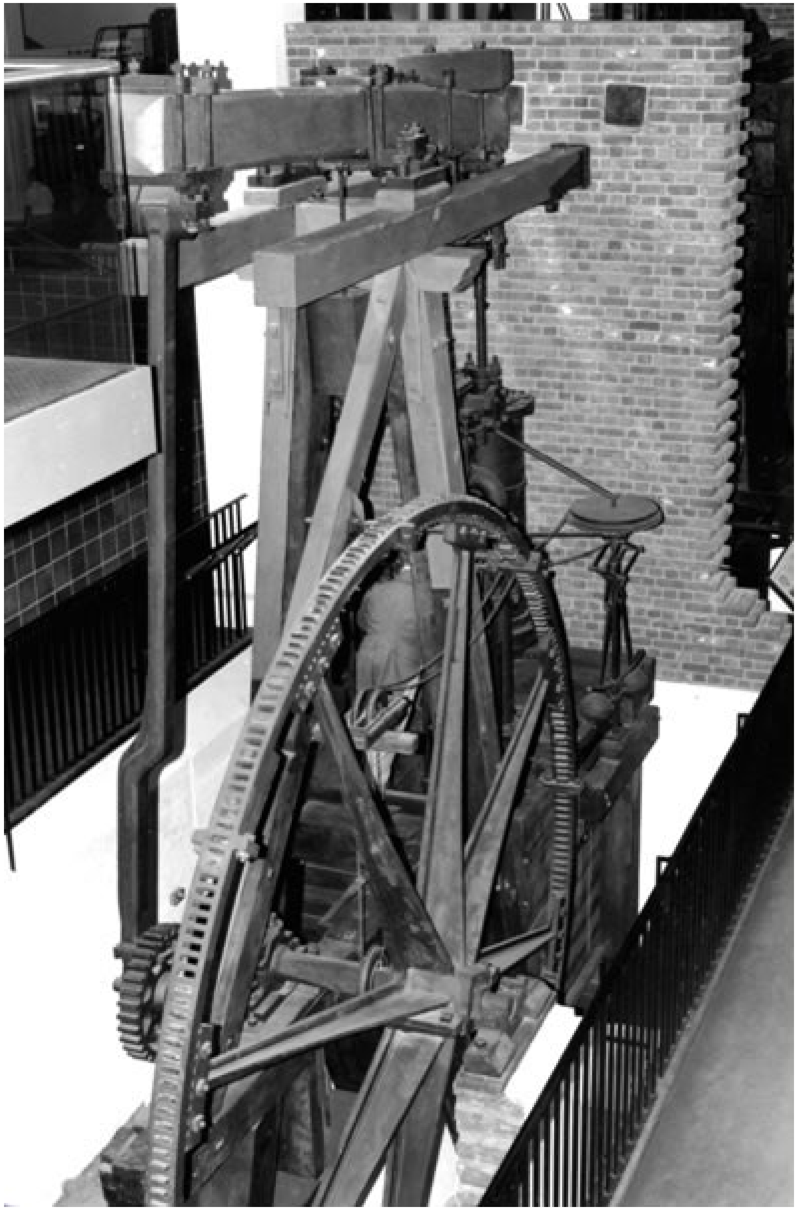
Class 6
Analysis of Thermodynamic Cycles



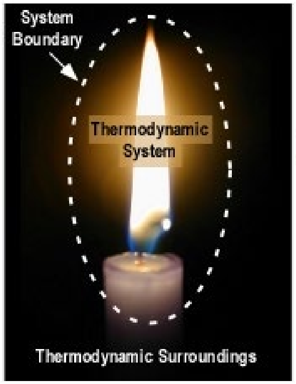
Boulton and Watt Steam Engine. Watt's use of the double-acting piston, an external condenser, and planetary gearing to change reciprocal into rotary motion made the steam engine into a practical power producer.
(British Science Museum, London)

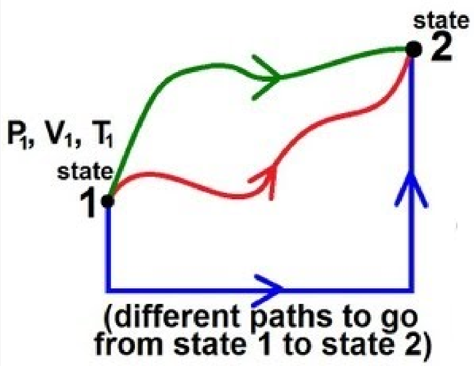
M. Muñoz Rojo/ G.G.M. Stoffels

Roadmap Engineering Thermodynamics

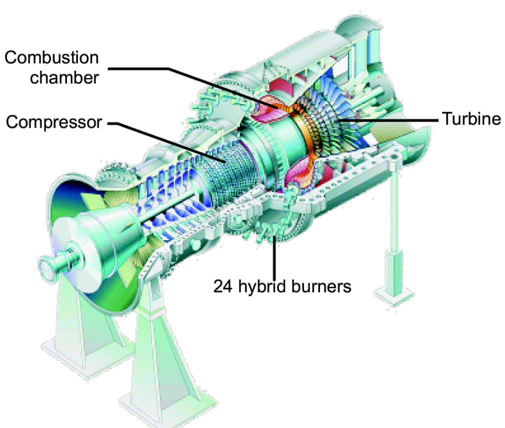
- Using thermodynamics for practical applications requires knowledge of:

Concepts and definitions (Class 1) → Various forms of energy (Class 2)

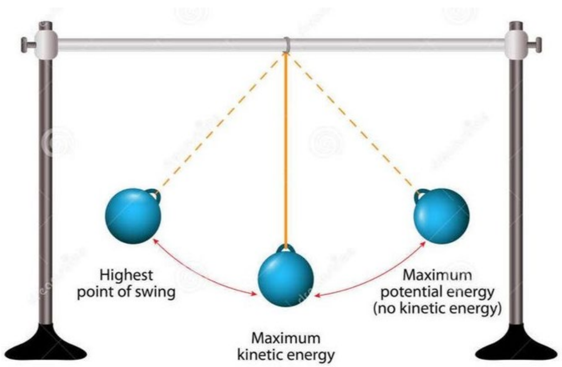




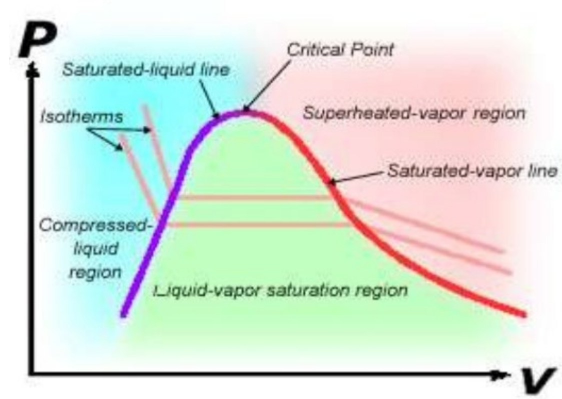
Power cycles
(Class 6 – 11)



Laws of Thermo
(Class 4 and 5)

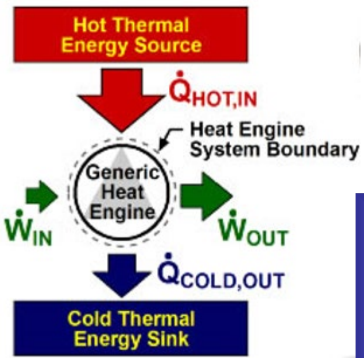


Properties of Substances
(Class 3, 9)

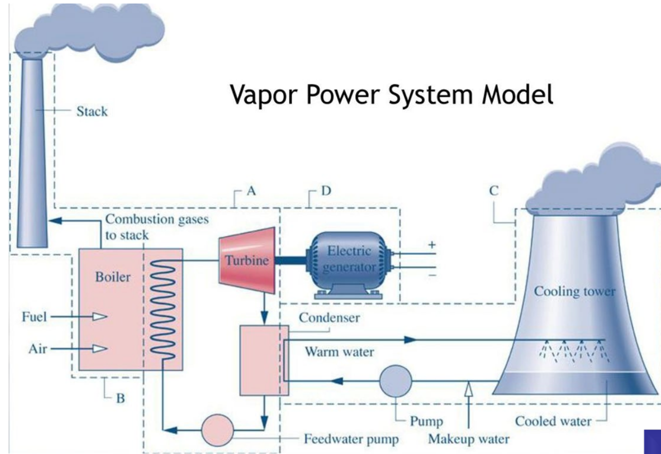


Roadmap Engineering Thermodynamics

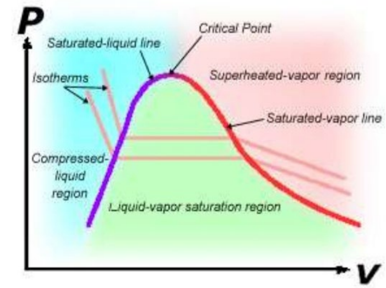
Thermodynamic cycles (Class 6)



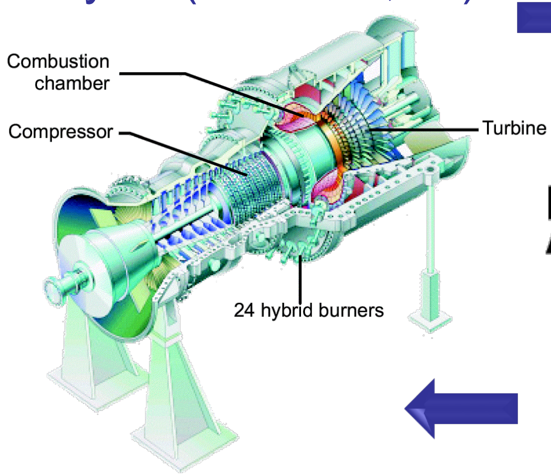
Vapor power cycles – Rankine cycle (Class 7, 8)



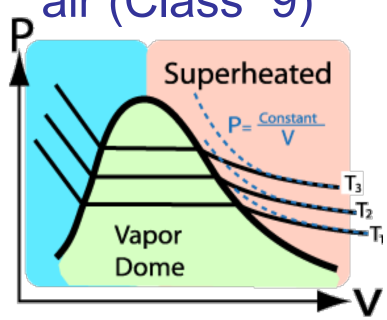
Properties of water (Class 3)



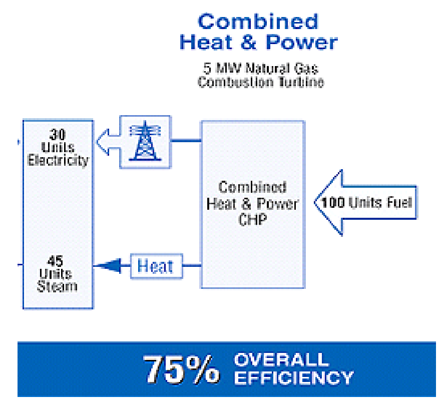
Gas power cycles – Brayton cycle (Class 10, 11)

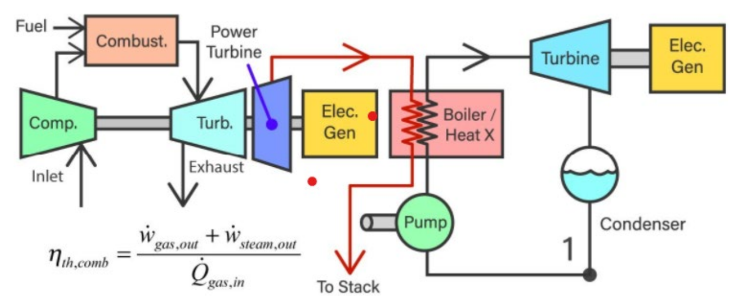


Properties of air (Class 9)



