Class 2:
Energy, work, heat transfer, enthalpy, entropy, efficiency

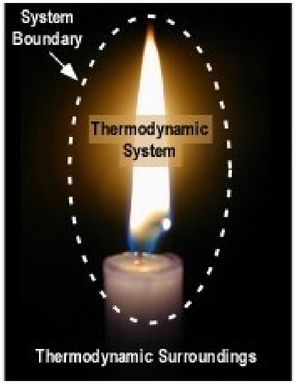
Launch of US Air Force early warning satellite - conversion of internal (chemical) energy into kinetic energy

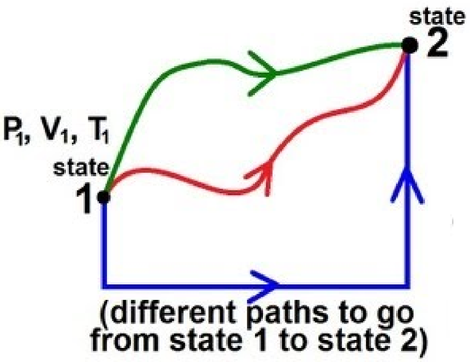
(Courtesy USAF)

Roadmap Engineering Thermodynamics

- Using thermodynamics for practical applications requires knowledge of:

Concepts and definitions (Class 1)



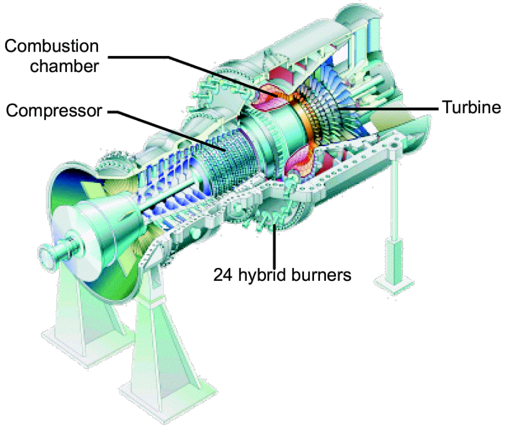


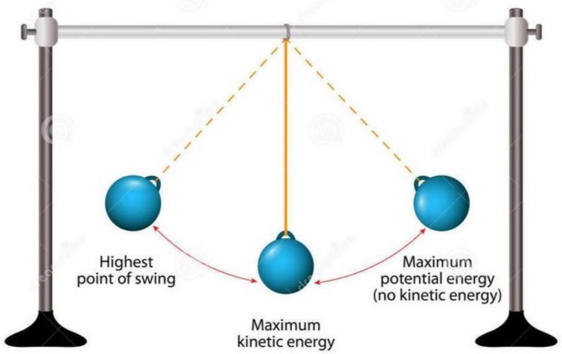
Various forms of energy (Class 2)

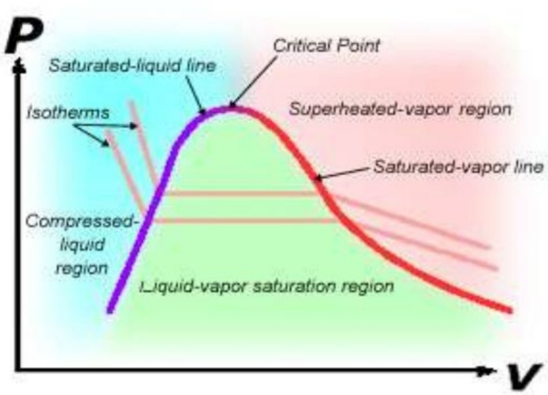
Power cycles
(Class 6 – 11)

Laws of Thermo
(Class 4 and 5)

Properties of Substances
(Class 3, 9)

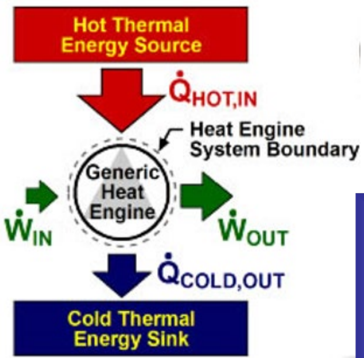




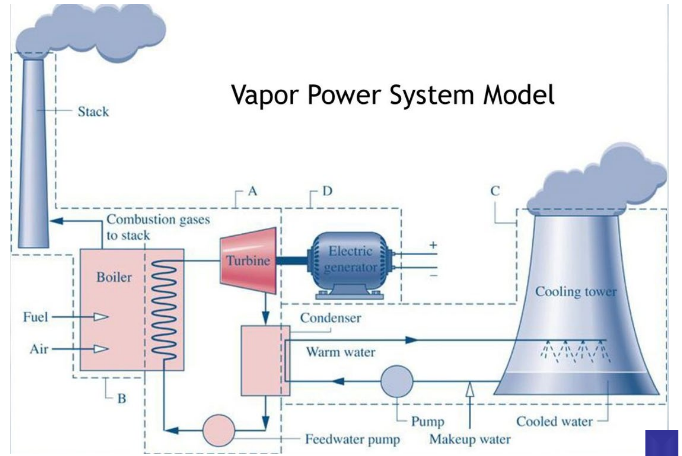


Roadmap Engineering Thermodynamics

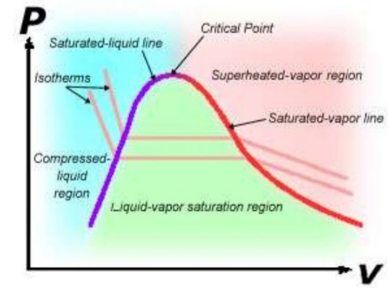
Thermodynamic cycles (Class 6)

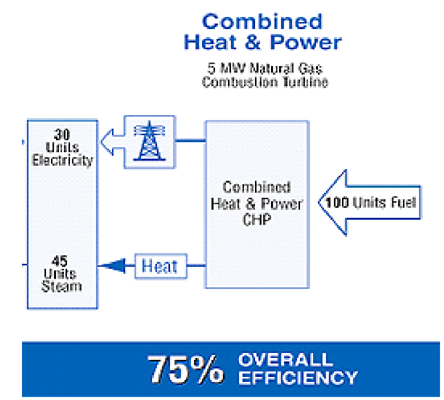


Vapor power cycles – Rankine cycle (Class 7, 8)

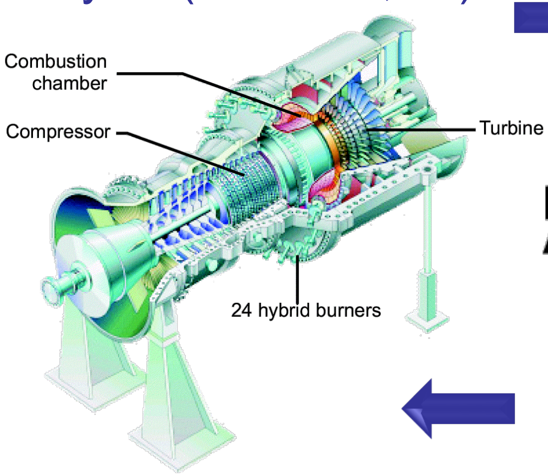


Properties of water (Class 3)



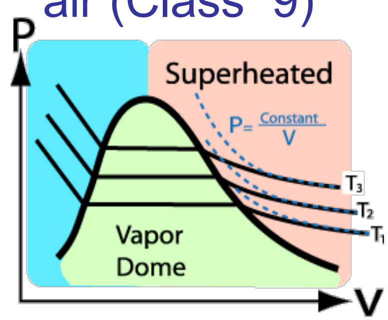


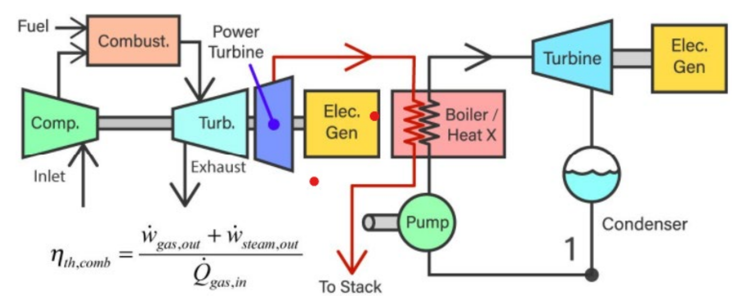
Gas power cycles – Brayton cycle (Class 10, 11)



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

Properties of air (Class 9)



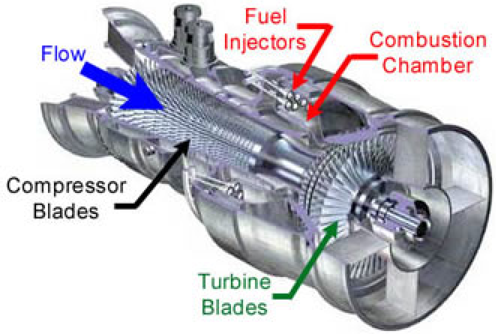


M Muñoz Rojo/GGM Stoffels

Recapitulate Class 1

- What is thermodynamics? → science on using heat and power, conversion of different forms of energy

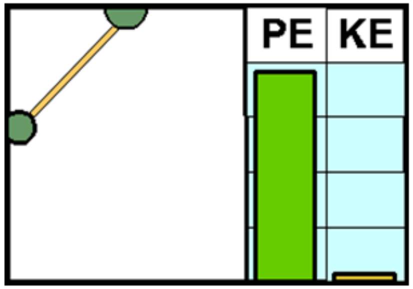
- Systems and boundaries
  - Open / closed / isolated systems
- Properties
  - Extensive / intensive / specific
- States and State Postulate
- Equilibrium and quasi-equilibrium
- Processes and cycles
  - Isobaric / isotherm / isochoric / adiabatic
  - Process diagrams
- Metric system and fundamental units
- Temperature and the zeroth law of thermodynamics
- Pressure (absolute and gauge pressure)



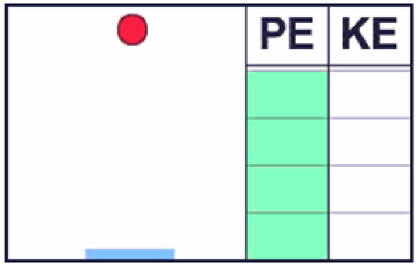
Content Class 2

- **Energy, work, heat, enthalpy, entropy, efficiency**

- Concept of energy and various forms of energy
  - Internal, kinetic and potential energy
- State and path functions
- Mechanisms of energy transfer
  - Heat and heat transfer
  - Work
  - Flow Work (Pv)
- The rate of doing work, heat & mass transfer
- The first law of thermodynamics
- New properties: Enthalpy & Entropy
- Efficiencies of energy conversion processes



Conservation of mechanical energy: potential energy transforms into kinetic energy and visa versa

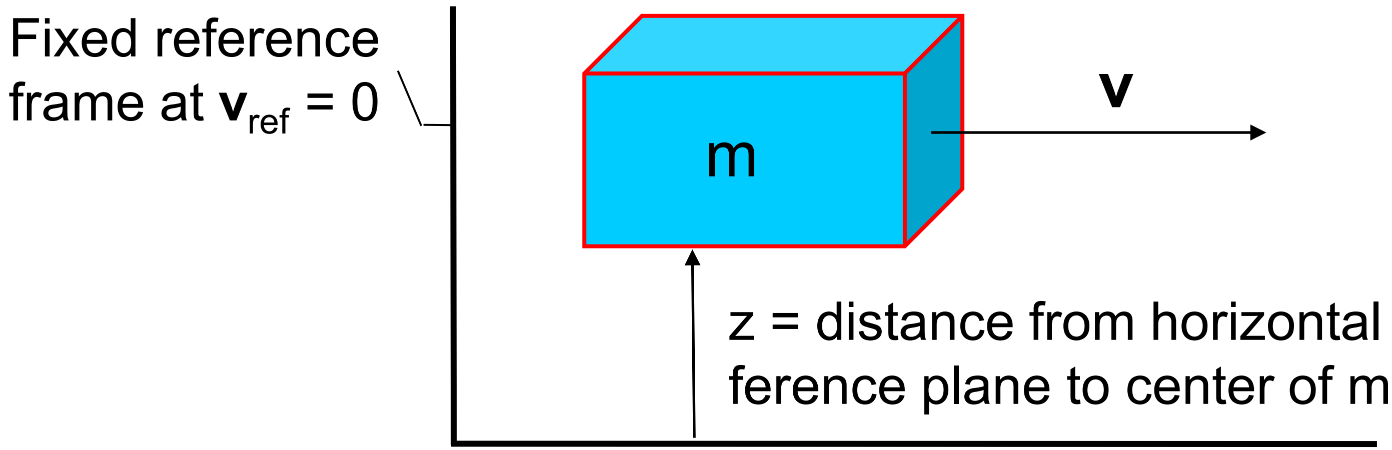


But where does the potential energy go in this case? Is the energy not conserved?

