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Basic thermodynamics

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Content

Introduction to the notion of **energy**.

Laws of **energy** transformation

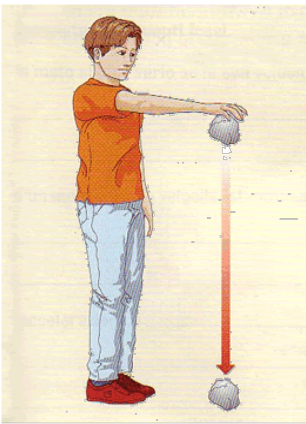
The **energy** at the microscopic scale

and the **entropy**

Energy

In physics, energy (Ancient Greek: ἐνέργεια energeia "activity, operation”) is an indirectly observed quantity that is often understood as the **ability of a physical system to do work on other physical systems**

Capability of doing WORK… WORK = FORCE x Displacement



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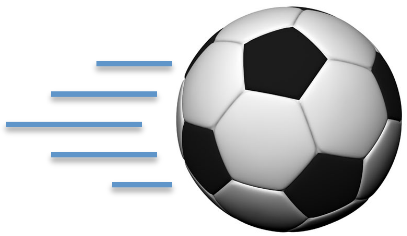

Energy ?

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Energy

"*It is important to realize that in physics today, we have no knowledge what energy is*."

Richard Feynman, in The Feynman Lectures on Physics (1964) Volume I, 4-1

Energy: a hint of history

The *vis viva* (living force), which **Gottfried Leibniz** defined as the product of the mass of an object and its velocity squared; he believed that total vis viva was conserved.

To account for slowing due to friction, Leibniz theorized that thermal energy consisted of **the random motion of the constituent parts of matter**, a view shared by **Isaac Newton**, although it would be more than a century until this was generally accepted.

Energy: a hint of history

The **conservation of energy** was proposed by Gottfried Leibniz over the period 1676–1689, the theory was controversial as it seemed to oppose the theory of conservation of momentum advocated by Sir Isaac Newton and René Descartes. The two theories are now understood to be complementary.

In 1807, **Thomas Young** was possibly the first to use the term "energy" instead of vis viva, in its modern sense.

Energy: a hint of history

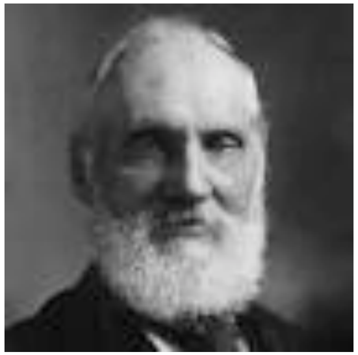
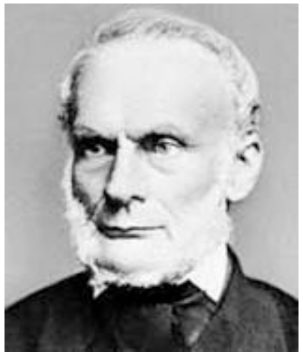
Gustave-Gaspard Coriolis described "kinetic energy" in 1829 in its modern sense.

In 1853, **William Rankine** coined the term "potential energy".

William Thomson (Lord **Kelvin**) amalgamated all of these laws into the laws of thermodynamics, which aided in the rapid development of explanations of chemical processes by

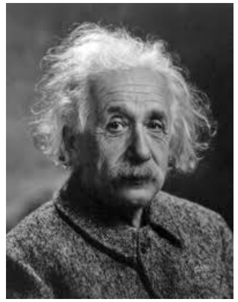
Rudolf Clausius, **Josiah Willard Gibbs**, and **Walther Nernst**.



Energy: a hint of history

It also led to a mathematical formulation of the concept of entropy by Clausius and to the introduction of laws of radiant energy by **Jožef Stefan**.



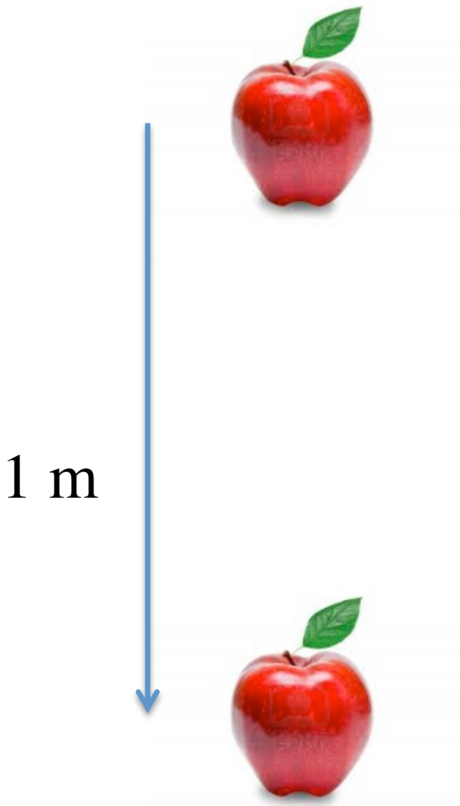
Albert Einstein proposed mass–energy equivalence in 1905 in a paper entitled "Does the inertia of a body depend upon its energy-content?".

