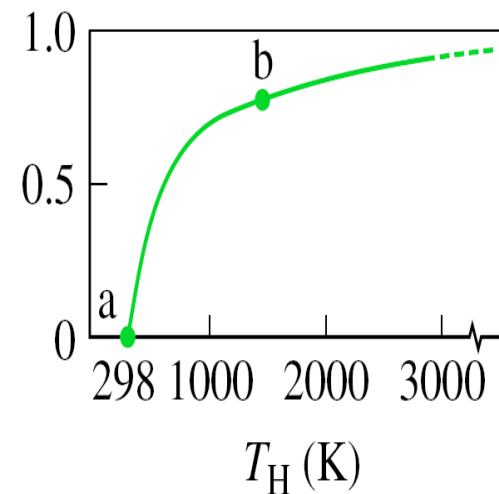
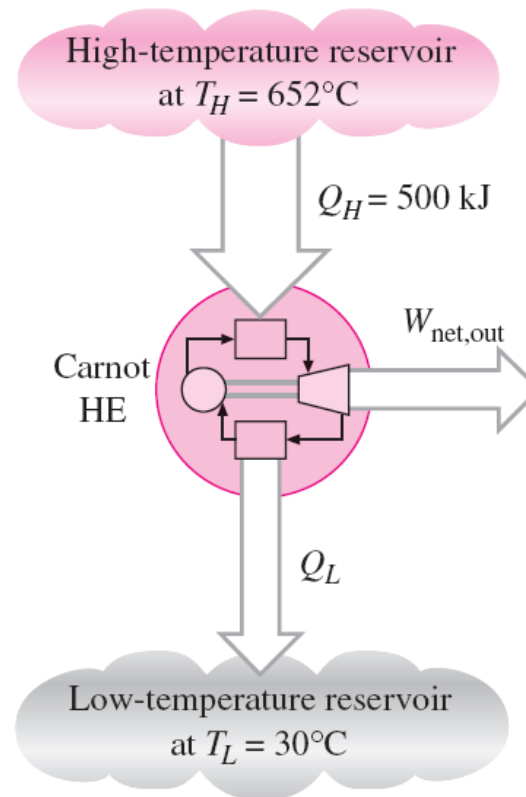
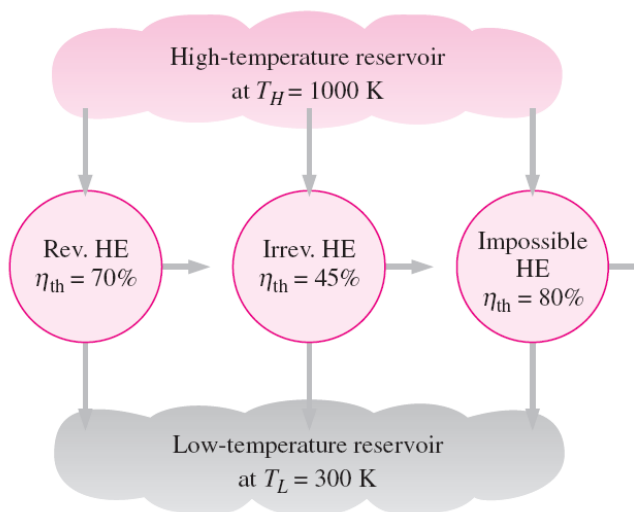
$$\begin{aligned}\text{COP}_{\text{Refr}} &= Q_L / W \\ &= Q_L / (Q_H - Q_L)\end{aligned}$$

Corollaries of 2nd law

- **Corollary 1:**
 - Operating between the same T_H and T_L
 - $W_R > W_I$
 - $\eta_R > \eta_I$
 - $Q_{LR} < Q_{LI}$
- **Corollary 2:**
 - Operating between the same T_H and T_L
 - $\eta_{R1} = \eta_{R2} = \eta_{R3}$
 - $W_{R1} = W_{R2} = W_{R3}$

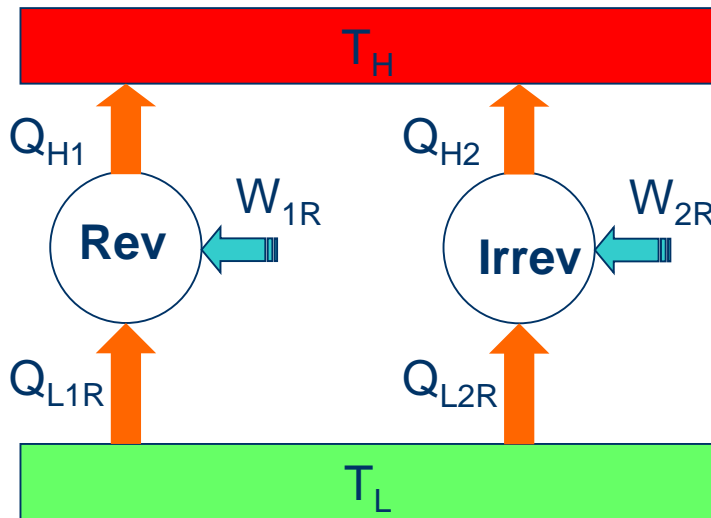


Corollaries applicable to Heat Engines...



What is the efficiency?

Corollaries applicable to Heat Pumps or Refrigerators

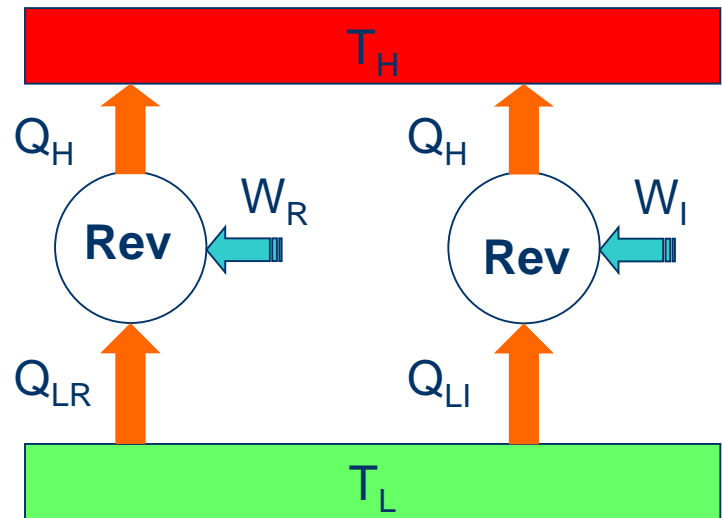


For the same Q_H (i.e., the same Heat Pump outputs)

$$W_R < W_I$$

$$COP_1 > COP_2$$

Corollary 1



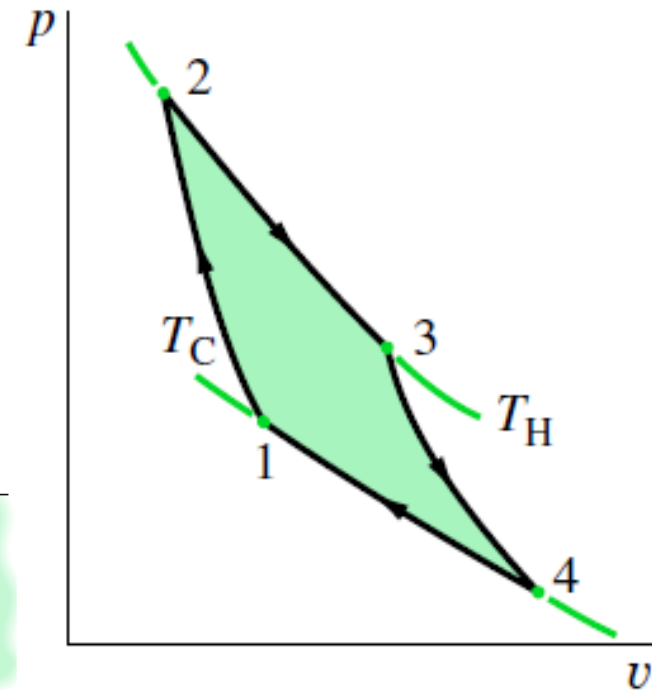
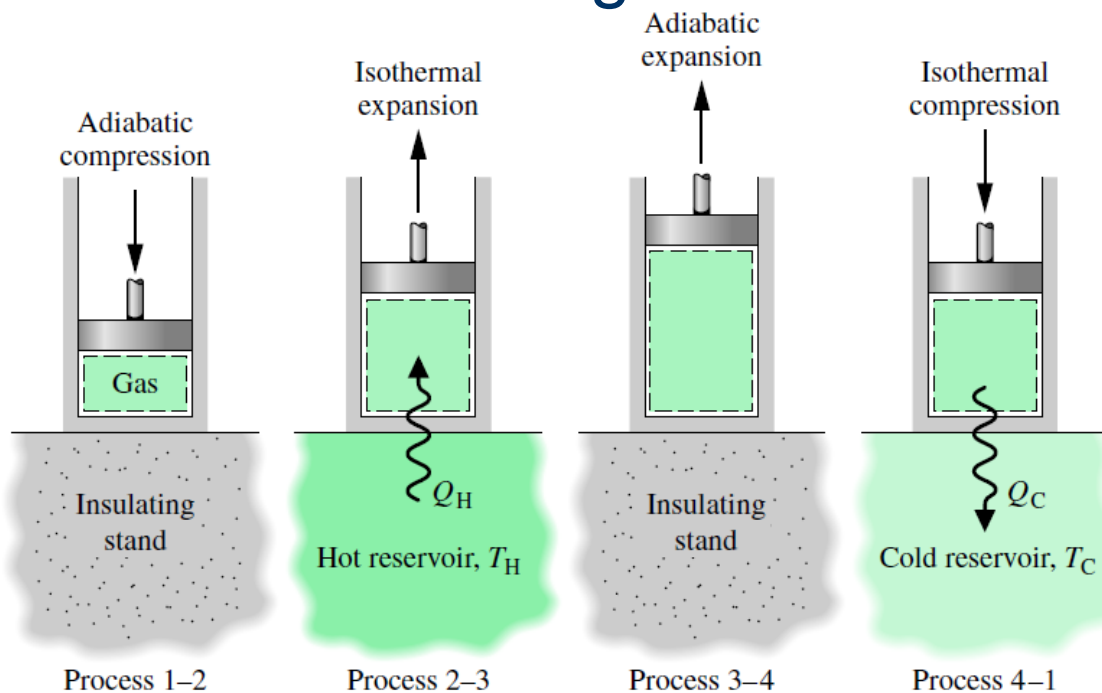
$$W_{1R} = W_{2R}$$