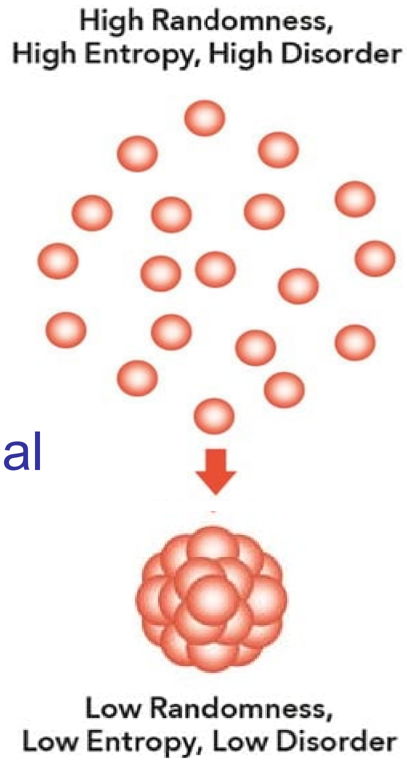
Combined cycles Combined heat & power (Class 8, 11)





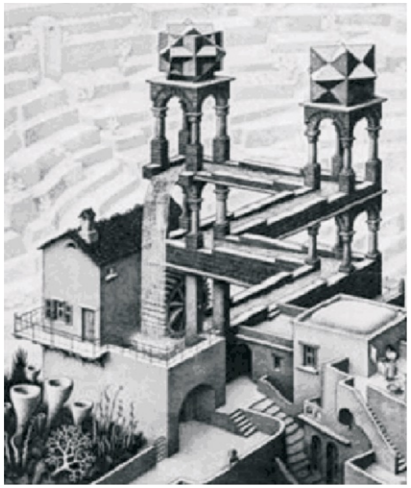
Recapitulate class 5

- **Entropy** (s [kJ/kgK]), is a measure of the randomness, disorder of the energy of a system, it gives information about irreversibility and is used to describe the direction of processes
- The second law of thermodynamics states that actual processes proceed in direction of overall increasing entropy
- Entropy is not conserved, in real processes it increases, entropy is generated: $\delta s_{gen} = ds_{system} + ds_{surroundings} \geq 0$
- Inequality of Clausius: $ds \geq \left(\frac{\delta q_{net}}{T_{out}}\right)_{irrev}$ (= reversible process)
- Heat transfer $\delta q_{net} \leq Tds$, reversible $\delta q_{rev,net} = Tds$
- Gibbs equations $Tds = du + Pdv$ and $Tds = dh - vdP$
- **Isentropic efficiency,** gives information on how close a real device or processes is to an ideal (=optimal) behavior
  - Output producing systems: $\eta_{OUTPUT,S} = \frac{w_{OUT,A}}{w_{OUT,S}}$
  - Input requiring systems: $\eta_{INPUT,S} = \frac{w_{IN,S}}{w_{IN,A}}$

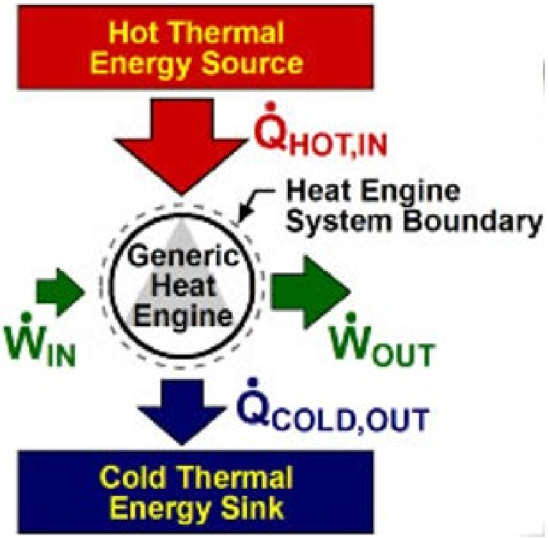


Content class 6

- **Cycles for work, cold and heat, Carnot**
- Processes and devices are combined to make practical cycles (engines / installations)
  1. **Heat power cycles**
  2. **Refrigeration / heat pump cycles**
- The laws of thermodynamics for cycles
- Thermal efficiency of a heat power cycle
- Carnot cycle and Carnot efficiency
- COP of refrigeration and heat pump cycles
- Kelvin-Planck and Clausius statement
- Perpetual - Motion Machines
- **Learning goal:** explain the working of general thermodynamic power and refrigeration cycles

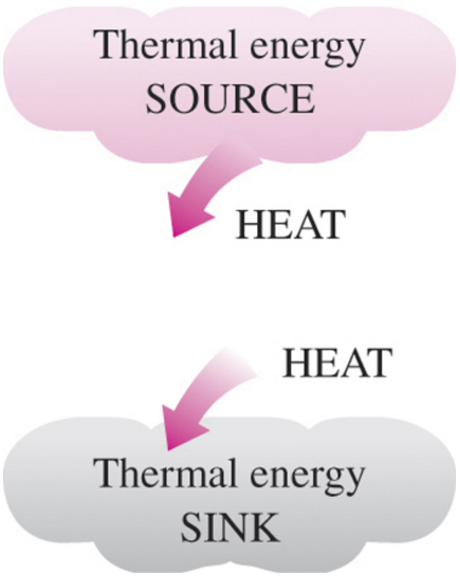


A perpetual – motion machine, an impossible cycle (M.C. Escher)



Thermal energy reservoirs

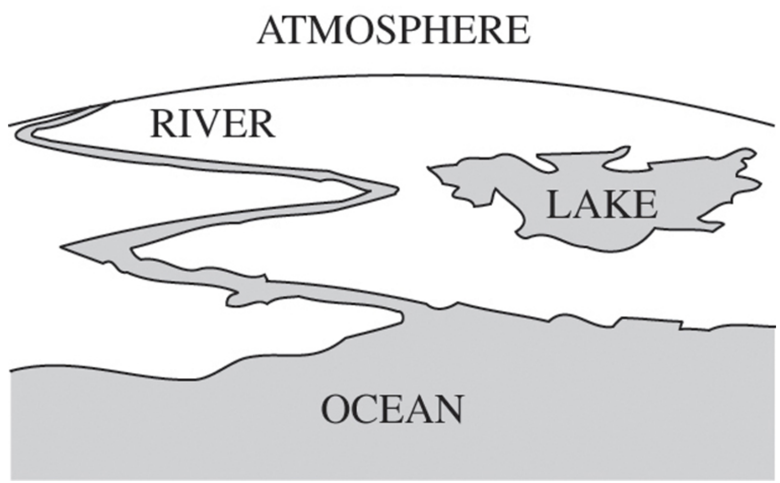
- **Thermal energy reservoir:** a hypothetical body with a relatively large thermal energy capacity (mass *x* specific heat) that can supply (source) or absorb (sink) finite amounts of heat without undergoing any change in temperature



A source supplies energy in the form of heat, and a sink absorbs it

Thermal energy reservoirs

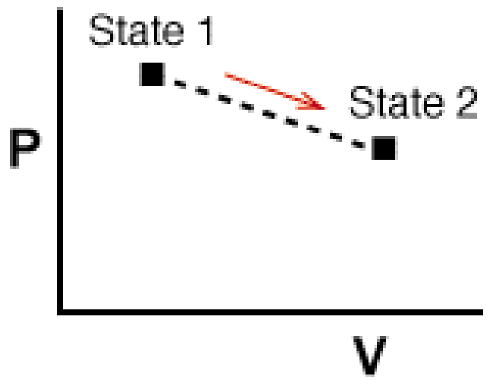
- In practice, large bodies of water such as oceans, lakes, and rivers as well as the atmospheric air can be modeled accurately as thermal energy reservoirs because of their large thermal energy storage capabilities or thermal masses



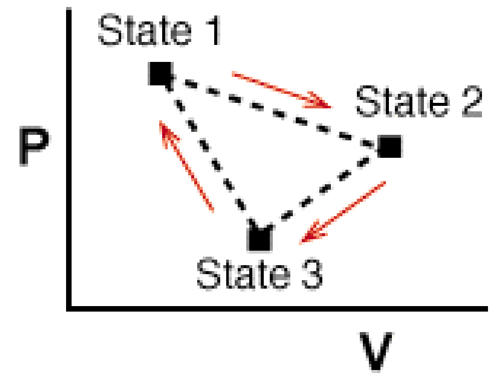
Bodies with relatively large thermal masses can be modeled as thermal energy reservoirs

Thermodynamic cycles

- **Thermodynamic cycle:** series of thermo-dynamic processes where the initial and final states are the same



Not a thermodynamic cycle, no enclosed area, this is a process.



A thermodynamic cycle, closed area.

Thermodynamic cycles

- **Two kind of thermodynamic cycles**

  1. Thermodynamic **power** cycles are used in **heat engines** and produce mechanical power by converting thermal energy from a hot source into work

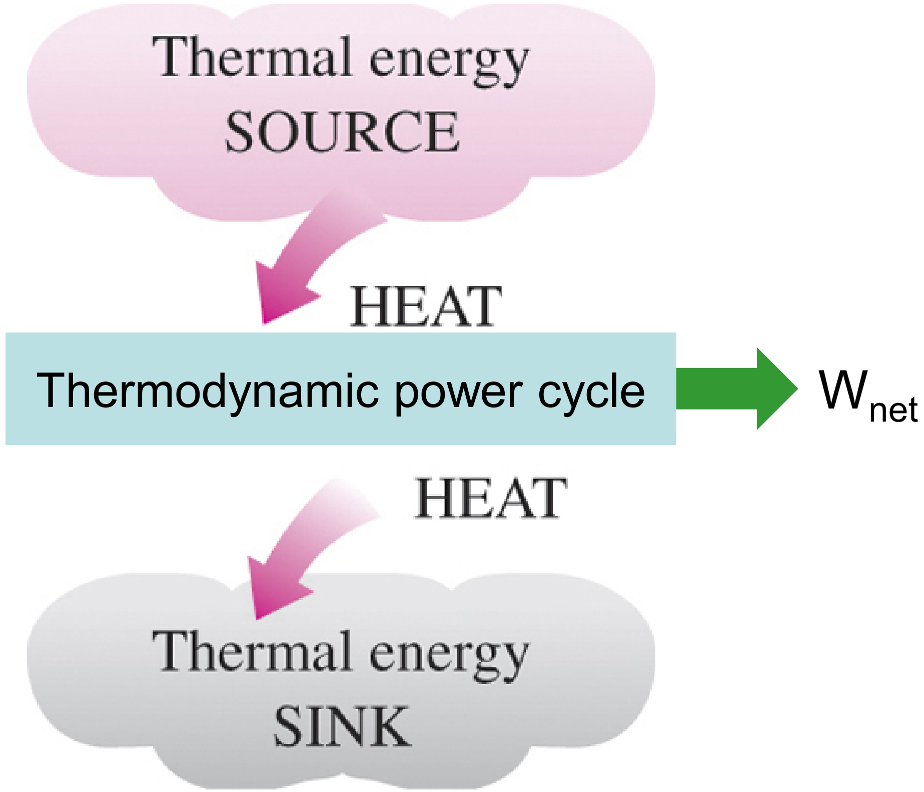
  2. Thermodynamic cycles are also used in refrigerators, air conditioners and heat pumps to **move thermal energy** from a **cold** source to a **hot** sink using power