- **Learning goal:** distinguish different kinds of thermodynamic energies and mathematically describe how these can be transformed into each other

Energy within a system boundary: KE & PE

- There are various forms of energy, all have the unit Joule (J)
- Two of them are **kinetic energy (KE) and potential energy (PE)**



- Total kinetic energy of the mass: $\mathrm{KE} = \frac{1}{2} m v^2$ [J]
- Total potential energy of the mass: $\mathrm{PE} = mgz$ [J]

- The total KE and PE are related to a reference frame in the outside world and therefore macroscopic forms of energy
- They can be calculated if m, v and / or z are known

Energy within a system boundary: KE & PE

- Total kinetic energy (KE): $\mathrm{KE} = \frac{1}{2} m \boldsymbol{v}^2 \quad [\mathrm{J}]$
- Total potential energy (PE): $\mathrm{PE} = mgz \quad [\mathrm{J}]$

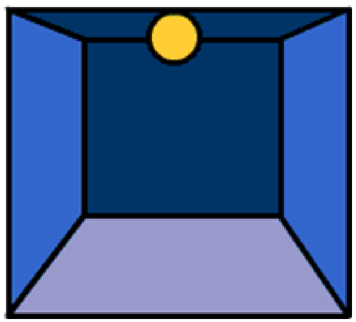
Extensive or Intensive properties?

- The total KE and PE are extensive properties (if you make the system two times larger, i.e. m → 2*m, the KE and PE gets two times larger)
- They can be made specific (ke and pe), i.e. independent of the mass by division by the mass, m

- Specific kinetic energy (ke): $\mathrm{ke} = \frac{\mathrm{KE}}{m} = \frac{1}{2} \boldsymbol{v}^2 \quad [\mathrm{J/kg}]$
- Specific potential energy (pe): $\mathrm{pe} = \frac{\mathrm{PE}}{m} = gz \quad [\mathrm{J/kg}]$

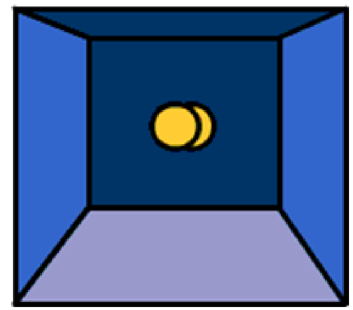
Energy within a system boundary: U

- An other form of energy is the **internal energy (U)**

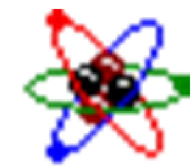


Translational

Rotational



Vibrational



Chemical, Nuclear & Electrical

- **Internal energy (U):** energy related to matter, including bounding energy and energy related to the movement of the molecules of which the matter exists
- The internal energy is strongly dependent on the temperature
- The internal energy is not related to the outside world and therefore a microscopic form of energy

Energy within a system boundary: U

- The total internal energy (U) of a system is an extensive property, like the total kinetic (KE) and potential energy (PE)

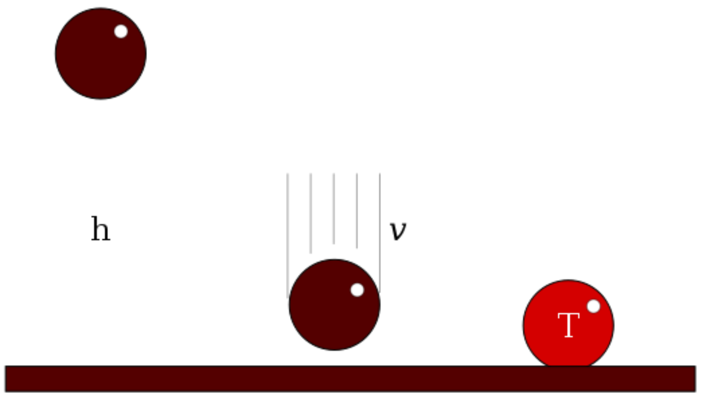
- Total internal energy: U in Joules or kilo Joule [J or kJ]
- Specific internal energy: $u = U/m$ in Joule per kg [J/kg or kJ/kg]

- The internal energy can not be measured directly
- It can be determined but always a reference state should be chosen at which the internal energy is zero (compare this to the potential energy that is zero at $z = 0$)
- The internal energy can often be looked up in tables (class 3)

- In thermodynamics only changes in internal energy are important as we are mainly interested in the effect of the process between two or more different states

Energy within a system boundary: KE, PE & U

- The various forms of energy (kinetic energy, potential energy, internal energy) can be converted into each other



Three types of energy: potential, kinetic and internal

$$U = KE = PE$$

$$U = \frac{1}{2} m C \boldsymbol{v}^2 = mgh \ \ [J]$$

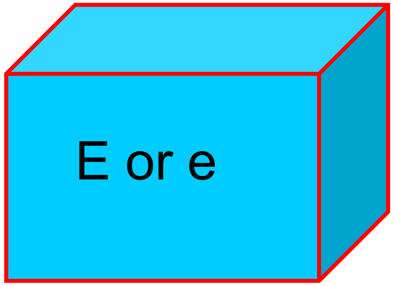
http://nl.wikipedia.org/wiki/Energie

Potential, kinetic and strain (internal) energy are successively converted into each other till the motion stops and all potential energy is converted into internal energy

Energy within a system boundary: KE, PE & U

- The **total energy** of a system is the sum of all different forms of energy within the system:

$$E = U + KE + PE \quad \text{[in Joule, J or kJ]}$$



- The **specific energy** of a system is:

$$e = u + ke + pe \quad \text{[in J/kg or kJ/kg]}$$

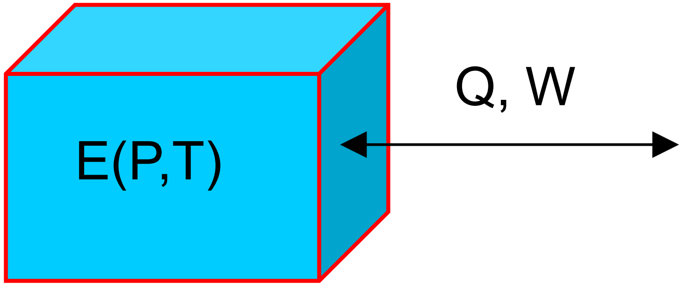
- The difference between the two is the mass
- The total energy is dependent on the mass while the specific energy is independent of the mass

- Note the total energy is denoted by capitals and the specific energy by small caps (and take care of the difference in units)

Change of energy of a system

- The energy of a system can change by **transferring energy** across the system boundary
- There are different ways to do this

1. **Adding or substracting work (W)**
   Different types of work excist
   - Compression (PdV)
   - Mechanical e.g. shaft
   - Electricity



2. **Adding or substracting heat called, heat transfer (Q)**

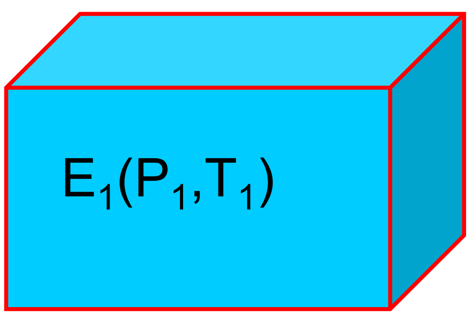
- Work and heat transfer can be total work (W) or heat transfer (Q) with the unit Joule (J)
- They can also be specific (w and q) if they are independent of the mass with the unit Joule per kilogram (J/kg)

State and path functions

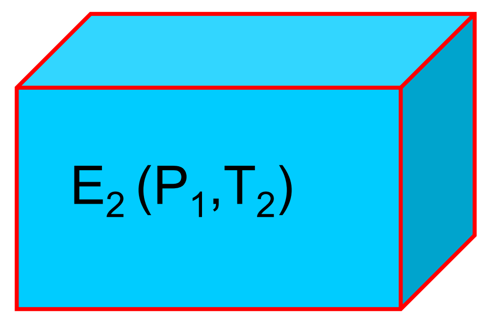
- There is a fundamental difference between the energies in the form of potential, kinetic and internal energy which are related to a specific state and work and heat transfer that cross the system boundary

- Potential, kinetic and internal energy (which form the total energy E of a system) are **state functions**, this means that these energies only depend on the state the system is in (e.g. internal energy depends on the temperature of the state and potential energy on the height of the state)

- Between two states of the system an energy difference ΔE can exists (e.g. if the temperature is different), but if the system returns to its original state the energy has not changed

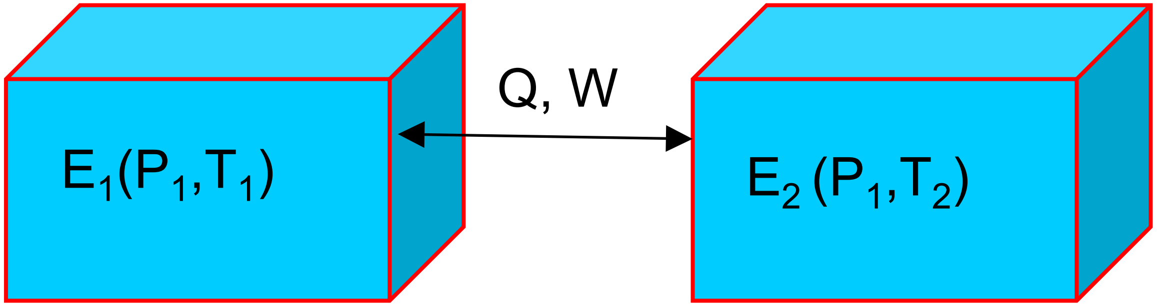


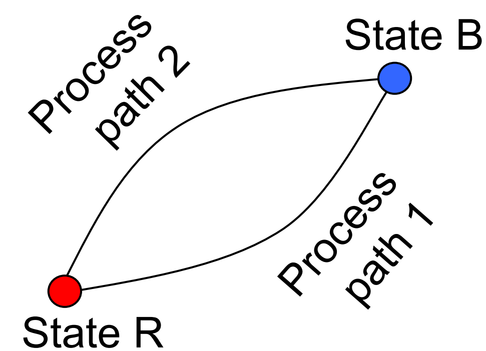
$$\Delta E = E_1 - E_2$$



State and path functions

- On the other hand the energies that cross the system boundary, work and heat transfer are **path functions**, this means that the work or heat added or subtracted from a system depends on the path (the process) the system has followed
- Between two different paths/processes a difference in work/heat can exist
- If a system returns to its original state work and/or heat added to or subtracted from the system are not zero
- To go from one to another state a certain amount of work or heat is needed, this is not a difference in work or heat, therefore ΔW and ΔQ do not have a meaning for a single path
- Note: a state does not have work or heat transfer



