

# **Energy in technical and biological systems**

## **WS 2017/2018**

### **Lecture 8**

#### **Second rule of thermodynamics**

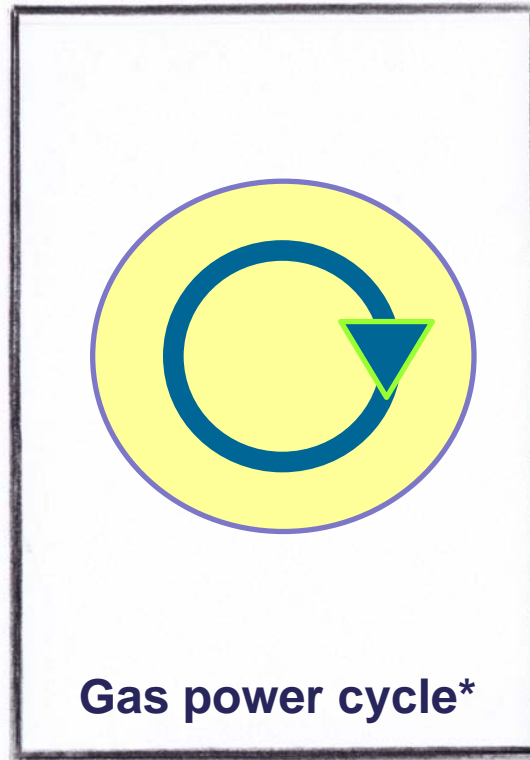
#### **Thermodynamic cycles**

#### **Gas power cycle**

#### **Stirling cycle**

# How to receive work or power from a system?

**Closed system**

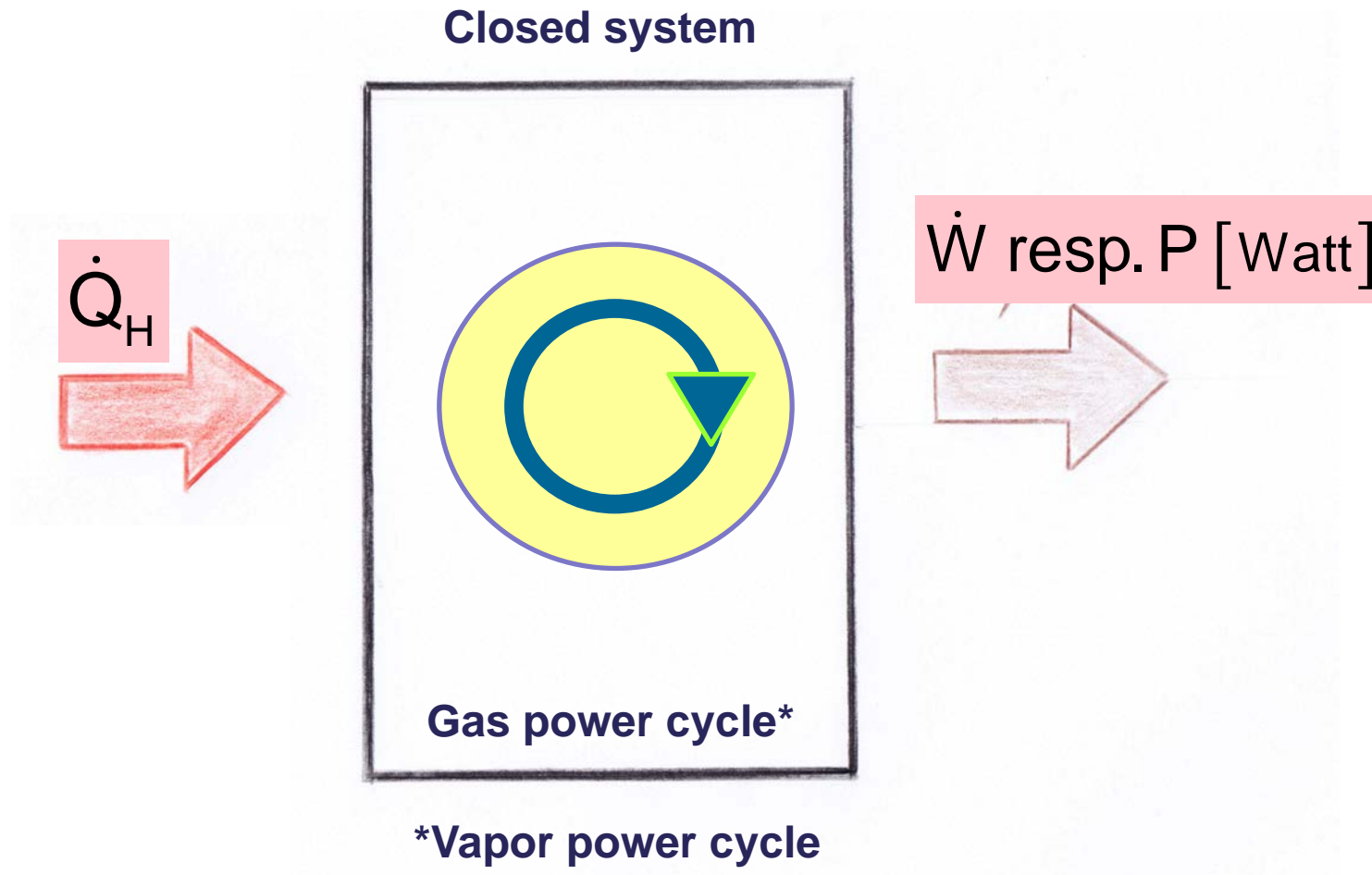


**\*Vapor power cycle**

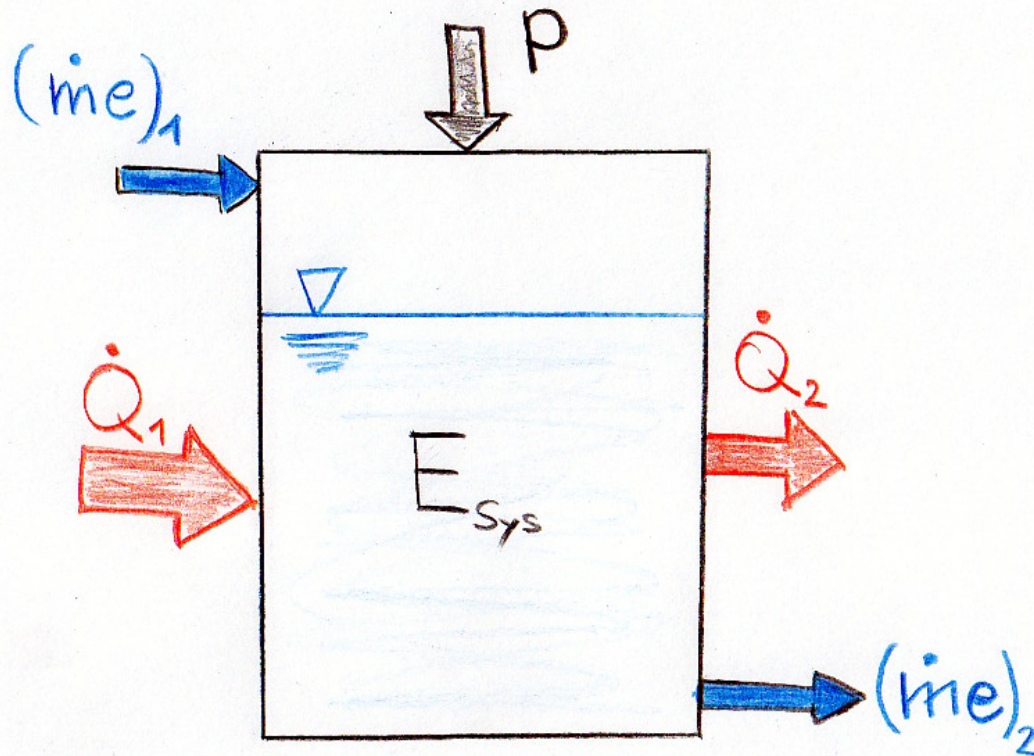
$\dot{W}$  resp.  $P$  [Watt]



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



# First law of thermodynamics



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

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

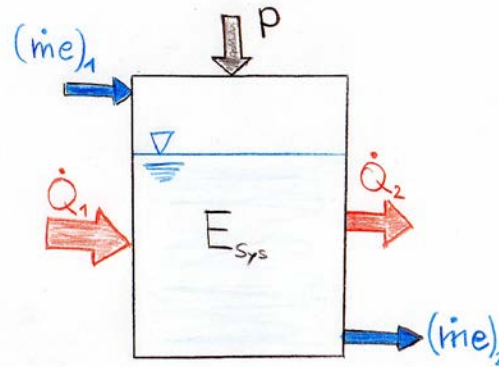
$$E_{\text{Sys},2} - E_{\text{Sys},1} = \sum \dot{Q} \cdot \Delta t + \sum P \cdot \Delta t + \sum \dot{m} \cdot \Delta t \cdot e$$

