European Summer Campus 2013
Strasbourg

Energy on all scales

Joël Pouthas

Laboratoire de Physique Corpusculaire
ENSICAEN, Caen, France

pouthas@lpccaen.in2p3.fr

European Summer Campus 2013
Strasbourg

What is energy ?

Richard
Feynman

Lectures
on
Physics

Summer Science Program 1960

European Summer Campus 2013
Strasbourg

Energy, the rise of a concept

Part I - Historical sketch

English: energy

French: énergie

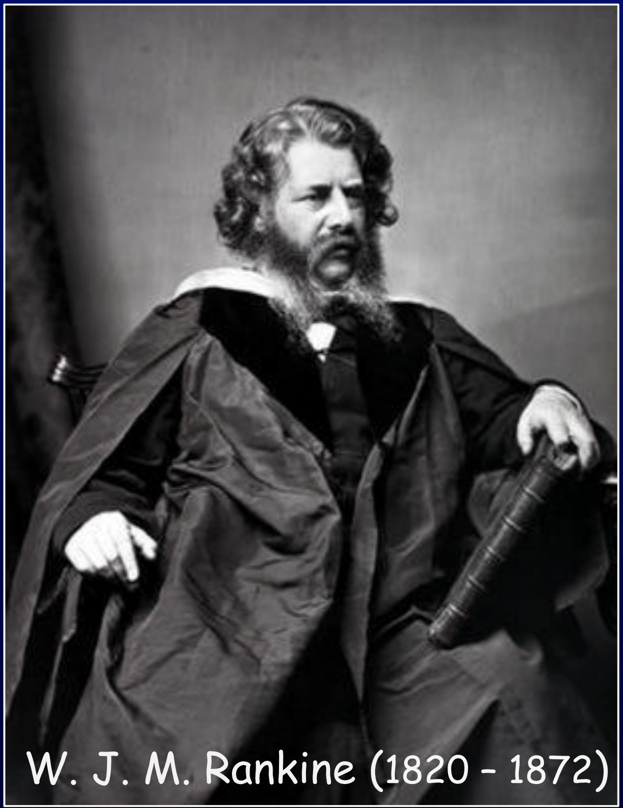
German: energie

Italian: energia

Greek: ἐνέργεια , energeia

Latin: energia

Origins in Physics (Natural Philosophy)



W. J. M. Rankine (1820 – 1872)

Outlines of the Science of Energetics

Read before the Philosophical Society of Glasgow on May 2, 1855

On the phrase "Potential Energy", and on the Definitions of Physical Quantities

Read before the Philosophical Society of Glasgow on January 23, 1867

7. About the beginning of the present century,★ the word "energy" had been substituted by Dr. Thomas Young for "vis viva," to denote the capacity for performing work due to velocity; and the application of the same word had at a more recent time been extended by Sir William Thomson to capacity of any sort for performing work. There can be no doubt that the word "energy" is specially suited for that purpose; for not only does the meaning to be expressed harmonise perfectly with the etymology of ενέργεια, but the word "energy" has never been used in precise scientific writings in a different sense; and thus the risk of ambiguity is avoided.

★1807

Miscellaneous Scientific Papers by W. J. Macquorn Rankine
London, Charles Griffin and Company, 1881

Origins in Physics (Natural Philosophy)

Late introduction of the word "Energy" in physics
(Nineteenth century)

… but

Notions of "force", "work", ""vis viva" already used in Mechanics

Capacity of performing work

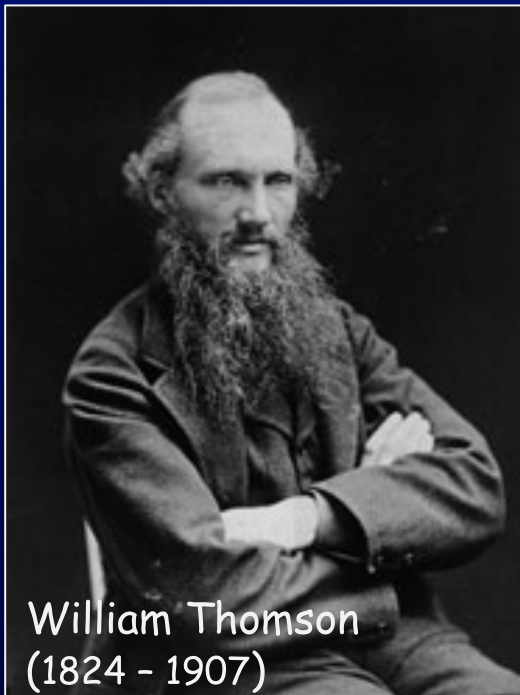
Steam engines
(Development in eighteen century)

Mid-nineteenth century

Development of "Thermodynamics"

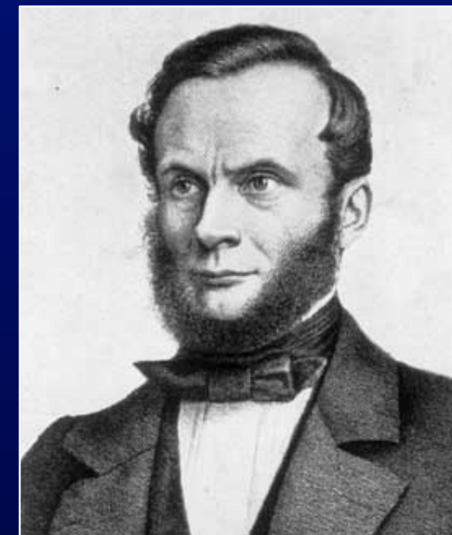
Relations between "heat" and "work"

Thermodynamics



William Thomson
(1824 – 1907)

Mid
Nineteenth
Century



Rudolf Clausius
(1822 – 1888)

Thermodynamics - Clausius

1822 Born in Pomerania (Prussia)

1844 Graduate From University of Berlin
1848 Doctorate from University of Halle
(Reflected light in the sky)

1850 Professor at Berlin (Royal Artillery School)
1855 Chair of Mathematical Physics at ETH Zurich
1867 University of Würzburg
1869 University of Bonn (Rector in 1884 and 1885)

