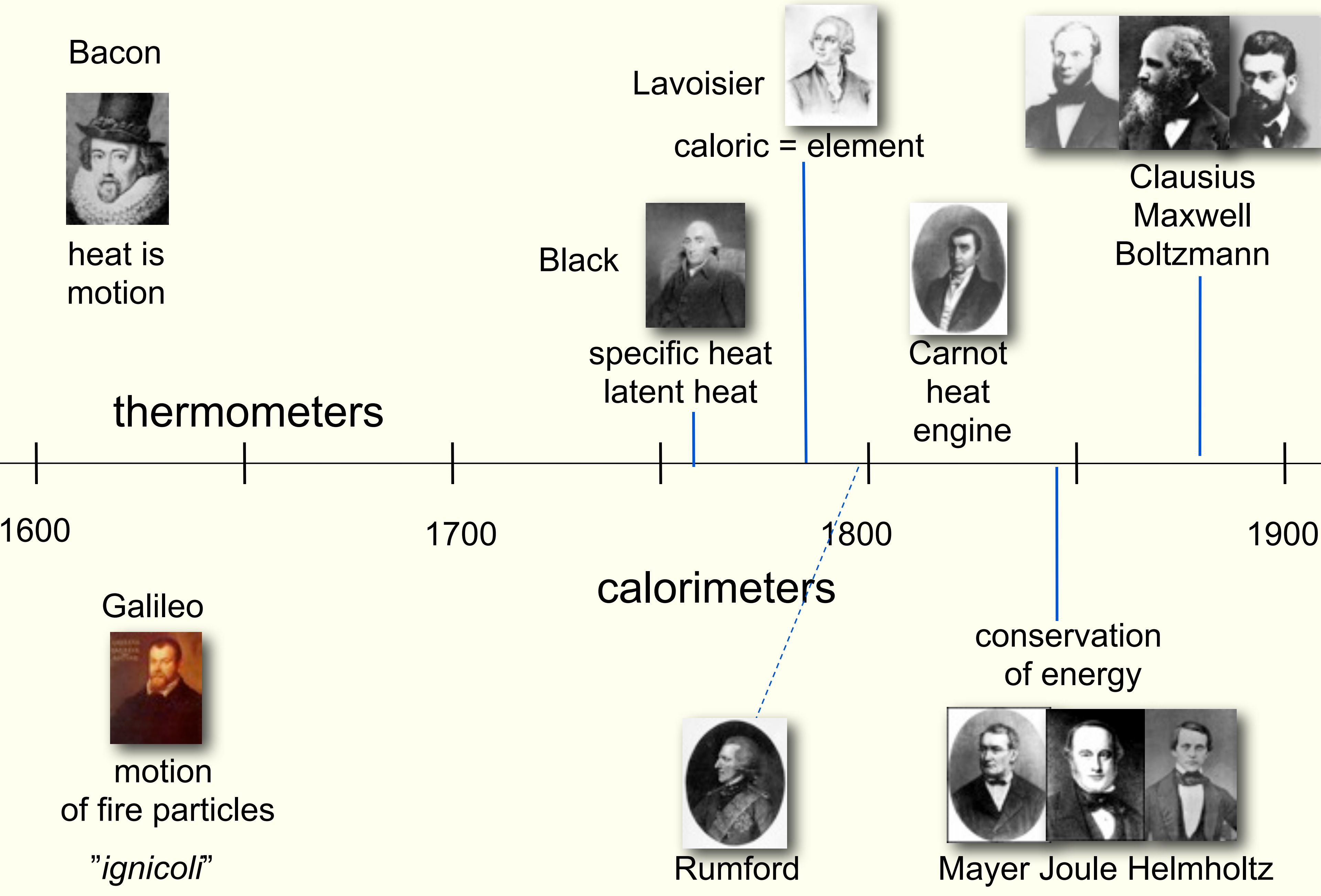
Physics of the XIXth century
part 2

Termodynamics
and statistical physics

Three centuries of the history of heat



Kinetic theory, thermodynamics, statistical physics

1738 D. Bernoulli gas pressure

1789 Lavoisier caloric → element

1798 B. Thompson heat through friction

1799 Davy ” ”

1812 Davy rotational motion of particles

1821 Herapath translational motion of particles

1824 Carnot η (caloric theory)

1840-43 Joule mechanical equivalent of heat

1842 Mayer conservation of energy

1847 Helmholtz conservation of energy

Mathematical theory of heat (Poisson, Laplace)

Quantity of caloric $q = f(p, \rho, t) = f(p, t)$
because pressure p, density ρ, and temperature t
are connected by equation $p = a\rho\,(1 + \alpha t)$

[Nowadays $U = U(p, V)$ <u>and</u> $S = S(p, V)$]

$$dq = (\partial q/\partial p)_V dp + (\partial q/\partial V)_p dV \Rightarrow q = f(pV^\gamma)$$

$$\gamma = C_p/C_V = [(\partial q/\partial T)_V / (\partial q/\partial T)_p]$$

Laplace: simplest assumption that f is a linear function

$$q = A + B\,t\,p^{(1-\gamma)/\gamma}$$

Agreement with experimental data for $\gamma = 1.4$

THÉORIE

MATHÉMATIQUE

DE LA CHALEUR;

PAR S. D. POISSON,

Membre de l'Institut, du Bureau des Longitudes et de l'Université de France; des Sociétés royales de Londres et d'Édimbourg; des Académies de Berlin, de Stockholm, de Saint-Pétersbourg, de Boston, de Turin, de Naples, et de plusieurs autres villes d'Italie; de l'Université de Wilna; des Sociétés italienne, astronomique de Londres, philomatiques de Paris et de Varsovie, et de la Société des Sciences d'Orléans.

PARIS,

BACHELIER, IMPRIMEUR-LIBRAIRE

POUR LES MATHÉMATIQUES, LA PHYSIQUE, ETC.,

QUAI DES AUGUSTINS, Nº 55.

1835

Exemplary pages from Poisson's book

rature extérieure ζ sera devenue stationnaire et égale à μ; si donc on appelle v l'excès de u sur la température de l'espace, au lieu où la Terre se trouve au bout de ce temps t, on aura $v = u - \mu$; et si l'on fait, en outre,

$$\theta = \frac{2z^2}{t}, \quad d\theta = \frac{4z\,dz}{t},$$

il en résultera

$$v = \frac{8ba\lambda}{\pi t}\int_0^\infty \frac{\left[\left(b + \frac{z}{a\sqrt{t}}\right)\cos\left(2z^2 - \frac{xz}{a\sqrt{t}}\right) + \frac{z}{a\sqrt{t}}\sin\left(2z^2 - \frac{xz}{a\sqrt{t}}\right)\right] e^{-\frac{xz}{a\sqrt{t}}}\, z\,dz}{\left(b^2 + \frac{2bz}{a\sqrt{t}} + \frac{2z^2}{a^2 t}\right)\left(1 + \frac{4a^2 z^2}{t}\right)}.$$

Or, par le développement suivant les puissances descendantes de t, sous le signe $\int$, et en dehors du sinus, du cosinus et de l'exponentielle, il en résultera pour la valeur de v une série très convergente dans ses premiers termes; et en négligeant les termes qui seront divisés par le carré ou les puissances supérieures de t, on aura

$$v = \frac{8a\lambda}{\pi t}\int_0^\infty \cos\left(2z^2 - \frac{xz}{a\sqrt{t}}\right) e^{-\frac{xz}{a\sqrt{t}}}\, z\,dz$$
$$+ \frac{8a\lambda}{\pi b a t\sqrt{t}}\int_0^\infty \left[\sin\left(2z^2 - \frac{xz}{a\sqrt{t}}\right) - \cos\left(2z^2 - \frac{xz}{a\sqrt{t}}\right)\right] e^{-\frac{xz}{a\sqrt{t}}}\, z^2\,dz;$$

en sorte qu'il ne restera plus qu'à déterminer les valeurs de ces deux intégrales relatives à z, à quoi l'on parviendra, comme on va le voir, par la considération des exponentielles imaginaires.

On aura, en premier lieu,

$$\int_0^\infty e^{2z^2\sqrt{-1} - \frac{xz}{a\sqrt{t}}(1+\sqrt{-1})}\, dz = e^{-\frac{x^2}{4a^2t}}\int_0^\infty e^{-\left[z(1-\sqrt{-1}) + \frac{x\sqrt{-1}}{2a\sqrt{t}}\right]^2} dz.$$

En faisant

$$z(1-\sqrt{-1}) + \frac{x\sqrt{-1}}{2a\sqrt{t}} = y, \quad dz = \frac{dy}{1-\sqrt{-1}},$$

et, pour abréger,

$$\frac{x\sqrt{-1}}{a\sqrt{t}} = x_1,$$

les limites de l'intégrale relative à y, qui répondent à $z = 0$ et $z = \infty$, seront

$y = x_1$ et $y = \infty$; de plus, on pourra prendre d'abord cette intégrale depuis $y = 0$ jusqu'à $y = \infty$, puis en retrancher la même intégrale prise depuis $y = 0$ jusqu'à $y = x_1$; par conséquent, il en résultera

$$\int_0^\infty e^{2z^2\sqrt{-1} - \frac{xz}{a\sqrt{t}}(1+\sqrt{-1})}\, dz = \frac{e^{-\frac{x^2}{4a^2t}}}{1-\sqrt{-1}}\left(\int_0^\infty e^{-y^2}dy - \int_0^{x_1} e^{-y^2}dy\right).$$

En observant qu'on a

$$\int_0^\infty e^{-y^2}dy = \frac{1}{2}\sqrt{\pi}, \quad \frac{d}{dx}\int_0^{x_1} e^{-y^2}dy = \frac{dx_1}{dx}e^{-x_1^2} = \frac{\sqrt{-1}}{2a\sqrt{t}}e^{\frac{x^2}{4a^2t}},$$

différentiant l'équation précédente une première et une seconde fois par rapport à x, et réduisant, on aura

$$\int_0^\infty e^{2z^2\sqrt{-1} - \frac{xz}{a\sqrt{t}}(1+\sqrt{-1})}\, z\,dz = \frac{x e^{-\frac{x^2}{4a^2t}}}{4a\sqrt{t}}\left(\frac{1}{2}\sqrt{\pi} - \int_0^{x_1} e^{-y^2}dy\right) + \frac{\sqrt{-1}}{4},$$

$$\int_0^\infty e^{2z^2\sqrt{-1} - \frac{xz}{a\sqrt{t}}(1+\sqrt{-1})}\, z^2\,dz = \frac{1}{16}(1+\sqrt{-1})\frac{x}{a\sqrt{t}}$$
$$- \frac{1}{8}\left(1 - \frac{x^2}{2a^2t}\right)(1-\sqrt{-1})\left(\frac{1}{2}\sqrt{\pi} - \int_0^{x_1} e^{-y^2}dy\right)e^{-\frac{x^2}{4a^2t}}.$$

Faisons encore

$$y = x_1 y_1, \quad dy = x_1 dy_1;$$

les limites relatives à y_1, qui répondent à $y = 0$ et $y = x_1$, seront $y_1 = 0$ et $y_1 = 1$; et d'après ce que x_1 représente, nous aurons

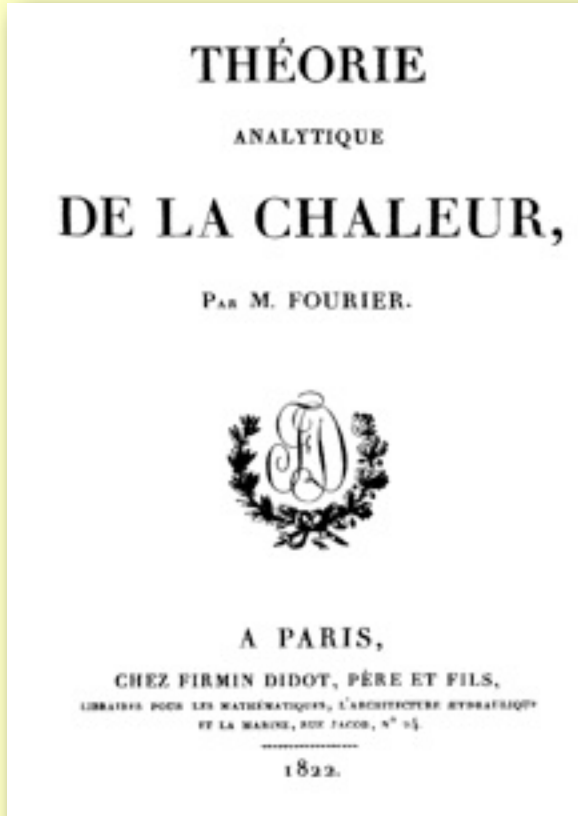
$$\int_0^{x_1} e^{-y^2}dy = \frac{x\sqrt{-1}}{2a\sqrt{t}}\int_0^1 e^{\frac{x^2y_1^2}{4a^2t}}dy_1.$$