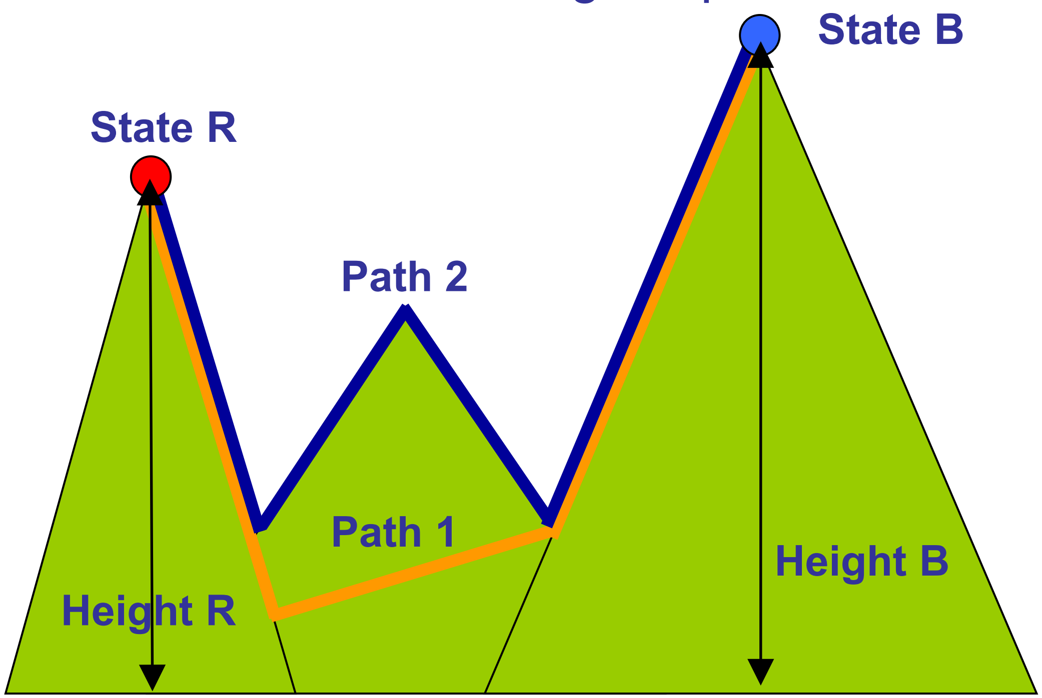


Process path 1 & 2 have different Q and W

Path and state functions and hiking

- **Energy → height & potential energy (State functions)**
- **Work and heat → way & distance (Path functions)**

- The potential energies of state R and B depend on the height (property) only and are always the same, also the difference is constant
- By travelling from state R to state B and back the potential energy will change during the travel but at the end there is no change in potential energy
- Traveling from R to B can go via different paths, the distance travelled is different, the work performed is different
- Returning to the original state does not mean the distance travelled (the work) is zero however the potential energy is not changed



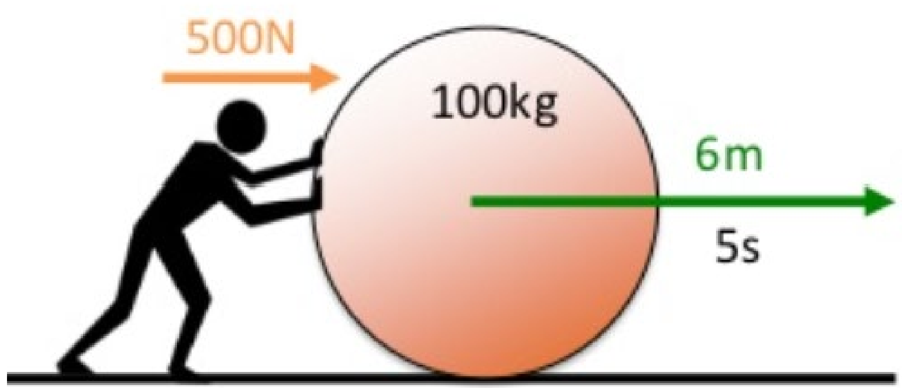
Energy transfer across a boundary: Work

- Energy transfer by work is the application of a force over a distance
- When we push an object and it moves, we do work
- The force is the weight of the object (F) in Newton [N] and the distance is the distance (s) in meter [m] the object moves

$$\delta W = FdS \rightarrow W_{a-b} = \int_a^b FdS = F\,\Delta S \ \text{[J]}$$

- Units: Work, W in [N.m = J]

  Specific work, w = W/m in [J/kg]



Total work

$$W = F\Delta S = 500 * 6$$
$$= 3000\ Nm = 3000\ J = 3\ kJ$$

Specific work

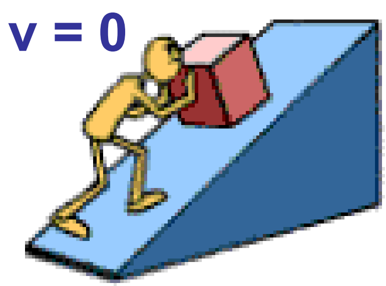
$$\mathrm{w} = \frac{W}{m} = \frac{3000}{100} = 30\ J/kg$$

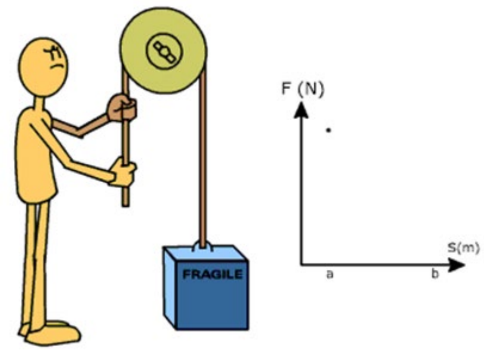
Power

$$\dot{W} = \frac{W}{t} = \frac{3000}{5} = 600\ J/s$$

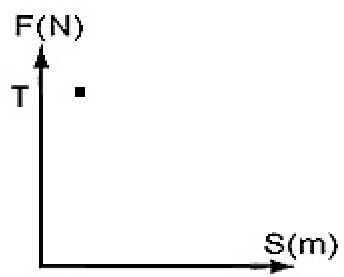
Energy transfer across a boundary: Work

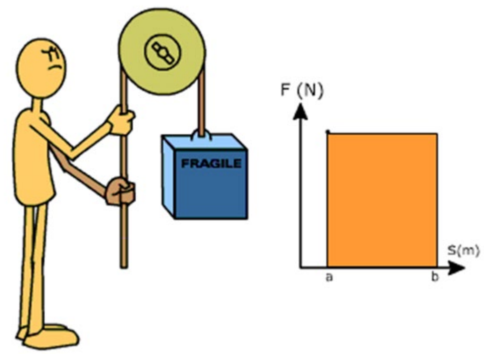
- **Energy transfer by work:**





- **Does this man perform work?**
  → No work since dS = 0
  → No area in FS - diagram



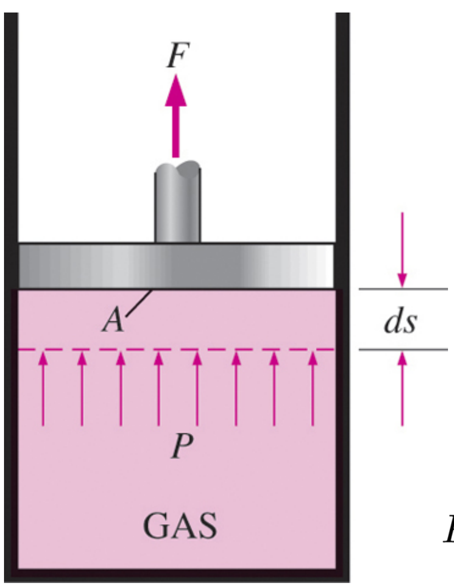


- **Does this man perform work?**
  → Yes, depends on mass and distance
  → Work = area under FS - diagram

Boundary work (PdV)

- In thermodynamic systems work is often done by piston cylinder device
- The pressure inside the system is related to the force and volume change is related to the distance, and F dS can be rewritten to

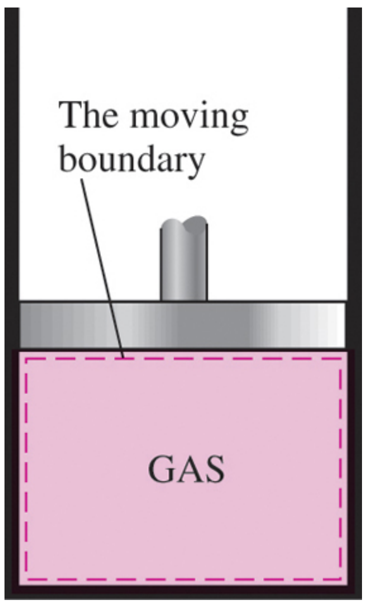
$$W_{a-b} = \int_{S_a}^{S_b} \mathbf{F}\cdot d\mathbf{S} = \int_{\mathbf{S_a}}^{\mathbf{S_b}} (\mathbf{PA})d\mathbf{S} = \int_{\mathbf{S_a}}^{\mathbf{S_b}} \mathbf{P}d(\mathbf{AS}) = \int_{\mathbf{V_a}}^{\mathbf{V_b}} \mathbf{P}d\mathbf{V} \rightarrow [\mathbf{J}]$$



A gas does a differential amount of work δW_b as it forces the piston to move by a differential amount *ds*.

$$P = \frac{F}{A} \rightarrow F = PA$$

The work associated with a moving boundary is called *boundary work.*



Boundary work (PdV)

- Boundary work is the work needed to change the volume of a compressible substance (e.g. in a piston – cylinder device)

$$W_{a-b} = \int_{S_a}^{S_b} \mathbf{F} \cdot d\mathbf{S} = \int_{\mathbf{S_a}}^{\mathbf{S_b}} (\mathbf{PA}) d\mathbf{S} = \int_{\mathbf{S_a}}^{\mathbf{S_b}} \mathbf{P} d(\mathbf{AS}) = \int_{\mathbf{V_a}}^{\mathbf{V_b}} \mathbf{P} d\mathbf{V} \rightarrow [\mathrm{J}]$$

- Therefore boundary work in thermodynamics is defined as:

Total boundary work: $\delta W = P\,dV$ [J]

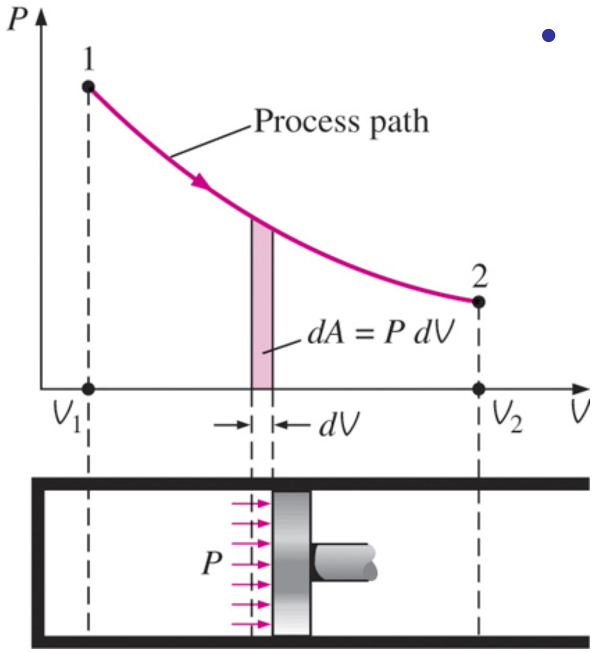
Specific boundary work: $\delta w = P\,dv$ [J/kg]

The symbol δ (Greek delta) denotes a small, differential change for a path function, like work or heat transfer it is like the 'd' you now as a small, differential change of a property. Integrating: $\int \delta W = \mathrm{W}$ and $\int \mathrm{d}V = \Delta V$

- W_{in}: Work added to the system from surroundings
  - Compression → dV negative → **W_{in} = negative**
- W_{out}: Work taken from the system to surroundings
  - Expansion → dV positive → **W_{out} = positive**

Boundary work (PdV)

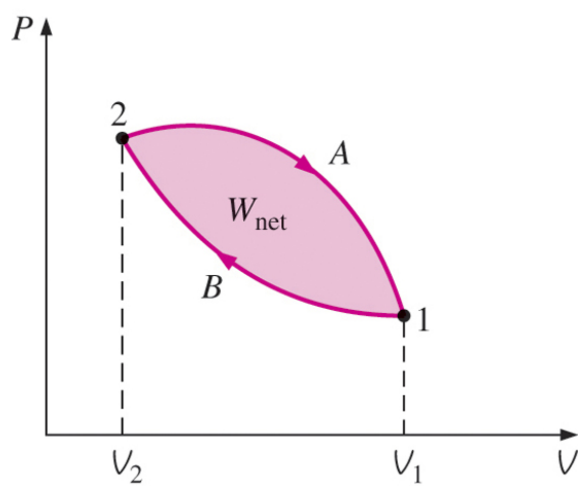
- The work done is represented by the area under the Pv – diagram



