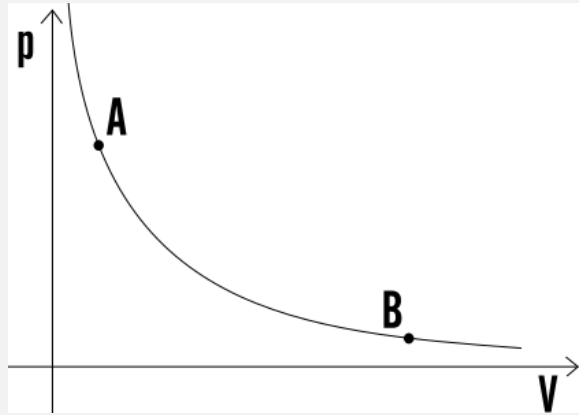


THERMODYNAMICS MACHINES

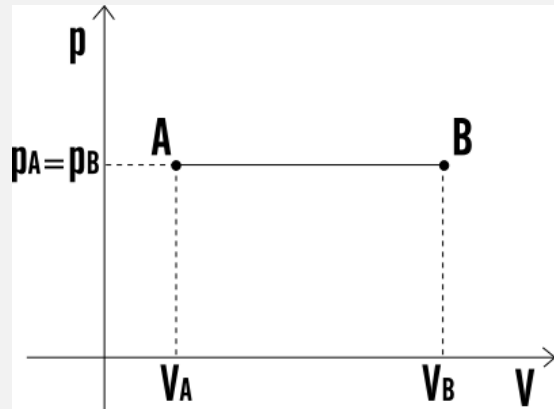
SUMMARY



$$Q_{AB} = nRT \ln \left(\frac{V_B}{V_A} \right)$$

$$W_{AB} = nRT \ln \left(\frac{V_B}{V_A} \right)$$

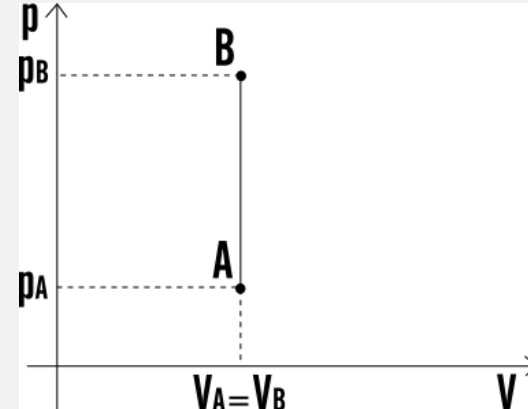
$$\Delta U_{AB} = 0$$



$$Q_{AB} = n c_P (T_B - T_A)$$

$$W_{AB} = p_A (V_B - V_A)$$

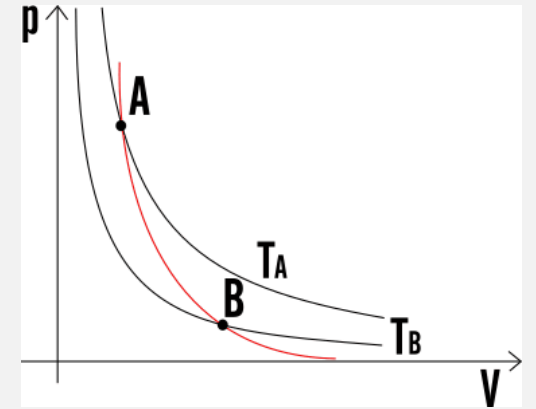
$$\Delta U_{AB} = n c_V (T_B - T_A)$$



$$Q_{AB} = n c_V (T_B - T_A)$$

$$W_{AB} = 0$$

$$\Delta U_{AB} = Q_{AB} = n c_V (T_B - T_A)$$



$$Q_{AB} = 0$$

$$W_{AB} = -n c_V (T_B - T_A)$$

$$\Delta U_{AB} = -W_{AB} = n c_V (T_B - T_A)$$

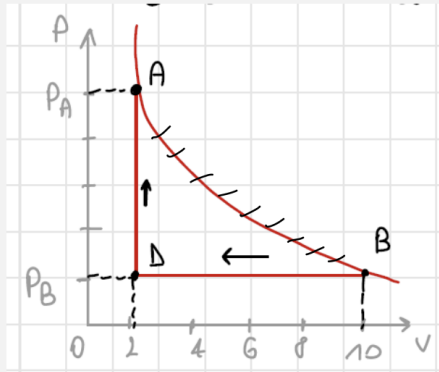


Example

An ideal gas is slowly compressed at a constant pressure of 2 atm from 10 L to 2 L. In the figure, the transformation is represented as path BD, in which heat is released. Subsequently, heat is supplied to the gas, kept at constant volume, while pressure and temperature are raised (DA), until the temperature returns to its original value ($T_A = T_B$).

a) Calculate the total work done by the gas in the BDA transformation and b) the total heat absorbed by the gas.

trasformazione BDA e b) il calore totale assorbito dal gas.



$$P_B = P_D = 2 \text{ atm}$$

$$V_B = 10 \text{ L}$$

$$V_D = 2 \text{ L}$$

$$2 \text{ atm} = 2 \cdot 0.2 \cdot 10^5 \text{ Pa}$$

$$10 \text{ L} = 10 \cdot 10^{-3} \text{ m}^3$$

$$2 \text{ L} = 2 \cdot 10^{-3} \text{ m}^3$$

$$L_{\text{TOT}} ? \rightarrow L_{BD} + L_{DA}$$

$$Q_{\text{TOT}} ? \quad \downarrow \quad \downarrow$$

$$P\Delta V \quad 0$$

$$R \rightarrow \frac{\text{Pa} \cdot \text{m}^3}{\text{mol K}}$$

$$\downarrow$$

$$\frac{\text{l} \cdot \text{atm}}{\text{mol K}}$$

$$L_{BD} = 2 \cdot 0.2 \cdot 10^5 \text{ Pa} \cdot (2 \cdot 10^{-3} \text{ m}^3 - 10 \cdot 10^{-3} \text{ m}^3)$$

$$= -1.6 \cdot 10^3 \text{ J}$$

$$BDA \rightarrow \Delta U = 0$$

(perché T non cambia)

$$\rightarrow Q - L = \Delta U$$

$$Q_{BDA} - L_{BDA} = 0 \rightarrow Q_{BDA} = L_{BDA} = -1.6 \cdot 10^3 \text{ J}$$



Example

A cylinder divided by a movable piston contains 96 g of O_2 initially at pressure $p_i=150$ kPa and at temperature $T_i=290$ K. A) Determine the initial volume of gas.

Subsequently, the gas expands at constant pressure, performing work $W=7.2$ kJ. B) Calculate its final volume.