Cela étant, si l'on prend successivement $\sqrt{-1}$ avec le signe $+$ et avec le signe $-$, dans les deux dernières intégrales relatives à z et dans leurs valeurs, et si l'on fait disparaître les exponentielles imaginaires, au moyen de leurs expressions en sinus et cosinus d'arcs réels, on en déduira

$$\int_0^\infty \cos\left(2z^2 - \frac{xz}{a\sqrt{t}}\right)e^{-\frac{xz}{a\sqrt{t}}}\, z\,dz = \frac{x\sqrt{\pi}}{8a\sqrt{t}}e^{-\frac{x^2}{4a^2t}},$$

Theory of heat transport

Jean-Baptiste Joseph Fourier
(1768-1830)



THÉORIE

ANALYTIQUE

DE LA CHALEUR,

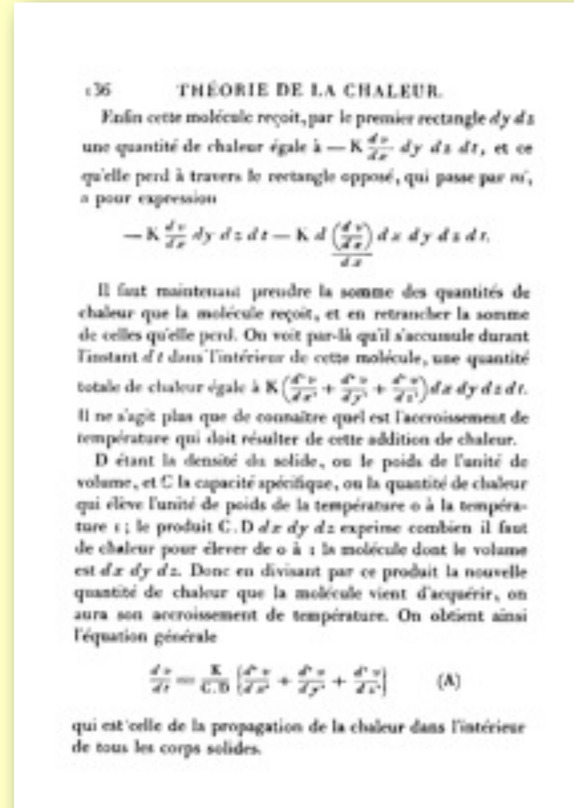
PAR M. FOURIER.

A PARIS,

CHEZ FIRMIN DIDOT, PÈRE ET FILS,

LIBRAIRES POUR LES MATHÉMATIQUES, L'ARCHITECTURE HYDRAULIQUE ET LA MARINE, RUE JACOB, N° 24.

1822.



136 THÉORIE DE LA CHALEUR.

Enfin cette molécule reçoit, par le premier rectangle $dy\,dz$ une quantité de chaleur égale à $-K\frac{dv}{dx}\,dy\,dz\,dt$, et ce qu'elle perd à travers le rectangle opposé, qui passe par m', a pour expression

$$-K\frac{dv}{dx}\,dy\,dz\,dt - K\,d\frac{\left(\frac{dv}{dx}\right)}{dx}\,dx\,dy\,dz\,dt.$$

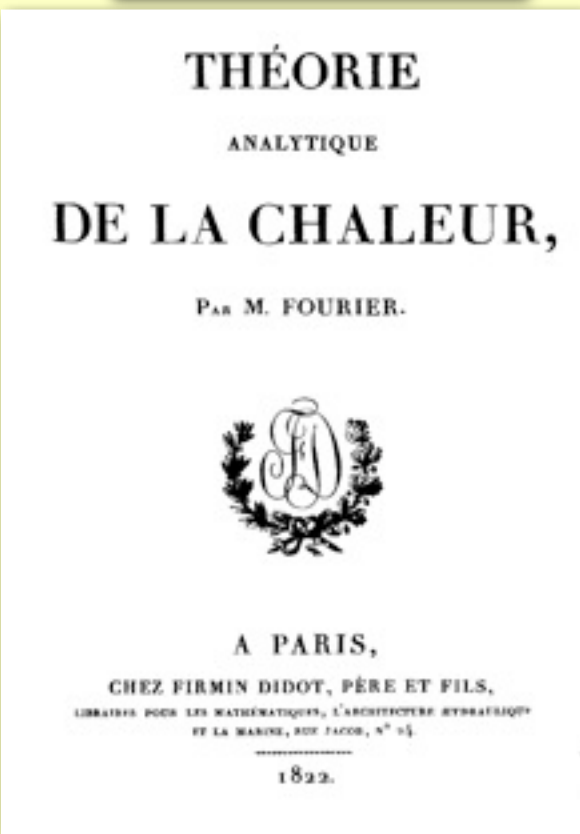
Il faut maintenant prendre la somme des quantités de chaleur que la molécule reçoit, et en retrancher la somme de celles qu'elle perd. On voit par-là qu'il s'accumule durant l'instant dt dans l'intérieur de cette molécule, une quantité totale de chaleur égale à $K\left(\frac{d^2v}{dx^2}+\frac{d^2v}{dy^2}+\frac{d^2v}{dz^2}\right)dx\,dy\,dz\,dt$. Il ne s'agit plus que de connaître quel est l'accroissement de température qui doit résulter de cette addition de chaleur.

D étant la densité du solide, ou le poids de l'unité de volume, et C la capacité spécifique, ou la quantité de chaleur qui élève l'unité de poids de la température 0 à la température 1; le produit $C.D\,dx\,dy\,dz$ exprime combien il faut de chaleur pour élever de 0 à 1 la molécule dont le volume est $dx\,dy\,dz$. Donc en divisant par ce produit la nouvelle quantité de chaleur que la molécule vient d'acquérir, on aura son accroissement de température. On obtient ainsi l'équation générale

$$\frac{dv}{dt} = \frac{K}{C.D}\left(\frac{d^2v}{dx^2}+\frac{d^2v}{dy^2}+\frac{d^2v}{dz^2}\right) \qquad (A)$$

qui est celle de la propagation de la chaleur dans l'intérieur de tous les corps solides.

Jean Baptiste Joseph Fourier



THÉORIE

ANALYTIQUE

DE LA CHALEUR,

Par M. FOURIER.

A PARIS,

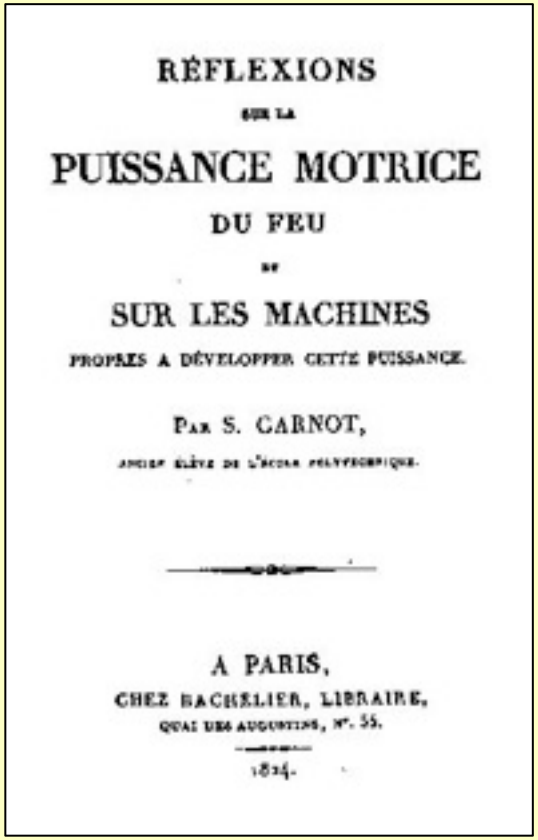
CHEZ FIRMIN DIDOT, PÈRE ET FILS,

1822.

”The effects of heat are subject to constant laws which cannot be discovered without the aid of mathematical analysis. The object of the theory which we are about to explain is to demonstrate these laws; it reduces all physical researches on the propagation of heat, to problems of the integral calculus whose elements are given by experiment.”

***Analytical Theory of Heat*, Chapter 1**

Sadi Carnot (1796-1832)

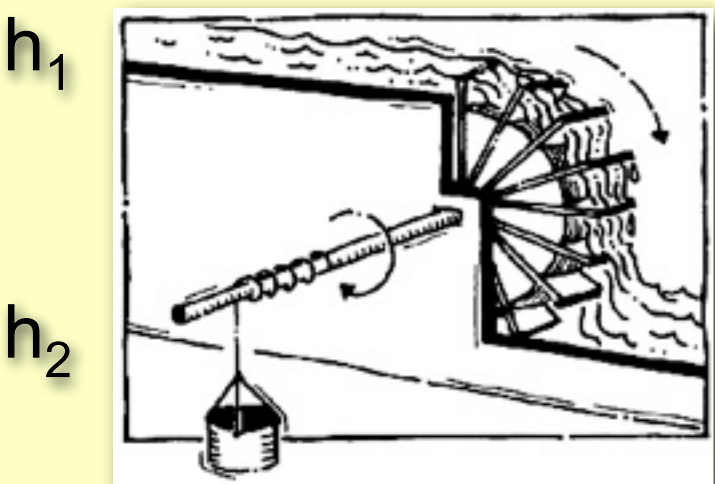


RÉFLEXIONS
SUR LA
PUISSANCE MOTRICE
DU FEU
ET
SUR LES MACHINES
PROPRES A DÉVELOPPER CETTE PUISSANCE.
PAR S. CARNOT,
ANCIEN ÉLÈVE DE L'ÉCOLE POLYTECHNIQUE.

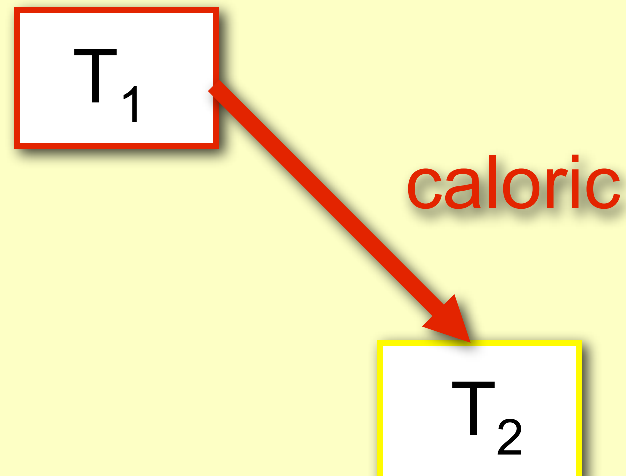
A PARIS,
CHEZ BACHELIER, LIBRAIRE,
QUAI DES AUGUSTINS, N°. 55.
1824.

