The Physics of Energy

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Corso di Laurea in Fisica, 2020-2021

Thermodynamics

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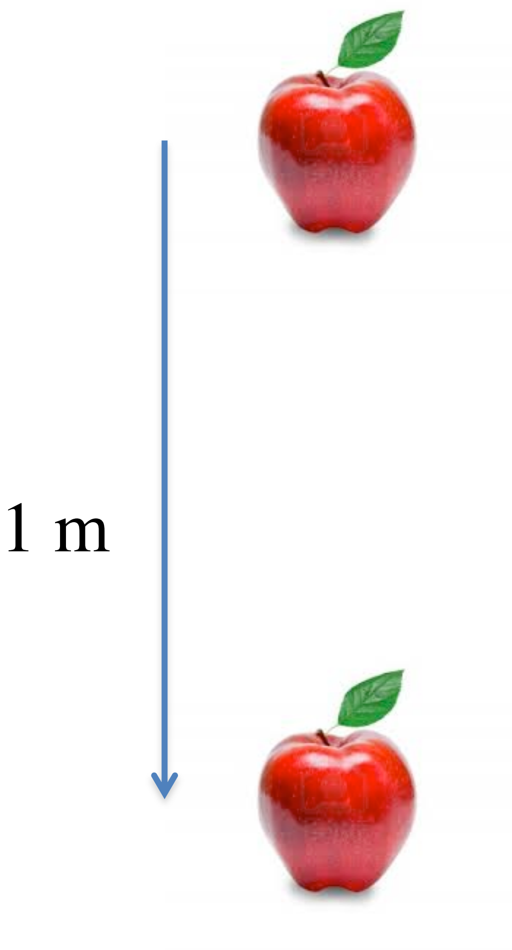
Use of energy

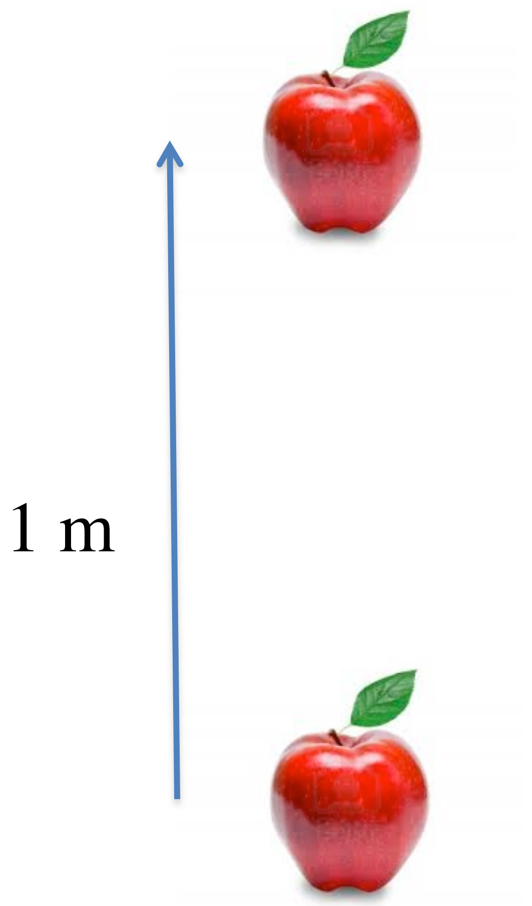
Unit of measure: Joule = 1 J = 1 N x 1 m

Power = Energy /time



Task	Power (W)
Average power of a Boing 747 airplane	10^8
Full power aircraft fighter	10^6
Full power car engine	10^5
Operate a microwave oven	10^3
Being alive for an average adult human	10^2
Brain functioning for an average human	10
mobile phone calling	1
Emission of a standard WI-FI router	10^{-1}
Functioning of a LED light	10^{-2}
Functioning of a miniature FM receiver	10^{-3}
Functioning o a wireless sensor node	10^{-4}
Low power radio module	10^{-5}
Functioning of a quartz wristwatch	10^{-6}
Operation of a quartz oscillator	10^{-7}
Sleep mode of a microcontroller	10^{-8}
1 bit information erasure at room T (min)	10^{-21}

Energy is a property of a physical system that thanks to this property can do some work.