1888 Died in Bonn

1850 On the motive power of heat and on the laws which can be deduced from it for the theory of heat*

I. Consequences of the principle of the equivalence of heat and work

II. Consequences of Carnot's principle in connection with the one already introduced

*Ueber die bewegende Kraft der Wärme und die Gesetze, welche sich daraus für die Warmelehre selbst ableitenlassen (Annalen der Physik und Chemie)

Equivalence of Heat and Work

Several actors in the 1840s
"Work" "Force" "Power" "Energy"

"Precursors"

- Benjamin **Thompson** (Count **Rumford**) (1753 – 1814)
  American-born. England. Bavaria. France. Interest in gunnery and explosives
  An Experimental Enquiry Concerning the Source of the Heat which is Excited by Friction (1798)

- Karl Friedrich **Mohr** (1806 – 1879) German chemist
  Uber die Natur der Wärme (1837) Transformation of "Kraft"

Julius Robert von Mayer

German physician and natural philosopher (1814 - 1878)

Travel on boat as a ship's doctor. Idea of equivalence of heat and work (1840)

4 papers: 1 rejected (1841) 1 published (1842)
2 printed at his own expense (1845 and 1848)

No personal experiment but use of existing results to obtain the First figure for equivalence between heat and work

Equivalence of Heat and Work

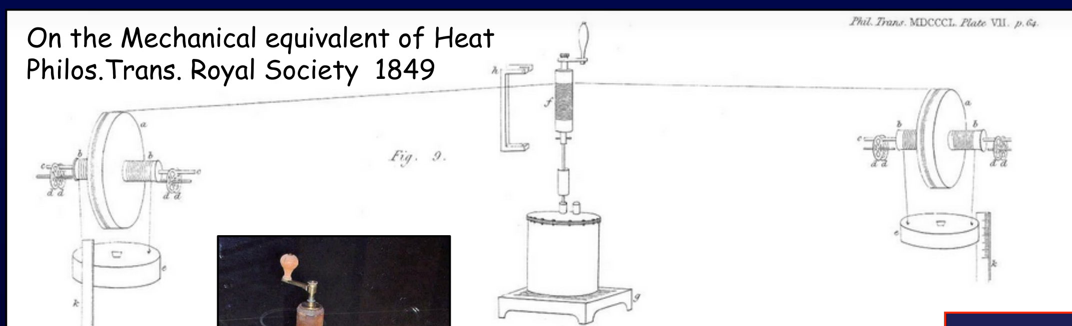
Several actors in the 1840s
"Work" "Force" "Power" "Energy"

James Prescott Joule

English brewer and physicist (1818 - 1889)

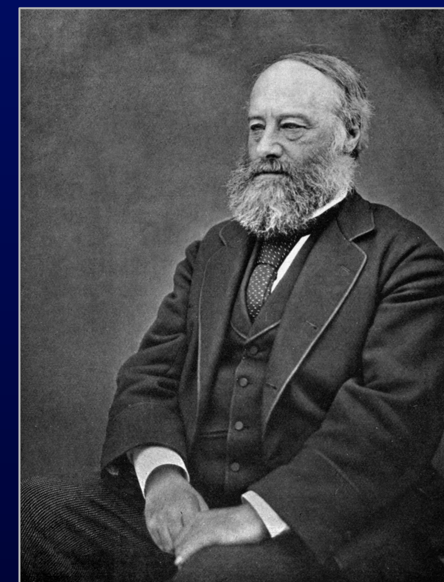
Interest in electricity (Heat and current => Joule's law)

On the Mechanical Equivalent of heat (1845 and 1847)
(Reports of the British Association for the advancement of Science)



On the Mechanical equivalent of Heat
Philos.Trans. Royal Society 1849


Apparatus
Science Museum, London


Joule (1818 – 1889)

To day

The joule (J) is the Unit of Energy

$$1 \text{ J} = 1 \text{ kg. m}^2 / \text{s}^2$$

Equivalence of Heat and Work

Several actors in the 1840s
"Work" "Force" "Power" "Energy"

"Others"

- Ludwig August Colding (1815 - 1888) Danish civil engineer and physicist
- Gustave-Adolphe Hirn (1815 - 1890) French manufacturer and physicist

Hermann von Helmholtz

German physiologist and physicist (1821 - 1894)

On the Conservation of Force (1847)
Über die Erhaltung der Kraft

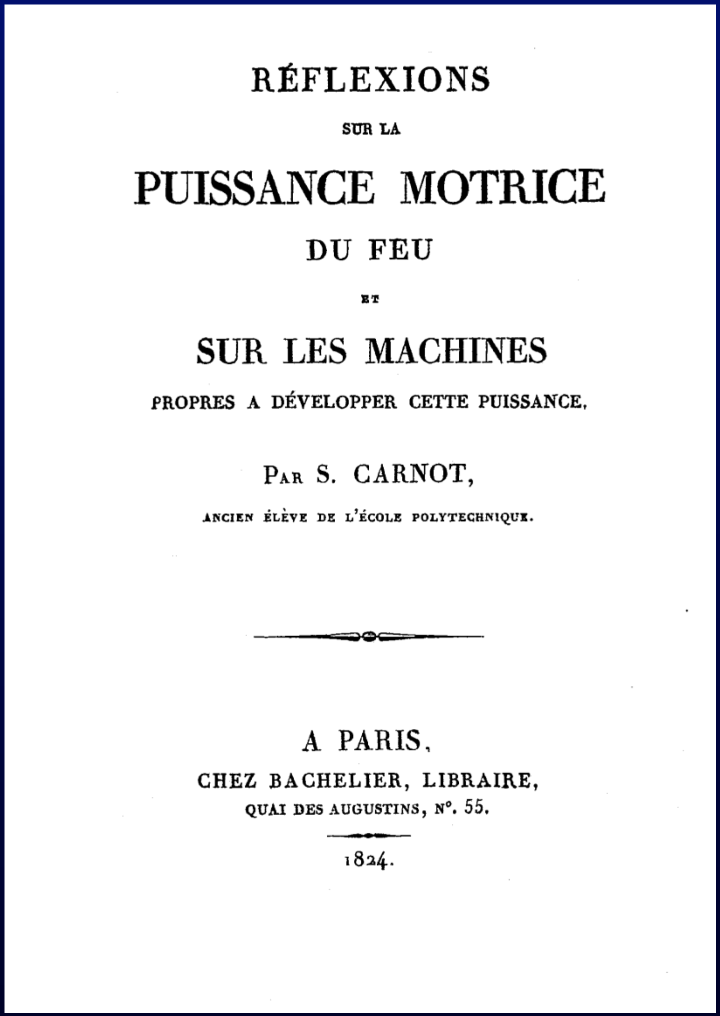
Considerations on heat and human action versus
the impossibility of perpetual motion
Formulation of the concept of "Conservation (Erhaltung)"
in the framework of mechanics

Carnot's principle ?