Since 1918 it has been known that the law of conservation of energy is the direct mathematical consequence of the translational symmetry of the quantity conjugate to energy, namely time (**Emmy Noether**).

Use of energy

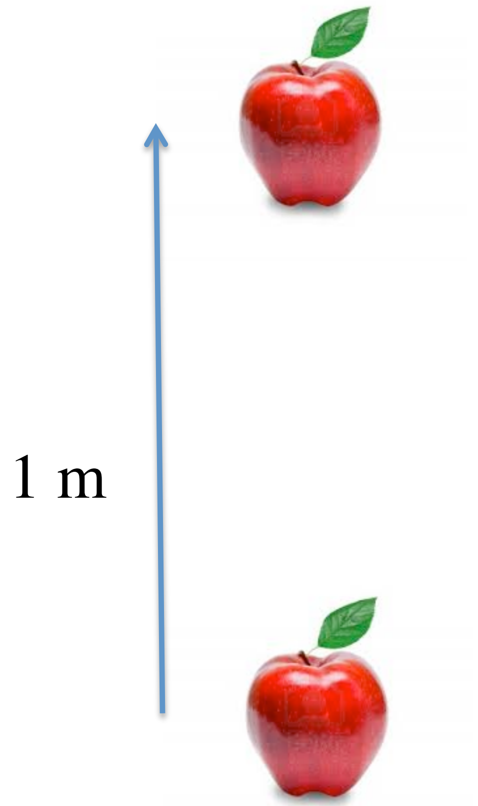
Unit of measure: Joule = 1 J = 1 N x 1 m

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

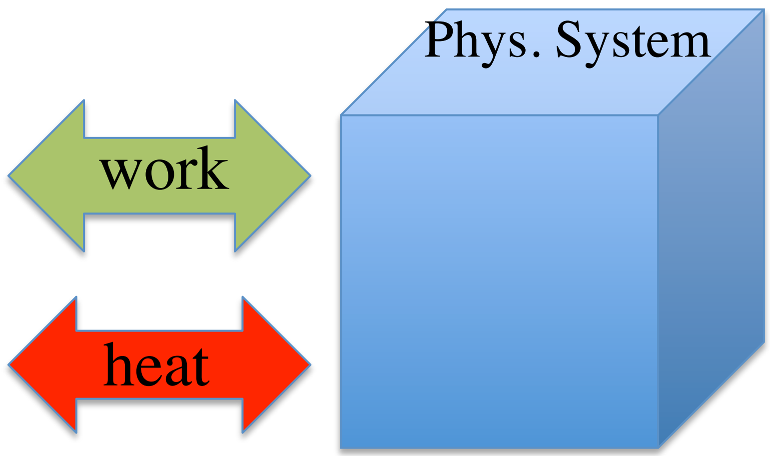
Is there any other way to change the energy content of a system?

Yes!

We can warm it up!

Energy

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



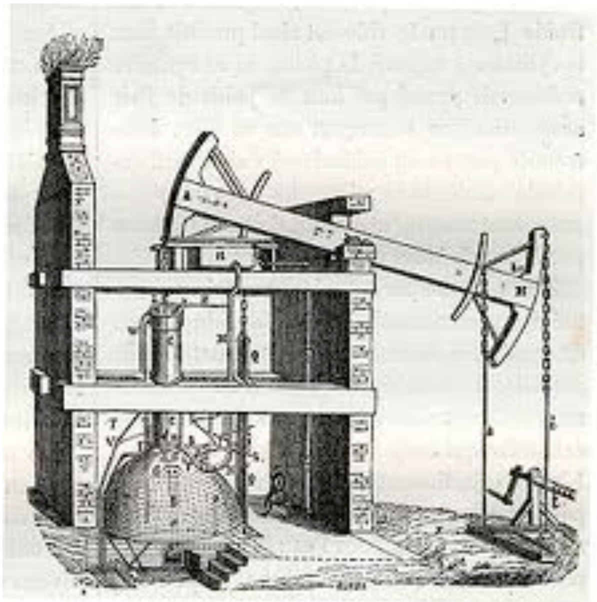
but there are some limitations…

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:

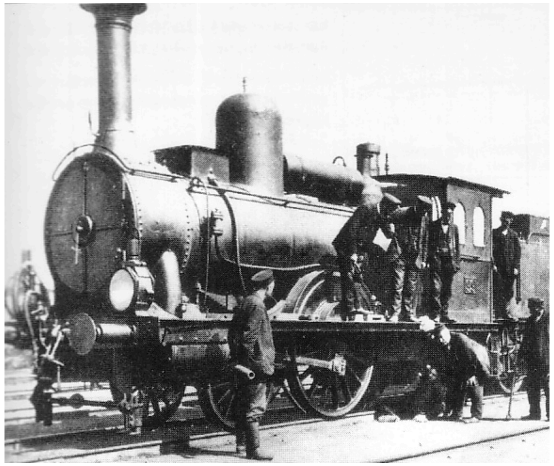
- how can we make the energy contained in a litre of gasoline to push forward a car
- how can we use the heat produced by burning coal to make the train run?

