Energy in technical and biological systems
WS 2017/2018

Lecture 8

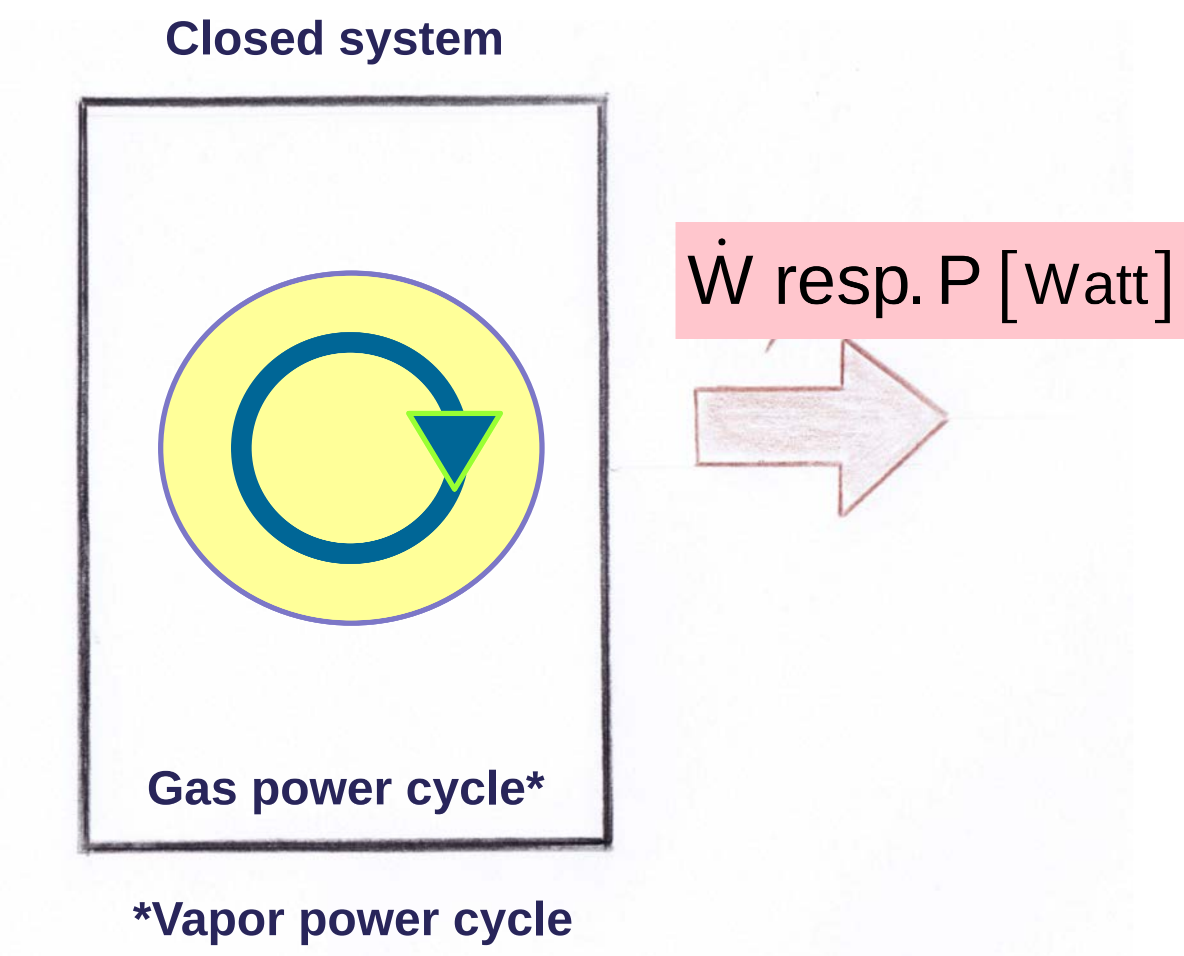
Second rule of thermodynamics

Thermodynamic cycles

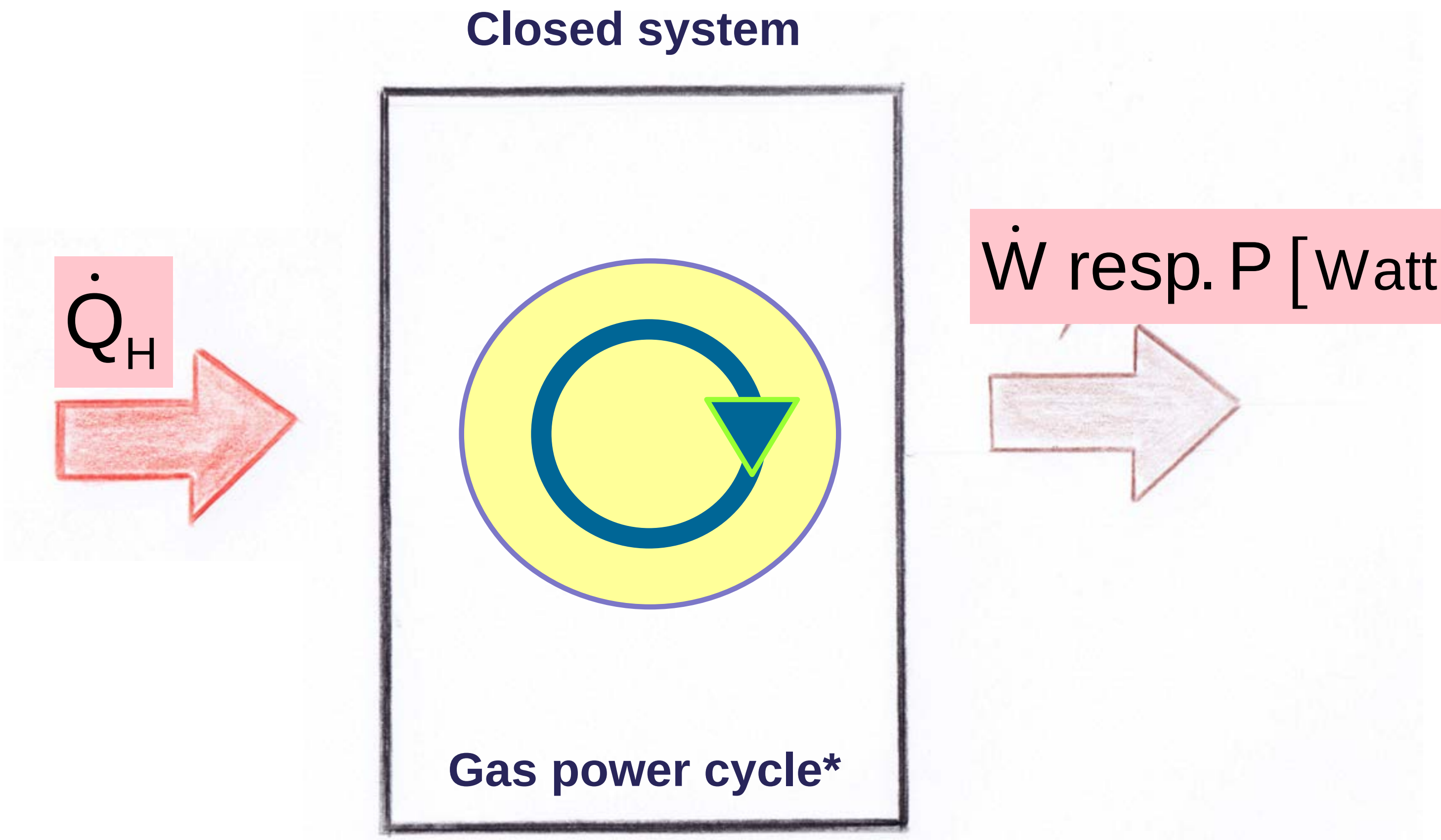
Gas power cycle

Stirling cycle

How to receive work or power from a system?



How to receive work or power from a system by heat supply?

