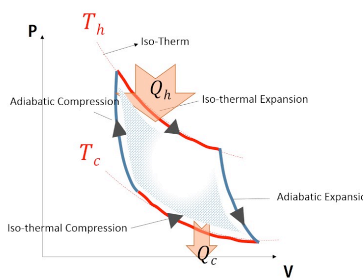
General Physics II: Thermodynamics

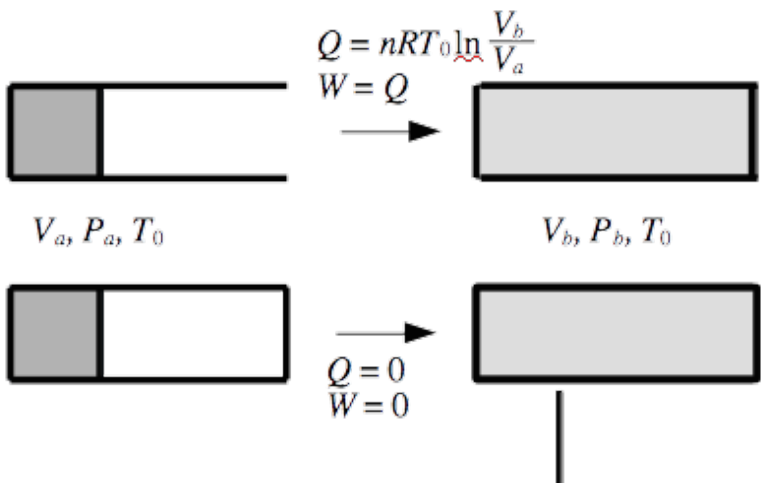
Prof. M. Hirschmann

Spring semester 2024



Recap Chapter 8… Reversible and irreversible processes

- What is the definition of reversible and irreversible processes?



Recap Chapter 8… What is Entropy?

Recap Chapter 8 … Entropy

- How does entropy of a system due to heat exchange with environment and due to production differ for reversible and irreversible processes?

Recap Chapter 8 … Entropy and the three laws of Thermodynan

- How can we connect entropy to the first law of TD?

- What is the second law of Thermodynamics?

- What is the third law of Thermodynamics?

Recap Chapter 8 Statistical interpretation of entropy

- How can we interpret entropy from a microscopic/statistical point of view?

- What are then the implications of the second law of TD?

- What are the implications for the third law of TD?

- Entropy change for irreversible Joule free expansion in an thermally isolated system can be approximated by a reversible, isothermal expansion:

$$\Delta S \approx nR \ln \frac{V_b}{V_a}$$

Content of this course — today's lecture

Lecture 1: —Chapter 1. Introduction
—Chapter 2. Temperature and zeroth law of thermodynamics

Lecture 2: —Chapter 3. Gas laws

Lecture 3: —Chapter 4. Statistical thermodynamics I: Kinetic theory of gas (slides in previous file)
—Mathematical Excursion — Preparation for Chapter 5.

Lecture 4: —Chapter 5. Statistical thermodynamics II (Boltzmann factor, Maxwell-Boltzmann distribution)

Lecture 5: —Chapter 6. Energy, heat and heat capacity

Lecture 6: —Chapter 7. First law of thermodynamics and thermal processes

Lecture 7: — Mock exam I *with Dr. Tress*

Lecture 8: —Chapter 8. Entropy and the second and third law of thermodynamics

Lecture 9/10: —Chapter 9. Thermal machines

Lecture 11: —Chapter 10. Thermodynamic potentials and equilibria

Lecture 12: —Mock Exam II *with Dr. Tress*
Lecture 13: —Chapter 11. Heat transfer (Conduction, Convection, Radiation)

Lecture 14: —Final review and open questions

9. Thermal machines

- 9.1 Thermal machines/Heat engines
- 9.2 Carnot cycle
- 9.3 Refrigerators, Air Conditioners
- 9.4 Heat pumps
- 9.5 On the impossibility of perpetual motion machines
- 9.6 Stirling engines, Diesel engines, Otto engines

9.1 Heat engines

Thermal machine: TD system that transfers heat between a hot & cold reservoir by means of machines that periodically pass through the same state.