”The production of motive power in the steam-engine is therefore not due to a real consumption of caloric, but to its transfer from a hotter to a colder body – that is to say, to the reestablishment of its equilibrium, which is assumed to have been destroyed by a chemical action such as combustion, or by some other cause. We shall soon see that this principle is applicable to all engines operated by heat”

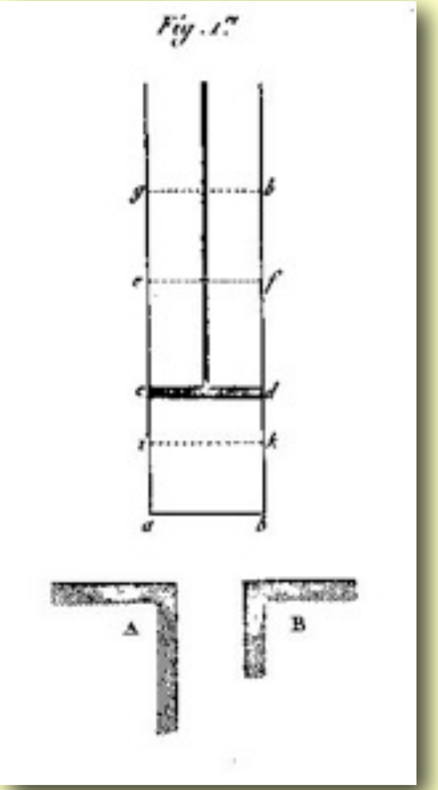
Carnot's picture



water-wheel



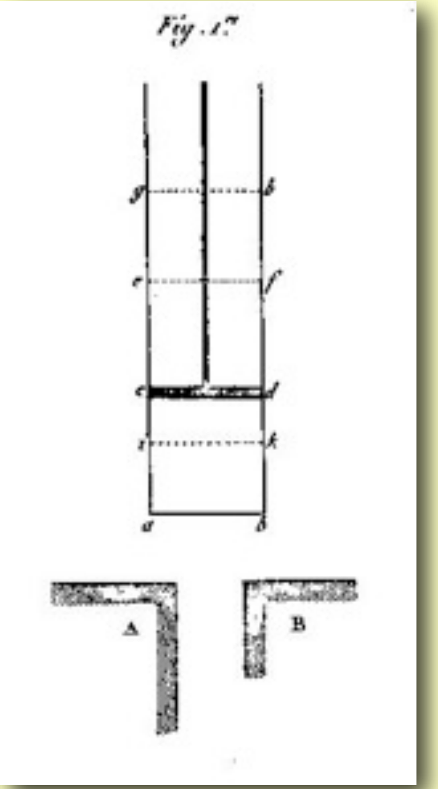
heat engine



”Let us imagine an elastic fluid - atmospheric air, for example - enclosed in a cylindrical vessel *abcd* furnished with a movable diaphragm or piston *cd;* let us also assume the two bodies *A, B* both at constant temperatures, that of *A* being higher than that of *B,* and let us consider the series of operations...

1. Contact of *A* with the air in *abcd*; the air attains the same temperature as *A*; the piston is at *cd*
2. The piston raises gradually until it takes the position *ef*; The body *A* furnishes the caloric necessary to maintain the constant temperature.”

”3. The body *A* is removed...the piston continues to move to *gh;* the air is rarified without receiving the caloric, its temperature falls until it becomes equal to that of *B*



4. The air is brought in contact with *B;* it is compressed by the piston which returns to *cd;* the air gives up its caloric to *B*

5. The body *B* is removed, the compression continues; the temperature of the air, which is now isolated, rises to that of A; the piston passes from *cd* to *ik*.

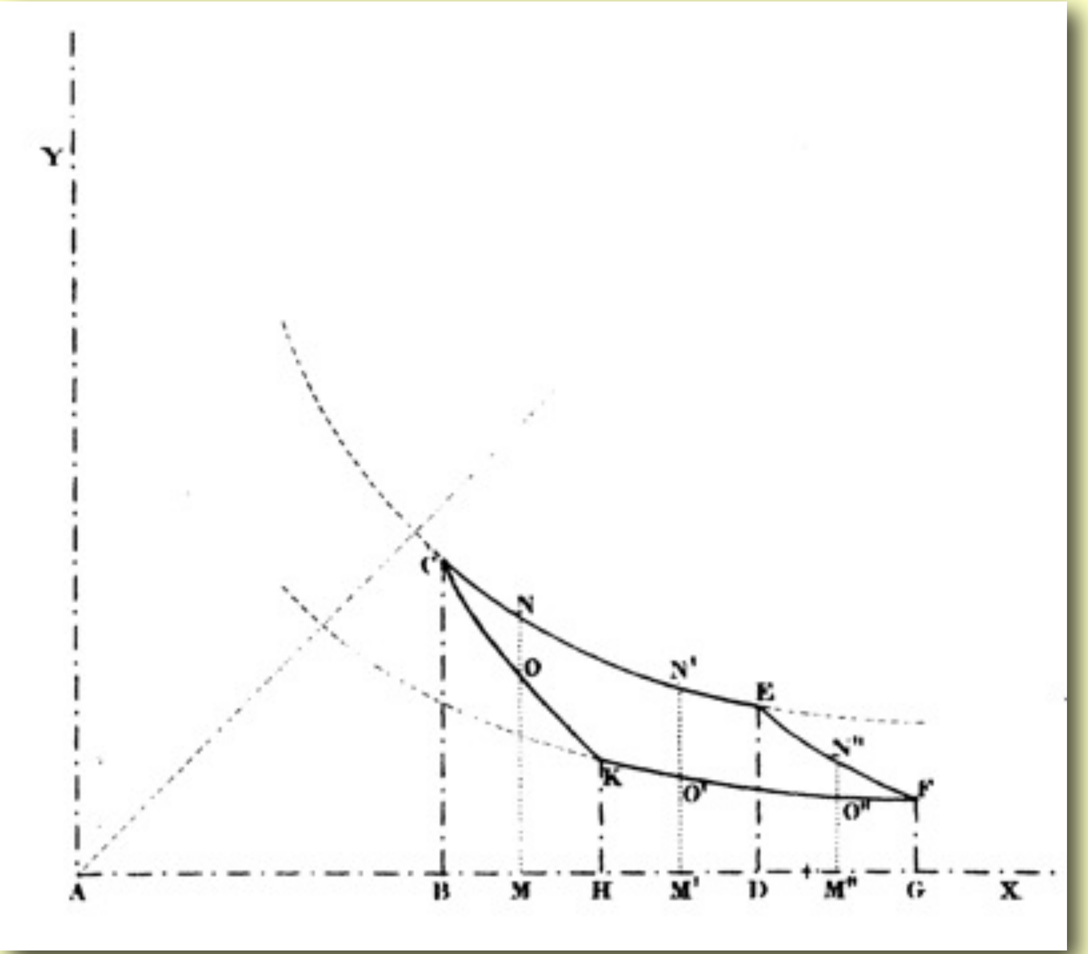
6. The air is again brought in contact with *A*, the piston returns from *ik* to *ef*; the temperature remains constant

7. The operation described in 3 is repeated, and then the operations 4, 5, 6, 3, 4, 5, 6, 3, 4, 5, and so on...”

”In these various operations a pressure is exerted upon the piston by the air contained in the cylinder; the elastic force of this air varies with the changes of volume as well as with the changes of temperature; but we should notice that at equal volumes - that is, for similar positions of the piston - the temperature is higher during the expansions than during the compressions. During the former, therefore, the elastic force of the air is greater, and consequently the quantity of motive power produced by the expansions is greater than that which is consumed in effecting the compressions. Thus there remains an excess of motive power, which we can dispose of for any purpose whatsoever. The air has therefore served as a heat-engine; and it has been used in the most advantageous way possible, for there has been no useless re-establishment of equilibrium in the caloric.
All the operations described above can be carried out in a direct and in a reverse order.”

”We have chosen atmospheric air as the agency employed to develop the motive power of heat; but it is evident that the same reasoning would hold for any other gaseous substance, and even for all the bodies susceptible of changes of temperature by successive contractions - that is, for all bodies in Nature, at least, all those which are capable of developing the motive power of heat. Thus we are led to establish this general proposition: **The motive power of heat is independent of the agents employed to develop it; its quantity is determined solely by the temperatures of the bodies between which, in the final result, the transfer of caloric occurs**.”

Carnot, *Reflexions on the Motive power of Fire*... (1824)



Carnot’s cycle in the familiar graphic form was first introduced in 1834 by Émile Clapeyron

The discovery of the conservation of energy

Julius Robert Mayer (1814-1878)

Bemerkungen über die Kräfte der unbelebten Natur (1842)

James Prescott Joule (1818-1889)

On the calorific effects of magneto-electricity and on the mechanical value of heat (1843)

Hermann Helmholtz (1821-1894)

Über die Erhaltung der Kraft (1847)

The discovery of conservation of energy was ”hanging in the air” since about 1830

Many scientists wrote on that subject, for example

- Sadi Carnot (< 1832),
- Carl Friedrich Mohr (1837),
- Marc Seguin (1839),
- Michael Faraday (1840),
- Justus Liebig (1844),
- Karl Holtzmann (1845),
- William Robert Grove (1846),
- Ludvig August Colding (1851),
- Gustave Adolph Hirn (1854)

Their statements were, however, rather vague and not supported by new experimental data or new analysis of existing results

Example: Justus Liebig, *Letters on Chemistry* (1844):

”Out of nothing, no kind of force can arise... Heat, electricity, and magnetism are equivalent to each other, just as carbon, zinc, and oxygen are. By a certain measure of electricity we produce a corresponding proportion of heat or of magnetic power, equivalent to each other and to the electricity producing them; we purchase that electricity with chemical affinity, which in one shape produces heat, in another electricity or magnetism...”

”Forces are causes; accordingly, we may in relation to them make full application of the principle *causa aequat effectum*. If the cause c has the effect e, then $c = e$; if, in its turn, e is the cause of a second effect f, we have $e = f$, and so on: $c = e = f .... = c$. In a chain of causes and effects, a term or a part of a term can never, as plainly appears from the nature of an equation, become equal to nothing. This first property of all causes we call their *indestructibility*.”

Robert Mayer, *Annalen der Chemie und Pharmacie* (1842)

”If the given cause *c* has produced an effect *e* equal to itself, it has in that very act ceased to be: *c* has become *e*; if, after the production of *e*, *c* still remained in whole or in part, there must be still further effects corresponding to this remaining cause; the total effect of *c* would thus be > *e* which would be contrary to the supposition *c* = *e*. Accordingly, since *c* becomes *e*, and *e* becomes *f*, etc., we must regard these various magnitudes as different forms under which one and the same object makes its appearance...Taking both properties together, we may say, causes are (quantitatively) *indestructible* and (qualitatively) *convertible* objects...”

Robert Mayer, *Annalen der Chemie und Pharmacie* (1842)

"By applying the principles that have been set forth to the relations subsisting between the temperature and the volume of gases, we find that in the sinking of a mercury column by which a gas is compressed is equivalent to the quantity of heat set free by the compressions; and hence it follows, the ratio between the capacity for heat of air under constant pressure and its capacity under constant volume being taken as = 1,421 that the warming of a given weight of water from 0° to 1° C corresponds to the fall of an equal weight from the height of about 365 metres. If we compare with this result the working of our best steam-engines, we see how small a part only of a heat applied under the boiler is really transformed into motion or the raising of weights; and this may serve as justification for the attempts at the profitable production of motion by some other method than the expenditure of chemical difference between carbon and oxygen – more particularly by the transformation into motion of electricity obtained by chemical means."

Fallkraft und Bewegung stattfindenden Gleichungen mußte der Fallraum für eine bestimmte Zeit, z. B. für die erste Secunde durch das Experiment bestimmt werden; gleichermaßen ist zur Auflösung der zwischen Fallkraft und Bewegung einer- und der Wärme andererseits bestehenden Gleichungen die Frage zu beantworten, wie groß das einer bestimmten Menge von Fallkraft oder Bewegung entsprechende Wärmequantum sey. Z. B. wir müssen ausfindig machen, wie hoch ein bestimmtes Gewicht über den Erdboden erhoben werden müsse, daß seine Fallkraft aequivalent sey der Erwärmung eines gleichen Gewichtes Wasser von 0° auf 1° C.? Daß eine solche Gleichung wirklich in der Natur begründet sey, kann als das Resumé des bisherigen betrachtet werden.