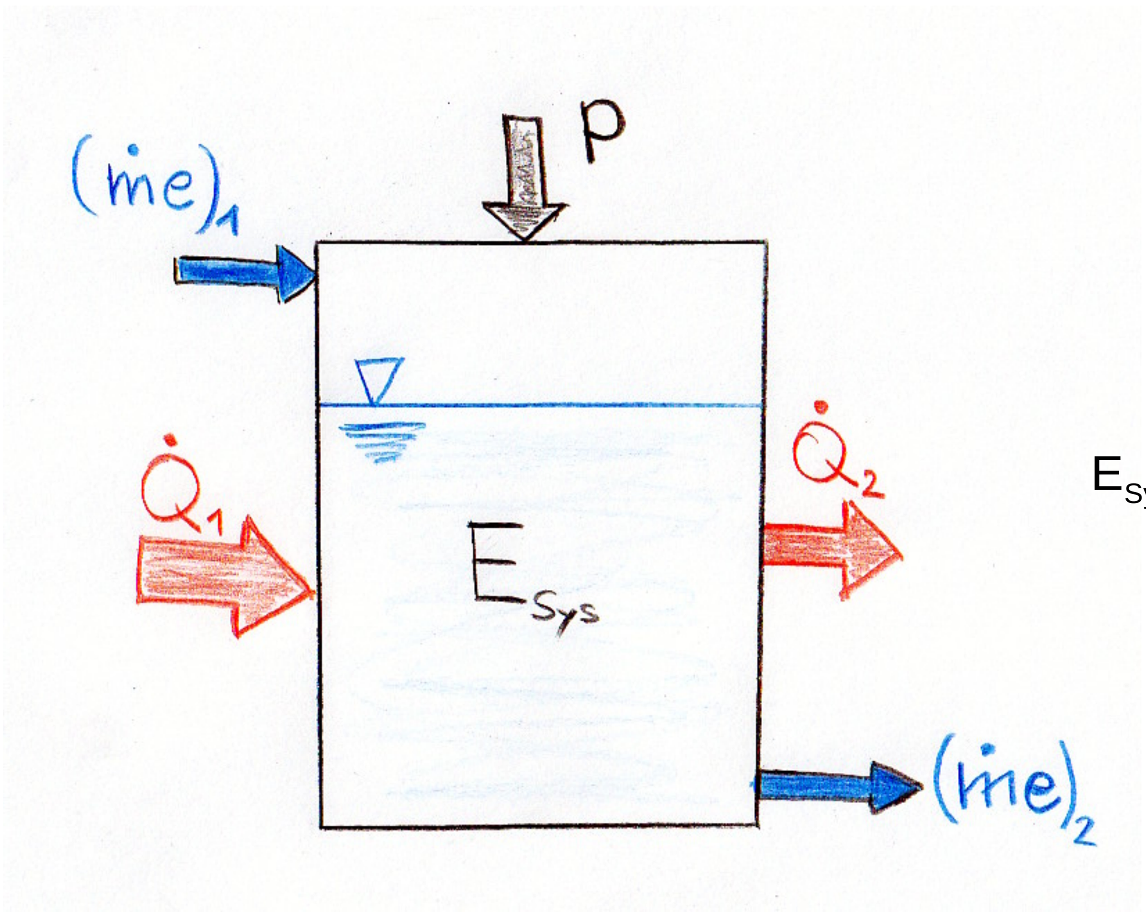


*Vapor power cycle

Prof. Dr.-Ing. Joachim Gebel

HOCHSCHULE RHEIN-WAAL
Rhine-Waal University of Applied Sciences

First law of thermodynamics



$$\frac{dE_{Sys}}{dt} = \sum \dot{Q} + \sum P + \sum \dot{m} \cdot e$$

„Before and after approach“ $dt \rightarrow \Delta t$

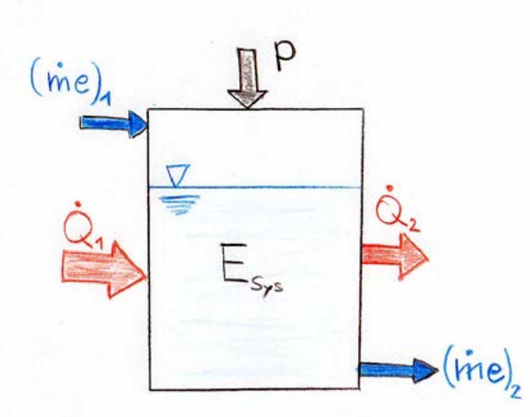
$$E_{Sys,2} - E_{Sys,1} = \sum \dot{Q} \cdot \Delta t + \sum P \cdot \Delta t + \sum \dot{m} \cdot \Delta t \cdot e$$