Finally, the gas pressure is increased to $p_f=300$ kPa through an isochoric transformation. C) Determine the work done by the gas in the entire process.

$$i \rightarrow T_i = 290 \text{ K}$$

$$p_i = 150 \text{ kPa}$$

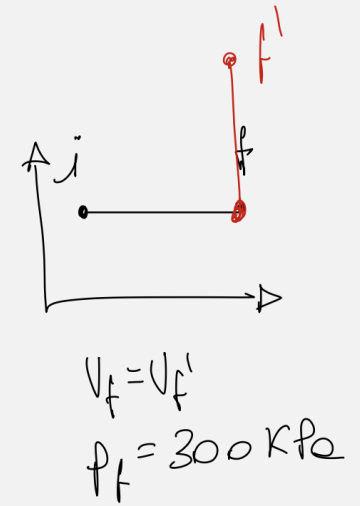
$$V_i = ?$$

$$p_i V_i = n R T_i$$

$$V_i = \frac{n R T_i}{p_i}$$

$$n = \frac{96 \text{ g}}{32} = \sim 3 \text{ mol}$$

$$V_i = \frac{3 \text{ mol} \cdot 8.31 \cdot 290 \text{ K}}{150 \cdot 1000 \text{ Pa}} = 4.82 \cdot 10^{-2} \text{ m}^3$$



$$L_{if} = 7.2 \text{ kJ}$$

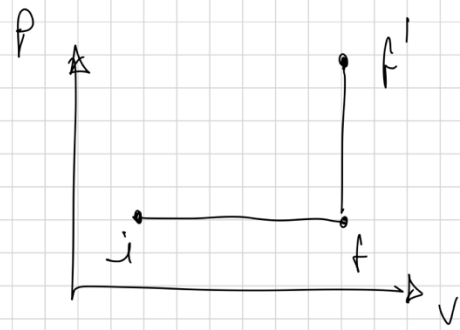
$$V_i \approx 4.82 \cdot 10^{-2} \text{ m}^3$$

$$V_f = ?$$

$$p_i = p_f = 150 \text{ kPa}$$

$$L = p \Delta V \rightarrow \Delta V = \frac{L}{p} = 4.8 \cdot 10^{-2} \text{ m}^3$$

$$V_f = V_i + \Delta V = 4.82 \cdot 10^{-2} \text{ m}^3 + 4.8 \cdot 10^{-2} \text{ m}^3 = 9.62 \cdot 10^{-2} \text{ m}^3 \approx 2V_i$$



$$V_f = V_{f'} = 9.62 \cdot 10^{-2} \text{ m}^3$$

$$p_{f'} = 300 \text{ kPa}$$

$$p_A = 150 \text{ kPa}$$

$$L_{\text{TOT}} ? \quad \underline{L_{if}} + \underline{L_{ff'}}$$

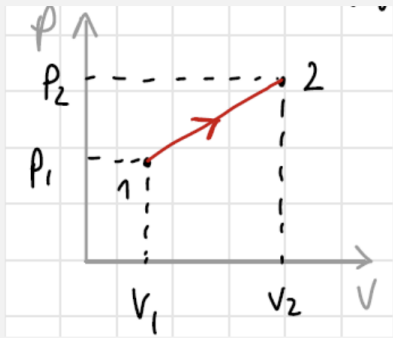
\swarrow \searrow \ominus
 7.2 kJ

$$L_{\text{TOT}} = L_{if} = 7.2 \text{ kJ}$$



Example

Consider 2 moles of an ideal diatomic gas initially at pressure $p_1 = 2 \text{ atm}$ and temperature $T_1 = 300 \text{ K}$. Starting from this state, the gas follows the reversible expansion shown in the figure, reaching state 2, where $2p_1 = p_2$ and $V_2 = 3V_1$. Determine: a) the volume V_1 and the temperature T_2 ; b) the internal energy change of the gas $\Delta U_{1,2}$; c) the heat exchanged $Q_{1,2}$



$$\begin{aligned} n &= 2 \text{ mol} & V_1 &= ? & T_2 &= ? & \Delta U_{1,2} &= ? & Q_{1,2} &= ? \\ p_1 &= 2 \text{ atm} & V_2 &= 3V_1 & & & & & & \\ p_2 &= 4 \text{ atm} & T_1 &= 300 \text{ K} & & & & & & \end{aligned}$$

$$p_1 V_1 = nRT_1 \rightarrow V_1 = \frac{nRT_1}{p_1} = \frac{2 \text{ mol} \cdot 0.082 \cdot 300 \text{ K}}{2 \text{ atm}} = 24.6 \text{ L} = 24.6 \text{ dm}^3$$

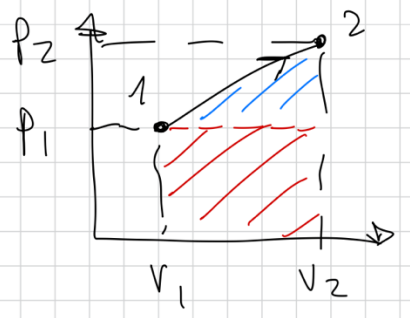
$$V_2 = 3V_1 = 73.8 \text{ L} = 73.8 \text{ dm}^3$$

$$p_2 V_2 = nRT_2 \rightarrow T_2 = \frac{p_2 V_2}{nR} = \frac{4 \text{ atm} \cdot 73.8 \text{ L}}{2 \text{ mol} \cdot 0.082} = 1800 \text{ K}$$

$$\Delta U_{1,2} = n c_v \Delta T = 2 \text{ mol} \cdot \frac{5}{2} R \cdot (1800 \text{ K} - 300 \text{ K}) = 6.23 \cdot 10^4 \text{ J}$$

$\hookrightarrow 8.31$

L



gen. $L = p \Delta V$



$Q - L = \Delta U$

$$L_{1,2} = p_1 \cdot \Delta V$$

$$\underbrace{p_1 (V_2 - V_1)}_{\text{reunayado}} + \frac{(p_2 - p_1) (V_2 - V_1)}{2} = 1.48 \cdot 10^4 \text{ J}$$

\downarrow
 \uparrow

reunayado
reunayado

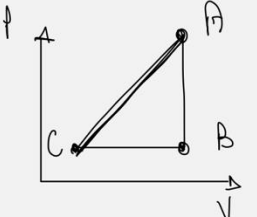
$$Q_{1,2} = \Delta U + L = 6.23 \cdot 10^4 \text{ J} + 1.48 \cdot 10^4 \text{ J} = 7.73 \cdot 10^4 \text{ J}$$



Example

A diatomic gas occupies a volume $V_A = 0.03 \text{ m}^3$ and has a pressure $p_A = 3 \times 10^5 \text{ Pa}$. Keeping the volume constant, the gas is cooled to 180 K and brought to a pressure $p_B = p_A/3$. Finally, through an isobaric transformation, a volume V is reached $V_C = V_A/3$.

