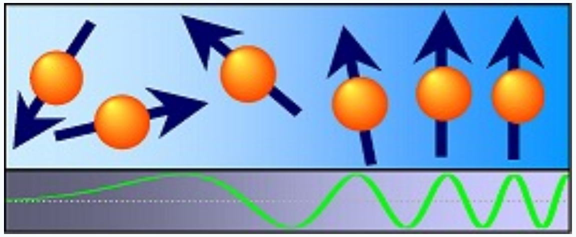
Experimental Physics EP2
Thermodynamics

– 2nd Law of Thermodynamics –
Heat engines, Carnot cycle

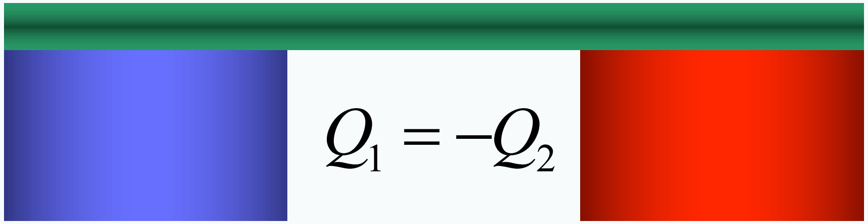


https://bloch.physgeo.uni-leipzig.de/amr/

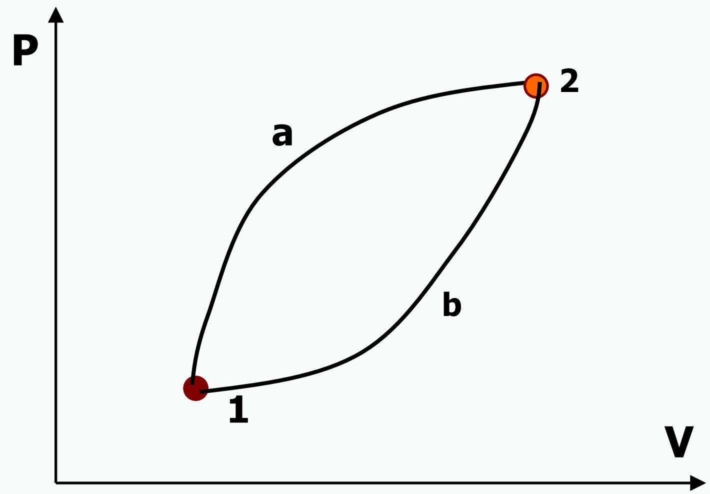
Basis for 2nd law of thermodynamics

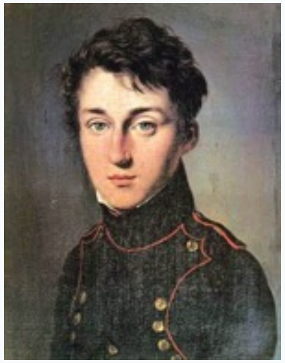
$$Q = \Delta U + W$$

The net heat added to system equals the change of the internal energy of the system plus the work done by the system.



$$Q_1 = -Q_2$$





Sadi Carnot

$$Q_1 = U_2 - U_1 + W_1$$

$$-Q_2 = U_1 - U_2 - W_2$$

$$Q_1 - Q_2 = W_1 - W_2$$

$$\eta \equiv \frac{W}{Q_1} = \frac{Q_1 - Q_2}{Q_1}$$

efficiency

The 2nd law of thermodynamics

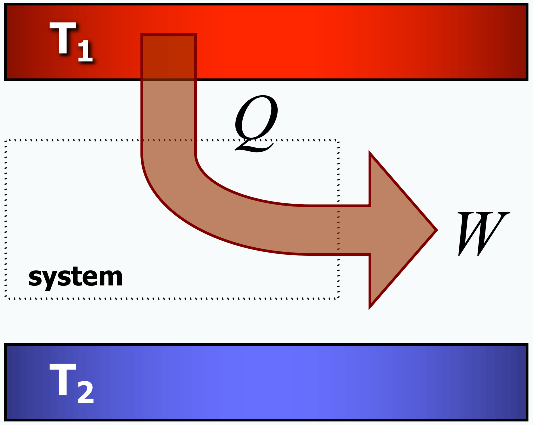
$$\eta \equiv \frac{W}{Q_1} = 1 - \frac{|Q_2|}{Q_1}$$

$$\eta = 1 - ?$$

***perpetuum mobile* of 2nd kind**

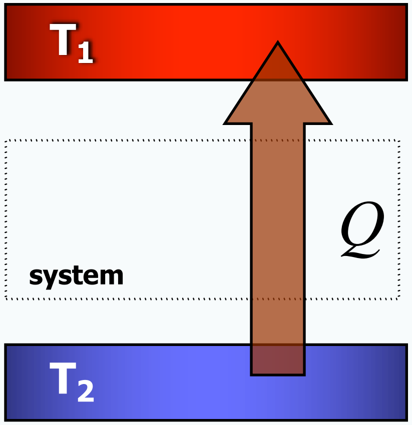
Wilhelm Ostwald

<u>Lord Kelvin</u>: No cyclic process is possible in which the sole result is the absorption of heat from a reservoir and its complete conversion into work.