$$E_{Sys,2} - E_{Sys,1} = \sum Q + \sum W + \sum m \cdot e$$

$$E_{Sys} = E_{Kin} + E_{Pot} + U$$

Assumptions and simplifications

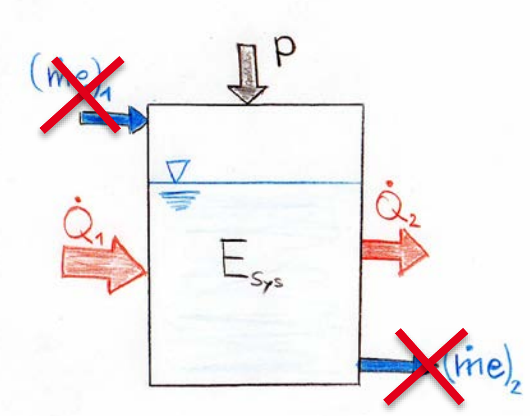
1 **Open system**



$$E_{Sys,2} - E_{Sys,1} = \sum Q + \sum W + \sum m \cdot e$$

2 **Closed system**

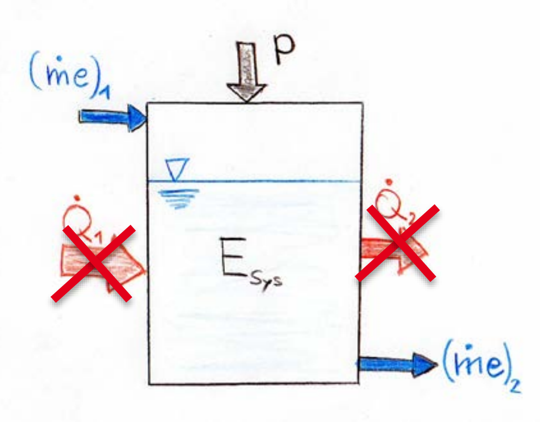
Steady state



$$\cancel{E_{Sys,2}} - E_{Sys,1} = \sum Q + \sum W$$

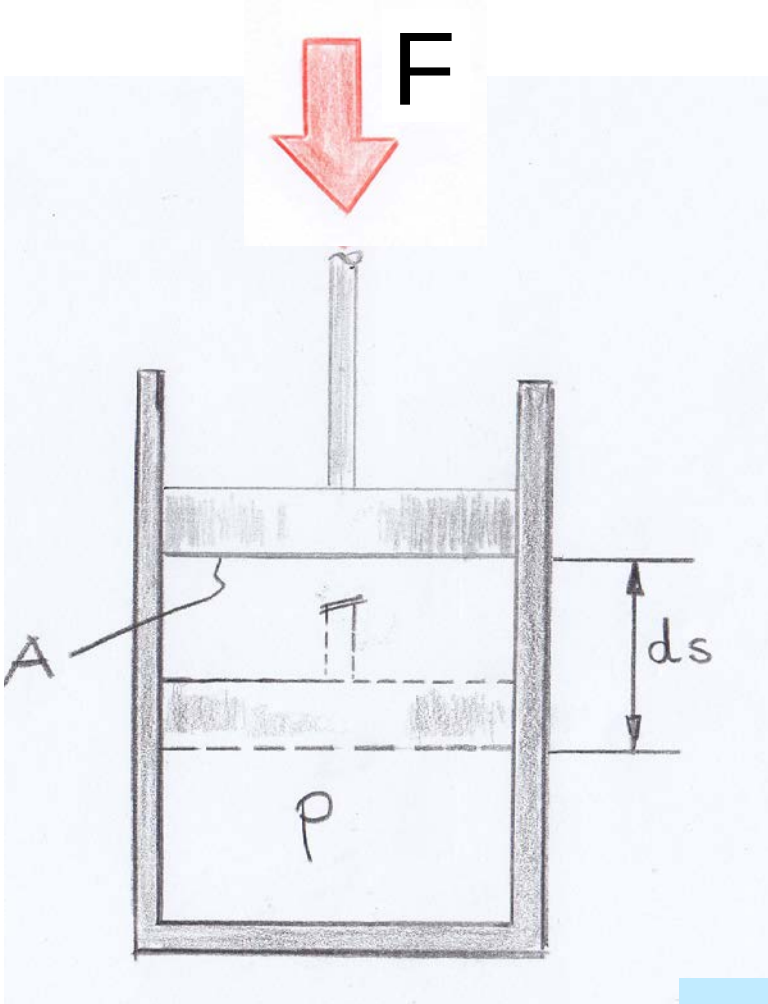
$$0 = \sum Q + \sum W$$

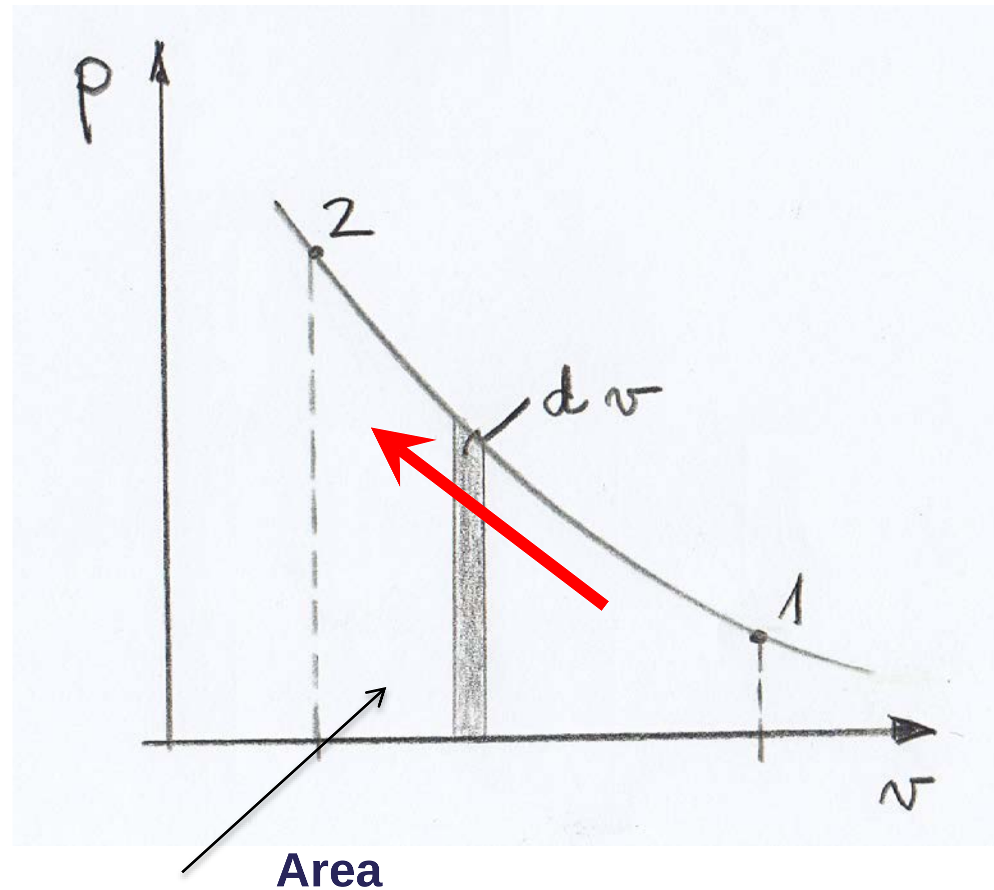
3 **Adiabatic system**



$$E_{Sys,2} - E_{Sys,1} = \sum W + \sum m \cdot e$$

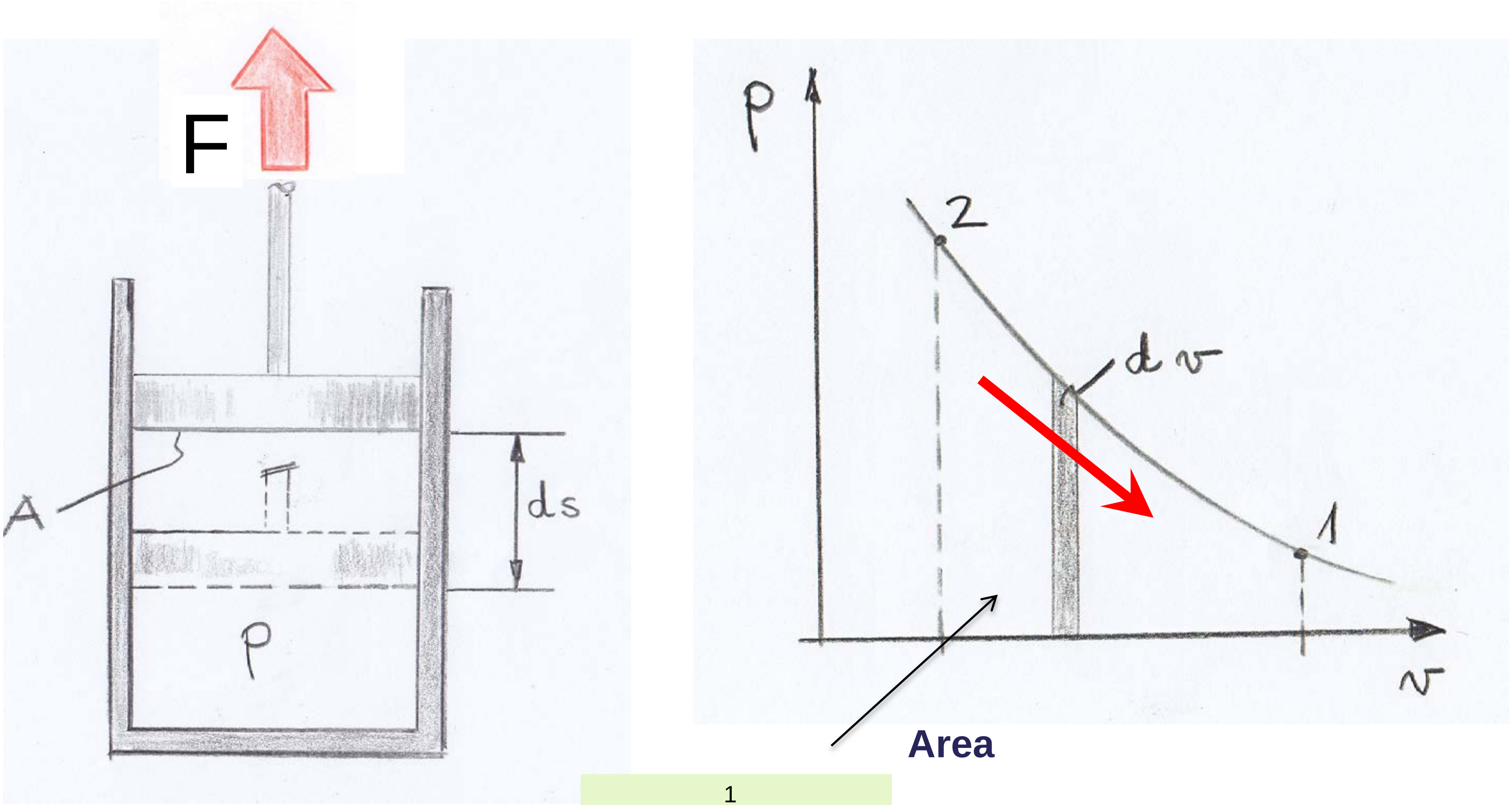
Work done **on** a closed system





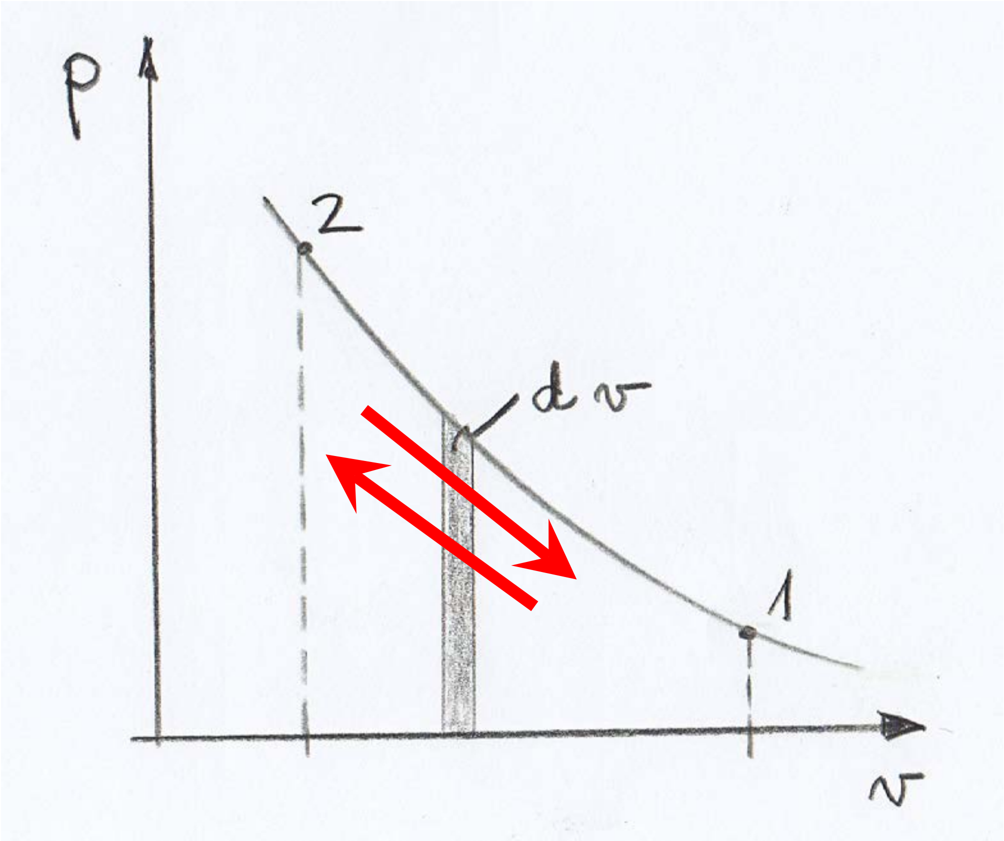
$$W_{12} = -\int_{1}^{2} p(s) \cdot dV$$

Work done **by** a closed system



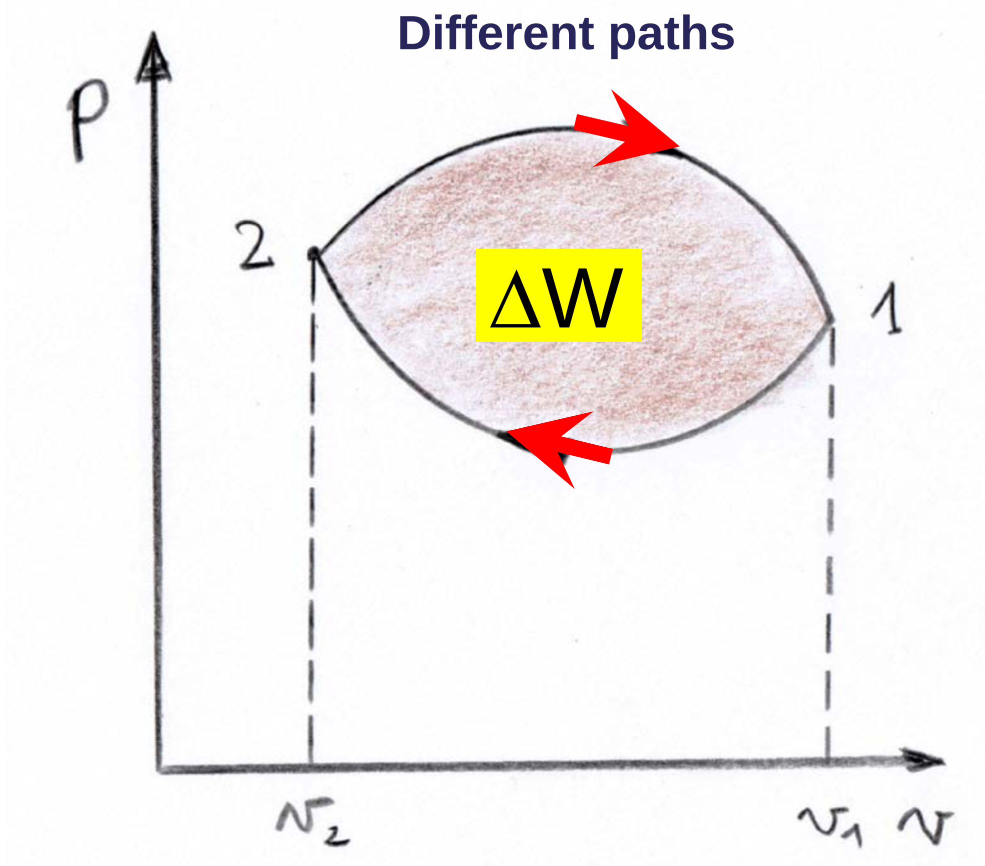
$$W_{21} = -\int_{2}^{1} p(s) \cdot dV$$

Net work output



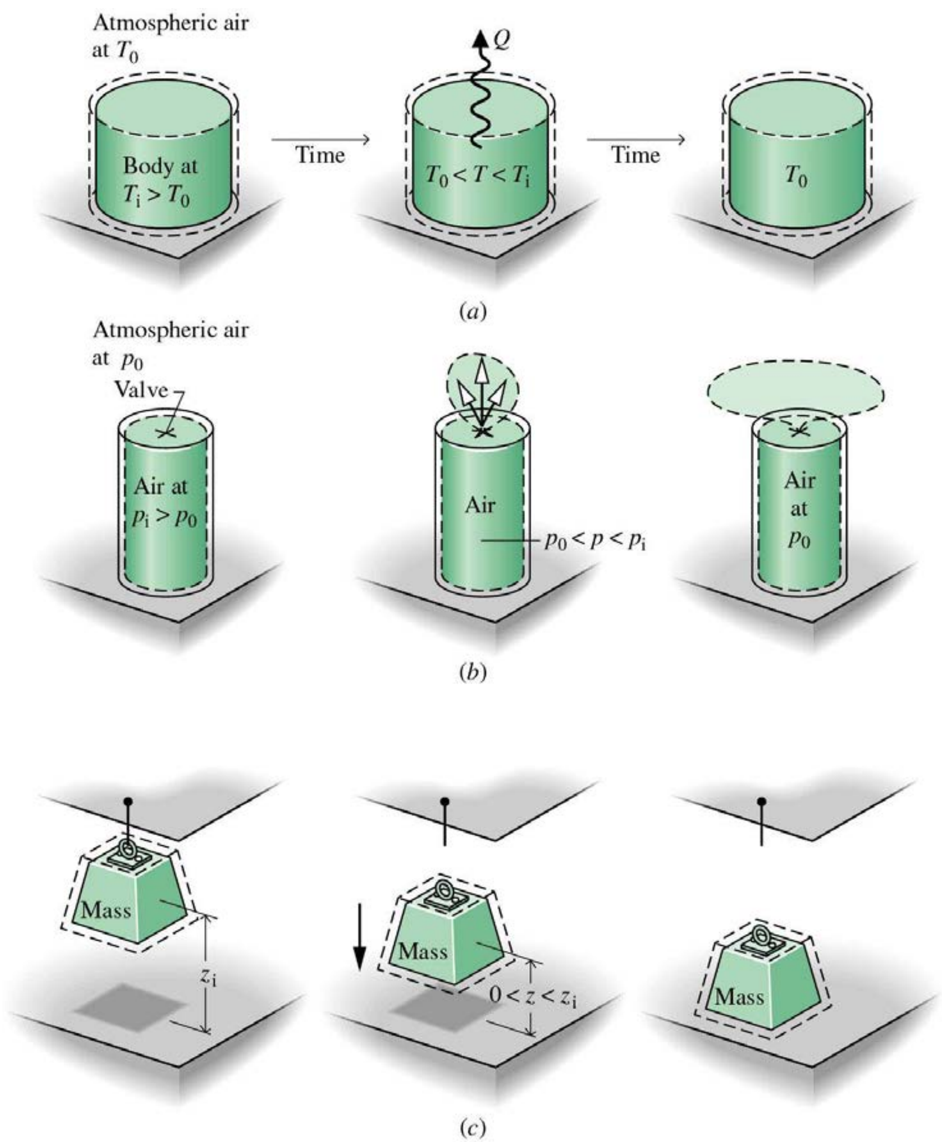
$$\Delta W = W_{21} = -\int_2^1 p(s) \cdot dV - W_{12} = -\int_1^2 p(s) \cdot dV = 0$$