$$COP_1 = COP_2$$

Corollary 2

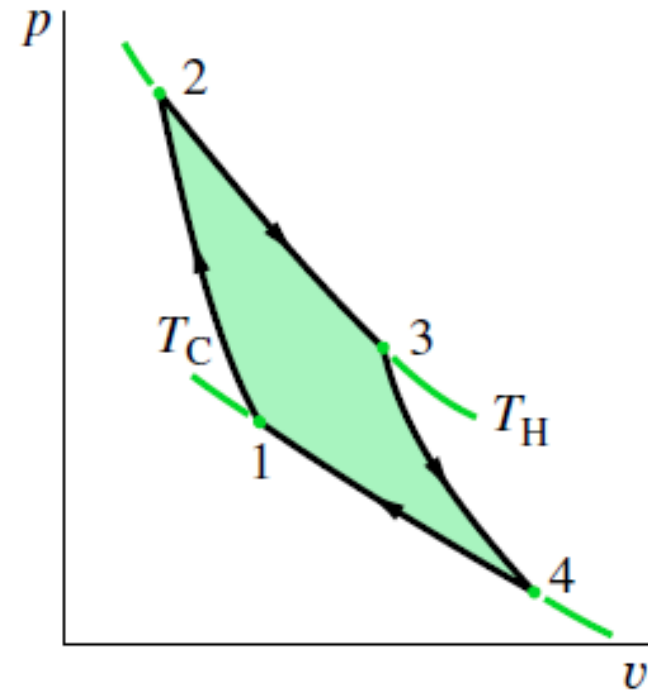
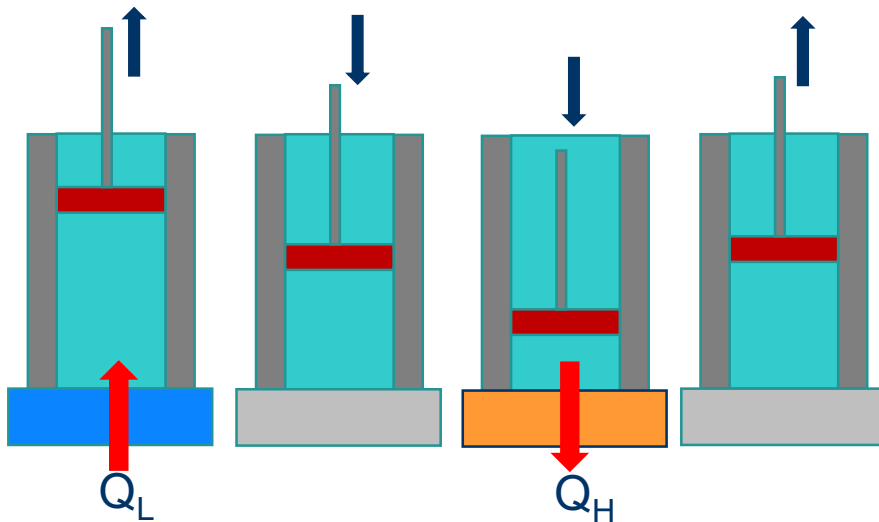
Example of reversible cycle

- Carnot heat engine



Example of reversible cycle

- Carnot heat pump/ refrigerator

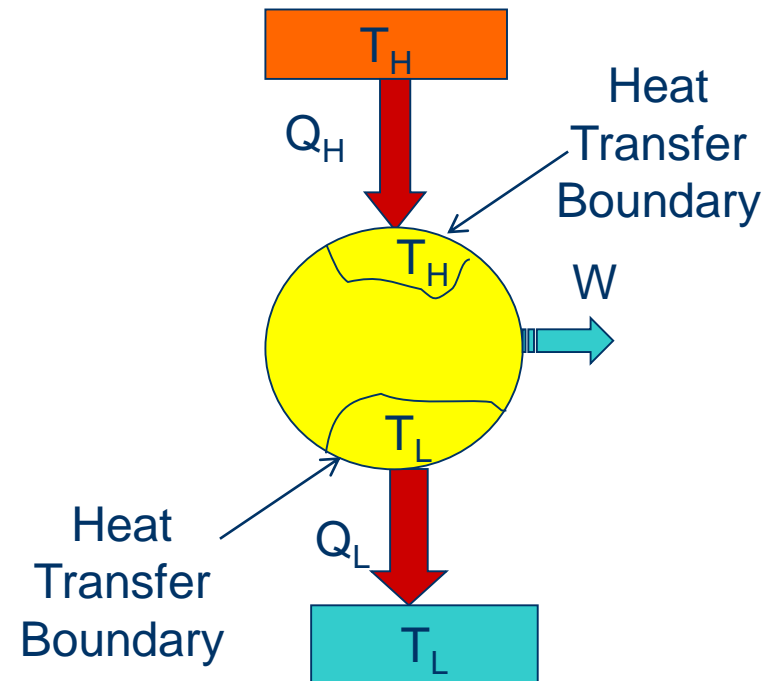


Corollary III: Clausius inequality

- For any cycle,
 - $\eta \leq \eta_{\text{Rev}}$
 - $\eta = 1 - (Q_L/Q_H)$
 - $\eta_{\text{Rev}} = 1 - (T_L/T_H)$
 - $\therefore \{1 - (Q_L/Q_H)\} \leq \{1 - (T_L/T_H)\}$
 - i.e., $(Q_H/T_H - Q_L/T_L) \leq 0$

Or $\oint (\delta Q / T_b) \leq 0$

T_b = Boundary temperature



Entropy

- For reversible process: $\oint (\delta Q / T_b)_{\text{Rev}} = 0$

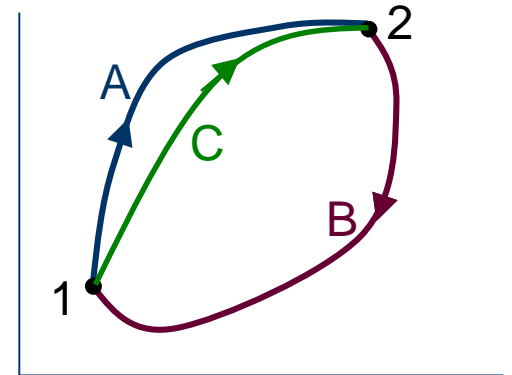
For the reversible process 1A2B1

$$\int_{1A}^2 (\delta Q / T_b)_{\text{Rev}} + \int_{2B}^1 (\delta Q / T_b)_{\text{Rev}} = 0$$

For the reversible process 1C2B1

$$\int_{1C}^2 (\delta Q / T_b)_{\text{Rev}} + \int_{2B}^1 (\delta Q / T_b)_{\text{Rev}} = 0$$

$$\int_{1A}^2 (\delta Q / T_b)_{\text{Rev}} = \int_{1C}^2 (\delta Q / T_b)_{\text{Rev}}$$