Sadi Carnot

1796	Born in Paris (Son of Lazare Carnot)
1812	Ecole Polytechnique
1814	Ecole de Metz and (weak) military activities
1819	Paris (General Staff). Personal works
1828	Retired (without pension) from the army
1832	Died of cholera

Carnot's principle ?



RÉFLEXIONS

SUR LA

PUISSANCE MOTRICE

DU FEU

ET

SUR LES MACHINES

PROPRES A DÉVELOPPER CETTE PUISSANCE,

PAR S. CARNOT,

ANCIEN ÉLÈVE DE L'ÉCOLE POLYTECHNIQUE.

A PARIS,

CHEZ BACHELIER, LIBRAIRE,

QUAI DES AUGUSTINS, N°. 55.

1824.

1824

In 1813 by Louis-Léopold Boilly

Reflexions
on the
Motive power
of fire
and
on machines
fitted to develop that power

Carnot's principle ?

RÉFLEXIONS

SUR LA

PUISSANCE MOTRICE

DU FEU.

Personne n'ignore que la chaleur peut être la cause du mouvement, qu'elle possède même une grande puissance motrice : les machines à vapeur, aujourd'hui si répandues, en sont une preuve parlante à tous les yeux.

C'est à la chaleur que doivent être attribués les grands mouvemens qui frappent nos regards sur la terre ; c'est à elle que sont dues les agitations de l'atmosphère, l'ascension des nuages, la chute des pluies et des autres météores, les courans d'eau qui sillonnent la surface du globe et dont l'homme est parvenu à employer pour son usage une faible partie ; enfin les tremblemens de terre, les éruptions volcaniques, reconnaissent aussi pour cause la chaleur.

C'est dans cet immense réservoir que nous pouvons puiser la force mouvante nécessaire à

1824

(2)

nos besoins ; la nature, en nous offrant de toutes parts le combustible, nous a donné la faculté de faire naître en tous temps et en tous lieux la chaleur et la puissance motrice qui en est la suite. Développer cette puissance, l'approprier à notre usage, tel est l'objet des machines à feu.

Steam engines – Historical roots

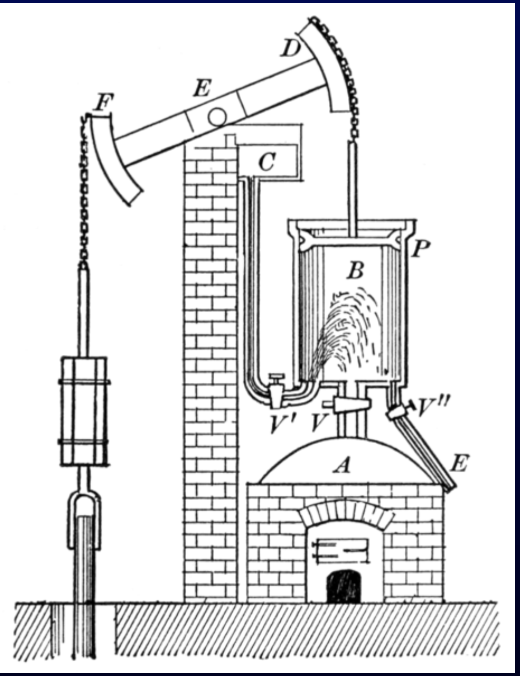
Condensation of hot steam -> Production of a partial vacuum in a vessel

~ 1700 Piston in a cylinder : Denis Papin (1647 - 1712)

1698 "Fire engine" by Thomas Savery (1650 - 1715)
Pumping water in mines (only few samples)

1712 Engine by Thomas Newcomen (1654 - 1729)
Pumping water in mines (Savery's patent)

~ 75 engines on 1730

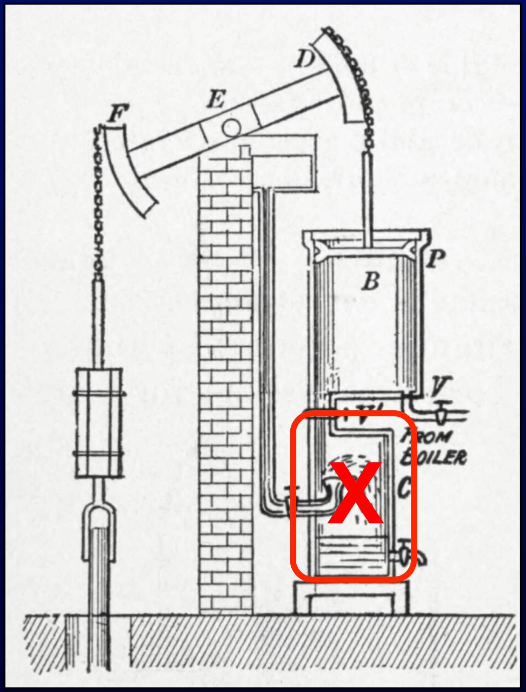


"Atmospheric condensing engine"

The "motive power"
is the
Atmospheric pressure

Steam engines - Watt

Work on the Newcomen engine
(Model, economy)
-> 1765 Introduction of the Condenser