<u>Planck</u>: It is impossible to construct a device, which is operating in a cycle, the sole result of which will be lifting up a weight due to a decrease of an internal energy of the heat bath.

Clausius: No process is possible whose sole result is the transfer of heat from a body of lower temperature to a body of higher temperature.

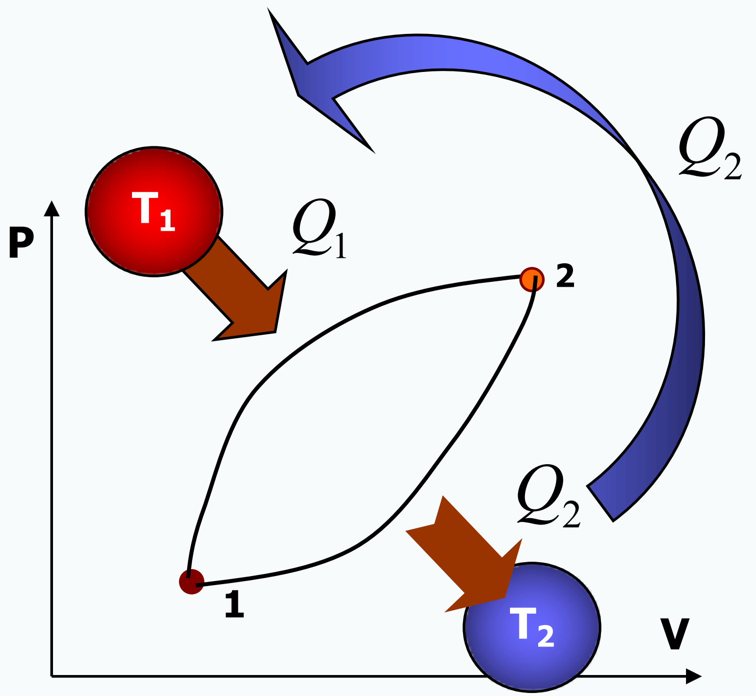


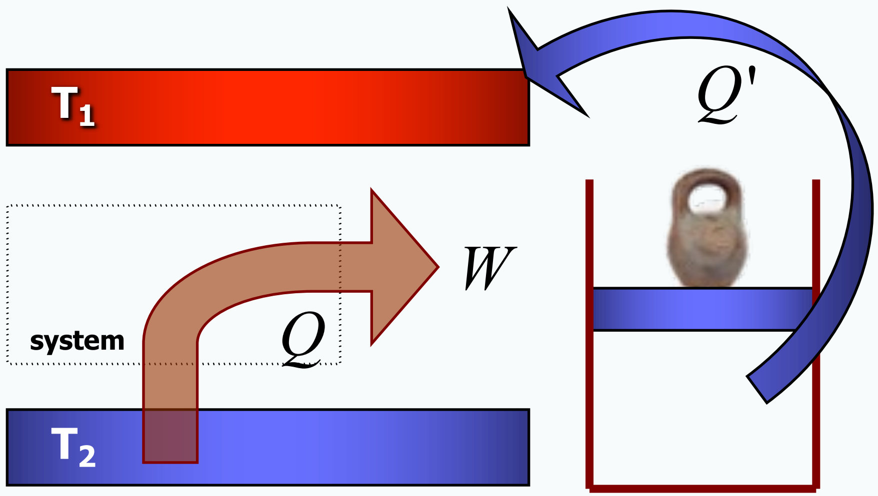
All statements of the 2nd law of thermodynamics are equivalent.