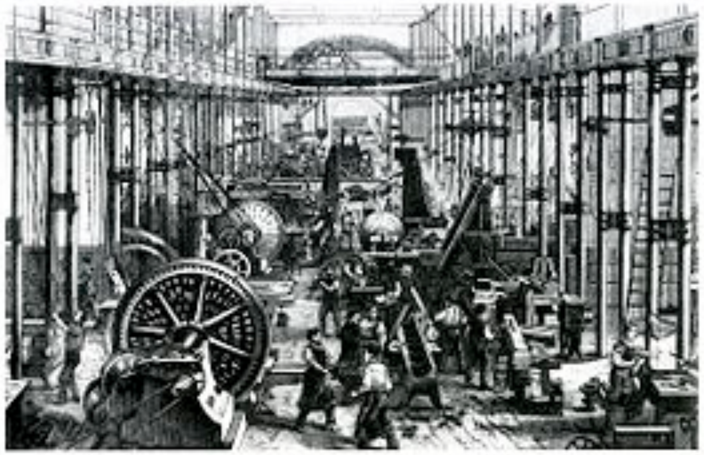


Questions like these were at the very base of the activities performed in the early seventeen hundreds by the first inventors of the so-called thermal machines.
People like **Thomas Newcomen** (1664-1729) who built the first practical steam engine for pumping water and **James Watt** (1736-1819) who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

Thermal Machines

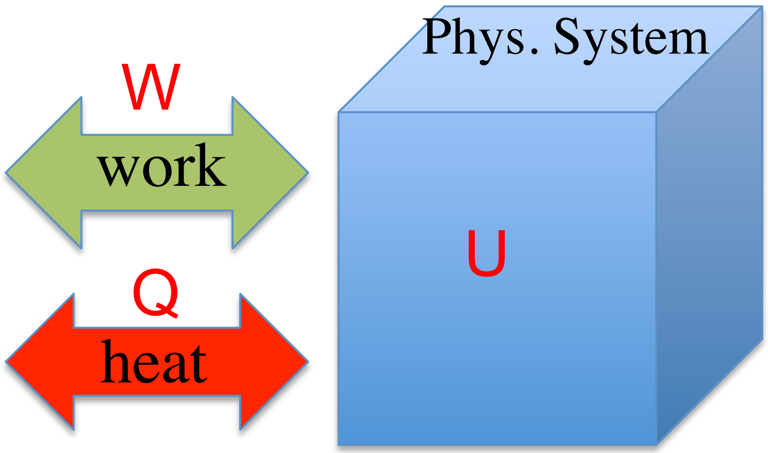
It is thanks to the work of scientists like Sadi Carnot (1796-1832) and subsequently of Émile Clapeyron (1799 - 1864), Rudolf Clausius (1822 - 1888) and William Thomson (Lord Kelvin) (1824 – 1907) that studies on the efficiency of these machines aimed at transforming heat (just a form of energy) into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

"Now, in the *second* law of thermodynamics . . ."

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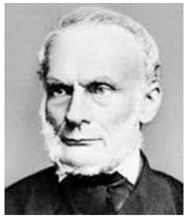
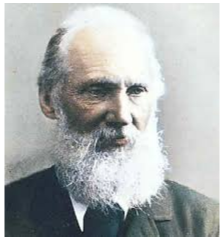
There exist different formulations that are all equivalent.
The two most popular are ascribed to Clausius and Kelvin:



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**".

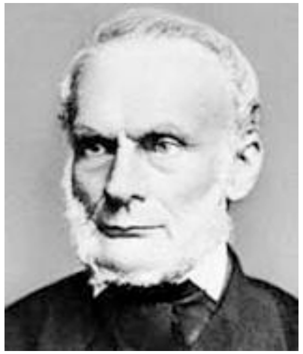


Kelvin formulation: "**No process is possible in which the sole result is the absorption of heat from a reservoir and its complete conversion into work**".

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.

ENTROPY



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

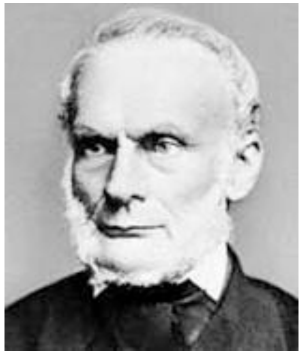
$$S_B - S_A = \int_A^B \frac{dQ}{T}$$

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*

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



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

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

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 an increase of the system entropy***. If we are not carefully enough the situation is even worst and we get even less work.***

This is sometimes accounted by the introduction of the so-called ***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).

$$F = U - T S$$

To learn more:

Energy Management at the Nanoscale
L. Gammaitoni

in the book "ICT - Energy - Concepts Towards Zero - Power Information and Communication Technology” InTech, February 2, 2014