ENTROPY

$$(\delta Q / T_b)_{\text{Rev}} = dS$$

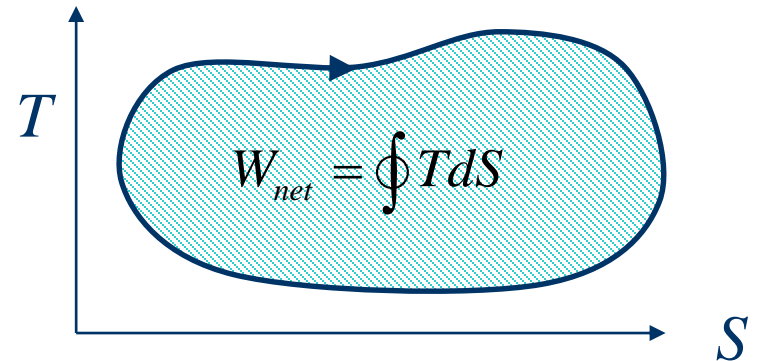
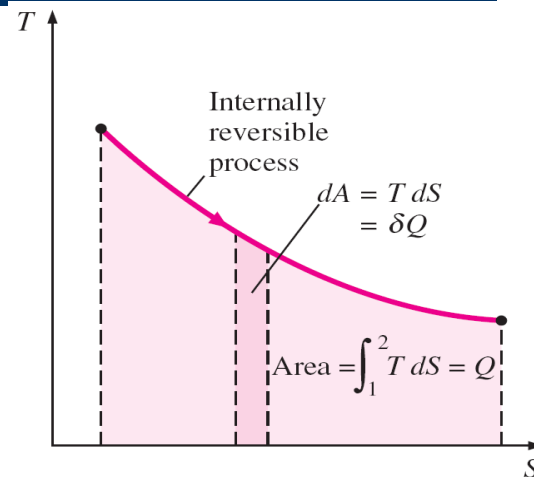
I

II

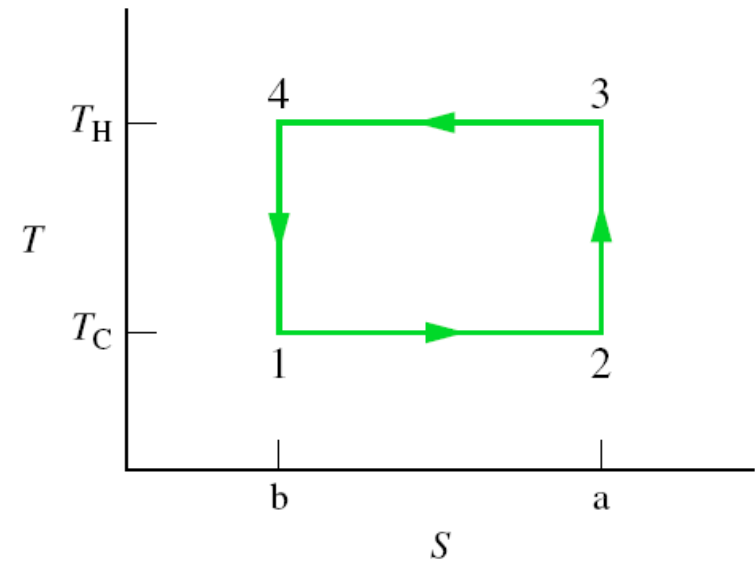
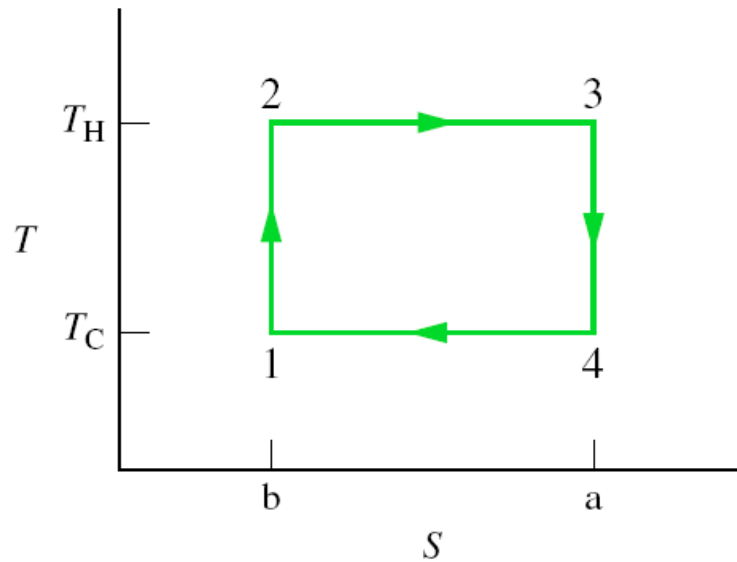
I-II

Significance of T-s diagrams

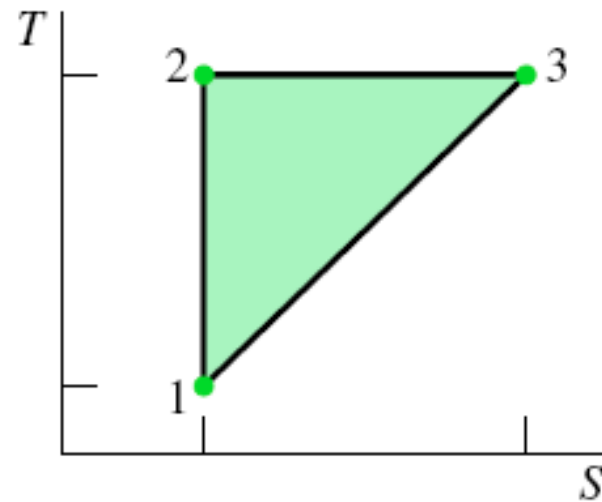
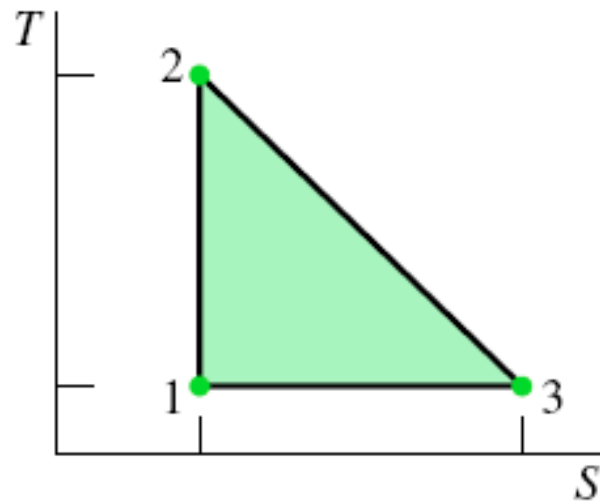
- $\delta Q_{\text{Rev}} = TdS$ [kJ]
 - Area under T-s diagram
 - **Not applicable for irreversible process**
- For an internally reversible cycle:
 - Net work = area enclosed by the cycle in T-S diagram



Which one is a power producing cycle?



Which cycle has greater efficiency?



$\epsilon\nu$ = to put into
 $\tau\rho\pi\eta'$ = turn / conversion

What is Entropy?

- In general, it is the a thermodynamic property which provides a quantitative measure of the disorder of a given thermodynamic state
 - **Entropy** increases from solid to liquid to gas corresponding to an increase in positional probability.
 - **Entropy** increases when you dissolve a solid in liquid corresponding to an increase in positional probability.
 - The larger the **volume** the larger the positional probability and the greater the entropy (n constant).
 - The larger the **pressure** the smaller the positional probability and the lower the entropy (n constant).
 - The larger the **molecule** the larger the number of relative positions of the atoms resulting in a greater positional probability and a greater entropy.
 - The higher the **temperature** the greater the range of energies, therefore the larger the entropy.

Calculation of entropy change

- For solids and liquids (having only one specific heat, c)

$$ds = \frac{\delta q}{T} = \frac{c dT}{T}$$

$$s_2 - s_1 = \int_{T_1}^{T_2} \frac{c dT}{T} \approx c \ln \left(\frac{T_2}{T_1} \right)$$

c = average specific heat within the temperature range $[T_1, T_2]$

Calculation of entropy change (contd..)