Equivalency of different statements

$$\eta \equiv \frac{W}{Q_1} = \frac{Q_1 - Q_2}{Q_1}$$

$$W = Q_1 - \cancel{Q_2} = Q_1$$



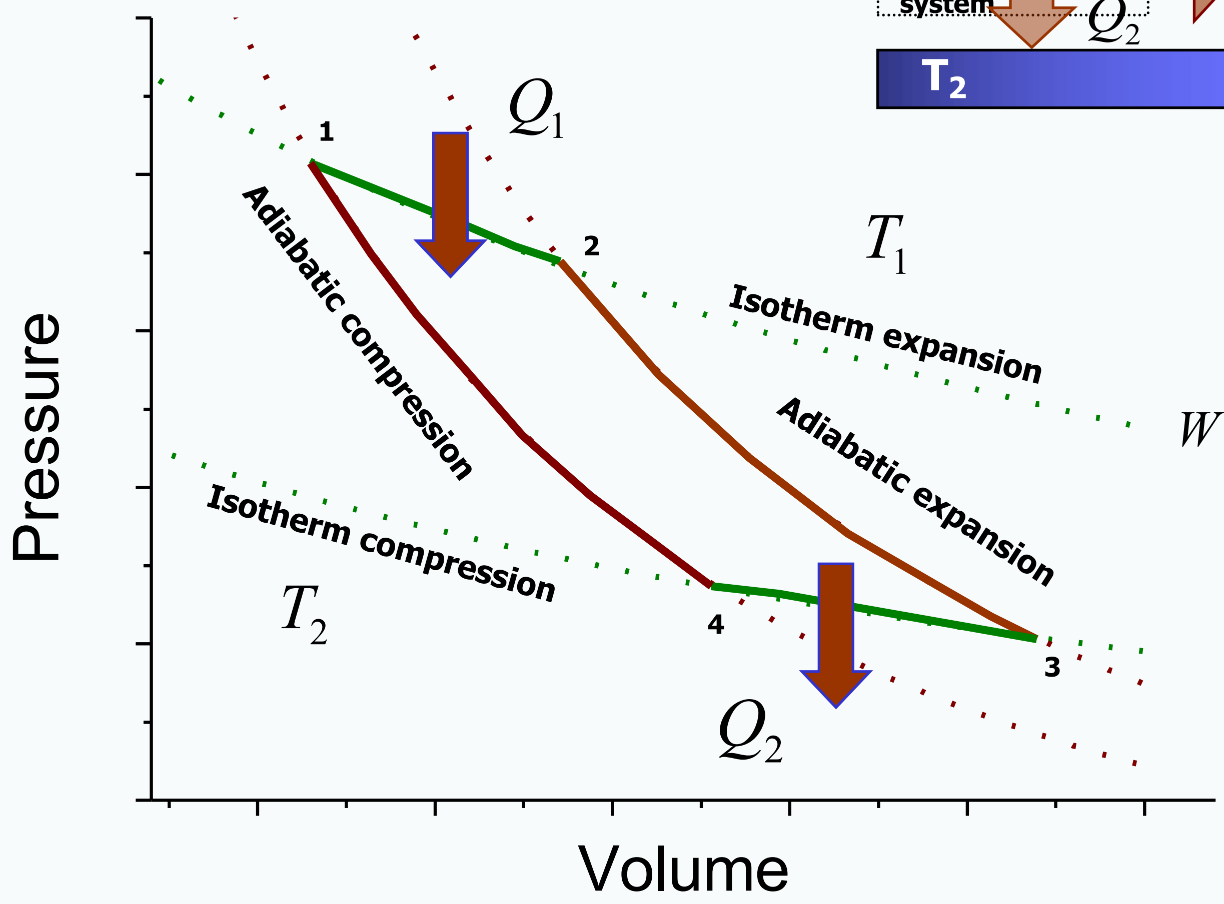


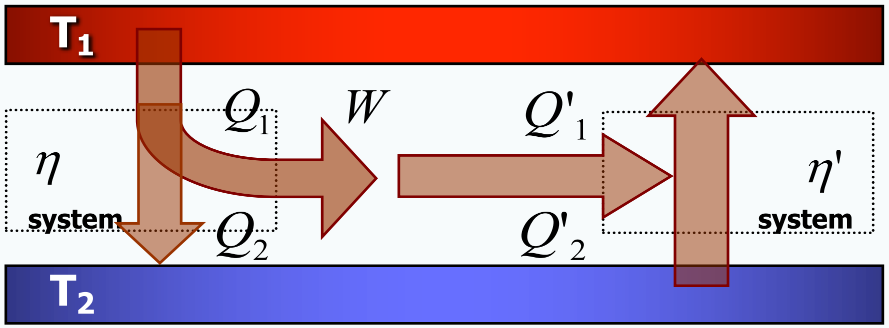
Principle of Carathéodory:

In an arbitrary neighborhood of every point in macroscopic state space there are adjacent points which cannot be reached from the first point by adiabatic means.