1: Thermodynamic power cycle

2: Thermodynamic refrigeration cycle

Thermodynamic cycles

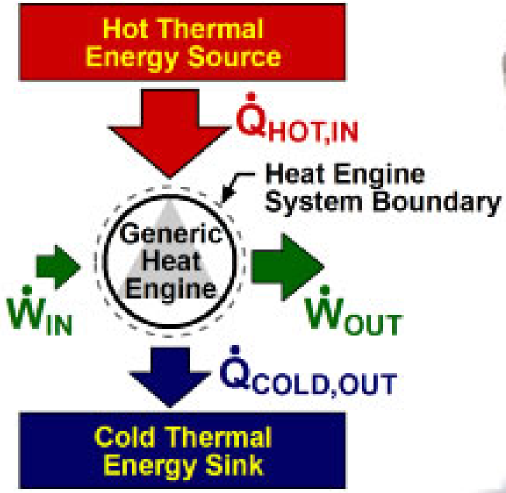
- In a thermodynamic cycle heat (energy) is always transported **between two thermal temperature reservoirs,** a source and a sink



Examples of thermodynamic cycles

1. Examples of thermodynamic power cycles

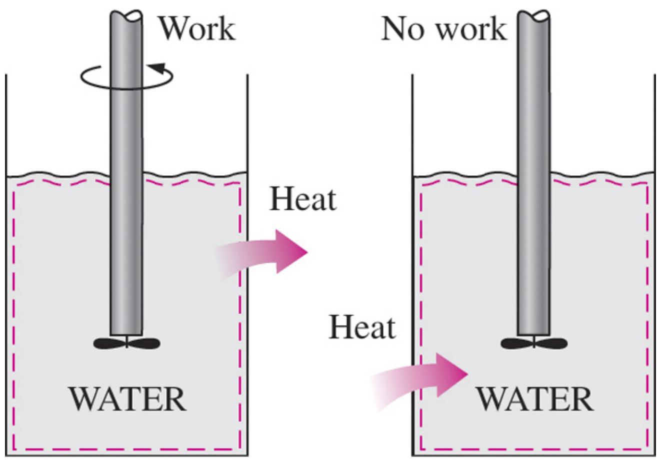
- Steam power plants
- Steam machines
- Gas turbines
- Diesel engines
- Gasoline engines
- Turbo jet engines



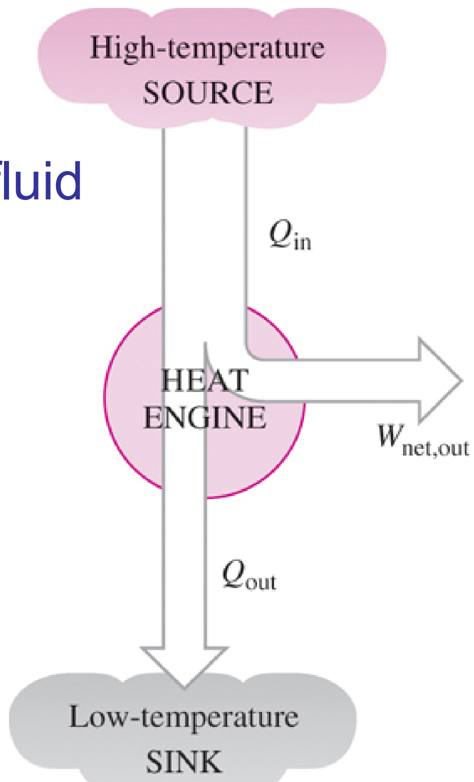
ThermoNet: Wiley

Power cycles / Heat engines

- A **heat engine** is the devices that converts heat to work
  1. It receives heat from a high-temperature thermal source (solar energy, oil furnace, nuclear reactor, geothermal etc.)
  2. Is converts part of this heat to work (often in the form of a rotating shaft)
  3. Is rejects the remaining waste heat to a low-temperature thermal sink (the atmosphere, rivers, etc.)
  4. It operates on a cycle, that usually involves a fluid to and from which heat is transferred while undergoing a cycle, this fluid is called the working fluid



Work can always be converted to heat directly and completely, but the reverse is not true

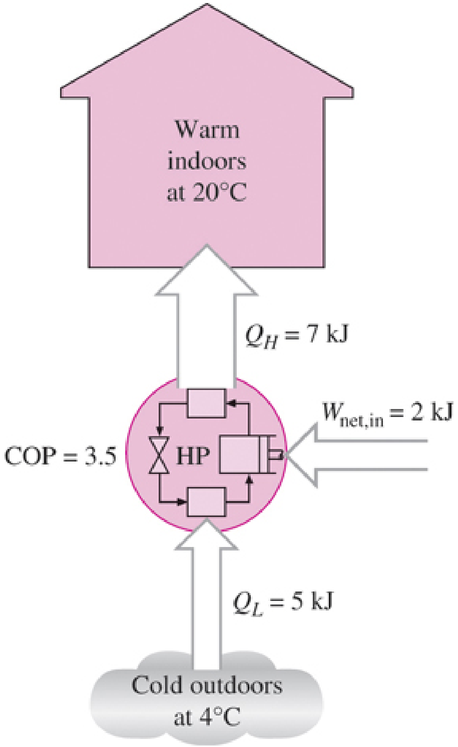


Part of the heat received by a heat engine is converted to work, while the rest is rejected to a sink

Examples of thermodynamic cycles

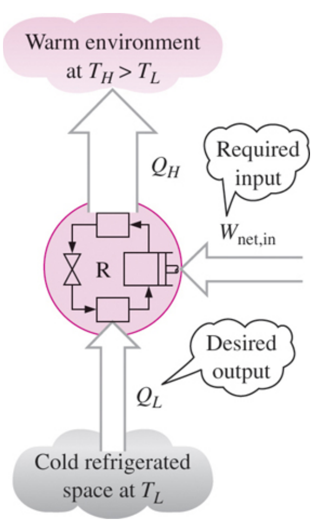
2. Thermodynamic refrigeration cycles and heat pumps

- Air conditioners
- Refrigerators
- Chillers
- Heat pumps

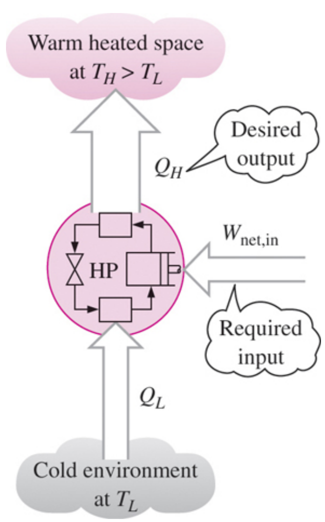


Refrigerators and heat pumps

- A **refrigerator or heat pump** is a device that transfers heat from a cold space to a warm environment
  1. Receives heat (cold) from a low-temperature thermal source
  2. Uses work to transport this heat
  3. Rejects heat to high-temperature thermal sink
  4. Heat transferred by working fluid in cyclic process
  5. Working fluid → refrigerant
  6. Vapor-compression refrigeration

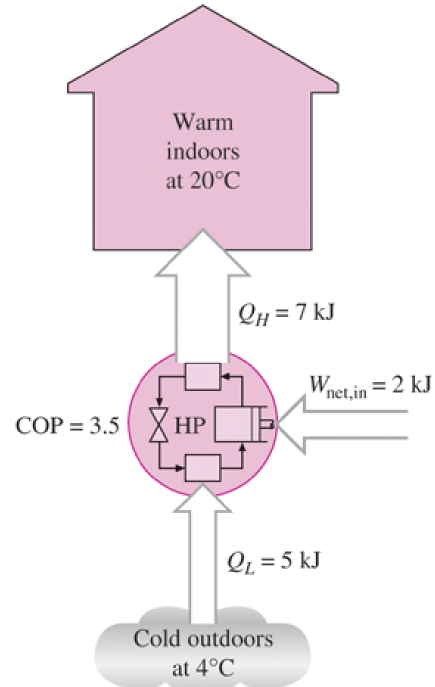


Refrigerator (R)



Heat pump (HP)

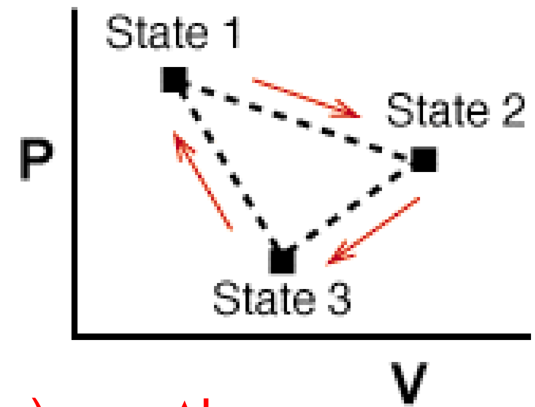
The objective of a refrigerator is to remove Q_L from the cooled space. The objective of a heat pump is to supply heat Q_H into the warmer space.



The work supplied to a heat pump is used to extract energy from the cold outdoors and carry it into the warm indoors.

First law for cycles

- **Conservation of energy for a cycle (first law)**
- Change in any thermodynamic property (e.g. T, P, v, s, u, h) over a cycle = 0



- First law for closed systems

  $du = \delta q - \delta w$ or $\Delta u = q_{net} - w_{net}$
- First law for open system

  $q_{in} + w_{in} + (h + ke + pe)_{in} = q_{out} + w_{out} + (h + ke + pe)_{out}$ or $\Delta h = q_{net} - w_{net}$

- First law applied to a cycle (recall for a cycle: $\Delta u = \Delta h = \Delta ke = \Delta pe = 0$, state functions)

$$\oint(\delta q_{in} - \delta q_{out}) + \oint(\delta w_{in} - \delta w_{out}) =$$
$$q_{in} - q_{out} + w_{in} - w_{out} = \oint de_{cm} = 0$$

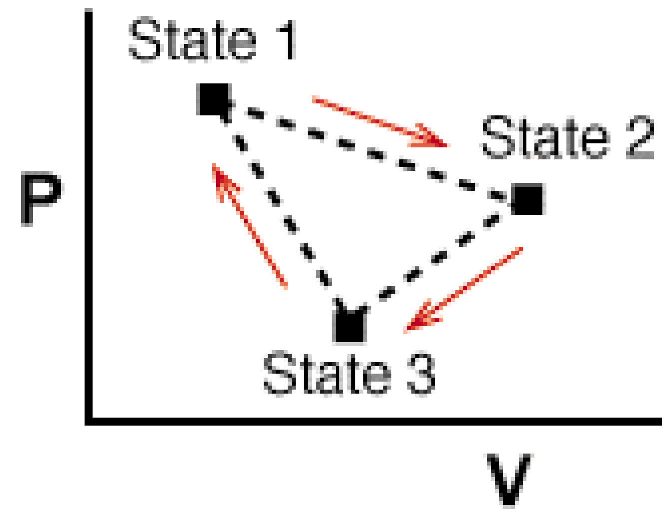
$\oint$ = cyclic integral = integral over a closed circle

- For all complete thermodynamic cycles

$$q_{in} - q_{out} = w_{out} - w_{in} \rightarrow q_{net} = w_{net}$$

Second law for cycles

- Generation of entropy (second law) for a cycle
- Recall $(\Delta s)_{cycle} = 0$ (**s** is a state function, its value depends only on the state and not on the path followed