Unter Anwendung der aufgestellten Sätze auf die Wärme- und Volumenverhältnisse der Gasarten findet man die Senkung einer ein Gas comprimirenden Quecksilbersäule gleich der durch die Compression entbundenen Wärmemenge und es ergiebt sich hieraus, — den Verhältnißexponenten der Capacitäten der atmosphärischen Luft unter gleichem Drucke und unter gleichem Volumen = 1,421 gesetzt, daß dem Herabsinken eines Gewichtstheiles von einer Höhe circa 365m, die Erwärmung eines gleichen Gewichtstheiles Wasser von 0° auf 1° entspreche. Vergleicht man mit diesem Resultate die Leistungen unserer besten Dampfmaschinen, so sieht man, wie nur ein geringer Theil der unter dem Kessel angebrachten Wärme in Bewegung oder Lasterhebung wirklich zersetzt werde und dies könnte zur Rechtfertigung dienen, für die Versuche, Bewegung auf anderem Wege als durch Aufopferung der chemischen Differenz von C und O, namentlich also durch Verwandlung der auf chemischem Wege gewonnenen Elektricität in Bewegung, auf ersprießliche Weise darstellen zu wollen.

Ausgegeben am 31sten Mai 1842.

Known forms of forces according to Mayer (1845)

I Force of gravity

II Motion

A. Direct

B. Wave, vibration

Imponderable fluids

III Heat

Magnetism

IV Electricity,

galvanic current

V Chemical separation

of certain substances

Chemical binding

of certain other substances

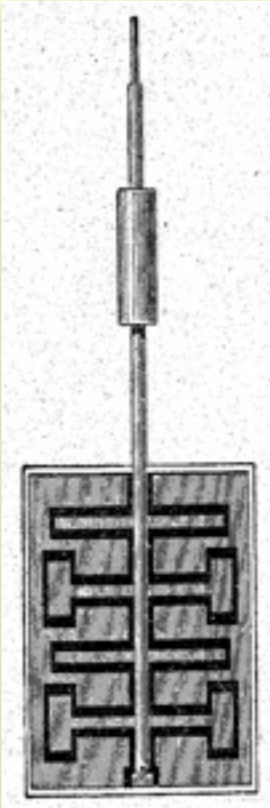
Chemical forces

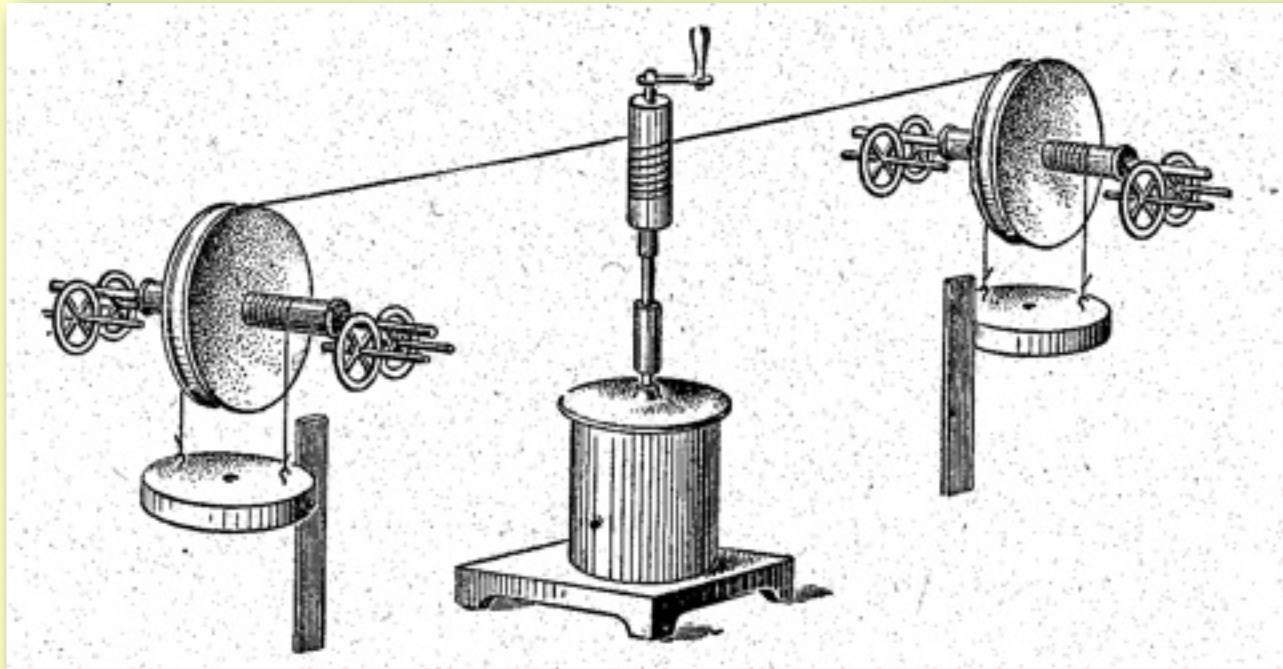
Principle of conservation of energy as formulated by Mayer

”In all physical and chemical processes a given force remains constant”

”Die organische Bewegung in ihren Zusammenhange mit dem Stoffwechsel” (1845)

Mechanical equivalent of heat





”The quantity of heat capable of increasing the temperature of a pound of water by one degree of Fahrenheit’s scale is equal to, and may be converted into, a mechanical force capable of raising 838 lb. to the perpendicular height of one foot.”

(Mechanical equivalent of heat = 460 Kgm/cal) [Joule (1843)]

The most precise result of further experiments: 432.852 Kgm/cal

”*Die Erhaltung der Kraft*” by Hermann Helmholtz

Introduction

I. The conservation of *vis viva*

II. The conservation of force

III. Application to mechanics

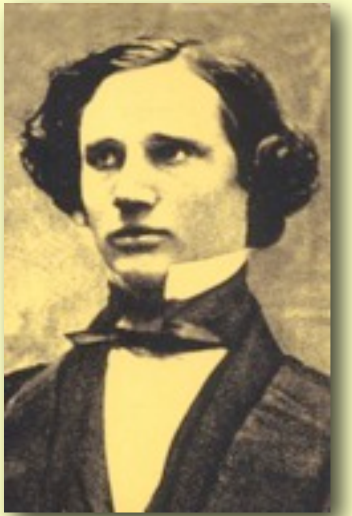
IV. The force equivalent of heat

V. The force equivalent of electric processes

VI. The force equivalent of magnetism and electromagnetism

”I believe that all that I presented above shows that the discussed law is not in contradiction with any of the known facts of natural sciences, and it is confirmed by very many facts in a striking manner. I tried to present as completely as possible the consequences which follow from the association of this law with the other laws of nature, the consequences which still await experimental confirmation. The aim of this study, which justifies its hypothetical part, was to present to the physicists the theoretical, practical and heuristic significance of this law; its full confirmation must be taken as the principal goal in the nearest future of physics”

BAAS Meeting in Oxford, June 1847



First meeting of William Thomson
with James Joule

”Joule is, I am sure, wrong in many of his ideas...”

[Thomson to his father, July 1, 1847]

On the moving force of heat (1850)

The ideas of Carnot and Joule could be reconciled

1. During generation of work from heat a part of heat is lost
2. Heat always passes from hotter to colder bodies

Rudolf Clausius

(1822-1888)

”1. There is at present in the material world a universal tendency to the dissipation of mechanical energy.

2. Any restoration of mechanical energy, without more than an equivalent of dissipation, is impossible in inanimate material processes, and is probably never effected by means of organized matter, either endowed with vegetable life or subjected to the will of an animated creature.”

W. Thomson – *On a Universal Tendency in Nature to the Dissipation of Mechanical Energy* (1852)

Changes in terminology

Helmholtz - living force (***Lebendige Kraft***)
tension force (***Spannkraft***)

Thomson - **statical** energy
dynamical energy

Rankine - **potential** (hidden) energy
actual (visible) energy

Thomson & Tait - **potential** energy
- **kinetic** energy

Treatise on natural philosophy (1867)

W. J. Macquorn **Rankine** on energy:

”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”

On the General Law of the Transformation of Energy (1853)

The second law of thermodynamics (1850-1851)

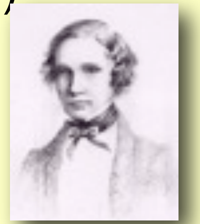
Rudolf Clausius
(1822-1888)

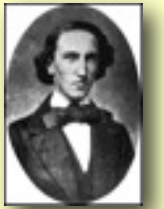
”Heat can never pass from a colder to a warmer body without some other change, connected therewith, occuring at the same time” (1850, 1854)

”It is impossible, by means of inanimate material agency, to derive mechanical effect from any portion of matter by cooling it below the temperature of the coldest of the surrounding objects” (1851)

William Thomson
(1824-1907)

A kind of motion we call heat


1738	D. Bernoulli	gas pressure
1848	Joule (publ. 1851)	calculation of v
1849	W. Thomson	η (caloric theory)
1843-45	Waterston	(kinetic theory)
1850-51	Clausius	η, U, II law of thermodynamics
1851	W. Thomson	η, II law of thermodynamics
1856	Krönig	$p \sim 1/6\ v^2$
1857	Clausius	$p \sim 1/3\ v^2$
1858	Clausius	$\langle v^2 \rangle$, λ
1860	Maxwell	f(v)
1865	Clausius	S
1873-78	Gibbs	thermodynamic potentials
1872	Boltzmann	H-theorem
1877	Boltzmann	$S \sim \log P$,

Founders of the statistical physics

Rudolf Emanuel Clausius (1822-1888)

James Clerk Maxwell (1831-1879)

Ludwig Eduard Boltzmann (1844-1906)

Josiah Willard Gibbs (1839-1903)

”If we think of that quantity which with reference to a single body I have called its entropy, as formed in a consistent way, with consideration of all its circumstances, for the whole universe, and if we use in connection with it the other simpler concept of energy, we can express the fundamental laws of the universe which correspond to the two fundamental theorems of the mechanical theory of heat in the following simple form:

1. The energy of the universe is constant.

2. The entropy of the universe tends to a maximum.”

Clausius, *Ann. Phys. & Chem.* **125**, 353 (1865)

Ludwig Boltzmann

1868 energy distribution of molecules in the presence of an external field

1872 *Further studies of thermal equilibrium of gas molecules* ("*H*-theorem"); description of the time evolution of a system

1877 **$S = k \log W$**
entropy connected with thermodynamic probability

Fight with the supporters of the Energetics (Wilhelm Ostwald, Ernest Mach, and others)

”As the first part of *Gas Theory* was being printed, I had already almost completed the present second and last part... It was just at this time that attacks on the theory of gases began to increase. I am convinced that these attacks are merely based on a misunderstanding, and that the role of gas theory in science has not yet been played out...
In my opinion it would be a great tragedy for science if the theory of gases were temporarily thrown into oblivion because of a momentary hostile attitude toward it, as was for example the wave theory of light because of Newton’s authority.
I am conscious of being only an individual struggling weakly against the stream of time. But it still remains in my power to contribute in such a way that, when the theory of gases is again revived, not too much will have to be rediscovered. Thus in this book I will now include the parts that are the most difficult and most subject to misunderstanding, and give (at least in outline) the most easily understood exposition of them.”