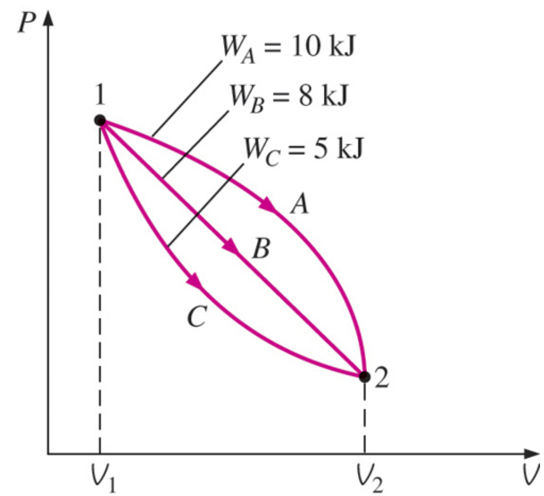
The area under the process curve on a *PV* - diagram represents the boundary work.

$$\text{Area} = A = \int_1^2 dA = \int_1^2 P\,dV$$

- The work is different for different paths / processes (work is a path function) and therefore in the end work is done by the system or on the system



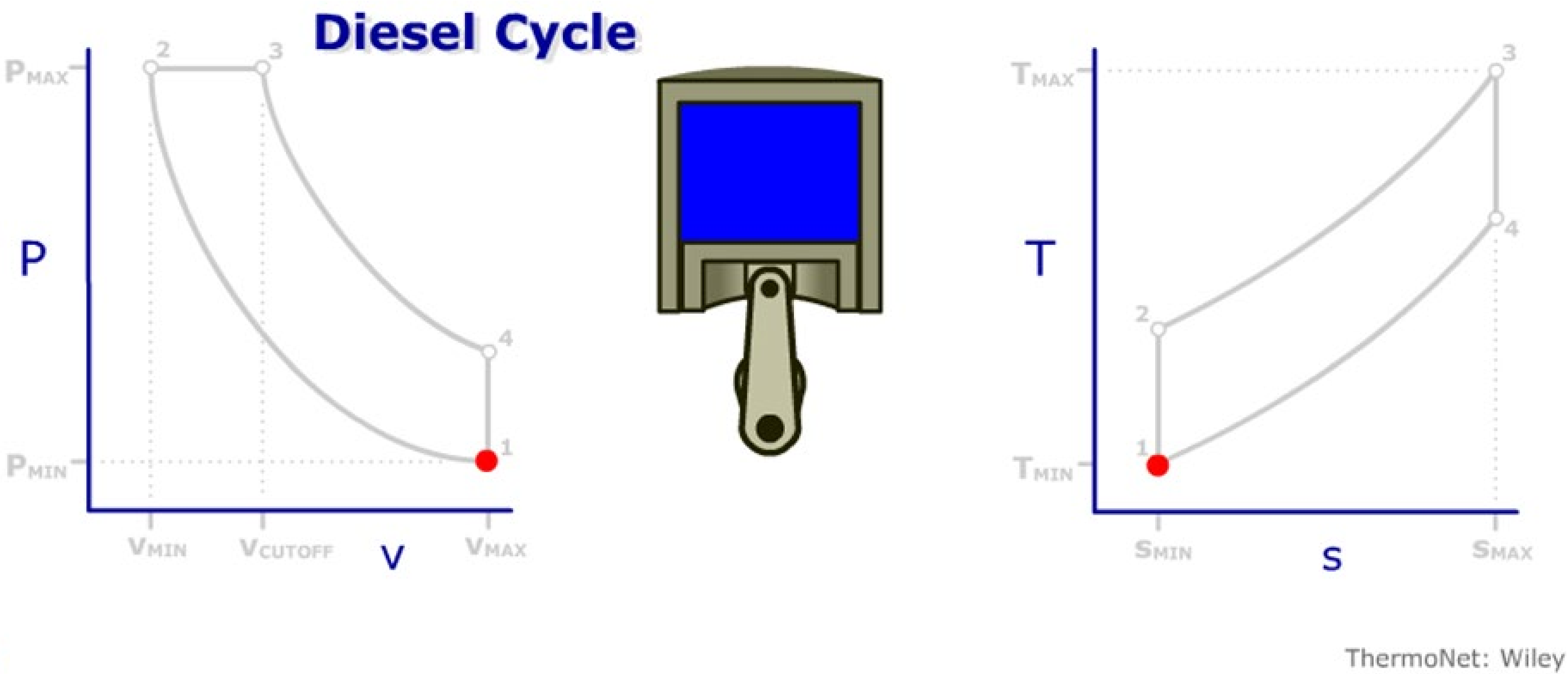
The net work done during a cycle is the difference between the work done by the system and the work done on the system.



The boundary work done during a process depends on the path followed as well as the end states, see example at the end.

Boundary (PdV) work in Diesel engine

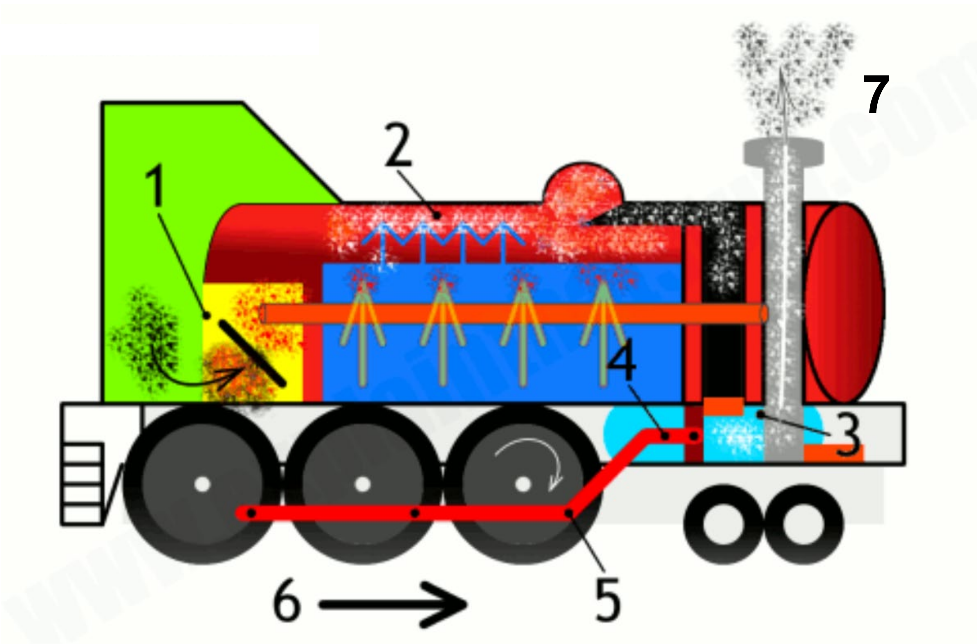
- Example of energy transfer by boundary work



- Step 1 → 2: Boundary work added to the engine
- Step 2 → 3 and step 3 → 4: Boundary work extracted from the engine
- Net work is the area enclosed in the PV diagram by the curve: 1-2-3-4-1

Boundary (PdV) work in a locomotive

- Example of energy transfer by boundary work
- The moving piston delivers to and extracts (boundary) work from the system

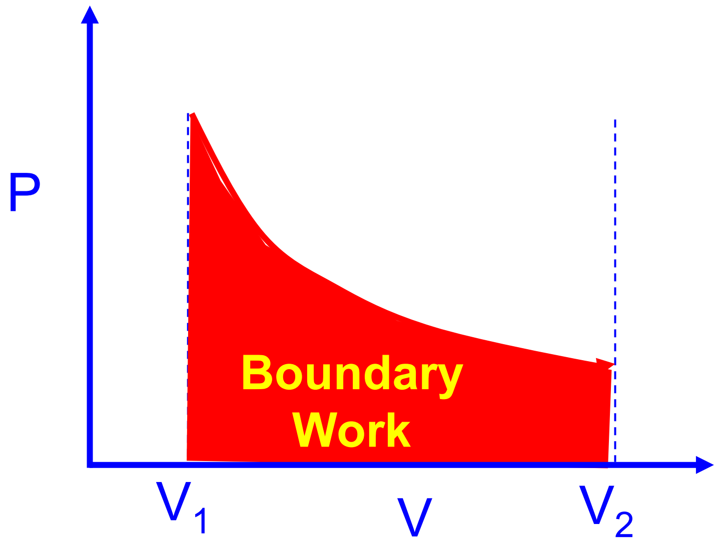


https://100cia.site/index.php/fisica/item/9638-que-es-exactamente-un-motor-que-tienen-de-malo-los-motores-de-vapor

Steam engines, like the one in this locomotive, are examples of external combustion engines. The fire that provides the energy by combustion (1) is outside (external) of the cylinder, where the thermal energy is converted into mechanical energy (3). Between the two there is a boiler (2) that converts thermal energy into steam. The steam acts as a heat transfer fluid, pushing a piston (4) that moves the wheels with a crank (5) and propels the train (6). Steam and heat energy is constantly expelled from the chimney (7), which makes this a particularly inefficient and inconvenient way to power a moving machine. But it was fine in the days when coal was plentiful and nobody cared much about damaging the planet.

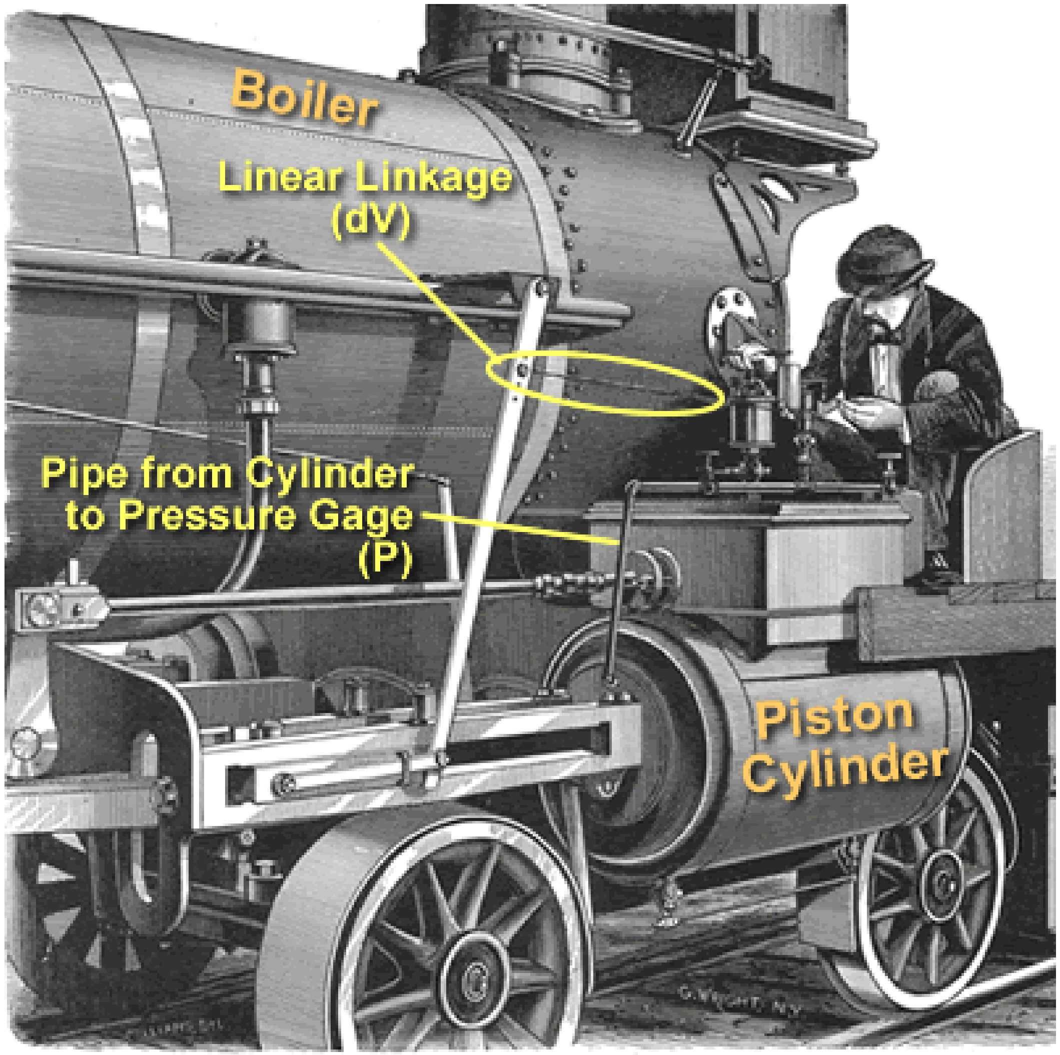
Example P-V (Indicator) diagram

- **Old steam engine**
  Area under P-V diagram
  = boundary work added
  to the locomotive



- $\delta W = P\,dV$

$$W_{OUT,1-2} = \int_{V_1}^{V_2} P dV$$



An engineer producing an indicator (P-V) diagram to test a steam engine.