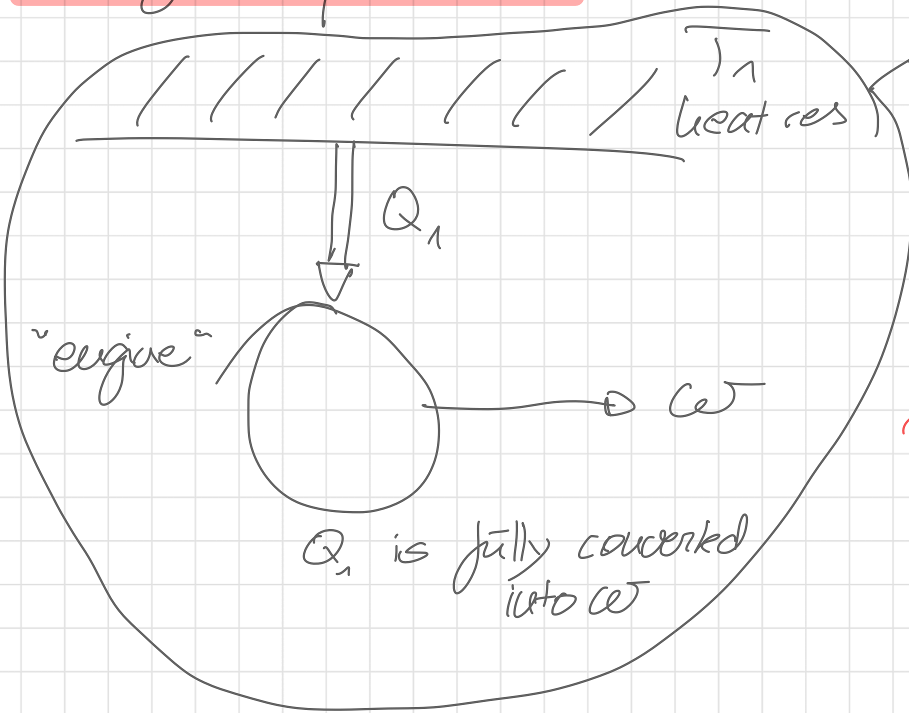
↳ allowing a mechanical action from the environment on the system or vice versa

Cycle process: no single continuous process but series of distinct processes.

Only reversible processes considered

General consideration: Why two reservoirs?

Thought experiment:



isolated system

"Perpetual motion machine of 2nd kind"

Problem: 2nd law TD

Consider isolated system composed of engine + heat res. (therm.)

$$\Delta S_{total} = \underbrace{\oint dS}_{=0} - \frac{|Q_1|}{T_1} < 0 \quad ↯$$