- For ideal gases (the specific heat depends on path)

$$\delta q = du + pdv = c_v dT + R \frac{dv}{v}$$

$$\delta q = dh - vdp = c_p dT - R \frac{dp}{p}$$

$$s - s_0 = \int_{T_0}^T \frac{c_v dT}{T} + R \ln \left(\frac{v}{v_0} \right)$$

$$s - s_0 = \int_{T_0}^T \frac{c_p dT}{T} - R \ln \left(\frac{p}{p_0} \right)$$

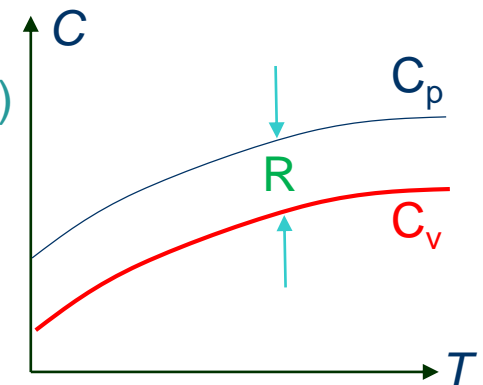
T_0 = Ref. temperature (0 K for ideal gas)

p_0 = Re. pressure (1 atm)

v_0 = Reference specific volume (depends on the MW)

Both C_p and C_v depend on temperature for ideal gas

- Therefore, one must know the functional dependence $C_p(T)$ and $C_v(T)$ for evaluation of the first integrals



Evaluation of $\int_{T_1}^{T_2} \frac{c_p dT}{T}$

$$c_p = a + bT + cT^2 + dT^3 + \dots$$

$$\int_{T_0}^T \frac{c_p dT}{T} = \int_{T_0}^T \frac{(a + bT + cT^2 + dT^3 + \dots) dT}{T}$$

$$= a \ln\left(\frac{T}{T_0}\right) + b(T - T_0) + \frac{1}{2}c(T^2 - T_0^2) + \frac{1}{3}d(T^3 - T_0^3) \dots$$

Thus, for an ideal gas, $\int_{T_1}^{T_2} \frac{c_p dT}{T}$ is a function of temperature only

The integral is either calculated from the coefficients $a, b, c, d,$

...

or is tabulated as function of temperature

$$\int_{T_0}^T \frac{c_p dT}{T} = s^0(T)$$

Temperature dependence of Molar C_p

TABLE A-21 Variation of \bar{c}_p with Temperature for Selected Ideal Gases

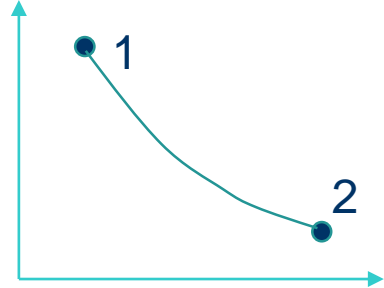
$$\frac{\bar{c}_p}{R} = \alpha + \beta T + \gamma T^2 + \delta T^3 + \varepsilon T^4$$

T is in K, equations valid from 300 to 1000 K

Gas	α	$\beta \times 10^3$	$\gamma \times 10^6$	$\delta \times 10^9$	$\varepsilon \times 10^{12}$
CO	3.710	-1.619	3.692	-2.032	0.240
CO ₂	2.401	8.735	-6.607	2.002	0
H ₂	3.057	2.677	-5.810	5.521	-1.812
H ₂ O	4.070	-1.108	4.152	-2.964	0.807
O ₂	3.626	-1.878	7.055	-6.764	2.156
N ₂	3.675	-1.208	2.324	-0.632	-0.226
Air	3.653	-1.337	3.294	-1.913	0.2763
SO ₂	3.267	5.324	0.684	-5.281	2.559
CH ₄	3.826	-3.979	24.558	-22.733	6.963
C ₂ H ₂	1.410	19.057	-24.501	16.391	-4.135
C ₂ H ₄	1.426	11.383	7.989	-16.254	6.749
Monatomic gases ^a	2.5	0	0	0	0

^aFor monatomic gases, such as He, Ne, and Ar, \bar{c}_p is constant over a wide temperature range and is very nearly equal to $5/2 \bar{R}$.

Source: Adapted from K. Wark, *Thermodynamics*, 4th ed., McGraw-Hill, New York, 1983, as based on NASA SP-273, U.S. Government Printing Office, Washington, DC, 1971.



Evaluation of entropy change

$$s_2 - s_1 = \left\{ \int_{T_0}^{T_2} \frac{c_p dT}{T} - \int_{T_0}^{T_1} \frac{c_p dT}{T} \right\} - R \ln \left(\frac{p_2}{p_1} \right)$$

$$s_2 - s_1 = \left\{ s_2^0(T_2) - s_1^0(T_1) \right\} - R \ln \left(\frac{p_2}{p_1} \right)$$

TABLE A-22 Ideal Gas Properties of Air

T	h	u	s°
200	199.97	142.56	1.29559
210	209.97	149.69	1.34444
220	219.97	156.82	1.39105
230	230.02	164.00	1.43557
240	240.02	171.13	1.47824
290	290.16	206.91	1.66802
295	295.17	210.49	1.68515
300	300.19	214.07	1.70203
305	305.22	217.67	1.71865
310	310.24	221.25	1.73498
350	350.49	250.02	1.85708
400	400.98	286.16	1.99194
450	451.80	322.62	2.11161
500	503.02	359.49	2.21952
550	554.74	396.86	2.31809

From Moran and Shapiro

$$\oint (\delta Q / T_b)_{Irrev} < 0$$

Clausius inequality for an irreversible process

For the reversible process 1A2B1

I

$$\int_{1A}^2 (\delta Q / T_b)_{Irrev} + \int_{2B}^1 (\delta Q / T_b)_{Rev} < 0$$

For the reversible process 1C2B1

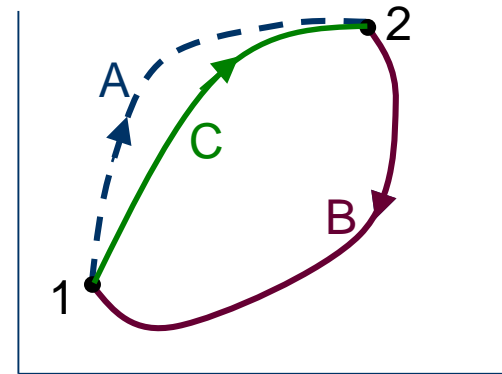
II

$$\int_{1C}^2 (\delta Q / T_b)_{Rev} + \int_{2B}^1 (\delta Q / T_b)_{Rev} = 0$$

I-II

$$\int_{1A}^2 (\delta Q / T_b)_{Irrev} < \int_{1C}^2 (\delta Q / T_b)_{Rev}$$

$$\int_1^2 (\delta Q / T_b)_{Irrev} < S_2 - S_1$$



$$\int_1^2 (\delta Q / T_b)_{Irrev} < S_2 - S_1$$

Entropy balance equation

S_{gen}

$$S_2 - S_1 = \int_1^2 (\delta Q / T_b)_{Irrev} + \text{something}$$

$$dS = \underbrace{\frac{\delta Q}{T_b}}_I + \underbrace{\delta S_{gen}}_{II}$$

$$\frac{dS}{dt} = \sum \underbrace{\frac{\dot{Q}_i}{T_{bi}}}_I + \underbrace{\dot{S}_{gen}}_{II}$$

I: Entropy transferred to the system with heat

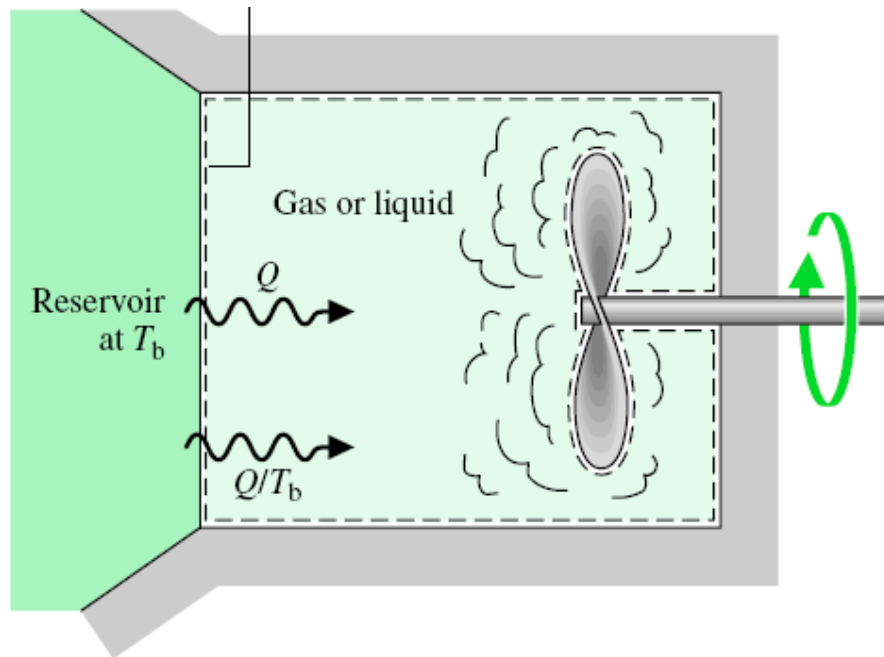
II: Entropy generation due to irreversibilities