Immersion of the condenser
in cold water

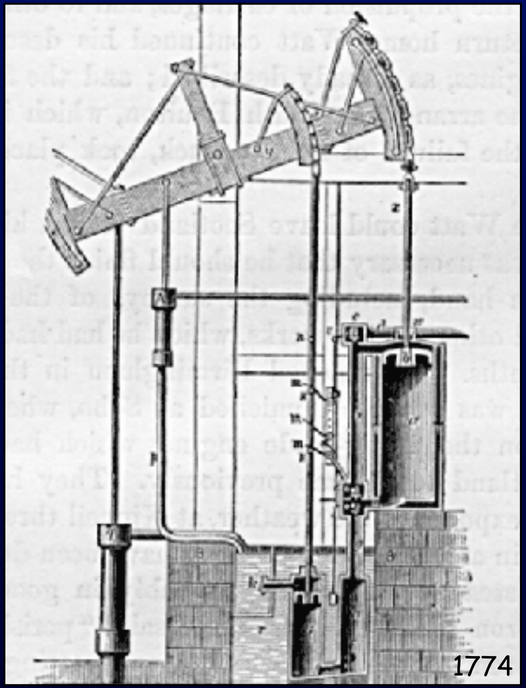
James Watt (1736 – 1819)

Steam engines - Watt

Matthew Boulton (1728 – 1809)

Manufacturer

Other improvements:
Sealing the top of the cylinder
and injection of steam on the upper part
Etc…

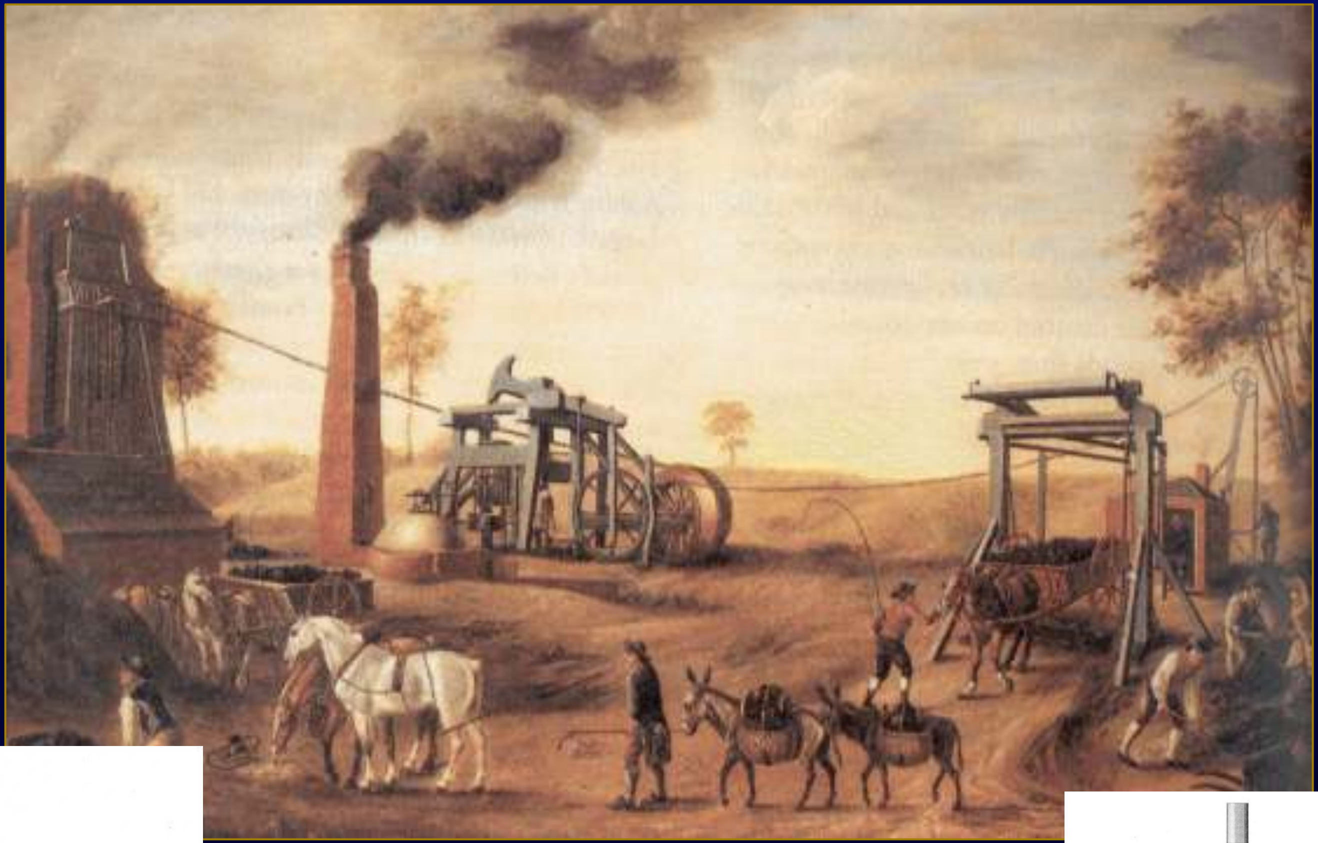


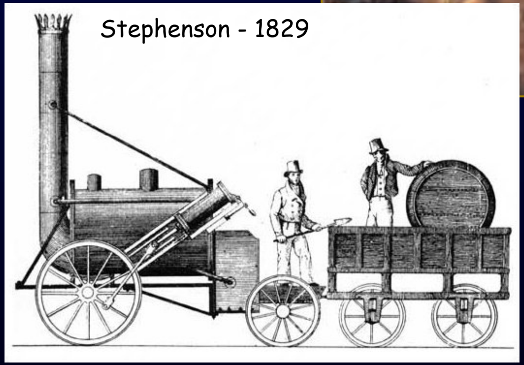
James Watt (1736 – 1819)