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

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

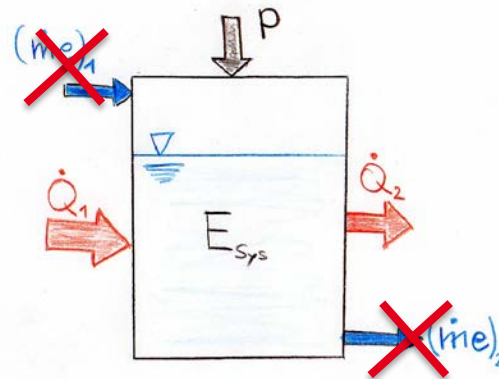
# Assumptions and simplifications

## 1 Open system



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

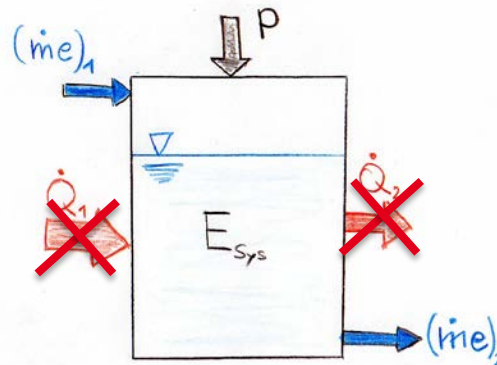
## 2 Closed system Steady state



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

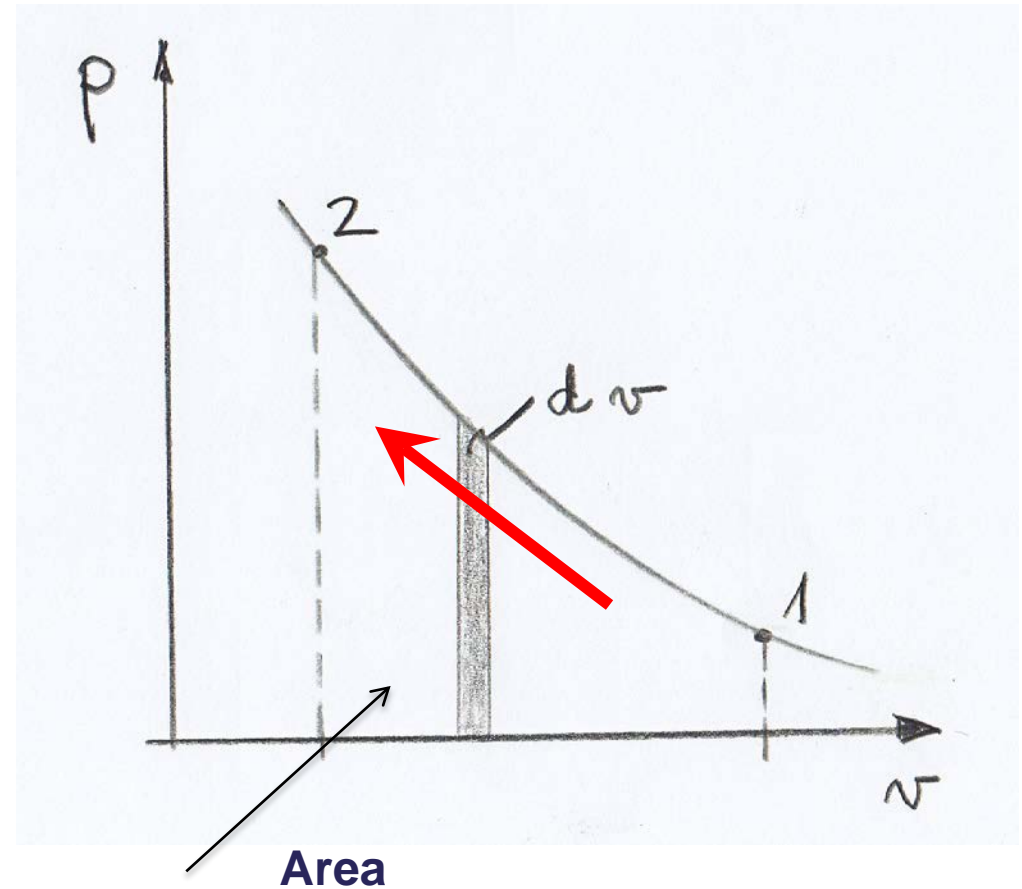
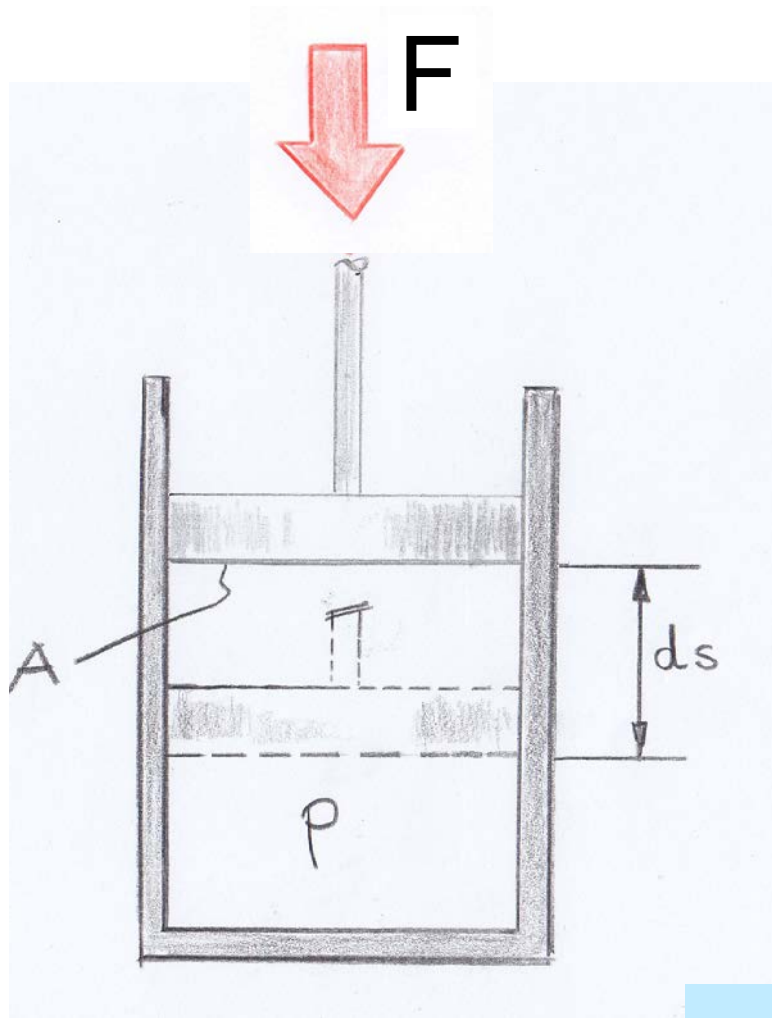
$$0 = \sum Q + \sum W$$

## 3 Adiabatic system



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

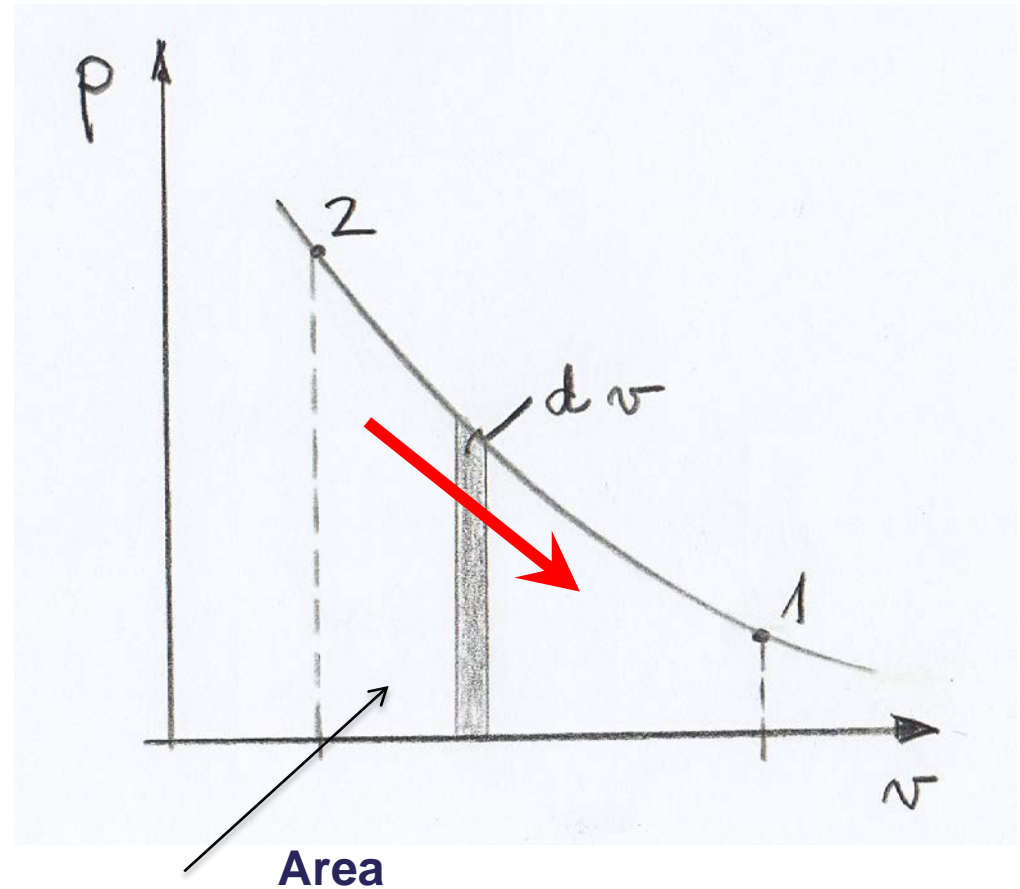
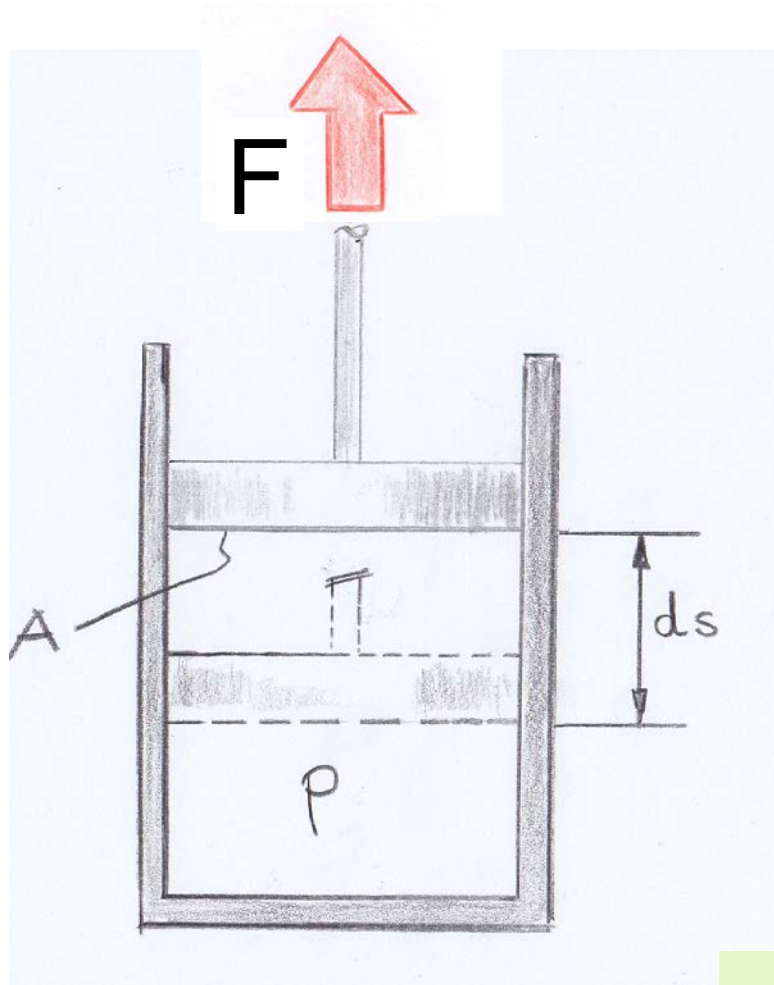
# Work done **on** a closed system



