# Historical aspects in the development of the concept of energy

## from Aristotle to Rankine

Alessandro Pascolini

Pöllau, Energietag 2014

# the offer:

- the word ‘energy’
- what is energy?
- the concept and the principle of conservation of energy
- the threads to the principle
  ~ force of body in motion
  ~ mechanics and mathematics
  ~ the concept of work
  ~ vital forces
  ~ thermology and heat
- the principle of conservation
- the concept and the language
- what is energy?
- new paradigm, new concept

# Words: ‘energeia’

It all started with Aristotle, whose use of the word profoundly marked European philosophy and science in all stages of their development.
The meaning of 'actuality' (energeia) can be explained only together with its counterpart 'potentiality’ (dynamis).
This pair of opposites underlies the most important problem in Aristotelian physics, namely that of motion. Matter is the potential thing actualized by the 'energy' of form; but matter and form are inseparable, inasmuch as the actual is itself potential having reached completion.
Aristotle's definition of motion:
“The fulfilment of what exists potentially, insofar as it exists potentially, is motion” (*Physics, book III*)

The dichotomy energeia/dynamis foreruns the energy/force dichotomy of the XIX century

The great Aristotelian interpreters of Nature, Albertus Magnus and Thomas Aquinas, accepted in principle that the most original Aristotelian contribution to physical science consisted in the discovery of pure potentiality as a reality.

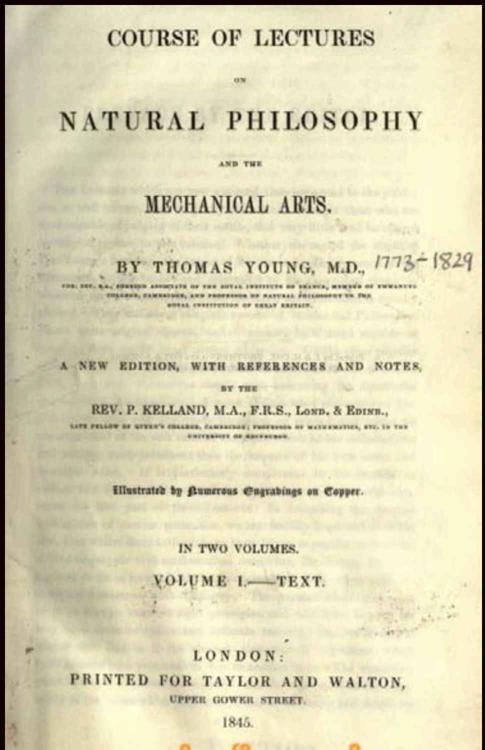
**After Aristotle, the term ‘energy’ (in various languages) was commonly used by scientists but as a literary, non-technical term.**

**The *Oxford English Dictionary* defines energy as**
**‘force or vigour of expression’ (since 1599);**
**‘exercise of power’ (1626);**
**‘ability to produce an effect’ (1677)**

**The first modem usage of the word in English was by Thomas Young in 1807, but this term did not achieve widespread currency before William Thomson (1852)**

# The concept and the language

**Young coined the very term 'energy' in 1807 in his *Lectures On Natural Philosophy* for "living or ascending force" for the kinetic quantity $mv^2$ (*vis-viva),* and stated that this was "proportional to the labour expended in producing [the] motion".**



COURSE OF LECTURES

ON

NATURAL PHILOSOPHY

AND THE

MECHANICAL ARTS.

BY THOMAS YOUNG, M.D., 1773–1829

A NEW EDITION, WITH REFERENCES AND NOTES,

BY THE

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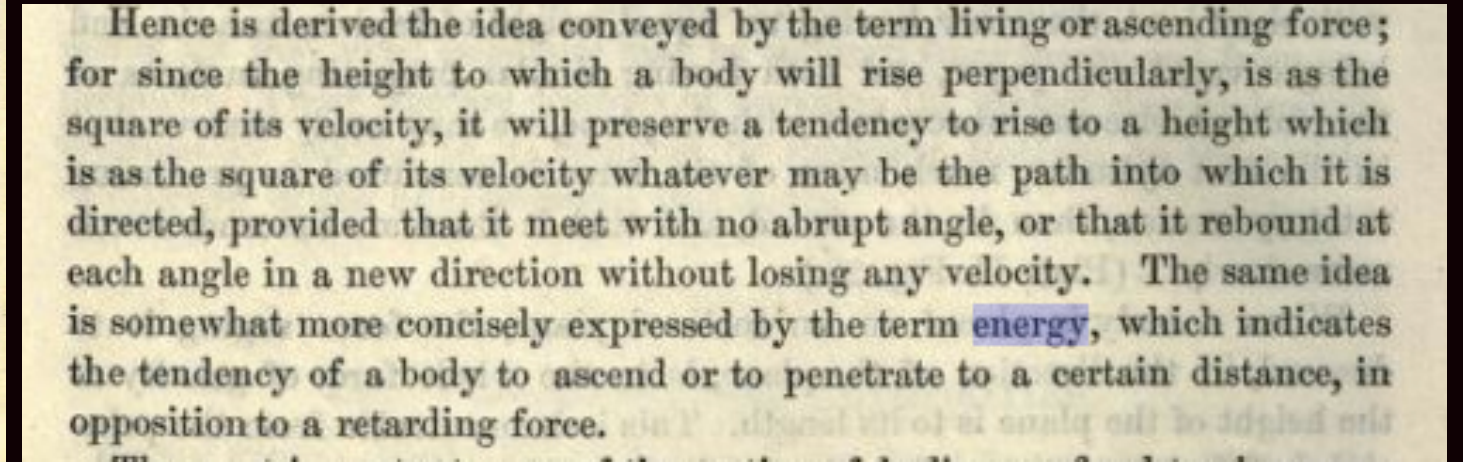


Hence is derived the idea conveyed by the term living or ascending force; for since the height to which a body will rise perpendicularly, is as the square of its velocity, it will preserve a tendency to rise to a height which is as the square of its velocity whatever may be the path into which it is directed, provided that it meet with no abrupt angle, or that it rebound at each angle in a new direction without losing any velocity. The same idea is somewhat more concisely expressed by the term energy, which indicates the tendency of a body to ascend or to penetrate to a certain distance, in opposition to a retarding force.

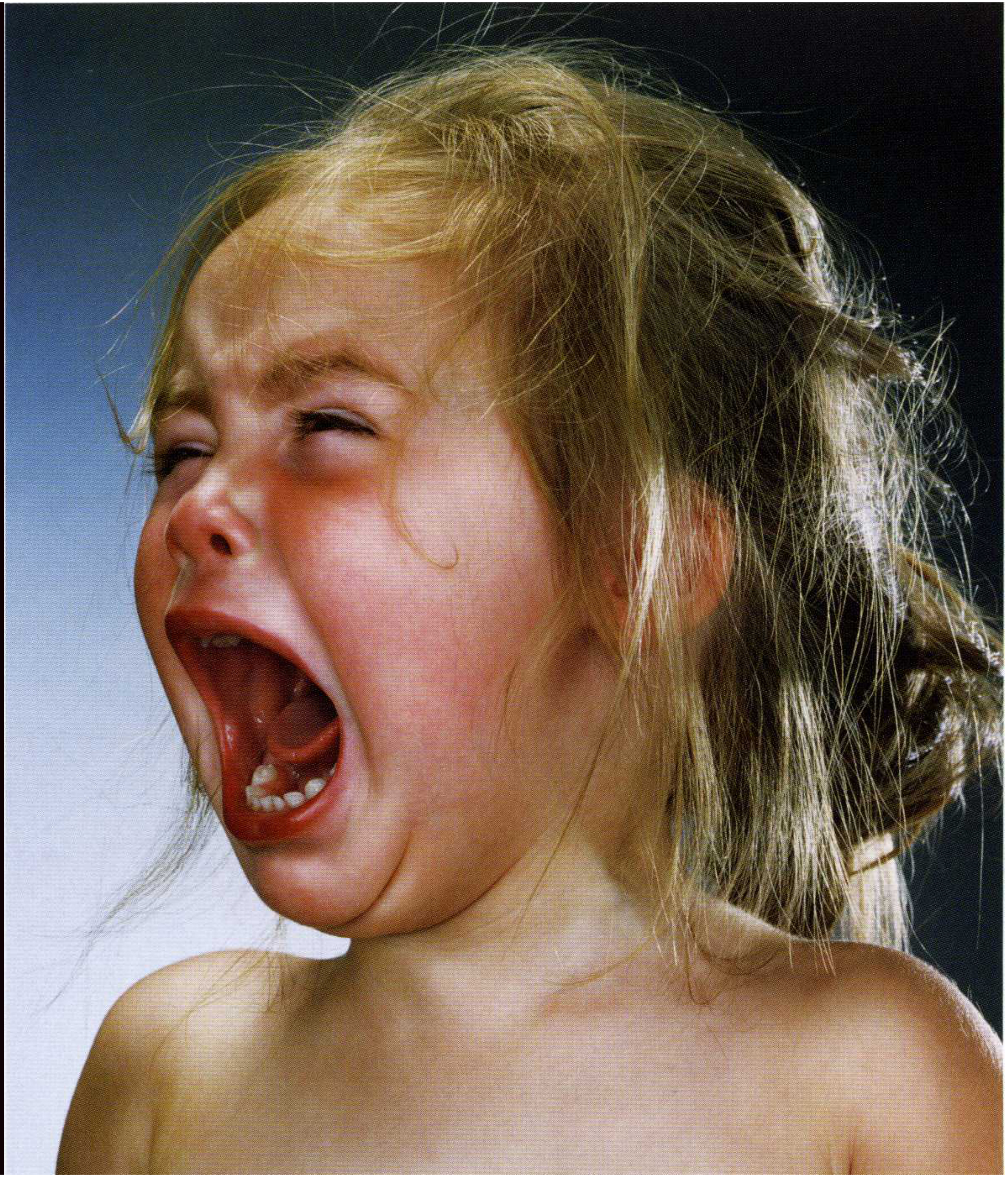
# words, words, words

**forza, potenze, impeto, talento, energia, virtù, possanza, momento della potenza, impetus, ability, energy, momentum of descent of the moving body, virtus movens, impetuosity, propensity, quantity of motion, labour, travail, effet naturel, effet general, potentia, duty, capacity for work, power, living force, ascending force, fall-force, hidden vis viva, latent vis viva, moment of activity, ordinary momentum, mechanical momentum, source of work, mechanical equivalent, mechanical value, mechanical power, potential, force vive virtuelle, vis potentialis, potential function, work-function, vis mortua, vis potentia, vitesse virtuelle, vis, force, vis vivaactual energy, efficaciam quandam, Kraft, Spannkraft, Arbeitakraft, Bewegungskraft, bewegende Kraft, lebendige Kraft, wirkende Kraft…**

# No despair!

**"In the world of human thought generally, and in physical science particularly, the most important and fruitful concepts are those to which it is impossible to attach a well-defined meaning"**

*H.A. Kramers*



# What is energy?

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

**However, there are formulas for calculating some numerical quantity, and when we add it all together it gives always the same number. The energy has a large number of different forms, and there is a formula for each one. These are: gravitational energy, kinetic energy, heat energy, elastic energy, electrical energy, chemical energy, radiant energy, nuclear energy, mass energy.**
**If we total up the formulas for each of these contributions, it will not change except for energy going in and out."**

**“There is a fact, or if you wish, a law, governing all natural phenomena that are known to date. There is no known exception to this law — it is exact so far as we know.**

**The law is called the conservation of energy.**
**It states that there is a certain quantity, which we call energy, that does not change in the manifold changes which nature undergoes.**
**That is a most abstract idea, it is not a description of a mechanism, or anything concrete; it is just a strange fact that we can calculate some number and when we finish watching nature go through her tricks and calculate the number again, it is the same.”**

*Richard Feynman, 1964*

**The general concept of energy became meaningful only through the establishment of the principle of conservation of energy in all its generality. Thus the story of the emergence of the energy concept and the story of the establishment of the conservation law cannot be disentangled.**

**"I shall deal with the concept of energy only so far as it can be connected with the principle, presupposing that the concept of energy gains its meaning in physics first of all through the principle of conservation, which contains it."**

*Max Planck, 1887*

**"There only remains for us one enunciation of the principle of the conservation of energy: there is something which remains constant."**

*Poincaré, 1902*

# The principles of conservation

**"We do not believe a priori in a law of conservation, but we know a priori the possibility of a logical form" (*Wittgenstein*).**

**Parmenides introduced the the very conception that behind the variability of phenomena someting immutable should exist.**

**The period ~1650 to ~1850 saw the fixing of several laws of conservation:**

**- conservation of matter or mass**
**- conservation of momentum**
**- conservation of angular momentum**
**- [conservation of heat]**
**- conservation of energy**
**- conservation of electric charge**

**The conservation laws weren't derived by symmetry principles, but laboriously worked out on ontological basis, with (often heated) discussions in the process of fixing the concepts and finding a comprehension of the basic phoenomena**

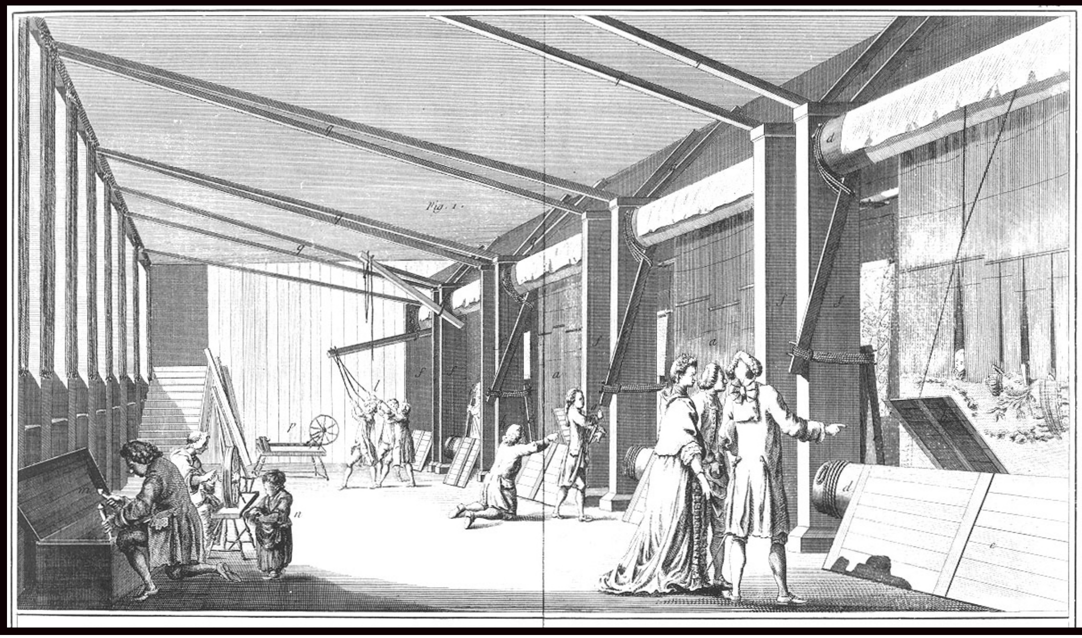

**the result was the establishment of a fully mechanicistic concept of Nature**

**“The factors which were a solid and necessary basis for the enunciation of the conservation principle were:**
**(1) An *a priori* belief in general conservation principles in Nature.**
**(2) Realization that it is not enough that two formulations of mechanics: the vectorial-Newtonian and scalar-analytical-Lagrangian, are mathematically equivalent, they must also be conceptually correlated.**
**(3) An awareness of the physiological problem on 'animal heat' or more generally of 'vital forces', and a belief that these are reducible to the laws of inanimate nature.**
**(4) A mathematician's certainty that whatever is the entity which is conserved in Nature it must be expressible in mathematical terms, and a mathematician's skill to perform the task.”**

***Yehuda Helkana, 1970***

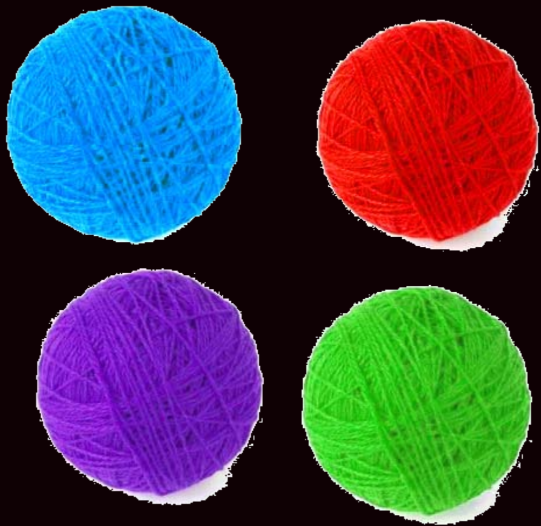
The principle of energy conservation is the result of the work in the span of 1840-60 of different groups of people in different places on different problems.
They came up with different answers, which turned out to be related, until finally in the ‘860s they proved to be more than related, they turned out to be logically derivable one from the other.