The Carnot cycle

$$Q_2 = (1-\eta)Q_1$$





$$m: \quad W = Q_1 - Q_2$$

$$m': \quad W' = Q'_1 - Q'_2$$

$$W - W' = (Q_1 - Q'_1) - (Q_2 - Q'_2)$$

$$m' q'_1 - m q_1 = 0 \Rightarrow Q'_1 - Q_1 = 0$$

$$Q'_2 - Q_2 = W - W'$$

$$= (\eta - \eta')Q_1$$

~~**Heat extracted from cooler is spent solely to produce work.**~~

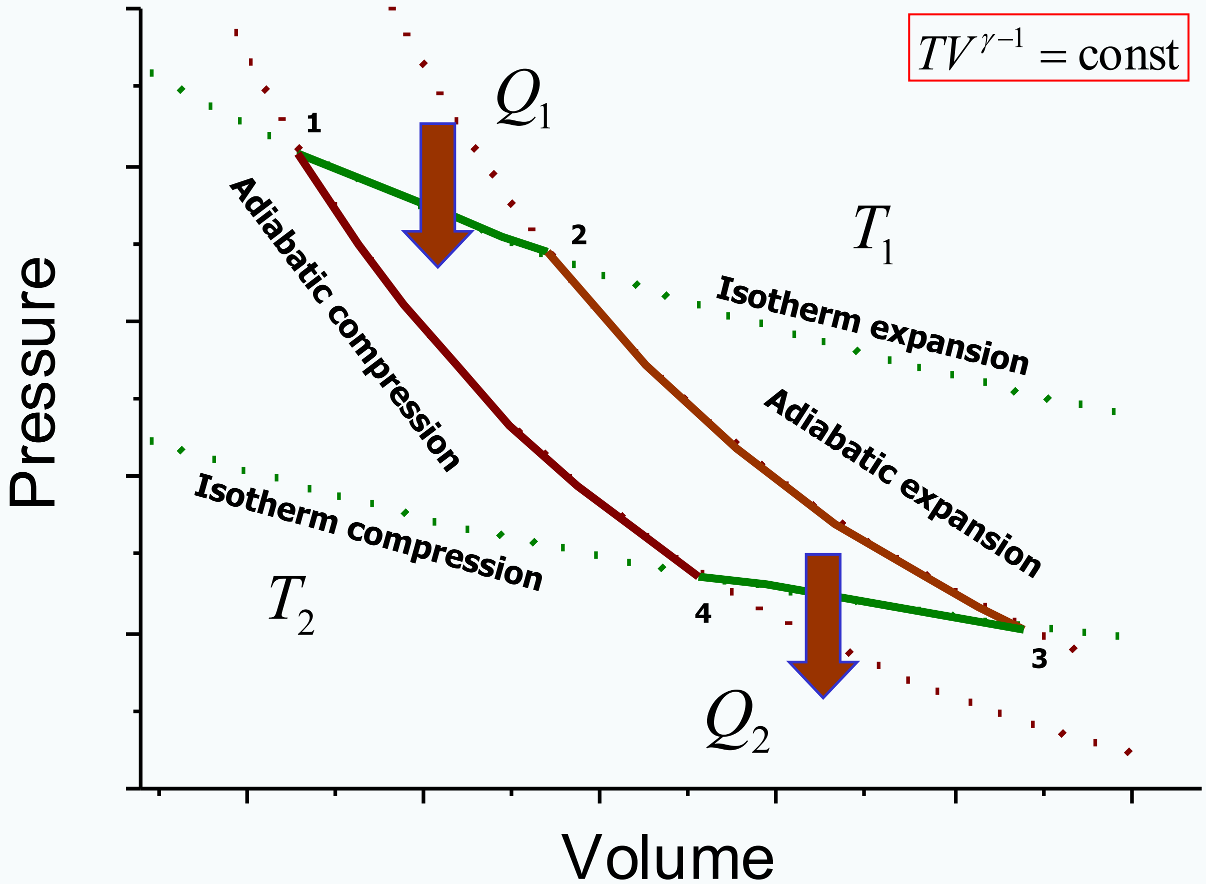
The Carnot cycle

$$\eta = 1 - \frac{|Q_2|}{Q_1}$$

$$Q_1 = W_1 = \int_1^2 P\,dV = \nu R T_1 \ln\left(\frac{V_2}{V_1}\right)$$

$$|Q_2| = \nu R T_2 \ln\left(\frac{V_3}{V_4}\right)$$

$$TV^{\gamma-1} = \text{const}$$



$$T_1 V_2^{\gamma-1} = T_2 V_3^{\gamma-1}$$

$$T_2 V_4^{\gamma-1} = T_1 V_1^{\gamma-1}$$

$$\left(\frac{V_3}{V_4}\right)^{\gamma-1} = \left(\frac{V_2}{V_1}\right)^{\gamma-1}$$