$S_{gen} = 0$ for reversible process

$S_{gen} > 0$ for irreversible



Entropy generation due to irreversibility



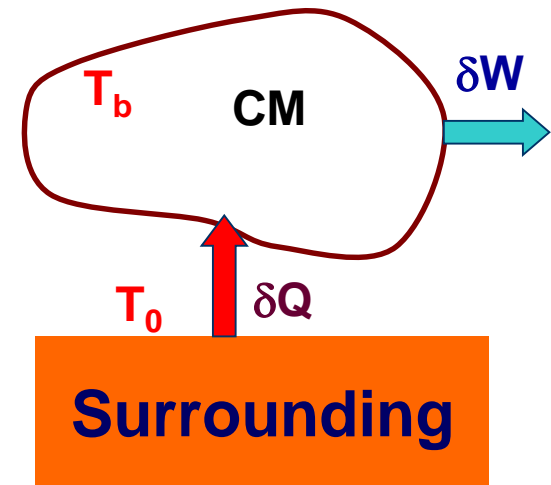
- The increase of entropy of the gas (as measured in terms of its T , and V) is greater than (Q/T_b)
- The extent of entropy rise will depend on how much the friction is

Principle of increase of entropy

- Internally reversible system
 - Temperature of the system is T_b everywhere
- No irreversibility in the surrounding
 - Temperature of the surrounding is T_0 everywhere
- For the system: $dS_{CM} = \delta Q / T_b$
- For the surrounding: $dS_{surr} = -\delta Q / T_0$

$$\begin{aligned}
 dS_{univ} &= dS_{CM} + dS_{surr} \\
 &= \delta Q / T_b + (-\delta Q / T_0) \\
 &= \delta Q (1/T_b - 1/T_0)
 \end{aligned}$$

Positive quantity, since $T_b < T_0$



Spontaneous heat transfer from the surrounding, under $T_0 > T_b$

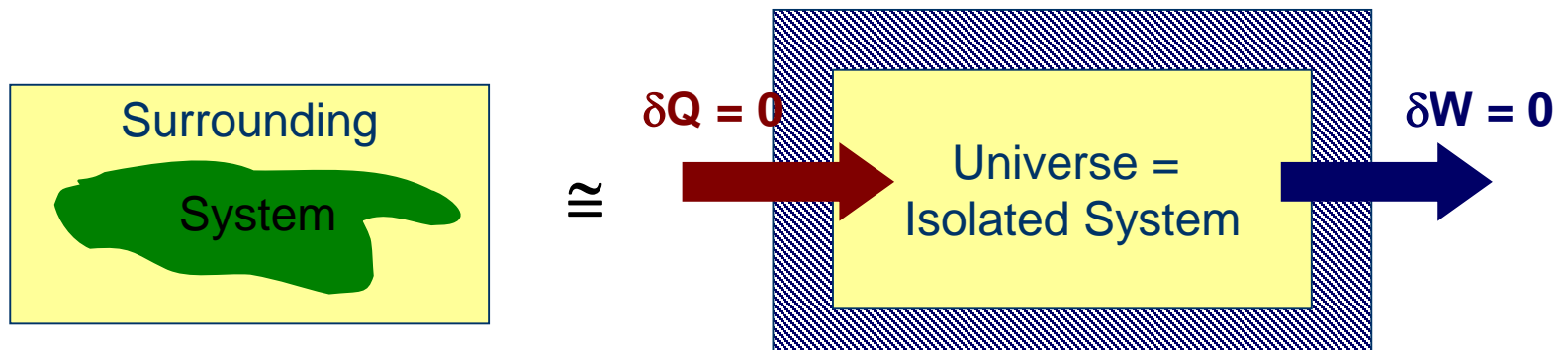
$$dS_{CM} + dS_{surr} \geq 0$$

Entropy generation in the Universe

- Universe is an *Isolated System*

- $dS_{\text{Universe}} = \cancel{\delta Q/T_b} + \delta S_{\text{gen,Universe}} = \delta S_{\text{gen}}$

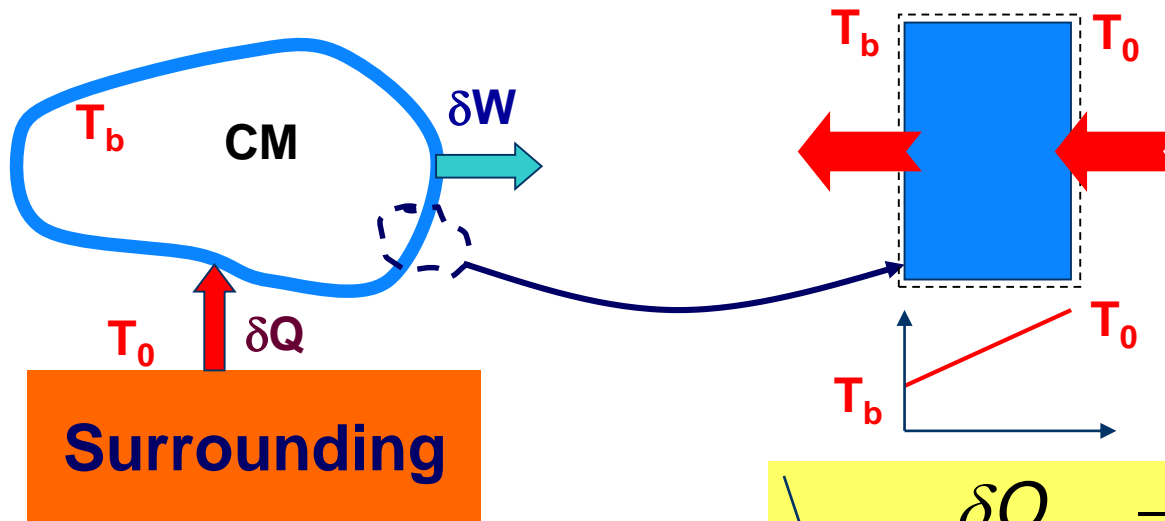
$$dS_{\text{CM}} + dS_{\text{surr}} = \delta S_{\text{gen,Universe}} \geq 0$$



Where does the entropy generation take place in the previous case??

It takes place in the wall....!

Why? That is where heat transfer takes place with a finite ΔT ...



Different parts of the wall are maintained at their same respective temperature (e.g., the outer side is steadily at T_0 while the inner side is at T_b)

Hence, overall entropy of the wall does not change

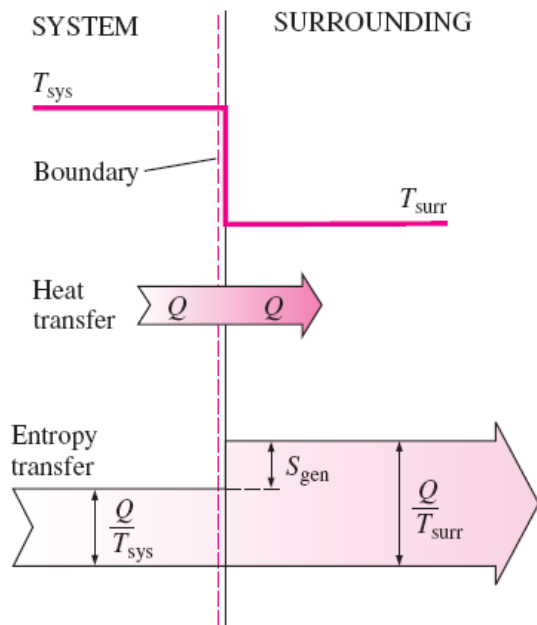
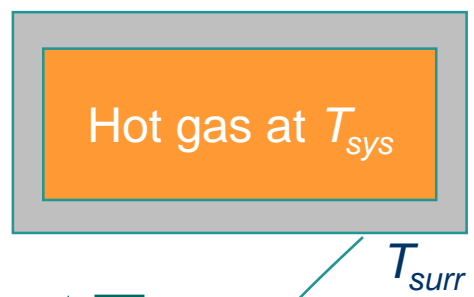
Spontaneous heat transfer from the surrounding, under $T_0 > T_b$

$$dS = \frac{\delta Q}{T_0} + \frac{-\delta Q}{T_b} + \delta S_{gen}$$

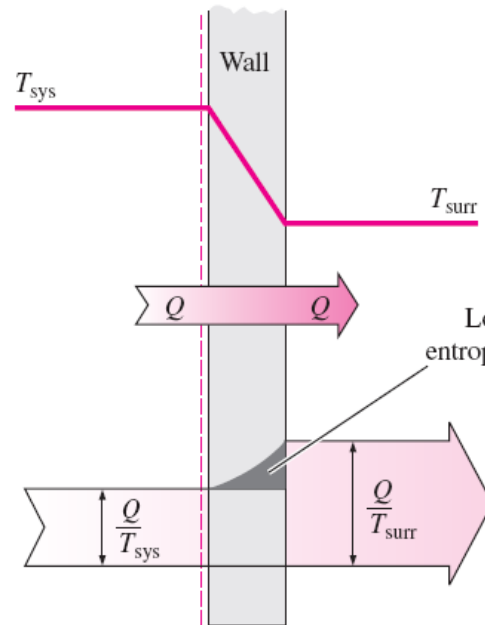
$= 0$

$$\delta S_{gen} = \delta Q \left(\frac{1}{T_b} - \frac{1}{T_0} \right)$$

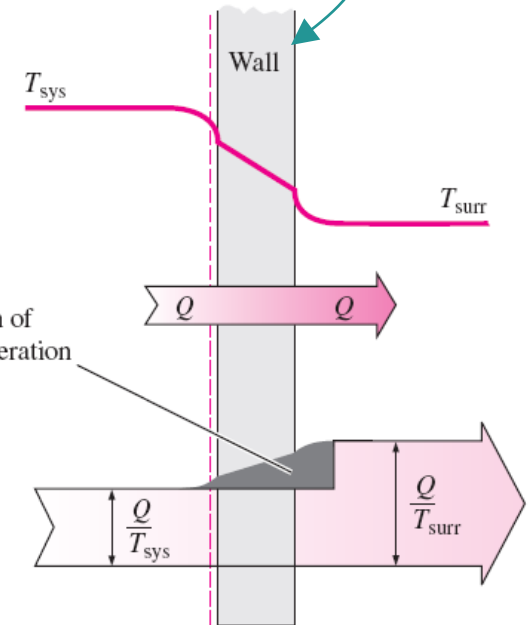
Entropy generation associated with heat transfer under a finite ΔT