This final coherent result was possible by properly weaving different threads in order to produce a coherent image, like in producing a tapestry

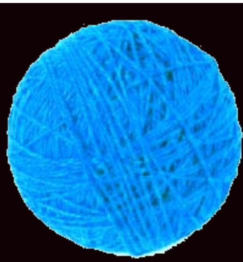


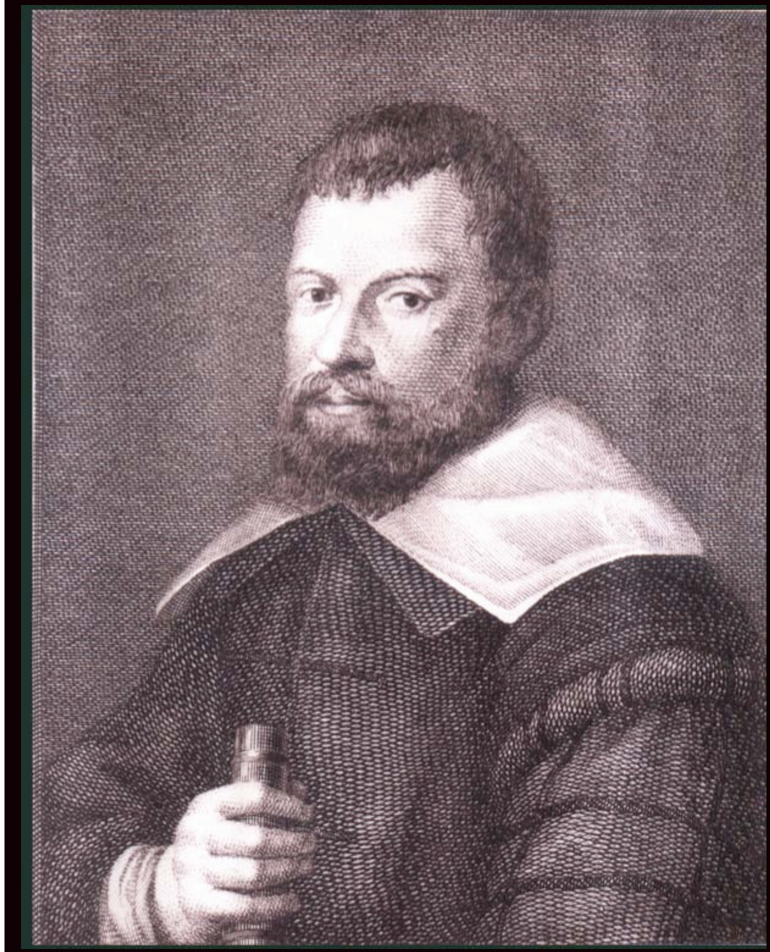

# the threads to follow

- the clarification of the philosophical belief in general conservation principles in Nature
- clarification of the ' force of a body in motion'
- mathematical formulation of the mechanics
- fixing the concept of work
- mathematical treatment of the power of machines
- comprehension of the basis of chemistry
- evolution of the thermology and the theories of heat
- acquiring the laws of electricity and magnetism
- reduction of the 'animal heat' or 'vital forces' of physiology to the laws of inanimate nature



# Mechanization of the world picture
# the thread of the 'force' of motion





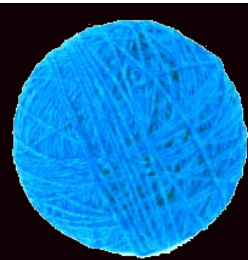
the study of bodies in motion brought forth in XVII-XVIII centuries a conception  of Nature irreducible to Plato or Aristotle.

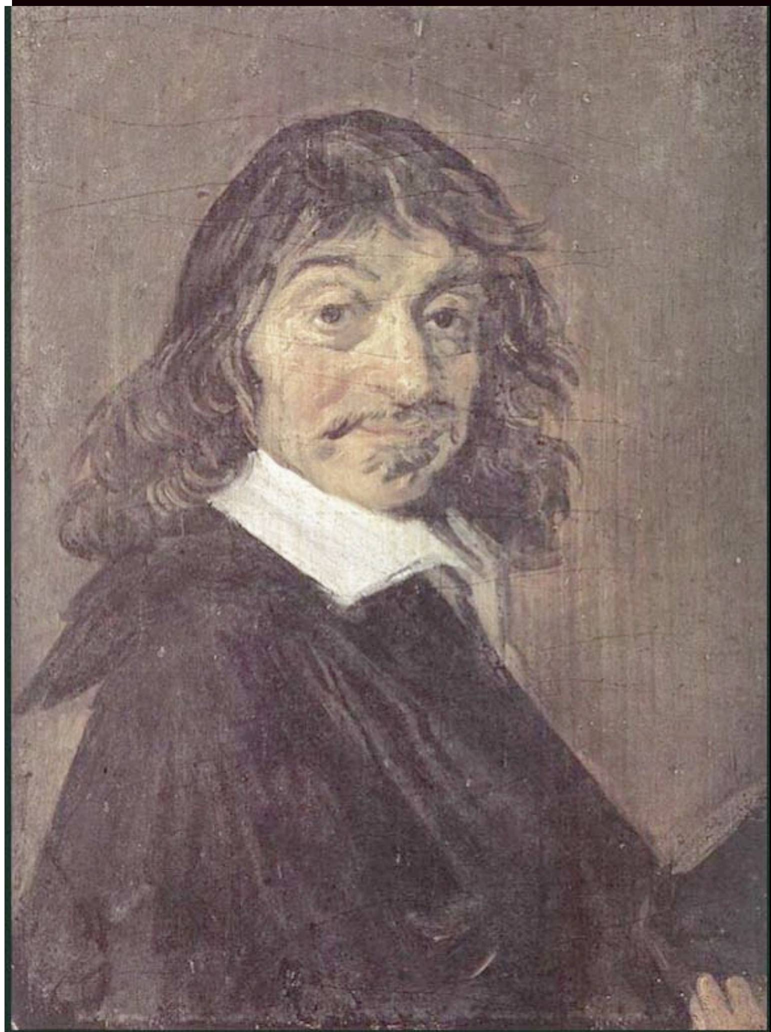
Its basic tenets:

- the physical universe is constituted by a matter whose first element are knowable
- these elements' activity can be reduced to motion phoenomena, subject on their turn to intelligible laws.

Galileo's *Discorsi e dimostrazioni* (1638) opened the way to a kind of reasoning making possible a mathematical treatment of a particle conception of matter

# René Descartes
# and the conservation of motion



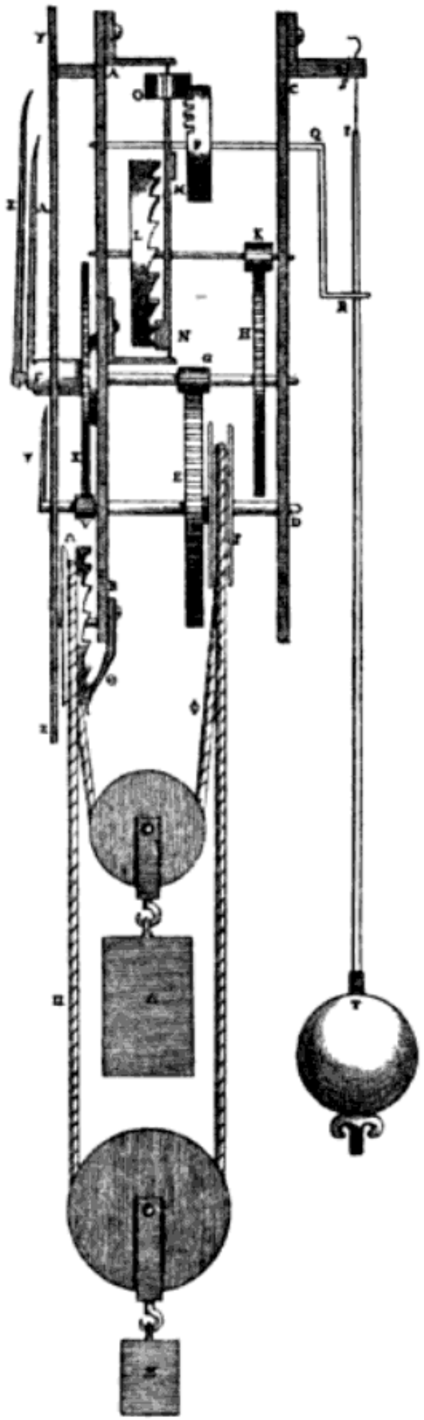


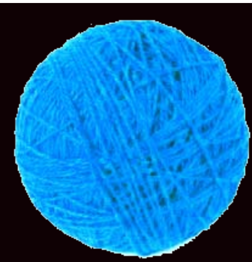
Descartes's program is a geometrization of physics: "I do not accept or desire any other principle in Physics than in Geometry or abstract Mathematics, because all the phenomena of nature may be explained by their means, and a sure demonstration can begiven of them." *(Principia philosophiae 1644)*.

All natural phenomena are to be deduced from only two fundamental kinematic assumptions:

- the law of the conservation of [quantity of] motion as a real physical content
- and his theory of swirling ethereal vortices.

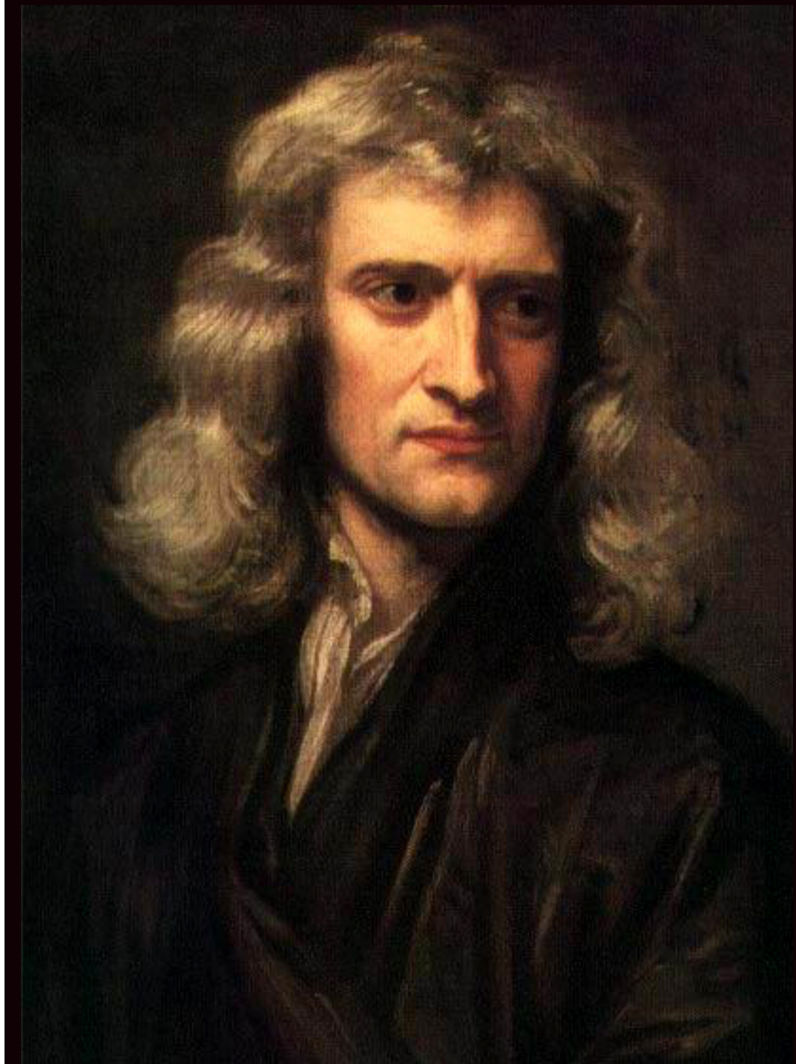
Descartes did not clearly define the word 'motion', being satisfied with an easy metaphysical intuition





**Christiaan Huygens studying, in the context of the Galilean principle of relativity of motion, elastic collisions and the fall of bodies of different weight (mass) obtained (1673) for these processes the laws of conservation of both the quantities**
**$m_1v_1+m_2v_2$ and $m_1v_1^2+m_2v_2^2$**

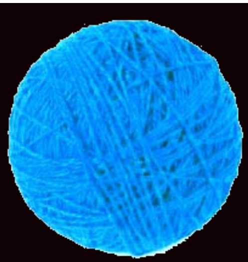
# Isaac Newton and the Law of the Conservation of momentum



Newton introduced dynamical concepts in studying motion, distinguishing the force of inertia (*vis insita*) and the active forces (*vis impressa*). His first two laws recall the principle of inertia and express the variations of motion in terms of the balance of the competing forces (*Philosophiae naturalis principia mathematica* 1660).

He defined the 'quantity of motion' as the product of the 'quantity of matter' [mass] times the velocity in vectorial form, and his third law extends the conservation of momentum in general conditions.

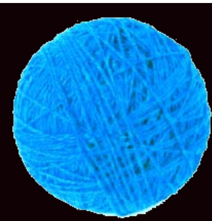
# Leibnitz search for a unifying principle



The search for a unitary principle is the basic aim of Gottfried Wilhelm von Leibniz. He spoke of such a fundamental principle as conservation of ‘force’ to which the whole universe can be reduced.

For Leibniz that force has *an effect* $mv^2$, or $mv$, or the height reached by a body thrown upwards, as the case may be; in his later works he says that it is 'a metaphysical entity', 'the essence of matter' or 'the main attribute of a monad', a fundamental entity uniting in it not only all physical effects but also the spiritual ones.

# Leibnitz *vis viva* (*$mv^2$*) and its conservation

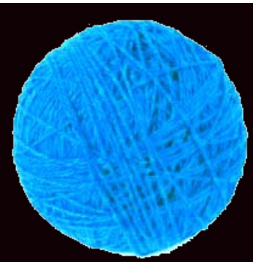


Leibniz distinguished between the tendency of a body to start a movement (*vis mortua – mdv*) and the ‘force’ of the body in actual movement (*vis viva – $mv^2$*).

On the basis of the principle of causality he was confident in the conservation of *vis viva* in both elastic and inelastic impacts: in the latter case the *vis viva* which appeared to have been dissipated had not vanished but had taken on a new and latent form as motion of the internal components of objects.

# The *vis viva* controversy

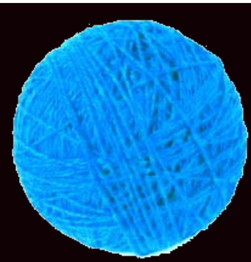
## Cartesians vs. Leibnizians vs. Newtonians



**The *vis viva* controversy began with Leibniz' publication of his *Brief Demonstration of a Notable Error of Descartes* in 1686 and ended at some undetermined date in the eighteenth or possibly even in the nineteenth century, never actually resolved. The enthusiasm of the combatants subsided either from fatigue, or more likely from the realization that they had been talking past each other for over fifty years and were in disagreement over basic suppositions about the nature of force and matter.**

**The concept of the 'force of a body in motion' which taxed the scientific minds of the XVII and XVIII centuries is ambiguous; it can refer either to the momentum or to the energy of a moving body**

# $mv$ vs. $mvv$ or force vs. vis viva

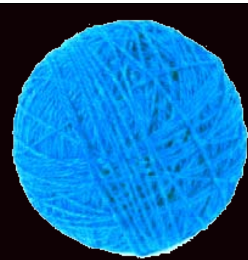


There were two conservation principles:
- the momentum ($mv$) conserved under all conditions in its vectorial formlation,
- the scalar quantity $mv^2$ conserved at least in elastic collisions.

Both were considered 'forces' of some sort; the first conservation law did not enable the calculation of velocities after collision, while for the second law it was not clear what happens in inelastic collisions.

Every investigator performed different experiments (falling bodies, compressed springs, clay cylinders, colliding balls of glass, clay, wool, etc.), and in view of the special case of his experiments gave different names to the entities involved; the very fact that none of them realized that all these experiments were obeying the same laws shows how superficial their conservation laws were.