L. Boltzmann, *Vorlesungen über Gastheorie,* 1898

Liquefaction of gases 1

1822 Charles Cagniard de la Tour - critical state

> 1825 Michael Faraday - liquefaction of gases except for a few 'permanent' (H_2 , N_2 , O_2 ,CO, NO, CH_4)

1861 Thomas Andrews - critical point (isoterms of CO_2)

1873 Johannes Van der Waals

1877 Louis Cailletet, Raoul Pictet - **dynamic** liquefaction of air

Liquefaction of gases 2

1883 Karol Olszewski, Zygmunt Wróblewski
static liquefaction of air, oxygen, nitrogen, carbon monoxide

1894 Olszewski - liquefaction of argon

1898 James Dewar - liquefaction of hydrogen

1908 Heike Kamerlingh-Onnes - liquefaction of helium

1911 Kamerlingh Onnes - superconductivity

1927 Willem Keesom, Mieczysław Wolfke - helium II

1938 Piotr Kapitsa, John Allen - superfluidity of helium II

Maxwell’s synthesis

James Clerk Maxwell

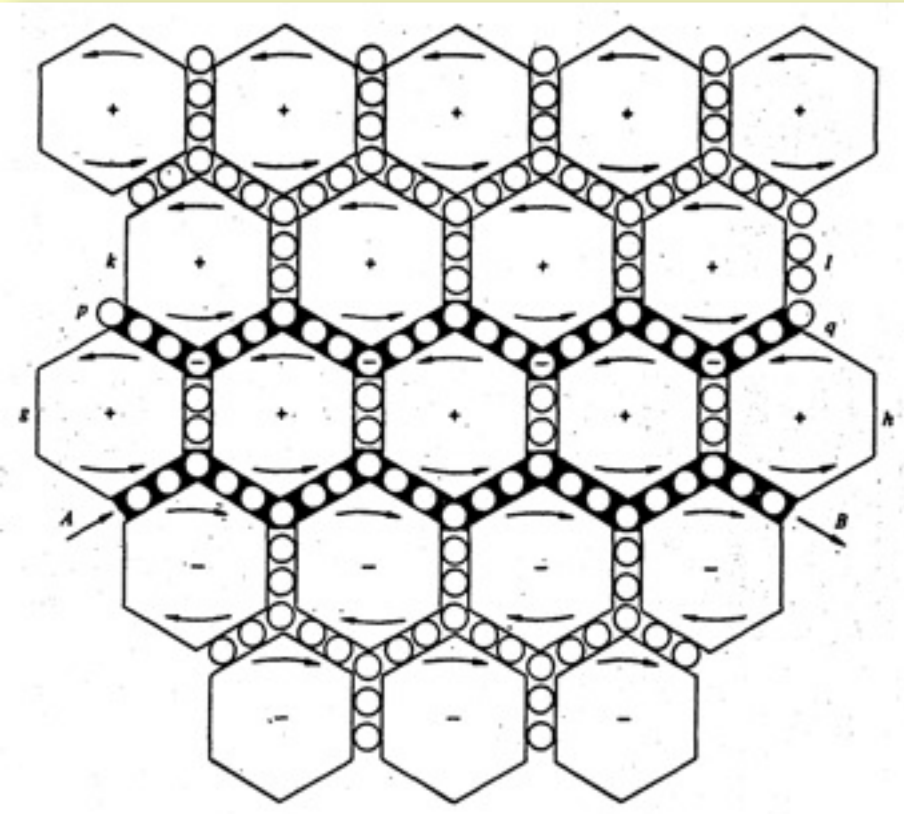
13 July 1831	Born in Edinburgh
1847 - 1850	Studied in Edinburgh
1850 - 1854	Studied in Cambridge
1855 - 1856	*Faraday's Lines of Force*
1856 - 1860	Professor in Aberdeen
1860 - 1865	Professor at King's College, London
1859	*Stability of the Motion of Saturn's rings*
1859	*Illustrations of the Dynamical Theory of Gases*
1861 - 1862	*On Physical Lines of Force*
1864	*A Dynamical Theory of the Electromagnetic Field*
since 1871	Professor of experimental physics in Cavendish Laboratory
1873	*Treatise on Electricity and Magnetism*
5 Nov. 1879	Died in Cambridge

”I suppose that the ‘magnetic medium’ is divided into small portions or cells, the divisions of cell walls being composed of a single stratum of spherical particles, these particles being ‘electricity’. The substance of the cells I suppose to be highly elastic, both with respect to compression and to distortion; and I suppose the connection between the cells and the particles in the cell walls to be such that there is perfect rolling without slipping between them and that they act on each other tangentially.

I then find that if the cells are set in rotation, the medium exerts a stress equivalent to a hydrostatic pressure combined with a longitudinal tension along the lines of axes of rotation...”

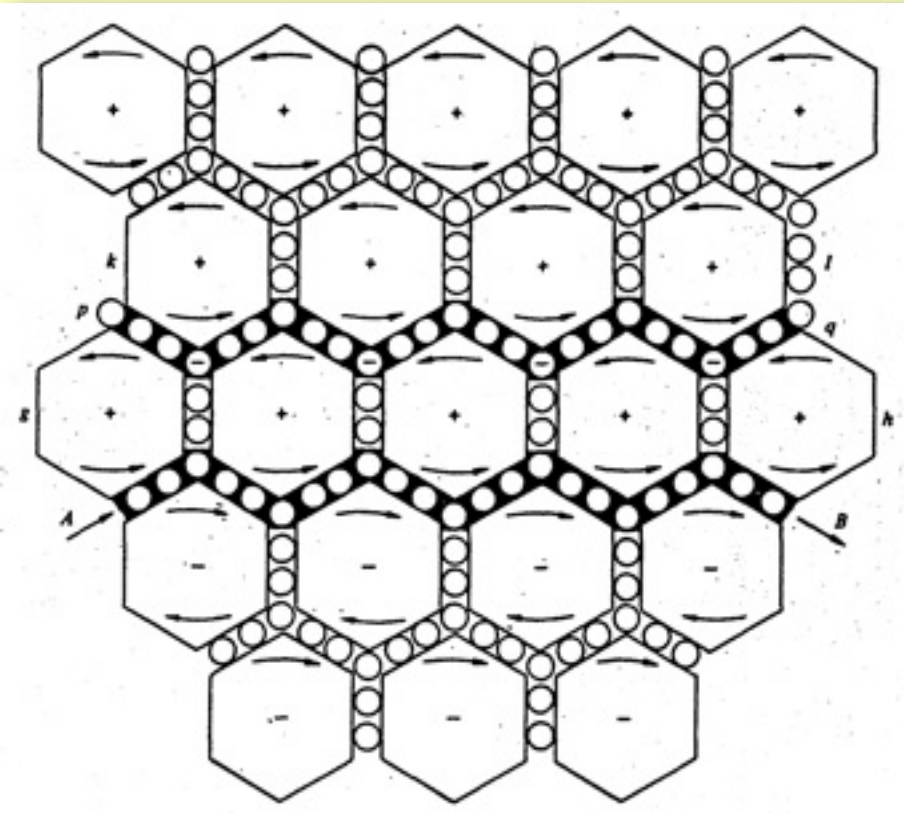
Maxwell to William Thomson
December 10, 1861

Maxwell, *On the physical lines of force*, 1861

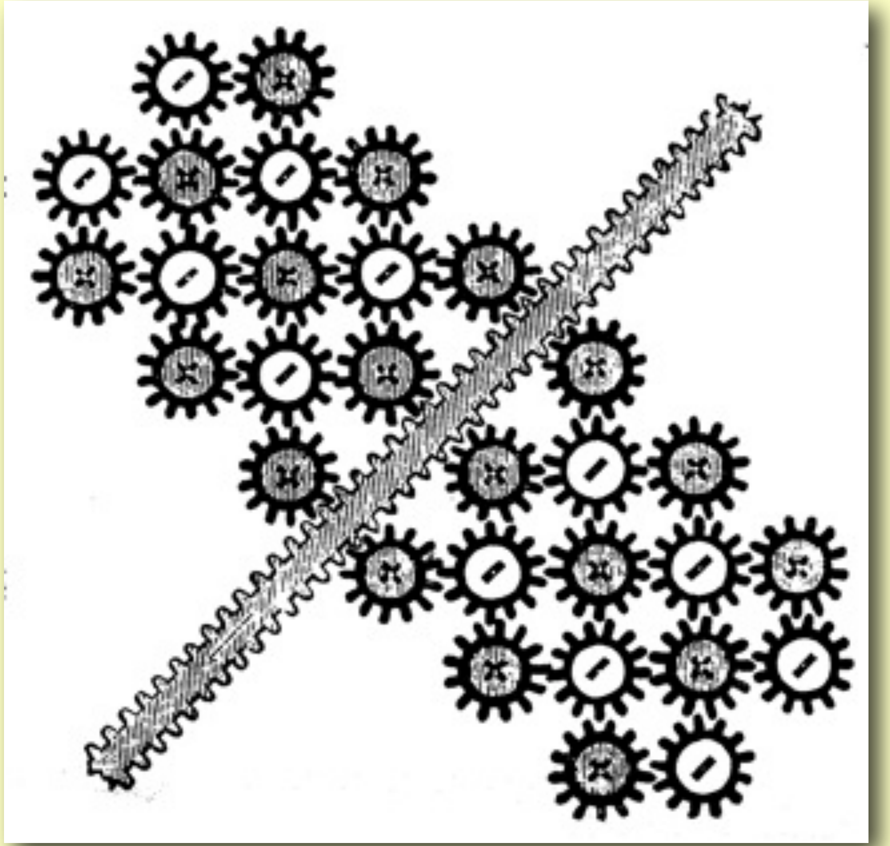


”Let *AB* represent a current of electricity in the direction from *A* to *B*. Let the large spaces above and below represent the vortices, and let the small circles separating the vortices represent the layers of particles placed betwen them, which in our hypothesis represent electricity.”

Maxwell, *On the physical lines of force*, 1861



”Now let the electric current from left to right commence in *AB*. The row of vortices *gh* above *AB* will be set in motion in the opposite direction to that of a watch. (We shall call this direction + , and that of a watch –) We shall suppose the row of vortices *kl* still at rest, then the layer of particles between these rows will be acted on by the row *gh* on their lower sides, and will be at rest above. If they are free to move, they will rotate in the negative direction, and will at the same time move from right to left, or in the opposite direction from the current, and so form an *induced* current.”



Representation of Maxwell's vortices by Oliver Lodge (*Modern Views on Electricity,*1889). The rod represents electric charges; when a current flows it moves, setting in motion the wheels (+) which produce the effect of a magnetic field. The wheels (-) serve only to set the more distant wheels in motion.

James Clerk Maxwell, *A Dynamical Theory of the Electromagnetic Field*
Philosophical Transactions **155**,459 (1865)

”1. The most obvious mechanical phenomenon in electrical and magnetical experiments is the mutual action by which bodies in certain states set each other in motion while still at a sensible distance from each other. The first step, therefore, in reducing these phenomena into scientific form, is to ascertain the magnitude and direction of the force acting between the bodies, and when it is found that this force depends in a certain way upon the relative position of the bodies and on their electric or magnetic condition, it seems at first sight natural to explain the facts by assuming the existence of something either at rest or in motion in each body, constituting its electric or magnetic state, and capable of acting at a distance according to mathematical laws..”

”In this way mathematical theories of statical electricity, of magnetism, of the mechanical action between conductors carrying currents, and of the induction of currents have been formed. In these theories the force acting between the two bodies is treated with reference only to the condition of the bodies and their relative position, and without any express consideration of the surrounding medium.
These theories assume, more or less explicitly, the existence of substances the particles of which have the property of acting on one another at a distance by attraction or repulsion. The most complete development of a theory of this kind is that of M. W. Weber, who has made the same theory include electrostatic and electromagnetic phenomena. In doing so, however, he has found it necessary to assume that the force between two electric particles depends on their relative velocity, as well as on their distance.”

James Clerk Maxwell, *A Dynamical Theory of the Electromagnetic Field*

”This theory, as developed by MM. W. Weber and C. Neumann, is exceedingly ingenious, and wonderfully comprehensive in its application to the phenomena of statical electricity, electromagnetic attractions, induction of currents and diamagnetic phenomena; and it comes to us with the more authority, as it has served to guide the speculations of one who has made so great an advance in the practical part of electric science, both by introducing a consistent system of units in electrical measurement, and by actually determining electrical quantities with an accuracy hitherto unknown.

2. The mechanical difficulties, however, which are involved in the assumption of particles acting at a distance with forces which depend on their velocities are such as to prevent me from considering this theory as an ultimate one though it may have been, and may yet be useful in leading to the coordination of phenomena.”

James Clerk Maxwell, *A Dynamical Theory of the Electromagnetic Field*

”I have therefore preferred to seek an explanation of the fact in another direction, by supposing them to be produced by actions which go on in the surrounding medium as well as in the excited bodies, and endeavouring to explain the action between distant bodies without assuming the existence of forces capable of acting directly at sensible distances.

3. The theory I propose may therefore be called a theory of the Electromagnetic Field, because it has to do with the space in the neighbourhood of the electric or magnetic bodies, and it may be called a Dynamical Theory, because it assumes that in that space there is matter in motion, by which the observed electromagnetic phenomena are produced.”

James Clerk Maxwell, *A Dynamical Theory of the Electromagnetic Field*

”4. The electromagnetic field is that part of space which contains and surrounds bodies in electric or magnetic conditions. It may be filled with any kind of matter, or we may endeavour to render it empty of all gross matter, as in the case of Geissler's tubes and other so-called vacua.
There is always, however, enough of matter left to receive and transmit the undulations of light and heat, and it is because the transmission of these radiations is not greatly altered when transparent bodies of measurable density are substituted for the so-called vacuum, that we are obliged to admit that the undulations are those of an aethereal substance, and not of the gross matter, the presence of which merely modifies in some way the motion of the aether.”