I want to find $T_A, T_C, Q_{AB}, Q_{BC}, Q_{CA}, U_{AB}, U_{BC}, U_{CA}, L_{CA}$. Draw the transformations on the pV .

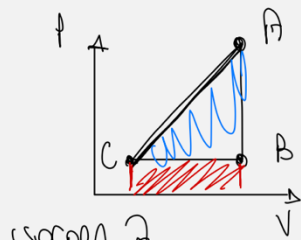


$V_A = 0.03 \text{ m}^3$ $V_B = V_A = 0.03 \text{ m}^3$ $V_C = V_A/3 = 0.01 \text{ m}^3$ $Q_{AB} ?$ $U_{AB} ?$
 $p_A = 3 \cdot 10^5 \text{ Pa}$ $p_B = \frac{p_A}{3} = 10^5 \text{ Pa}$ $p_C = p_B = 10^5$ $Q_{BC} ?$ $U_{BC} ?$
 $T_A ?$ $T_B = 180 \text{ K}$ $T_C ?$ $Q_{CA} ?$ $U_{CA} ?$

$pV = nRT \rightarrow T_A = \frac{p_A V_A}{nR} \rightarrow n = \frac{p_B V_B}{RT_B} = \frac{10^5 \text{ Pa} \cdot 0.03 \text{ m}^3}{8.31 \cdot 180 \text{ K}} \approx 2 \text{ mol}$

$\frac{p_A}{T_A} = \frac{p_B}{T_B} \rightarrow \frac{p_A}{p_B} = \frac{T_A}{T_B} = 3 \rightarrow T_A = 3 \cdot 180 \text{ K} = 540 \text{ K}$

$T_C = \frac{p_C V_C}{nR} \quad \text{isob.} \rightarrow \frac{V_B}{T_B} = \frac{V_C}{T_C} \rightarrow \frac{V_B}{V_C} = \frac{T_B}{T_C} = 3 \rightarrow T_C = \frac{1}{3} \cdot 180 \text{ K} = 60 \text{ K}$



ISOCORA \downarrow
 $Q = \Delta U$

$$Q = \Delta U = U_B - U_A = -14965 \text{ J}$$

ISOBARA \downarrow

$$Q - L = \Delta U \rightarrow -6984 \text{ J} - 10^5 \cdot 2 \cdot 10^{-2} = -4984 \text{ J}$$

$$\hookrightarrow p \Delta V = 10^5 \cdot 2 \cdot 10^{-2}$$

$$\text{TRANSFORM. CA} \rightarrow \Delta U = n C_{V,AB} \Delta T = 2 \text{ mol} \cdot \frac{5}{2} \cdot R \cdot (540^{\text{K}} - 80^{\text{K}}) = +19954 \text{ J}$$

$$\text{CICLO} \rightarrow \Delta U_{\text{TOT}} = 0 \rightarrow -14965 - 4984 + 19954 \approx 0$$

$$L_{CA} = p_C \cdot (V_B - V_C) + \frac{1}{2} (V_B - V_C) (p_A - p_B) = 4000 \text{ J}$$

$Q_{AB} \rightarrow$ ISOCORA

$$\hookrightarrow Q_{AB} = n C_V \Delta T = 2 \cdot \frac{5}{2} R (180^{\text{K}} - 540^{\text{K}}) = -14965 \text{ J}$$

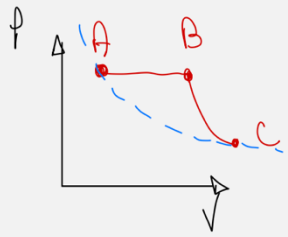
$Q_{BC} \rightarrow$ ISOBARA

$$\hookrightarrow = n C_p \Delta T = 2 \cdot \frac{7}{2} R (60^{\text{K}} - 180^{\text{K}}) = -6984 \text{ J}$$



Example

Two moles of an ideal monatomic gas go from initial state A to final state C through an isobaric expansion AB, followed by an adiabatic expansion BC. The temperature at A and C is the same and equals $T_A = T_C = 18^\circ\text{C}$; $p_A = 2 \times 10^5 \text{ Pa}$; $V_B = 2V_A$. Calculate: a) the value of the thermodynamic variables p , V , T at the three points; b) the amount of heat exchanged in the transformations from A to C. Draw the graph of the transformation on the pV .



$$n = 2 \text{ mol}$$
$$T_A = T_C = 18^\circ\text{C} = 291 \text{ K}$$
$$p_A = 2 \cdot 10^5 \text{ Pa}$$
$$V_B = 2V_A = 0.048 \text{ m}^3$$
$$p, V, T (A, B, C)? \rightarrow p_A V_A = nRT_A$$
$$V_A = \frac{nRT_A}{p_A} = 0.024 \text{ m}^3$$

$$\textcircled{B} p_B = p_A = 2 \cdot 10^5 \text{ Pa}$$
$$V_B = 0.048 \text{ m}^3 \rightarrow p_B V_B = nRT_B \rightarrow T_B = \frac{p_B V_B}{nR} = 577.6 \text{ K} \approx 2 \cdot T_A$$

$$\textcircled{C} T_C = T_A = 291 \text{ K}$$
$$T_B V_B^{\gamma-1} = T_C V_C^{\gamma-1} \rightarrow V_C^{\gamma-1} = \frac{T_B V_B^{\gamma-1}}{T_C} \Rightarrow \underline{V_C = 0.14 \text{ m}^3}$$

$$p_C V_C = nRT_C \rightarrow p_C = \frac{nRT_C}{V_C} = 0.35 \text{ Pa}$$

a) ✓

$$Q_{AC} = Q_{AB} + Q_{BC}$$

BC adiabatic $\rightarrow Q=0$

$$Q_{AC} = Q_{AB} \rightarrow \text{ISOBARA}$$

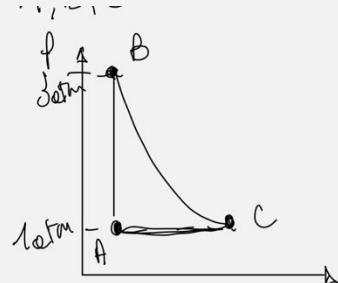
$$Q_{AB} = n c_p \Delta T = 2 \text{ mol} \cdot \frac{5}{2} R (577.6 \text{ K} - 29 \text{ K})$$

$= 12091 \text{ J}$



Example

An ideal monatomic gas occupies in state A a volume $V_A=5$ L at atmospheric pressure and temperature $T_A=300$ K. It is heated at constant volume up to state B at pressure $p_B=3$ atm. Then it expands isothermally up to state C at pressure $p_C=1$ atm, and finally is compressed isobarically up to the initial state A. a) Draw on the pV the graph of the transformation undergone by the gas and calculate the number of moles n of which the gas consists and the thermodynamic coordinates (p , V , T) of states A, B and C; b) calculate the heat Q , the work L and the internal energy change ΔU for the transformations AB, BC, CA and for the entire cycle.