$\oint dS = 0$: ΔS of engine

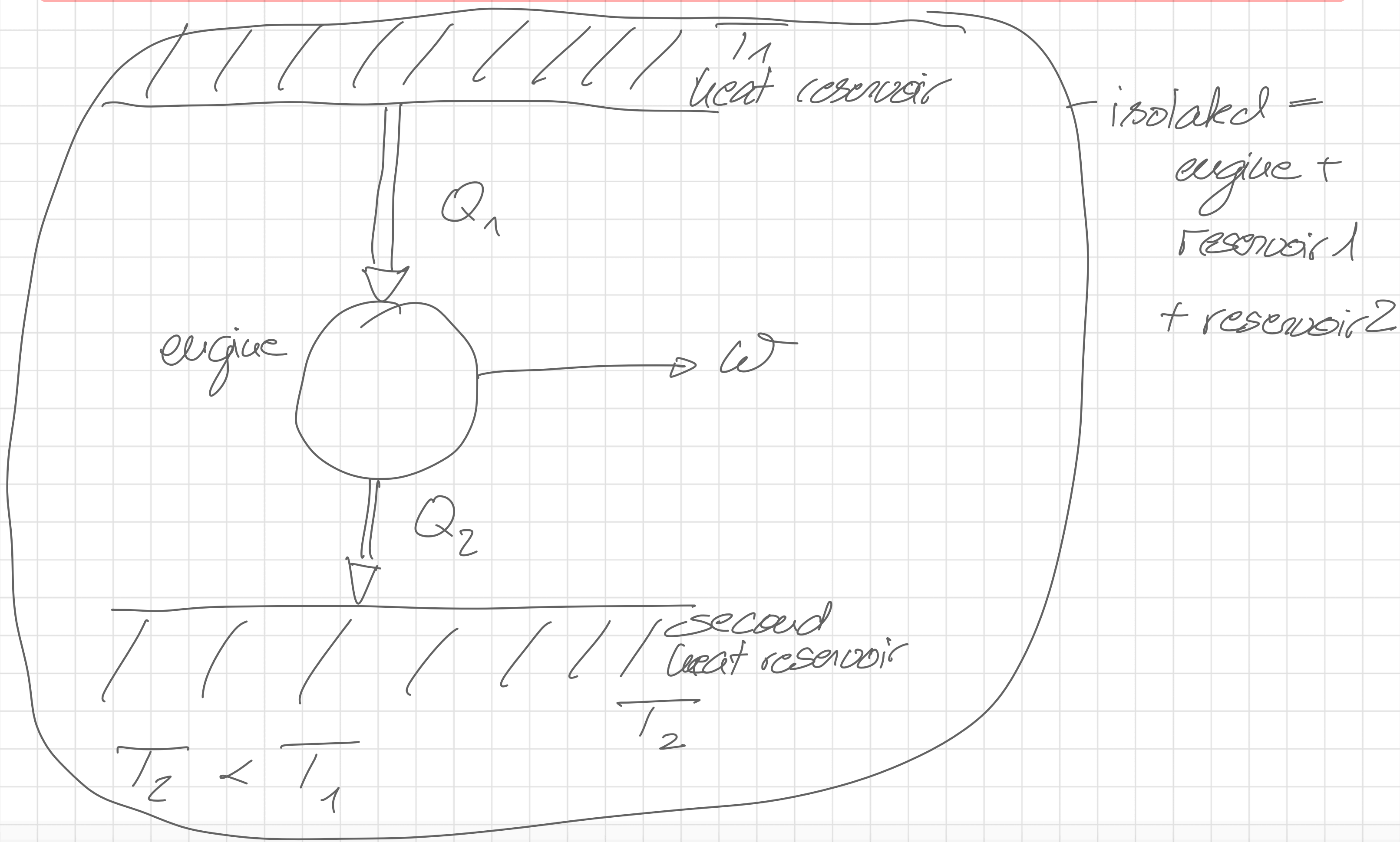
$\frac{|Q_1|}{T_1}$: heat taken out of reservoir

inconsistent with 2nd law: $\Delta S_{total} \geq 0$

Equivalent formulation of 2nd law:

A perpetual motion machine of the 2nd kind does not exist.

How can we make a thermal machine work?



What is ΔS in this case?

heat added into 2nd reservoir

$$\Delta S = \underbrace{\oint dS}_{=0} - \frac{|Q_1|}{T_1} + \frac{|Q_2|}{T_2} \geq 0$$

↑ 2nd law

$$\frac{|Q_2|}{T_2} \geq \frac{|Q_1|}{T_1} \quad \Big| : Q_1 ; \cdot T_2$$

$$\hookrightarrow \boxed{\frac{|Q_2|}{|Q_1|} \geq \frac{T_2}{T_1}} \quad *$$

Efficiency of this engine:

energy cons.

$$\varepsilon : \frac{W}{|Q_1|} = \frac{|Q_1| - |Q_2|}{|Q_1|} = 1 - \frac{|Q_2|}{|Q_1|}$$

