EPFL

ETA-Lab
Energy Transport Advances

ME-251: Thermodynamics and energetics I
Second Law III

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EPFL Mechanical Engineering

2025 Fall Semester

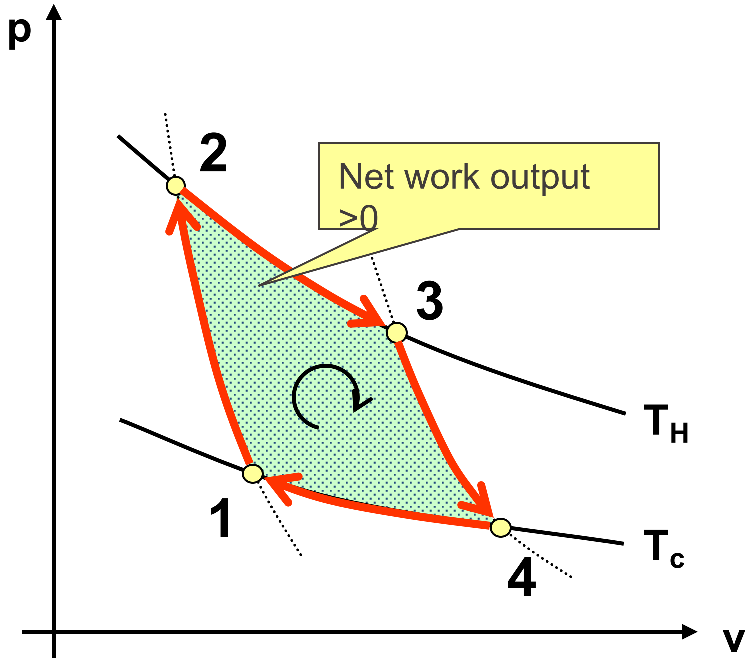
Photo Credit: Trougnouf

Last Time

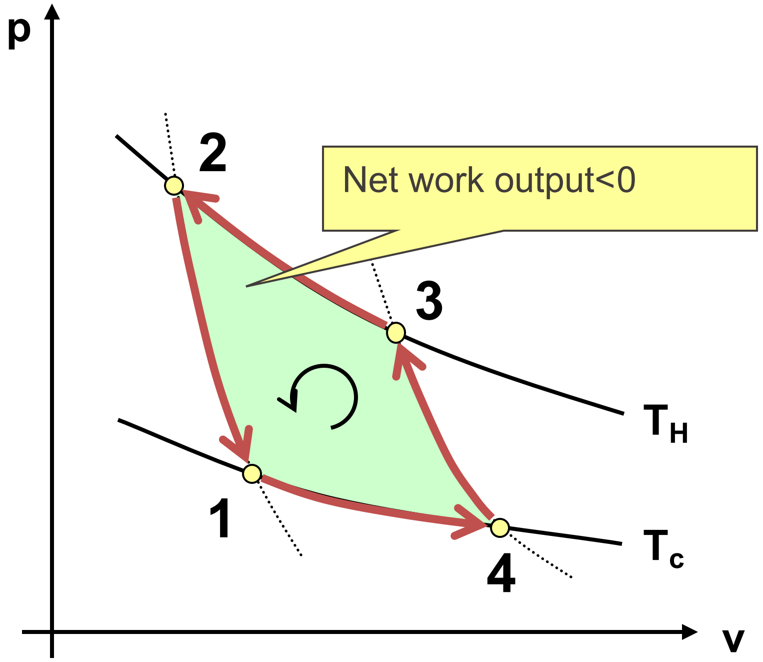
- Thermodynamic temperature scale
- Carnot efficiency
- Carnot cycle
- Clausius inequality and its relation to entropy
- Evaluation of entropy change

Carnot Cycle

Power Cycle



Refrigeration cycle



Clausius Inequality

For any thermodynamic cycle (reversible or not), $\oint \frac{\delta Q}{T} \leq 0$

