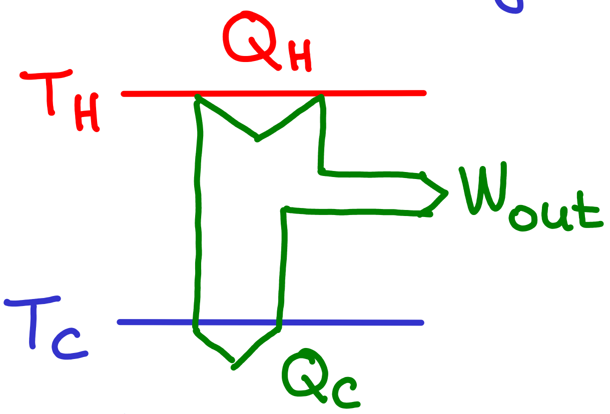
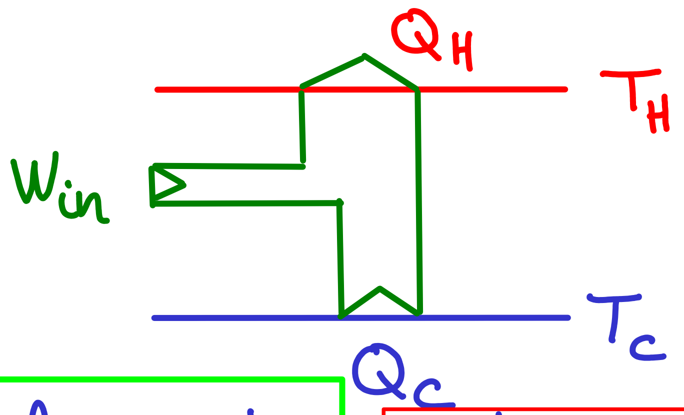
Heat-engines, heat-pumps



heat-engine

efficiency: $\eta = \frac{W_{out}}{Q_H}$

$0 \le \eta < 1$



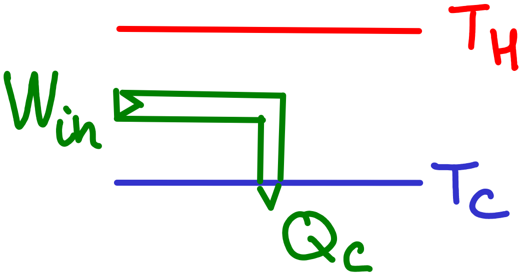
refrigerator ; heat-pump

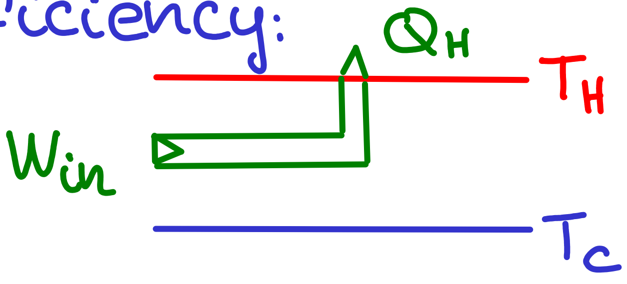
coefficient of performance

$\boxed{K = \frac{Q_c}{W_{in}}}$ $\boxed{K = \frac{Q_H}{W_{in}}}$

$0 \le K < \infty$

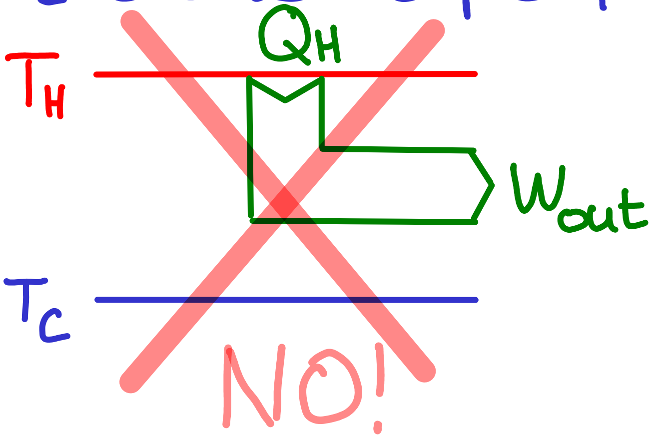
Mechanical work can be converted to heat with 100% efficiency:

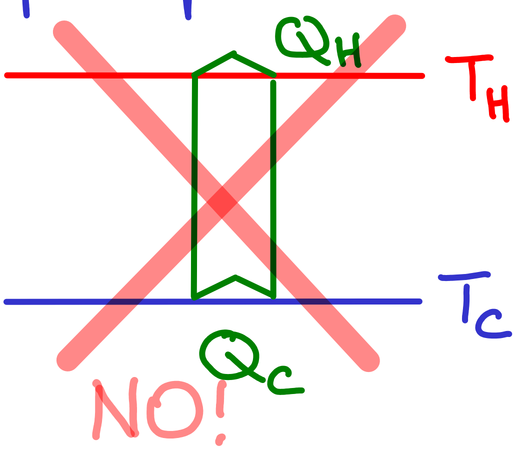




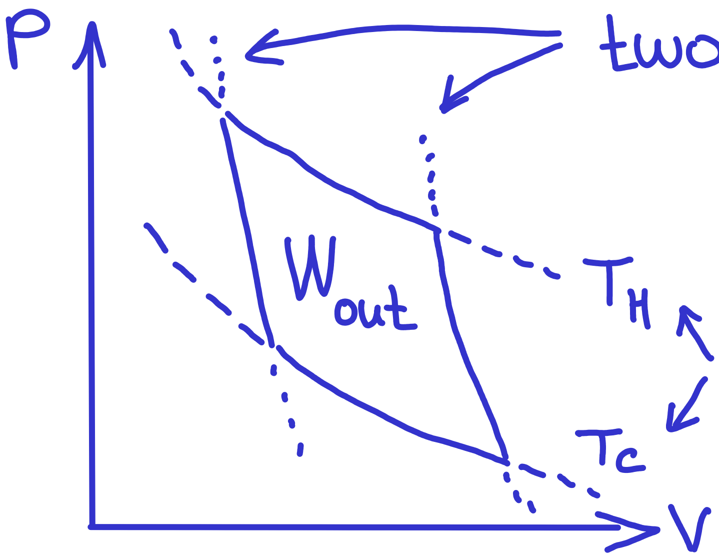
2nd law with engines/pumps:

- ▷ there is no perfect heat engine with $\eta = 1$
- ▷ there is no perfect heat pump with $K = \infty$





The Carnot-cycle



two adiabats ($Q=0$)

two isotherms

Sadi Carnot
(1824)

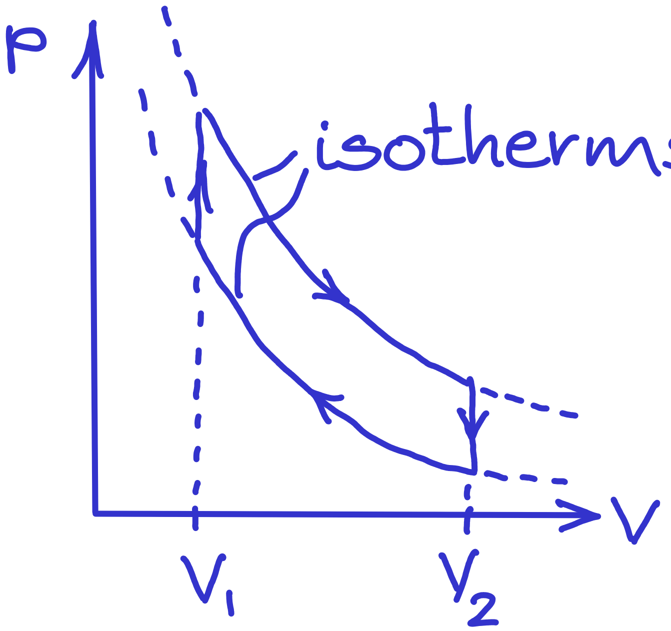
Definition: $\eta = \frac{W_{out}}{Q_H} = \frac{Q_H - Q_c}{Q_H}$

Carnot: $\boxed{\eta_{Carnot} = \frac{T_H - T_c}{T_H}}$ $\boxed{K_{Carnot} = \frac{T_c}{T_H - T_c}}$