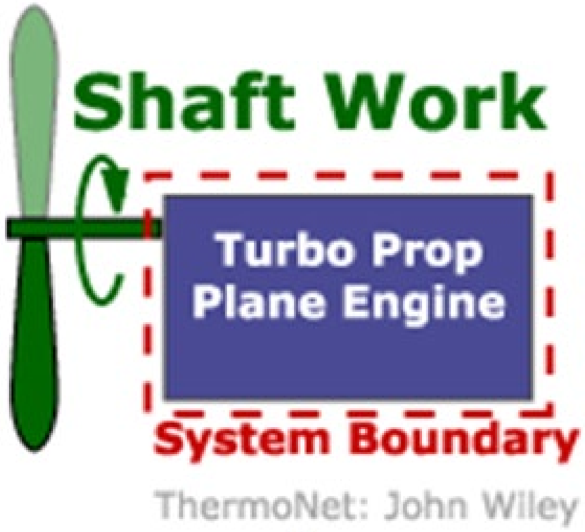
ThermoNet:Wiley

Different types of work

- Three different types of work can be distinghuised:
  1. Boundary work (also called volume work) → $\delta w = Pdv$
  2. Mechanical work (e.g. shaft work, spring work)
  3. Electrical work

- To identify the presence of shaft work: draw a system boundary around system, if any rotating shafts crosses the system boundary, shaft work is present.

- Shaft work common for:
  - Pumps
  - Compressors
  - Blowers
  - Engines

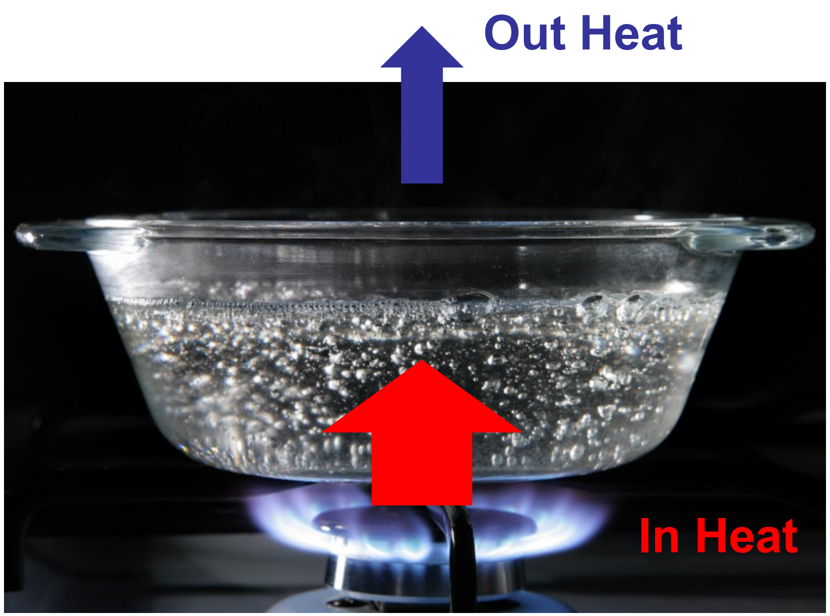


Energy transfer across boundary: Heat Transfer

- Besides by work the energy of a system can change by **transfer of heat** across the boundaries
- **Heat Transfer** is the energy crossing the system boundary because of a temperature difference between the system and the surroundings
- Spontaneously the energy always goes from high to low temperature
- Heat transfer can carry energy into, Q_{in}, or out of, Q_{out}, the system, depending on whether the system has a lower or higher temperature than the surroundings

- $Q_{heat\text{-}transfer} = Q_{in} - Q_{out}$

- Units
  - Heat transfer: Q in [J or kJ]
  - Specific heat transfer: [J/kg or kJ/kg]



Modes of Heat Transfer

- Heat transfer can occur by 1: Conduction
  2: Convection
  3: Radiation
- Note that a detailed study of heat transfer is fairly complex and beyond the scope of thermodynamics classes → next year module 7
- In thermodynamics, we will be concerned with how heat transfer relates to work and energy, and not on the fundamental mechanisms that control heat transfer

Conduction

Courtesy US DOE

A well isolated house losses less heat through conduction through the walls and the glass

Elephants rely on their ears to cool their blood. Heat transfer from their ears to the air occurs by convection. The large size of the ears (large A) serves to increase the heat transfer rate. As the weather gets hotter, the temperature difference between the elephant's ears and the ambient air decreases (smaller T). The elephants compensate by flapping their ears, which increases the velocity of the air passing by their ears (larger h).

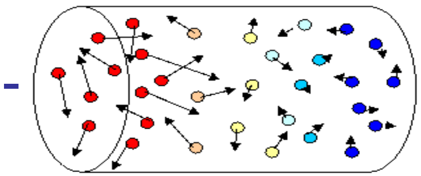
CA

Radiation

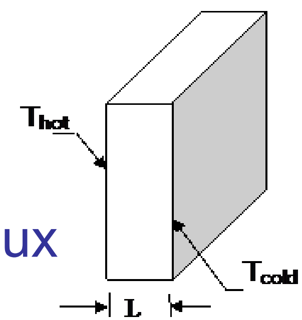
Infrared dryer for automotive paint

Heat transfer: Conduction

- **Conduction heat transfer** is heat transfer associated with a random molecular motion and occurs in gases, liquids, and solid



- Joseph **Fourier** first published the phenomenological relationship that governs heat transfer by conduction in 1822
- Fourier found that the rate of heat transfer is proportional to the temperature difference across the material of interest, and is inversely proportional to the thickness of the material
- The constant of proportionality between the heat transfer rate per unit area and the temperature gradient is called the thermal conductivity, k [W/mK]
- In a differential sense, the heat transfer rate divided by the area can be written as: $$\frac{\dot{Q}}{A} = -k\frac{dT}{dx} \approx -k\frac{\Delta T}{L}$$



- The heat transfer rate per unit area, Q/A, is called the heat flux
- The thermal conductivity is a property of the material and can vary with the local temperature of the material
- In general, for the three phases of matter, gasses have the smallest values of thermal conductivity and solids the largest

(Extra information, not part of the exam)

Heat transfer: Convection

- Heat transfer from a surface to a moving fluid occurs by **convection**
- The rate at which energy is transferred between a solid object and a flowing fluid is proportional to the temperature difference between the surface and the fluid
- The law governing this transfer process is called **Newton's Law of Cooling**
- The constant of proportionality between the heat flux and the temperature difference is the heat transfer coefficient, h [W/m^{2}K], which is a function of the fluid properties and the flow
- The rate of convection from a surface at temperature, T_s to a fluid at temperature, T_f is governed by the equation $\dot{Q} = hA(T_s - T_f)$
- Liquids tend to have higher heat transfer coefficients than gases and heat transfer coefficients tend to increase with the velocity of the fluid. Elephants rely on their ears, to cool their blood heat transfer from their ears to the air occurs by convection.

(Extra information, not part of the exam)

Heat transfer: Radiation

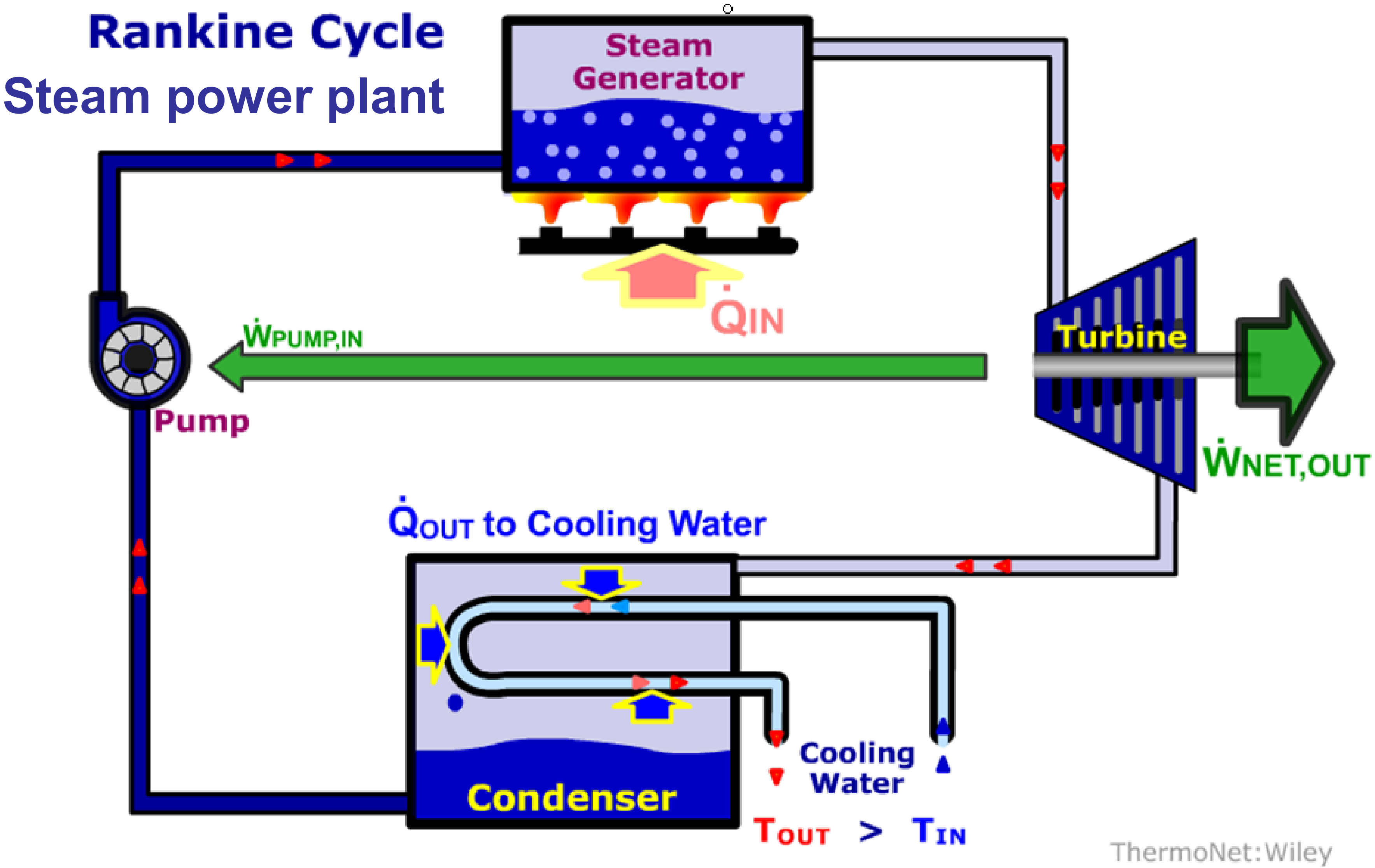
- Heat transfer by electromagnetic waves is called **thermal radiation**
- All substances with a temperature greater than absolute zero emit radiation
- The following equation can be used in many cases as a first approximation to estimate the amount of heat transfer due to radiation

$$\dot{Q} = \epsilon\sigma A(T_1^4 - T_s^4)$$

- Here ε is the emissivity of the surface, σ is the Stefan-Boltzmann constant (5.67×10^{-8} W/m^2·K^4), A is the surface area of the body, T_1 is the surface temperature of the body, and T_s is the temperature of the surroundings
- Heat transfer due to radiation is often negligible until temperatures much greater than room temperature are reached
- Radiation is the only of the three modes of heat transfer that can occur in a vacuum (i.e., in the absence of matter, such as in space)
- Examples of heat transfer by radiation include all of the energy that reaches the earth from the sun and the majority of the energy that is emitted by a heat lamp
- The emissive power of a blackbody is spread across a spectrum of λ 's