It goes also the other way around…

By doing work I can increase the energy content of a physical system

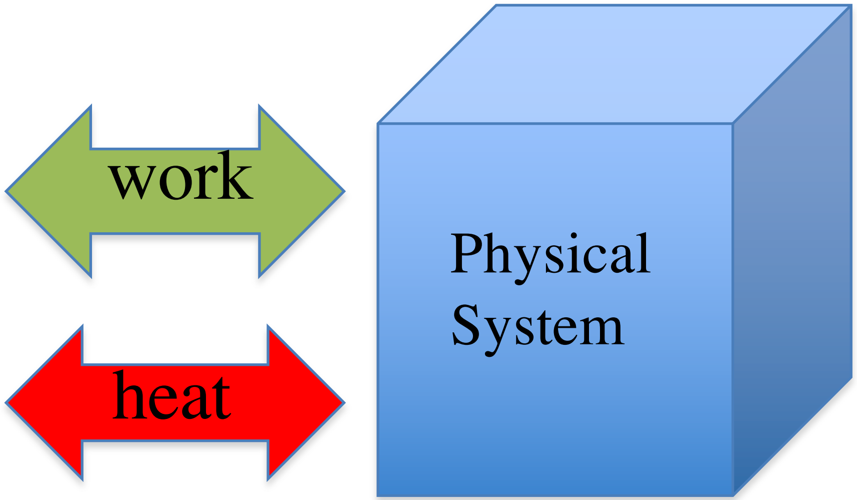
Is there any other way to change the energy content of a system?

Yes!

We can warm it up!

Energy

The energy content of a system can be changed via exchanges of work and heat



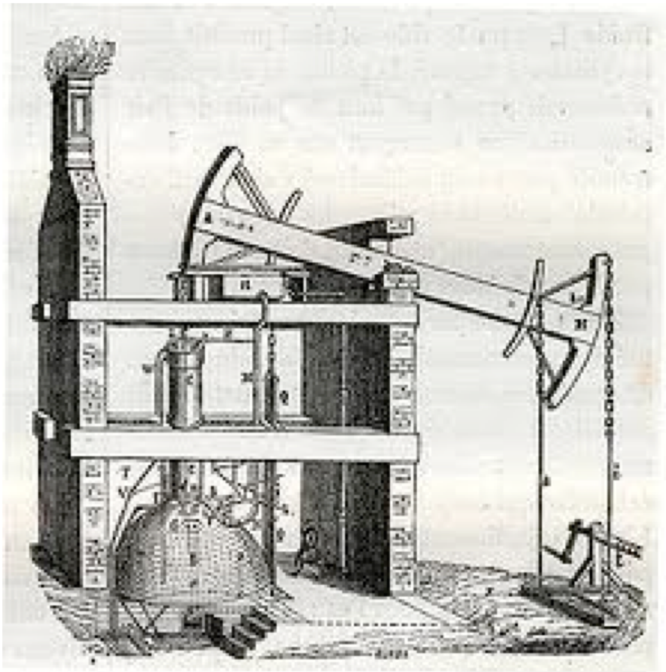
but there are some limitations…

Energy

Energy is a property of physical systems that can be used to perform work and usually comes inside physical objects like a **hot gas** or a **gasoline tank**.

Thinking about it we can ask questions like:

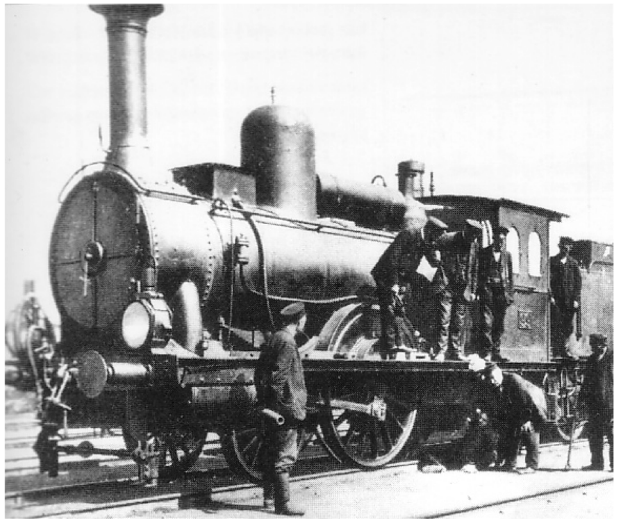
- how can we make the energy contained in a litre of gasoline to push forward a car
- how can we use the heat produced by burning coal to make the train run?