(a) The wall is ignored

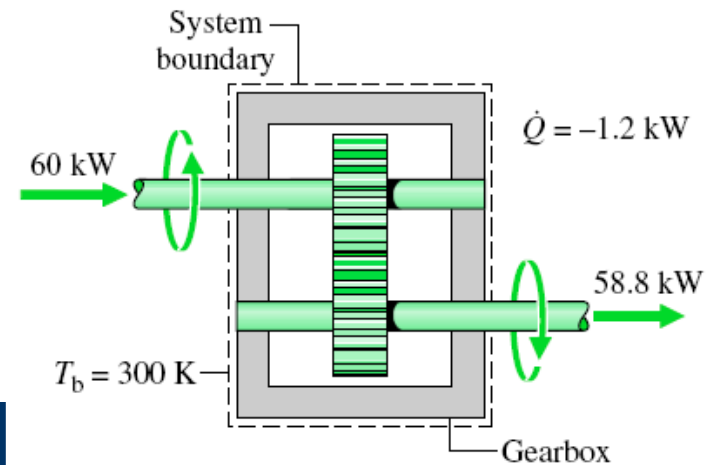


(b) The wall is considered

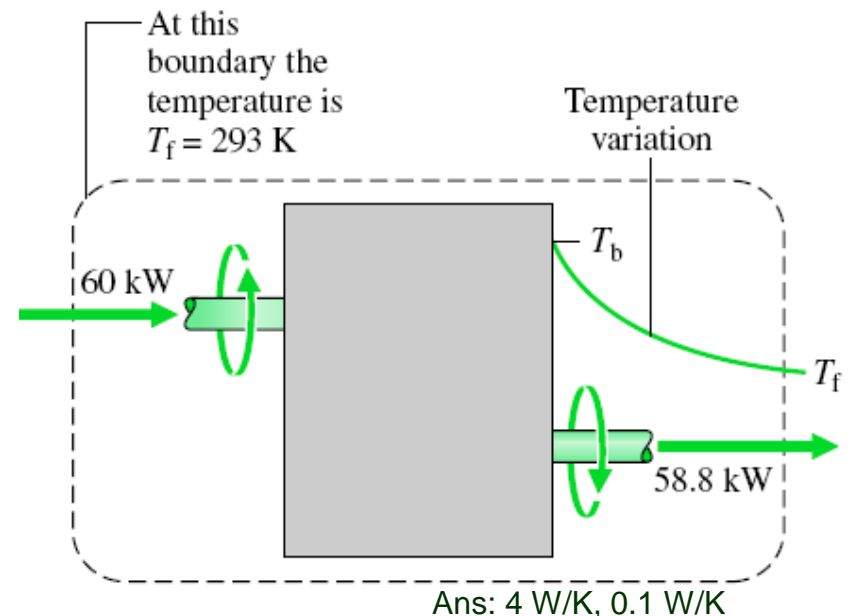


(c) The wall as well as the variations of temperature in the system and the surroundings are considered

Example 1:

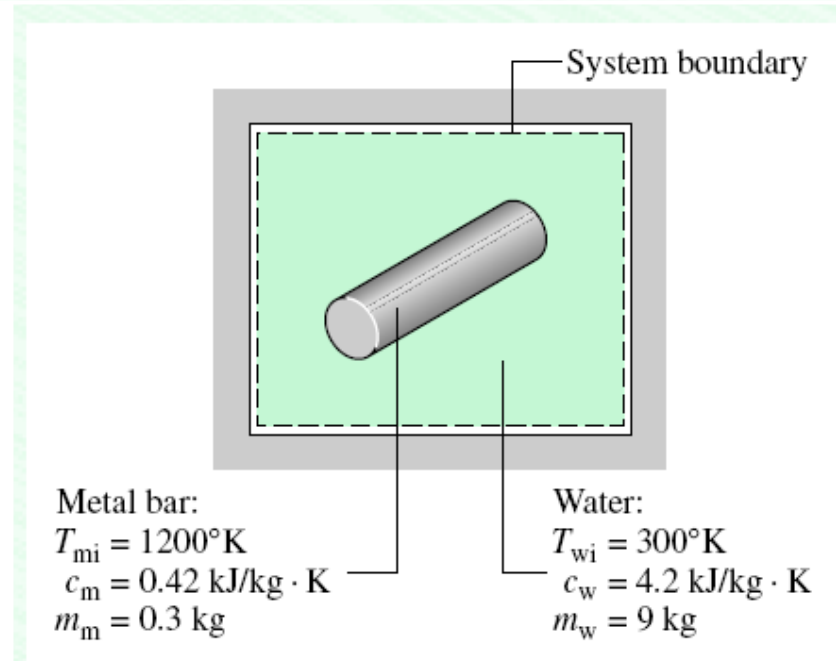


A gearbox assembly of a truck receives 60 kW power in the driving shaft (that connects the engine and the gearbox) and transmits 58.8 kW to its driven shaft (gear box to the axel). Both the shafts are rotating at 600 rpm. The outer surface of the wall of the gearbox is maintained at 27 °C, while the ambient is at 20 °C. What is the entropy generation rate (i) within the gearbox assembly, and (ii) outside?



Example 2

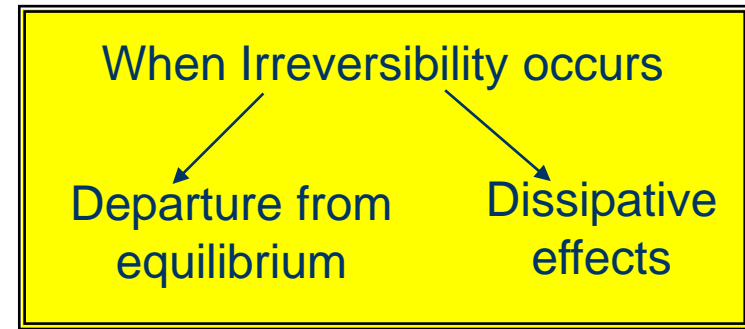
A 0.3 kg metal bar initially at 1200°K is removed from an oven and quenched by immersing it in a closed tank containing 9 kg of water initially at 300°K. Each substance can be modeled as incompressible. An appropriate constant specific heat value for the water is $c_w = 4.2 \text{ kJ/kg} \cdot \text{K}$, and an appropriate value for the metal is $c_m = 0.42 \text{ kJ/kg} \cdot \text{K}$. Heat transfer from the tank contents can be neglected. Determine (a) the final equilibrium temperature of the metal bar and the water, in °K, and (b) the amount of entropy produced, in kJ/K.



One myth about entropy...

- **Myth: Entropy of a system would always increase during a process**
- **Truth: Entropy of the system may increase (e.g., if you supply heat to the system) or decrease (e.g., if the system releases heat to the surrounding). However, the combined entropy of the (system + Surroundings) should always increase (or, stay unchanged if it's a reversible process).**
 - *For example, if a system of hot gas rejects heat to a colder surrounding, the entropy of the system will decrease, while the entropy of the surroundings will increase. The magnitude of the entropy increase (of the surrounding) will exceed the entropy reduction (of the system) so that the total entropy of the Universe will increase.*

Entropy generation would take place



- Un-resisted expansion or compression
- Friction (fluid-fluid, fluid-solid or solid-solid)
- Heat transfer with finite temperature difference
- I^2R heating (Joule heating)
- Magnetization with hysteresis
- Spontaneous mixing in finite concentration difference
- Spontaneous chemical reaction
- Inelastic deformation

Any spontaneous process leads to entropy generation....