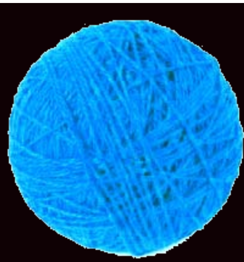
# Willem Jacob 's Gravesande impact of falling weights




In 1722 he published the results of a series of experiments in which brass balls were dropped from varying heights onto a soft clay surface.
He found that a ball with twice the speed of another would leave an indentation four times as deep, from which he concluded that the correct expression for the 'live force' of a body in motion is proportional to $mv^2$.

Similar observations were published independently by Giovanni Poleni at the university of Padua

# Rational mechanics

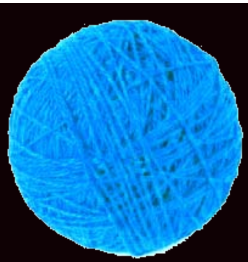


**During most of the XVIII century, the development of mechanics was in the hands of the mathematicians.**

**The landmarks in this development are**
- **Euler's *Mechanica* in 1736,**
- **d'Alembert's *Traite de Dynamique* in 1743,**
- **Lagrange's *Mecanique Analytique* in 1788.**

**By that time, the concepts in which mechanics was analysed had been hammered out, except the concept of 'force' which was still in a state of flux, and the concept of 'energy' which had not yet been born.**

# The question of *Perpetual Motion*



The attempts continued for centuries to create power out of nothing have slowly abated. This was the result of the new realization, an inductive conclusion, that man could not construct a perpetual motion machine.

The resolution of the *Royal Academy of Sciences* in Paris not to entertain communications relating to Perpetual Motion, was passed in 1775 and reads as follows:
"This year the Academy has passed the resolution not to examine any solution of problems on the following subjects:
The duplication of the cube, the trisection of the angle, the quadrature of the circle, or any machine announced as showing perpetual motion."

The realization of the impossibility of a *perpetuum mobile* had little to do with the establishment of the principle of conservation of energy. In other words, the fact that the principle of conservation does imply the impossibility of a perpetual motion machine, is not a sufficient condition for it but only a necessary one.

# Leonhard Euler's *Mechanica*

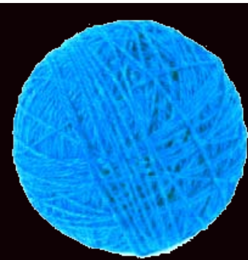
He carried out the Newtonian programme in mathematical language, clarifying the Newtonian concept of force. For him power *(potentia)* or force *(vis)* is characterized by the modification of the motion of a particle that is produced by it. A power is directional:

"Potentia est vis corpus vel ex quiete in motum perducens, vel motum ejus alterans. Directio potentiae est linea recta secundum quam ea corpus movere conatur."

And the force of inertia is a force like any other:

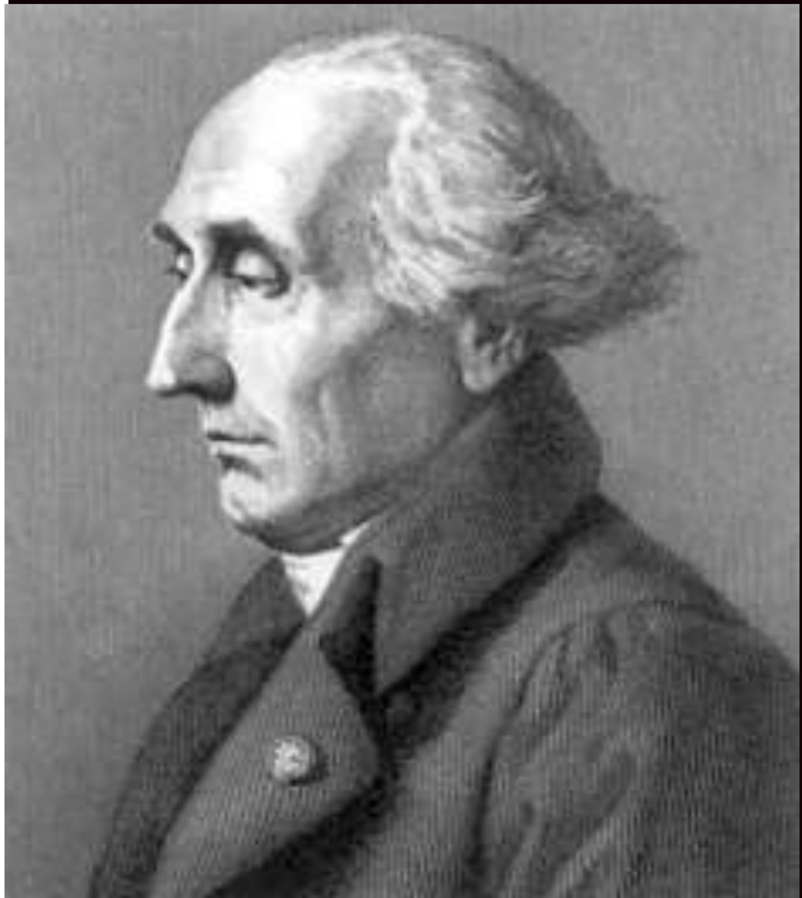
"Vis inertiae est illa in omnibus corporibus facultas vel in quieto permanendi vel motum uniformiter in directum continuendi"

# Jean-Baptiste le Rond d'Alembert



His work *Traite de Dynamique* is based on three distinct principles: the force of inertia, the principle of compound motion, and the principle of equilibrium. He states that the forces acting on a system of interconnected bodies will increase its *vis viva* by the amount $\sum m_i u_i^2$, where the $u_i$ are the velocities that the masses $m_i$ would have acquired if moved freely over the same paths by the same forces.

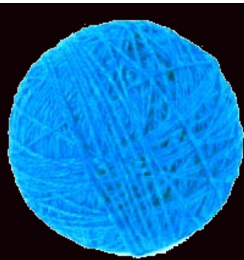
# Lagrange’s analytical mechanics



Joseph-Louis Lagrange aimed to building mechanics as a branch of pure mathematics analogous to a geometry of four dimensions, namely, the time and the three space coordinates. Consistently, he gave only perfunctory definitions of 'force' and 'power' not really caring what was physically implied by them. He successfully derived his equations from Newton laws (in Euler's formulation), with a transformation from vector to scalar language.

His *Mécanique analytique,* instead of following the motion of each individual part of a material system, considers the dynamical problem of the entire system, determining its configuration by as many generalized variables as the number of the degrees of freedom possessed by the system, taking also into account the active constraints.

# The mathematical formulation of the conservation of mechanical energy



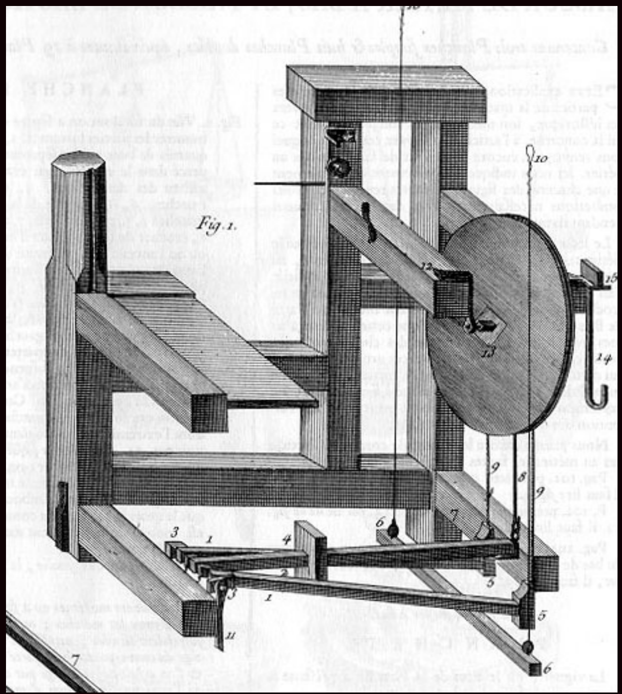
In analytic machanics the *vis viva* and a function corresponding to the potential of the forces of the system can be expressed in terms of generalized variables, and the differential equations of motion are thence deduced by simple differentiation, for the whole of mechanics, both of solids and fluids.

The *vis viva* is the conceptual parameter which dominates the analytic approach and exclusive emphasis is given to central forces derivable from potential functions, i.e. the integral of force times differential path element.

The Lagrange dynamical law itself equates *vis viva* with the potential function and a direct consequence is the conservation of mechanical energy for forces and constraints which are time and velocity independent.

# The thread of work

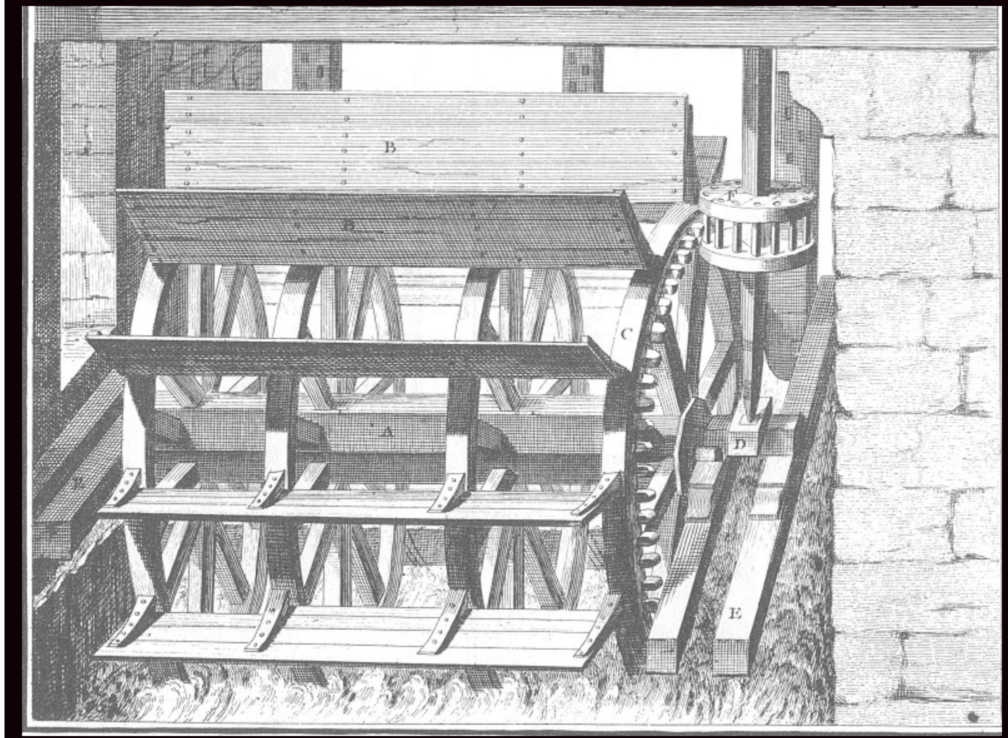
**The concept grew from both engineering experience and theoretical reflections, which gradually came together.**



**Galileo in *Discorsi e dimostrazioni matematiche intorno a due nuove scienze attenenti alla meccanica e i movimenti locali* (1638) started a rational science of machines and the origin of the concept of work.**
**He stated that for all the machines known at his time (lever, pulley, wedge, screw, inclined plane, capstan) the weight (force) applied to them multiplied by its speed must equal the load multiplied by its speed.**

# Antoine Parent and the overall efficiency of engines.

In *Sur la plus grande perfection possible des machines* (1704) he applied Galileo's principle to a water-wheel. A given load will stop such a machine and Parent defines the product of this load and the velocity of the water as the *effet naturel*—the natural power—of the stream.
The problem then is, what is the greatest proportion of this *effet naturel* that can be harnessed ?



The 'effort' of the stream against the blades is measured by the product of the amount of water and its velocity of impact, which must equal the 'stopping' load.
Parent set out an equation relating the *effet general* (the product of the load and its velocity) to the velocities of the stream and the wheel. He showed that the maximum *effet general* is only 4/27ths of the *effet naturel* and that to yield this maximum the wheel must move with 1/3rd the velocity of the stream.

# Smeaton experimental results

Experience convinced John Smeaton (*An experimental enquiry concerning the natural powers of water and wind*, 1759) that the efficiency of water wheels exceeded 4/27 and, in a series of meticulous experiments, he confirmed that for undershot wheels the fraction was approximately 3/10 while for the same wheel overshot it was about *6/10*. The two-fold advantage of the overshot wheel was due to the fact that such wheels worked by the weight of water only and that there was consequently no waste of 'mechanic power' in distorting the stream by turbulent impact on the blades, and all the power of the water can, in theory, be harnessed.
In 1776, Smeaton published experimental results which supported his argument that the 'mechanic power' exerted on a body is proportional to the *vis viva*.

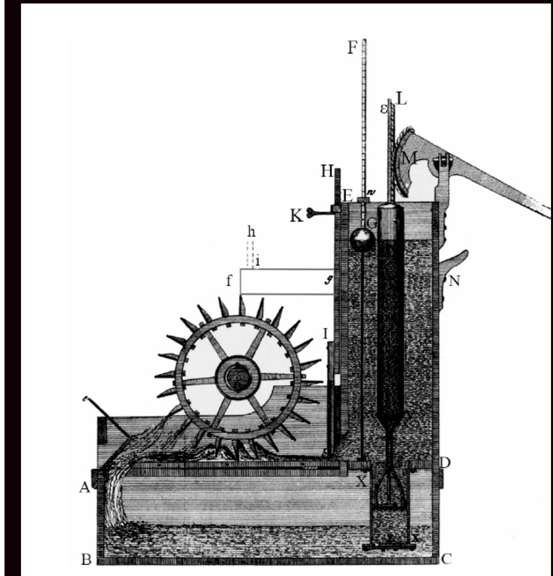
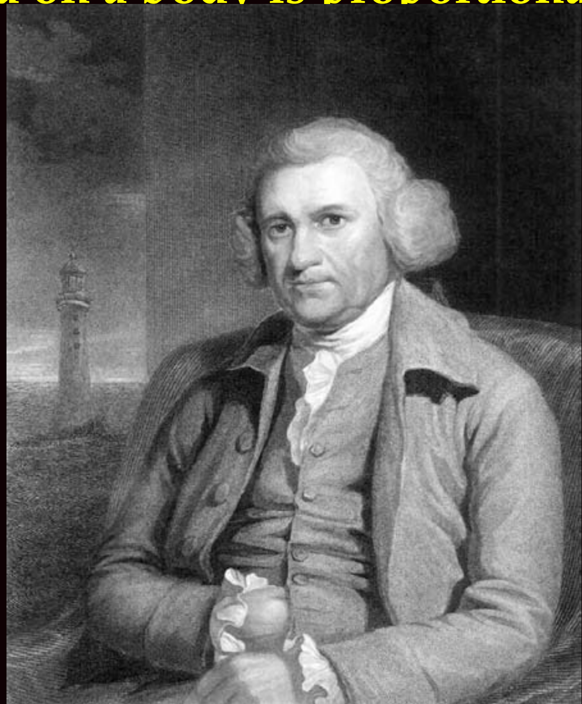
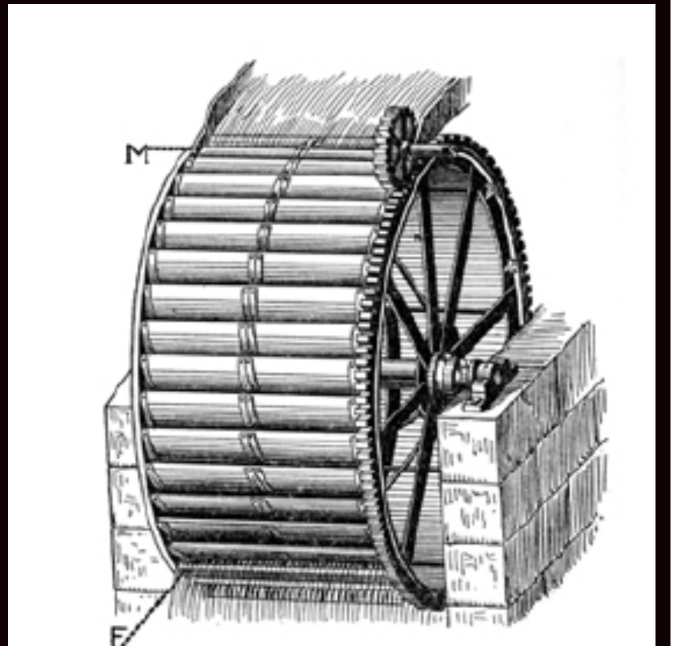