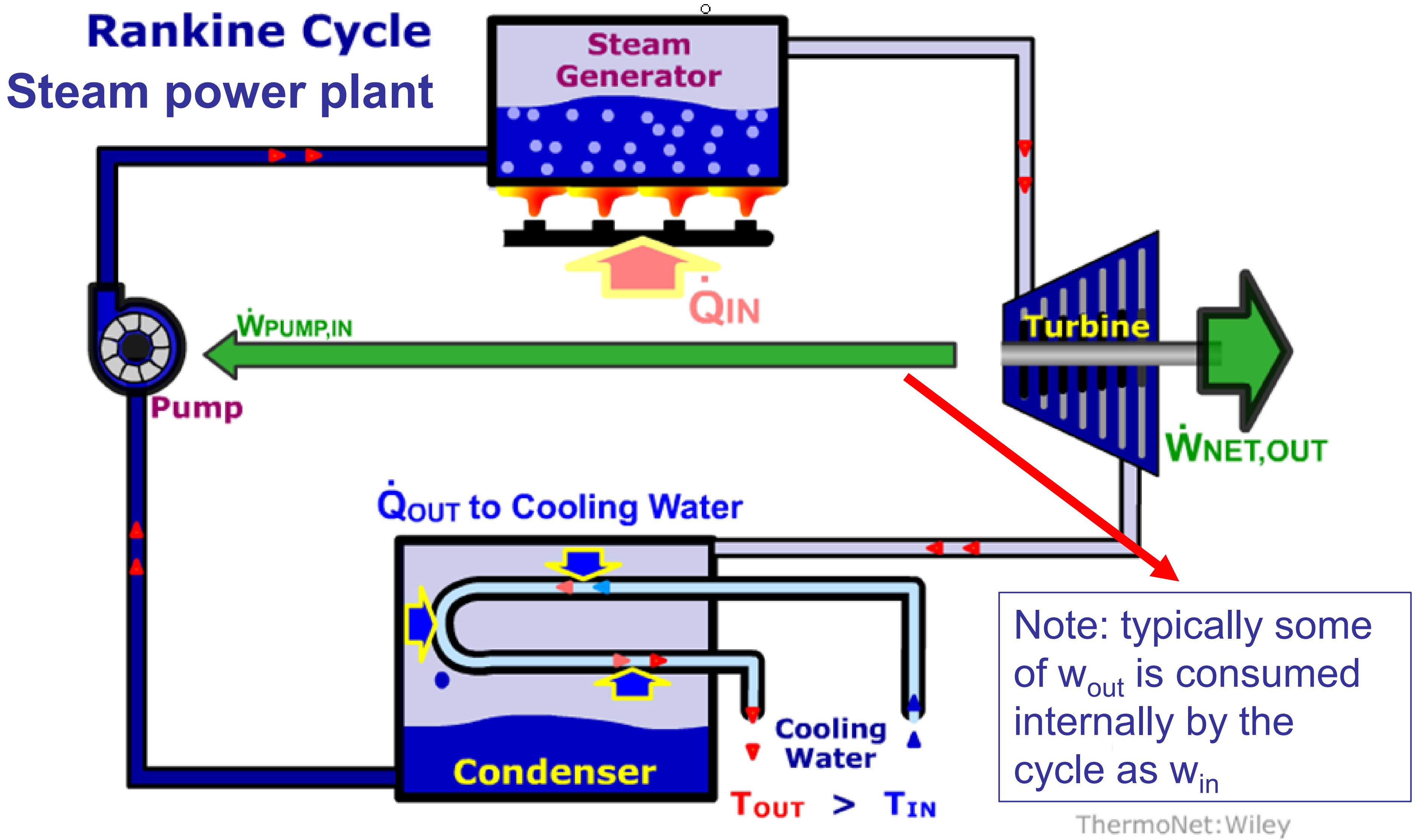
- **Entropy,** $\frac{\delta q_{net}}{T} \leq ds$, applied to a cycle:

$$\oint \sum_{i=1}^{n} \frac{\delta q_{net,i}}{T_i} = \sum_{i=1}^{n} \oint \frac{\delta q_{net,i}}{T_i} = \sum_{i=1}^{n} \frac{q_{net,i}}{T_i} \leq \oint ds_{cm} = 0$$

- **Second law** for a complete cycle: $\sum_{i=1}^{n} \frac{\delta q_{net,i}}{T_i} \leq 0$ or $\oint \frac{\delta q_{net,i}}{T_i} \leq 0$

- The net entropy of all heat transfer processes in a cycle should increase

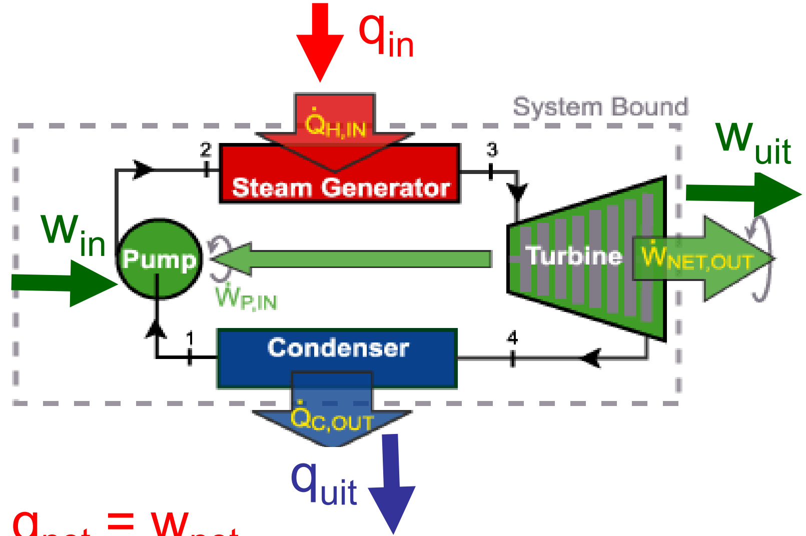
Example: 1st & 2nd law for cycle



Note: typically some of w_{out} is consumed internally by the cycle as w_{in}

Example: 1st & 2nd law for cycle

- Consider the steam cycle (see class 7)
- Energies in and out (see class 7)
  - w_{in} = 1 kJ/kg
  - q_{in} = 3182 kJ/kg at $T_{in} \cong 311°C$
  - w_{out} = 1000 kJ/kg
  - q_{out} = 2183 kJ/kg at T_{uit} = 45°C



- Check the first law: $q_{in} - q_{out} = w_{out} - w_{in} \rightarrow q_{net} = w_{net}$

$$\left.\begin{aligned} q_{net} &= q_{in} - q_{out} = 3182 - 2183 = 999 \text{ kJ/kg} \\ w_{net} &= w_{out} - w_{in} = 1000 - 1 = 999 \text{ kJ/kg} \end{aligned}\right\} \rightarrow q_{net} = w_{net} \rightarrow \text{Right !}$$

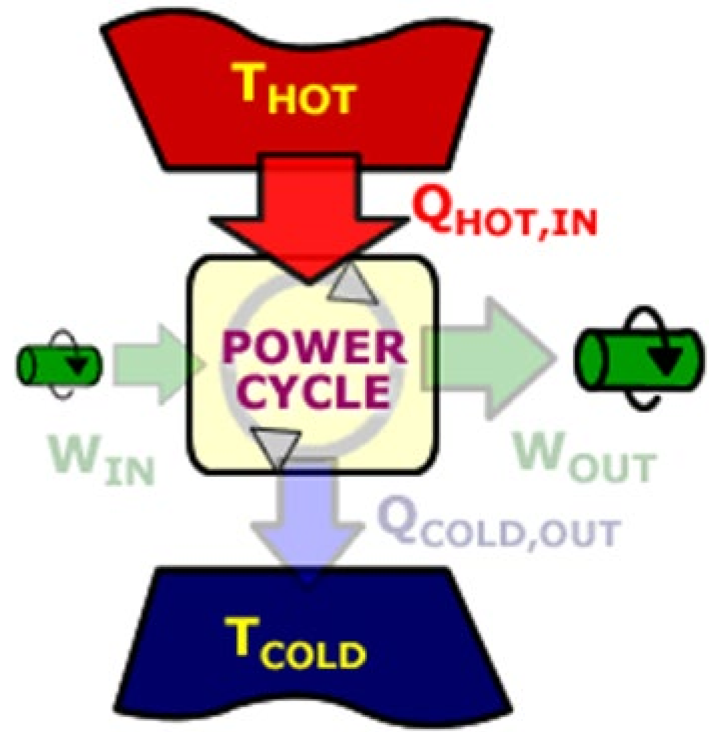
- Check the second law: $\sum_{i=1}^{n} \frac{q_{net,i}}{T_i} \leq 0$ (Clausius inequality: $\frac{\delta q_{net}}{T} \leq ds$)

$$\sum_{i=1}^{n} \frac{q_{net,i}}{T_i} = \underbrace{\frac{q_{in}}{T_{in}} - \frac{q_{out}}{T_{out}}}_{ds_{in} - ds_{out}} = \frac{3185}{584} - \frac{2183}{318} = 5.45 - 6.86 = -1.41 \; kJ/kgK \leq 0 \; kJ/kgK \rightarrow \text{Right !}$$

- Both laws are valid for this cycle 1: energy is conserved ($e_{in} = e_{out}$)
  2: entropy is created ($ds_{out} > ds_{in}$)

Thermodynamic power cycle efficiency

- **Power cycle efficiency**, also called:
  - Heat engine efficiency (η_{he})
  - Thermal efficiency (η_{th})
  - Cycle efficiency
  - Thermodynamic efficiency



ThermoNet: Wiley

- Defined as

$$\eta_{he} = \eta_{th} = \frac{What\ we\ want}{What\ we\ pay\ for}$$

$$\eta_{he} = \eta_{th} = \frac{w_{out} - w_{in}}{q_{in}} = \frac{q_{in} - q_{out}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}}$$

- Note: the efficiency is only 100% if $q_{out} = 0$, which is impossible! see later

Carnot cycle

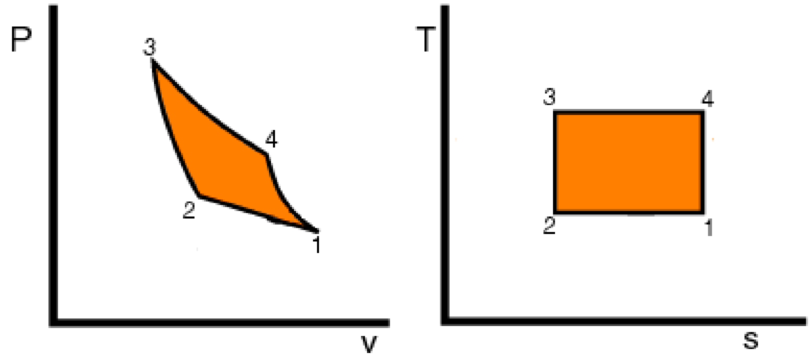
- Real processes generate entropy and therefore are irreversible
- The most efficient processes are reversible processes which are only possible in theory
- Isentropic efficiencies compare real processes to reversible (ideal) processes
- Analogue, real cycles generate entropy and are therefore irreversible
- Analogue, irreversible real cycles are compared to reversible ideal cycles to determine how closely a real cycle approaches its theoretical efficiency
- Not all reversible cycles have the same maximum efficiency, it depends on the temperatures
- The cycle with the highest possible efficiency is the **Carnot Power Cycle**
- Developed by Sadi Carnot (1796 – 1832)