$$\eta_{\text{Carnot}} = 1 - \frac{T_2}{T_1}$$

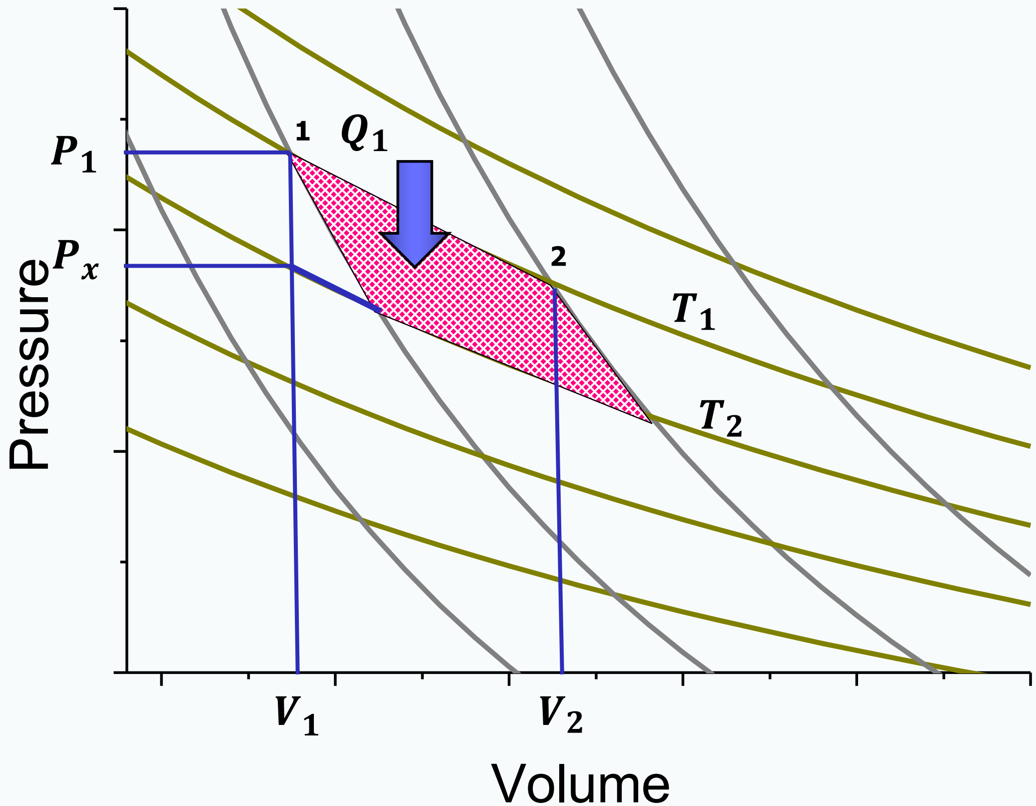
$$\frac{T_2}{T_1} = \frac{|Q_2|}{Q_1}$$

Selected applications: $U=U(V)$; $C_P - C_V$

$$W = (\Delta P)_V (\Delta V)_T = \left(\frac{\partial P}{\partial T}\right)_V (T_1 - T_2)(V_2 - V_1)$$

$$\frac{W}{Q_1} = 1 - \frac{T_2}{T_1}$$

$$Q_1 = U_2 - U_1 + W_1 = \left(\frac{\partial U}{\partial V}\right)_T (V_2 - V_1) + P(V_2 - V_1)$$



$$\left(\frac{\partial U}{\partial V}\right)_T = T\left(\frac{\partial P}{\partial T}\right)_V - P$$

$$C_P - C_V = \left[\left(\frac{\partial U}{\partial V}\right)_T + P\right]\left(\frac{\partial V}{\partial T}\right)_P$$

$$C_P - C_V = T\left(\frac{\partial P}{\partial T}\right)_V \left(\frac{\partial V}{\partial T}\right)_P$$

$$C_P - C_V = T\alpha^2 K \frac{V_0}{V^2}$$

To remember!

- **Adiabatic processes occur when there is no heat exchange.**
- **The efficiency of a heat engine is the ratio of the work done to the total heat absorbed.**
- **According to the second law of thermodynamics it is impossible for a heat engine working in a cycle to remove heat from a reservoir and to convert it completely into work without any other effects.**
- **The Carnot cycle consist of two isothermal and two adiabatic processes.**
- **The efficiency of any Carnot engine depends only on the temperature difference.**