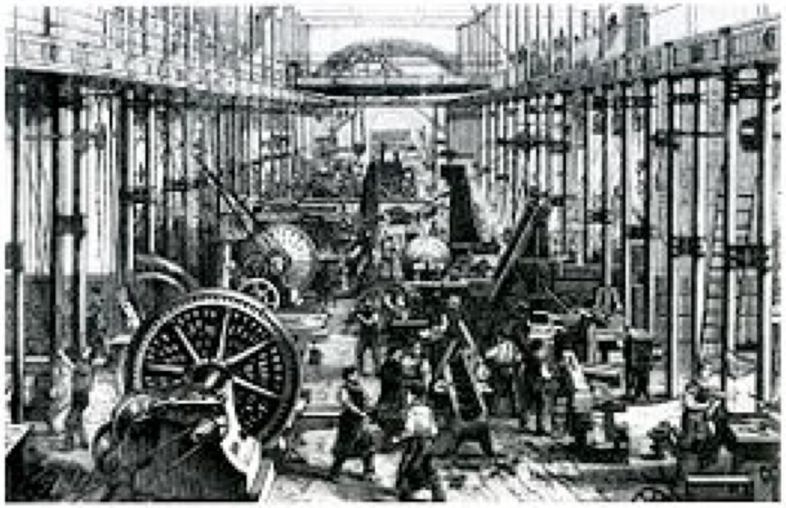


Questions like these were at the very base of the activities performed in the early seventeen hundreds by the first inventors of the so-called thermal machines.
People like **Thomas Newcomen** (1664-1729) who built the first practical steam engine for pumping water and **James Watt** (1736-1819) who few decades after proposed an improved version of the same machine.

Thermal Machines

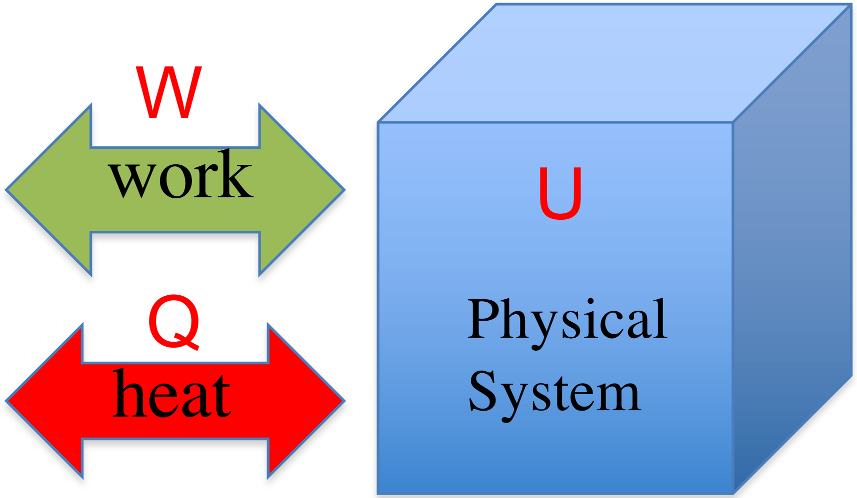
It is thanks to the work of scientists like Sadi Carnot (1796-1832) and subsequently of Émile Clapeyron (1799 - 1864), Rudolf Clausius (1822 - 1888) and William Thomson (Lord Kelvin) (1824 – 1907) that studies on the efficiency of these machines aimed at transforming heat (just a form of energy) into work brought us the notion of entropy and the laws of thermodynamics.





These laws do not tell us much about what energy is but they are very good in ruling what can we do and what we cannot do with energy. Let's briefly review them.

The first law of thermodynamics states that the total energy of an isolated physical system is conserved during any transformation the system can go through.



$$\Delta U = Q - W$$

Change in internal energy | Heat added to the system | Work done by the system

It was initially formulated in this form by Julius Robert von Mayer (1814 - 1878) and subsequently reviewed by James Prescot Joule (1818-1889) and Hermann Ludwig Ferdinand von Helmholtz (1821-1894).

The second law states that there are limitations to how much work we can get from a given amount of energy present in the form of heat.

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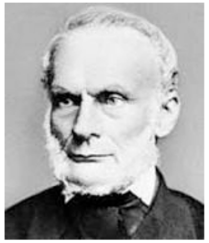
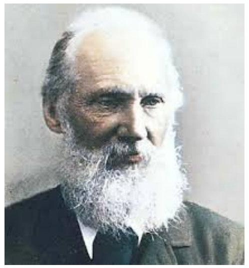
There exist different formulations that are all equivalent.
The two most popular are ascribed to Clausius and Kelvin:



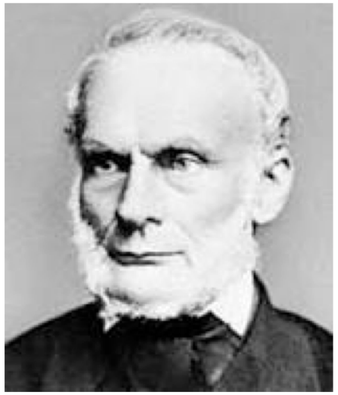
Clausius formulation: "**No process is possible whose sole result is the transfer of heat from a body of lower temperature to a body of higher temperature**".