* backup

Boundary condition: $\frac{|Q_2|}{|Q_1|} \geq \frac{T_2}{T_1} \quad \Big| \cdot (-1) \Rightarrow$

$$-\frac{|Q_2|}{|Q_1|} \leq -\frac{T_2}{T_1}$$

$$\Rightarrow \quad \varepsilon = 1 - \frac{|Q_2|}{|Q_1|} \leq \underbrace{1 - \frac{T_2}{T_1}}$$

neg. ε does not make sense

Positive ε : $1 - \frac{T_2}{T_1}$ must be pos. $\Rightarrow$ $T_1 > T_2$

$$0 < \varepsilon < 1$$

Best possible engine, compatible with 2nd law:

$\varepsilon = 1 - \frac{T_2}{T_1}$ only for reversible process

$\Rightarrow$ T_1 & T_2 determine ε of a engine.

Caveats: * idealised assumption to have reversible proc.

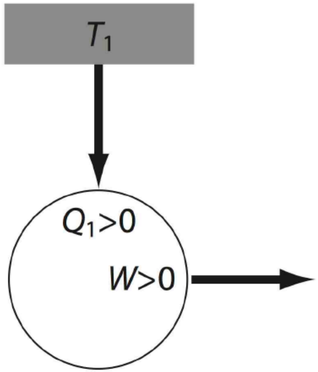
* in reality most if not all macroscopic proc. are irreversible

* high ε of $1-\frac{T_2}{T_1}$ in reality not achievable

* Still thermal machines are important to theoretically understand of how to optimise their efficiencies.

Summary 9.1 — Heat engines

- Thermal machine is a TD system if it performs a heat transfer between two thermal baths
    - allowing for mechanical work being done by a system on the environment and vice versa
    - by means of a machine that periodically passes though the same state (cycle of distinct processes)
- Equivalent formulation of 2nd law of TD: Perpetual motion machine of the 2nd kind does not exist (as Entropy change would be negative)



Summary 9.1 — Heat engines

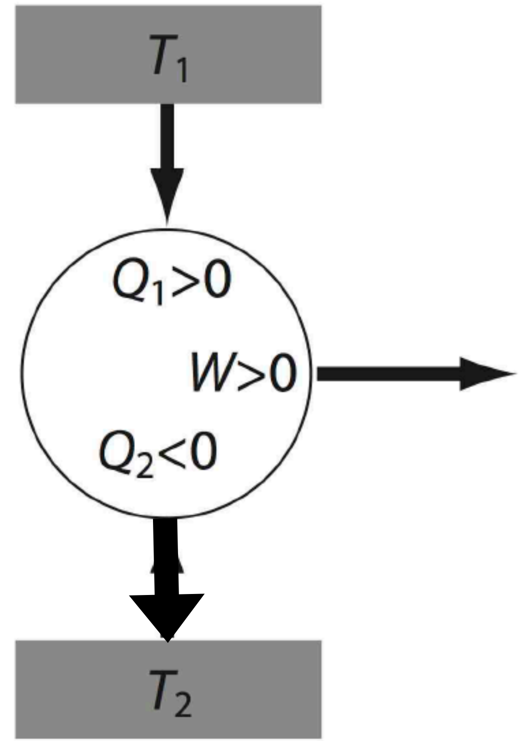
- A thermal machine has the following general set up: Heat taken from hot reservoir, Work conducted on environment, heat given back to cold reservoir

- Efficiency of heat engine smaller than 1:

$$\epsilon := \frac{W}{|Q_1|} = \frac{|Q_1| - |Q_2|}{|Q_1|} = 1 - \frac{|Q_2|}{|Q_1|} \leq 1 - \frac{T_2}{T_1}$$