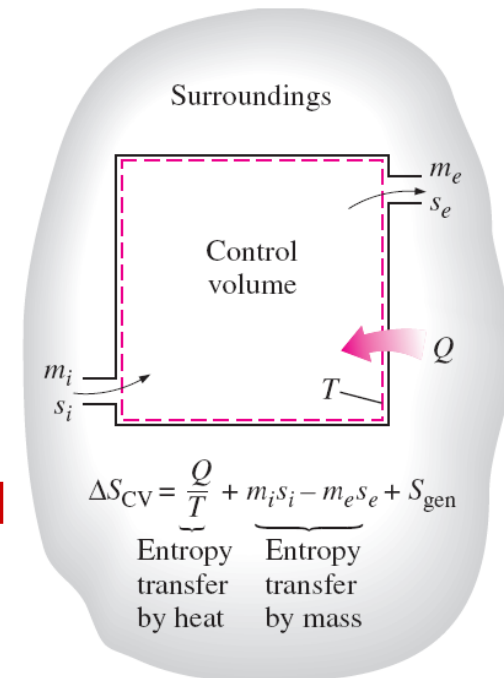
"CLEANING GOES AGAINST ENTROPY AND THE NATURAL ORDER."

Entropy balance equation for flow system

$$\frac{dS}{dt} = \sum \frac{\dot{Q}}{T_b} + \sum_{inlet} \dot{m}_i s_i - \sum_{exit} \dot{m}_e s_e + \dot{S}_{gen}$$

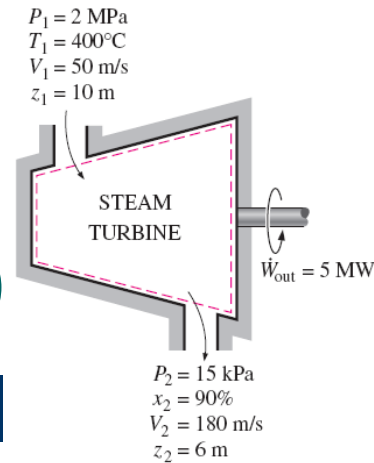
Entropy of a system can change

1. Due to heat transfer across its boundary
2. Attributed to the entropy transfer associated mass entering or leaving the system
3. Due to entropy generation (irreversibility)



Work transfer has nothing associated with entropy transfer

Iisentropic efficiency (turbine)



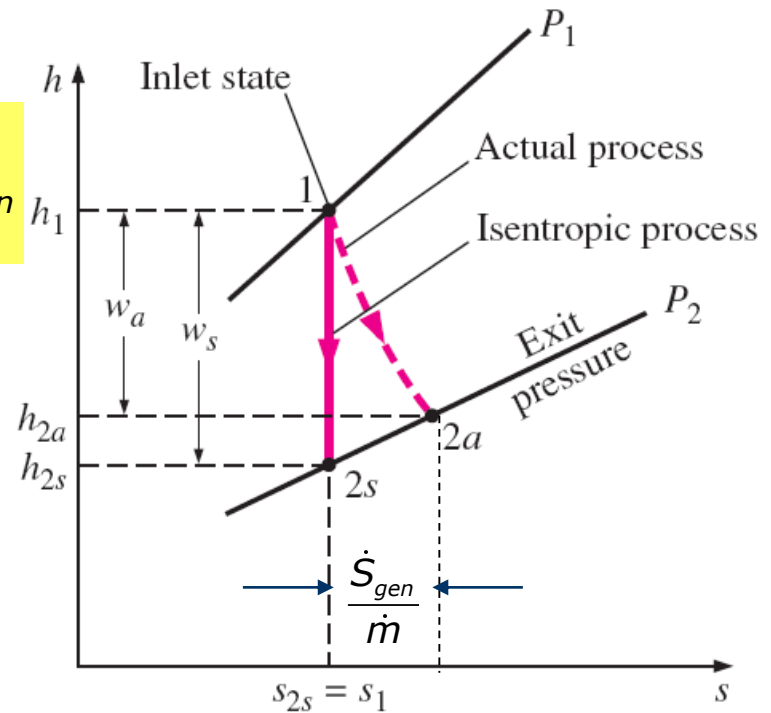
Steady flow, adiabatic, **internally irreversible**

$$\frac{dS}{dt} = \sum \frac{\dot{Q}}{T_b} + \sum_{\text{inlet}} \dot{m}_i s_i - \sum_{\text{exit}} \dot{m}_e s_e + \dot{S}_{\text{gen}}$$

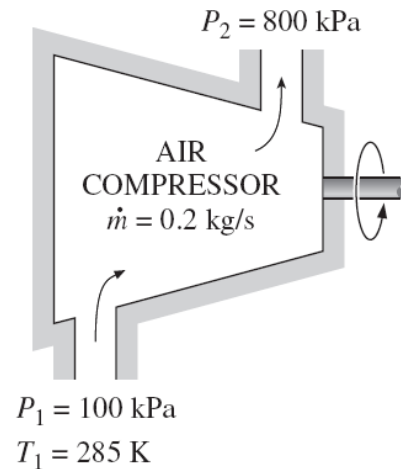
$$s_e = s_i + \frac{\dot{S}_{\text{gen}}}{\dot{m}}$$

$$\eta_T = \frac{\text{Actual turbine work}}{\text{Isentropic turbine work}}$$

$$\eta_T \cong \frac{h_1 - h_{2a}}{h_1 - h_{2s}}$$



Isentropic efficiency (compressor and pump)

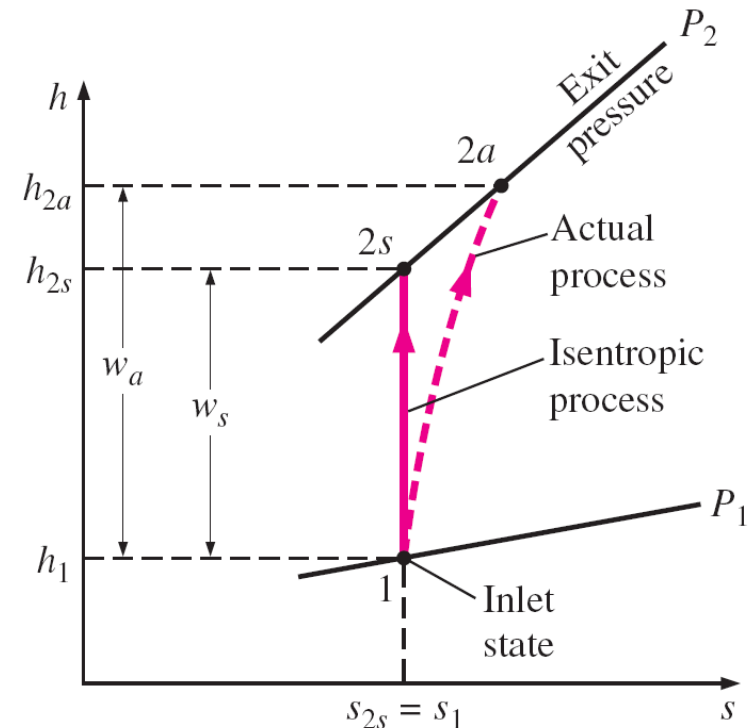
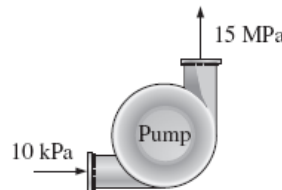


- Adiabatic, internally irreversible

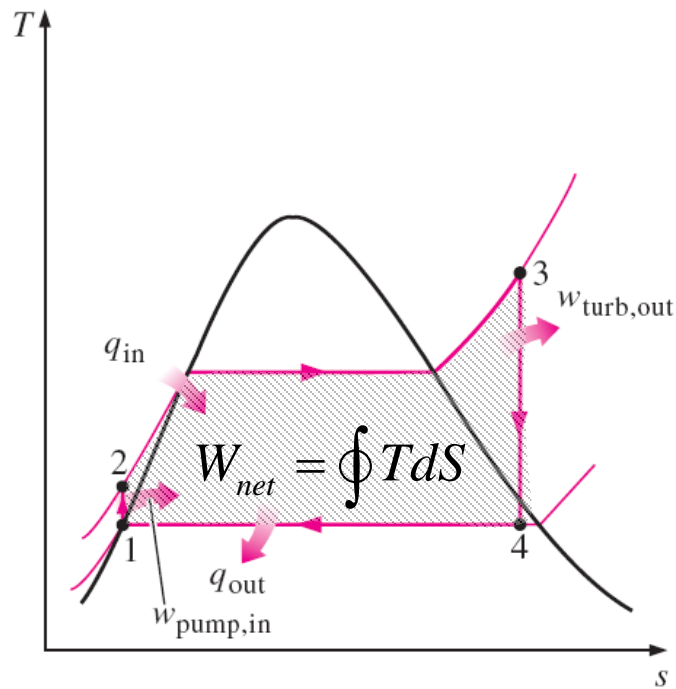
$$\eta_c = \frac{\text{Isentropic compressor work}}{\text{Actual compressor work}}$$