$$W_{12} = - \int_1^2 p(s) \cdot dv$$

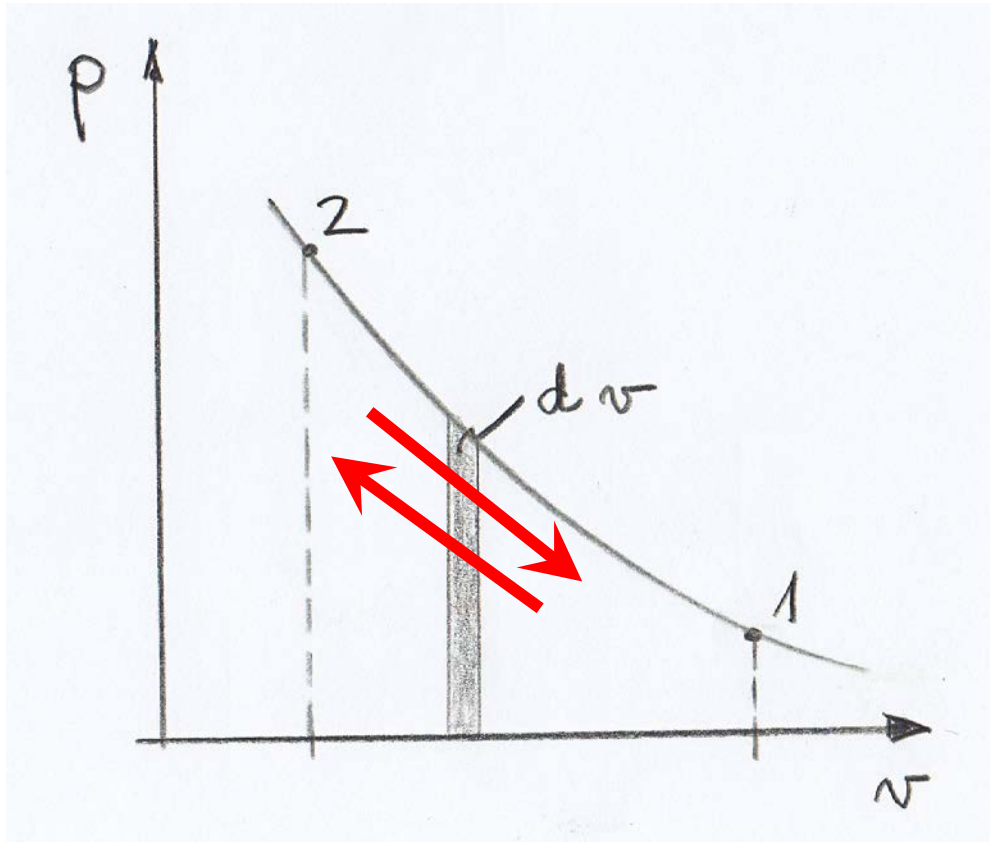


# Work done **by** a closed system



$$W_{21} = - \int_2^1 p(s) \cdot dv$$

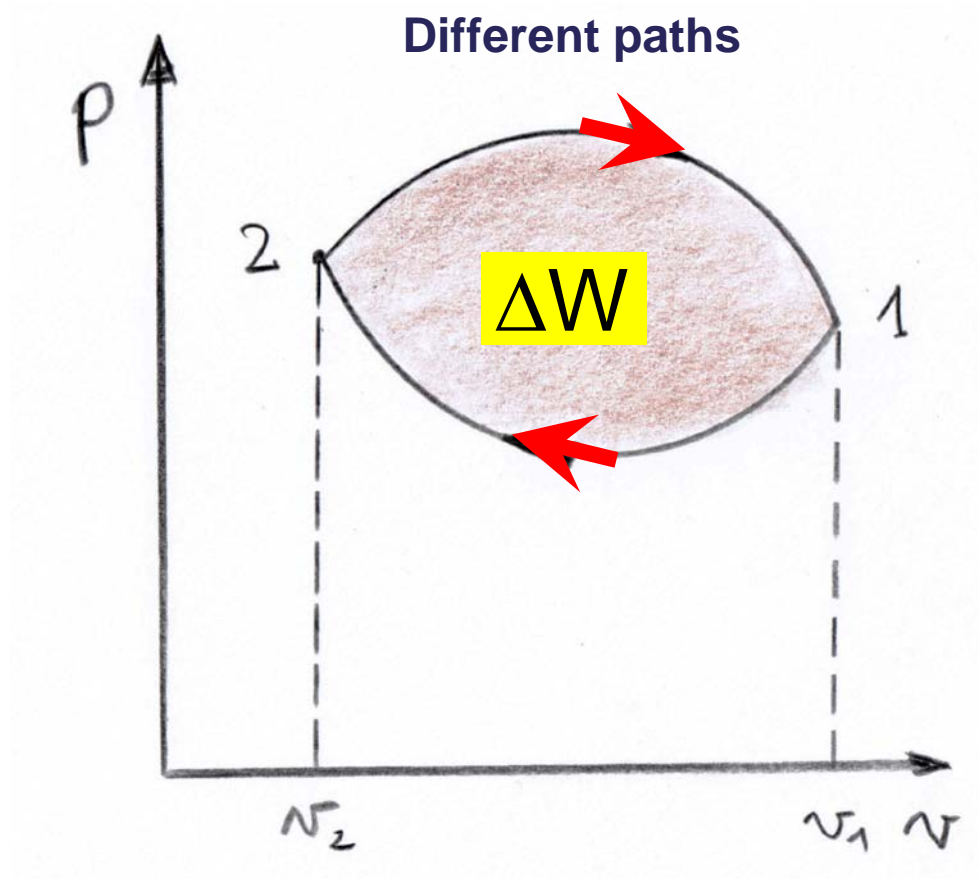
# Net work output



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

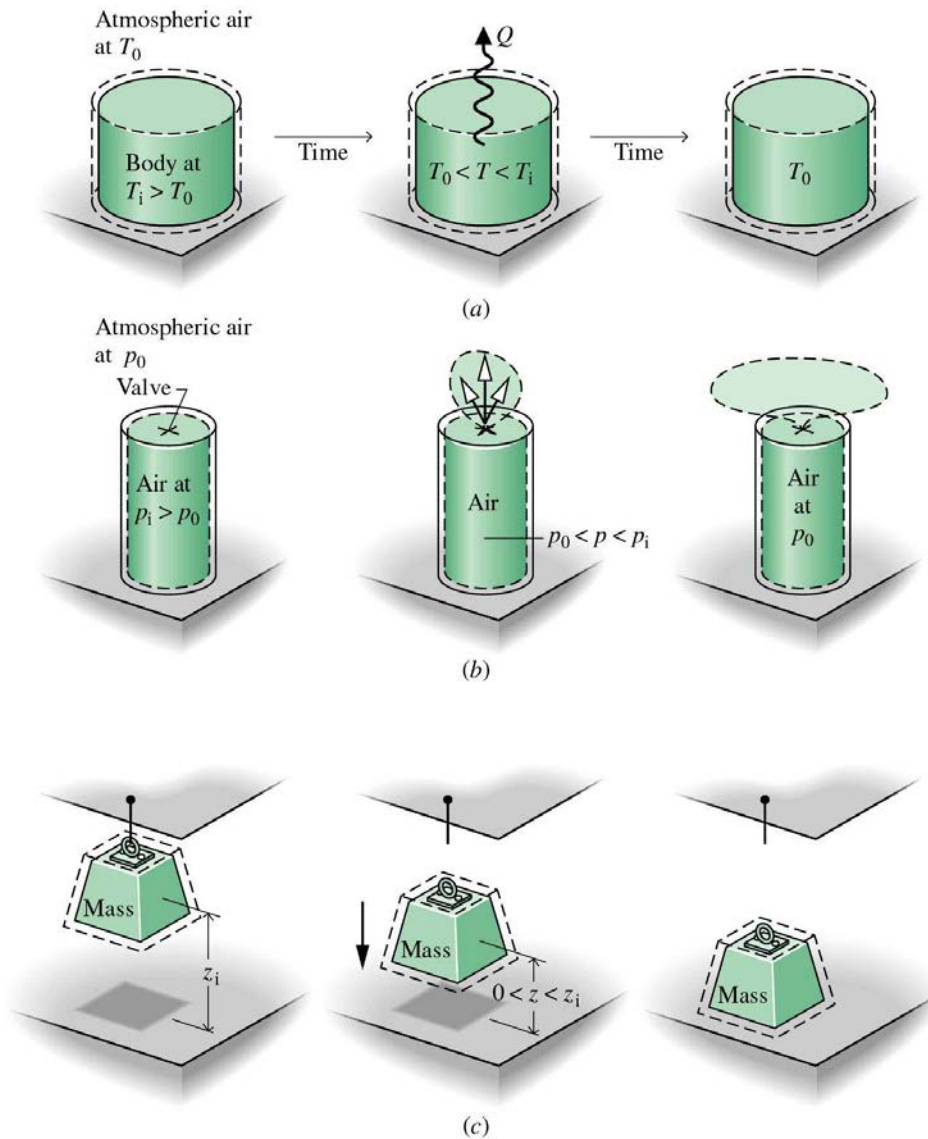


# Net work output for a cycle



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

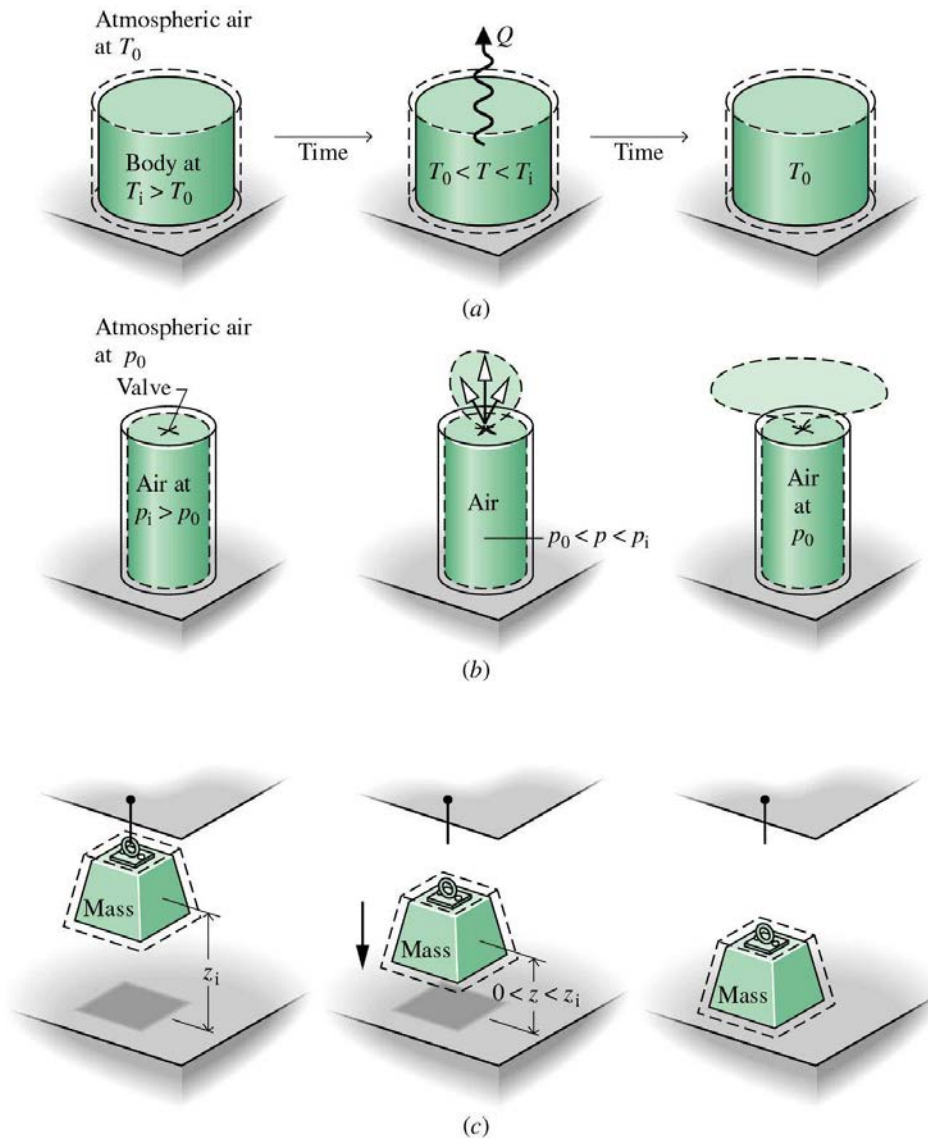
# Second law of thermodynamics



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.

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# 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?

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# Second law of thermodynamics

## Second law of thermodynamics



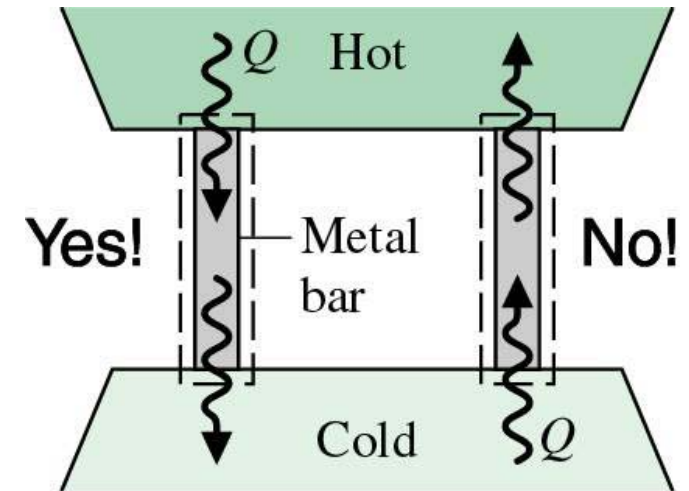
- ☐ Predict process direction