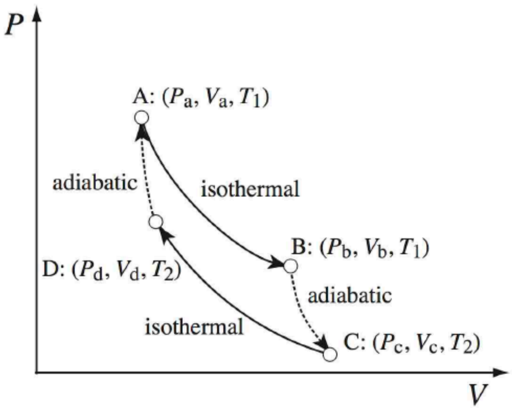
- Best possible engine, equality for reversible processes only

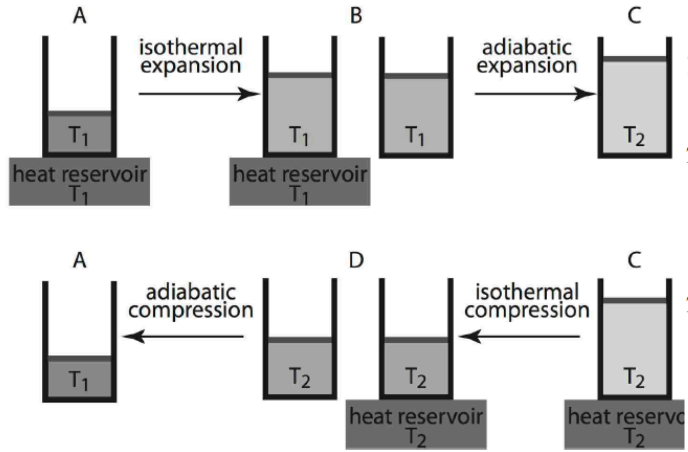
- Note that in nature most (makroscopic processes) are irreversible (friction) —> reducing epsilon

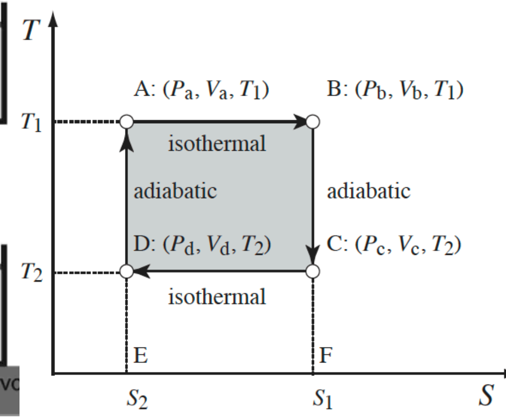


9.2 Carnot cycle

Summary 9.2 — Carnot cycle







$A(V_a, P_a, T_1)$: A cylinder with an ideal gas is attached to a heat reservoir with a temperature T_1.

A→B: Isothermal expansion with a constant temperature T_1, heat $Q_1 > 0$ into the cylinder from the reservoir, and work $W_{ab} > 0$ being done.

$B(V_b, P_b, T_1)$: The cylinder is removed from the heat reservoir and thermally isolated.

B→C: Adiabatic expansion ($Q = 0$) till the temperature drops to T_2 and work done, $W_{bc} > 0$

$C(V_c, P_c, T_2)$: The cylinder is attached to another heat reservoir with a temperature T_2.

C→D: Isothermal compression with a constant temperature T_2, heat $Q_2 < 0$ out of the cylinder to the reservoir, and work $W_{cd} < 0$ being done.

$D(V_d, P_d, T_2)$: The cylinder is removed from the heat reservoir and thermally isolated.

D→A: Adiabatic compression ($Q = 0$) till the temperature raise to T_1 and work, $W_{da} < 0$, done from the outside.