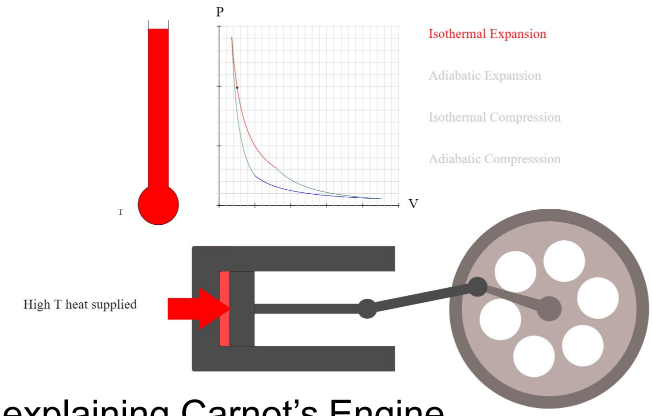
Sadi Carnot

Carnot power cycle

- The **Carnot cycle** is a completely reversible cycle that is only possible in theory (δs_{gen} = 0 for all processes)
- It sets a limit for actual cycles; the efficiency of a real cycle cannot be higher than the Carnot efficiency

- The Carnot cycle consists out of 4 reversible processes:
  - 1 → 2 Isothermal compression (dT = 0)
  - 2 → 3 Isentropic (adiabatic & reversible) compression (ds = 0)
  - 3 → 4 Isothermal expansion (dT = 0)
  - 4 → 1 Isentropic (adiabatic & reversible) expansion (ds = 0)



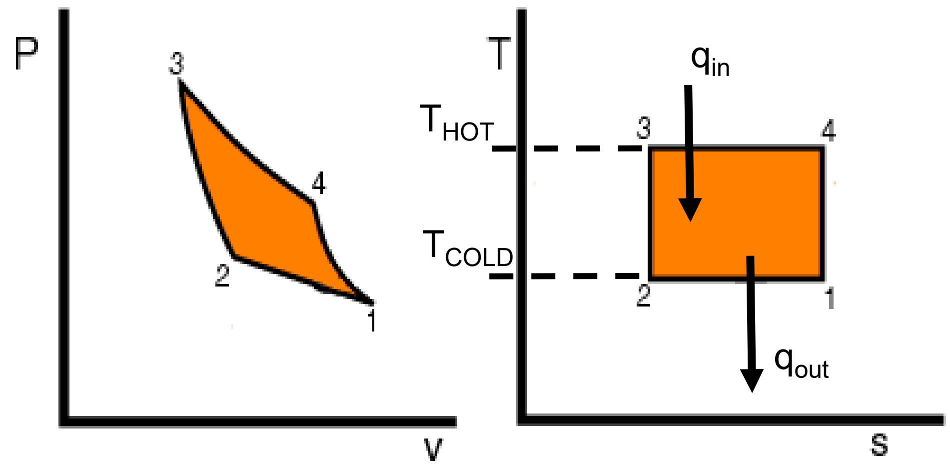


Movie explaining Carnot's Engine

http://galileoandeinstein.phys.virginia.edu/more_stuff/Applets/carnot_cycle/carnot_cycle.html

Carnot power cycle

- The **Carnot Power Cycle** consists of **two isentropic** & **two isothermal** processes
- A gas undergoing a Carnot cycle in a piston-cylinder device undergoes the following reversible processes

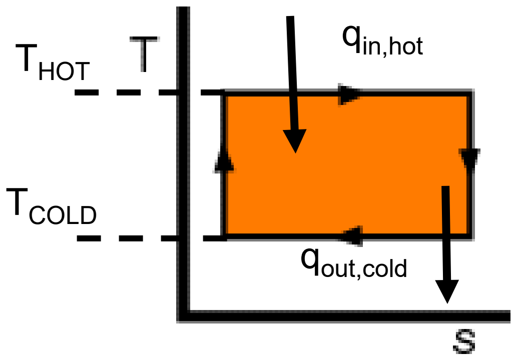


Pv and Ts diagram of a Carnot cycle

- Process 1-2: **Isothermal compression** with heat transfer to a cold thermal reservoir at T_{cold} (W_{in} > 0, Q_{out} > 0 and T_{cold} = constant)
- Process 2-3: **Isentropic compression** causing the temperature of the gas to increase from T_{cold} to T_{hot} (W_{in} > 0, Q = 0 and s = constant)
- Process 3-4: **Isothermal expansion** with heat transfer from a hot thermal reservoir at T_{hot} (W_{out} > 0, Q_{in} > 0 and T_{hot} = constant)
- Process 4-1: **Isentropic expansion** causing the temperature of the gas to decrease from T_{hot} to T_{cold} (W_{out} > 0, Q = 0 and s = constant)

Carnot power cycle

- Consider the **Carnot cycle** where
  - All q_{in} occurs at T_{hot} ($q_{in,hot}$)
  - All q_{out} occurs at T_{cold} ($q_{out,cold}$)



- **Second law**
  - Reversible (ideal / theoretical) cycle

$$\sum_{i=1}^{2} \frac{q_{net,i}}{T_i} = \frac{q_{in,hot}}{T_{hot}} - \frac{q_{out,cold}}{T_{cold}} = 0 \quad \rightarrow \quad \frac{q_{out,cold}}{q_{in,hot}} = \frac{T_{cold}}{T_{hot}}$$

  - Irreversible (real) cycle

$$\sum_{i=1}^{2} \frac{q_{net,i}}{T_i} = \frac{q_{in,hot}}{T_{hot}} - \frac{q_{out,cold}}{T_{cold}} < 0 \quad \rightarrow \quad \frac{q_{out,cold}}{q_{in,hot}} > \frac{T_{cold}}{T_{hot}}$$

- For any real power cycle, 2nd Law requires $q_{out,cold} > 0$ for $T_{cold} > 0$ K $\rightarrow$ always a cold thermal reservoir is required in addition to the hot thermal reservoir

Carnot power cycle

- $\frac{q_{out,cold}}{q_{in,hot}} \geq \frac{T_{cold}}{T_{hot}}$ places an upper limit on heat engine efficiency or thermal efficiency

$$\eta_{he} = \frac{w_{out} - w_{in}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}} \leq 1 - \frac{T_{cold}}{T_{hot}}$$

- **Carnot efficiency**: Maximum efficiency for any power cycle operating between T_{hot} and T_{cold}

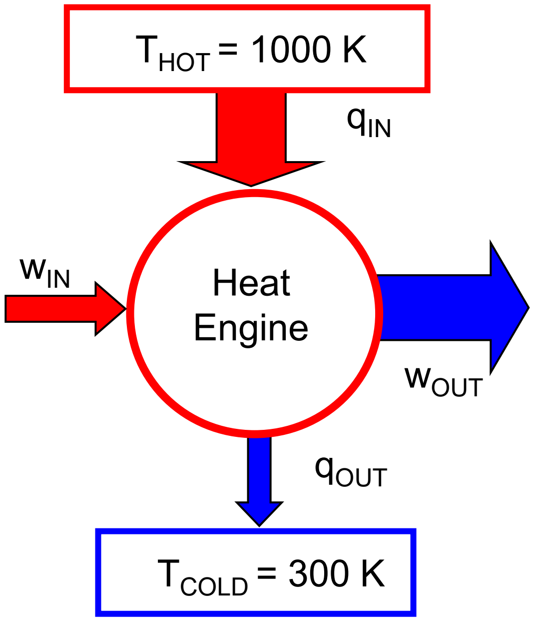
$$\boxed{\eta_{carnot} = 1 - \frac{T_{cold}}{T_{hot}}}$$

- The higher T_{hot} or the lower T_{cold} the higher the efficiency that can be achieved

  $\eta_{carnot} \rightarrow$ 1 (100%) as T_{cold} = 0 Kelvin or as $T_{hot} \rightarrow$ Infinite

Carnot cycle: example

- A Carnot engine operates between a source at 1000 K and a sink at 300 K. If the heat engine is supplied with heat at a rate of 600 kJ/min determine
  1. The thermal efficiency
  2. The net power output



- **Solution:**

T_{hot} = 1000 K, T_{cold} = 300 K, $\dot{Q}_{IN}$ = 600 kJ/min

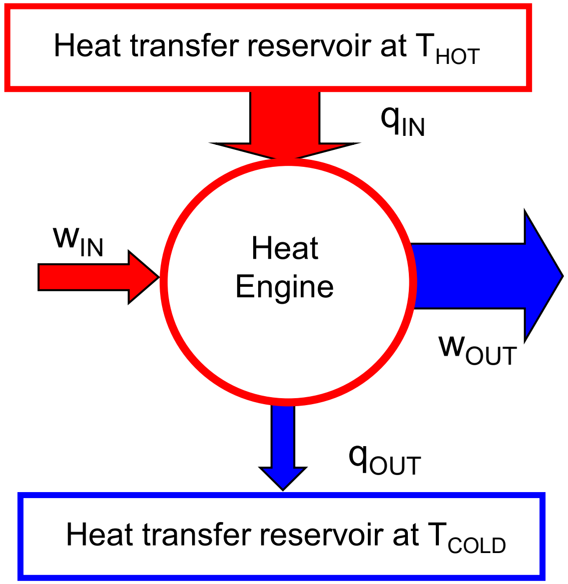
1. $$\eta_{Carnot} = \eta_{he} = 1 - \frac{T_{cold}}{T_{hot}} = 1 - \frac{300}{1000} = 0.7 \rightarrow 70\%$$

2. $$\eta_{he} = \frac{\dot{W}_{out} - \dot{W}_{in}}{\dot{Q}_{in}} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} \rightarrow \dot{W}_{net} = \eta_{he}\dot{Q}_{in} \rightarrow \dot{W}_{net} = 0.7\frac{600}{60} = 7 \text{ kW}$$

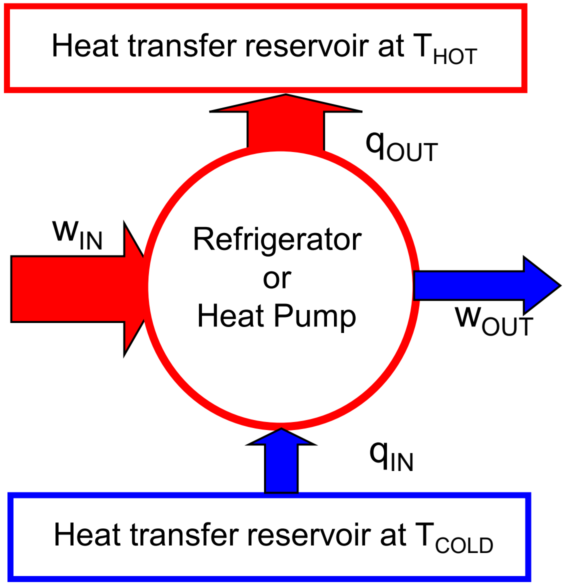
- 70% of the 10 kW input heat is converted to work (7 kW) in reality it will be only around half of this due to irreversibility's

Compare heat engine and refrigeration cycle

- The purpose of a **heat engine (power cycle) is to convert heat from a hot thermal reservoir into power** (and it should rejects some heat to a cold reservoir)
- In **refrigeration cycles power is used to transport heat from a cold to a hot place** (opposite to the natural direction)
- Refrigeration cycles have reversed energy flows compared to the heat engine
  - Refrigerator
  - Heat pump
- Often $w_{out} = 0$
- Note **always two temperature reservoirs, flow direction reversed**