Net work output for a cycle



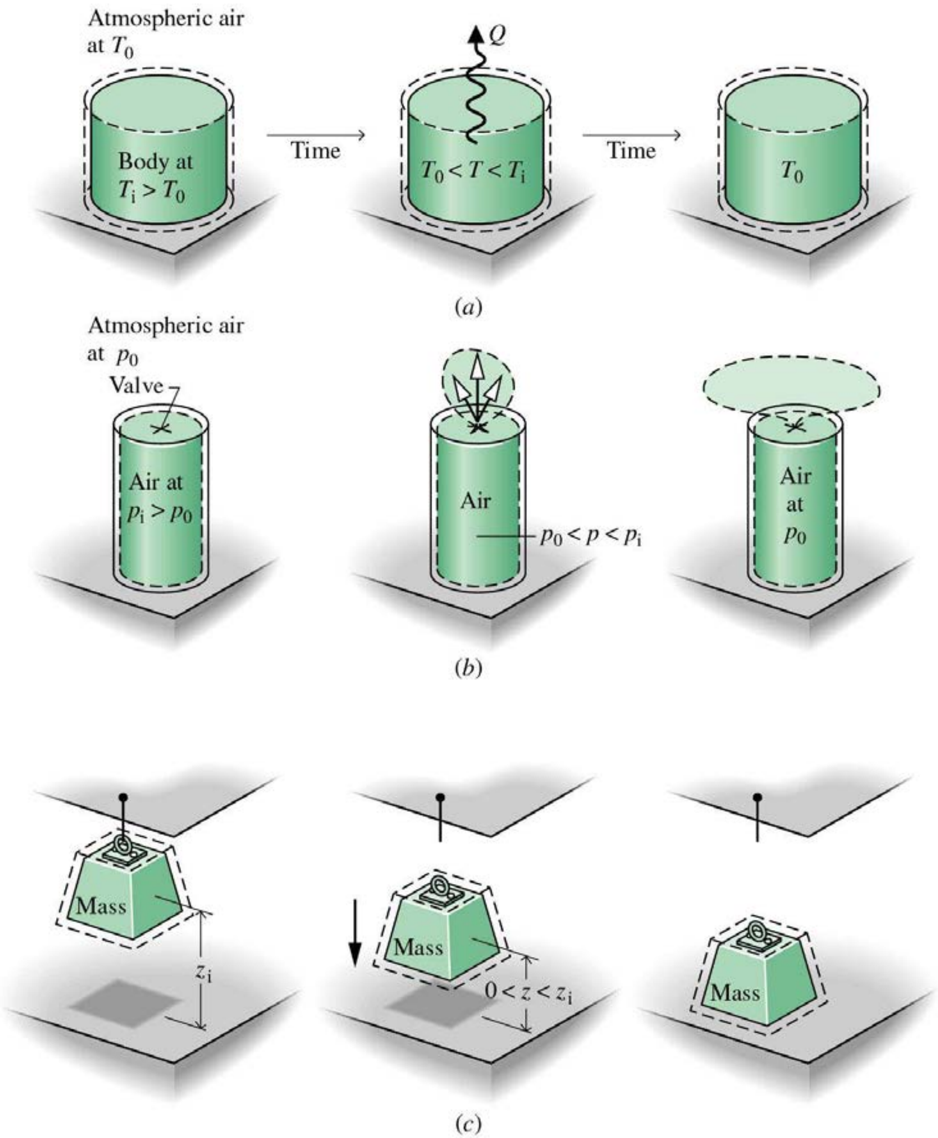
$$\Delta W = W_{21} = -\int_2^1 p(s)\cdot dV - W_{12} = -\int_1^2 p(s)\cdot dV \neq 0$$

Second law of thermodynamics



When an imbalance exists between two systems, there is an opportunity for developing work that would be irrevocably lost if the systems were allowed to come into equilibrium in an uncontrolled way.

Second law of thermodynamics



When an imbalance exists between two systems, there is an opportunity for **developing work** that would be irrevocably lost if the systems were allowed to come into equilibrium in an uncontrolled way.

- ❑ What is the theoretical **maximum value for the work** that could be obtained?
- ❑ What are the factors that would **preclude** the realization of the maximum value?

Second law of thermodynamics

Second law of thermodynamics

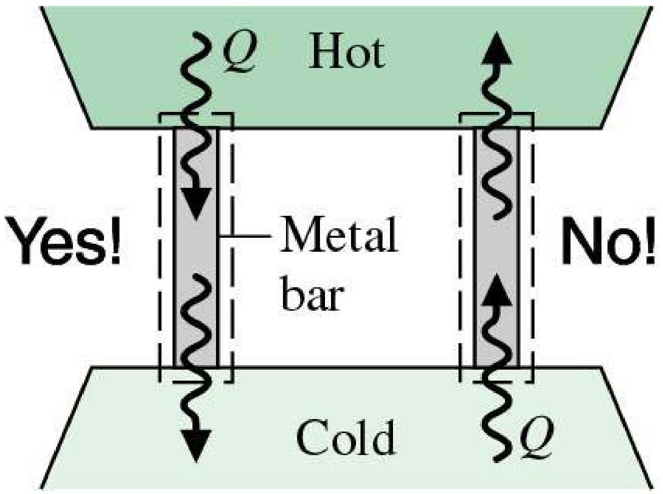
- ❑ Predict process direction
- ❑ Establish equilibrium conditions
- ❑ Determine theoretical best performance
- ❑ Evaluate factors limiting best performance
- ❑ Define a temperature scale independent of properties
- ❑ Develop means for evaluating properties, such as h and u in terms of properties that are more readily obtained experimentally.

Fundamentals of Engineering Thermodynamics; 6e, SI Version, 2010, p. 175

Statements of the Second Law

Clausius statement

It is impossible for any system to operate in such a way that the sole result would be an energy transfer by heat from a cooler to a hotter body.



What about refrigerators ???

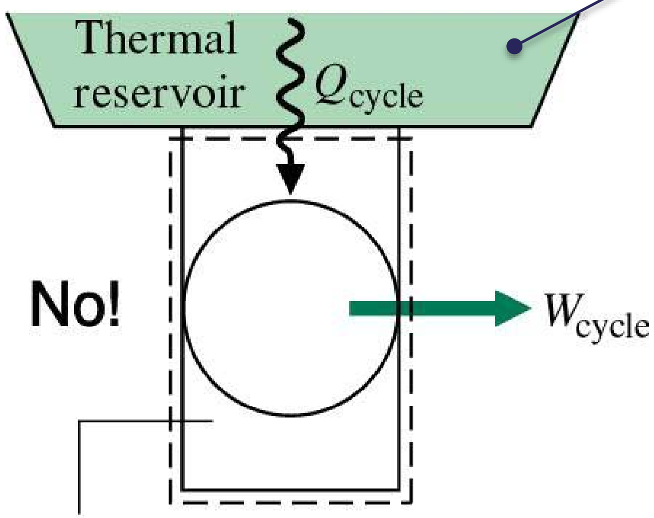
Statements of the Second Law

Kelvin-Planck statement

It is impossible for any system to operate in a thermodynamic cycle and deliver a net amount of energy by work to its surroundings while receiving energy from a single thermal reservoir.

A thermal reservoir is a special kind of system that always remains at constant temperature even though energy is added or removed by heat transfer.

- Earth's atmosphere
- Large bodies of water (lakes, oceans)
- Large block of copper



?

Thermodynamic cycle

Fundamentals of Engineering Thermodynamics; 6e, SI Version, 2010, p. 178

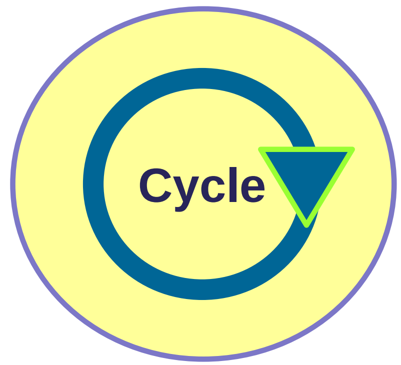
Open and closed gas power cycles

Carnot Cycle

The Carnot cycle is the most efficient cycle.