$$\eta_c \cong \frac{h_{2s} - h_1}{h_{2a} - h_1} \quad \text{For compressor}$$

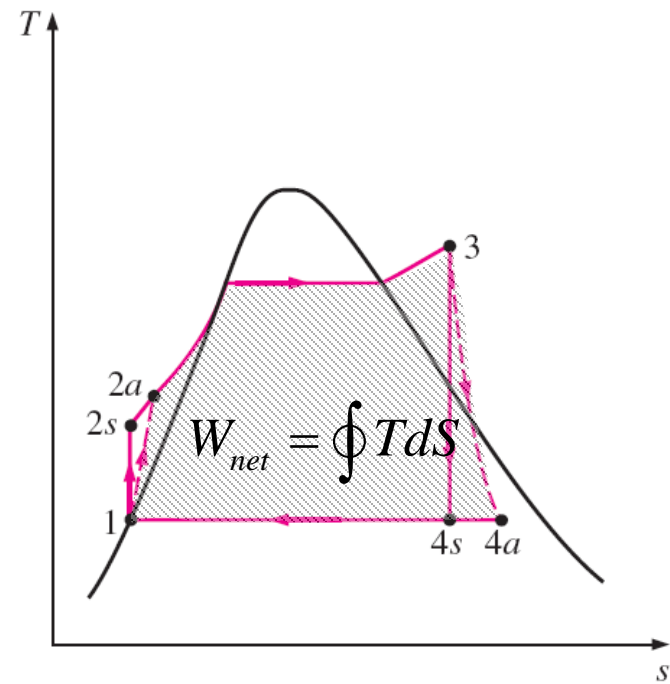
$$\eta_P = \frac{w_s}{w_a} = \frac{v(P_2 - P_1)}{h_{2a} - h_1} \quad \text{For pump}$$



Are both the statements correct?



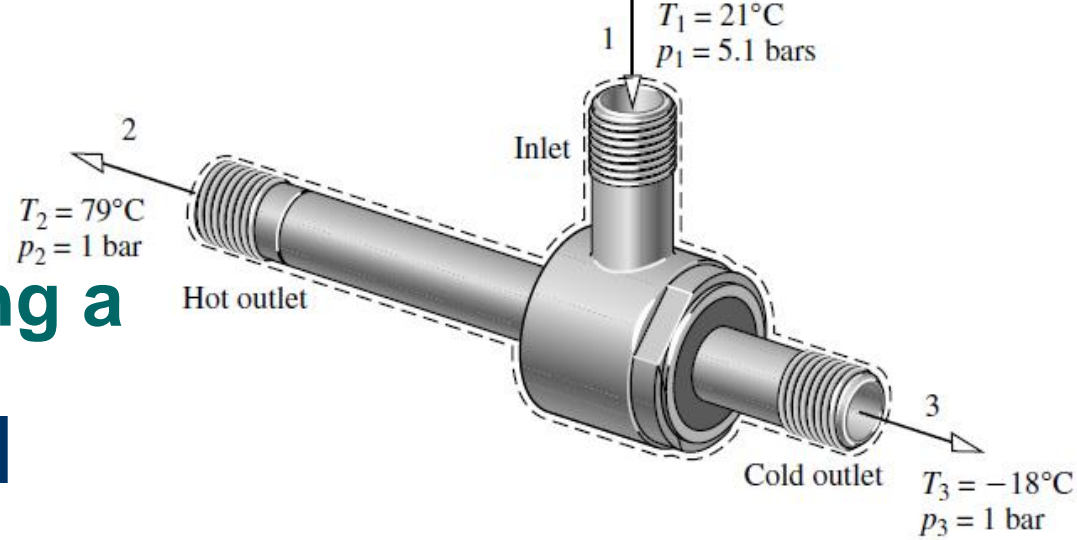
Ideal Rankine cycle



Actual Rankine cycle

$$\frac{dS}{dt} = \sum \frac{\dot{Q}}{T_b} + \sum_{inlet} \dot{m}_i s_i - \sum_{exit} \dot{m}_e s_e + \dot{S}_{gen}$$

Example: Evaluating a performance claim

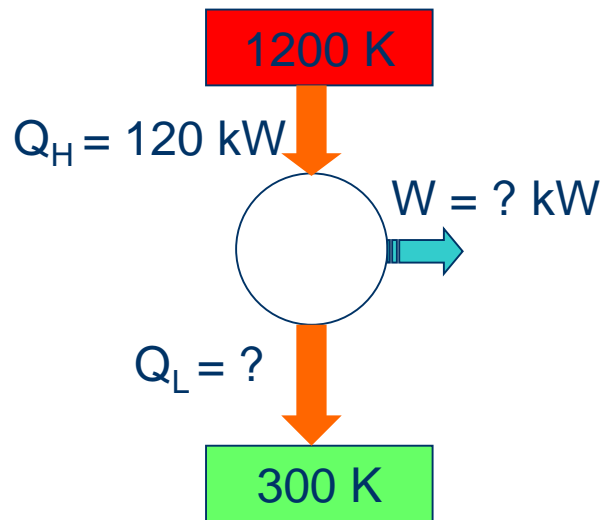


An inventor claims to have developed a device requiring no energy transfer by work or heat transfer, yet able to produce hot and cold streams of air from a single stream of air at an intermediate temperature. The inventor provides steady-state test data indicating that when air enters at a temperature of 39°C and a pressure of 5.0 bars , separate streams of air exit at temperatures of -18°C and 79°C , respectively, and each at a pressure of 1 bar . Sixty percent of the mass entering the device exits at the lower temperature. Evaluate the inventor's claim, employing the ideal gas model for air and ignoring changes in the kinetic and potential energies of the streams from inlet to exit.

$$\begin{aligned} \frac{\dot{S}_{gen}}{\dot{m}} &= 0.4 \left[c_p \ln \frac{T_2}{T_1} - R \ln \frac{p_2}{p_1} \right] + 0.6 \left[c_p \ln \frac{T_3}{T_1} - R \ln \frac{p_3}{p_1} \right] \\ &= 0.4 \left[\left(1.0 \frac{\text{kJ}}{\text{kg} \cdot \text{K}} \right) \ln \frac{352}{294} - \left(\frac{8.314}{28.97} \frac{\text{kJ}}{\text{kg} \cdot ^\circ\text{K}} \right) \ln \frac{1}{5.0} \right] \\ &\quad + 0.6 \left[\left(1.0 \frac{\text{kJ}}{\text{kg} \cdot ^\circ\text{K}} \right) \ln \frac{255}{294} - \left(\frac{8.314}{28.97} \frac{\text{kJ}}{\text{kg} \cdot ^\circ\text{K}} \right) \ln \frac{1}{5.0} \right] \\ &= 0.454 \text{ kJ/kgK} \end{aligned}$$

What are the efficiencies of these reversible engines?

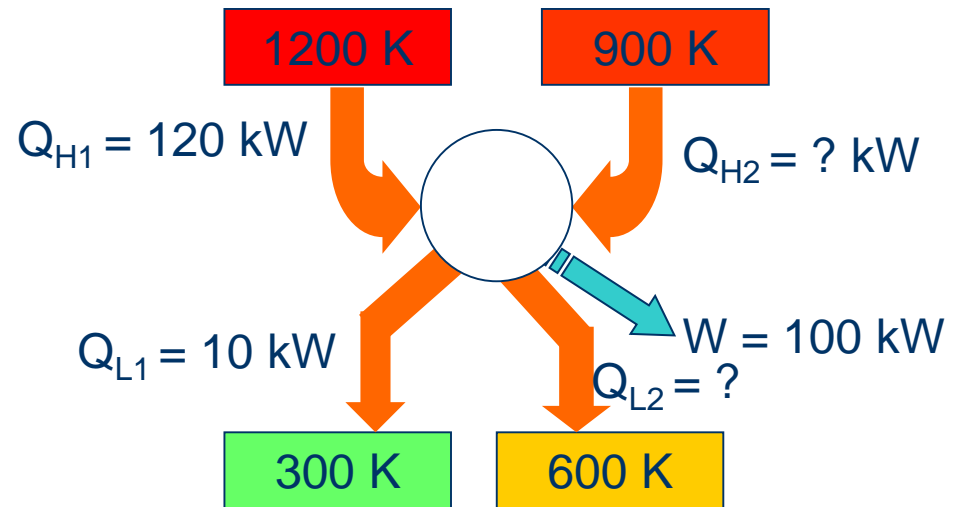
Power plant with single heat source and sink



$\eta = ?$

$W = 90 \text{ kW}, Q_{L2} = 30 \text{ kW}, \eta = 75\%$

Power plant with multiple heat sources and sinks



$\eta = ?$

$Q_{H2} = 90 \text{ kW}, Q_{L2} = 100 \text{ kW}, \eta = 47.6\%$