(Extra information, not part of the exam)

Heat transfer and work in a steam power plant



- Example: See the shaft work and heat transfer in the steam power plant

BREAK

https://www.cafepress.com/+thermodynamics+mugs

Power: The Rate of Doing Work / Heat Transfer

- Speed determines how quickly we can travel a certain distance → m/s
- Power determines how quickly we can do a certain amount of work or heat transfer → J/s
- **Power = Rate of doing work or heat transfer**

$$\dot{W} = \lim_{\Delta t \to 0} \frac{W}{\Delta t} = \frac{\delta W}{dt} \to [\text{in Watt}, W = \frac{J}{s}]$$

- Power is denoted by a dot on the variable, $\dot{W}$ or $\dot{Q}$
- Lightning has a lot of power; however, it occurs so rapidly (small Δt) that, relative to its power, it cannot do a lot of work:

$$W = \int_{t_1}^{t_2} \dot{W} dt \quad [J] = [W s]$$

- Also the rate of heat transfer:

$$Q = \int_{t_1}^{t_2} \dot{Q} dt \quad [J] = [W s]$$

Photo Courtesy US NOAA

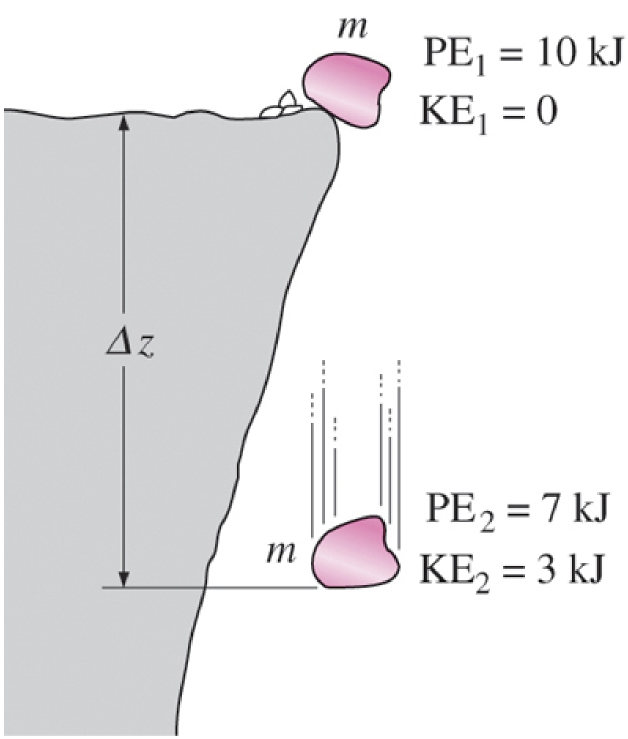
Energy Transfer: Work and Heat

Symbol	Definition	Units
W	Work	kJ
w	Specific work = work per unit mass, w = W/m	kJ/kg
$\dot{W}$	Power = rate of work*	kW (= kJ/s)
Q	Heat transfer	kJ
q	Specific heat transfer = heat transfer per unit mass, q = Q/m	kJ/kg
$\dot{Q}$	Rate of heat transfer*	kW (= kJ/s)

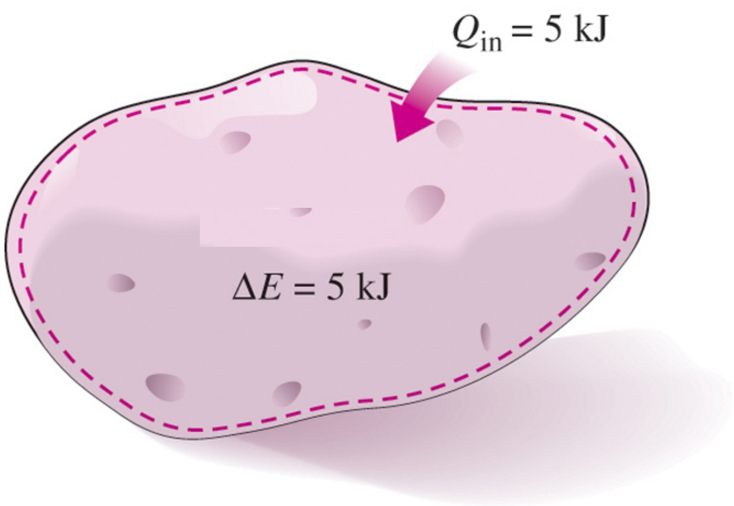
* Note: rates are denoted by a dot on top of the variable
* However, sometimes these dots are hard to see

First law of thermodynamics

- First law of thermodynamics: the total energy is conserved
- Energy can not be destroyed but it can be transformed to a different form of energy (with a different quality)



Energy cannot be created or destroyed; it can only change forms.

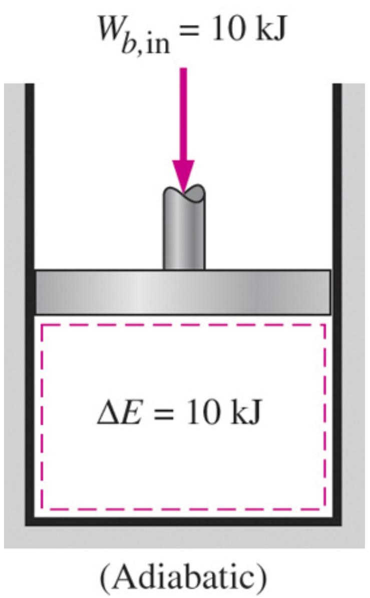


The increase in the energy of a piece of steel in an oven is equal to the amount of heat transferred to it.

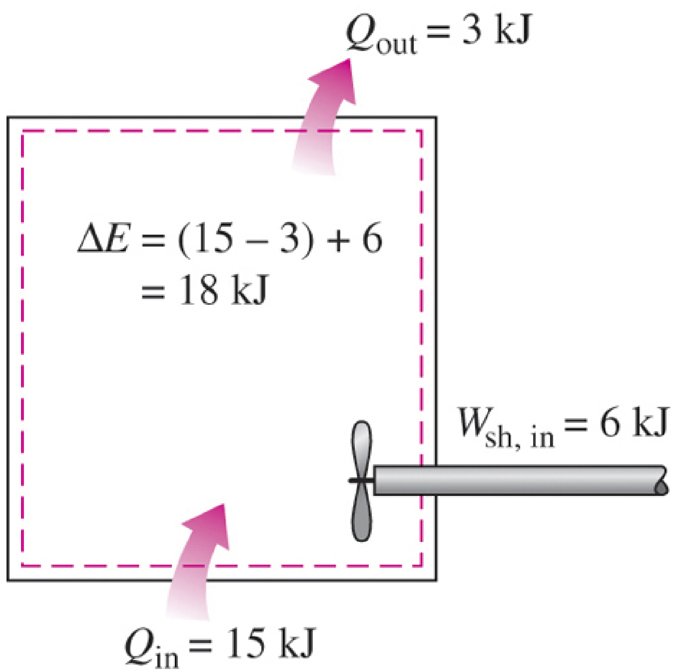
Energy balance

- The net change (increase or decrease) in the total energy of the system during a process is equal to the difference between the total energy entering and the total energy leaving the system during that process:

$$E_{in} - E_{out} = \Delta E_{system}$$



The work (boundary) done on an adiabatic system is equal to the increase in the energy of the system.



The energy change of a system during a process is equal to the *net* work and heat transfer between the system and its surroundings.

Enthalpy – a combination property

- In the analysis of thermodynamic processes, particularly in open flow processes like, power generation we frequently encounter the combination of properties, u + Pv

- This combination is defined as a new property, for the sake of simplicity and convenience

- It is called **enthalpy** and defined as: $h = u + Pv$
  - u = internal energy
  - Pv = flow work (see next slide)

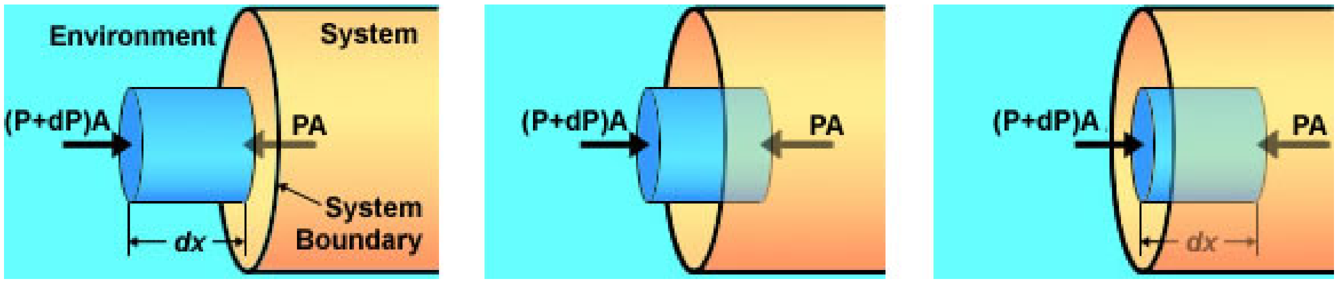
- It was Professor Richard Mollier who recognized the importance of the combination u + Pv in the analysis of steam turbines and in the representation of properties of steam in tables and diagrams

- The famous Mollier diagram, a diagram with h on the y – axis and s on the x – axis is named after him

Energy Transfer by Mass Transport & Enthalpy

- **Flow Work (Pv),** work required to push mass across the system boundary into the open system

  $\delta W_{flow} = FdX = PAdX = Pd(AX) = PdV = Pd(vm) = Pvdm$ [J or kJ]



- Energy (due to mass) inside system boundary

  $dE_{IN,MASS} = (u + ke + pe)\, dm$

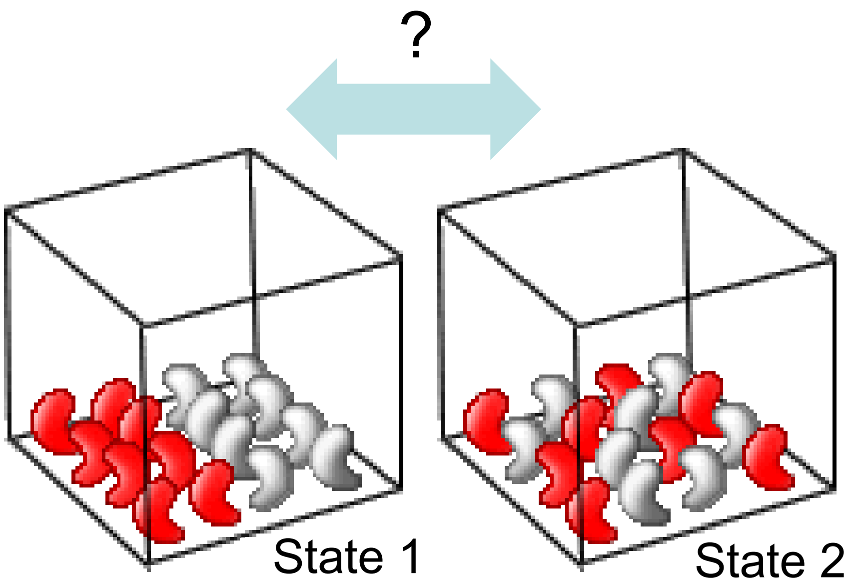
- Energy crossing system boundary with mass transfer (energy inherent to mass + flow work)

  $dE_{IN,TOTAL} = (u + Pv + ke + pe)\, dm = (h + ke + pe)\, dm$

- **Enthalpy** by definition: $h = u + Pv$ (Units: like energy [J/kg])

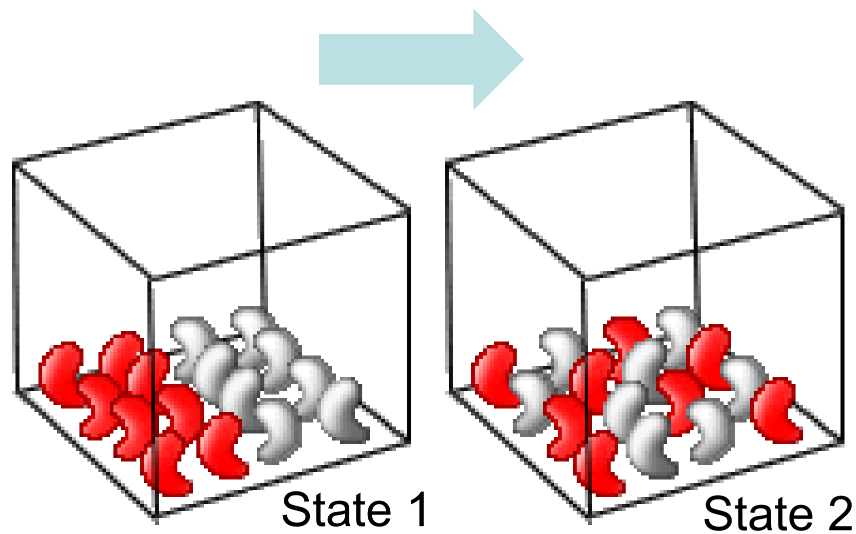
Direction of processes

- What happens spontaneously?
- Which direction will the process go?