James Clerk Maxwell, *A Dynamical Theory of the Electromagnetic Field*

”We have therefore some reason to believe, from the phenomena of light and heat, that there is an aethereal medium filling space and permeating bodies, capable of being set in motion and of transmitting that motion from one part to another, and of communicating that motion to gross matter so as to heat it and affect it in various ways.

5. Now the energy communicated to the body in heating it must have formerly existed in the moving medium, for the undulations had left the source of heat some time before they reached the body, and during that time the energy must have been half in the form of motion of the medium and half in the form of elastic resilience. From these considerations Professor W. Thomson has argued, that the medium must have a density capable of comparison with that of gross matter, and has even assigned an inferior limit to that density.”

James Clerk Maxwell, *A Dynamical Theory of the Electromagnetic Field*

”6. We may therefore receive, as a datum derived from a branch of science independent of that with which we have to deal, the existence of a pervading medium, of small but real density, capable of being set in motion, and of transmitting motion from one part to another with great, but not infinite, velocity.

Hence the parts of this medium must be so connected that the motion of one part depends in some way on the motion of the rest; and at the same time - these connexions must be capable of a certain kind of elastic yielding, since the communication of motion is not instantaneous, but occupies time.

The medium is therefore capable of receiving and storing up two kinds of energy, namely, the "actual" energy depending on the motions of its parts, and "potential" energy, consisting of the work which the medium will do in recovering from displacement in virtue of its elasticity...”

James Clerk Maxwell, *A Dynamical Theory of the Electromagnetic Field*

”In order to bring these results within the power of symbolical calculation, I then express them in the form of the General Equations of the Electromagnetic Field. These equations express:

(A) The relation between electric displacement, true conduction, and the total current, compounded of both.

(B) The relation between the lines of magnetic force and the inductive coefficients of a circuit, as already deduced from the laws of induction.

(C) The relation between the strength of a current and its magnetic effects, according to the electromagnetic system of measurement.

(D) The value of the electromotive force in a body, as arising from the motion of the body in the field, the alteration of the field itself, and the variation of electric potential from one part of the field to another.

(E) The relation between electric displacement, and the electromotive force which produces it.

(F) The relation between an electric current, and the electromotive force which produces it.

(G) The relation between the amount of free electricity at any point, and the electric displacements in the neighbourhood.

(H) The relation between the increase or diminution of free electricity and the electric currents in the neighbourhood.

There are twenty of these equations in all, involving twenty variable quantities.”

Twenty 'Maxwell's equations'

the same field with a magnet, I shew the distribution of its equipotential magnetic surfaces, cutting the lines of force at right angles.

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(G) The relation between the amount of free electricity at any point, and the electric displacements in the neighbourhood.

(H) The relation between the increase or diminution of free electricity and the electric currents in the neighbourhood.

There are twenty of these equations in all, involving twenty variable quantities.

(19) I then express in terms of these quantities the intrinsic energy of the Electromagnetic Field as depending partly on its magnetic and partly on its electric polarization at every point.

From this I determine the mechanical force acting, 1st, on a moveable conductor carrying an electric current; 2ndly, on a magnetic pole; 3rdly, on an electrified body.

The last result, namely, the mechanical force acting on an electrified body, gives rise to an independent method of electrical measurement founded on its

”20. The general equations are next applied to the case of a magnetic disturbance propagated through a non-conducting field, and it is shewn that the only disturbances which can be so propagated are those which are transverse to the direction of propagation, and that the velocity of propagation is the velocity *v*, found from experiments such as those of Weber, which expresses the number of electrostatic units of electricity which are contained in one electromagnetic unit.
This velocity is so nearly that of light, that it seems we have strong reason to conclude that light itself (including radiant heat, and other radiations if any) is an electromagnetic disturbance in the form of waves propagated through the electromagnetic field according to electromagnetic laws...”

Maxwell - *A Dynamical Theory of the Electromagnetic Field (1864)*

James Clerk Maxwell

Treatise on Electricity and Magnetism (1873)

I. Electrostatics
II. Electrokinematics
III. Magnetism
IV. Electromagnetism

866 numbered paragraphs in 57 chapters

”In the following *Treatise* I propose to describe the most important of these phenomena, to shew how they may be subjected to measurements, and to trace the mathematical connexions of the quantities measured. Having thus obtained the data for a mathematical theory of electromagnetism, and having shewn how this theory may be applied to the calculation of phenomena, I shall endeavour to place in as clear light as I can the relations between the mathematical form of this theory and that of the fundamental science of Dynamics, in order that we may be in some degree prepared to determine the kind of dynamical phenomena among which we are to look for illustrations or explanations of the electromagnetic phenomena.”

Maxwell, *Treatise on Electricity and Magnetism* (1873), Preface

”According to Fechner’s hypothesis... an electric current consists of two equal currents of positive and negative electricity, flowing in opposite directions through the same conductor...
It appears to me, however, that while we derive great advantage from the recognition of the many analogies between the electric current and a current of a material fluid, we must carefully avoid making any assumption not warranted by experimental evidence, and that there is, as yet, **no experimental evidence to shew whether the electric current is really a current of material substance**, or a double current, or whether its velocity is great or small as measured in feet per second.”

James Clerk Maxwell, *Treatise on Electricity and Magnetism* §574

”A knowledge of these things would amount to at least the beginnings of a complete dynamical theory of electricity, in which we should regard electrical action, not, as in this treatise, as a phenomenon due to an unknown cause, subject only to the general laws of dynamics, but as a result of known motions of known portions of matter, in which not only the total effects and final results, but the whole intermediate mechanism and details of the motion, are taken as the objects of study.”

James Clerk Maxwell, *Treatise on Electricity and Magnetism* §574

"The quantity V, in Art. 793, which expresses the velocity of propagation of electromagnetic disturbances in a non-conducting medium is, by equation (9), equal to $1/\sqrt{K}$.
If the medium is air, and if we adopt the electrostatic system of measurement, K = 1, and $\mu = 1/v^2$, so that $V = v$, or the velocity of propagation is numerically equal to the number of electrostatic units of electricity in one electromagnetic unit. If we adopt the electromagnetic system, $K = 1/v^2$ and $\mu = 1$, so that the equation $V = v$ is still true."

James Clerk Maxwell, *Treatise on Electricity and Magnetism* §786

”On the theory that light is an electromagnetic disturbance, propagated in the same medium through which other electromagnetic actions are transmitted, *V* must be the velocity of light, a quantity the value of which has been estimated by several methods. On the other hand, *v* is the number of electrostatic units of electricity in one electromagnetic unit, and the methods of determining this quantity have been described in the last chapter. They are quite independent of the methods of finding the velocity of light. Hence the agreement or disagreement of the values of *V* and *v* furnishes a test of the electromagnetic theory of light.”

James Clerk Maxwell, *Treatise on Electricity and Magnetism* §786

”In the following table, the principal results of direct observation of the velocity of light, either through the air or through the planetary spaces, are compared with the principal results of the comparison of the electric units:

Velocity of Light (mètres per second).		Ratio of Electric Units.	
Fizeau	314000000	Weber	310740000
Aberration, &c., and Sun's Parallax	308000000	Maxwell	288000000
Foucault	298360000	Thomson	282000000.

It is manifest that the velocity of light and the ratio of the units are quantities of the same order of magnitude. Neither of them can be said to be determined as yet with such a degree of accuracy as to enable us to assert that the one is greater or less than the other. It is to be hoped that, by further experiment, the relation between the magnitudes of the two quantities may be more accurately determined. In the meantime our theory, which asserts that these two quantities are equal, and assigns a physical reason for this equality, is certainly not contradicted by the comparison of these results such as they are.”

James Clerk Maxwell, *Treatise on Electricity and Magnetism* §787

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787.] In the following table, the principal results of direct observation of the velocity of light, either through the air or through the planetary spaces, are compared with the principal results of the comparison of the electric units:—

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* {In the following table, taken from a paper by E. B. Rosa, *Phil. Mag.* 28, p. 315, 1889, the determinations of 'v' corrected for the error in the B.A. unit are given:—

1856	Weber and Kohlrausch	$3{\cdot}107 \times 10^{10}$ (cm. per second)
1868	Maxwell	$2{\cdot}842 \times 10^{10}$
1869	W. Thomson and King	$2{\cdot}808 \times 10^{10}$
1872	M'Kichan	$2{\cdot}896 \times 10^{10}$
1879	Ayrton and Perry	$2{\cdot}960 \times 10^{10}$
1880	Shida	$2{\cdot}955 \times 10^{10}$
1883	J. J. Thomson	$2{\cdot}963 \times 10^{10}$
1884	Klemenčič	$3{\cdot}019 \times 10^{10}$
1888	Himstedt	$3{\cdot}009 \times 10^{10}$
1889	W. Thomson	$3{\cdot}004 \times 10^{10}$
1889	E. B. Rosa	$2{\cdot}9993 \times 10^{10}$
1890	J. J. Thomson and Searle	$2{\cdot}9955 \times 10^{10}$

VELOCITY OF LIGHT IN AIR.

Cornu (1878)	$3{\cdot}003 \times 10^{10}$
Michelson (1879)	$2{\cdot}9982 \times 10^{10}$
Michelson (1882)	$2{\cdot}9976 \times 10^{10}$
Newcomb (1885)	$\left\{ \begin{matrix} 2{\cdot}99615 \\ 2{\cdot}99682 \\ 2{\cdot}99766 \end{matrix} \right\} \times 10^{10}$ }

788.] In other media than air, the velocity V is inversely proportional to the square root of the product of the dielectric and the magnetic inductive capacities. According to the undulatory theory, the velocity of light in different media is inversely proportional to their indices of refraction.

There are no transparent media for which the magnetic capacity differs from that of air more than by a very small fraction. Hence the principal part of the difference between these media must depend on their dielectric capacity. According to our theory, therefore, the dielectric capacity of a transparent medium should be equal to the square of its index of refraction.

But the value of the index of refraction is different for light of different kinds, being greater for light of more rapid vibrations. We must therefore select the index of refraction which corresponds to waves of the longest periods, because these are the only waves whose motion can be compared with the slow processes by which we determine the capacity of the dielectric.

789.] The only dielectric of which the capacity has been hitherto determined with sufficient accuracy is paraffin, for which in the solid form MM. Gibson and Barclay found *

$$K = 1{\cdot}975. \qquad (12)$$

Dr. Gladstone has found the following values of the index of refraction of melted paraffin, sp. g. 0·779, for the lines A, D and H:—

Temperature	A	D	H
54°C	1·4306	1·4357	1·4499
57°C	1·4294	1·4343	1·4493;

from which I find that the index of refraction for waves of infinite length would be about 1·422.

The square root of K is 1·405.

The difference between these numbers is greater than can be accounted for by errors of observation, and shews that our theories of the structure of bodies must be much improved before we can deduce their optical from their electrical properties. At the same time, I think that the agreement of the numbers is such that if no greater discrepancy were found between the numbers derived from the optical and the electrical properties of a considerable number of substances, we should be warranted in

* *Phil. Trans.* 1871, p. 573.