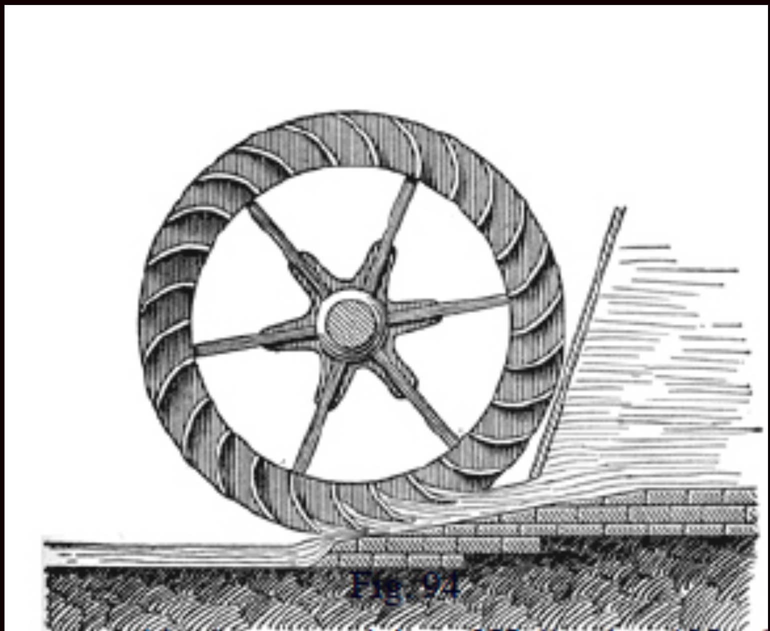

**Figure 4.**
Smeaton's experimental set (Smeaton, 1756: p. 102).





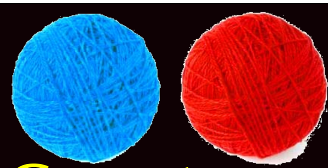
# Work: The Establishment of the Concept

**In 1767, Jean-Charles, chevalier de Borda, published a short paper correcting the two main errors of Parent and harmonizing theory with experiment.**
**Borda brought the *vis-viva* doctrine into the consideration of the problem of water power: he showed that a water-wheel with curved blades wasted no *vis-viva,* for the water 'struck' it without shock; such a wheel should therefore attain a maximum efficiency, at least in theory.**
**Borda gave for a formal expression of the loss of *vis-viva* in inelastic collisions:**
**the loss of *vis-viva* is determined by $m(V-v)^2$, where $V$ *is* the velocity of the stream before, and $v$ after the collision.**




# Measuring power

The engineers of the eighteenth century chose to quantify their measure of power, or duty, in the most convenient way. Mining, the great power-using industry, required, as a natural measure, the raising of a given weight a given distance in a given time. The idea of taking the product of weight and distance moved in unit time necessarily implies understanding and acceptance of Galileo's principle.
The quantification of power in this way first became important in France and England. Among the pioneers were Amontons and Desaguliers. The latter postulated as the 'power of a horse' - the natural 'unit' to choose - the ability to raise 44,000 lb 1foot high in 1 minute. He was followed by Smeaton whose figure was 23,000 lb 1 foot high in 1 minute and finally by James Watt whose standard, sanctioned by his immensely successful work on the steam engine, was accepted: 33,000 lb 1 foot high in 1 minute (735.5 W)



**Lazare Nicolas Marguerite, Comte Carnot, provided the desideratum of the *vis viva* theory, the attachment of the doctrine to a general theory of mechanics.**

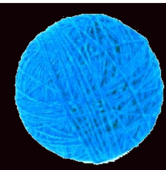
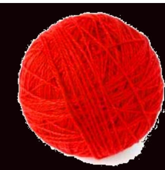
**In his *Essai sur les machines en general* (1783) he has an elementary theory of dimensions which he uses to establish homogeneity between $MV^2$ *and* $PH$, where $P$ is a force and $H$ a distance.**

**"In the impact of inelastic bodies, whatever their number and whether they act directly or by means of a machine without elasticity, the sum of the *vis-viva* before the impact is always equal to the sum of the *vis-viva* which would have existed if each body had moved freely with the velocity it lost in the impact."**

**Or, $MW^2 = MV^2 + MU^2$ where $U$ *is* the velocity lost in the impact.**

**Carnot is concerned to mitigate the last factors as much as possible in the design of all machines. Hence his insistence that the motive agent acts without 'shock' and that when it has done its duty, quits without velocity.**

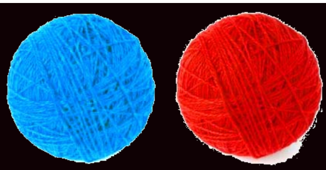
# The establishment of the language

Carnot uses the term ‘moment of activity’ for what we call ‘work’ and he has a concept –*’force vive latent’*– which is close to the concept of potential energy. In fact, with Carnot the expression $PH = \frac{1}{2}MV^2$ is quite explicit. Carnot's book of 1783 was the first of a large number of very competent works published in France, the products perhaps of revolutionary temper and the establishment of the Ecole Polytechnique. They reveal a steady clarification in ideas and language. What has been in the eighteenth century a matter of confusing terminology became steadily clearer in the opening decades of the nineteenth century: 'duty' of an engine 'mechanic power', 'moment of activity', 'dynamical effect', 'quantity of action'.
In 1811 Hachette introduced his dynamical unit: 1,000 kg, or 1 cubic metre of water, raised 1 metre high. Gaspard-Gustave de Coriolis to this measure gave the name 'dynamode', a unit of what he called 'work'.

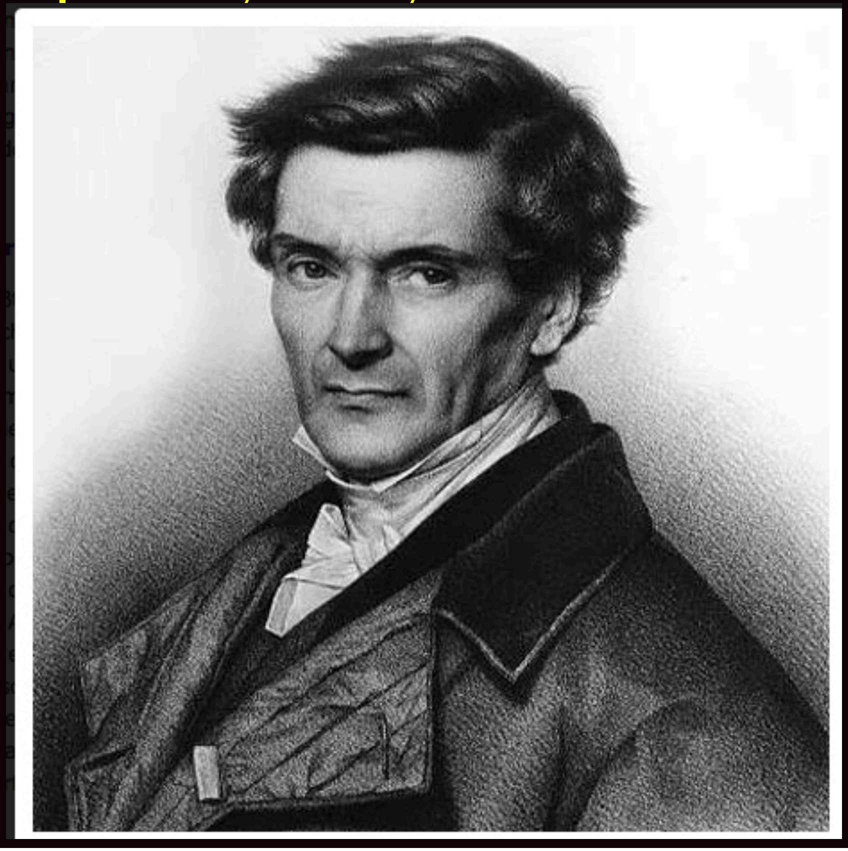
Jean Poncelet formulated the key concept of a 'source of work', or of 'agents of work', in the late 1820s (*Mécanique Industrielle*):
“Also men, animals in general, heat, currents of water, winds, are agents of work, motors if you wish.”

# Physical expression of the conservation of mechanical energy



**Coriolis fixes language and concept:**

**“ by this name work (*travail*) I mean the quantity which is fairly commonly called mechanical power, quantity of action or dynamical effect. …**
**If they (mathematicians) previously used the name of living force for the product of mass and velocity squared, it is because they did not pay attention to *work*. . . . All practitioners today mean by living force the work which can produce the velocity acquired by a body”**



**The implication of this is quite simply that if *work,* or *gMH,* is taken as fundamental then 'living force' must be $\frac{1}{2}MV^2$.**

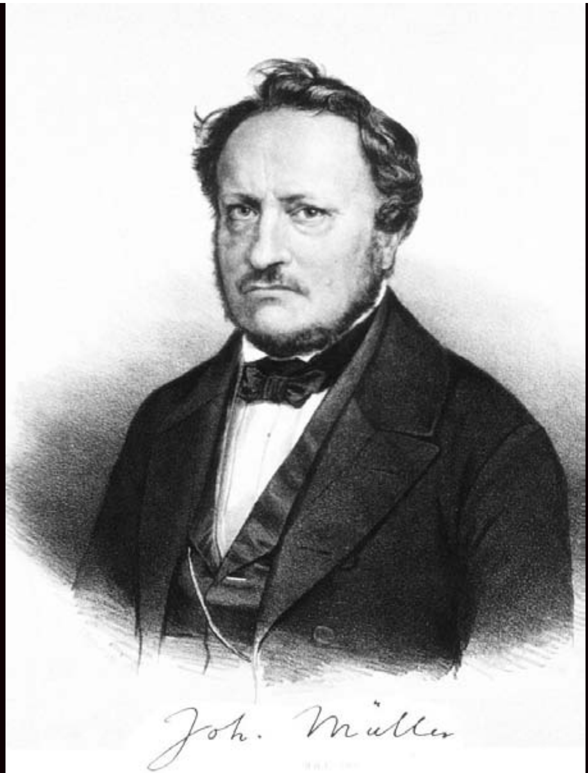
***Calcul de l'Effet des Machines***
**(1829)**

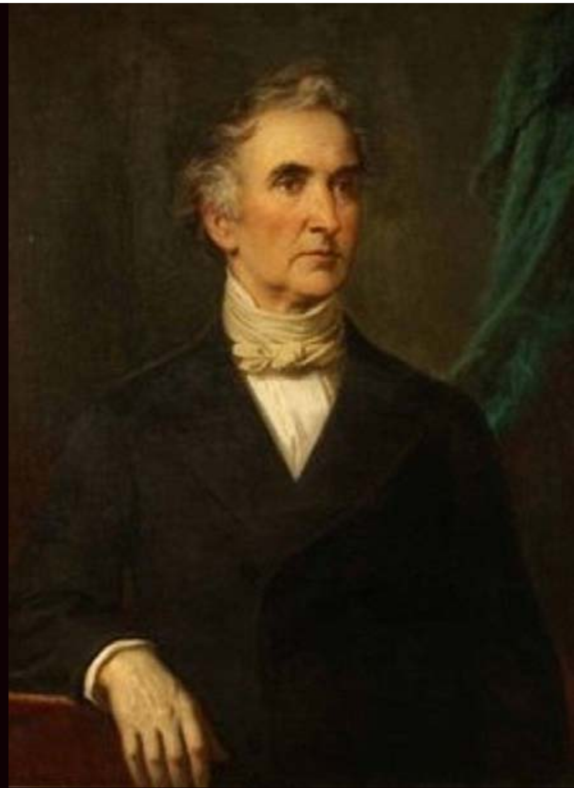
# The thread of 'vital forces' of physiology

On philosophical grounds the problem of vital forces arose around 1820.
The basic question is whether the production of organic compounds and the development of living creatures can be fully accounted for by the laws of chemistry or require a special ‘force’ of non mechanical or chemical origin.


# Liebig's laboratory in Giessen

**Jöns Jacob Berzelius around 1815 propounded the vital force theory. Vital force theory described the mechanism of organic compound formation. It states that the organic compounds are naturally formed and their synthesis is only possible from living plants and animals by means of some mysterious force called the *vital force* and organic compounds could not be prepared in laboratory using inorganic compounds**

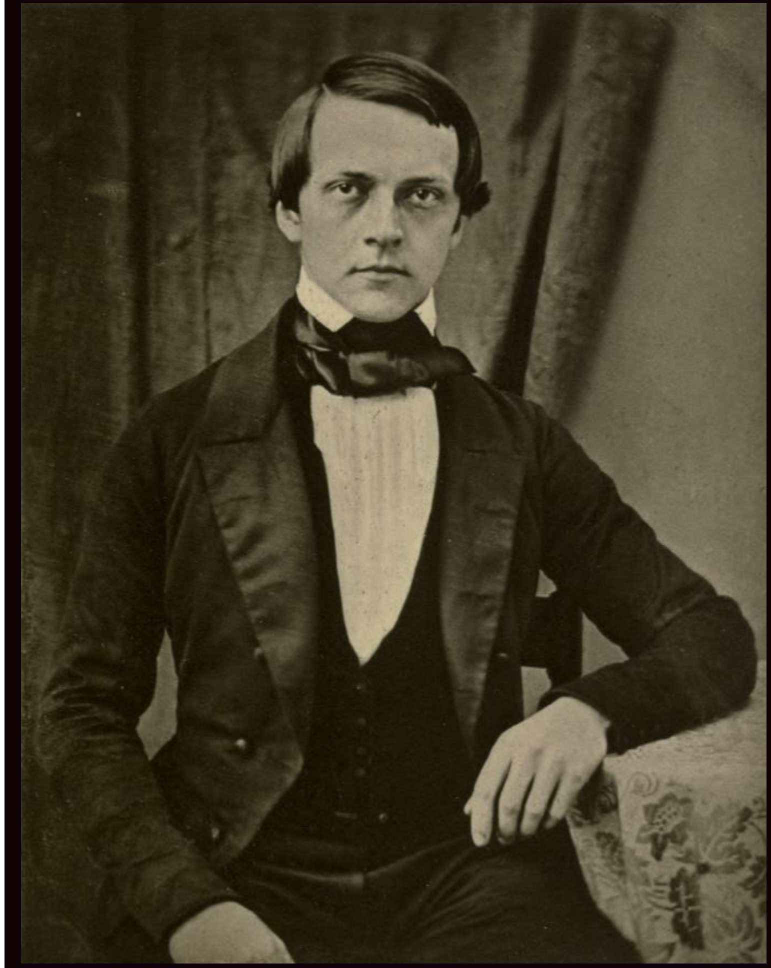


**Justus Freiherr von Liebig and Johannes Peter Müller were the most important physiologists of their time and in their researches they had a personal balance of the role of the vital forces and true chemical and physical agents.**

**The importance of the absorption of oxygen in the living processes war clearly recognized and the necessary balance of strictly biological processes and a purely physiochemical 'Kraft' .**

# Hermann Ludwig Ferdinand von Helmoltz

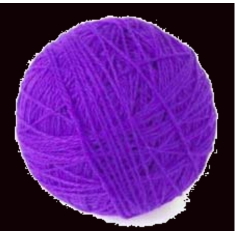


The young Helmoltz, working with Müller on the anatomy and physiology of the nervous system, soon recognized the limits of the theory of vital force and the necessity of a fully empirical approach to physiology (1842). At the same time he envisaged the necessity of the conservation of matter and a basic 'Kraft' in all biological processes.

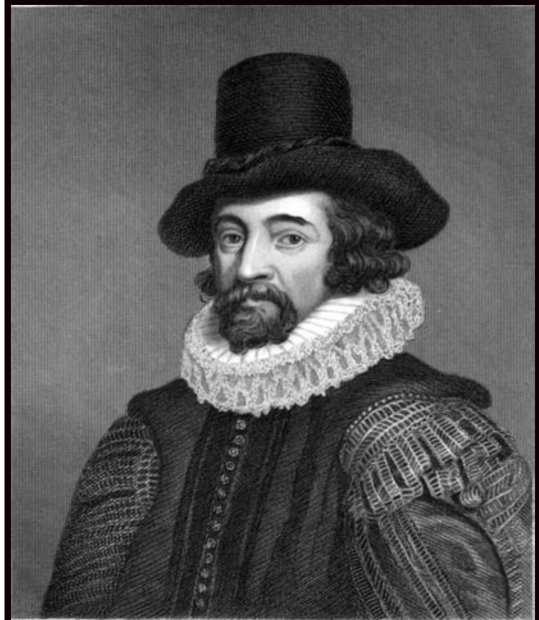
# The thread of thermology and heat

- the heat as movement
- the heat as a fluid
- the caloric theory of heat
- the motive-power of heat
- the wave theory of heat
- the dynamical theory of heat

# Seventeenth century the heat as movement



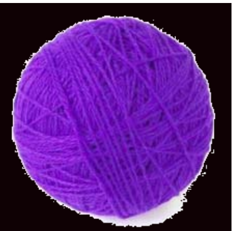
**The old theory on the nature of heat was dynamical, starting with Galileo; its chief representatives were Bacon, Boyle, Hooke, Locke and Leibniz. Newton also considered (*Opticks*) the heat as movement, but in a very complex form, including a role of a pervasive aether.**



**"When I say of motion that it is the genus of which heat is a species, I would be understood to mean, not that heat generates motion, or that motion generates heat (though both are true in certain cases) but that heat itself, its essence and quiddity, is motion, and nothing else."**

***Francis Bacon 1620***

# Eighteenth century

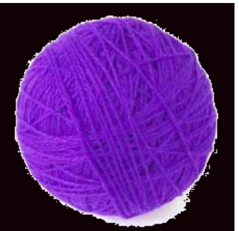


In the eighteenth century the study of heat was mainly of interest of chemists: “Chemistry is the study of the effects of heat and misture” (J. Black 1806).