Direction of processes

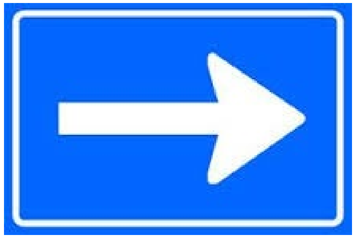
- What happens spontaneously?
- Which direction will the process go?



- Ice cubes will melt, coffee will cool down and state 1 goes to 2
- You know what happens based on your observations in this world
- The reversed process will not take place unless we put effort in it

Direction of processes

- A spontaneous process always goes in one direction

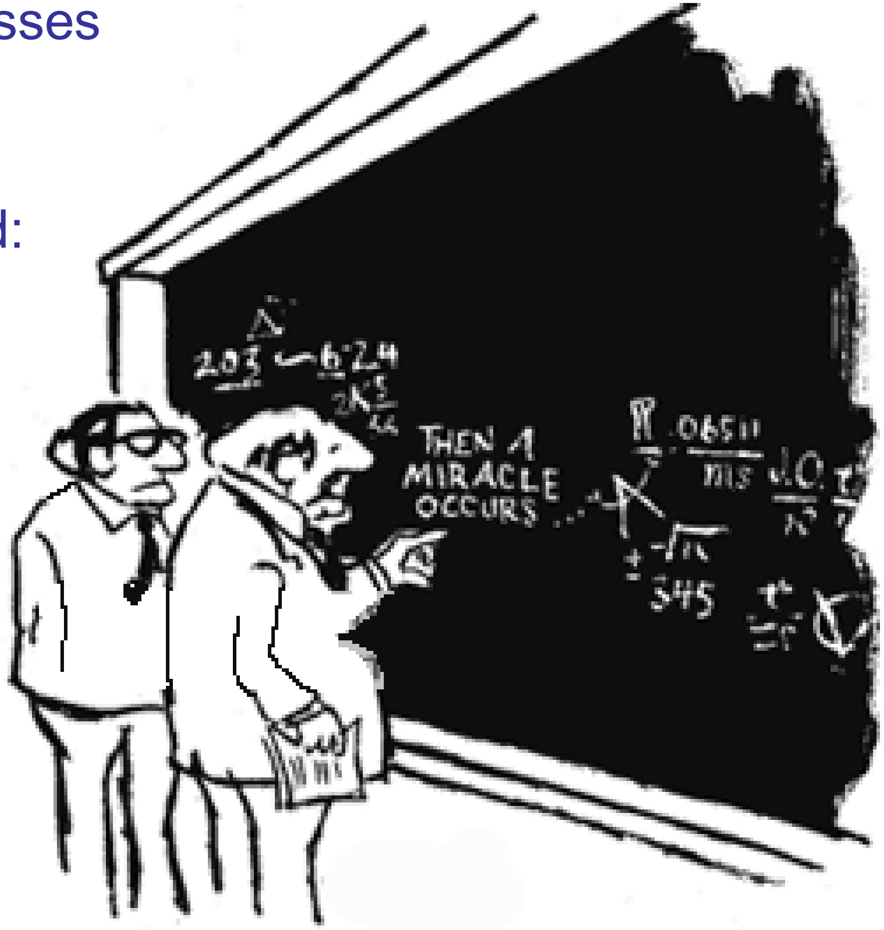


- A spontaneous process always reaches a state of equilibrium in which ‘things’ (mass, heat) are distributed more evenly throughout the system
  - Cold ice cubes will melt and get the temperature of the environment
  - Hot coffee will cool down and get the temperature of the environment

- The reversed process does not take place although the energy is still conserved (if we put effort in it, we can reverse the process)
- How to understand and describe this theoretically?

Entropy

- In the 19th century a lot of scientist looked for a property that could be used to describe the direction of processes
- It was Clausius who in 1865 the key concept of thermodynamics discovered: a new thermodynamic property
- The 'mystery' property is called **entropy (S),** [unit J/K]
- Entropy is an extensive property
- It can be made specific: **specific entropy** s = S/m [unit J/kgK]



"I THINK YOU SHOULD BE MORE EXPLICIT HERE IN STEP TWO."

Entropy

- Entropy is an abstract property that is difficult to understand and best understood by its use in engineering processes
- Understanding is mostly intuitively based on expected direction of processes in combination with order and disorder
- Entropy always increases in a spontaneous process and is at a maximum in equilibrium when disorder is at a maximum

- The **second law of thermodynamics** is based on entropy (Class 5)

Efficiency of energy conversion

- An **efficiency** indicates how well an energy conversion or energy transfer process is accomplished

$$Efficiency = \frac{What\ we\ get\ out}{What\ we\ put\ in} = \frac{Desired\ outcome}{Necessary\ input}$$

Efficiency of a power plant: The ratio of the energy (heat), delivered to the plant through burning the fuel over the energy (work / electricity), produced by the plant

Efficiency of a water heater: The ratio of the energy delivered to the house by hot water to the energy supplied to the water heater

Overall efficiency of an energy installation

- The **overall efficiency of a complete thermal installation** is the ratio of the net electrical power output over the rate of fuel energy input

$$\eta_{overall} = \frac{Net\ electrical\ power\ output}{Rate\ of\ fuel\ energy\ input} = \frac{\dot{W}_{net\ electrical}}{\dot{Q}_{in\ fuel}}$$

- In general this efficiency is a combination of the efficiency of different devices and processes of the powerplant:
  - the combustion / burning of the fuel
  - the boiler
  - the thermal power cycle / heat engine
  - the generator

- **The overall efficiency** can be calculated by multiplying the individual efficiencies

$$\eta_{overall} = \eta_{combustion}\eta_{boilerl}\eta_{thermal\_cycle}\eta_{generator}$$

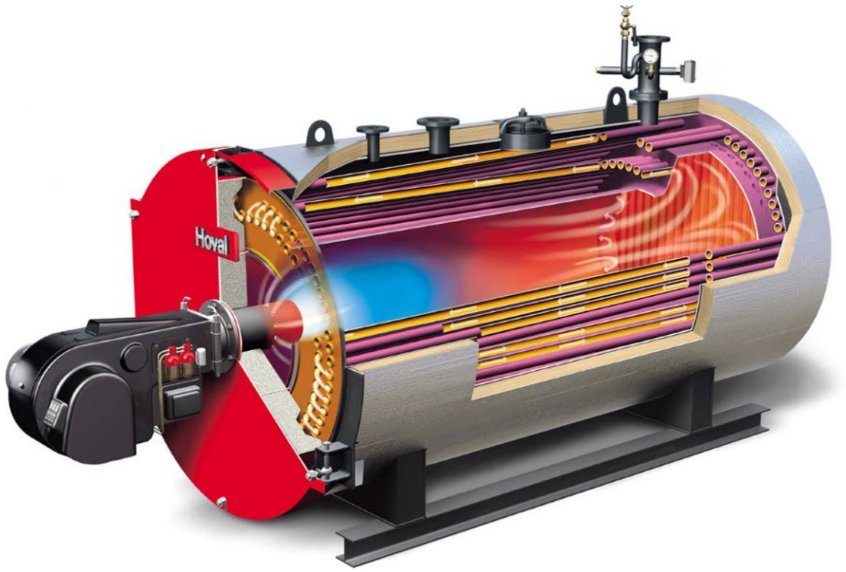
Efficiency of combustion

- The efficiency of the combustion process can be characterized by the **combustion efficiency**

$$\eta_{Combustion} = \frac{Q_{fuel}}{HHV} = \frac{Amount\ of\ heat\ released\ during\ combustion}{Heating\ value\ of\ the\ burned\ fuel}$$

- **Heating value of the fuel**: The amount of heat released when a unit amount of fuel at room temperature is completely burned and the combustion products are cooled to the room temperature

1. **Lower heating value (LHV):** When the water in the combustion gases leaves as a vapor
2. **Higher heating value (HHV):** When the water in the combustion gases is completely condensed and thus the heat of vaporization is also recovered

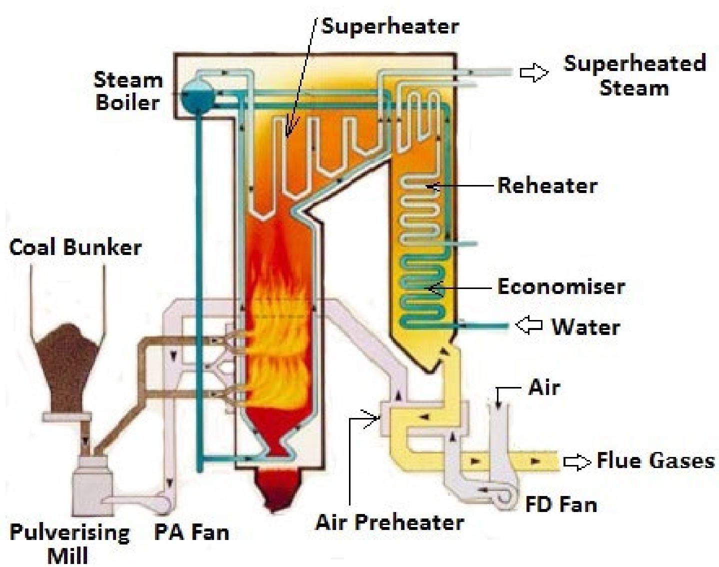


Efficiency of a boiler

- A **boiler** is used to transfer the energy of the burned fuel to the water in the vapor power cycle
- Not all energy is transferred to the water, a part of the energy leaves the boiler through the flue gasses
- The **boiler efficiency** is the ratio of the power released by the fuel over the power (rate of heat) transferred to the thermal vapor power cycle:

$$\eta_{boiler} = \frac{\dot{Q}_{fuel}}{\dot{Q}_{in\_cycle}}$$

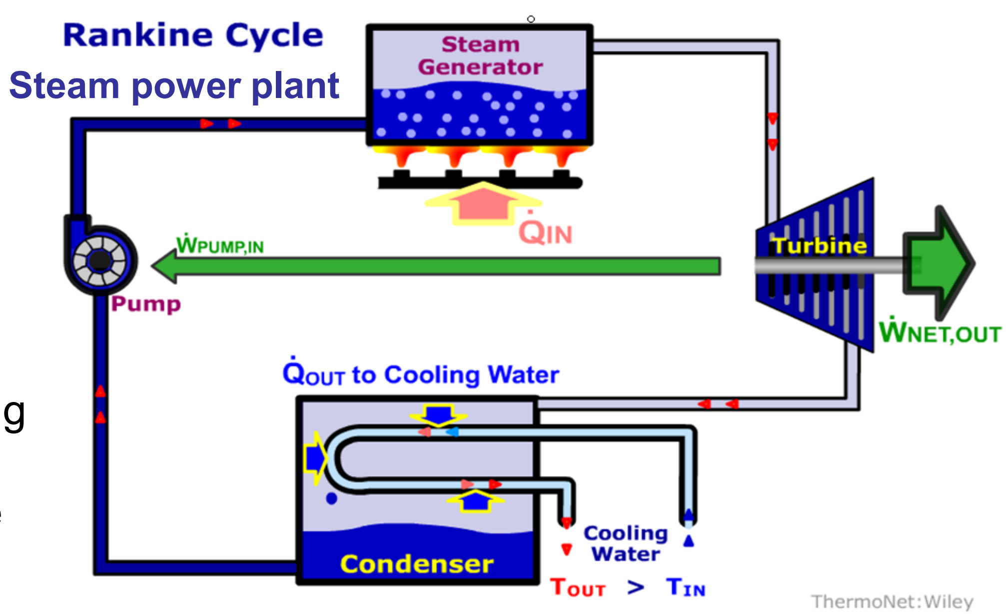
A boiler of a power plant is a very large structure consisting of different parts right). Pulverized industrial boiler (left) https://www.coalhandlingplants.com/boiler-in-thermal-power-plant/