(A)
 $V_A = 5$ L
 $p_A = 1$ atm
 $T_A = 300$ K

(B)
 $V_B = V_A$
 $p_B = 3$ atm
 T_B ✓

(C)
 V_C ✓
 $p_C = 1$ atm
 $T_C = T_B = 900$ K

$n \approx V$

$$\boxed{Q - L = \Delta U}$$

AB \rightarrow ISOCORA $\rightarrow L=0 \rightarrow Q=\Delta U$

$$Q = \Delta U = n c_V \Delta T = 0.203 \text{ mol} \cdot \frac{3}{2} R \cdot (900 - 300) = 1.52 \cdot 10^3 \text{ J}$$

BC \rightarrow ISOTERMA $\rightarrow Q - L = 0 \rightarrow Q = L$

$$L_{BC} = nRT \cdot \ln\left(\frac{V_C}{V_B}\right) = 0.203 \text{ mol} \cdot 8.31 \cdot 900 \text{ K} \cdot \ln\left(\frac{15}{5}\right) = 1.67 \cdot 10^3 \text{ J} = Q_{BC}$$

$$p_A V_A = n R T_A \rightarrow n = \frac{p_A V_A}{R T_A} = 0.203 \text{ mol}$$

$$p_B V_B = n R T_B \rightarrow T_B = \frac{p_B V_B}{n R} = 900 \text{ K}$$

$$p_C V_C = n R T_C \rightarrow V_C = \frac{n R T_C}{p_C} = 15 \text{ L}$$

CA → ISOBARA $Q = L = \Delta U$

$$L_{CA} = p\Delta V = p_A(V_A - V_C) = 1.01 \cdot 10^5 \text{ Pa} (5 \cdot 10^{-3} \text{ m}^3 - 15 \cdot 10^{-3} \text{ m}^3) = -1.01 \cdot 10^3 \text{ J}$$

$$\Delta U = nC_V \Delta T = 0.203 \text{ mol} \cdot \frac{3}{2} R \cdot (T_A - T_C) = -1.52 \cdot 10^3 \text{ J}$$

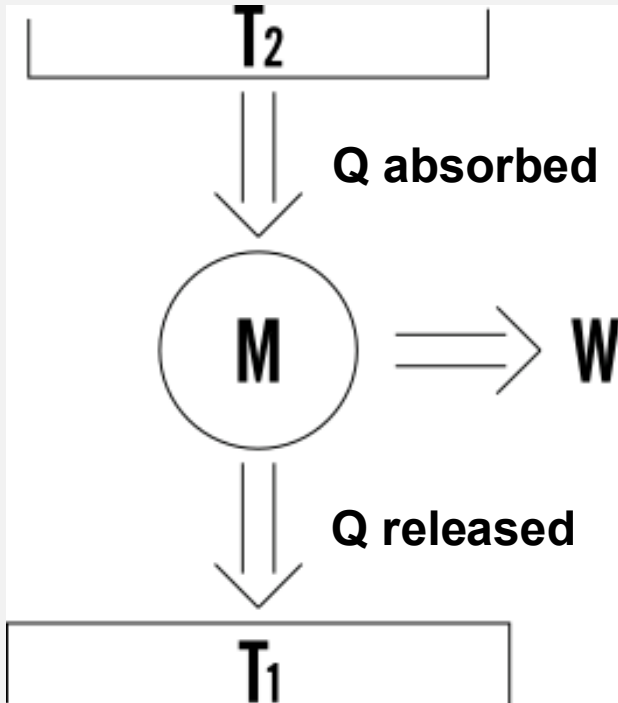
$$Q = \Delta U + L = nC_p \Delta T \rightarrow -2.53 \cdot 10^3 \text{ J}$$

$$Q_{\text{TOT}} = Q_{AB} + Q_{BC} + Q_{CA} = +0.66 \cdot 10^3 \text{ J}$$

$$L_{\text{TOT}} = L_{AB} + L_{BC} + L_{CA} = +0.66 \cdot 10^3 \text{ J}$$

$$\Delta U_{\text{TOT}} = \Delta U_{AB} + \Delta U_{BC} + \Delta U_{CA} = 0$$

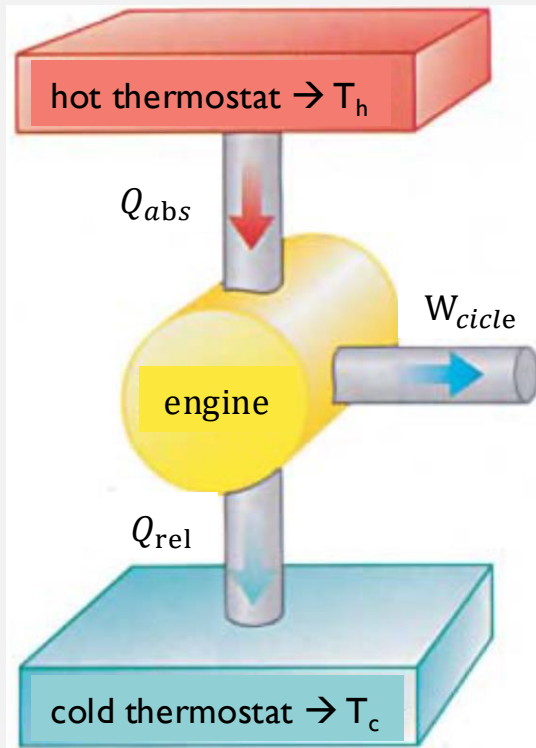
HEAT ENGINES



A high-temperature source transfers a quantity of heat Q to the system to perform work, and the same system then transfers a quantity of heat to the second thermal source at a lower temperature

A heat engine must necessarily operate on a cycle.
For a cycle, the first law of thermodynamics states:
 $\Delta U = \Delta Q - W \rightarrow \Delta Q = W$

HEAT ENGINES



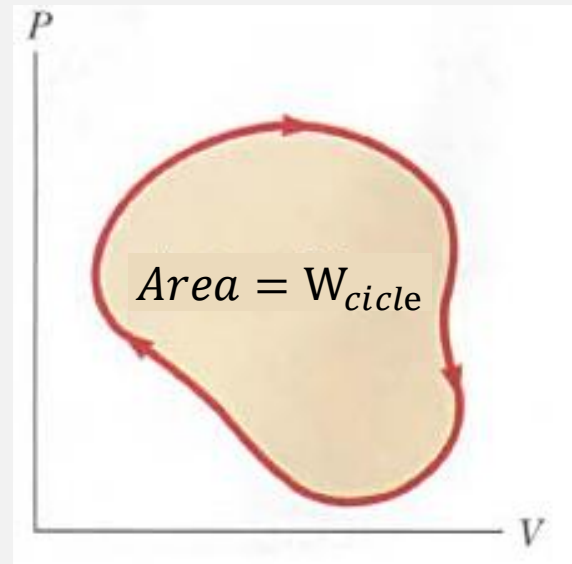
Absorb Q_{abs} , release Q_{rel} and perform work W_{cicle}