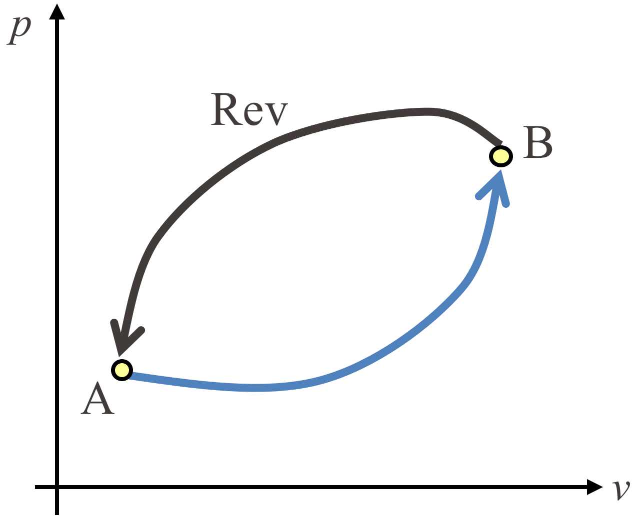
where δQ represent the heat increment supplied to the system at temperature T (negative value means heat discharge)

$$\oint \frac{\delta Q_{rev}}{T} = 0$$

Entropy

Construct a state function S $$S(B) - S(A) = \int_A^B \frac{\delta Q_{rev}}{T}$$

This defines the entropy S up to a constant $$S_A = S_{ref} + \int_{ref}^A \frac{\delta Q_{rev}}{T}$$



$$dS = \frac{\delta Q_{rev}}{T}$$ $$dS \geq \frac{\delta Q}{T}$$

Thermodynamics Relation

$$du = Tds - pdv \qquad dh = Tds + vdp$$

For liquid-vapor phase change $h_{fg} = T\Delta s_{fg}$

Incompressible substance $s_2 - s_1 = \int_{T_1}^{T_2} \frac{c(T)}{T} dT$

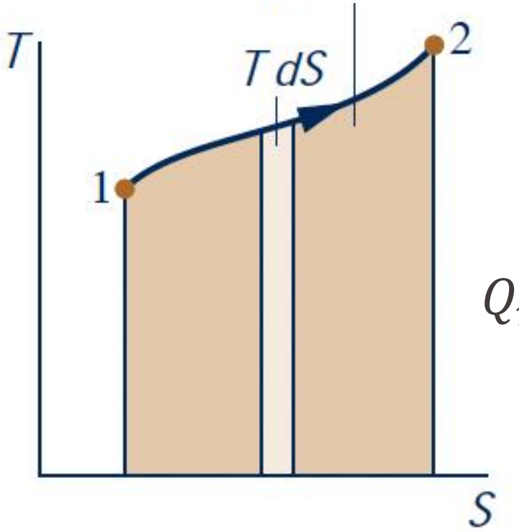
For constant heat capacity, $s_2 - s_1 = c \ln \frac{T_2}{T_1}$

Ideal gas $s_2 - s_1 = \int_{T_1}^{T_2} \frac{c_v(T)}{T} dT + R \ln \frac{v_2}{v_1} = \int_{T_1}^{T_2} \frac{c_p(T)}{T} dT - R \ln \frac{p_2}{p_1}$

For perfect gas $s_2 - s_1 = c_v \ln \frac{T_2}{T_1} + R \ln \frac{v_2}{v_1} = c_p \ln \frac{T_2}{T_1} - R \ln \frac{p_2}{p_1}$