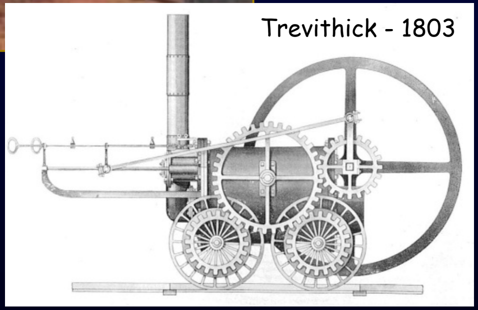
Engineer

Final quarter of the 18th century

Steam engines - Industrialisation





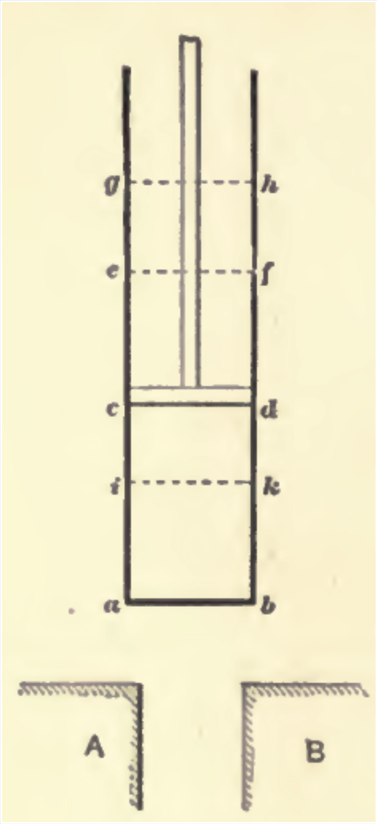


Steam engines - Industrialisation

Ebley Cloth Mills, Gloucestershire c.1850 Painting by Alfred Newland Smith

"Carnot cycle"

1824 S. Carnot Reflexions on the motive power of fire and on machines fitted to develop that power



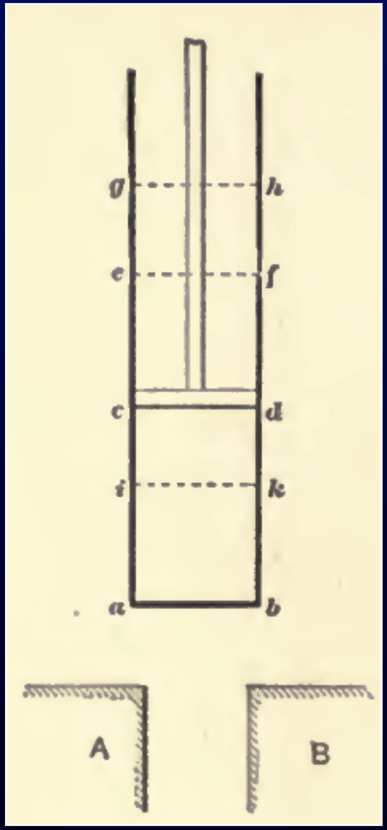
Carnot's work

1824 S. Carnot — Reflexions on the motive power of fire and on machines fitted to develop that power

1834 E. Clapeyron — Mémoire sur la puissance motrice de la chaleur (Memoir on the motive power of heat)

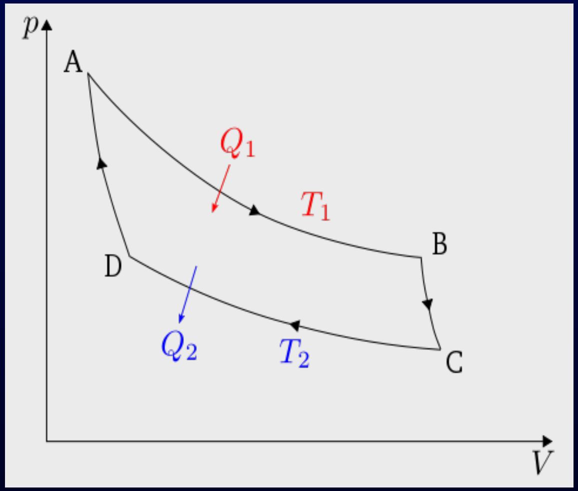
Journal de L'Ecole Polytechnique

Emile Clayperon (1799 – 1864)



Carnot cycle

Modern representation on a pressure-volume graph



(Not in the Carnot treatise)

Legacy of the Carnot's work

1824	S. Carnot	Reflexions on the <u>motive power</u> of fire and on machines fitted to develop that power (French)
1834	E. Clapeyron	Memoir on the motive power of heat (French) Translations: English 1837, German 1843
1848	W.Thomson	On an Absolute Thermometric Scale founded on Carnot's Theory of the Motive Power of Heat, and calculated from Regnault's observations (English)
1849	W.Thomson	An Account of Carnot's Theory of the Motive Power of Heat with Numerical Results deduced from Regnault's Experiments on Steam (English)
1850	R. Clausius	On the motive power of heat and on the laws which can be deduced from it for the theory of heat (German)

Thermodynamics - Thomson

1822	Born at Belfast
1833	Family moved to Glasgow
1845	High level graduation (Mathematics) at Cambridge
1846	Professor at Glasgow (Natural Philosophy)
1892	Baron Kelvin of Largs (Knighted in 1866)
1907	Died at Largs, Scotland

Thermodynamics - Clausius

1850 On the motive power of heat and on the laws which can be deduced from it for the theory of heat

I. Consequences of the principle of the equivalence of heat and work

II. Consequences of Carnot's principle in connection with the one already introduced

1854 On another form of the second law of the mechanical theory of heat

Zweite Haupsatze
der mechanishen Warmetheorie

(Second "main proposition" of the mechanical theory of heat)

Satz von der Aequivalenz der Verwandlungen

("Principle" of the equivalence of transformations)

For all the reversible close cycles,
the analytical expression of the second law of the mechanical theory of heat is:

$$\int dQ/T = 0$$

Thermodynamics - Clausius

1850 On the motive power of heat and on the laws which can be deduced from it for the theory of heat

1854 On another form of the second law of the mechanical theory of heat

1862 On the application of the principle of the equivalence of transformations to internal work

1865 On several convenient forms of the fundamental equations of the mechanical theory of heat

On a reversible cycle : "Equivalence of transformation" $\int dQ/T = S - S_0$

"I propose to name the quantity S the entropy of the system, after the Greek word τροπη transformation.