By 1780 chemists and physicists had clear the concepts of:
- temperature (H. Boerhaave 1732),
- heat capacity (J. Black 1760),
- specific heat (J.C. Wilke 1781),
- latent heat (J. Black 1781)

and had at their disposal effective instrument for measuring temperatures:
- D.G. Fahrenheit 1724,
- R. A. Ferchault de Réaumur 1731,
- A. Celsius 1742

# the material theory of heat



An alternative theory considered heat as a form of a mass-less indestructible fluid, which could pass from a body to another.

For most of the eighteenth century the material—and the motion—theories of heat enjoyed equal popularity.

**Antoine-Laurent de Lavoisier and Pierre-Simon Laplace in 1780 developed the material theory of heat into a quantitative science (*Memoire sur La Chaleur*).**
**A serious attempt has been made to explain all phenomena of heat in terms of an elastic fluid, or as they also called it an 'igneous fluid'.**
**Lavoisier used the word 'caloric' which was later adopted as the official term for the matter of heat in the chemical usage.**

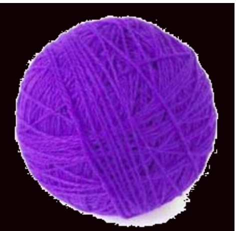
## TABLE OF SIMPLE SUBSTANCES.

Simple fubftances belonging to all the kingdoms of nature, which may be confidered as the elements of bodies.

| *New Names.* | *Correfpondent old Names.* |
|---|---|
| Light | Light. |
| Caloric | Heat.<br>Principle or element of heat.<br>Fire. Igneous fluid.<br>Matter of fire and of heat. |
| Oxygen | Dephlogifticated air.<br>Empyreal air.<br>Vital air, or<br>Bafe of vital air. |
| Azote | Phlogifticated air or gas.<br>Mephitis, or its bafe. |
| Hydrogen | Inflammable air or gas,<br>or the bafe of inflammable air. |

Oxydable and Acidifiable fimple Subftances not Metallic.

| *New Names.* | *Correfpondent old names.* |
|---|---|
| Sulphur<br>Phofphorus<br>Charcoal | The fame names. |
| Muriatic radical<br>Fluoric radical<br>Boracic radical | Still unknown. |

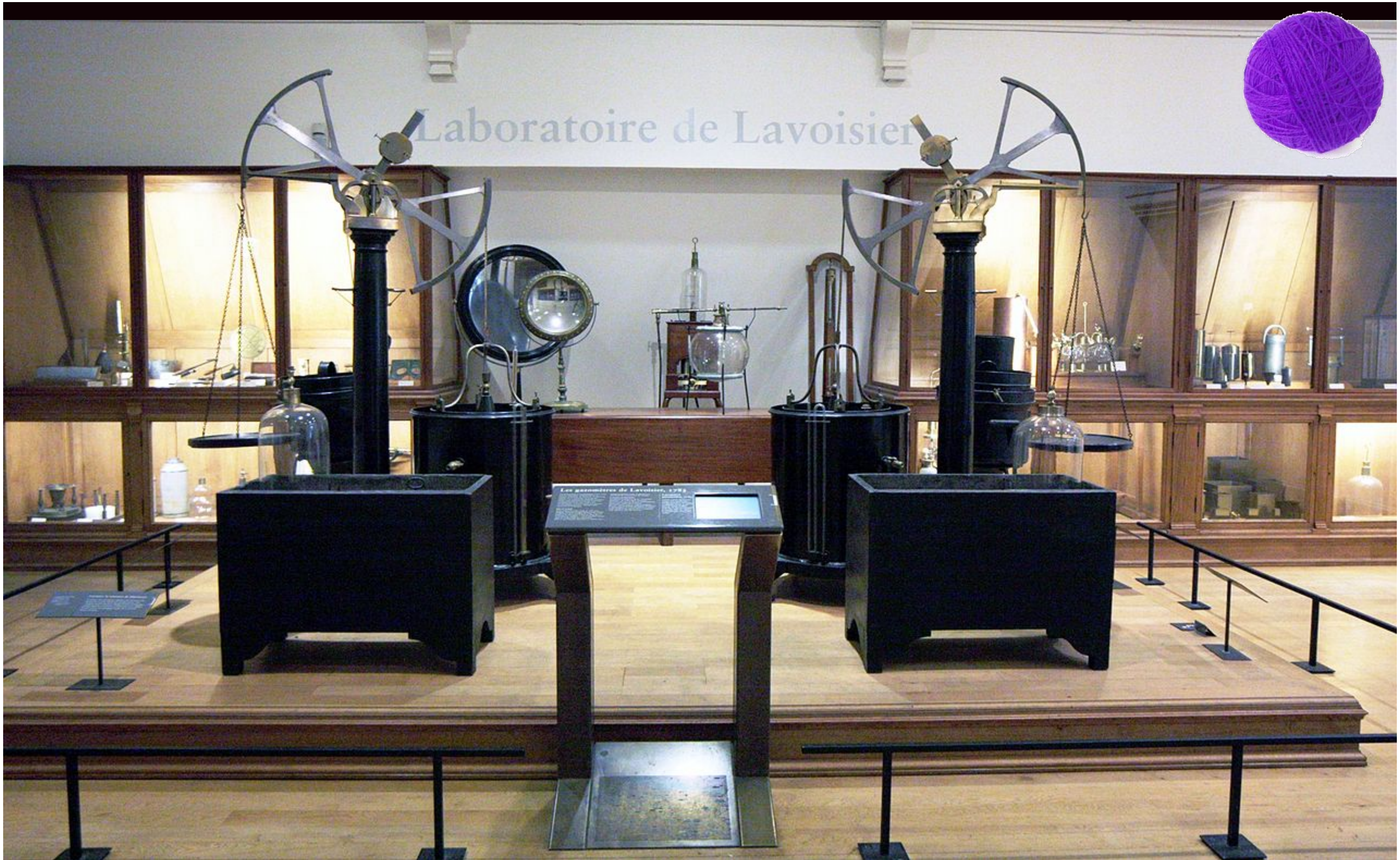


the heat as a substance

The 'caloric' was a fluid the particles of which were self-repulsive.

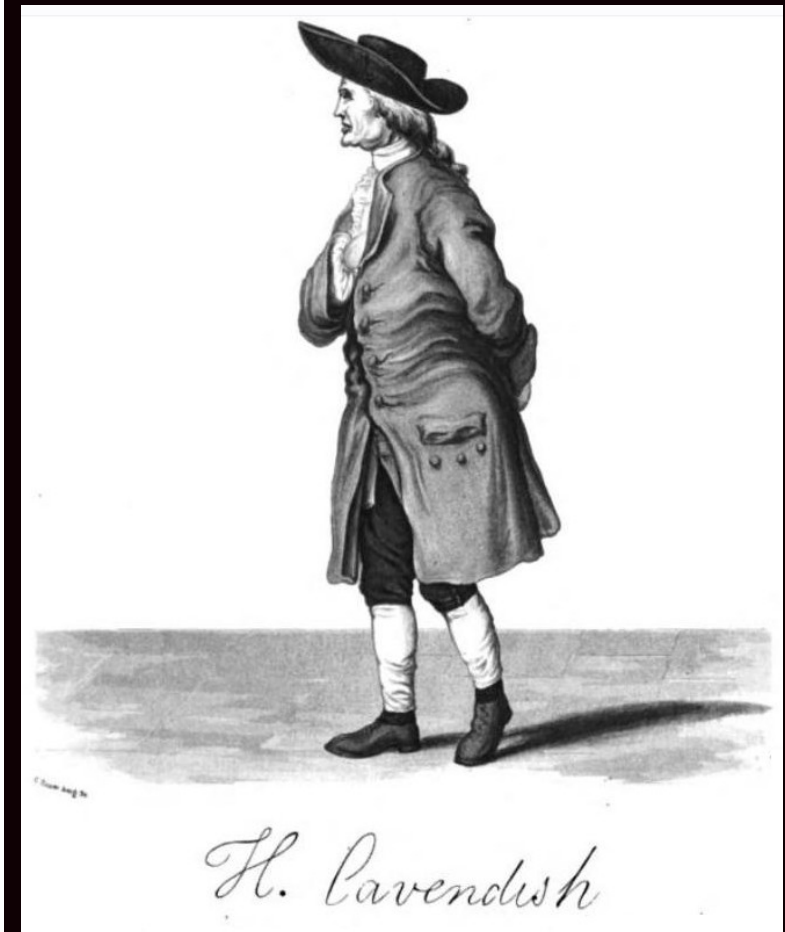
**The caloric model supplied solution to problems like the expansion on heating and contraction on cooling and latent heat was explained simply as a chemical combination between ordinary matter and the matter of heat. Two further discoveries were in full agreement with the caloric theory. In 1780 Laplace and Lavoisier showed that specific thermal capacities are not constants but functions of the temperature and that the product of the specific heat of each solid element by the weight of its atom gave a constant value.**

**The caloric theory has an enormous explanatory power covering most of the known phenomena of the time.**
**The success of French chemistry and the influence of Laplace ensured it a dominant role in the following 60 years.**



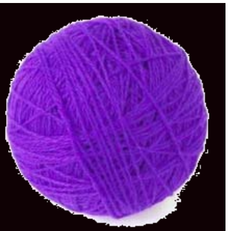

**Instruments of the laboratory of Lavoisier**

# Henry Cavendish
# from phlogiston to heat as movement




After having used a phlogistic approach in chemistry, Cavendish in 1787 converted to the new antiphlogistic theory of Lavoisier, though he remained skeptical about heat as material caloric. Working within the framework of Newtonian mechanism, Cavendish tackled the problem of the nature of heat, explaining heat as the result of the motion of matter. In a paper on the temperature at which mercury freezes he made use of the idea of latent heat.
He went on to develop a general theory of heat, at once mathematical and mechanical; it contained the principle of the conservation of 'heat' (an instance of conservation of energy) and even contained the concept of the mechanical equivalent of heat.

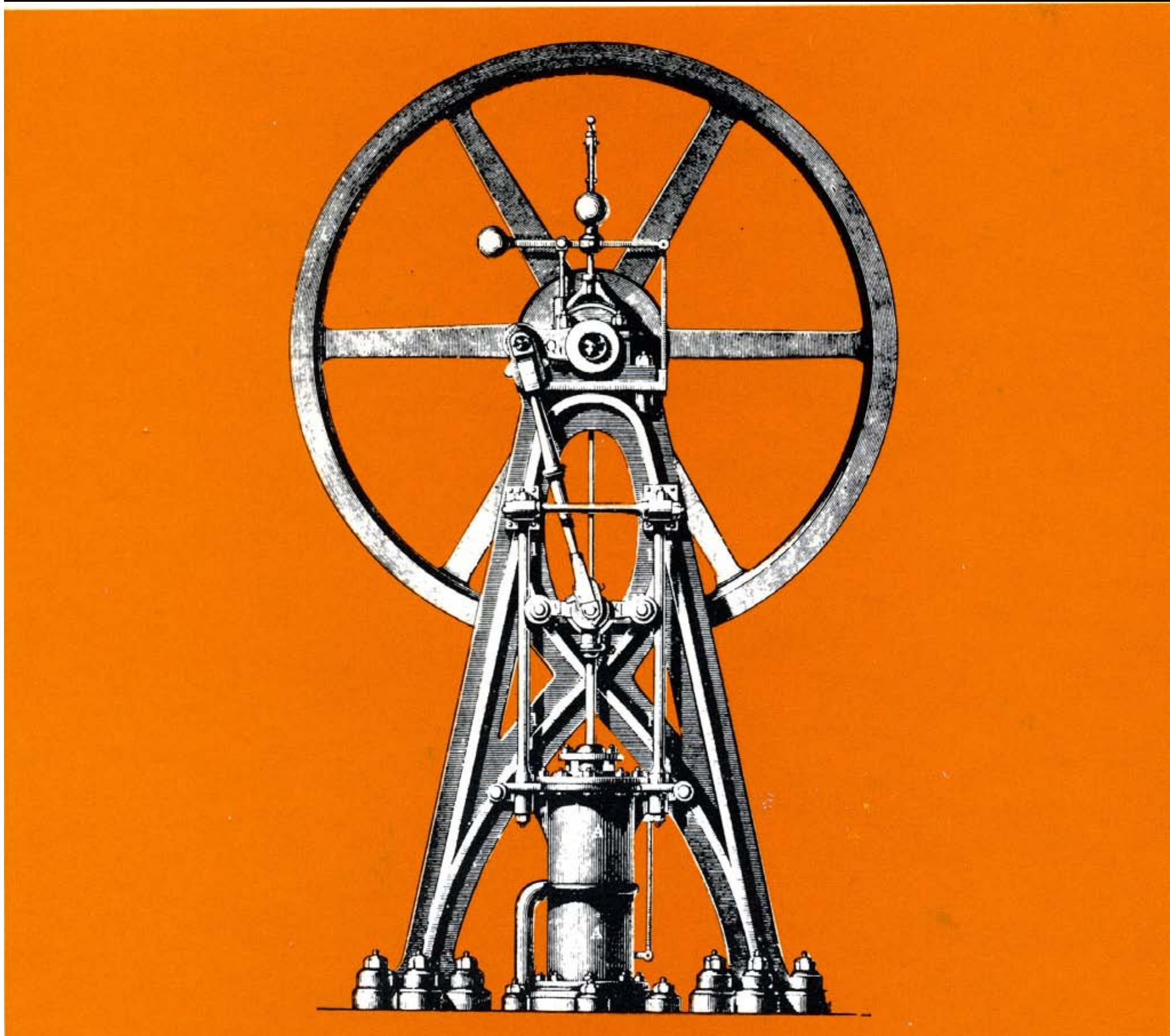
# The analytical theory of heat



**Jean Baptiste Joseph Fourier in 1822 published his work on heat flow in *Théorie analytique de la chaleur*, in which he based his reasoning on that the flow of heat crossing a geometrical surface is only related to the temperature gradient, avoiding any model of the heat and of the matter.**

**His approach opposed the program of mathematical physics of the school of Laplace, based on the detailed analysis of molecular forces; his work found criticism in France, while his methods become popular in Great Britain, in particular to young mathematicians in Cambridge and the group of physicists around William Thomson (the future Baron Kelvin of Largs).**

# The motive-power of heat mechanical work from heat



With the nineteenth century, steam engines had achieved widely recognized economic and industrial importance, but there had been no real scientific study of them.