Otto Cycle

Diesel Cycle

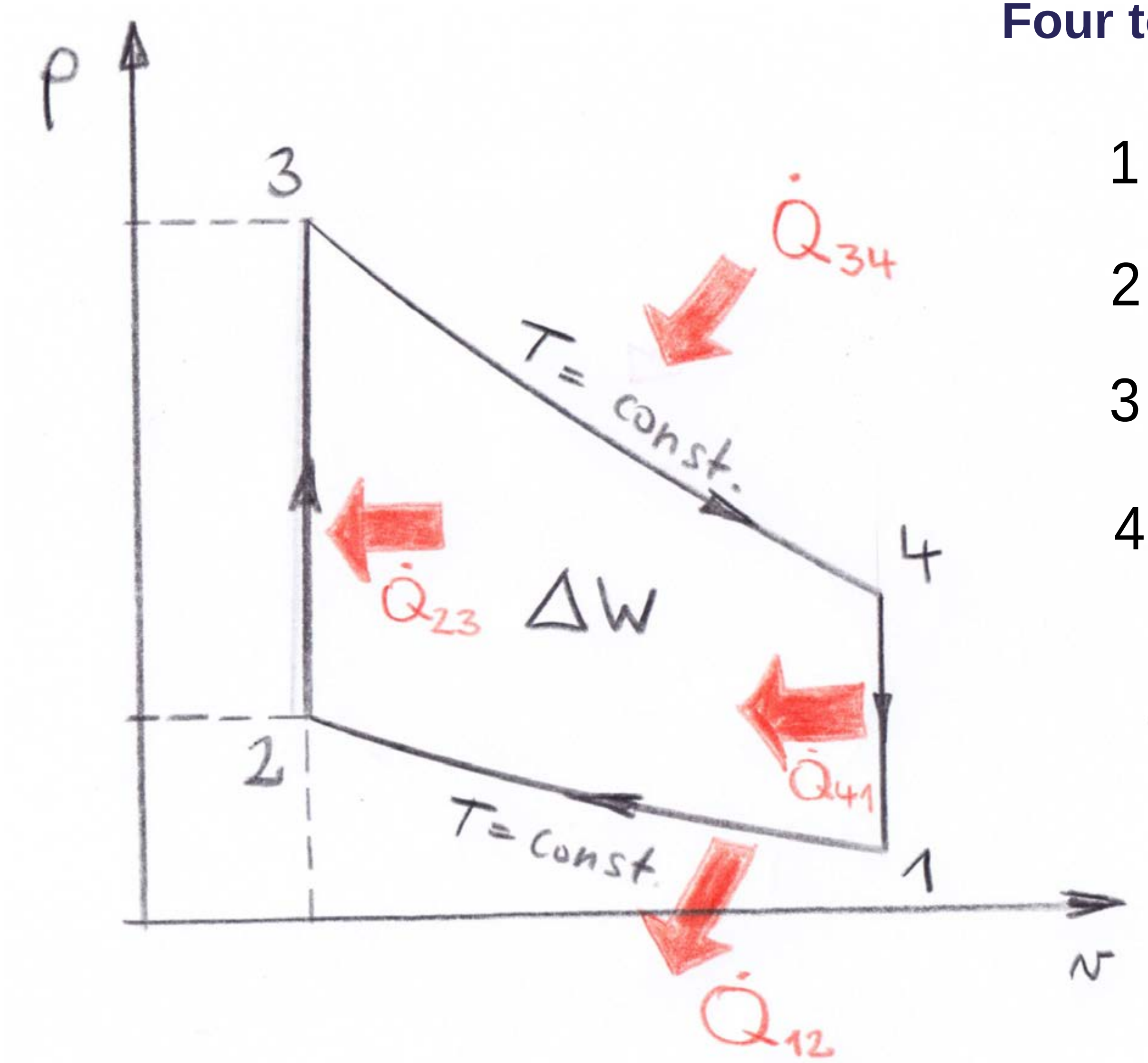


Ericsson Cycle

Stirling Cycle

Brayton Cycle

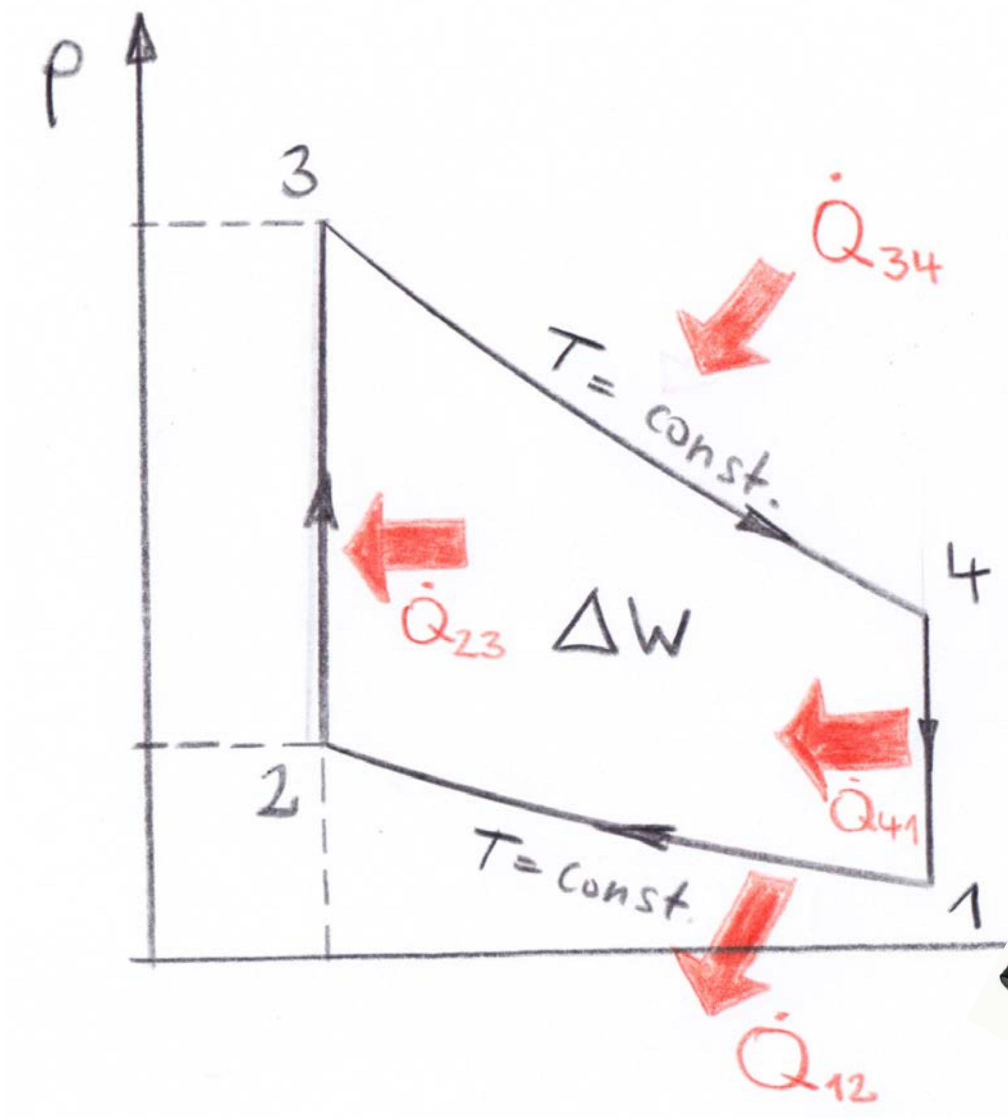
Stirling cycle



Four totally reversible processes:

1 → 2	**isothermal**
2 → 3	**isochore**
3 → 4	**isothermal**
4 → 1	**isochore**

Stirling cycle



Four totally reversible processes:

$1 \rightarrow 2$ **isothermal**

$T = \text{const.}$

Ideal gas $p \cdot v = R \cdot T$

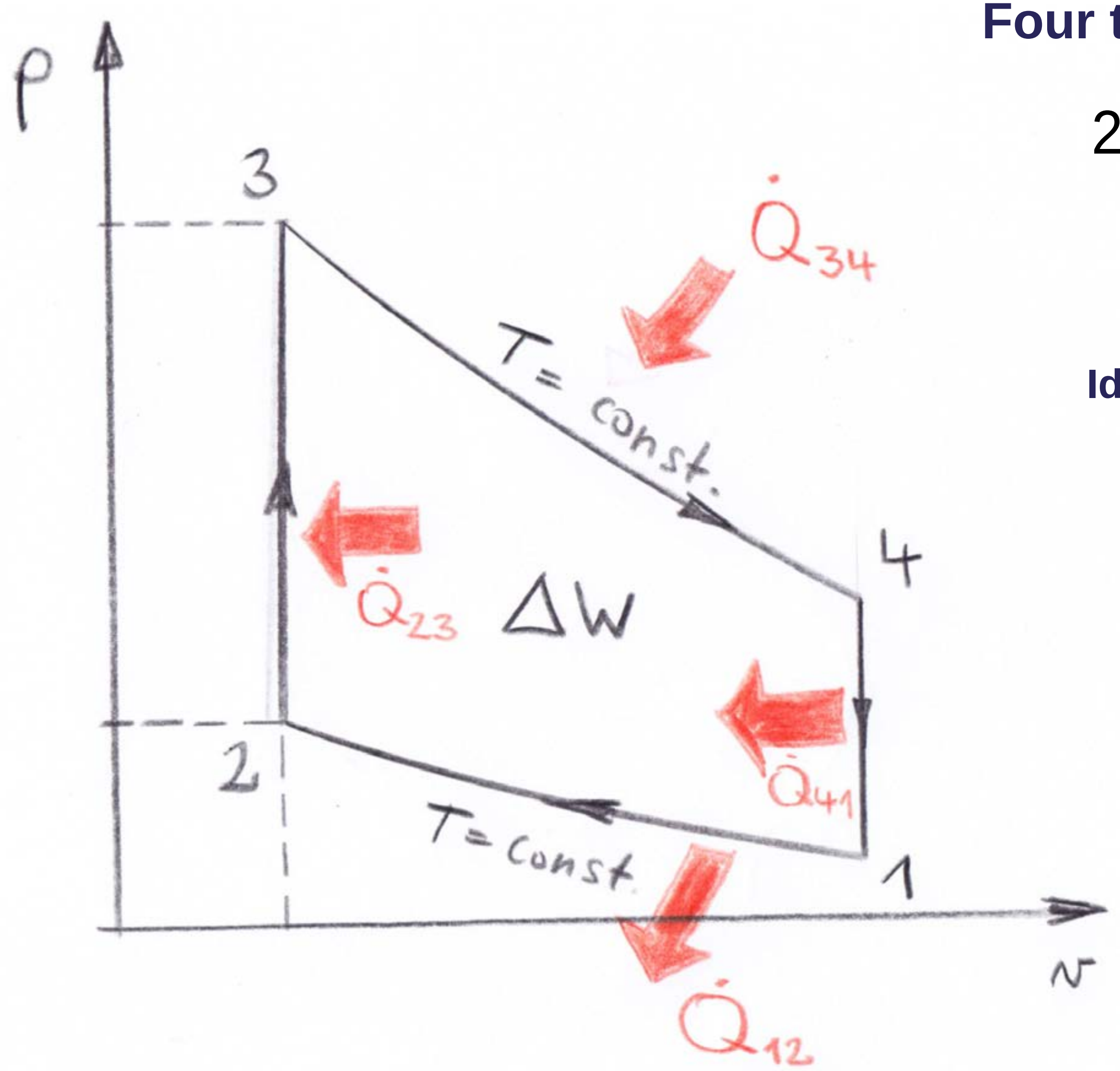
$p_1 \neq p_2$

$v_1 \neq v_2$

$$\underbrace{p_1 \cdot v_1 = R \cdot T = p_2 \cdot v_2}_{\text{Heat rejection}}$$

Bicycle pump

Stirling cycle



Four totally reversible processes:

$2 \rightarrow 3$ **isochore**

$$v = \text{const.}$$

Ideal gas $p \cdot v = R \cdot T$

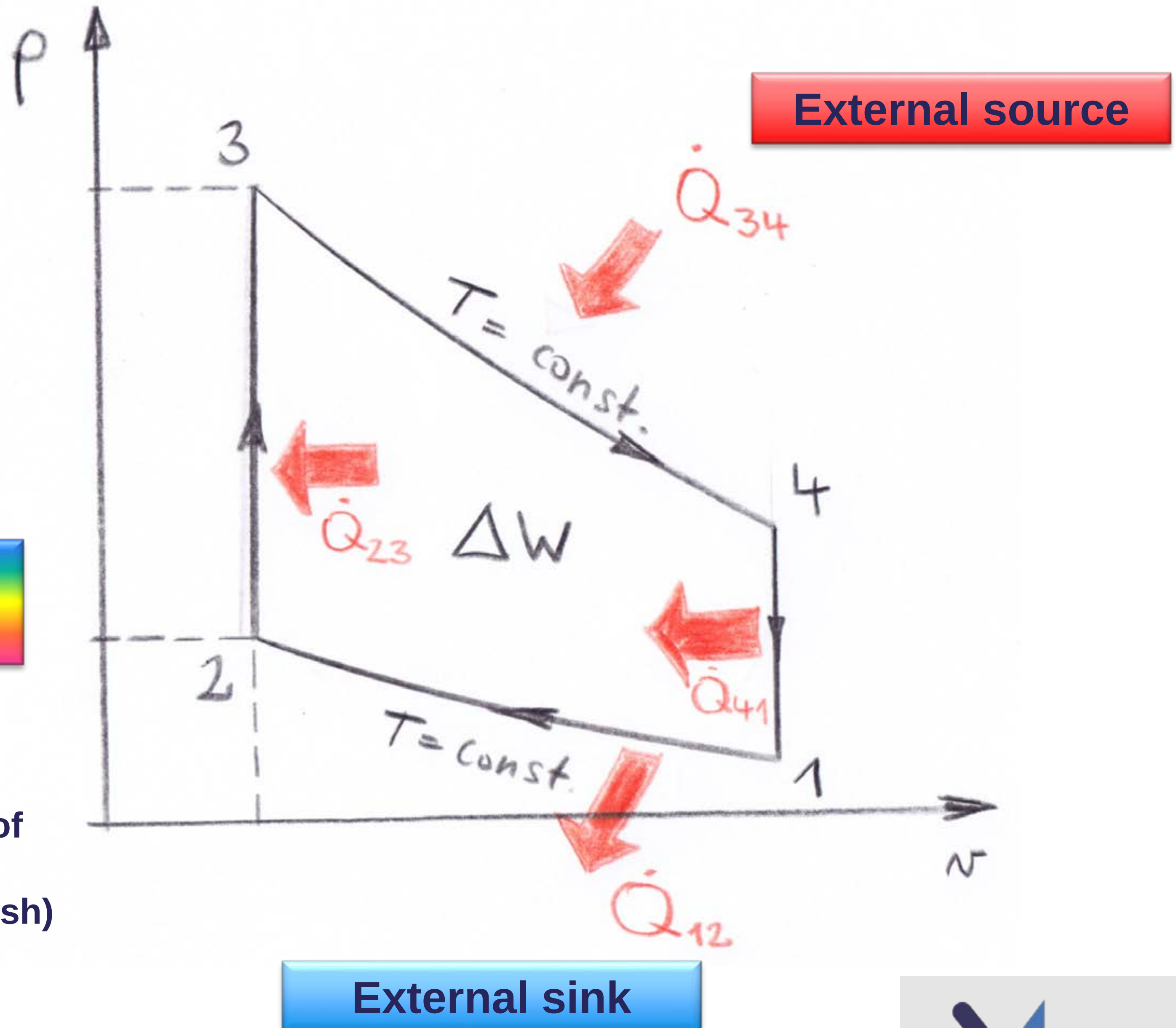
$$p_3 \neq p_2$$

$$T_3 \neq T_2$$

Heat addition

$$\dot{Q}_{23}$$

Stirling cycle



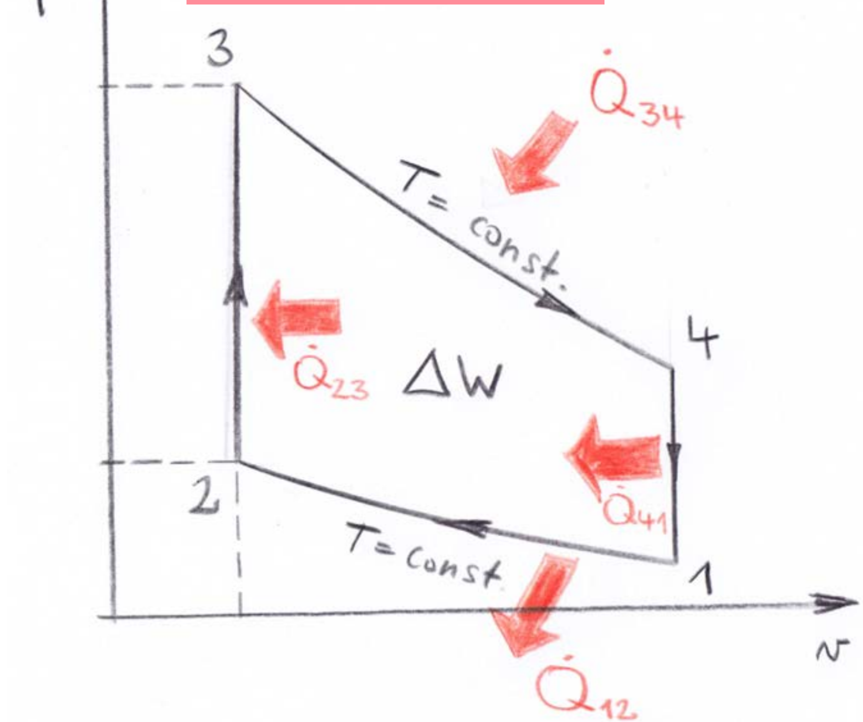
$$\dot{Q}_{23} = \dot{Q}_{41}$$

Internal regenerator

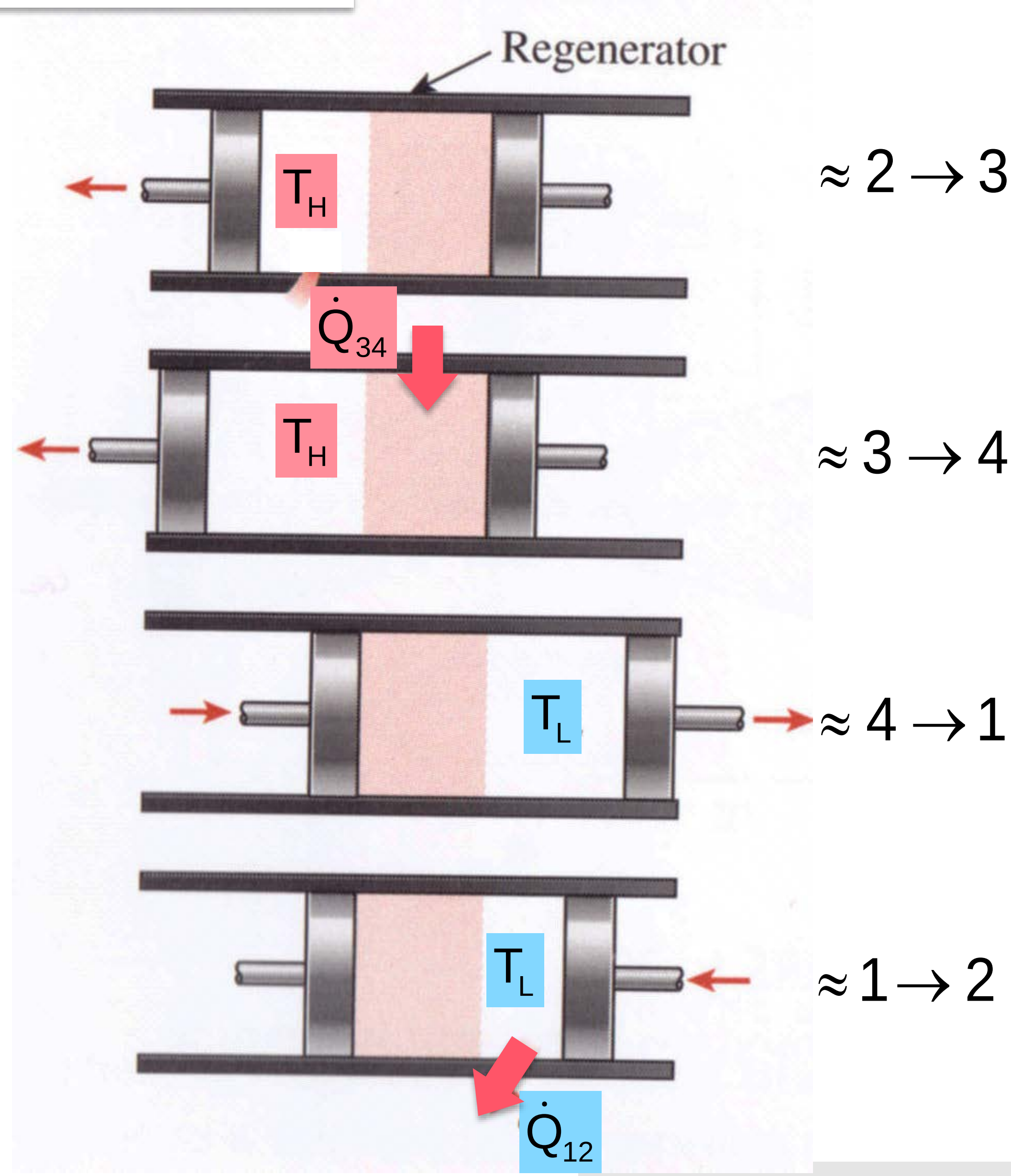
Temporary storage of thermal energy (Wire or ceramic mesh)

The execution of the Stirling cycle

$T_3 = T_4 = T_{High} = T_H$



$T_1 = T_2 = T_{Low} = T_L$



Yunus A. Cengel, Michael A. Boles
Thermodynamics - An Engineering Approach Seventh Edition in SI-Units, p. 501

Description of processes

The system consists of a cylinder with two pistons on each side and a regenerator in the middle. Then regenerator can be a wire or a ceramic mesh or any kind of porous plug with a high thermal mass (mass times specific heat). It is used for the temporary storage of thermal energy. The mass of the working fluid contained within the regenerator at any instant is considered negligible.