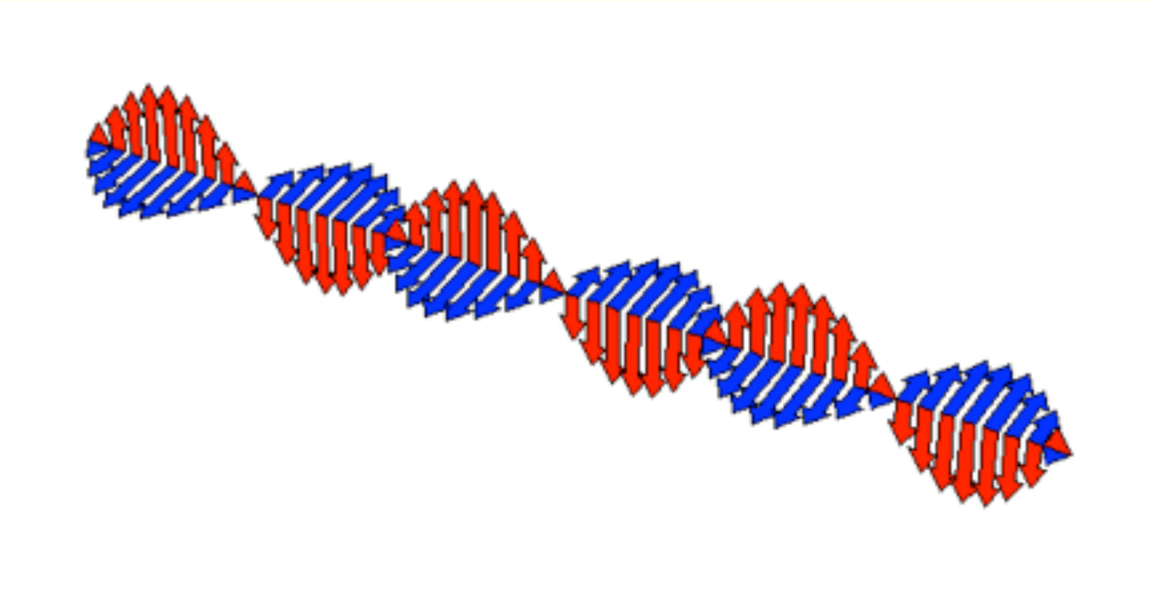
In Maxwell’s articles as well as in his *Treatise on Electricity and Magnetism* the equations are written down in components or quaternion notation. That’s why we do not find there Maxwell’s equations in the form presently used

Calculus of vectors has been introduced to physics mainly by Oliver Heaviside and Josiah Gibbs

Maxwell’s equations in the form familiar to us were first written down in 1885 by Oliver Heaviside

EQUATIONS OF:		MAXWELL'S NOTATION	VECTOR NOTATION
Magnetic Induction	(A)	$a = \frac{dH}{dy} - \frac{dG}{dz}$ $b = \frac{dF}{dz} - \frac{dH}{dx}$, $c = \frac{dG}{dx} - \frac{dF}{dy}$.	$B = \nabla \times A$
Electromotive Intensity	(B)	$P = c\frac{dy}{dt} - b\frac{dz}{dt} - \frac{dF}{dt} - \frac{d\Psi}{dx}$, $Q = a\frac{dz}{dt} - c\frac{dx}{dt} - \frac{dG}{dt} - \frac{d\Psi}{dy}$, $R = b\frac{dx}{dt} - a\frac{dy}{dt} - \frac{dH}{dt} - \frac{d\Psi}{dz}$.	$E = v \times B - \frac{\partial A}{\partial t} - \nabla \phi$
Mechanical Force	(C)	$X = cv - bw - e\frac{d\Psi}{dx} - m\frac{d\Omega}{dx}$ (First equation only)	$F = J_T \times B + eE - m\nabla\Omega$ (J_T includes displacement current)
Magnetization	(D)	$a = \alpha + 4\pi A$, $b = \beta + 4\pi B$, $c = \gamma + 4\pi C$.	$B = H + 4\pi M$
Electric Currents	(E)	$4\pi u = \frac{d\gamma}{dy} - \frac{d\beta}{dz}$, $4\pi v = \frac{d\alpha}{dz} - \frac{d\gamma}{dx}$, $4\pi w = \frac{d\beta}{dx} - \frac{d\alpha}{dy}$.	$\nabla \times H = 4\pi J_T$
Electric Displacement	(F)	$\mathfrak{D} = \frac{1}{4\pi} K \mathfrak{E}$ (Quaternion notation)	$D = \frac{K}{4\pi} E$
Conductivity	(G)	$\mathfrak{K} = C\mathfrak{E}$ (Quaternion notation)	$J = \sigma E$
True Current	(H)	$u = p + \frac{df}{dt}$, $v = q + \frac{dg}{dt}$, $w = r + \frac{dh}{dt}$.	$J_T = J + \frac{\partial D}{\partial t}$
Free Electricity	(J)	$\rho = \frac{df}{dx} + \frac{dg}{dy} + \frac{dh}{dz}$	$\nabla \cdot D = \rho$
	(K)	$\sigma = lf + mg + nh + l'f' + m'g' + n'h'$	$(D_2 - D_1) \cdot n = \sigma$
Induced Magnetization	(L)	$\mathfrak{B} = \mu \mathfrak{H}$ (Quaternion notation)	$B = \mu H$

”The most fascinating subject at the time that I was a student was Maxwell's theory. What made this theory appear revolutionary was the transition from action at a distance to fields as the fundamental variables. The incorporation of optics into the theory of electromagnetism, with its relation of the speed of light to the electric and magnetic absolute system of units as well as the relation of the index of refraction to the dielectric constant, the qualitative relation between the reflection coefficient of a body and its metallic conductivity - it was like a revelation.”



Einstein - *Autobiography*

”Aside from the transition to field theory, i.e., the expression of the elementary laws through differential equations, Maxwell needed only one single hypothetical step - the introduction of the electrical displacement current in the vacuum and in the dielectrics and its magnetic effect, an innovation that was almost preordained by the formal properties of the differential equations. In this connection I cannot suppress the remark that the pair Faraday-Maxwell has a most remarkable inner similarity with the pair Galileo-Newton - the former of each pair grasping the relations intuitively, and the second one formulating those relations exactly and applying them quantitatively.”

Einstein - *Autobiography*

”What rendered the insight into the essence of electromagnetic theory so much more difficult at that time was the following peculiar situation. Electric or magnetic ‘field intensities’ and ‘displacements’ were treated as equally elementary variables, empty space as a special instance of a dielectric body. Matter appeared as the bearer of the field, not space. By this it was implied that the carrier of the field should have velocity, and this was naturally to apply to the ‘vacuum’ (ether) also. Hertz's electrodynamics of moving bodies rests entirely upon this fundamental attitude.”

Einstein - *Autobiography*

”It was the great merit of H. A. Lorentz that he brought about a change here in a convincing fashion. In principle a field exists, according to him, only in empty space. Matter - considered to consist of atoms - is the only seat of electric charges; between the material particles there is empty space, the seat of the electromagnetic field, which is produced by the position and velocity of the point charges located on the material particles. Dielectric behavior, conductivity, etc., are determined exclusively by the type of mechanical bindings between the particles that constitute the bodies. The particle charges create the field, which, on the other hand, exerts forces upon the charges of the particles, thus determining the motion of the latter according to Newton's law of motion.”

Einstein - *Autobiography*

”If one compares this with Newton's system, the change consists in this: action at a distance is replaced by the field, which also describes the radiation. Gravitation is usually not taken into account because of its relative smallness; its inclusion, however, was always possible by enriching the structure of the field, that is to say, by expanding Maxwell's field laws. The physicist of the present generation regards the point of view achieved by Lorentz as the only possible one; at that time, however, it was a surprising and audacious step, without which the later development would not have been possible..”

Einstein - *Autobiography*

”Theory of light vibrations has led us to the conclusion that in space free of all solid, liquid or gaseous bodies there must be a certain medium for propagation of these vibrations. We call this medium the luminiferous ether, or simply ether.

When we very precisely pump out the air from a certain space and obtain so called ’vacuum’, we shall end up with ether, which - as far as we know - has the same properties as the ether which permeats interplanetary space.

This medium, the cosmic ether, exhibits uniformity by which it differs markedly from all other bodies which act on our senses. Therefore, it must be completely different from them.”

Hendrik Lorentz, *Sichtbare und unsichtbare Bewegungen* (1902)

”In order to express this difference we can describe ordinary bodies as ‘matter’, and we shall not apply this term to ether. We can also speak about ponderable matter, i.e. matter subject to gravity, in constrast to ‘imponderable’ ether. Such usage of words is justified because we have no indication that ether is subject to the force of gravity, in other words, that ether is a body which has weight...”

Hendrik Lorentz, *Sichtbare und unsichtbare Bewegungen* (1902)

”Let us assume that in all matter there are exceedingly small particles of which invariably one half has positive electric charges, and the other half - negative charges... These tiny particles are the smallest of those with which natural sciences have to deal, smaller than molecules and atoms... Let us attach to these positive and negative particles the name of ‘electrons’. Let us further assume that these electric particles - electrons - are common to all matter, that even the smallest granule of ponderable matter is not free from them, that they are present in countless number in each body, and that an electrically neutral body contains an equal number of electrons of both kinds.”

Hendrik Lorentz, *Sichtbare und unsichtbare Bewegungen* (1902)

”The ether, containing no electrons, remains the medium that only mediates interactions among electrically charged particles; it is endowed with different properties...
An electron excites in the surrounding ether certain changes, which depend on its charge and on its motion. These changes determine all actions of the electron on the surrounding particles and
all what happens in the ether around charged bodies and magnets. Thus, a vibrating electron will induce periodic changes in the ether.”

Hendrik Lorentz, *Sichtbare und unsichtbare Bewegungen* (1902)

Ether in 1884

”The phenomena of Light are best explained as those of undulations; but undulations even in the most extensive use of the term, as signifying any periodic motion or condition whose periodicity obeys the laws of wave-motion must be propagated through some medium... We are led to infer, therefore, that there is such a medium, which we call the Luminiferous Ether, or simply the Ether; that it can convey energy; that it can present it at any instant partly in the form of kinetic, partly in that of potential energy; that it is therefore capable of displacement and of exercising pressure or tension; and that it must have rigidity and elasticity. Calculation leads us to infer that its density is 936/1000,000000,000000,000000 that of water (Clerk Maxwell), or equal to that of our atmosphere at a height of about 210 miles, a density vastly greater than that of the same atmosphere in the interstellar spaces;”

Alfred Daniell, ***A Text-book of the Principles of physics*** (1884)

Ether in 1884

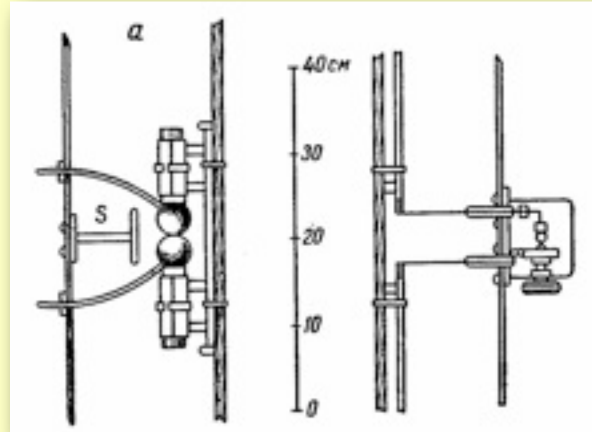
”that its rigidity is about 1/1000,000,000 that of steel hence that it is easily displaceable by a moving mass; that it is not discontinuous or granular; and hence that as a whole it may be compared to an impalpable and all-pervading jelly, through which Light and Heat waves are constantly throbbing, which is constantly being set in local strains and released from them, and being whirled in local vortices, thus producing the various phenomena of Electricity and Magnetism; and through which the particles of ordinary matter move freely, encountering but little retardation if any, for its elasticity, as it closes up behind each moving particle, is approximately perfect. Nothing of the nature of an air-pump can remove it from any given space; the most perfect vacuum conceivable must be defined as a plenum, a space fully occupied, but occupied by Ether alone.”