- ☐ Establish equilibrium conditions
- ☐ Determine theoretical best performance
- ☐ Evaluate factors limiting best performance
- ☐ Define a temperature scale independent of properties
- ☐ Develop means for evaluating properties, such as  $h$  and  $u$  in terms of properties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

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# 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 ???

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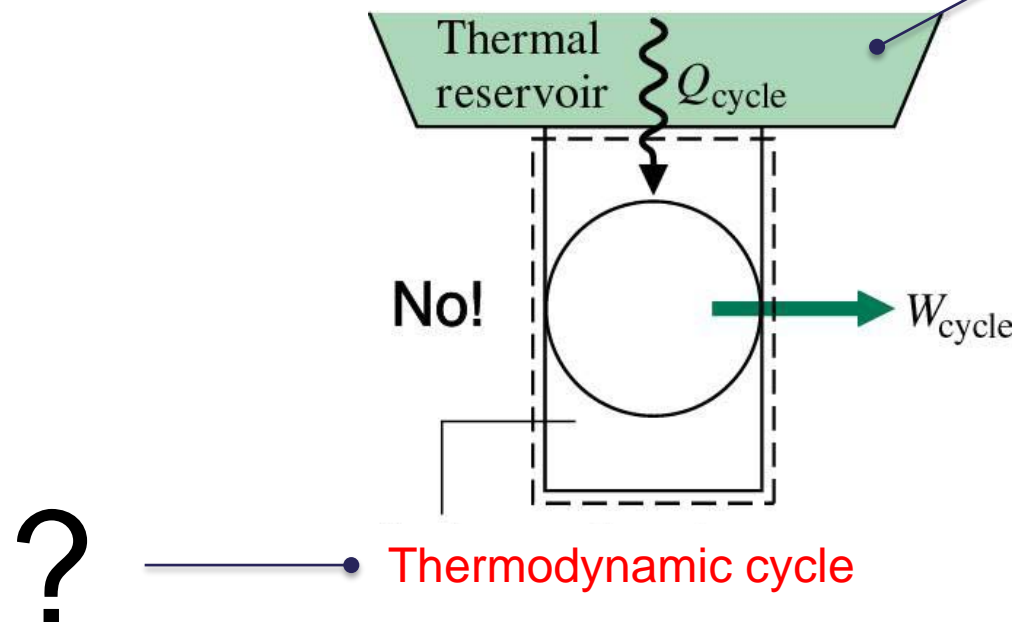
# Statements of the Second Law

## 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



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# Open and closed gas power cycles

## Carnot Cycle

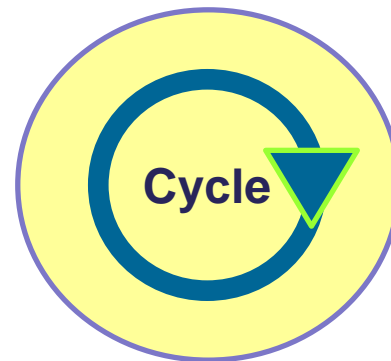
The Carnot cycle is the most efficient cycle.