Kelvin formulation: "**No process is possible in which the sole result is the absorption of heat from a reservoir and its complete conversion into work**".

An important consequence of the second law is that there is a limit to **the efficiency of a thermal machine**. This limit was discovered by Sadi Carnot in 1824 when he was only 28. He introduced the concept of thermal machine, generalizing the concept popular at that time of "steam engine", and showing that the efficiency of any thermal machine operating between two temperatures is bounded by a quantity that is a function of the two temperatures only.

Few years after the work of Carnot, Clausius used this result to introduce a quantity that is useful in describing how much heat can be changed into work during a transformation. He proposed the name "**entropy**" for his quantity.



Clausius proved a theorem that states that during a **cyclic transformation**, if you do the transformation carefully enough not to loose any energy in other ways (like friction), then **the sum of the heat exchanged with the external divided by the temperature at which the exchange occurs is zero:**

$$\oint \frac{dQ}{T} = 0$$

This is equivalent to say that it exists a state function *S* defined as

$$S_B - S_A = \int_A^B \frac{dQ}{T}$$

If you are not careful enough and you loose energy during the transformation than the inequality holds instead:

$$\oint \frac{dQ}{T} \leq 0$$

A transformation like this is also called an *irreversible transformation*

$$S_B - S_A \geq \int_{A\,irr}^B \frac{dQ}{T}$$

Spontaneous transformation

We call a transformation spontaneous if it can happen without any external work.

If we consider an infinitesimal transformation we have:

$$dS \geq \frac{dQ}{T} \quad \text{or} \quad TdS \geq dQ$$

where the equal sign hold during a reversible transformation only.

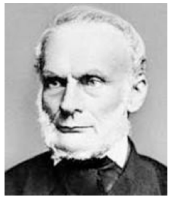
Let's suppose that we have a transformation where no heat nor work is exchanged.
It is called an adiabatic spontaneous transformation.
In this case we have:

$$dS > 0$$

Thus we conclude that during a spontaneous adiabatic transformation (i.e. without external work nor heat) the entropy always increases.

The second law

There exist different formulations that are all equivalent.



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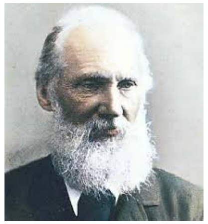

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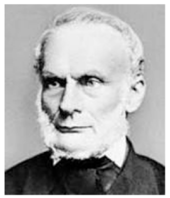

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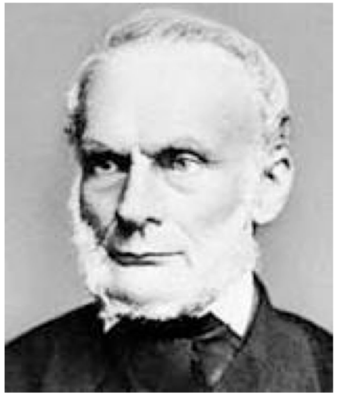
What happens if we have exchange of heat?

From Clausius we know that, for a reversible transformation we have:



$$S_B - S_A = \int_A^B \frac{dQ}{T}$$

The quantity of heat Q that appears in the Clausius equation is the amount of energy that goes into the increase of entropy.

For an infinitesimal transformation: $TdS = dQ$

It is useful to interpret the quantity ***TdS*** **as the amount of heat** (meaning thermal energy**) that cannot be used to produce work**.

In other words during a transformation, even if we are carefully enough not to waste energy in other ways, we cannot use all the energy we have to do useful work. Part of this energy will go into producing a change of the system entropy.

If we are not carefully enough the situation is even worst and we get even less work.

Free energy

The concept of Free energy was proposed by Helmholtz in the form:

$$F = U - TS$$

The free energy F measures the maximum amount of energy that we can use when we have available the internal energy U of a system.

Summary

Energy

Capability of doing WORK… WORK = FORCE x Displacement
Energy can be **changed** through flux of **work** and **heat**.

Energy is conserved (First Principle)

Entropy

Measures the capability of change…

Entropy increases in spontaneous transf. (Second Principle)

Equilibrium is the competition of the tendency of Energy to reach a minimum and Entropy to reach a maximum (minimum Gibbs free energy).

$$F = U - T S$$