**Sadi Carnot sought to answer two questions about the operation of heat engines *Réflexions sur la Puissance Motrice du Feu* (1824):**
**"Is the work available from a heat source potentially unbounded?" and**
**"Can heat engines in principle be improved by replacing the steam with some other working fluid or gas?"**

**He introduced an idealized machine to understand and clarify the fundamental principles of all heat engines, independent of their design. He showed that the efficiency of this idealized engine is a function only of the two temperatures of the reservoirs between which it operates, and that no thermal engine operating any other cycle can be more efficient, given the same operating temperatures.**

# 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.

# RÉFLEXIONS

SUR LA

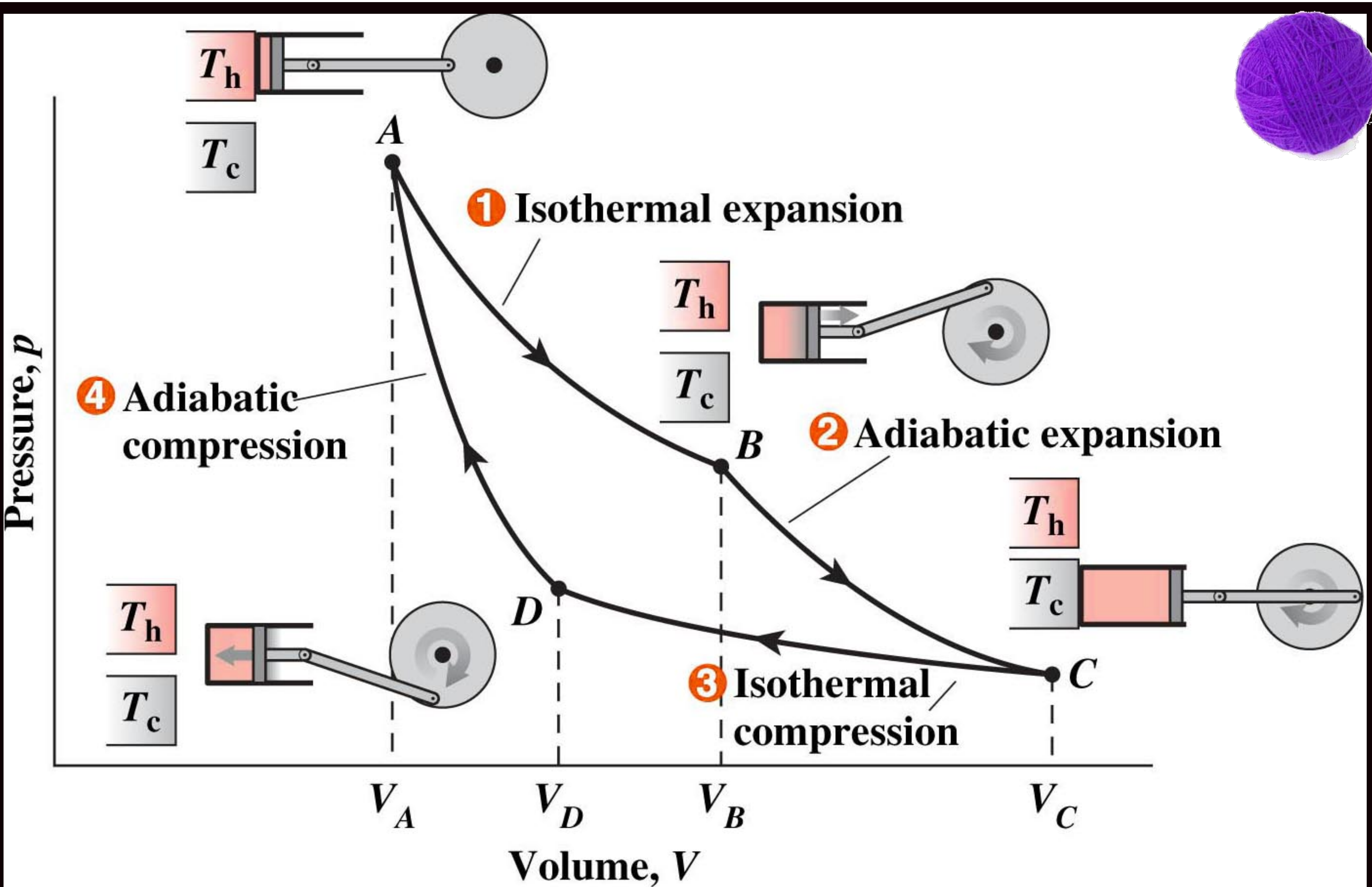
# PUISSANCE MOTRICE

## 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.

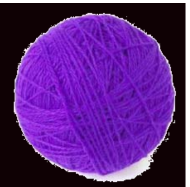
C'est à la chaleur que doivent être attribués les grands mouvemens qui frappent nos regards sur la terre; c'est à elle que sont dues les agitations de l'atmosphère, l'ascension des nuages, la chute des pluies et des autres météores, les courans d'eau qui sillonnent la surface du globe et dont l'homme 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




Carnot cycle, as elaborated by Benoît Paul Émile Clapeyron

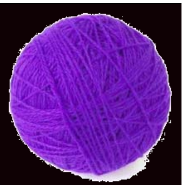
# Carnot’s Second Law of Thermodynamics



**Call a heat engine *simple* if its thermal interaction with its surroundings consists only in the absorption of heat from a reservoir at a fixed temperature, and the rejection of heat to another reservoir at another fixed temperature; and call any simple engine which is reversible a *Carnot engine.***
**Then Carnot's theorem is the following,**
**(a) All Carnot engines between the same two temperatures have the same efficiency;**
**(b) if the efficiencies of two simple engines between given temperatures are equal, and one of these is a Carnot engine, then so is the other;**
**(c) the efficiency of an irreversible simple engine between two temperatures is less than that of a Carnot engine between those two temperatures.**

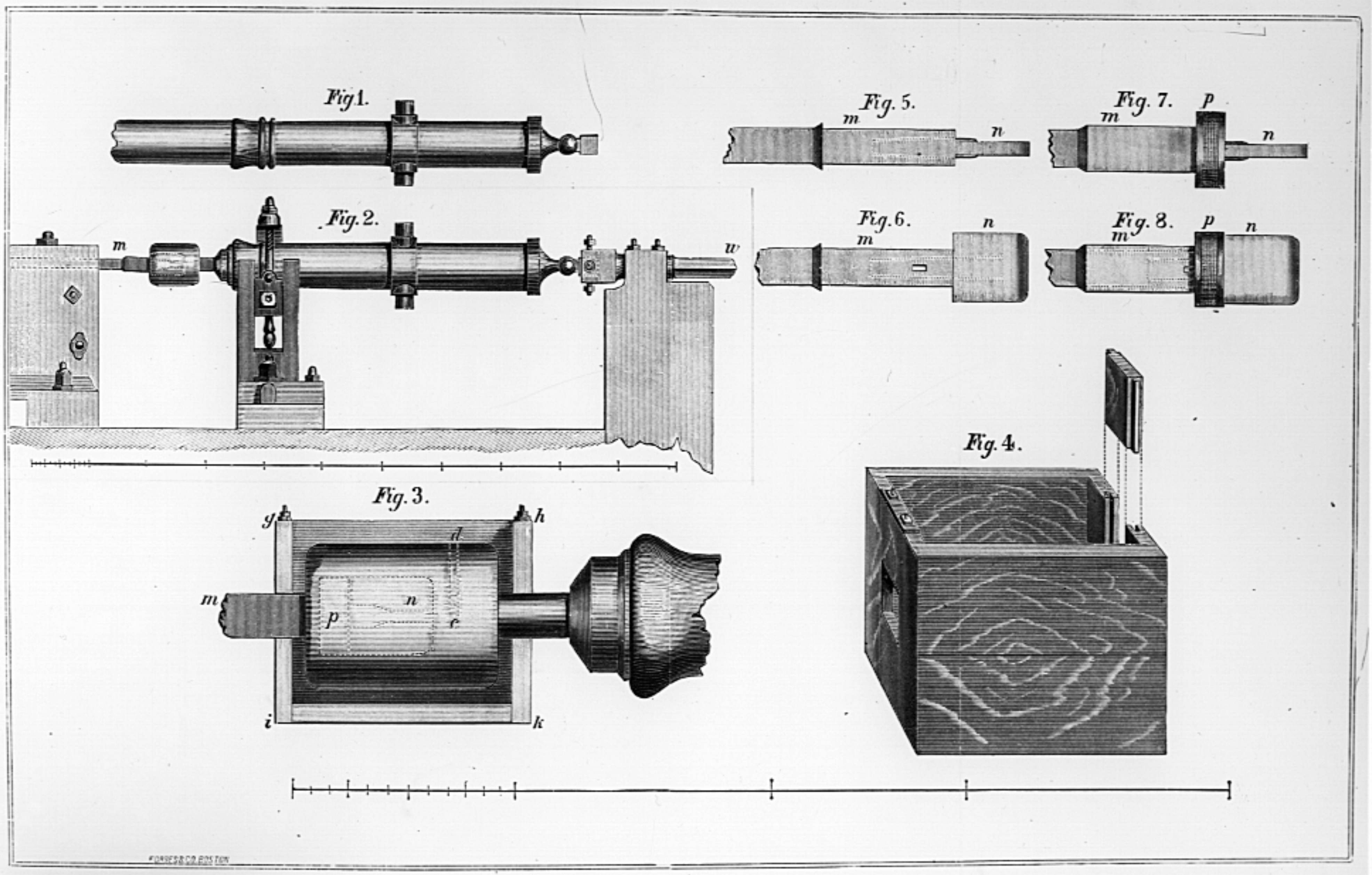
**The production of motive power is then due in steam engines not to an actual consumption *of caloric,* but to its *transportation from a warm body to a cold body.* . . . According to this principle, the production of heat is not sufficient to give birth to the impelling power; it is necessary that there should also be cold.**

# Friction processes and heat as motion again



**Sir Humphry Davy and Benjamin Thompson (later Count Rumford) observed heat produced by friction.**
**Sir Humphry Davy was philosophically-minded, while his scientific contribution to the theory of heat was negligible.**

**Rumford was focused on the problem of heat, and with a strong prejudice in favour of a theory that heat actually resided in the vibratory motion of the material particles. He performed a series of measurements on the transmission of heat and in its production by friction of metals.**



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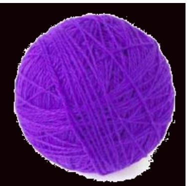
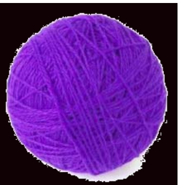
# Rumford lecture to the Royal Society on *An Experimental Inquiry concerning the Source of the Heat which is Excited by Friction,* held in 1798



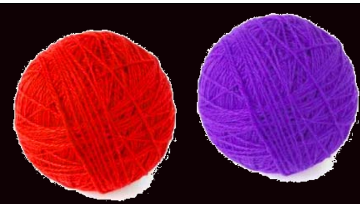
**"Being engaged lately in superintending the boring of cannons in the workshops of the military arsenal at Munich, I was struck with the very considerable degree of Heat which a brass gun acquires at a short time in being bored, and with the still more intense Heat (much greater than that of boiling water, as I found by experiment) of the metallic chips separated from it by the borer. …And, in reasoning on this subject, we must not forget to consider that most remarkable circumstance, that the source of the Heat generated by friction, in these experiments, appeared evidently to be *inexhaustible.***
**It is hardly necessary to add, that anything which any *insulated* body, or system of bodies, can continue to furnish *without limitation,* cannot possibly be a *material substance;* and it appears to me to be extremely difficult, if not quite impossible, to form any distinct idea of anything capable of being excited and communicated in the manner the Heat was excited and communicated in these experiments, except it be MOTION."**

# Wave theory of heat



**Thomas Young's experiments on diffraction of light were instrumental to give new life to the theory that light consists of waves in a medium, called by Christiaan Huygens** ***Luminiferous aether*** **in 1678**.

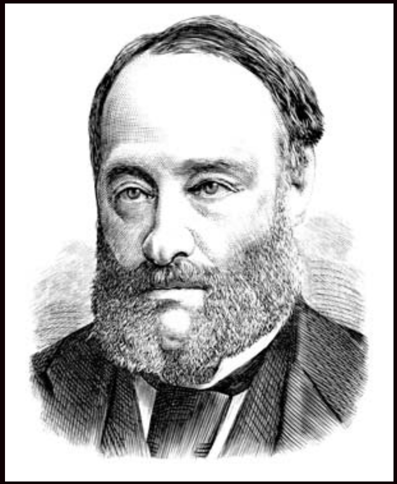
**Young put heat in relation to light and reached the conclusion that heat is also a wave motion of a space-filling aether. This approach found support by experimental researches which showed that radiant heat possesses nearly all the properties of light waves, as reflection, refraction, interference, diffraction and polarization.**

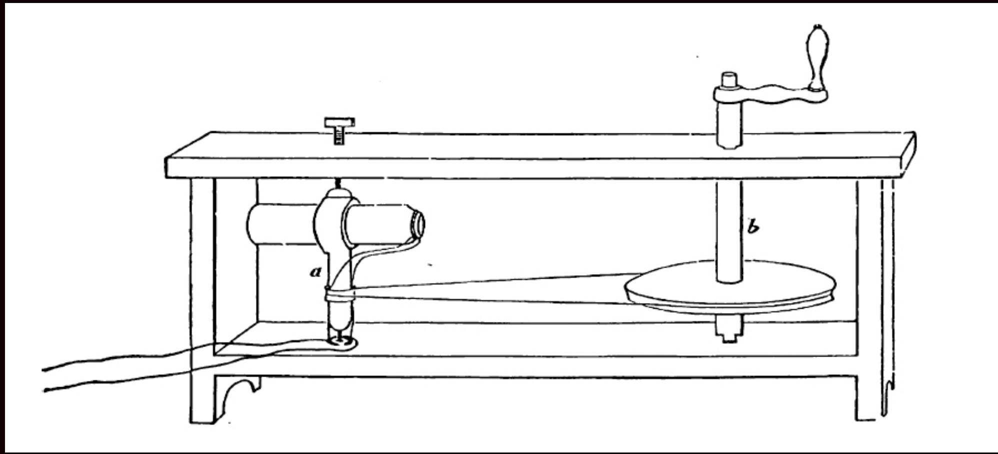



**conversion between heat and the various 'mechanical powers'**

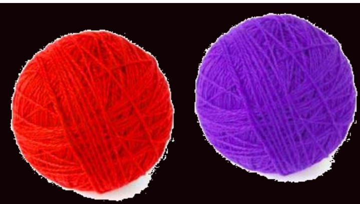
# Joule and the mechanical theory of heat

James Prescott Joule had a mechanical conception of nature as explanation of all phenomena, and made experiments to confirm his tenet in electricity, magnetism, heat, …With a magneto-electric machine he researched the calorific effects of this current. From the experiments carried out he concludes '"We have therefore in magneto-electricity an agent capable by simple mechanical means of destroying or generating heat" (*On the Calorific Effects of Magneto-Electricity, and on the Mechanical Value of Heat 1843*).
Hence, he searched a numerical relation between the mechanical power used in the motion of the machine and the heat evolved through the electric current. The constancy of the conversion factor (mechanical equivalent of heat) proves for Joule that heat cannot be a substance, but a kind of motion. If heat is motion and the calorific effects of the magneto-electricity are produced through motion, then we have a motion that causes another motion. The quantity of one kind is converted into the other.