Summary 9.2 — Carnot cycle

- Summed work during adiabatic processes is zero, thus the total work is the sum of the work during isothermal processes:

$$W = W_{ab} + W_{cd} = nR(T_1 - T_2)\ln\frac{V_b}{V_a}$$

- Efficiency of Carnot process is the maximum efficiency allowed by second law of TD, given by (T1>T2):

$$\varepsilon = \frac{W}{Q_1} = \frac{nR(T_1 - T_2)\ln V_b/V_a}{nRT_1 \ln V_b/V_a} = 1 - \frac{T_2}{T_1}$$

- Theoretically idealised engine (irreversibility and friction, isothermal processes require infinitely slow processes, no perfect insulation, non-ideal gases, no start-up and shutdown accounted for)

9.3 Refrigerators and Air conditioning

9.4 Heat pumps

9.5 On the impossibility of perpetual motion machines

Summary 9.3-9.5 — Refrigerators, heat pumps, perpetual motion machines

- Operation of refrigerators, ACs and heat pumps are the reverse of a heat engine transferring heat from a cool to a hot environment *by work done on the system*.
    - —> lower and upper limits for the integration of heat and work must be exchanged
    - —> signs of heat and work must be flipped
- Efficiency of these machines:

$$\varepsilon_{\text{refrigerator}} = \frac{\text{thermal energy extracted from the heat reservoir with } T = T_2}{\text{total work given to the refrigerator}} = \frac{T_2}{T_1 - T_2}$$

$$\epsilon_{\text{heatpump}} = \frac{\text{thermal heat put into hot heat reservoir T} = \text{T}_1}{\text{total work given to the heat pump}} = \frac{T_1}{T_1 - T_2}$$

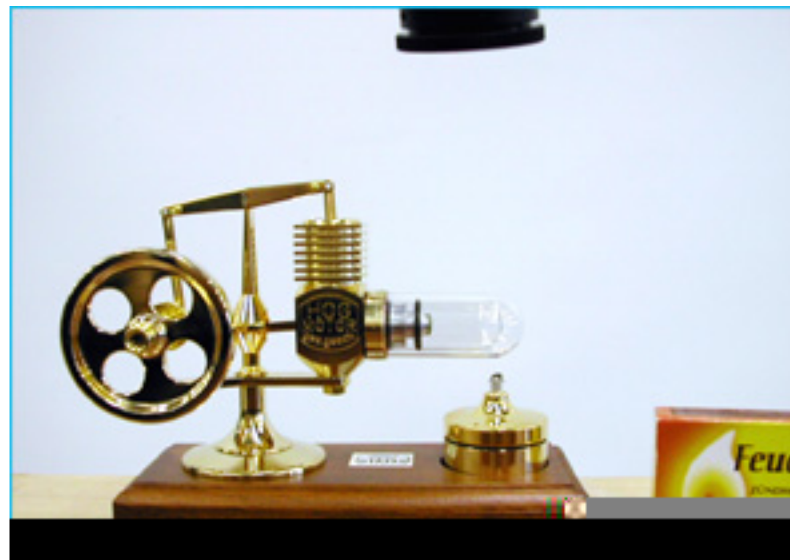
- No “miracle” perpetual motion machine possible with putting together one Carnot engine and a reversed one: irreversibility and friction, non-ideal gases, no perfect insulation, isothermal processes hard to achieve etc.

Experiment 133: Stirling engine

The Stirling engine was developed in 1816 by Robert Stirling, a Scottish minister. Stirling patented his design for a heat engine as an alternative to the steam engine, to have greater efficiency. The Stirling engine operates on a closed-cycle process that uses a fixed amount of gas (such as air or helium) which is alternately compressed and expanded at different temperatures, resulting in a net conversion of heat energy to mechanical work.

- This engine has good efficiency, approaching 40% nowadays, while the efficiency of an internal combustion engine for automotive use reaches 35% for gasoline and 42% for diesel.