Area Representation of Heat Transfer

$$dS = \frac{\delta Q_{rev}}{T} \Rightarrow \delta Q_{rev} = TdS$$

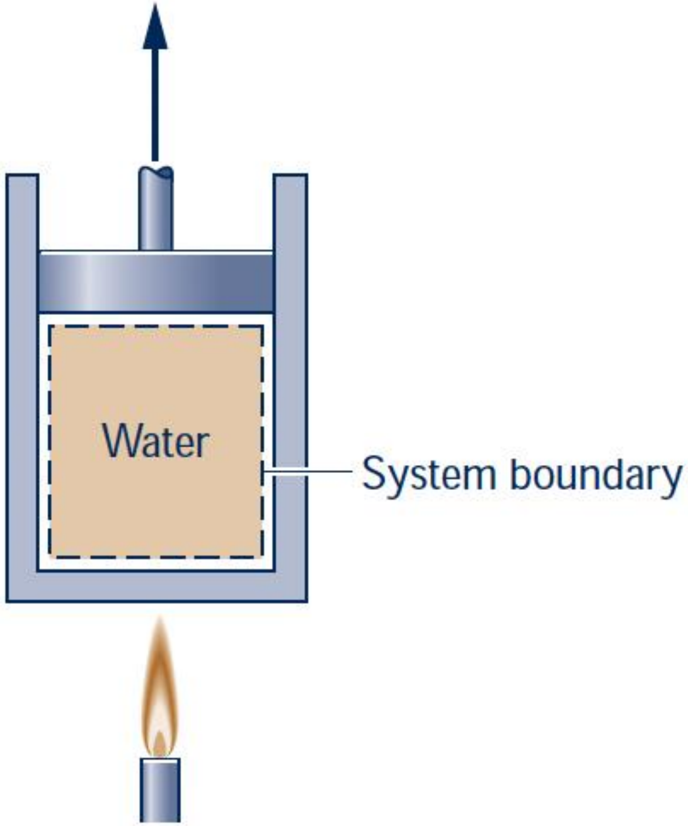


$$Q_{rev} = \int_1^2 TdS$$

Temperature must be in Kelvin

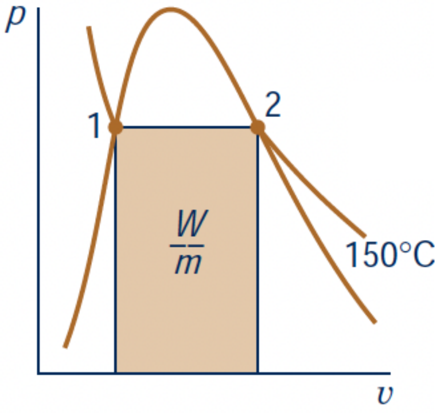
Area only represents the **reversible** heat transfer

Moran Example 6.1



Water contained in a piston-cylinder assembly undergoes a reversible process at 150 °C from saturated liquid to vapor

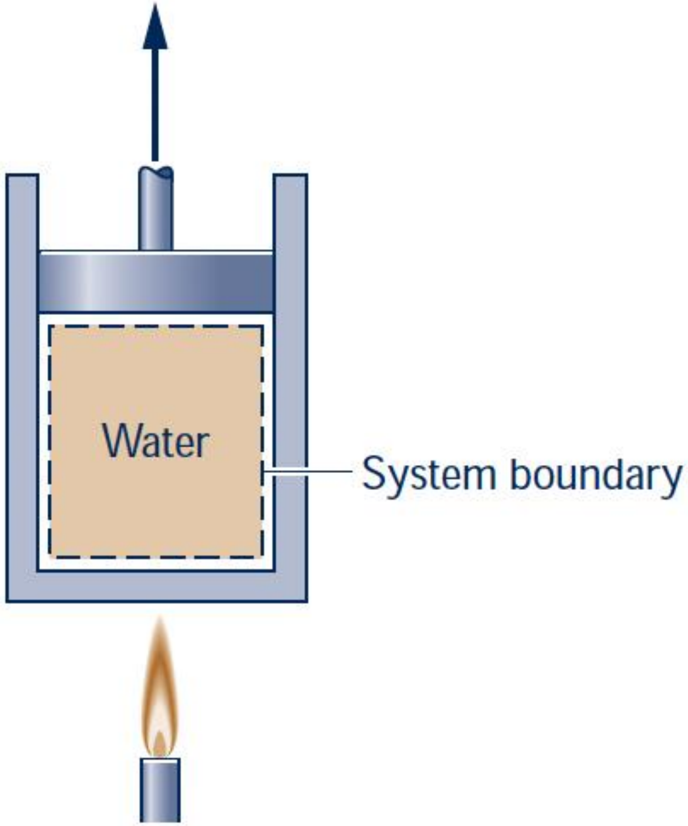
Determine the work and heat transfer per unit mass.



Pressure stays at the saturation pressure at 150 °C

$$\frac{W}{m} = \int_1^2 p dv = p(v_2 - v_1)$$

Moran Example 6.1



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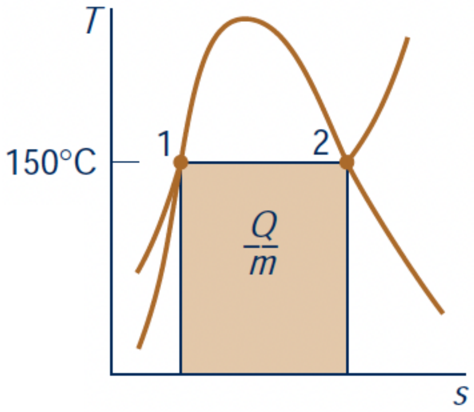