I have deliberately chosen the word entropy to be as similar as possible to the word energy: the two quantities to be named by these words are so closely related in physical significance that a certain similarity in their names appears to be appropriate."

Part I – Summary

Origins of the concept of energy in physics

Natural philosophy (Physics)

Motion of bodies - Forces
17th century

Human Physiology

19th century

Industrial revolution

Heat engines
18th century

1840's - Equivalency of Heat and Work
(Conservation of Energy)

1850's - Thermodynamics
2 Laws

To day "Classical Mechanics"

Kinetic energy $T = \frac{1}{2}mv^2$

Potential energy $V = mg.h$

(1 dimension,1 particle of mass m)

Lagrangian mechanics (1788)

Hamiltonian mechanics (1833)
$H = T + V$

To day "Classical Thermodynamics"

Energy (U) $dU = \delta Q + \delta W$
(Q: Heat ; W: Work)

Entropy (S) $dS = (\delta Q)_{rev}/T$
(T: absolute temperature)

Industrial revolution

Le Creusot (France) on 1847

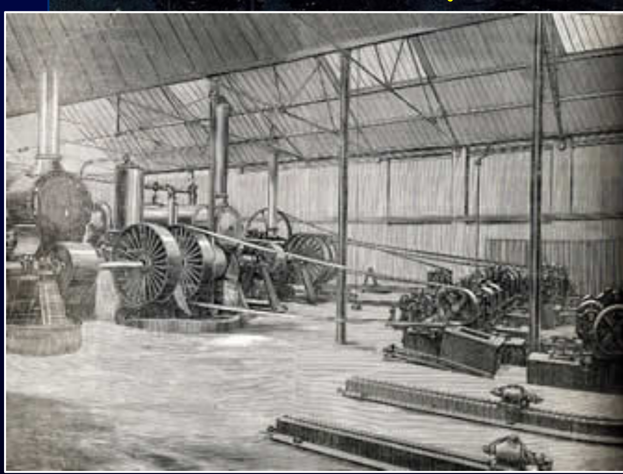
Lithography according to the watercolor of Trémaux

Industrial revolution

Thomas Edison (1847 – 1931)

Electricity

Chemistry



Nikola Tesla
(1856 – 1943)

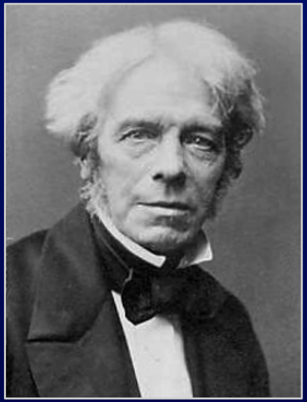
Brighton Electric Light Station in 1887.

Liebig Laboratory at Giessen , 1850's

Energy - Physics – Nineteenth century

Mechanics

Thermodynamics



Michael Faraday
(1791 – 1867)

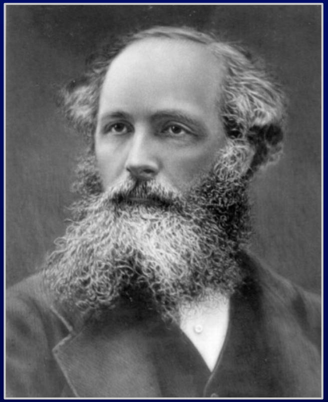
Electricity

Magnetism

Electromagnetism

(Waves)

Chemistry



James Clerk Maxwell
(1831 – 1879)

Energy - Physics – Nineteenth century

Mechanics Thermodynamics

Wilhelm Ostwald
(1853 – 1932)

Electricity Magnetism

Electromagnetism

(Waves)

Chemistry

Pierre Duhem
(1861 – 1916)

Energetik Energetics Energétisme

"Energy in all forms" at our (human) scale

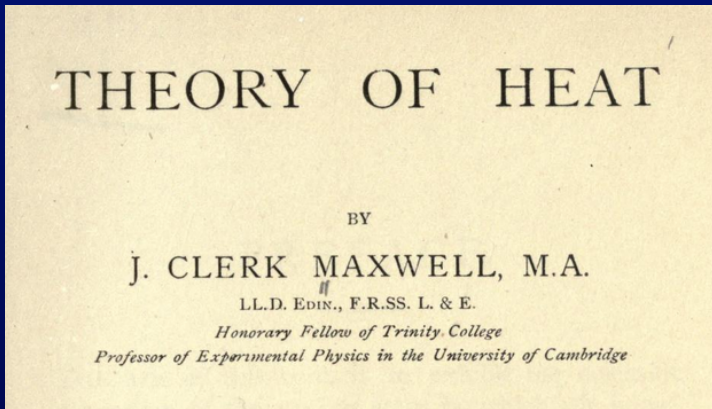
Production Storage Distribution Consumption
Efficiency Safety Management

European Summer Campus 2013
Strasbourg

Energy on all scales

Part II - Energy and atoms

Kinetic theory of gases


THEORY OF HEAT

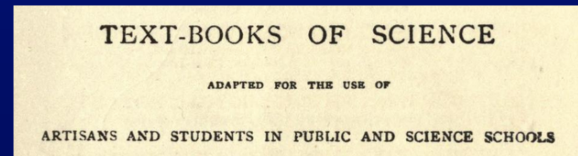
BY

J. CLERK MAXWELL, M.A.

LL.D. EDIN., F.R.SS. L. & E.