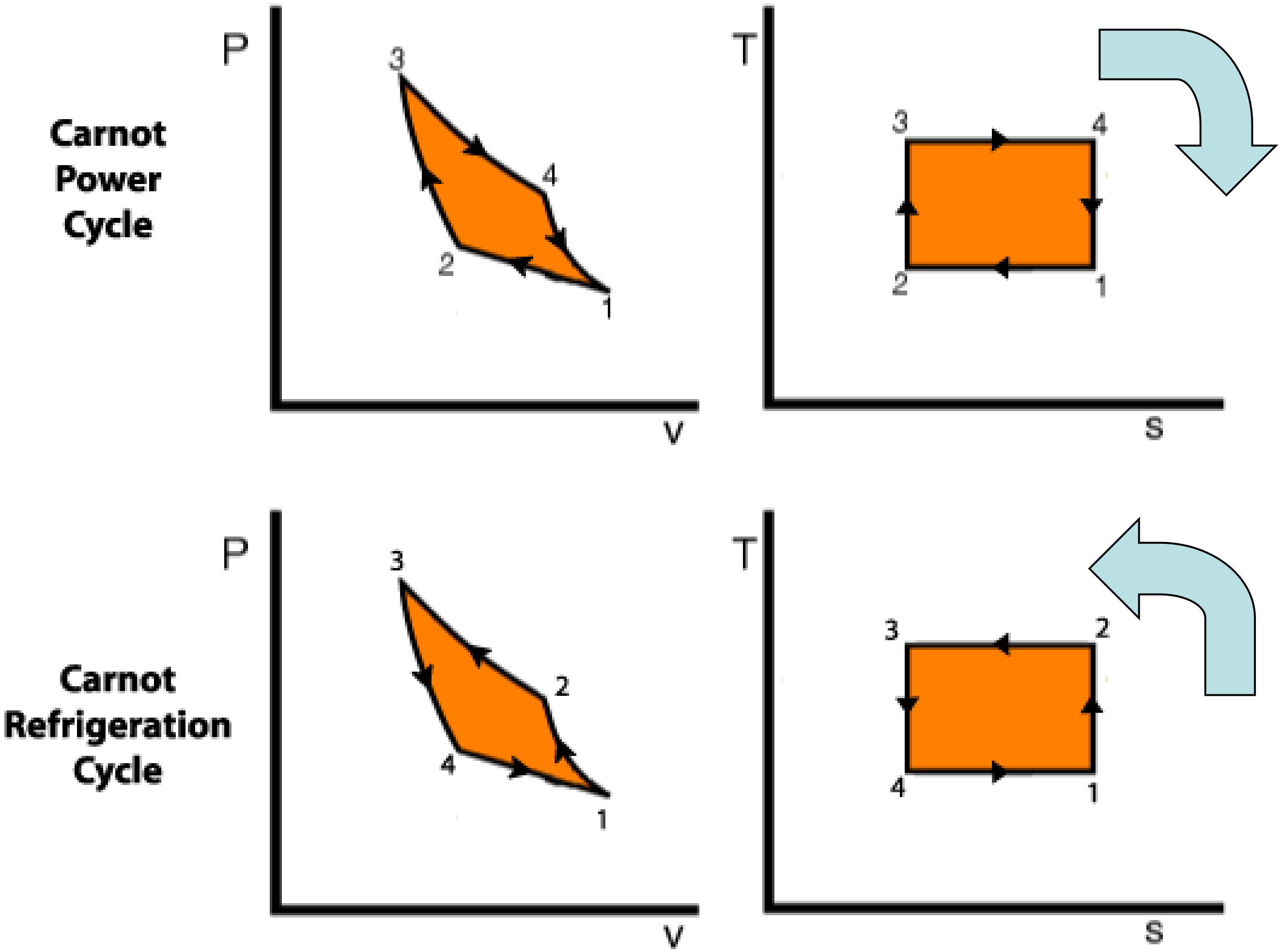
Heat Engine



Refrigerator or Heat pump

Refrigeration and Heat Pump Cycles

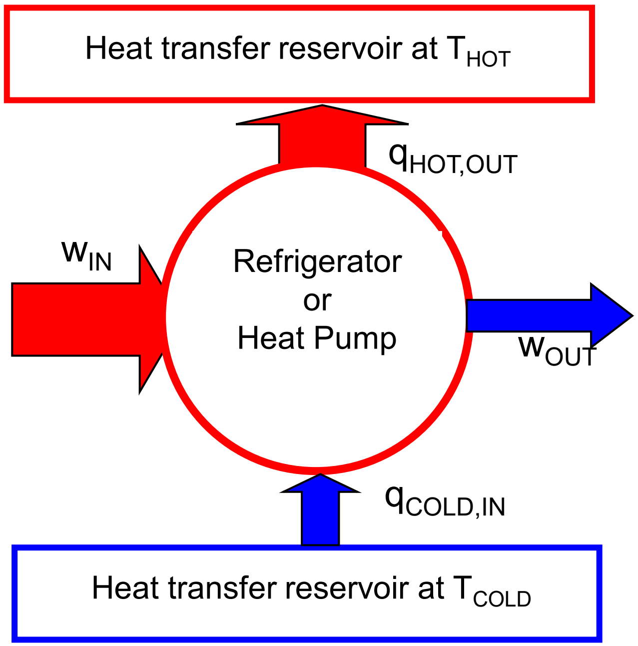
- Reverse Carnot Power Cycle → Carnot Refrigeration Cycle



Pv and Ts diagram of a Carnot Power Cycle and a Carnot Refrigeration Cycle
Note the direction of the cycle is reversed, arrows go the other way around

Coefficient of Performance (COP)

- Coefficient of performance says how good a device is
  - A better system has a higher COP
  - COP can be larger than 1



- Air conditioning, refrigeration and chiller cycle
- Assume $w_{out} = 0$ (typical)

$$\eta_{he} = \frac{What\ we\ want}{What\ we\ pay\ for}$$

- We want q_{cold} and we pay for the power w_{in}

$$COP_{ref} = \frac{q_{cold,in}}{w_{in}} = \frac{q_{cold,in}}{q_{hot,out} - q_{cold,in}} = \frac{1}{\frac{q_{hot,out}}{q_{cold,in}} - 1}$$

Coefficient of Performance (COP)

- For a heat pump cycle the COP is a bit different as the goal of the heat pump cycle is to heat while it for the refrigeration cycle is to cool, here we want $q_{hot,out}$ (instead of $q_{cold,in}$) and still pay w_{in}
- Assume again $w_{out} = 0$ (typical)

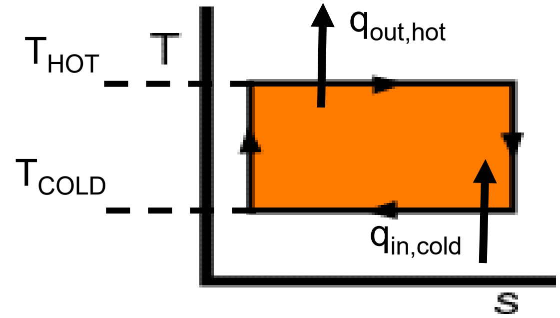
$$COP_{hp} = \frac{q_{hot,out}}{w_{in}} = \frac{q_{hot,out}}{q_{hot,out} - q_{cold,in}} = \frac{1}{1 - \frac{q_{cold,in}}{q_{hot,out}}}$$

- Same cycle used for refrigeration and heat pump
- Relation between $(COP)_{hp}$ and $(COP)_{ref}$

$$COP_{hp} - COP_{ref} = \frac{q_{hot,out}}{q_{hot,out} - q_{cold,in}} - \frac{q_{cold,in}}{q_{hot,out} - q_{cold,in}} = 1$$

Maximum $(COP)_{REF}$ and $(COP)_{HP}$

- **2nd Law for any cycle where**
  - All q_{in} occurs at T_{cold} ($q_{in,cold}$)
  - All q_{out} occurs at T_{hot} ($q_{out,hot}$)



$$\sum_{i=1}^{2} \frac{q_{net,i}}{T_i} = \frac{q_{in,cold}}{T_{cold}} - \frac{q_{out,hot}}{T_{hot}} \leq 0 \quad \rightarrow \quad \frac{q_{in,cold}}{q_{out,hot}} \geq \frac{T_{cold}}{T_{hot}}$$

- **Carnot COP for refrigeration, air conditioning, chillers**

$$COP_{ref} = \frac{1}{\frac{q_{out}}{q_{in}} - 1} \leq \frac{1}{\frac{T_{hot}}{T_{cold}} - 1} \qquad COP_{ref,Carnot} = \frac{1}{\frac{T_{hot}}{T_{cold}} - 1}$$

- **Carnot COP for heat pumps**

$$COP_{hp} = \frac{1}{1 - \frac{q_{in}}{q_{out}}} \leq \frac{1}{1 - \frac{T_{cold}}{T_{hot}}} \qquad COP_{hp,Carnot} = \frac{1}{1 - \frac{T_{cold}}{T_{hot}}}$$

Maximum $(COP)_{REF}$ for Refrigerator

- What is the maximum COP for a refrigerator and for a fridge?
- **Solution:**
- The maximum $(COP)_{ref}$ is given by the Carnot $(COP)_{ref,Carnot}$

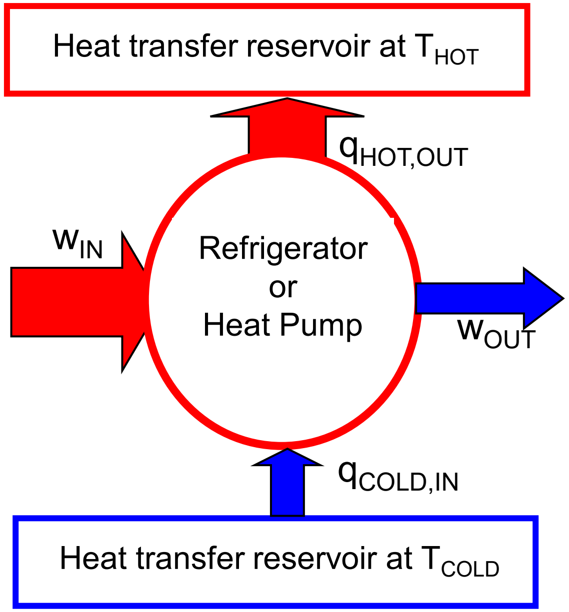
$$COP_{ref,Carnot} = \frac{1}{\frac{T_{hot}}{T_{cold}} - 1}$$

- T_{cold} is temperature inside the refrigerator or the fridge
- T_{hot} is temperature in the kitchen
- Assume T_{hot} = 293K
  $T_{cold,ref}$ = 277K, $T_{cold,fridge}$ = 253K

$$COP_{ref,Carnot} = \frac{1}{\frac{293}{277} - 1} = 17.3 \qquad COP_{fridge,Carnot} = \frac{1}{\frac{293}{253} - 1} = 6.3$$

- Small changes in temperature have a large influence on the COP
- In reality the COP will be much lower (about 4 for a refrigerator)