$$\frac{Q_{rev}}{m} = \int_1^2 T ds = T(s_2 - s_1)$$

ILOs Today

- Entropy balance for closed systems

- Reading: 6.7

Entropy Balance for Closed Systems

change in the amount of entropy contained within the system during some time interval	=	net amount of entropy transferred in across the system boundary during the time interval	+	amount of entropy produced within the system during the time interval

$$S_2 - S_1 = \int_1^2 \left(\frac{\delta Q}{T}\right)_b + \sigma \qquad \sigma \geq 0$$

entropy change — entropy transfer — entropy production

Interpreting Entropy Balance

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$$dS = \frac{\delta Q_{rev}}{T} \qquad dS \geq \frac{\delta Q}{T}$$

$$S_2 - S_1 \geq \int_1^2 \left(\frac{\delta Q}{T}\right)_b \qquad S_2 - S_1 = \int_1^2 \left(\frac{\delta Q}{T}\right)_b + \sigma \ \text{ with } \ \sigma \geq 0$$

Entropy balance is a re-interpretation of Clausius inequality

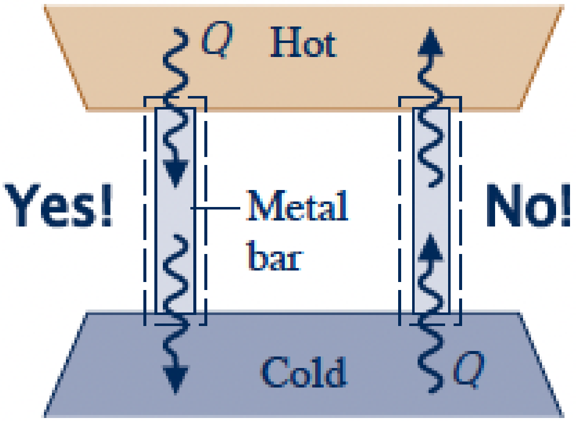
Entropy Statement of Second Law

Entropy production **is non-negative for any system**

For an isolated system (closed system with no heat transfer), entropy can only go up or stay the same

Internally reversible system: $\sigma = 0$

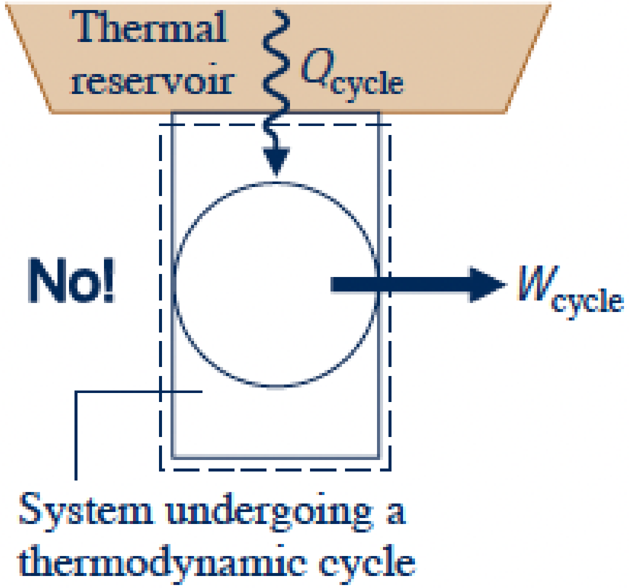
Revisiting Clausius Statement of 2nd Law