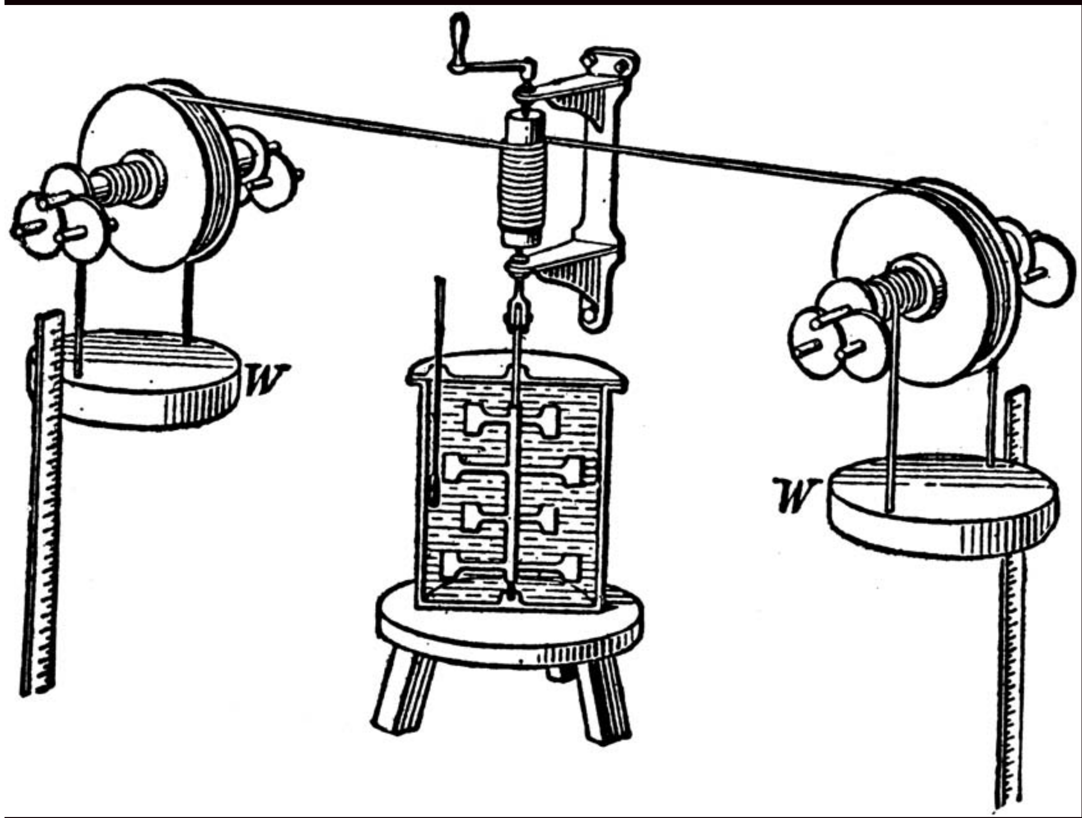




# 1845 Joule's process to determine the mechanical equivalent of heat



**The apparatus consists of a brass paddle-wheel working horizontally in a can of filled with water. This paddle-wheel moves by means of weights thrown over two pulleys working in opposite directions. The result was the following:**
**"for each degree of heat evolved by the friction of water a mechanical power equal to that which can raise a weight of 890 lb to the height of one foot had been expended".**



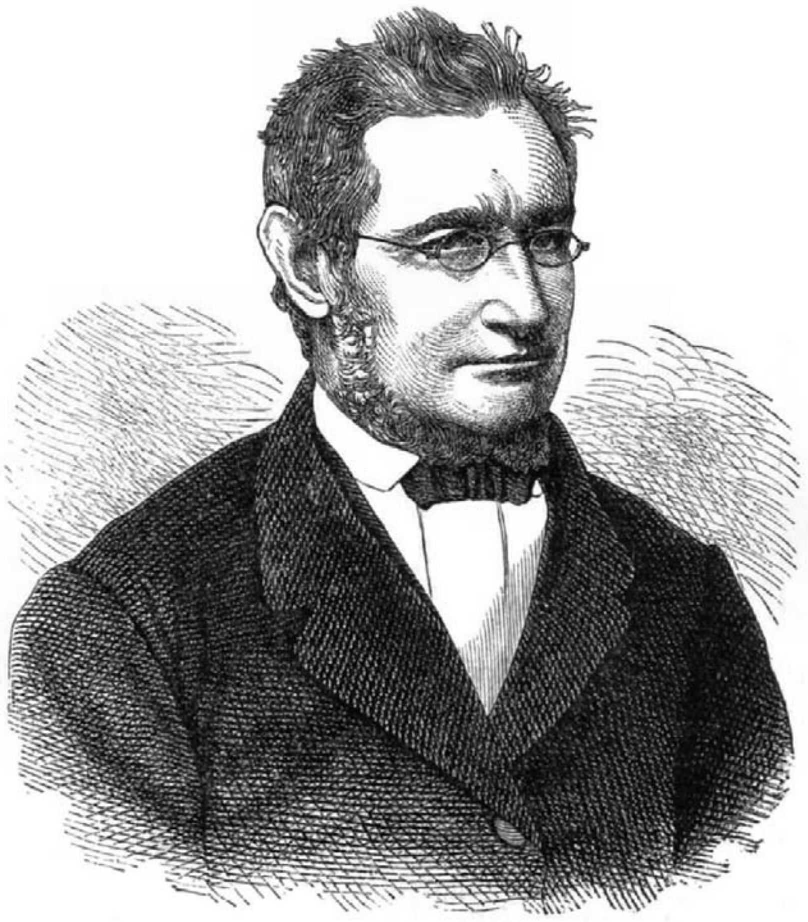

"The paddle moved with great resistance in the can of water, so that the weights (each of four pounds) descended at the slow rate of about one foot per second. The height of the pulleys from the ground was twelve yards, and consequently, when the weights had descended through that distance, they had to be wound up again in order to renew the motion of the paddle. After this operation had been repeated sixteen times, the increase of the temperature of the water was ascertained by means of a very sensible and accurate thermometer"

# Robert Mayer 1842

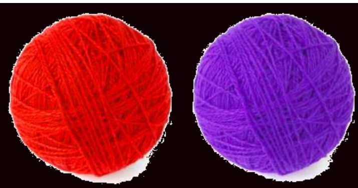
Mayer was committed philosophically to great conservation laws of nature, also because of the old medico-physiological tradition against metaphysical explanations.

His *Bemerkungen über die Kräfte der unbelebten Natur* (1842) shows a deep understanding and a full realization of the principle of energy ('Kraft') conservation. He considers several phenomena of transformation of Kräfte, treated as cause-effect: velocity of falling bodies, heat and motion, electricity and motion, chemical processes and mechanical effects.

The possibility of connecting causally a chain of observable and measurable physical processes implies that the Kräfte are quantitatively indestructible, qualitatively transformable and imponderable.



# Mayer’s mechanical equivalent of heat

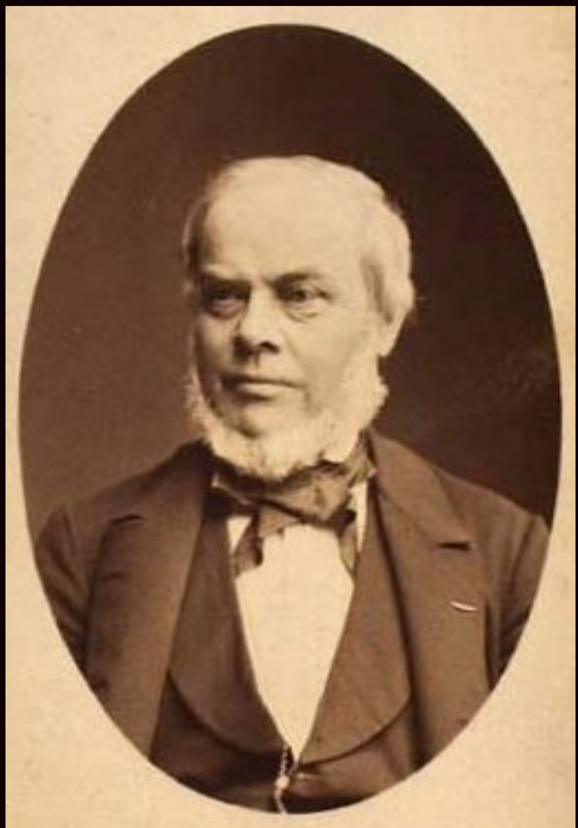


To write an equation relating heat to motion, Mayer made recourse to the specific heat of atmospheric air at constant pressure and constant volume.
As the first quantity of heat referred to is greater than the second one, but in the first case there is some motion and in the second there is none, Mayer considers the difference of the quantities of these heats equal to the force performed in the variation of volume against atmospheric pressure.

With the numerical values known at that time, he obtained: the fall of a weight from the height of ~365 m corresponds to the heating of an equal mass of water from 0 to 1 C.

# Ludvig August Colding, 1843

**Colding, City Engineer of Copenhagen, acquainted with Ørsted, studied various machines. In his 1843 paper *Die Erhaltung der Kraft* he announced the establishment of the conservation law of 'Kraft', based on measurements of expansion due to frictional heating of various metal strips. His philosophical tenet is:**



**"As the forces of nature are something spiritual and immaterial entities whereof we are cognizant only by their mastery over nature, these entities must, of course be very superior to everything material in the world; it is consequently quite impossible to conceive of these forces as anything naturally mortal or perishable. Surely, therefore, the forces ought to be regarded as absolutely imperishable."**

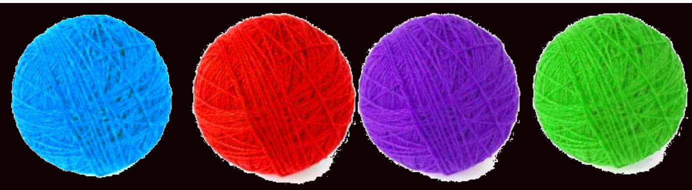
***On the History of the Principle of the Conservation of Energy*** **(1864)**

# Joule's *On Matter, Living Force and Heat* (28 April 1847)

**"This force possessed by moving bodies is termed by mechanical philosophers *vis viva,* or *living force*….The living force of bodies is regulated by their weight and by the velocity of their motion. We might reason, *a priori,* that such absolute destruction of living force cannot possibly take place, because it is manifestly absurd to suppose that the powers with which God has endowed matter can be destroyed any more than that they can be created by man's agency; but we are not left with this argument alone, decisive as it must be to every unprejudiced mind. The common experience of everyone teaches him that living force is not *destroyed* by the friction or collision of bodies….**

**Experiment has enabled us to answer these questions in a satisfactory manner; for it has shown that, wherever living force is apparently destroyed, an equivalent is produced which in process of time may be reconverted into living force. This equivalent is *heat*. The general rule, then, is that wherever living force is *apparently* destroyed, whether by percussion, friction, or any similar means, an exact equivalent of heat is restored. The converse of this proposition is also true, namely, that heat cannot be lessened or absorbed without the production of living force, or its equivalent attraction through space."**

# Helmholtz's contribution



**1847** ***Erhaltung der Kraft, eine physikalische Abhandlung*** **written by a 26 year old Helmholtz represents a general and correct proof of the law of the conservation of energy, with an exhaustive mathematical formulation.**
**Helmholtz started out with a vague, undefined 'Kraft', which he believed to be conserved in Nature, and to which all other physical forces were related, even the unknown 'vital force', and this force had to be brought into mathematical relationship with the entity which rational mechanics has proved to be conserved. Moreover, that entity must somehow tie up with the Newtonian force concept, and there must be at least a clear relationship between the two. Needless to say, the principle of the impossibility of a** ***perpetuum mobile*** **must be a consequence of this conservation law, whether we deal with dead or live matter.**

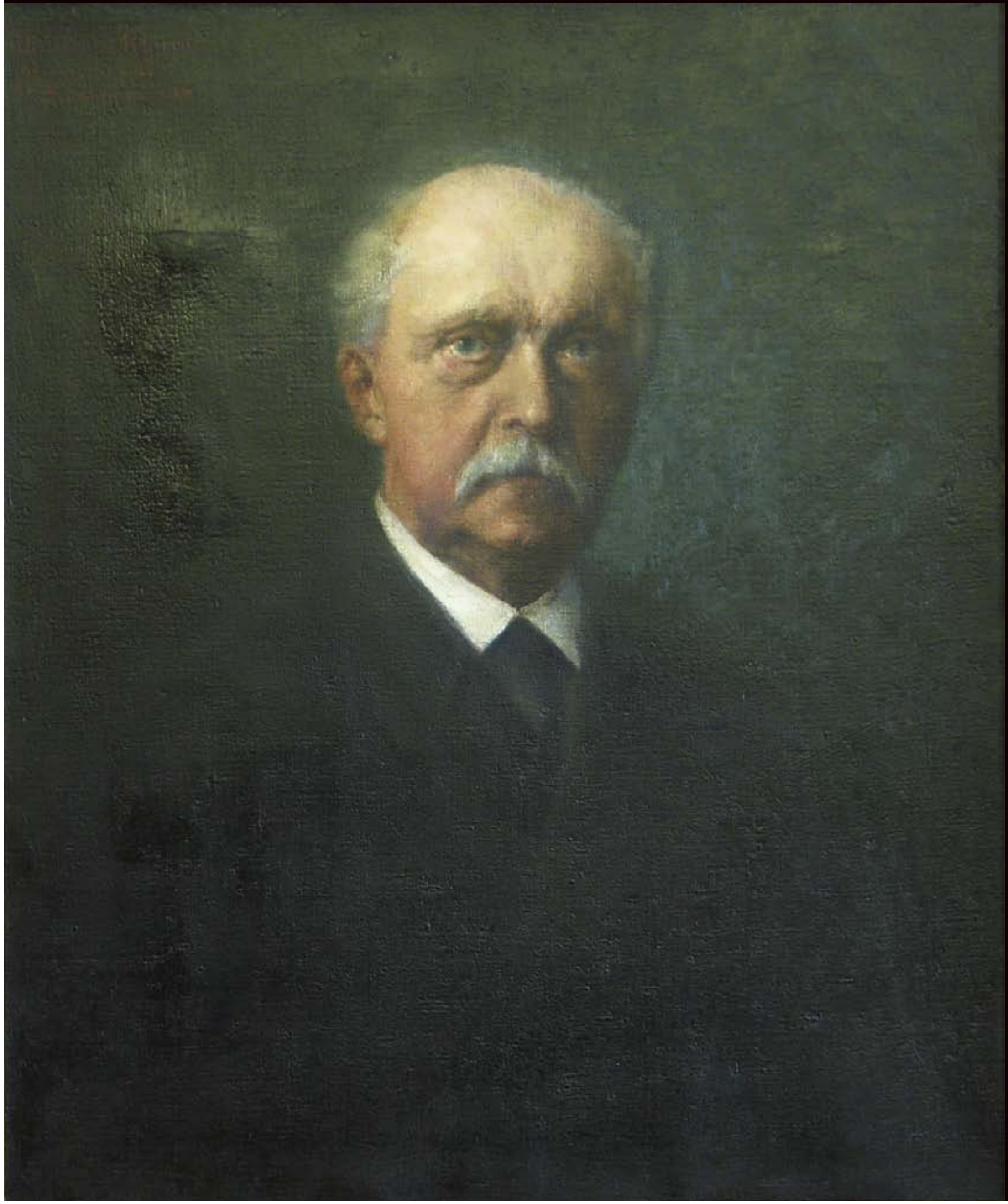
# **Helmholtz's *Erhaltung der Kraft***

**The essay is divided into an introduction and six sections. The introduction is mainly philosophical. The first section covers the principle of the conservation *of vis viva;* presupposing the impossibility "to produce force continually from nothing".
He shows that "in systems to which the principle of the conservation of force can he applied in all its generality, the elementary forces of the material points must be central forces".
In section 2 the Principle of Conservation of Force is dealt with.
Section 3 is the application of the principle in mechanical theorems. Section 4 is on the force-equivalent of heat. Section 5 deals with the force equivalent of electric processes. Section 6 concerns the force-equivalent of magnetism and electro-magnetism. In the same section, but in a new part, Helmholtz arrives at the problem of organic forces.**

# Helmholtz’s argument

**(i) Newtonian 'force' is a fundamental concept in mechanics.**
**(ii) Physics is reducible to mechanics.**
**(iii) The fundamental concept in physiology is 'force of life'; physiology is reducible to physics, i.e. to mechanics.**
**(iv) There is a basic entity in Nature which is being conserved.**
**(v) The Lagrangian formulation of mechanics is equivalent to the Newtonian formulation mathematically and conceptually: the Lagrangian formulation has as its fundamental entity 'kinetic energy plus potential energy'; this fundamental sum is being conserved.**

**Conclusion: The basic entity which is being conserved must be 'Kraft’. The basic entity 'Kraft' which is being conserved in Nature must be equivalent in dimension and form to mechanical energy. This is the generalized conservation of energy principle.**



the scientific importance of the principle of conservation of energy does not depend merely on its accuracy as a statement of fact, nor even on the remarkable conclusions which may be deduced from it, but on the fertility of the methods founded on this principle ....

To appreciate the full scientific value of Helmholtz's little essay on this subject, we should have to ask those to whom we owe the greatest discoveries in thermodynamics and other branches of modern physics, how many times they have read it over and over, and how often during their researches they felt the weighty statements of Helmholtz acting on their minds like an irresistible driving-power.