Alfred Daniell, ***A Text-book of the Principles of physics*** (1884)

James Clerk Maxwell
(1831-1879)

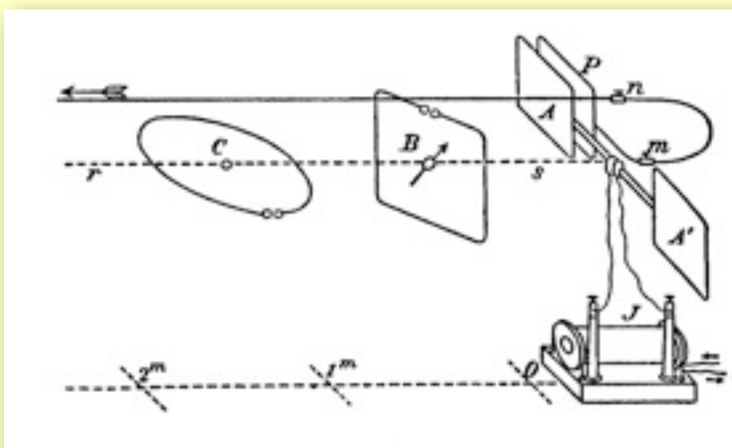
Heinrich Rudolf Hertz
(1857-1894)

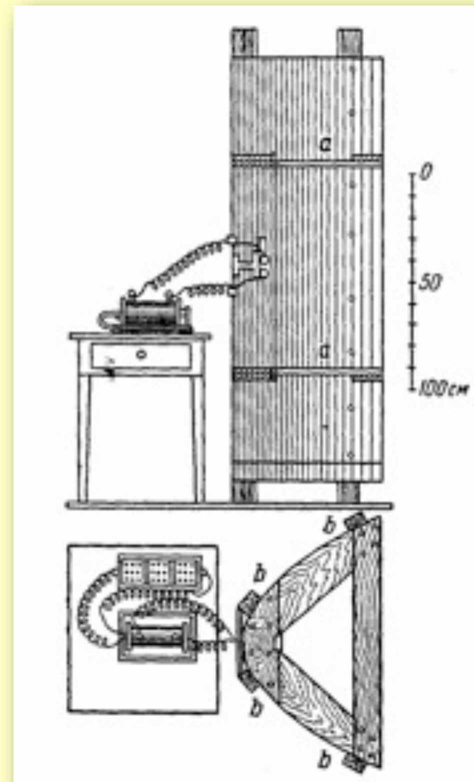
Guglielmo Marconi
(1874-1937)

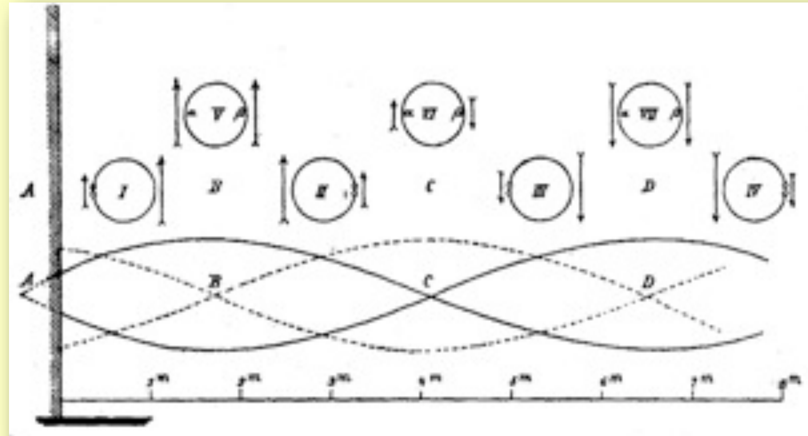


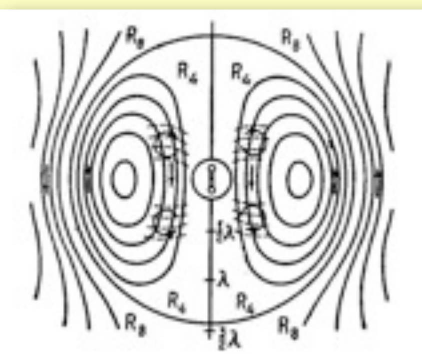
Heinrich Rudolf Hertz

(original drawings of 1888)

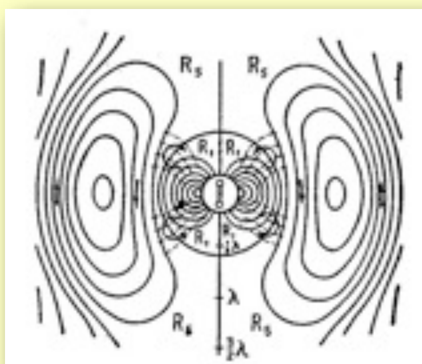




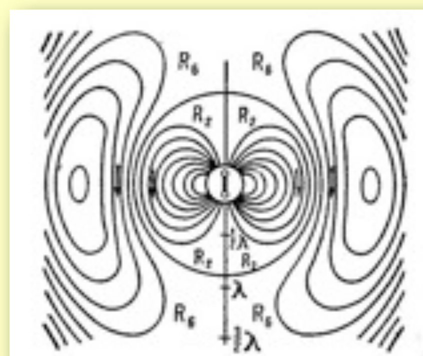




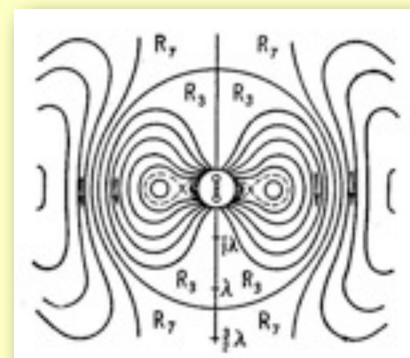
$t = 0$



$t = \lambda/4c$

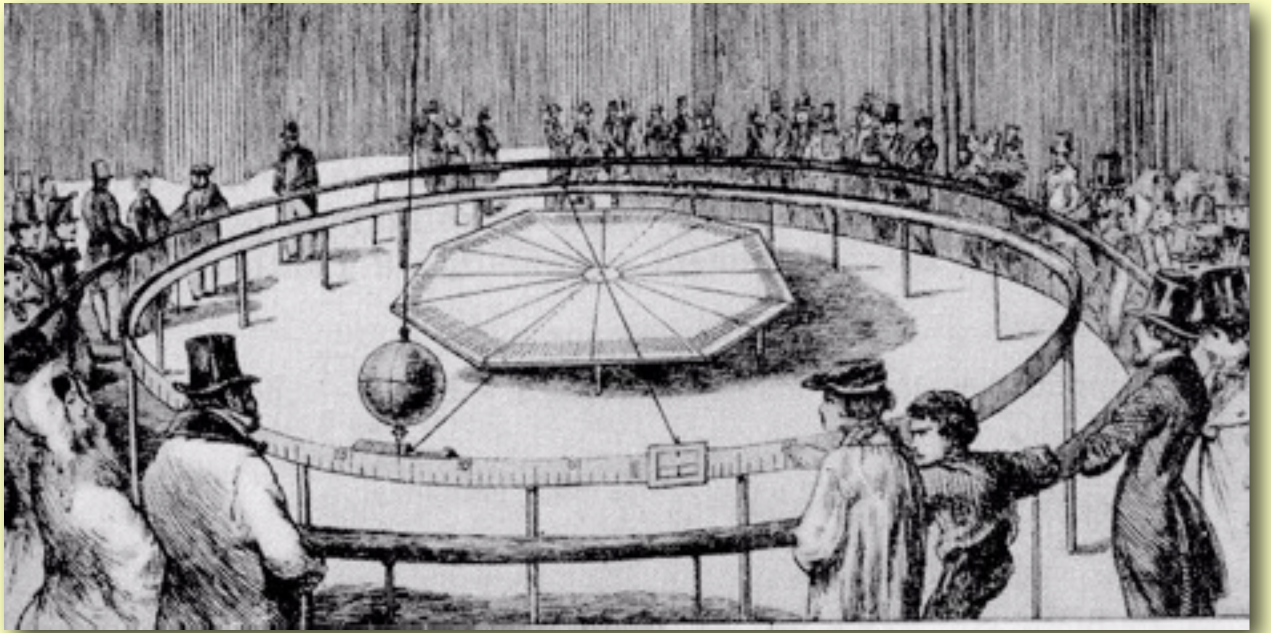


$t = \lambda/2c$



$t = 3\lambda/4c$

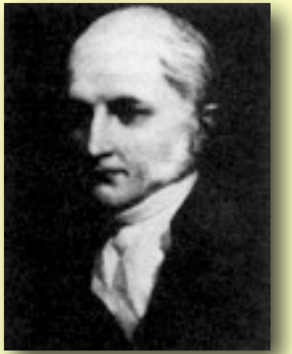
Jean Bernard Leon Foucault (1819-1868)



Public demonstration of the Foucault's pendulum in Paris (1851)

Discovery of the periodic system of elements

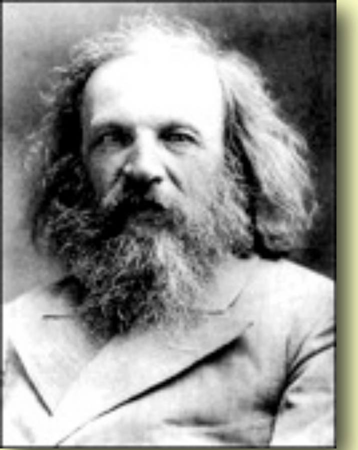
William Prout: All atomic weights are exact multiples of that of hydrogen (1815-1816)



Johann Döbereiner:
The law of triads (1829)

John Newlands:
The law of octaves (1863)

Julius Lothar Meyer: periodic system (published in 1870)



Ueber die Beziehungen der Eigenschaften zu den Atomgewichten der Elemente. Von D. Mendelejeff. — Ordnet man Elemente nach zunehmenden Atomgewichten in verticale Reihen so, dass die Horizontalreihen analoge Elemente enthalten, wieder nach zunehmendem Atomgewicht geordnet, so erhält man folgende Zusammenstellung, aus der sich einige allgemeinere Folgerungen ableiten lassen.

			Ti — 50	Zr — 90	? — 180
			V — 51	Nb — 94	Ta — 182
			Cr — 52	Mo — 96	W — 186
			Mn — 55	Rh — 104,4	Pt — 197,4
			Fe — 56	Ru — 104,4	Ir — 198
			Ni — Co — 59	Pd — 106,6	Os — 199
H — 1			Cu — 63,4	Ag — 108	Hg — 200
	Be — 9,4	Mg — 24	Zn — 65,2	Cd — 112	
	B — 11	Al — 27,4	? — 68	Ur — 116	Au — 197?
	C — 12	Si — 28	? — 70	Sn — 118	
	N — 14	P — 31	As — 75	Sb — 122	Bi — 210?
	O — 16	S — 32	Se — 79,4	Te — 128?	
	F — 19	Cl — 35,5	Br — 80	J — 127	
Li — 7	Na — 23	K — 39	Rb — 85,4	Cs — 133	Tl — 204
		Ca — 40	Sr — 87,6	Ba — 137	Pb — 207
		? — 45	Ce — 92		
		?Er — 56	La — 94		
		?Yt — 60	Di — 95		
		?In — 75,6	Th — 118?		

1. Die nach der Grösse des Atomgewichts geordneten Elemente zeigen eine stufenweise Abänderung in den Eigenschaften.
2. Chemisch-analoge Elemente haben entweder übereinstimmende Atomgewichte (Pt, Ir, Os), oder letztere nehmen gleichviel zu (K, Rb, Cs).
3. Das Anordnen nach den Atomgewichten entspricht der *Werthigkeit* der Elemente und bis zu einem gewissen Grade der Verschiedenheit im chemischen Verhalten, z. B. Li, Be, B, C, N, O, F.
4. Die in der Natur verbreitetsten Elemente haben *kleine* Atomgewichte

Zeitschrift für Chemie
12, 405-6 (1869)

On the relation of the properties and atomic weights of the elements

By ordering the elements to have atomic weights increasing in columns and placing elements of similar chemical properties in rows we obtain the following ordering from which certain general conlusions can be drawn.

1. The elements, if arranged according to their atomic weights, exhibit an evident periodicity of properties.
2. Elements which are similar as regards their chemical properties have atomic weights which are either of nearly the same value (e.g. Pt, Ir, Os), or which increase regularly (e.g. K, Rb, Cs).
3. The arrangement of the elements in the order of their atomic weights corresponds to their valencies as well as, to some extent, to their distinctive chemical properties (e.g.. Li, Be, B, C, O, F)...

The discovery of argon in 1894
(William Rayleigh and William Ramsay),
and of the next inert gases: neon, krypton, and xenon (1898), expanded the Mendeleyev system by a new column which included also helium (discovered first in 1868 during the solar eclipse, and later, in 1895, in earth’s rocks).
Soon later new radioactive elements have been discovered (polonium, radium, actinium...)

Hypothetical elements *nebulium* and *coronium* were not confirmed