$$0 = \frac{Q}{T_H} - \frac{Q}{T_C} + \sigma$$

$$\sigma \geq 0, T_H > T_C \Rightarrow Q \geq 0$$

Revisiting Kelvin-Planck Statement of 2nd Law

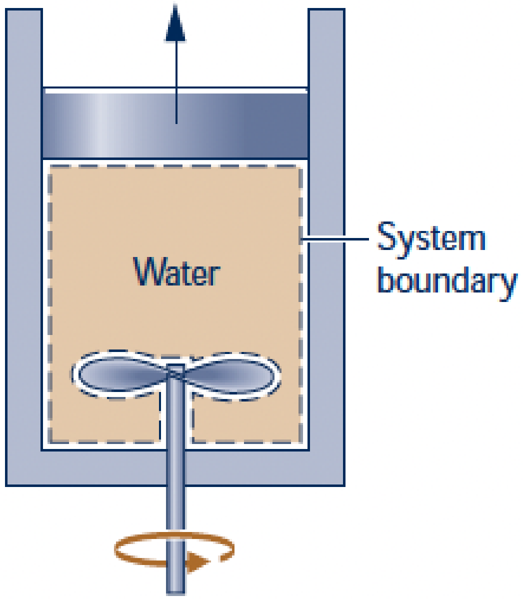


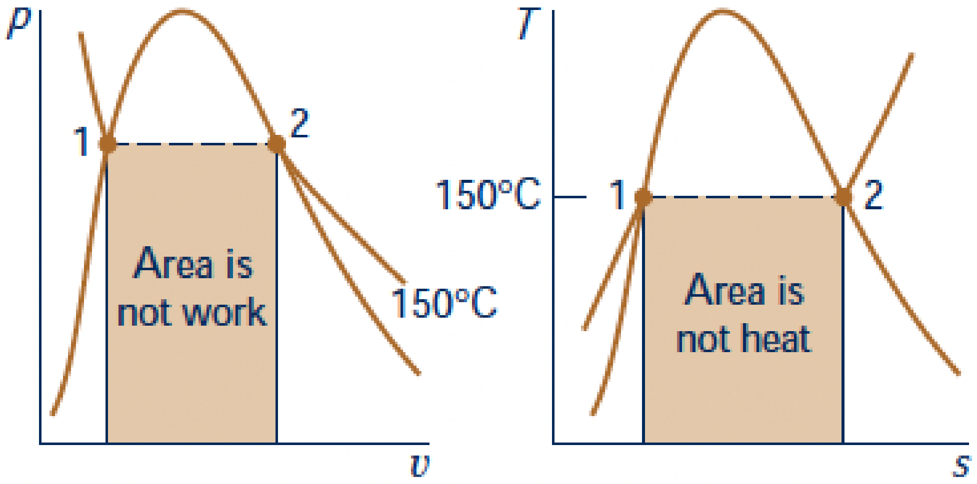
$$0 = \frac{Q_{cycle}}{T_{res}} + \sigma$$

$$\sigma \geq 0 \Rightarrow Q_{cycle} \leq 0 \Rightarrow W_{cycle} \leq 0$$

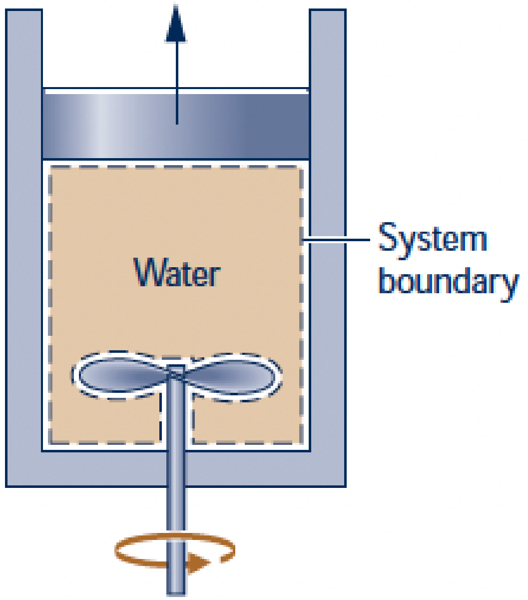
Moran Example 6.2

Water contained in a piston–cylinder assembly undergoes an adiabatic process from saturated liquid to saturated vapor at 150 °C. During the process, the piston moves freely, and the water is rapidly stirred by a paddle wheel. **Determine the net work per unit mass and the entropy production per unit mass.**





Moran Example 6.2



1st law $$\frac{W}{m} = -(u_2 - u_1)$$

2nd law $$\Delta S = \int_1^2 \frac{\delta Q}{T} + \sigma$$

$$\frac{\sigma}{m} = s_2 - s_1$$

Closed System Entropy Rate Balance

$$\frac{dS}{dt} = \sum_j \frac{\dot{Q}_j}{T_j} + \dot{\sigma}$$

dS/dt: rate of change of system entropy

$\frac{\dot{Q}_j}{T_j}$: entropy transfer transfer rate through the part of boundary that has temperature T_j

$\dot{\sigma}$: entropy generation rate in the system