*James Clerk Maxwell, 1877*

# Perceptions of energy conservation

**Sadi Carnot, before 1832, Marc Seguin in 1839, Karl von Holtzmann in 1845, and Gustave-Adolphe Hirn in 1854, all recorded their independent convictions that heat and work are quantitatively interchangeable, and all computed a value for the conversion coefficient or an equivalent.**

**Between 1837 and 1844, Liebig, Karl Friedrich Mohr, William Robert Grove, and Michael Faraday, all described the world of phenomena as manifesting but a single 'force', one which could appear in electrical thermal, dynamical, and many other forms, but which could never, in all its transformations, be created or destroyed.**

**Michael Faraday**
**in his "Relations of Chemical Affinity, Electricity, Heat, Magnetism, and other powers of Matter" (1834) stated:**
**"We cannot say that any one [of these powers] is the cause of the others, but only that all are connected and due to one common cause."**

# The principle of conservation of energy

"The principle of conservation of energy is an all-embracing principle of nature, with several other important conclusions considered as mere corollaries of it. Thus the mutual convertibility of the various kinds of energy is an equivalent statement to the principle of conservation. The mechanical nature of heat is a mere corollary from the conservation law. It is self-evident for us that phenomena of organic life are subsumed to the principle exactly as are the laws of inorganic nature. That this is so is a result of scientific proof of these equivalences, and to ascribe to it any historical truth is sheer hindsight. Historically there were at least two independent and simultaneous developments in England and Germany between 1840 and, let us say, 1855. The English group, originating with Joule was preoccupied by problems of the efficiency of conversion between the various 'mechanical powers'. Their work resulted in the final proof that heat was a mode of motion. The Germans Mayer and Helmholtz were troubled by the physiological problem of 'animal heat' and their work resulted in the formulation of a law of conservation, in Helmholtz's case mathematically proved on the basis of correct dimensional analysis. Mayer believed in the caloric theory while both Mayer and Helmholtz emphasized that whether heat was matter or motion was not germane to the principle of conservation. The connecting link between the two trends is the work of Carnot"

*Y. Hekana*

**William Thomson lord Kelvin of Largs**

**Thomson recognized the importance and significance of Joule's results and he set himself to remove the contradiction between the results of Joule and Carnot.**
**It was essential to decide between the caloric theory of heat and the dynamical theory of heat, that is between a conservation principle and a convertibility principle. If indeed heat is not lost on either theory there is something that is lost.**

**Finally, in 1851 Thomson had the answers: there is an entity [energy] which is conserved, and a diffrent one (*motivity* - concentration of energy) which is lost: this is the great generalization expressed as the "universal tendency in nature to the dissipation of energy" (*On the Dynamical Theory of Heat*).**

## Kelvin's synthesis

"The whole theory of the motive power of heat is founded on the two following propositions, due respectively to Joule and to Carnot and Clausius:

Prop. I (Joule) When equal quantities of mechanical effect are produced by any means whatever from purely thermal sources, or lost in purely thermal effects, equal quantities of heat are put out of existence or are generated.

Prop. II ( Carnot and Clausius) If an engine be such that when it is worked backwards the physical and mechanical agencies in every part of its motions are all reversed, it produces as much mechanical effect as can be produced by any thermo-dynamic engine with the same temperatures of sources and refrigerator, from a given quantity of heat."

# William John Macquorn Rankine

Rankine was primarily interested in molecular constitution of matter, trying to develop mathematical models for the elasticity of gases and vapours; this brought him to decide whether to adopt the caloric theory or the mechanical theory of heat. He accepted Joule's mechanical view of heat at an early stage mainly because he assumed a 'Hypothesis of Molecular Vortices', according to which:
"heat is the vis viva of the molecular revolutions or oscillations."

[ 106 ]

XVIII. *On the General Law of the Transformation of Energy.* By William John Macquorn Rankine, *C.E., F.R.S.E., F.R.S.S.A. &c.**

(1.) In this investigation the term *energy* is used to comprehend every affection of substances which constitutes or is commensurable with a power of producing change in opposition to resistance, and includes ordinary motion and mechanical power, chemical action, heat, light, electricity, magnetism, and all other powers, known or unknown, which are convertible or commensurable with these. All conceivable forms of energy may be distinguished into two kinds; actual or sensible, and potential or latent.

*Actual energy* is a measurable, transferable, and transformable affection of a substance, the presence of which causes the substance to tend to change its state in one or more respects; by the occurrence of which changes, actual energy disappears, and is replaced by

*Potential energy*, which is measured by the amount of a change in the condition of a substance, and that of the tendency or force whereby that change is produced (or, what is the same thing, of the resistance overcome in producing it), taken jointly.

If the change whereby potential energy has been developed be exactly reversed, then as the potential energy disappears, the actual energy which had previously disappeared is reproduced.

The law of the conservation of energy is already known, viz. that the sum of the actual and potential energies in the universe is unchangeable.

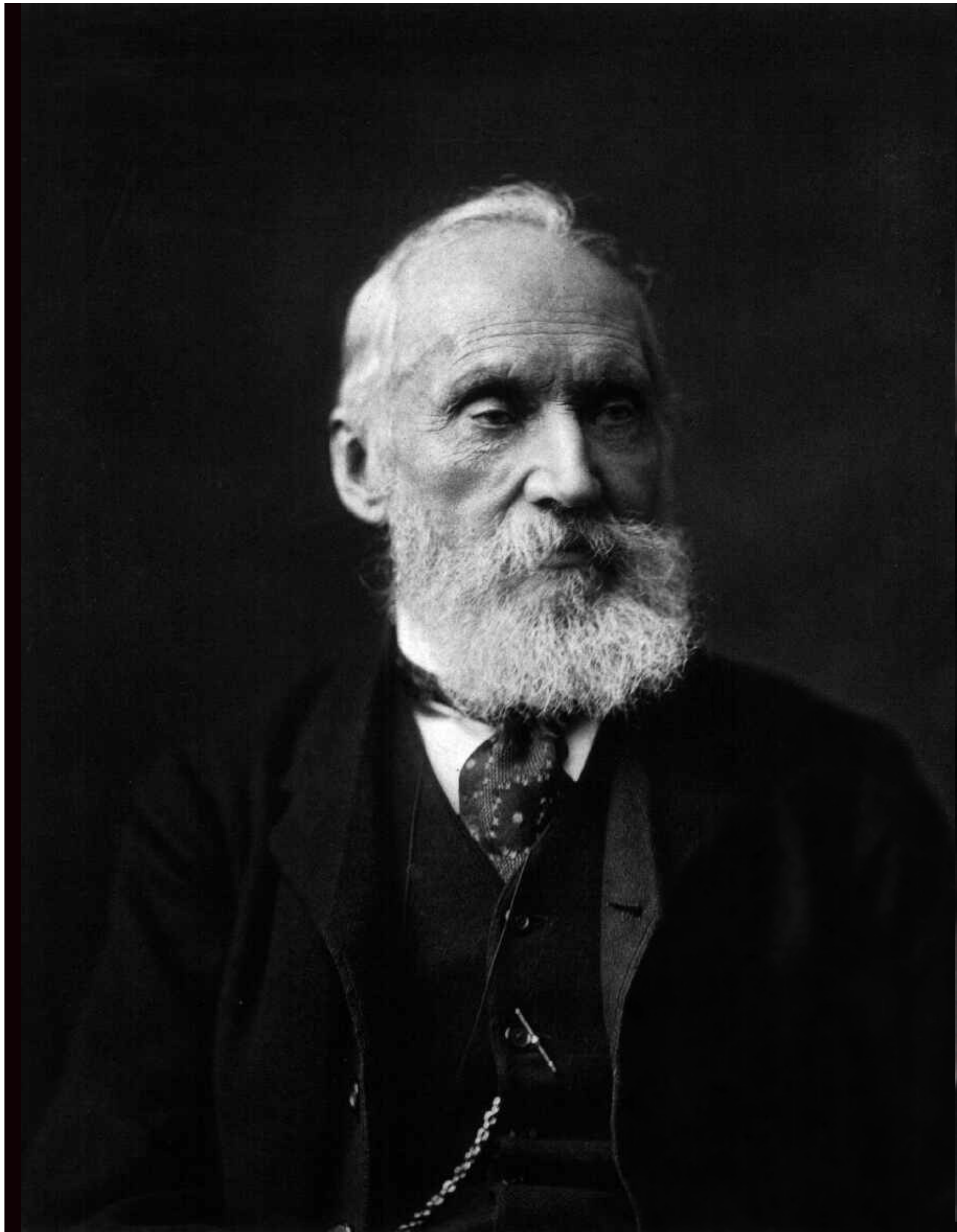
Rankine develops mathematically the dynamical theory of heat, determining also the absolute zero of temperature and the law of specific heats.
He arrived at general equations relating pressure, volume, temperature and heat. These equations implicitly conform to the law of conservation of energy and to Carnot's principle.

# Definitions by Kelvin and Rankine

**In the 1850s Kelvin and Rankine coined, defined and classified the concept of energy.**
**In 1852 Thomson classified 'stores of energy' by distinguishing between 'dynamical' energy and 'statical' energy:**
- **'Dynamical' energy: a mass of matter in motion, a volume of space through which undulations of light or radiant heat are passing, [and] a body having thermal motion among its particles.**
- **'Statical' energy: a quantity of weight at a height, ready to be displaced and do work when moved, an electrified body, a quantity of fuel.**

**Rankine introduced the term 'potential or latent energy' in 1853, contrasting it with 'actual or sensible energy':**
- **forms of actual energy [are] *vis viva,* radiant heat and light, chemical action, electric currents ...**
- **[forms] of potential energy are the mechanical power of gravitation, elasticity, chemical affinity, statical electricity and magnetism.**

**"the distinction between 'actual energy' and 'potential energy'... was suggested to me by Aristotle's use of the words *'dynamis'* and *'energeia'*"**




Kelvin and Rankine exposed a general theory of energy, underlying its unifying role in linking all physical and chemical processes in a chain of reciprocal transformations

# Kinetic energy, 1867

**In 1867, Thomson with Peter Guthrie Tait started a program of reconstruction of the whole body of physics on the very concept of energy.**
**In their *Treatise on Natural Philosophy,* they replaced Rankine's 'actual energy' by a new coinage, 'kinetic energy', expressed by $\frac{1}{2}mv^2$.**
**The term 'kinetic' had been used by Leibniz in relation to his *vis viva,* but now meant the capacity of a moving body to perform work.**

**It is likely that Thomson preferred 'kinetic energy' to 'actual or 'active energy' because of his mechanical or Cartesian view of all natural phenomena.**

TREATISE

ON

NATURAL PHILOSOPHY

BY

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FELLOW OF ST PETER'S COLLEGE, CAMBRIDGE,

AND

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PART I.

STEREOTYPED EDITION

CAMBRIDGE:
AT THE UNIVERSITY PRESS.
1896



**The *Treatise on Natural Philosophy* intended to be an all-comprehensive treatise on physical science, the foundations being laid in kinematics and dynamics, and the structure completed with the properties of matter, heat, light, electricity and magnetism.**
**It aimed at a complete mechanistic view of nature based on space, mass and energy.**

# What is energy?

**"The term 'energy' comprehends every state of a substance which constitutes the capacity for performing work.**
**Quantities of energy are measured by the quantities of work which they constitute the means of performing."**

***Rankine 1855***

# everything solved?

# 1905, new paradigm, new concept…



### 6. *Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt;* *von A. Einstein.*

Zwischen den theoretischen Vorstellungen, welche sich die Physiker über die Gase und andere ponderable Körper gebildet haben, und der Maxwellschen Theorie der elektromagnetischen Prozesse im sogenannten leeren Raume besteht ein tiefgreifender formaler Unterschied. Während wir uns nämlich den Zustand eines Körpers durch die Lagen und Geschwindigkeiten einer zwar sehr großen, jedoch endlichen Anzahl von Atomen und Elektronen für vollkommen bestimmt ansehen, bedienen wir uns zur Bestimmung des elektromagnetischen Zustandes eines Raumes kontinuierlicher räumlicher Funktionen, so daß also eine endliche Anzahl von Größen nicht als genügend anzusehen ist zur vollständigen Festlegung des elektromagnetischen Zustandes eines Raumes. Nach der Maxwellschen Theorie ist bei allen rein elektromagnetischen Erscheinungen, also auch beim Licht, die Energie als kontinuierliche Raumfunktion aufzufassen, während die Energie eines ponderabeln Körpers nach der gegenwärtigen Auffassung der Physiker als eine über die Atome und Elektronen erstreckte Summe darzustellen ist. Die Energie eines ponderabeln Körpers kann nicht in beliebig viele, beliebig kleine Teile zerfallen, während sich die Energie eines von einer punktförmigen Lichtquelle ausgesandten Lichtstrahles nach der Maxwellschen Theorie (oder allgemeiner nach jeder Undulationstheorie) des Lichtes auf ein stets wachsendes Volumen sich kontinuierlich verteilt.

Die mit kontinuierlichen Raumfunktionen operierende Undulationstheorie des Lichtes hat sich zur Darstellung der rein optischen Phänomene vortrefflich bewährt und wird wohl nie durch eine andere Theorie ersetzt werden. Es ist jedoch im Auge zu behalten, daß sich die optischen Beobachtungen auf zeitliche Mittelwerte, nicht aber auf Momentanwerte beziehen, und es ist trotz der vollständigen Bestätigung der Theorie der Beugung, Reflexion, Brechung, Dispersion etc. durch das



### 3. *Zur Elektrodynamik bewegter Körper;* *von A. Einstein.*

Daß die Elektrodynamik Maxwells — wie dieselbe gegenwärtig aufgefaßt zu werden pflegt — in ihrer Anwendung auf bewegte Körper zu Asymmetrien führt, welche den Phänomenen nicht anzuhaften scheinen, ist bekannt. Man denke z. B. an die elektrodynamische Wechselwirkung zwischen einem Magneten und einem Leiter. Das beobachtbare Phänomen hängt hier nur ab von der Relativbewegung von Leiter und Magnet, während nach der üblichen Auffassung die beiden Fälle, daß der eine oder der andere dieser Körper der bewegte sei, streng voneinander zu trennen sind. Bewegt sich nämlich der Magnet und ruht der Leiter, so entsteht in der Umgebung des Magneten ein elektrisches Feld von gewissem Energiewerte, welches an den Orten, wo sich Teile des Leiters befinden, einen Strom erzeugt. Ruht aber der Magnet und bewegt sich der Leiter, so entsteht in der Umgebung des Magneten kein elektrisches Feld, dagegen im Leiter eine elektromotorische Kraft, welcher an sich keine Energie entspricht, die aber — Gleichheit der Relativbewegung bei den beiden ins Auge gefaßten Fällen vorausgesetzt — zu elektrischen Strömen von derselben Größe und demselben Verlaufe Veranlassung gibt, wie im ersten Falle die elektrischen Kräfte.

Beispiele ähnlicher Art, sowie die mißlungenen Versuche, eine Bewegung der Erde relativ zum „Lichtmedium" zu konstatieren, führen zu der Vermutung, daß dem Begriffe der absoluten Ruhe nicht nur in der Mechanik, sondern auch in der Elektrodynamik keine Eigenschaften der Erscheinungen entsprechen, sondern daß vielmehr für alle Koordinatensysteme, für welche die mechanischen Gleichungen gelten, auch die gleichen elektrodynamischen und optischen Gesetze gelten, wie dies für die Größen erster Ordnung bereits erwiesen ist. Wir wollen diese Vermutung (deren Inhalt im folgenden „Prinzip der Relativität" genannt werden wird) zur Voraussetzung erheben und außerdem die mit ihm nur scheinbar unverträgliche



### 13. *Ist die Trägheit eines Körpers von seinem Energieinhalt abhängig?* *von A. Einstein.*

Die Resultate einer jüngst in diesen Annalen von mir publizierten elektrodynamischen Untersuchung[1]) führen zu einer sehr interessanten Folgerung, die hier abgeleitet werden soll.

Ich legte dort die Maxwell-Hertzschen Gleichungen für den leeren Raum nebst dem Maxwellschen Ausdruck für die elektromagnetische Energie des Raumes zugrunde und außerdem das Prinzip:

Die Gesetze, nach denen sich die Zustände der physikalischen Systeme ändern, sind unabhängig davon, auf welches von zwei relativ zueinander in gleichförmiger Parallel-Translationsbewegung befindlichen Koordinatensystemen diese Zustandsänderungen bezogen werden (Relativitätsprinzip).

Gestützt auf diese Grundlagen[2]) leitete ich unter anderem das nachfolgende Resultat ab (l. c. § 8):

Ein System von ebenen Lichtwellen besitze, auf das Koordinatensystem $(x, y, z)$ bezogen, die Energie $l$; die Strahlrichtung (Wellennormale) bilde den Winkel $\varphi$ mit der $x$-Achse des Systems. Führt man ein neues, gegen das System $(x, y, z)$ in gleichförmiger Paralleltranslation begriffenes Koordinatensystem $(\xi, \eta, \zeta)$ ein, dessen Ursprung sich mit der Geschwindigkeit $v$ längs der $x$-Achse bewegt, so besitzt die genannte Lichtmenge — im System $(\xi, \eta, \zeta)$ gemessen — die Energie:

$$l^* = l \frac{1 - \frac{v}{V} \cos \varphi}{\sqrt{1 - \left(\frac{v}{V}\right)^2}},$$

wobei $V$ die Lichtgeschwindigkeit bedeutet. Von diesem Resultat machen wir im folgenden Gebrauch.

1) A. Einstein, Ann. d. Phys. 17. p. 891. 1905.

2) Das dort benutzte Prinzip der Konstanz der Lichtgeschwindigkeit ist natürlich in den Maxwellschen Gleichungen enthalten.

**"Whereof one cannot speak, thereof one must be silent."**

*Ludwig Wittgenstein, 1921*

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