Initially, the left chamber houses the entire working fluid (a gas), which is at a high temperature and pressure. During process 3 – 4, heat is transferred to the gas at T_H from a source at T_H. As the gas expands isothermally, the left piston moves outward, doing work, and the gas pressure drops. During process 4 – 1, both pistons are moved to the right at the same rate (to keep the volume constant) until the entire gas is forced into the right chamber. As the gas passes through the regenerator, heat is transferred to the regenerator and the gas temperature drops from T_H to T_L. For this heat transfer process to be reversible, the temperature difference between the gas and the regenerator should not exceed a differential amount dT at any point. Thus, the temperature of the regenerator will be T_H at the left end and T_L at the right end of the regenerator when state 1 is reached. During process 1 – 2, the right piston is moved inward, compressing the gas. Heat is transferred from the gas to a sink at temperature T_L so that the gas temperature remains constant at T_L while the pressure rises. Finally, during process 2 – 3, both pistons are moved to the left at the same rate (to keep the volume constant), forcing the entire gas into the left chamber. The gas temperature rises from T_L to T_H as it passes through the regenerator and picks up the thermal energy stored there during process 4 – 1. This completes the cycle.

Notice that the second-constant volume process takes place at a smaller volume than the first one, and the net heat transfer to the regenerator during a cycle is zero. That is, the amount of energy stored in the regenerator during process 4 – 1 is equal to the amount picked up by the gas during process 2 – 3.

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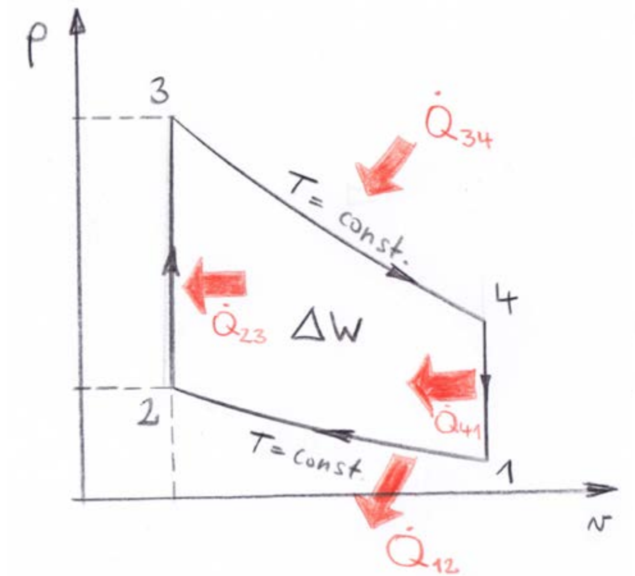
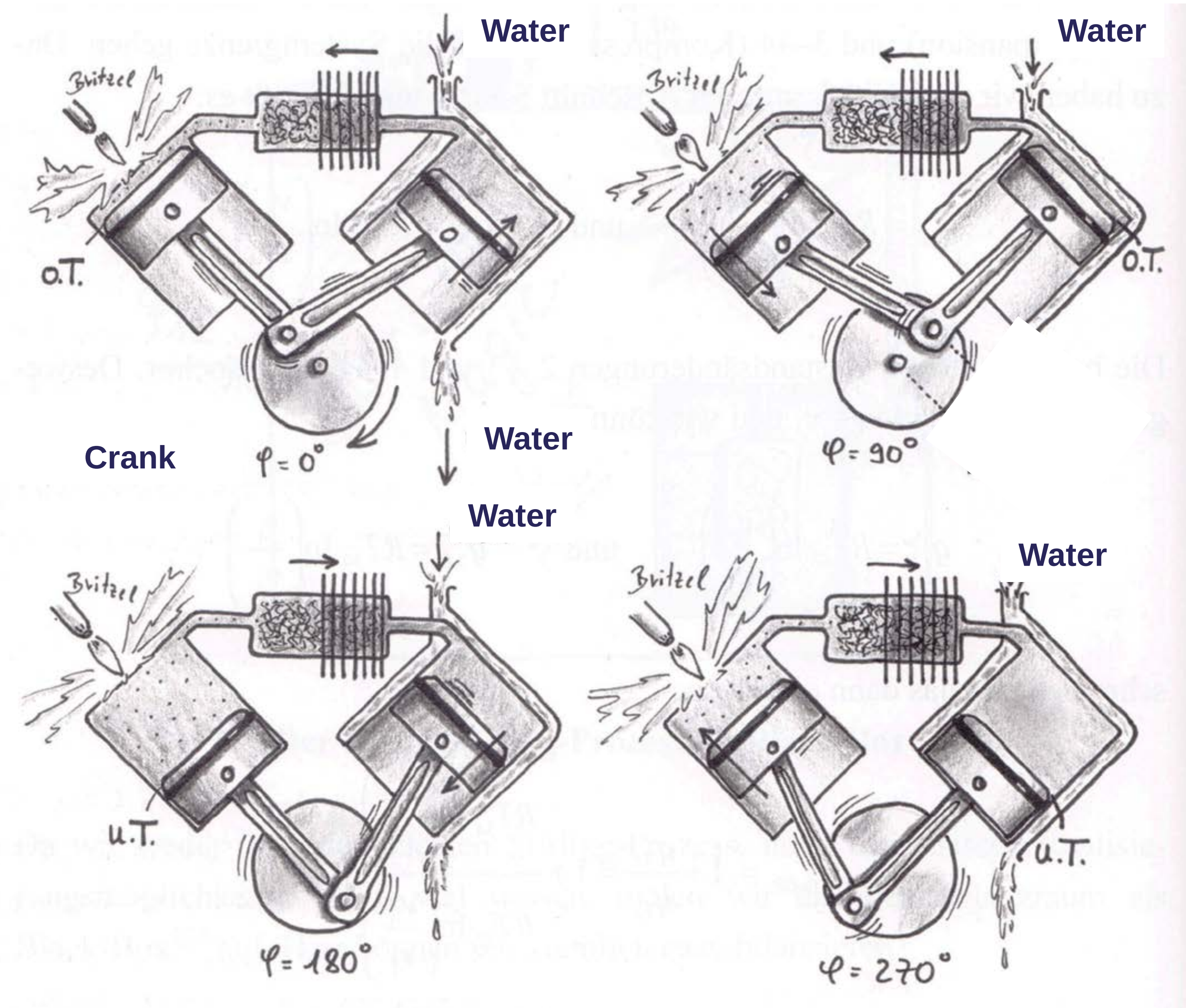
Stirling motor with two cylinders (V-motor)





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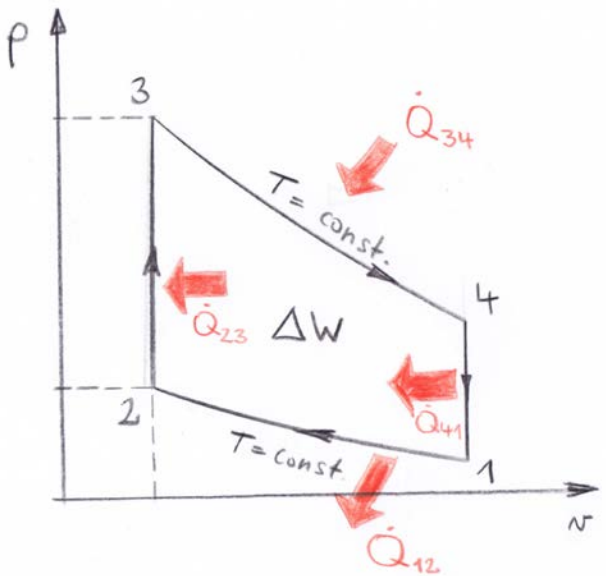
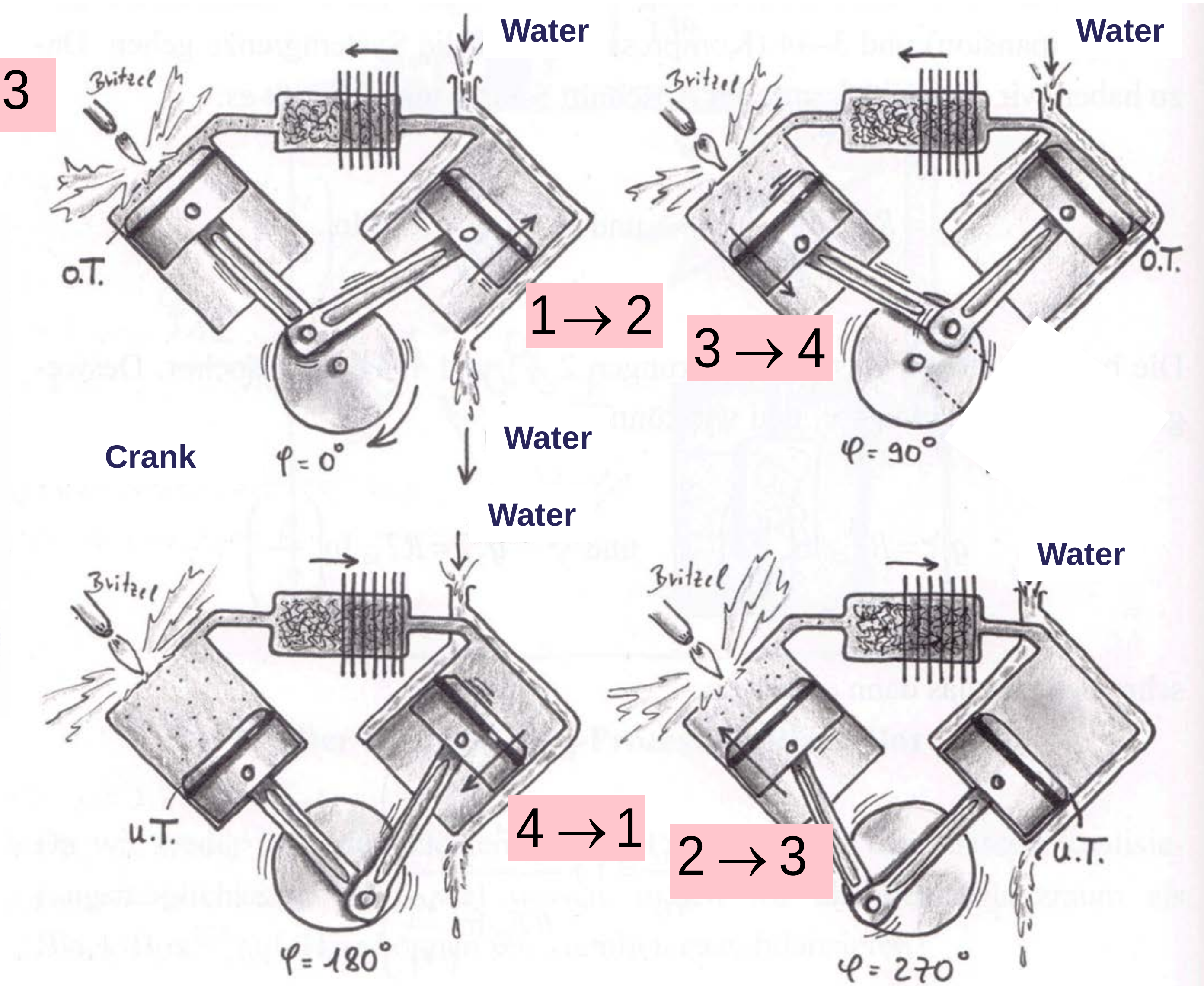
Stirling motor with two cylinders (V-motor)





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www.stirling-energie.de

Video

Sewage gas utilisation

Westsächsische Umweltdienste AG, Burgstädt
www.wudag.de | www.stirling-energie.de

www.stirling-energie.de

Stirling-Motor

Heizmedium:	Rauchgas
Arbeitsmedium	Helium
Heliumdruck:	~ 40
Asynchrongenerator:	6-polig
Nennspannung:	400 V
Synchrondrehzahl:	1.000 U/min
Stromstärke bei Volllast:	68 A
Stromstärke bei Leerlauf:	30,3 A

Leistung-Motor*

Nennwärmebelastung:	200 kW
Elektrische Nennleistung:	35 kW
Thermische Nennleistung des Stirling-BHKW:	140 bis 145 kW
Nutzwärmeleistung des Kühler-Wärmetauschers:	ca. 105 kW
Nutzwärmeleistung des Abgas-Wärmetauschers:	ca. 35 kW

$$\eta_{total} = \frac{P_{el}}{\dot{Q}_H} = \frac{35\,\text{kW}}{200\,\text{kW}} = 0.175$$

Brennstoffverbrauch:	200 kW
Brennstoffeinsatz:	Biogas, Klärgas, Deponiegas, etc. Pflanzenöl, Bio-ethanol, etc.