If $W_{cicle} > 0$ HEAT ENGINE

If $W_{cicle} < 0$ REFRIGERATOR

$$Q_{cicle} = Q_{abs} + Q_{rel} = Q_{abs} - |Q_{rel}| \quad \Delta U_{cicle} = 0 \quad W_{cicle} = Q_{cicle}$$

$$W_{cicle} = Q_{cicle} = Q_{abs} - |Q_{rel}|$$



EFFICIENCY is defined as:

$$\eta = \frac{W_{cicle}}{Q_{abs}} = \frac{Q_{abs} - |Q_{rel}|}{Q_{abs}} = 1 - \frac{|Q_{rel}|}{Q_{abs}} < 1$$

REFRIGERATORS

In a refrigerator:

$$Q_{cycle} = Q_{abs} + Q_{rel} = Q_{abs} - |Q_{rel}| \quad \Delta U_{cycle} = 0 \quad W_{cycle} = Q_{cycle}$$

$$W_{cycle} = Q_{cycle} = Q_{abs} - |Q_{rel}|$$

The Coefficient of Performance (COP) is defined as:

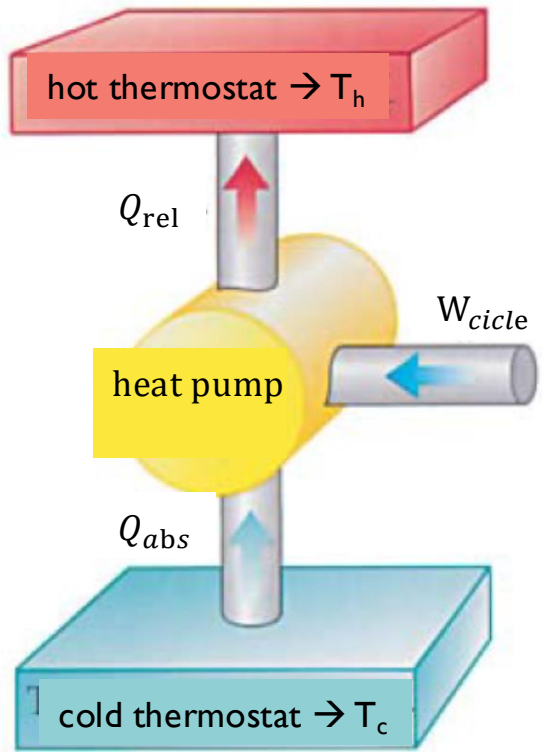
$$\text{COP} = \frac{Q_{abs}}{|W_{cycle}|} = \frac{|Q_{rel}| - |W_{cycle}|}{|W_{cycle}|} = \frac{|Q_{rel}|}{|W_{cycle}|} - 1 > 0$$

$$|W_{cycle}| = -Q_{abs} + |Q_{rel}|$$

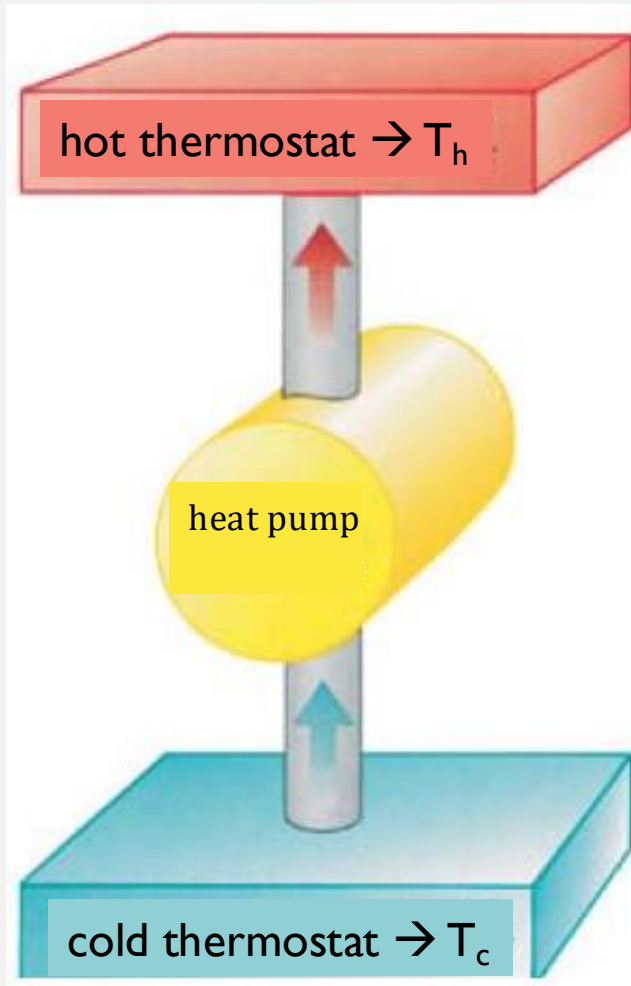
hence $|W_{cycle}| < |Q_{rel}|$

Why is it >0?