## Otto Cycle

## Diesel Cycle

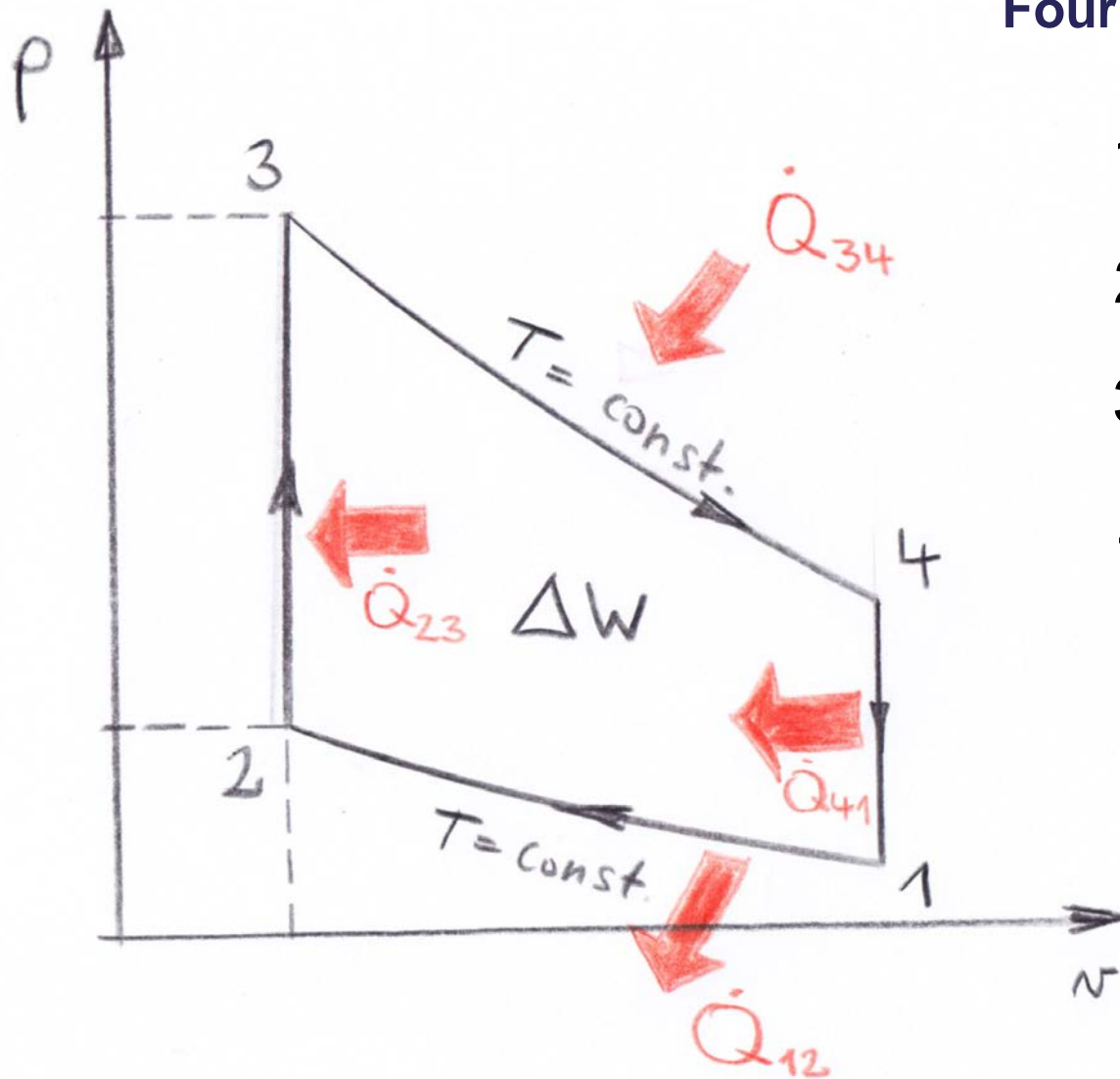
## Stirling Cycle

## Ericsson Cycle



## Brayton Cycle

# Stirling cycle



Four totally reversible processes:

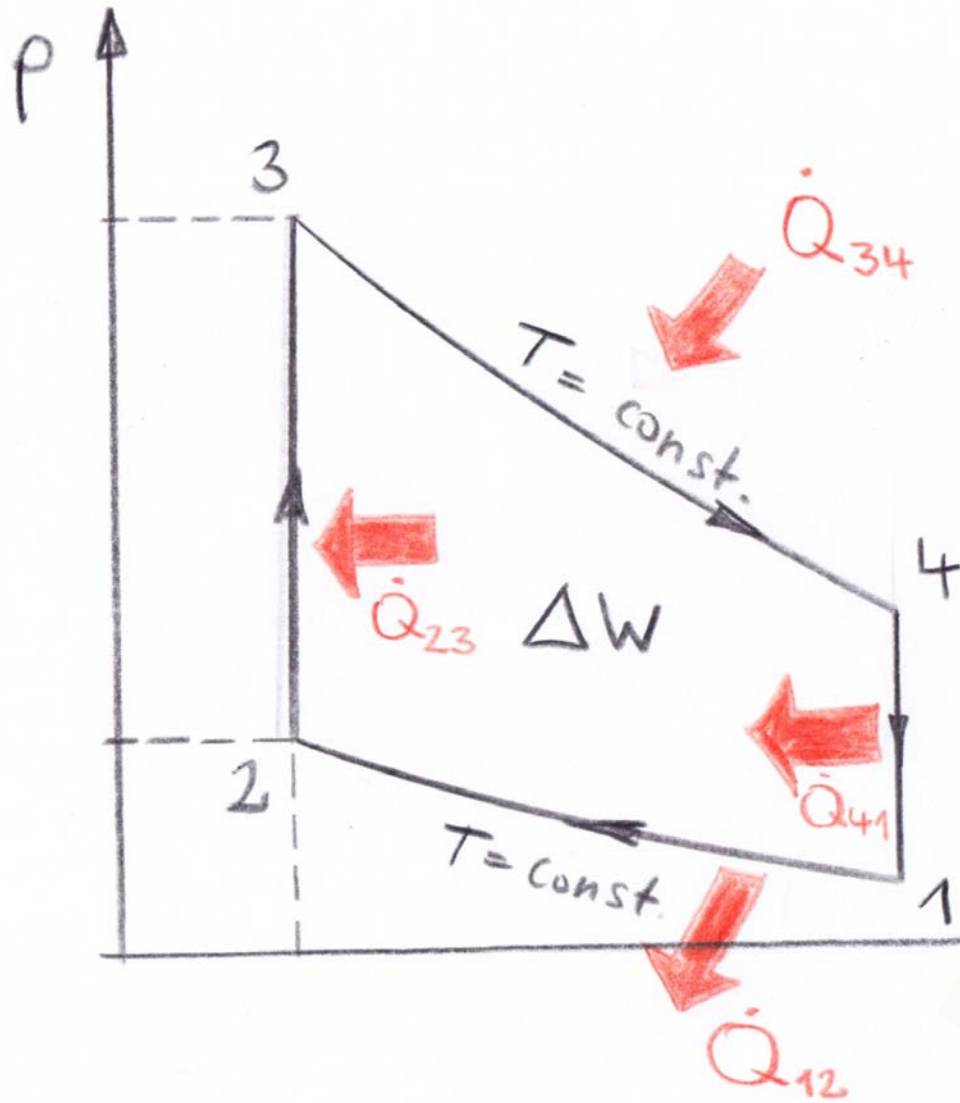
1 → 2 isothermal

2 → 3 isochore

3 → 4 isothermal

4 → 1 isochore

# Stirling cycle



Four totally reversible processes:

1 → 2

isothermal

$T = \text{const.}$

Ideal gas

$p \cdot v = R \cdot T$

$p_1 \neq p_2$

$v_1 \neq v_2$

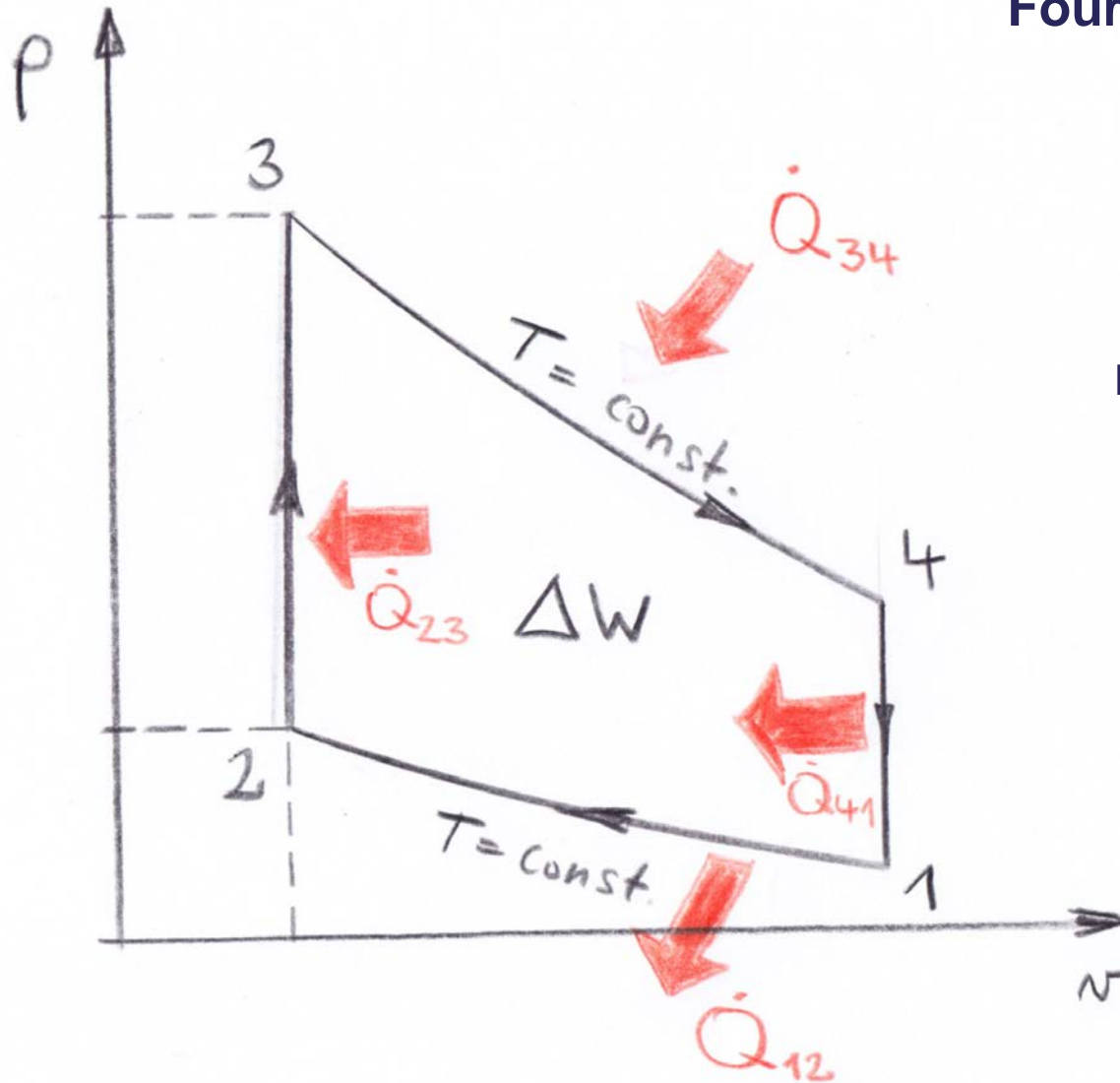
$p_1 \cdot v_1 = R \cdot T = p_2 \cdot v_2$