Thermal efficiency of a power cycle

- A **thermal power cycle (or heat engine)** converts thermal energy (e.g. heat released by fuel) to mechanical energy (e.g a turning turbine shaft)
- Thermal power cycles include vapor power cycles (Rankine) and gas power cycles (Brayton)
- Note that it is the goal of this course to analyse and design power cycles
- The **thermal efficiency** is the ratio of the power added to the cycle over the power produced by the cycle:

$$\eta_{thermal} = \frac{\dot{W}_{net\_out\_cycle}}{\dot{Q}_{in\_cycle}}$$

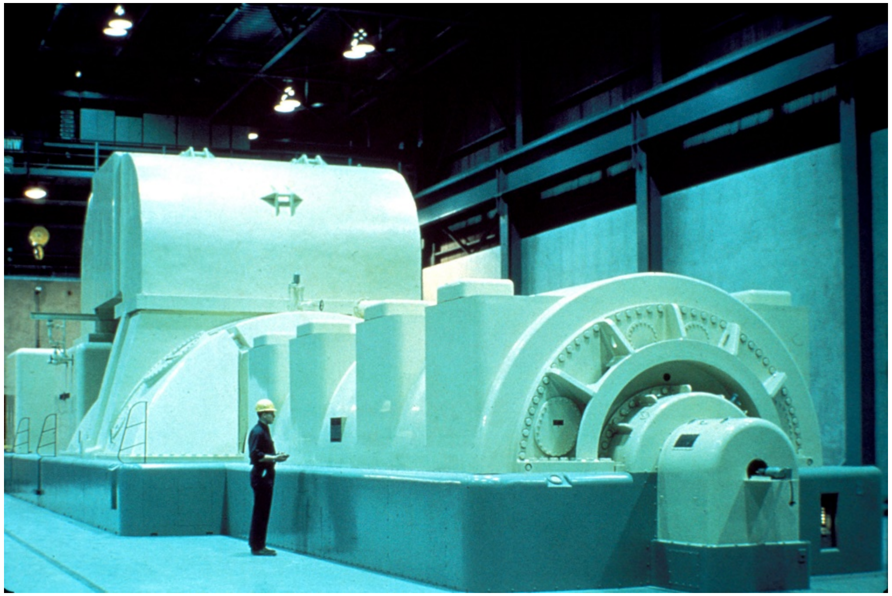


Rankine cycle / steam power cycle converting thermal energy, transferred to the cycle through a boiler, to mechanical energy in the form of a turning turbine shaft

Efficiency of a generator

- A **generator** is a device that converts the mechanical energy of the turbine into electrical energy by electromagnetic induction
- The **generator efficiency** is the ratio of the electrical power output over the mechanical power input of the turbine:

$$\eta_{generator} = \frac{\dot{W}_{net\ electrical}}{\dot{W}_{net\ turbine}}$$

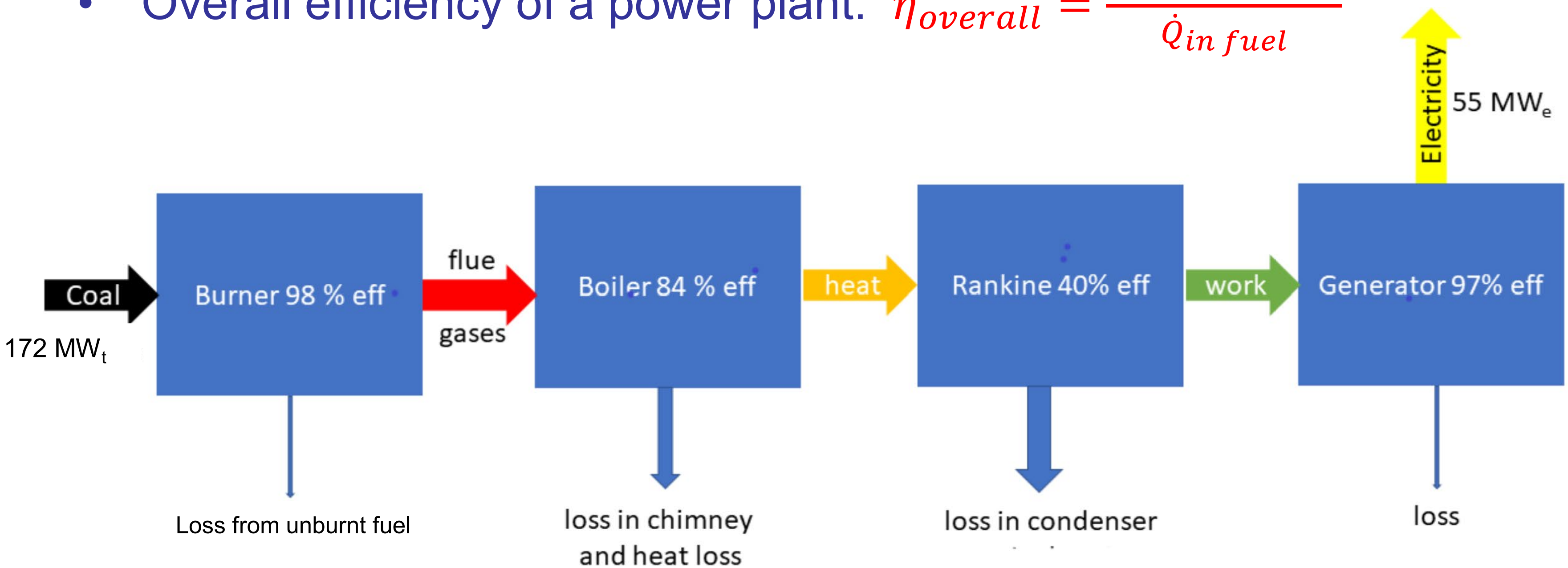


A modern steam turbine generator

A large generator with the rotor removed

Example: efficiency of an energy installation

- Overall efficiency of a power plant: $\eta_{overall} = \frac{\dot{W}_{net\ electrical}}{\dot{Q}_{in\ fuel}}$



$$\eta_{overall} = \frac{\dot{W}_{net\ electrical}}{\dot{Q}_{in\ fuel}} = \frac{55}{172} = 0.32\ (32\%)$$

or multiplying all individual efficiencies

$$\eta_{overall} = \eta_{combustion}\eta_{boilerl}\eta_{thermal\_cycle}\eta_{generator}$$

$$\eta_{overall} = 0.98 * 0.84 * 0.40 * 0.97 = 0.32\ (32\%)$$

Energy: What is it?

- Energy is a word that is very difficult to grasp into a precise definition, it is hard to describe and understand

Energy is any quantity that changes the state of a closed system when crossing the system boundary

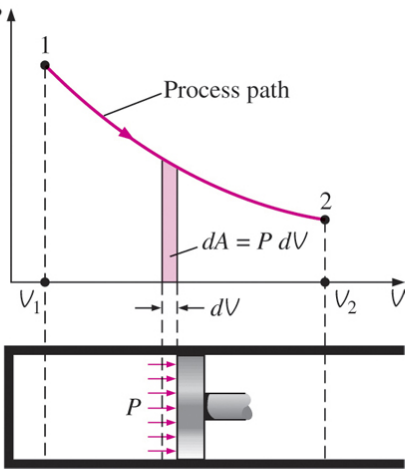
- For an open system also mass crossing the boundary of the system can change the state of the system

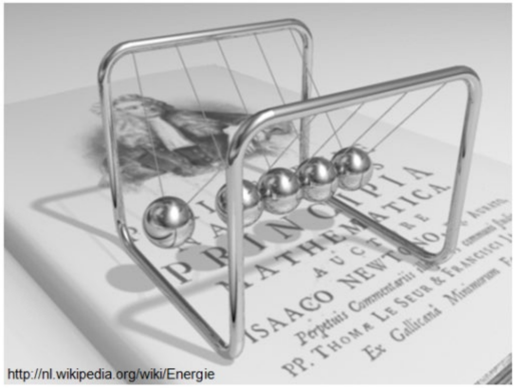
Solar Flare (Photo Courtesy US NOAA)

An amount of energy equivalent to 100-megaton hydrogen bombs is released when a solar flare occurs

Recapitulate class 2

- Energy within system boundaries
  - Kinetic / potential / internal energy / total energy
- State and path functions
- Mechanisms of energy transfer across system boundaries
  - Work
    - Boundary work, $\delta W = PdV$ or $\delta w = Pdv$
    - P-v diagrams (compare to F-s diagram)
    - Mechanical work
  - Heat transfer, due to a temperature difference
  - Flow work (Pv), energy transfer due to mass transport across the boundaries of an open system
- The rate of doing work (power) / heat transfer / mass
- First law of thermodynamics (conservation of energy)
- Energy balances, $E_{in} - E_{out} = \Delta E_{system}$
- New properties
  - Enthalpy, $h = u + Pv$, open systems
  - Entropy
- Efficiencies of energy conversion processes





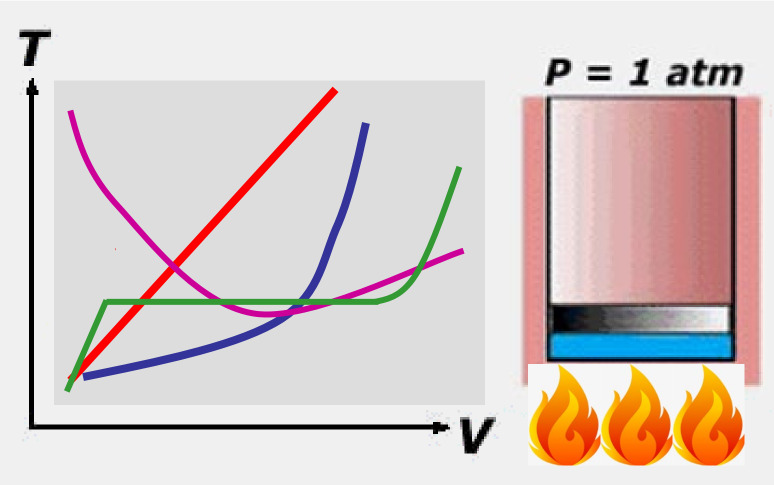
Next Class 3: Phase-change processes: Water

- How can we get values for properties of water?

- Pure substances
- Physics of phase change processes
- Phase change and P - v - T surface (diagrams)
- Liquid - steam - mixture
- Saturation and quality
- Tables / diagrams to obtain

  thermodynamica proporties of water
- Specific heat of water

How works a natural geyser?



Heating water at a constant pressure of 1 atm. Which of the lines displays the correct process?

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 $\delta w = Pdv$ or $\delta W = PdV$
- Enthalpy $h = u + Pv$, where u is internal energy,
  P is pressure
  v is volume (and not velocity!)
- Conservation of energy (first law) $E_{in} - E_{out} = \Delta E_{system}$
- Efficiency $$\eta_{thermal} = \frac{Net\ electrical\ power\ output}{Rate\ of\ fuel\ energy\ input} = \frac{\dot{W}_{net}}{\dot{Q}_{in}}$$