*gemäß Herstellerangaben

Stirling engine or Stirling motor

- A **practical engine** of the piston-cylinder type that operates on a closed regenerative cycle having features in common with the Stirling cycle has been under study in recent years → **Stirling engine or Stirling motor**.

- The Stirling engine offers the opportunity for high efficiency together with reduced emissions from combustion products because the combustion takes place **externally** and not within the cylinder as for internal combustion. In the Stirling engine, energy is transferred to the working fluid from products of combustion, which are kept separate.

- A stirling engine is an **external** combustion engine.

- The actual Stirling engine, including the original one patented by Robert Stirling, are **heavy and complicated**.

Power generation by solar energy

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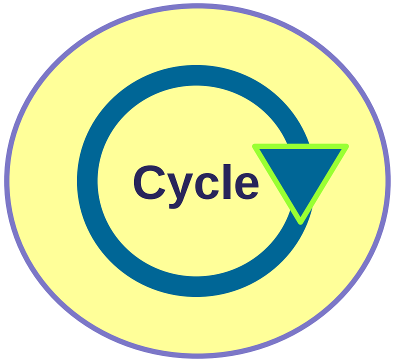
Open and closed gas power cycles

Carnot Cycle

The Carnot cycle is the most efficient cycle.

Otto Cycle

Diesel Cycle

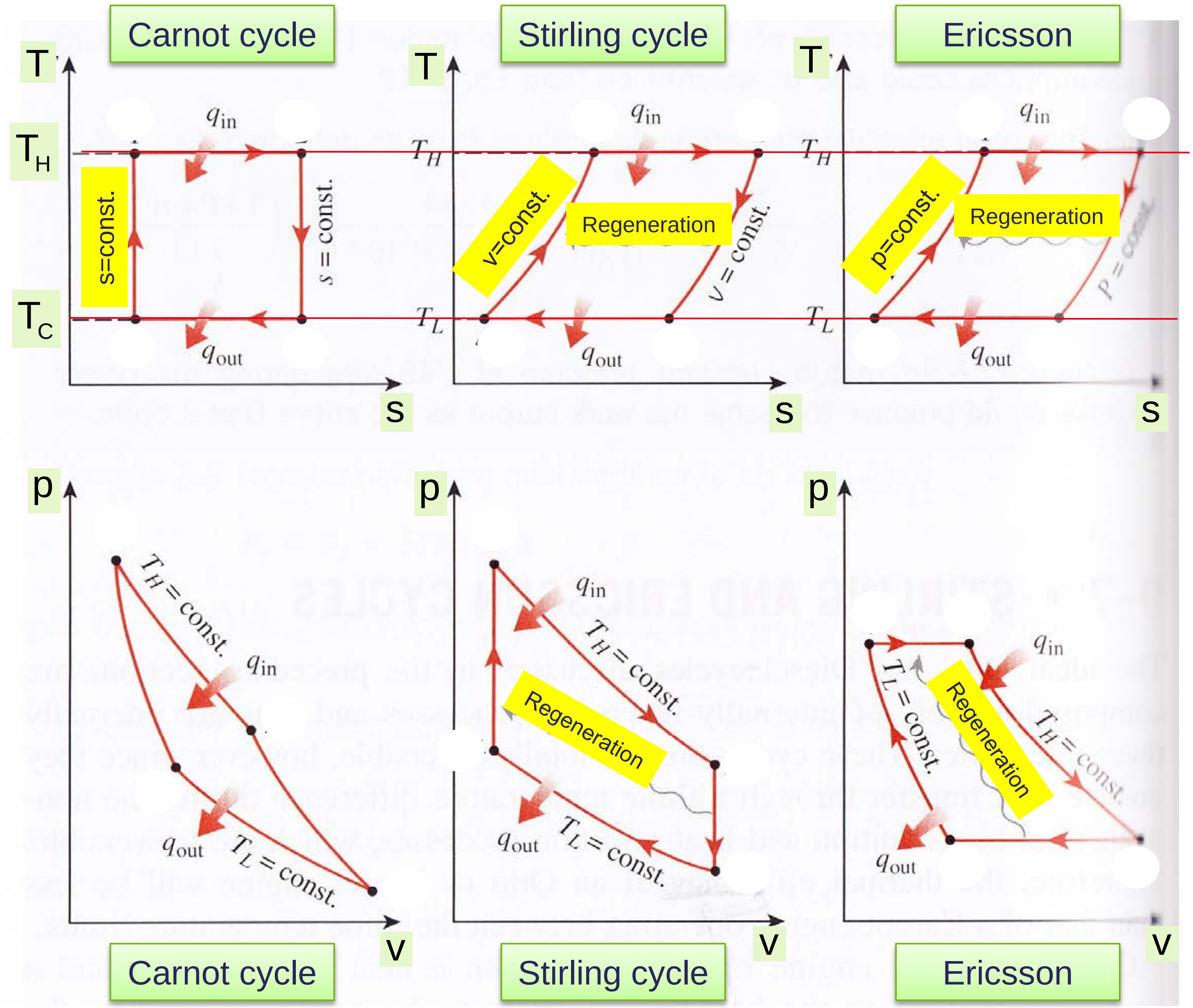


Stirling Cycle

Ericsson Cycle

Brayton Cycle

Summary



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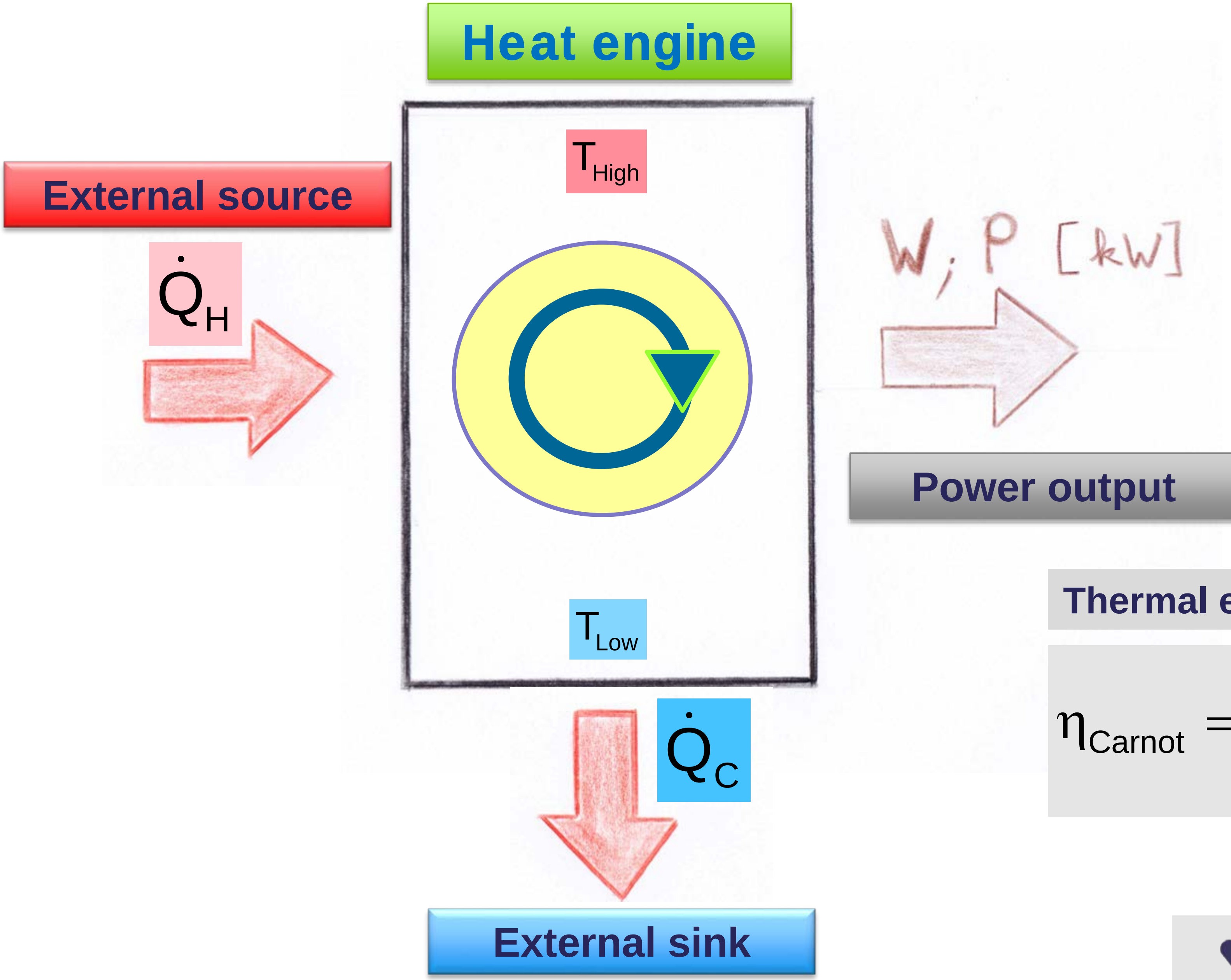
Summary



Thermal efficiency:

$$\eta_{Carnot} = \frac{P}{\dot{Q}_H} = 1 - \frac{T_{Low}}{T_{High}}$$

$$[T] = [K]$$

Literature

Robert Balmer
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ISBN 978-0-12-374996-3

Yunus A. Cengel, Michael A. Boles
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