Heat rejection

Bicycle pump



# Stirling cycle



Four totally reversible processes:

2 → 3

isochore

$v = \text{const.}$

Ideal gas

$p \cdot v = R \cdot T$

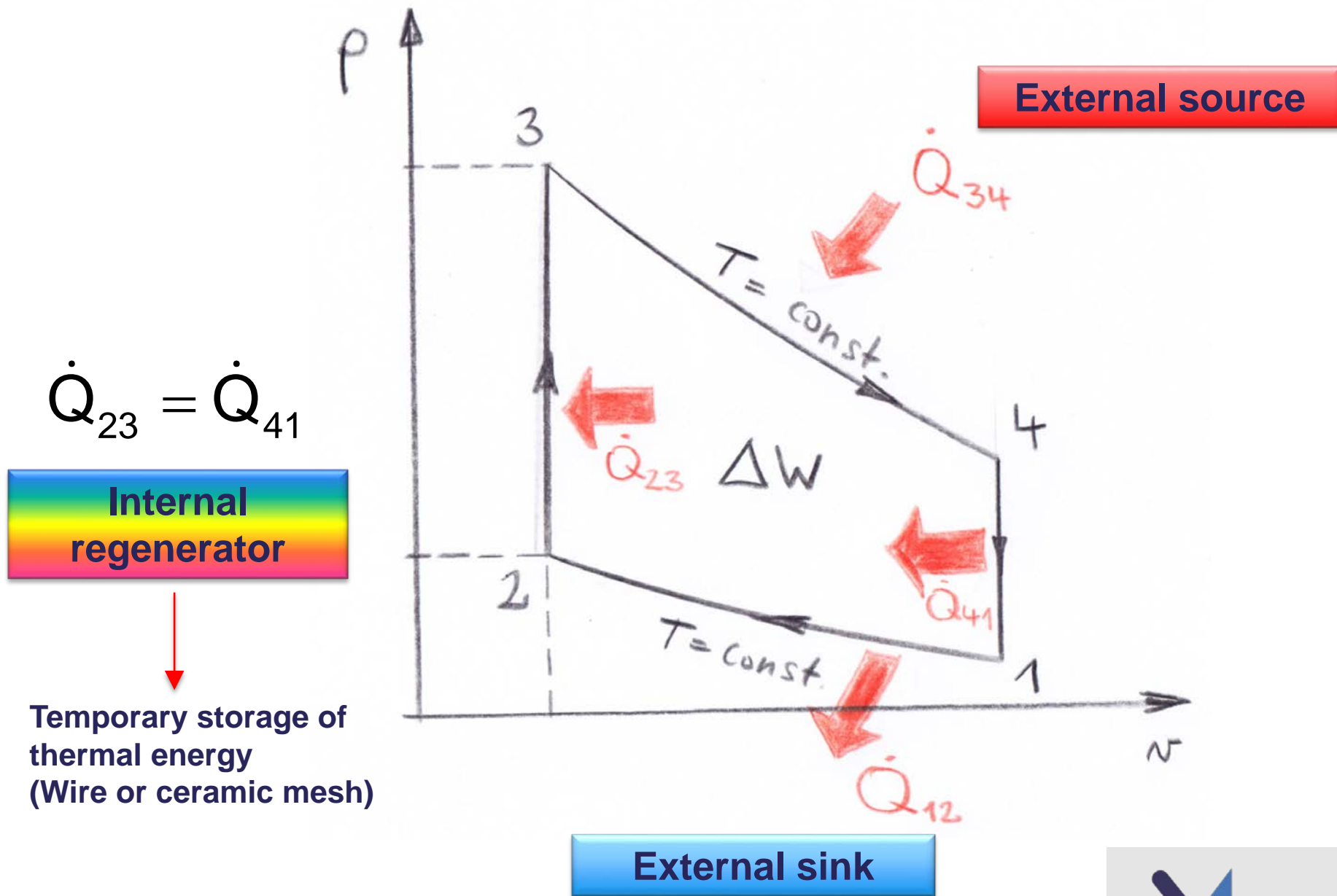
$p_3 \neq p_2$

$T_3 \neq T_2$

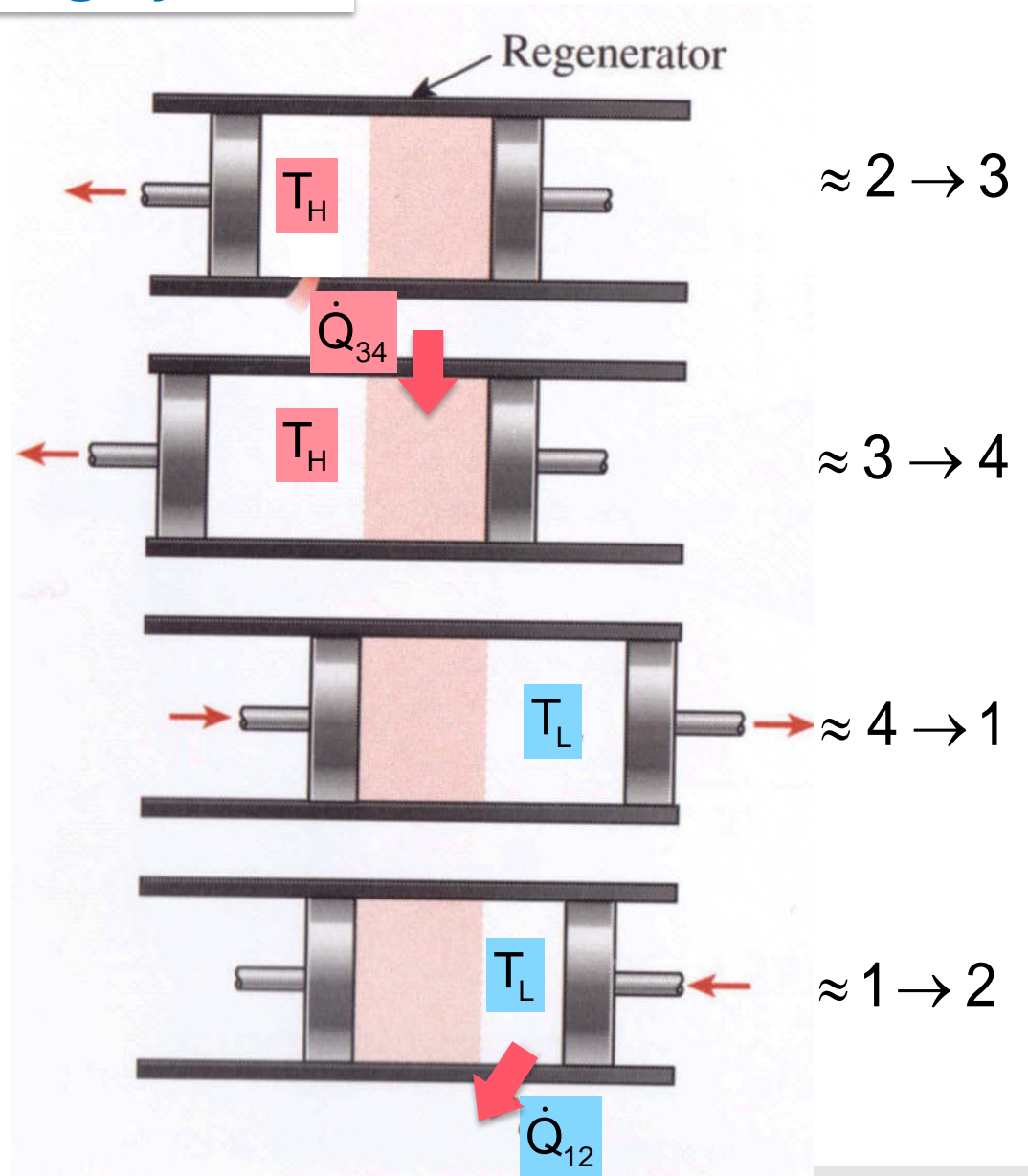
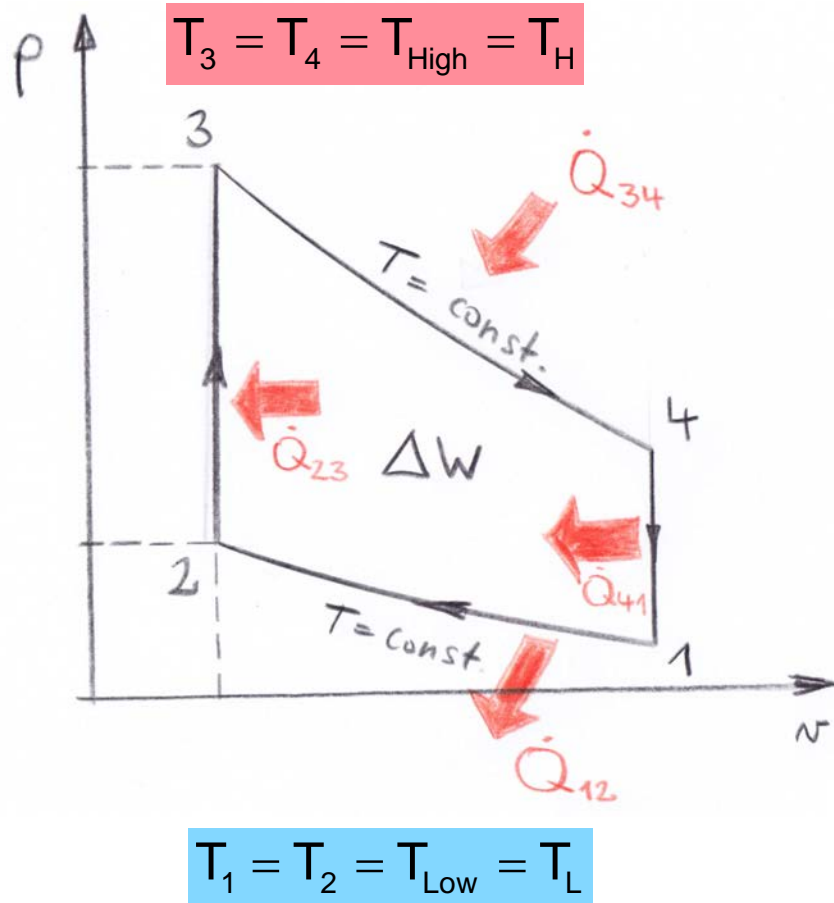
Heat addition

$\dot{Q}_{23}$

# Stirling cycle



# The execution of the Stirling cycle



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.