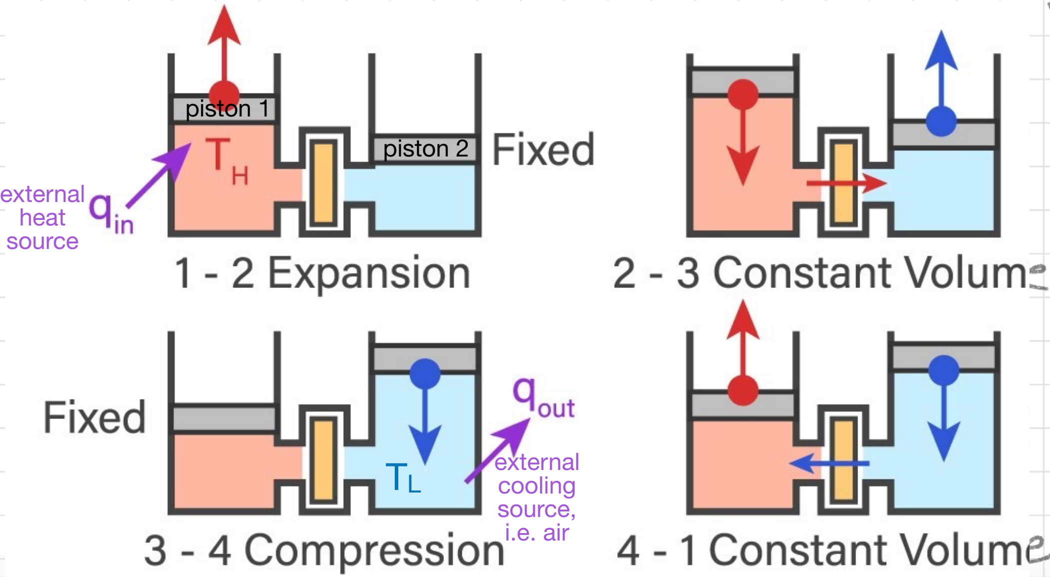
- Drawback is that is not very responsive to heat change, not useful for cars (for changing speed)

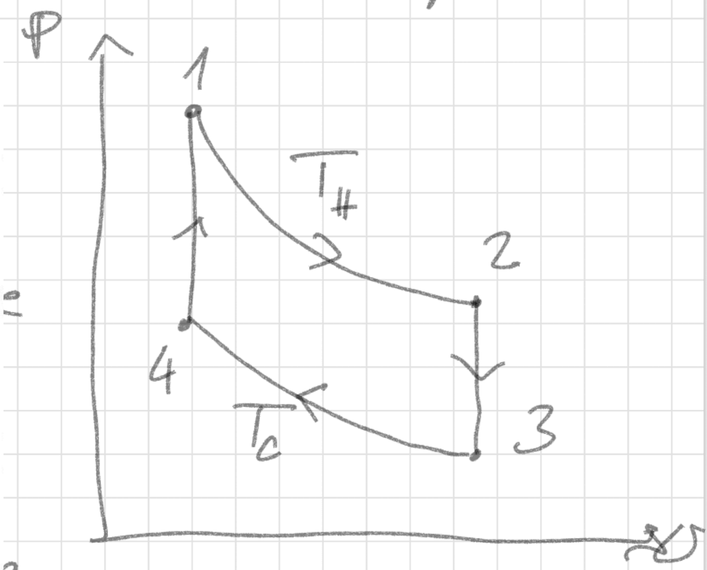


9.6 Stirling engine, Otto engine, Diesel engine

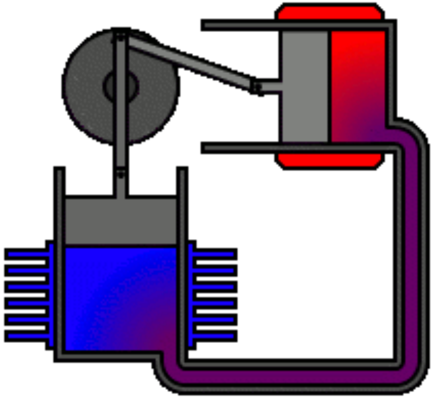
I. Stirling engine

Fixed amount of gas undergoes 2 isothermal & 2 isochoric processes.