Kitchen



Refrigerator Inside

Second law statements revisited

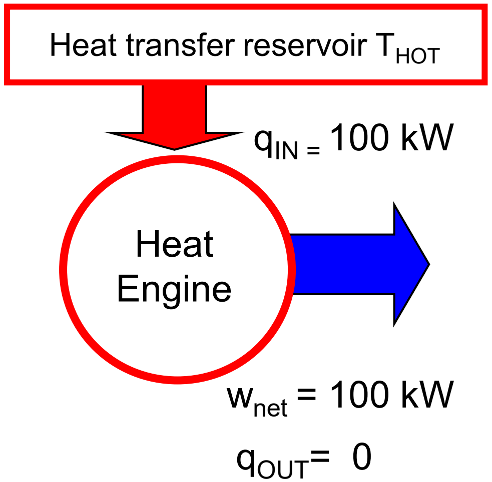
- **Kelvin - Planck Statement**
  - It is impossible to construct an engine that, operating continuously, will produce no effect other than the extraction of heat from a single reservoir and the performance of an equivalent amount of work

- **Clausius Statement**
  - It is impossible to construct an engine that, operating continuously, will produce no effect other than the transfer of heat from a cooler to a hotter body

- The Kelvin – Planck and the Clausius statement are both alternative formulations of the second law of thermodynamics
- The second law states that entropy should increase in real processes, in a power cycle this is only possible if heat is rejected to a cold reservoir as the Kelvin – Planck statement states, this is the fundamental reason that the efficiency of the power engine never can be 100%
- The Clausius statement states the heat cannot flow spontaneously from cold to hot, this is also due to fact that the entropy should increase

Kelvin-Planck statement

- A heat engine that violates the Kelvin- Planck statement of the second law as there is only one heat reservoir and no heat transfer to a low temperature reservoir
- The thermal efficiency of a heat engine can never be 100% as there must be heat transfer from a high to a low temperature reservoir
- The maximum efficiency is the Carnot efficiency and depends on T_{hot} and T_{cold}
- The impossibility of having 100% efficiency is **not** due to friction or dissipative effects, its limitation applies to real and ideal engines



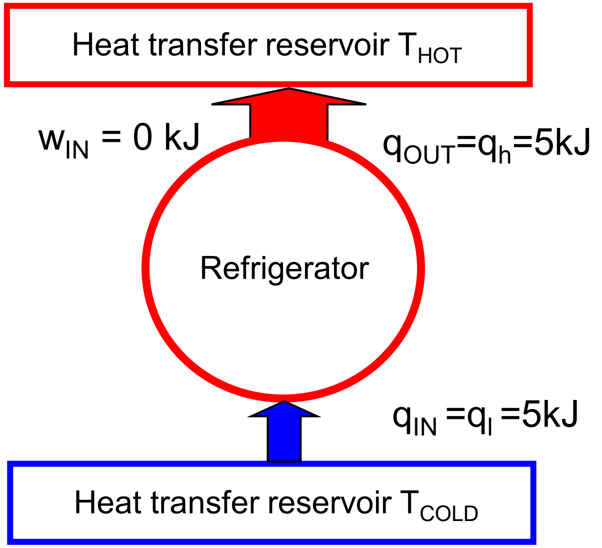
$$\eta_{he} = \frac{w_{out} - w_{in}}{q_{in}}$$

$$= 1 - \frac{q_{out}}{q_{in}}$$

The efficiency is 100% if q_{out} = 0 in violation with the Kelvin – Planck statement

Clausius statement

- A refrigerator that violates the Clausius statement of the second law as there is no work input required to transfer heat from a low temperature reservoir to a high temperature reservoir



- Note heat can flow from cold to hot but only if power is applied (like in a fridge)

- Both the Kelvin – Planck and the Clausius statement of the second law are negative statements which can not be proved

If W_{in} would be 0 kJ the performance would be infinite

$$COP_{ref} = \frac{Q_{in}}{W_{in}} = \frac{5}{0} \to \infty$$

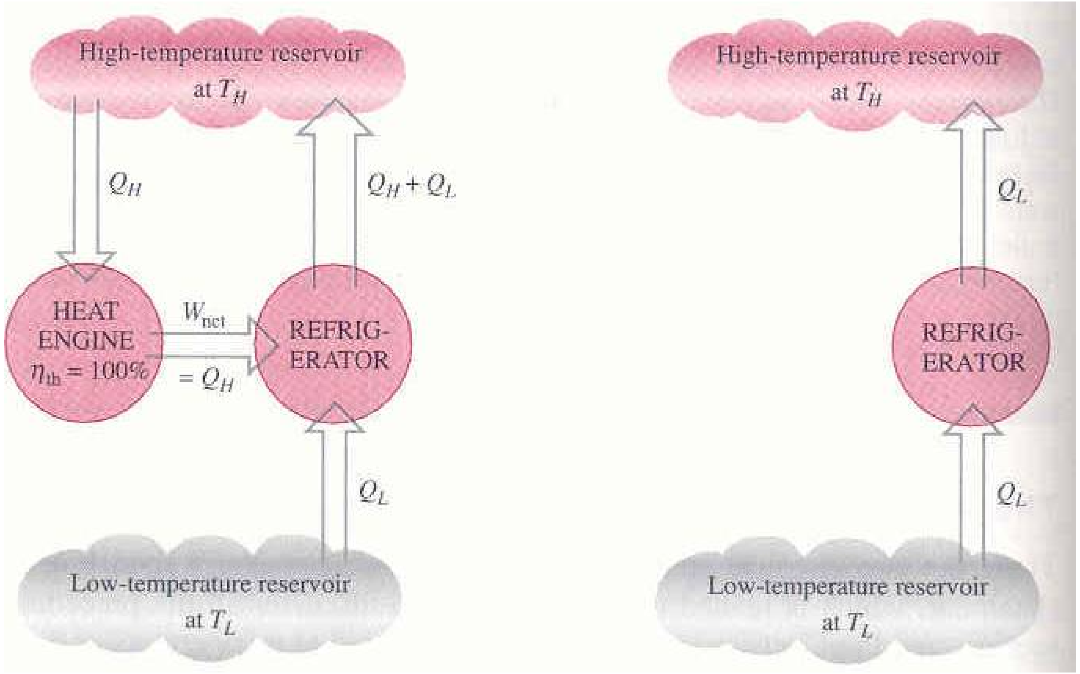
- The second law is based on experimental observations

- Till now no experiment has been conducted that contradicts the second law (even Maxwells Demon cannot violate the 2^{nd} law)

Equivalence: Kelvin-Planck and Clausius statement

- Either expression can be used as the expression of the second law
- A heat engine with 100% efficiency (violation of the Kelvin Planck statement) powers a refrigerator
- The engine receives Q_H from T_H and converts it completely into power $Q_H = W_{net,he} = W_{in,ref}$

- The refrigerator losses energy to T_H equal to $W_{in} + Q_L = Q_H + Q_L$
- During the process T_H receives a net amount of heat of Q_L
- The combination can be seen as a refrigerator that transfers Q_L from T_L to T_H without requiring input (violation of the Clausius statement)



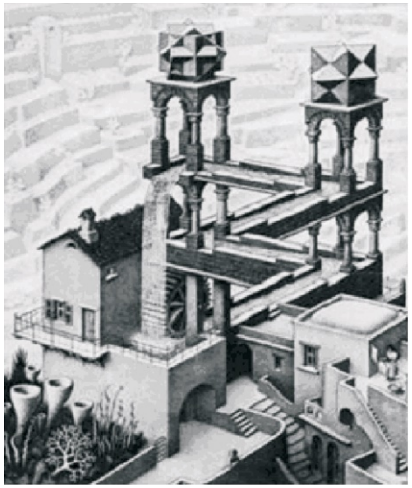
A refrigerator powered by a 100% efficient heat engine (left) and its equivalent refrigerator (right)

Perpetual - Motion machines

- A process can not take place unless it satisfies **both the first and the second** laws of thermodynamics

- Any device that violates either law is called **a perpetual – motion machine** (perpetuum mobile Latijn: Voortdurend (of eeuwig) bewegend)
  - A device that violates the first law (by creating energy) is called **a perpetual – motion machine of the first kind**
  - A device that violates the second law (no rejection of Q_{out}) is called **a perpetual – motion machine of the second kind**

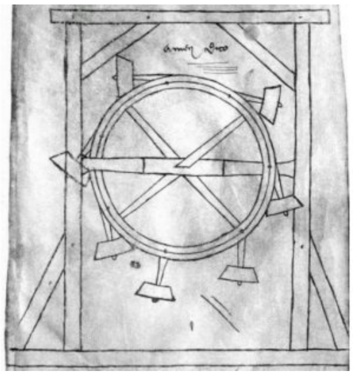
- Despites numerous attempts, no perpetual – motion machine is known to have worked
- But this never stopped inventors from trying to create new ones (see examples next pages)



A perpetual – motion machine, an impossible cycle (M.C. Escher)

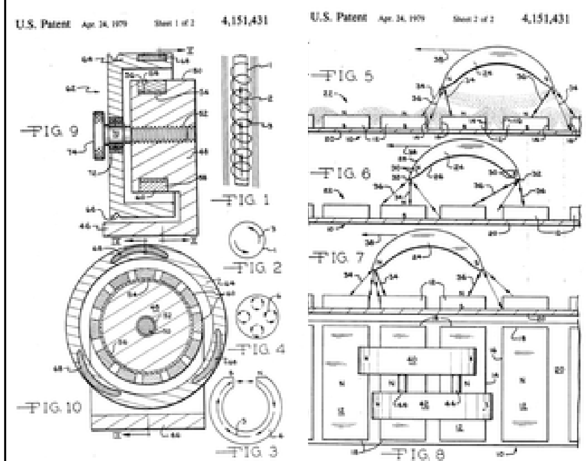
Perpetual - Motion machines: examples

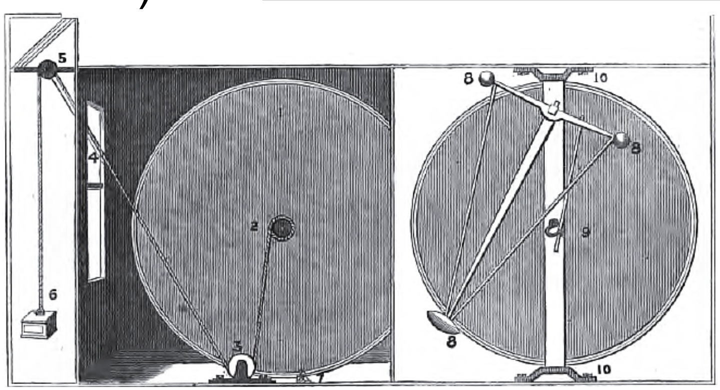
- **Inventors will never stop try to create new perpetual motion machines**



Perpetuum Mobile of Villard de Honnecourt (about 1230)

Howard R. Johnson, U.S. Patent 4.151.431



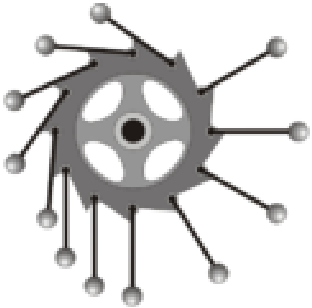


Orffyreus Wheel, designed by Johann Bessler

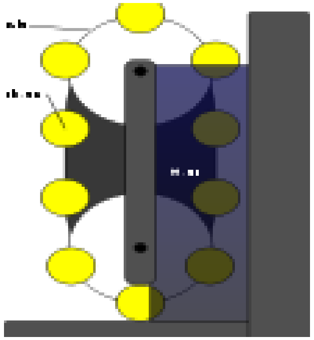
Robert Fludd's 1618 "water screw" perpetual motion machine from a 1660 woodcut. This device is widely credited as the first recorded attempt to describe such a device in order to produce useful work - driving millstones

Perpetual - Motion Machines: examples

- **Inventors will never stop try to create new perpetual motion machines**



The "Overbalanced Wheel" it was thought that the metal balls on the right side would turn the wheel because of the longer lever arm, but since the left side had more balls than the right side, the torque was balanced and the perpetual movement could not be achieved.