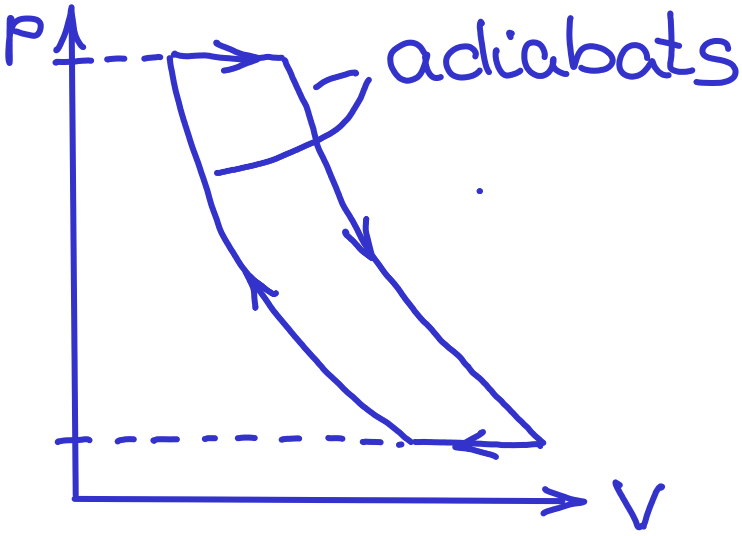
Second law: no heat engine operating between heat reservoirs with temperatures T_H and T_c can exceed the Carnot efficiency. (And no heat pump can exceed the Carnot coefficient of performance.)

Note: you cannot outperform the Carnot engine. But you cannot underperm it either. *All* *reversible* engines have the *same* efficiency for a given (T_H, T_c) pair.

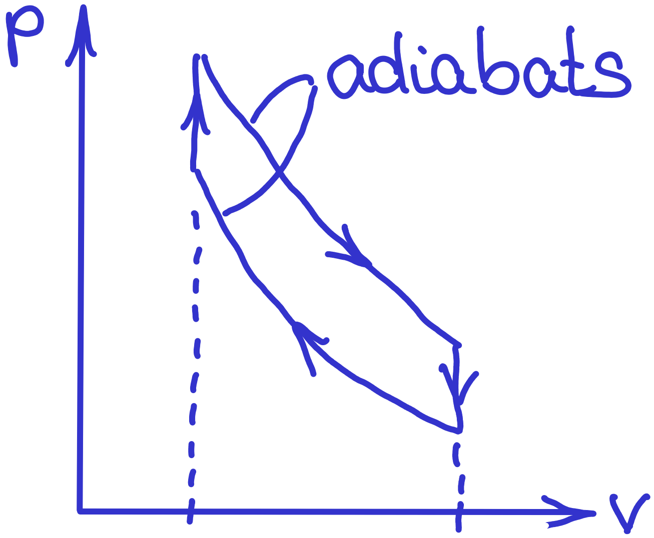
Examples of real engines



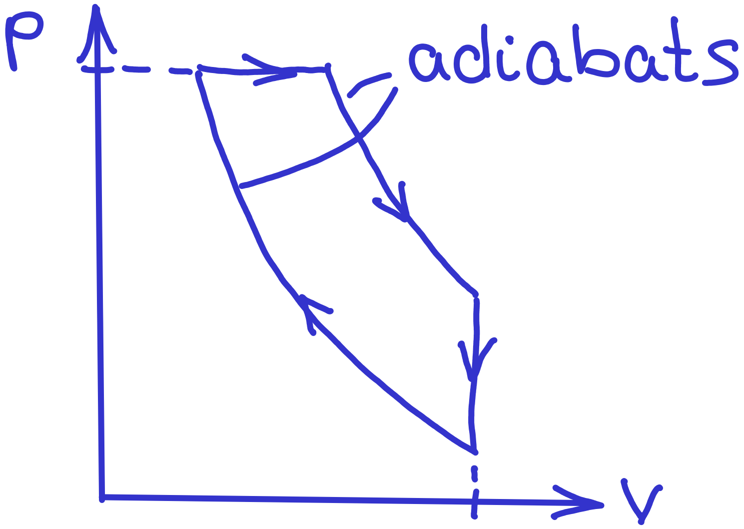
Stirling, 1816
reversible!