- Realistic construction of Stirling engine: two cylinders are placed in an angle of 90 degrees against each other, then the relative motion of the two pistons can move the wheel attached to both pistons and cylinders



- Advantages of the Stirling engine
    - High Efficiency,
    - Flexibility in Fuel Sources,
    - Quiet Operation,
    - Low Emissions,
    - Longevity and Low Maintenance

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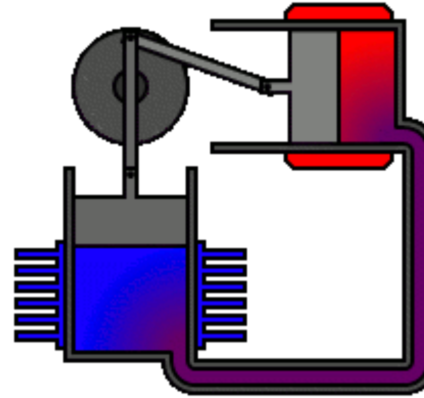


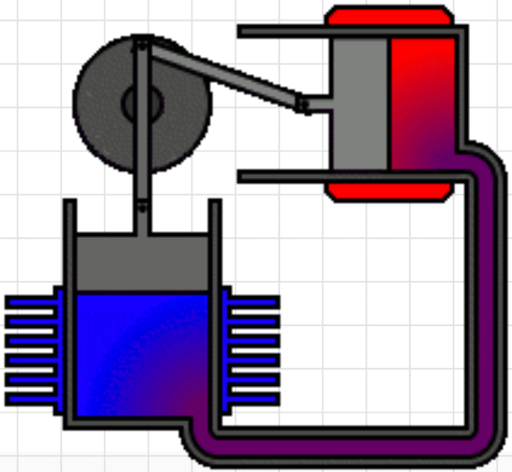
- Advantages of the Stirling engine
    - High Efficiency,
    - Flexibility in Fuel Sources,
    - Quiet Operation,
    - Low Emissions,
    - Longevity and Low Maintenance

- Disadvantages of the Stirling engine
    - Slower Response Time,
    - Heat Exchanger Challenges, (Regenerator)
    - Start-Up Time,
    - Limited High-Temperature Applications

Applications : × environmentally friendly Solar Engine (Sandia national Labs)

Reverse: Put work in : very good refrigeration system used for cryogenic cooling (very low T)

cooling electronics



Summary 9.6 — Stirling engine, Otto engine, Diesel engine

- Stirling engine: two isothermal and two isochoric processes (e.g. used for cryogenic cooling, same efficiency as Carnot, quiet, low emission but complex design, low-power-weight ratio, limited high-T use)
- Otto engine: two adiabatic and two isochoric processes (e.g. often used in cars, high power-to-weight ratio, fast response —> quick acceleration, low noise and vibration but lower efficiencies, higher emissions, potential overheating)
- Diesel engine: two adiabatic, one isochoric and one isobaric process (higher fuel efficiency, longer life time, but noisier and slower response, challenging start at low T)
- Efficiencies are lower than that of Carnot (except for Sterling).

Conceptual Questions:

- What is a perpetual motion machine of 2nd kind?
- What is a thermal engine and what is its efficiency? What is the maximum possible efficiency for a reversible process
- How does a heat pump work?
- The oceans contain a tremendous amount of thermal (internal energy). Why, in general, is it not possible to put this energy to useful work?
- Can you cool the kitchen in summer by leaving the fridge door open? Explain.
- Efficiencies are defined differently for heat pumps and ACs, how and why?
- You are asked to test a machine that the inventor calls an “in-room AC”, plugged to electricity, but otherwise with no connection to outside. How do you know that this machine will not cool down the room?
- Which of the following possibilities could increase the efficiency of a heat engine or a combustion engine
    - increase the T of the hot part and decrease the T of the exhaust
    - increase or decrease the T of both hot and exhaust part by same amount
    - decrease T of hot part and increase T of the cold part

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