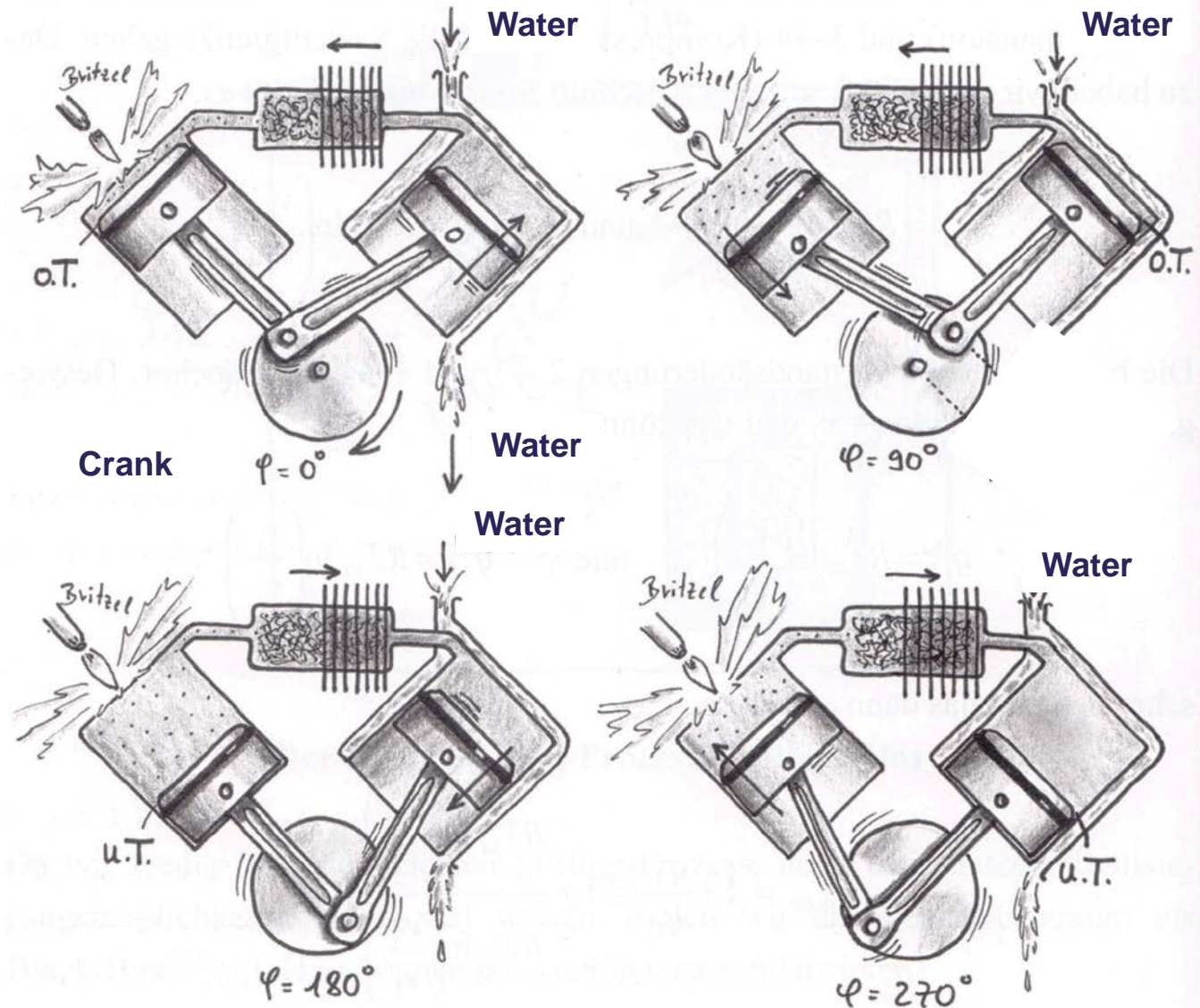
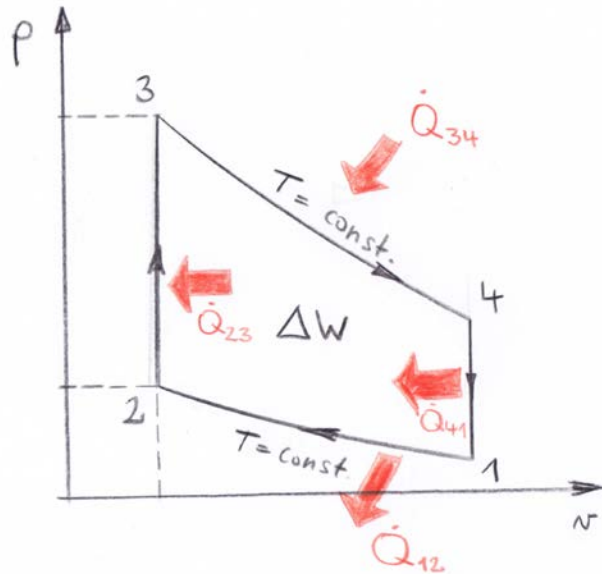
Initially, the left chamber houses the entire working fluid (a gas), which is at a high temperature and pressure. During process 3 – 4, heat is transferred to the gas at  $T_H$  from a source at  $T_H$ . As the gas expands isothermally, the left piston moves outward, doing work, and the gas pressure 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.

Yunus A. Cengel, Michael A. Boles

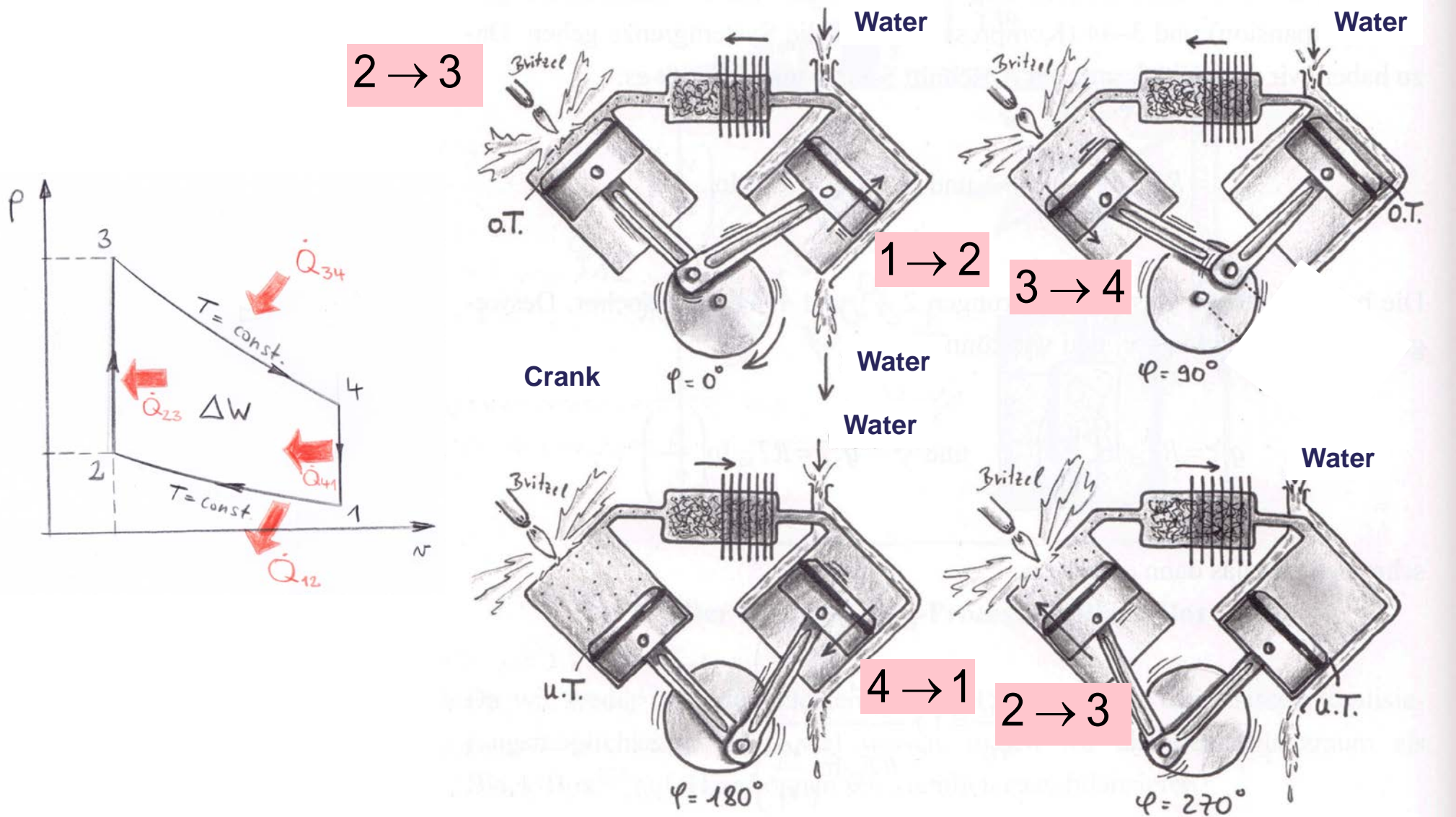
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# Stirling motor with two cylinders (V-motor)



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Keine Panik vor Thermodynamik! S. 180

# Stirling motor with two cylinders (V-motor)






Dirk Labuhn, Oliver Romberg  
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np-for-sewage-plants

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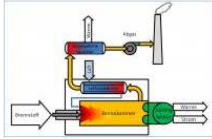
## Stirling CHP for sewage plants

### General description for sewage plants

Due to anaerobic fermentation during wastewater treatment, sewage gas is generated. During external combustion on the Stirling engine the sewage gas is turned into electricity and heat.