2



CLAUSIUS STATEMENT

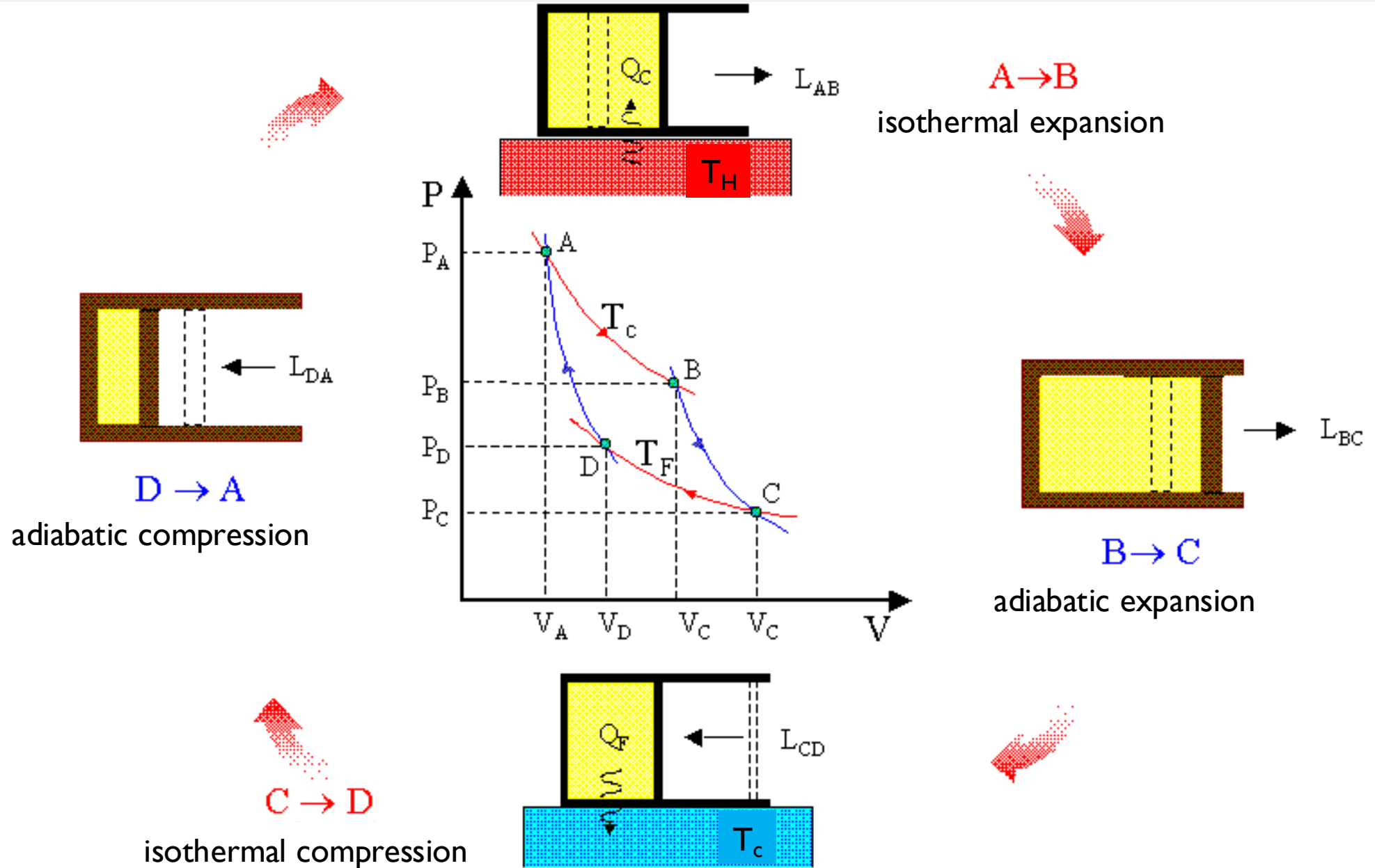


It is impossible to build a machine whose sole result is the transfer of heat from a cold body to a hot body:

This means it is impossible to have $COP = 1$

CARNOT ENGINE

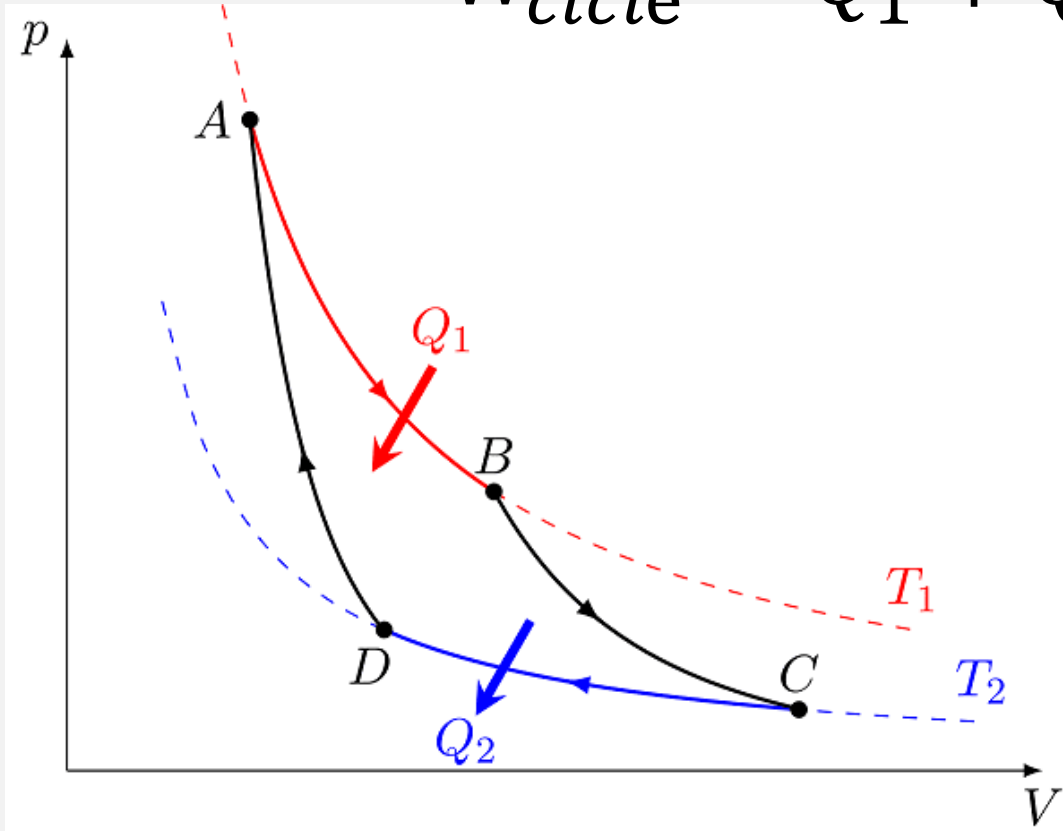
$$L = W$$



CARNOT ENGINE

$$\Delta U = 0$$

$$W_{\text{cycle}} = Q_1 + Q_2$$



$$W_{AB} = nRT_1 \ln\left(\frac{V_B}{V_A}\right) = Q_{AB} = Q_1 > 0$$

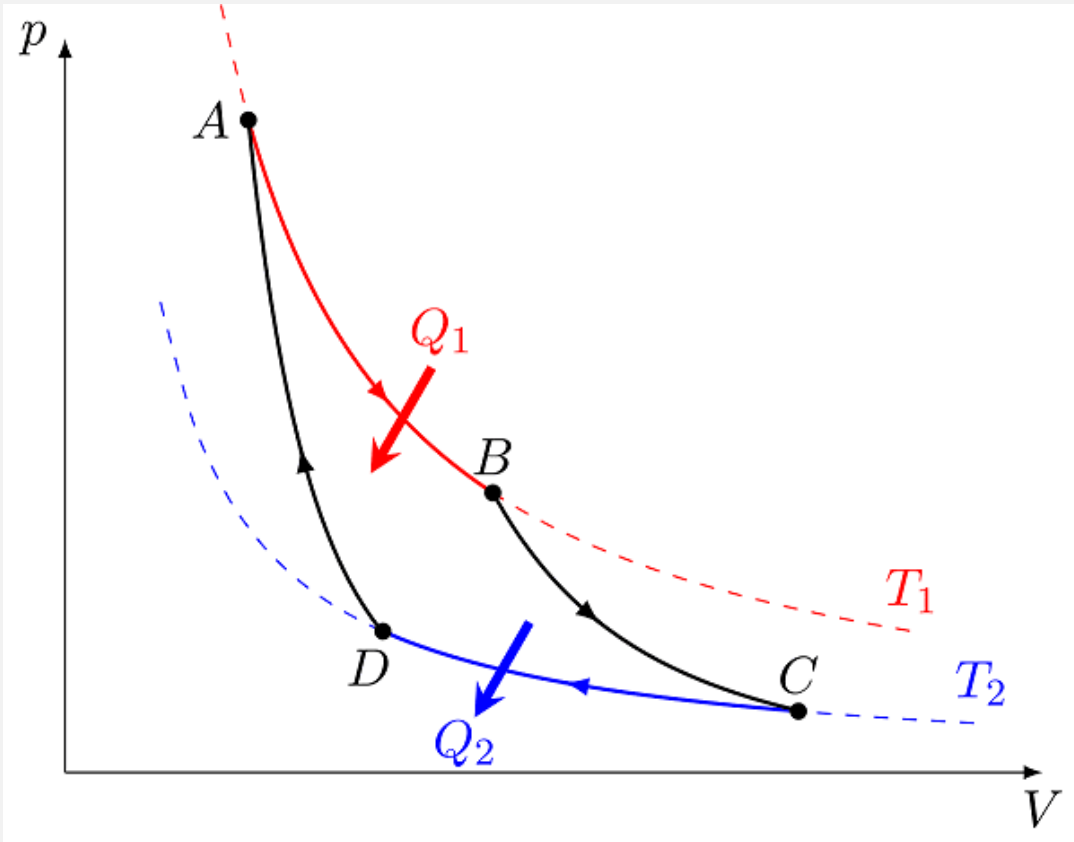
$$Q_{BC} = 0 \quad L_{BC} = -\Delta U_{BC} = -nc_V(T_C - T_B) = nc_V(T_B - T_C)$$

$$W_{CD} = nRT_2 \ln\left(\frac{V_D}{V_C}\right) = Q_{CD} = Q_2 < 0$$

$$Q_{DA} = 0 \quad W_{DA} = -\Delta U_{DA} = -nc_V(T_A - T_D) = nc_V(T_D - T_A)$$

$$\eta = \frac{W_{\text{cycle}}}{Q_{\text{abs}}} = 1 - \frac{|Q_{\text{rel}}|}{Q_{\text{abs}}} = 1 - \frac{\cancel{nRT_2 \ln\left(\frac{V_C}{V_D}\right)}}{\cancel{nRT_1 \ln\left(\frac{V_B}{V_A}\right)}} = 1 - \frac{T_2 \ln\left(\frac{V_C}{V_D}\right)}{T_1 \ln\left(\frac{V_B}{V_A}\right)}$$

CARNOT ENGINE



$$W_{AB} = nRT_1 \ln\left(\frac{V_B}{V_A}\right) = Q_{AB} = Q_1 > 0$$

$$Q_{BC} = 0 \quad L_{BC} = -\Delta U_{BC} = -nc_V(T_C - T_B) = nc_V(T_B - T_C)$$

$$W_{CD} = nRT_2 \ln\left(\frac{V_D}{V_C}\right) = Q_{CD} = Q_2 < 0$$

$$Q_{DA} = 0 \quad W_{DA} = -\Delta U_{DA} = -nc_V(T_A - T_D) = nc_V(T_D - T_A)$$

$$\eta = \frac{W_{\text{cycle}}}{Q_{\text{abs}}} = 1 - \frac{|Q_{\text{rel}}|}{Q_{\text{abs}}} = 1 - \frac{nRT_2 \ln\left(\frac{V_C}{V_D}\right)}{nRT_1 \ln\left(\frac{V_B}{V_A}\right)} = 1 - \frac{T_2 \ln\left(\frac{V_C}{V_D}\right)}{T_1 \ln\left(\frac{V_B}{V_A}\right)}$$

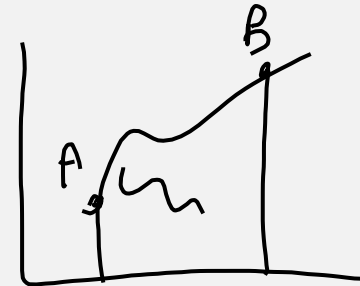
$$\begin{cases} T_1 V_B^{\gamma-1} = T_2 V_C^{\gamma-1} \\ T_1 V_A^{\gamma-1} = T_2 V_D^{\gamma-1} \end{cases}$$

$$\frac{\left(\frac{V_B}{V_A}\right)^{\gamma-1}}{\left(\frac{V_C}{V_D}\right)^{\gamma-1}} = \frac{V_B}{V_C} = \frac{V_D}{V_A}$$

$$\eta = 1 - \frac{T_2}{T_1} < 1$$

ENTROPY

Let us start from an infinitesimal reversible thermodynamic transformation



$$Q - W = \Delta U \quad \delta Q - \delta W = dU \quad \delta Q = nc_V dT + pdV$$

It is not a state function

$$\frac{\delta Q}{T} = \frac{nc_V dT}{T} + \frac{nRT dV}{TV}$$

$$\int_A^B \frac{\delta Q}{T} = \int_{T_A}^{T_B} \frac{nc_V}{T} dT + \int_{V_A}^{V_B} \frac{nR}{V} dV = nc_V \ln\left(\frac{T_B}{T_A}\right) + nR \ln\left(\frac{V_B}{V_A}\right)$$

is a state function

WE THEREFORE DEFINE ENTROPY:

$$\int_A^B \frac{\delta Q}{T} = S(B) - S(A) = \Delta S_{AB}$$

variazione di entropia

ENTROPY

$$\int_A^B \frac{\delta Q}{T} = S(B) - S(A) = \Delta S_{AB}$$

$$\Delta S_{AB} = nc_V \ln \left(\frac{T_B}{T_A} \right) + nR \ln \left(\frac{V_B}{V_A} \right)$$