Honorary Fellow of Trinity College

Professor of Experimental Physics in the University of Cambridge

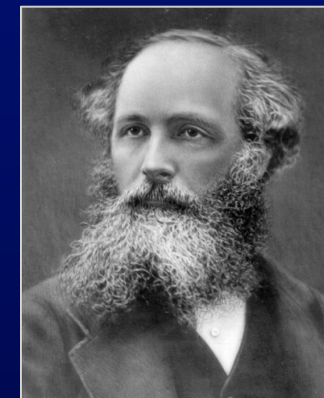

TEXT-BOOKS OF SCIENCE

ADAPTED FOR THE USE OF

ARTISANS AND STUDENTS IN PUBLIC AND SCIENCE SCHOOLS

First edition: 1872

James Clerk Maxwell
(1831 – 1879)



Energy of a hot body <-> Motion of its parts (molecules)

History (Overview by Maxwell)

Pressure of gases due to the impact of molecules on the recipient walls

Clausius: "Dynamical theory of gases"

Clausius 1857 "The living force of the translation movement is proportional to the absolute temperature"

1858 Introduction of the notion of "Mean (free) path" ("Mittlere Weglänge")

Mathematical relation between "macroscopic" and "microscopic" levels

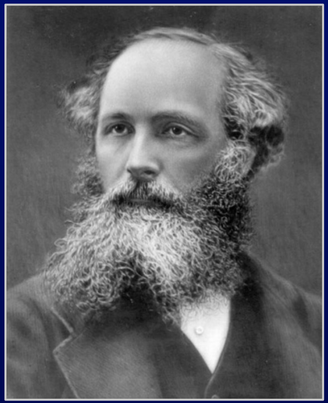
Kinetic theory of gases

James Clerk Maxwell

1860 Illustrations of the Dynamical Theory of Gazes
Read at the BAAS, Sept 1859. Published in Philosophical Magazine 1860

1866 On the Dynamical Theory of Gazes
Proceedings of the Royal Society of London (Received May 1866)

"Maxwell's Distribution"
Velocity distribution law of particles in gases



James Clerk Maxwell
(1831 – 1879)

Ludwig Boltzmann

1844 Born in Vienna, Austria

1866 Doctorate with Stefan. Lecturer

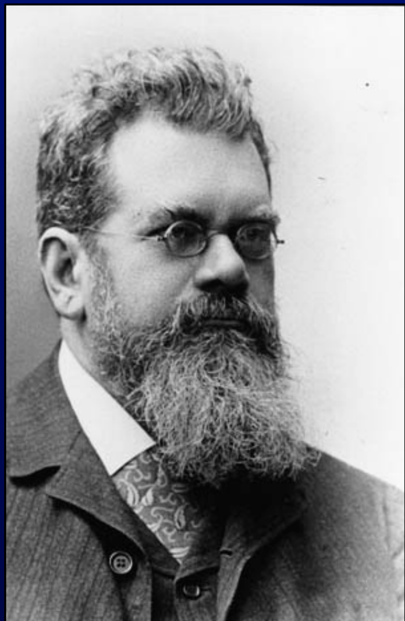
Professor

1869 Graz (Mathematical Physics) 1873 Vienna (Mathematics)
1876 Graz (Experimental Physics) 1890 Munich (Theoretical Physics)
1894 Vienna (Theoretical Physics) 1900 Liepzig (Invited by Ostwald)
1902 Vienna (Physics and Naturphilosophie)

1906 Suicide at Duino

Ludwig Boltzmann
(1844 – 1906)

Boltzmann – Entropy and statistics



Ludwig Boltzmann
(1844 – 1906)

$S = k.\log W$

1872 Weitere Studien über das Wärmegleichgewicht unter Gasmolekülen
Wiener Berichte 66 (1872) 275-370
(Complementary studies on the thermal equilibrium of gas molecules)

"Boltzmann equation"
Evolution of the distribution [f] of the kinetic energy of molecules in collisions

"H Theorem"
It exists a quantity [$H = \int f.\log(f)$] which never increase

1877 Über die Beziehung swischen dem zweiten Hauptsatze der mechanischen Wärmetheorie und der Wahrscheinlichkeitsrechung respektive den Sätzen ûber das Wärmegleichgewicht. Wiener Berichte 76 (1877) 373-435
(About the relation between the second law of the mechanical theory of heat and the probability calculations applied to the thermal equilibrium)

Proportionality of entropy and distribution of states of kinetic energy

1891 & 1893 (2 Vol.) Vorlesungen über Maxwells Theorie der Elektrizität und des Lichts

1896 & 1898 (2 Vol.) Vorlesungen über Gastheorie

1897 & 1904 (2 Vol.) Vorlesungen über Prinzipien der Mechanik

In the 19th century, Atomism was not prevailing in Physics… and Chemistry

Energy – Beginning of 20th century - Overview

Max Planck

1858 Born in Kiel, Germany

Educated at Munich and Berlin

1879 Doctorate dissertation (Munich):
Über den zweiten Hauptsatz der mechanischen Wärmetheorie

1889 - 1926 Professor at Berlin University

Book "Thermodynamik" (Thermodynamics) (1897)

1947 Died at Göttingen

Black-body radiation

Empirical laws (Wien)

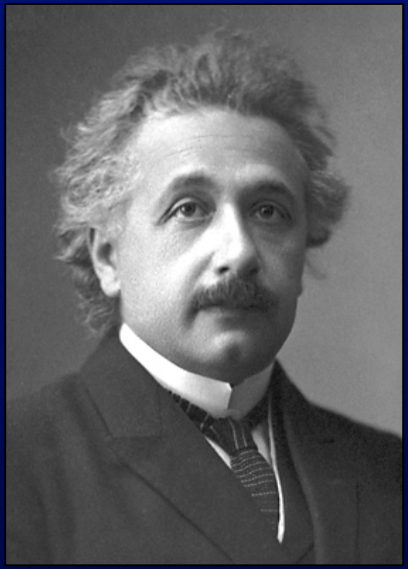
1900… Planck

Calculations based on a set of N resonators with frequency ν. (Energy element: ε = h.ν)

Publications: mainly in Annalen der Physik
Book: Theorie der Wärmestrahlung (Theory of heat radiation) (1906)

1918 Nobel Prize in Physics "in recognition of the services he rendered to the advancement of Physics by his discovery of energy quanta".