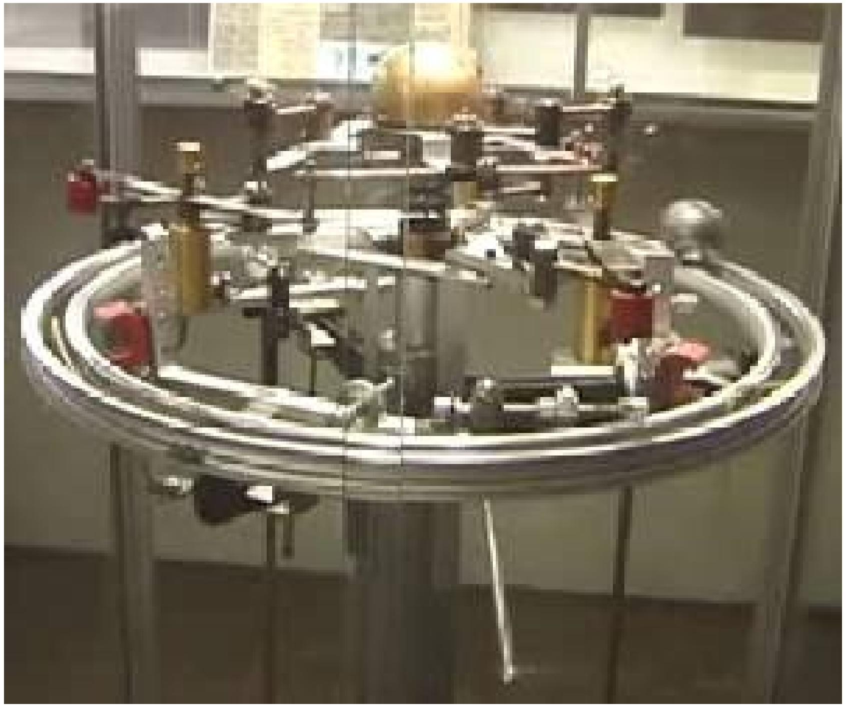


The "Float Belt" the yellow blocks indicate floaters. It was thought that the floaters would rise through the liquid and turn the belt. However pushing the floaters into the water at the bottom would require more energy than the floating could generate.

The "Capillary Bowl" it was thought that the capillary action would keep the water flowing in the tube, but since the cohesion force that draws the liquid up the tube in first place holds the droplet from releasing into the bowl, the flow is not perpetual.

Perpetual - Motion machines: examples

- The **Finsrud Wheel** is a moving sculpture built by Norwegian artist Reidar Finsrud (http://www.reidar-finsrud.com/sider/mobile/foto.html).
- **How it works:** It appears to use a combination of gravity, magnets, and pendulum effects, which modern physics would say is impossible, to generate continuous motion.
- Reidar says the machine does stop on occasions but that this is not on a daily basis. To start the machine the pendulums are swung by hand, this puts an external input energy into the system. It runs for about a month, until the glue is dried out, that holds the permanent magnets inside the footer. When a start up is required this takes about 15 minutes, this is due to the difficulty involved in getting all the parts moving in harmony.



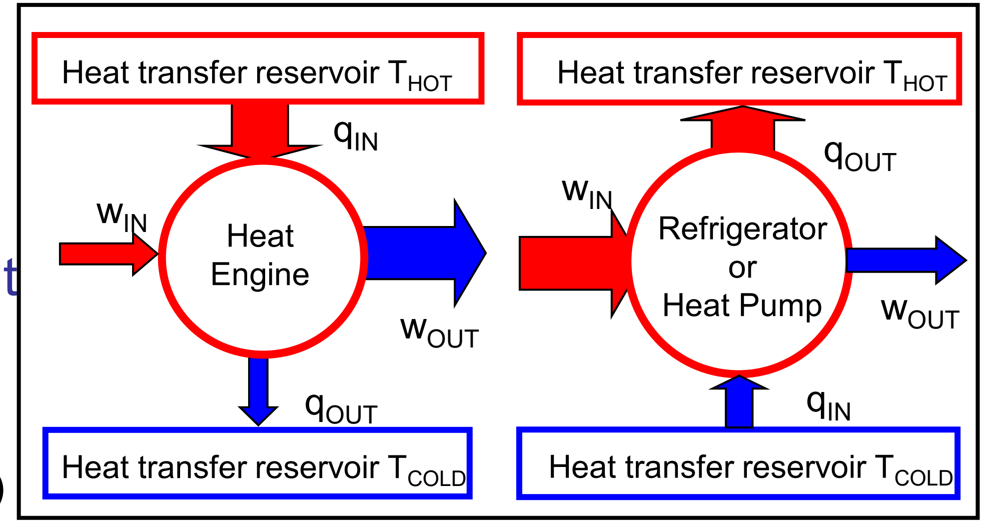
- Short clip: http://www.galleri-finsrud.no/sider/download/finsrud_PM_02.WMV

Recapitulate class 6

- A **thermodynamic cycle** is composed of a series of processes which return to the initial state and works between a hot and a cold thermal reservoir
  1. **Heat power cycles** produce power from heat
  2. **Refrigeration / heat pump cycles** transport heat using power
- First law for a cycle: $w_{net} = q_{net}$
- Second law for a cycle: $\sum_{i=1}^{n} \frac{q_{net,i}}{T_i} \leq 0$ or $\oint \frac{\delta q net, i}{T_i} \leq 0$
- Thermal efficiency for heat / power cycles: $\eta_{he} = \frac{w_{out} - w_{in}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}}$
- Carnot (ideal) cycle
- Carnot (maximum) efficiency

$$\eta_{carnot} = 1 - \frac{T_{cold}}{T_{hot}}$$

- Kelvin-Planck & Clausius statement (second law applied to cycles)



Energy flows in a heat engine (left) and in a refrigeration or heat pump cycle (right)

Next classes 7 – 11: Thermodynamic Power Cycles

- In class 1 to 6 we introduced the all the (basic) tools we need to study thermodynamic systems that generate power or heat / cold

- Now it time for the real job
- The thermodynamics power cycles !

- Class 7 & 8: **vapor power cycles,** cycles using **a working fluid that undergoes a phase transition** (mostly water) through the cycle (Rankine cycle)

- Class 10 & 11: g**as power cycles**, cycles using **gas as working** fluid through the whole cycle (Brayton cycle)

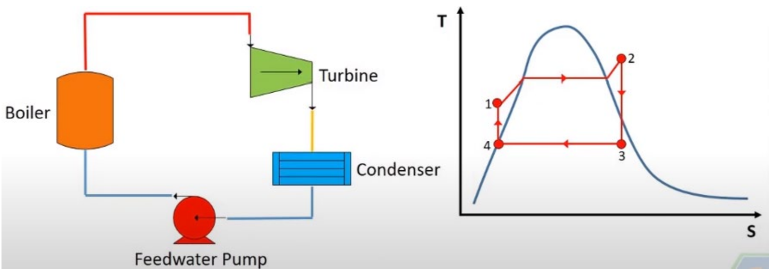
- **Refrigeration and heat pump cycles**, cycles moving heat opposite to the natural direction using power are treated in module 3

Jet engines are an example of gas power cycles

Power plants typically use vapor power cycles to generate electricity, e.g. the power plant in Geertruidenberg (NL)

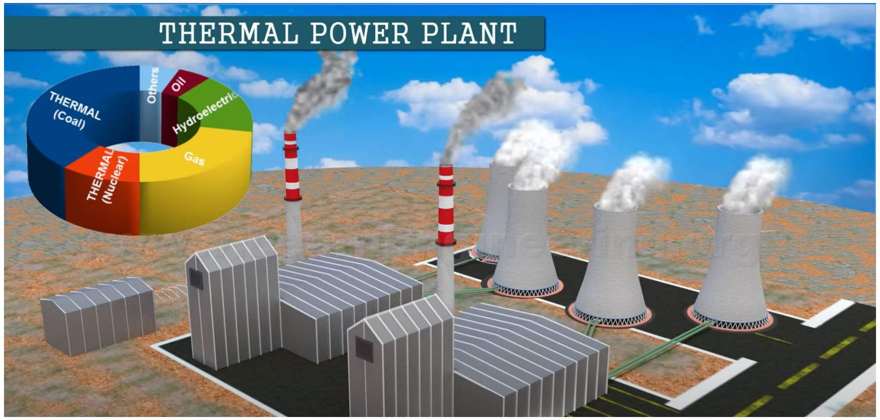
Next class 7: Vapor Power Cycles - Simple

- **Vapor power cycles,** cycles using **a working fluid that undergoes a phase transition** (mostly water) through the cycle
  - Piston steam engine & some history
  - Steam turbine
  - Comparison to Carnot
  - Ideal and real Rankine cycles
    - Heat and power in- and output
    - Thermal efficiency
  - Design parameters
  - Mollier diagram for water



Explanation about a simple Rankine cycle
https://www.youtube.com/watch?v=QFZN71MY71o&t=1s

- Vapor power cycles are widely used in power plant to generate electricity, how does such a thermal power plant work?



https://www.youtube.com/watch?v=IdPTuwKEfmA

Keep in mind: Important Formulas

- Specific volume $v = V/m$ [m^3/kg] and density $\rho = 1/v = m/V$ [kg/m^3]
- Volume work $\delta w = Pdv$
- Enthalpy $h = u + Pv$, (u internal energy, P pressure, v volume)
- Thermal efficiency $\eta_{thermal} = \frac{Net\ electrical\ power\ output}{Rate\ of\ fuel\ energy\ input} = \frac{\dot{W}_{net}}{\dot{Q}_{in}}$
- Mixture fraction $x = \frac{v - v_l}{v_v - v_l} \rightarrow v = v_l + x(v_v - v_l)$
- Conservation of mass $m_{in} = m_{out}$, mass flow rate $\dot{m} = \rho v A$
- Conservation of energy, first law of thermodynamics
  - Closed system $du = \delta q - \delta w \rightarrow \Delta u = q_{net} - w_{net}$
  - Open system $q_{in} + w_{in} + (h + ke + pe)_{in} = q_{out} + w_{out} + (h + ke + pe)_{out}$
- S increases, second law $ds_{total} = ds_{system} + ds_{surroundings} = \delta s_{gen} \geq 0$
- Inequality of Clausius $ds \geq \frac{\delta q_{net}}{T_{res}}$ (= for reversible process)
- Reversible heat transfer $\delta q_{net,rev} = Tds$, irreversible $\delta q_{net,irrev} < Tds$
- Gibbs equations $Tds = du + Pdv$ and $Tds = dh - vdP$
- Isentropic efficiencies $\eta_{INPUT,S} = \frac{w_{IN,S}}{w_{IN,A}}$, $\eta_{OUTPUT,S} = \frac{w_{OUT,A}}{w_{OUT,S}}$
- Thermal efficiency power cycles $\eta_{he} = \frac{w_{out} - w_{in}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}}$
- Carnot efficiency $\eta_{carnot} = 1 - \frac{T_{cold}}{T_{hot}}$
- Coefficient of performance $(COP)_{HP} = \frac{q_{HOT,OUT}}{w_{IN}}$ and $(COP)_{REF} = \frac{q_{COLD,IN}}{w_{IN}}$

- Phase diagrams