REVERSIBLE TRANSFORMATIONS

ISOTHERMAL

$$Q_{AB} = W_{AB} = nRT \ln \left(\frac{V_B}{V_A} \right)$$

$$\Delta S_{AB} = nR \ln \left(\frac{V_B}{V_A} \right)$$

ISOBARIC

$$Q_{AB} = nc_P(T_B - T_A)$$
$$\frac{dQ}{T} = \frac{nc_P dT}{T}$$

$$\Delta S_{AB} = nc_V \ln \left(\frac{T_B}{T_A} \right) + nR \ln \left(\frac{V_B}{V_A} \right)$$

ISOCHORIC

$$Q_{AB} = nc_V(T_B - T_A)$$
$$\frac{dQ}{T} = \frac{nc_V dT}{T}$$

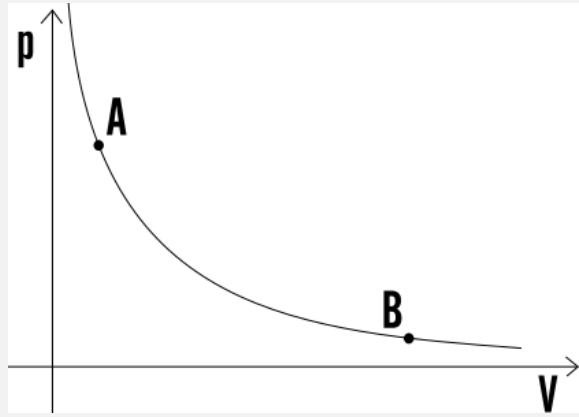
$$\Delta S_{AB} = nc_V \ln \left(\frac{T_B}{T_A} \right)$$

ADIABATIC

$$Q_{AB} = 0$$

$$\Delta S_{AB} = 0$$

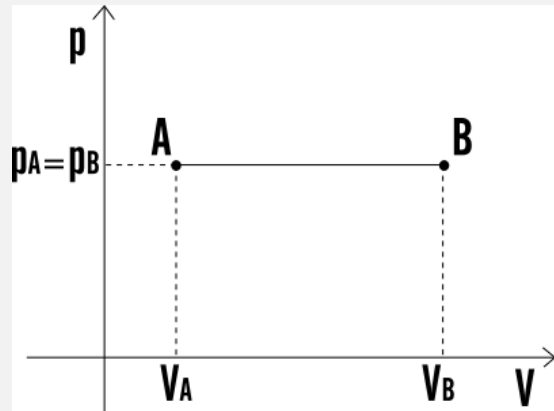
SUMMARY



$$Q_{AB} = nRT \ln \left(\frac{V_B}{V_A} \right)$$

$$L_{AB} = nRT \ln \left(\frac{V_B}{V_A} \right)$$

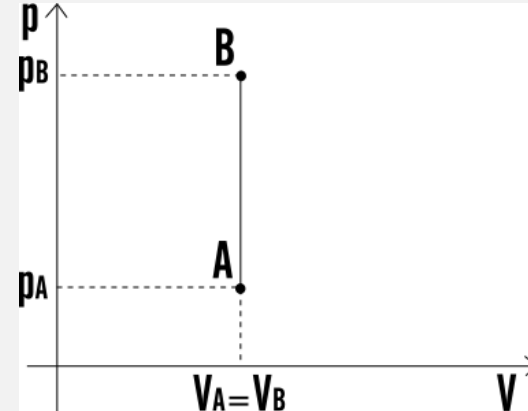
$$\Delta U_{AB} = 0$$



$$Q_{AB} = n c_P (T_B - T_A)$$

$$L_{AB} = p_A (V_B - V_A)$$

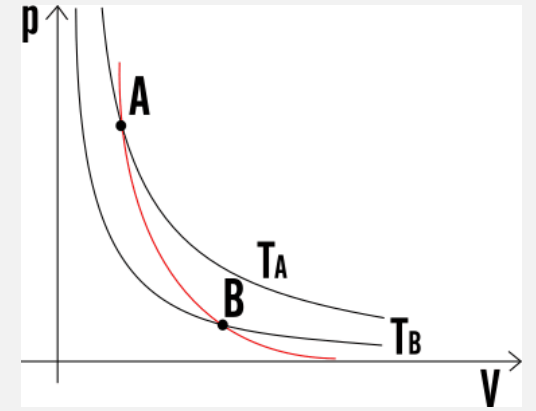
$$\Delta U_{AB} = n c_V (T_B - T_A)$$



$$Q_{AB} = n c_V (T_B - T_A)$$

$$L_{AB} = 0$$

$$\Delta U_{AB} = Q_{AB} = n c_V (T_B - T_A)$$



$$Q_{AB} = 0$$

$$L_{AB} = -n c_V (T_B - T_A)$$

$$\Delta U_{AB} = -L_{AB} = n c_V (T_B - T_A)$$

ENTROPY

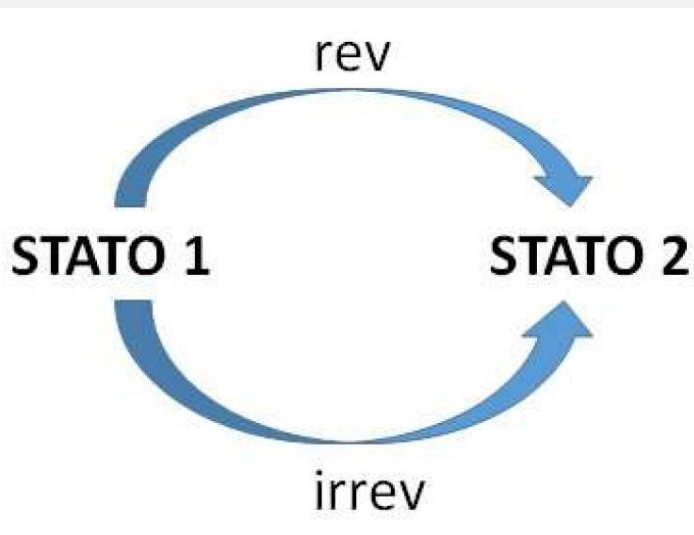
$$\Delta U = Q_{rev} - L_{rev} = Q_{non\ rev} - W_{non\ rev} \quad Q_{rev} - Q_{non\ rev} = W_{rev} - W_{non\ rev}$$

$$\rightarrow W_{rev} > W_{non\ rev} \quad W_{rev} - W_{non\ rev} > 0 \quad Q_{rev} - Q_{non\ rev} > 0$$

$$\frac{Q_{rev}}{T} - \frac{Q_{non\ rev}}{T} > 0 \quad \frac{Q_{rev}}{T} > \frac{Q_{non\ rev}}{T} \quad \int_A^B \frac{\delta Q_{rev}}{T} \geq \int_A^B \frac{\delta Q}{T}$$

$$\Delta S_{AB} \geq \int_A^B \frac{\delta Q}{T}$$

Clausius Inequality



The entropy of an isolated system can never decrease: it remains constant in a system of reversible transformations and increases whenever an irreversible transformation takes place