Energy – Beginning of 20th century - Overview



Albert Einstein

1879 Born in Ulm, Germany

1896 – 1900 Student at ETH Zurich (Polytechnic institute)
1896 – Stateless

1902 – 1909 Patent office at Bern
1901 – Swiss citizenship

1908 – 1914 Teaching positions at Bern, Zurich, Prague

1914 Professor at Berlin University

1932 Professor at IAS Princeton

1933 Emigration in US

1940 – US citizenship (Still Swiss)

1955 Died at Princeton

First publications in Annalen der Physik

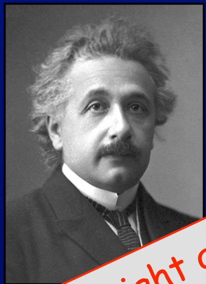
1901 and 1902 2 papers on intermolecular forces

1902 Kinetische Theorie des Wärmegleichgewichtes und des zweiten Hauptsatzes der Thermodynamik
(Kinetic Theory of Thermal Equilibrium and of the Second Law of Thermodynamics)

1903 Eine Theorie der Grundlagen der Thermodynamik (A Theory of the Foundations of Thermodynamics)

1904 Zur allgemeine molekulare Theorie der Wärme (On the General Molecular Theory of Heat)

Albert Einstein – 1905 - Overview



Light quanta

…ber einen die Erzeugung und Verwandlung des Lichtes betreffenden …uristischen Gesichtspunkt
On a Heuristic Point of View about the Creation and Conversion of Light

Received AdP
17th March

Brownian motion

…ber die von der molekularkinetischen Theorie der Wärme geforderte …ewegung von in ruhenden Flüssigkeiten suspendierten Teilchen
On the Movement of Small Particles Suspended in Stationary Liquids Required by the Molecular-Kinetic Theory of Heat

Received AdP
11th May

Relativity

…berZur Elektrodynamik bewegter Körper
On the Electrodynamics of Moving Bodies

Received AdP
30th June

Relativity

…t die Trägheit eines Körpers von seinem Energieinhalt abhängig?
Does the Inertia of a Body Depend Upon Its Energy Content?

Received AdP
27th Sept.

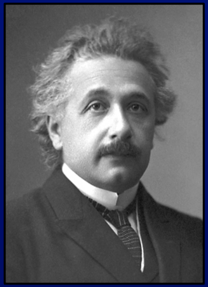
Brownian motion

…r Theorie der Brownschen Bewegung
On the Theory of Brownian Motion

Received AdP
19th Dec.

<u>Doctoral dissertation</u> Completed on 30th April - Printed in Bern (Buchdruckerei K. J. Wyss, Bern, 1906)
Submitted at Zurich University - Accepted on July - Published in AdP

Eine neue Bestimmung der Moleküldimensionen
A New Determination of Molecular Dimensions



Albert Einstein – 1905 - Overview

Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt
On a Heuristic Point of View about the Creation and Conversion of Light

Received AdP
17th March

"Photoelectric effect"
Proposal of the photon as a quantum of energy

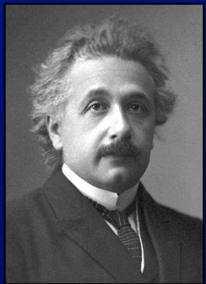
1921 Nobel Prize in Physics "for his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect"

The "Quantum discontinuity" was introduced in relation with radiation

ÜberZur Elektrodynamik bewegter Körper
On the Electrodynamics of Moving Bodies

Received AdP
30th June

"Special relativity"



Albert Einstein – 1905 - Overview

Ist die Trägheit eines Körpers von seinem Energieinhalt abhängig?
Does the Inertia of a Body Depend Upon Its Energy Content?

Received AdP
27th Sept.

Gibt ein Körper die Energie L in Form von Strahlung ab, so verkleinert sich seine Masse um L/V^2. Hierbei ist es offenbar unwesentlich, daß die dem Körper entzogene Energie gerade in Energie der Strahlung übergeht, so daß wir zu der allgemeineren Folgerung geführt werden:

Die Masse eines Körpers ist ein Maß für dessen Energieinhalt; ändert sich die Energie um L, so ändert sich die Masse in demselben Sinne um $L/9.10^{20}$, wenn die Energie in Erg und die Masse in Grammen gemessen wird.

Es ist nicht ausgeschlossen, daß bei Körpern, deren Energieinhalt in hohem Maße veränderlich ist (z. B. bei den Radiumsalzen), eine Prüfung der Theorie gelingen wird.

Wenn die Theorie den Tatsachen entspricht, so überträgt die Strahlung Trägheit zwischen den emittierenden und absorbierenden Körpern.

Bern, September 1905.

(Eingegangen 27. September 1905.)

E = mc² was introduced as a consequence of "relativity" (radiation & motion)

Energy – Beginning of 20th century - Overview

What about energy in atoms ?

Atomic nucleus

1911 Rutherford. Explanation of the diffusion of alpha particles
1913 Bohr. Introduction of the quantum of action (levels of energy)

Binding energy - Mass excess

1913 J.J. Thomson. Neon20 and 22. Notion of "Isotopes", "same place" (F. Soddy)
1919 Aston. Mass spectrograph. Precise "atomic weights" measurement

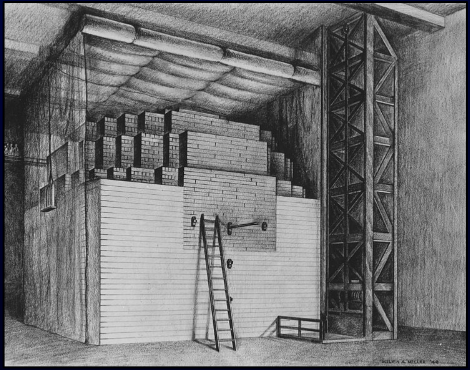
Huge energy in the nuclei ($E = mc^2$)... but not accessible !

Neutron and nuclei models

1932 Chadwick. Discovery of the neutron
Heisenberg Model of nuclei with protons and neutrons

Atom Fission and nuclear energy

1938 Hahn and Strassmann Experimental discovery of fission
1942 Fermi at Chicago First experimental nuclear reactor
1945 "Atomic bomb" Trinity site. Hiroshima and Nagasaki




Strasbourg, France
August 26 – September 5, 2013
European Summer Campus
École d'été franco-allemande
Energy on all scales
For Students in Physics having completed
3 years of university studies