The company WUDAG bought the engine, combustion chamber and operating controls from Stirling Denmark and independently designed the burner management system. WUDAG then had the task of building a sewage gas line and integrating the plant into the existing heating and process control system. The plant was successfully put into operation in May 2010 at the sewage plant Niederfrohna.

### Process description for sewage plants



The sewage plant Niederfrohna can serve 40,000 residents and is used to 85% of this capacity. It cleans the communal and industrial wastewater biologically according to the SBR procedure (Sequencing Batch Reactor). The sludge generated is anaerobically utilised. The sewage gas generated contains between 50 and 60% methane. The sewage gas from the sewage plant Niederfrohna is used as source to generate electricity and heat with a Stirling CHP.

On its way from the gas storage to the Stirling CHP it only passes through a biological desulphurisation and two condensate separators. The sewage gas is not purified with an activated carbon filter. Very high temperatures are generated in the combustion chamber during the combustion of the sewage gas, which are transmitted on to the heater of the Stirling engine. At the same time the part of the engine that has to be kept cool, is cooled by the connected heating coil. The electricity generated according to the Stirling principle of about 35 kWel is used to cover the energy demand of the sewage plant.

The combustion air is preheated according to the counter-current principle in the combustion chamber and the waste gasses reach a medium temperature of about 425°C at the exit of the combustion chamber. A downstream waste gas heat exchanger cools the waste gasses further down to about 100°C. The cooling of the Stirling engine, the combustion chamber as well as of the waste gasses generates up to 140 kWtherm of thermic power.

The heat is mainly used for the mesophilic run fermenter and also for heating the company building.

## STIRLING ENGINES

- The Stirling Principle
- Biomasse Stirling Prozess
- 35 kWel SD4-E Engine

## STIRLING BHKW

- General
- Stirling CHP for Sewage Plants

## FACTS

- Advantages
- Service
- Partner
- Reference
- Video
- Documents


Video

# Sewage gas utilisation




Westsächsische Umweltdienste AG, Burgstädt  
[www.wudag.de](http://www.wudag.de) | [www.stirling-energie.de](http://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

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

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**.



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# Power generation by solar energy



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# Open and closed gas power cycles

## Carnot Cycle

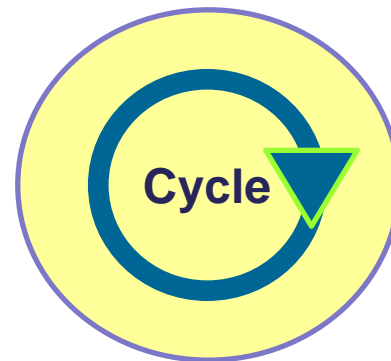
The Carnot cycle is the most efficient cycle.

## Otto Cycle

## Diesel Cycle

## Stirling Cycle

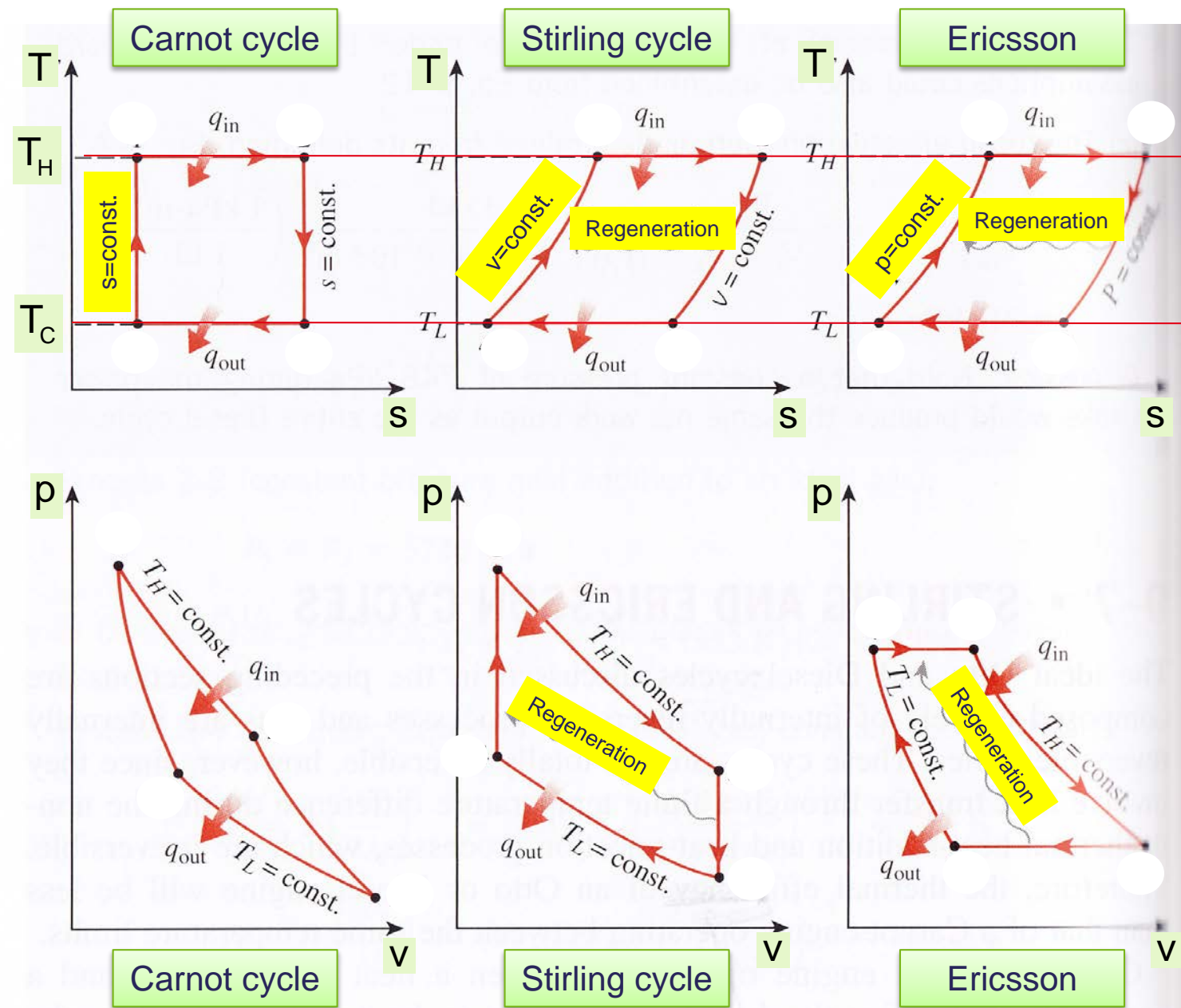
## Ericsson Cycle



## Brayton Cycle



# Summary

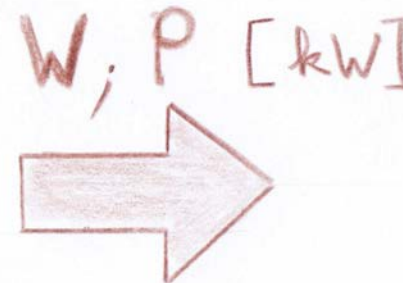
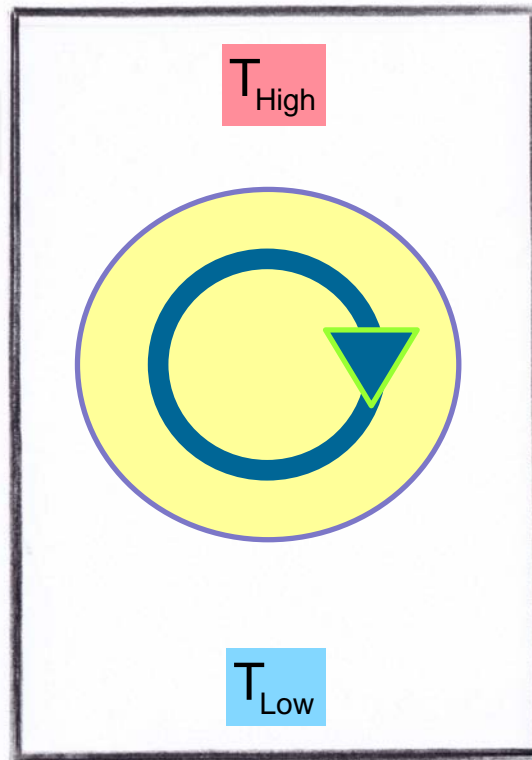
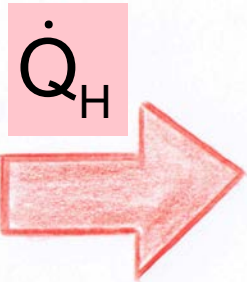


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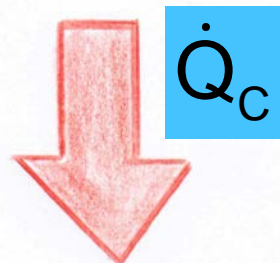
# Summary

## Heat engine

### External source



### Power output



### External sink

### Thermal efficiency:

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

$$[T] = [K]$$

# Literature

**Robert Balmer**

Modern Engineering Thermodynamics  
ISBN 978-0-12-374996-3

**Yunus A. Cengel, Michael A. Boles**

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