Brayton-Joule
(gas-turbine)



Otto, 1876
today's
cars



Rudolf Diesel, 1897
diesel-engine

The definition of entropy

Rudolf Clausius (1860-s):
"reduced heat" or entropy:
for any closed loop consisting only reversible processes:

$$\sum_i \frac{\Delta Q_i}{T_i} = 0 \Rightarrow \text{there exists a}$$

single valued function S such that $\Delta S = S_f - S_i$ is path independent.
S is a state function (like U), it depends only on the state of the system, and not how that state was reached.

Clausius:
1st law: $\Delta U = Q + W$
2nd law: $\frac{\Delta Q}{T} \leq \Delta S$ ↗ = for reversible ↘ < for irreversible

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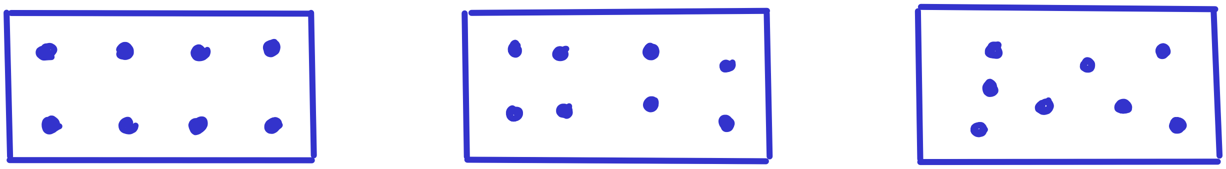
Ludwig Boltzmann: $S = k_B \cdot \log \Omega$
W: number of microstates realising the same macrostate.


low S medium S high S

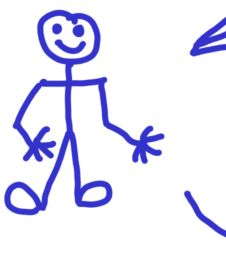
entropy ≈ randomness, disorder

The Second Law of Thermodynamics

Second Law with entropy: the entropy of a closed system cannot decrease. It remains the same for reversible processes and it increases for irreversible processes.

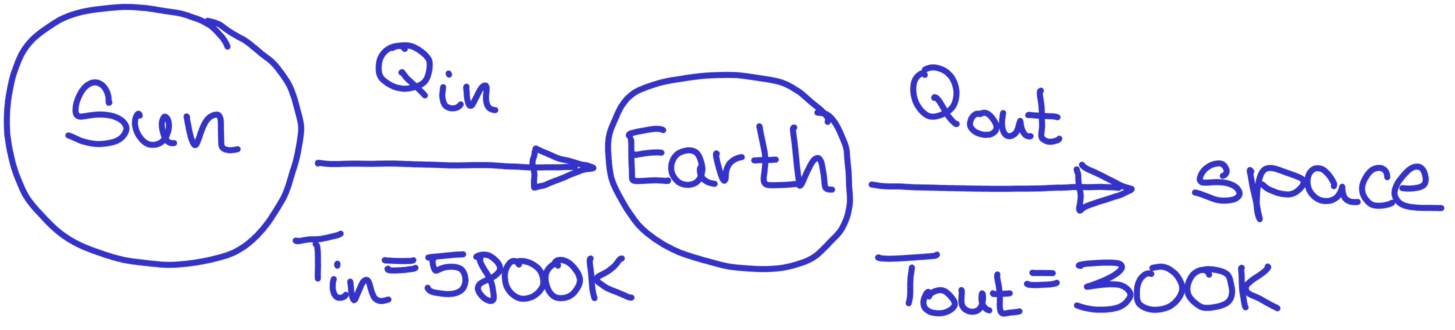
Q: Does life violate the 2nd law?

A: No!



In: sugar, protein and other very complex molecules: low entropy.

Out: H_2O, CO_2, NH_3 and other very simple molecules: high entropy.



$$\underbrace{Q_{in}}_{S_{in}=\frac{Q_{in}}{T_{in}}} = \underbrace{Q_{out}}_{S_{out}=\frac{Q_{out}}{T_{out}}}$$

Small entropy

large entropy