Art & Science ACROSS ITALY

L'eleganza della fisica

Giovanni Organtini

3ª edizione

NOV 2020 MAG 2022

INFN Istituto Nazionale di Fisica Nucleare

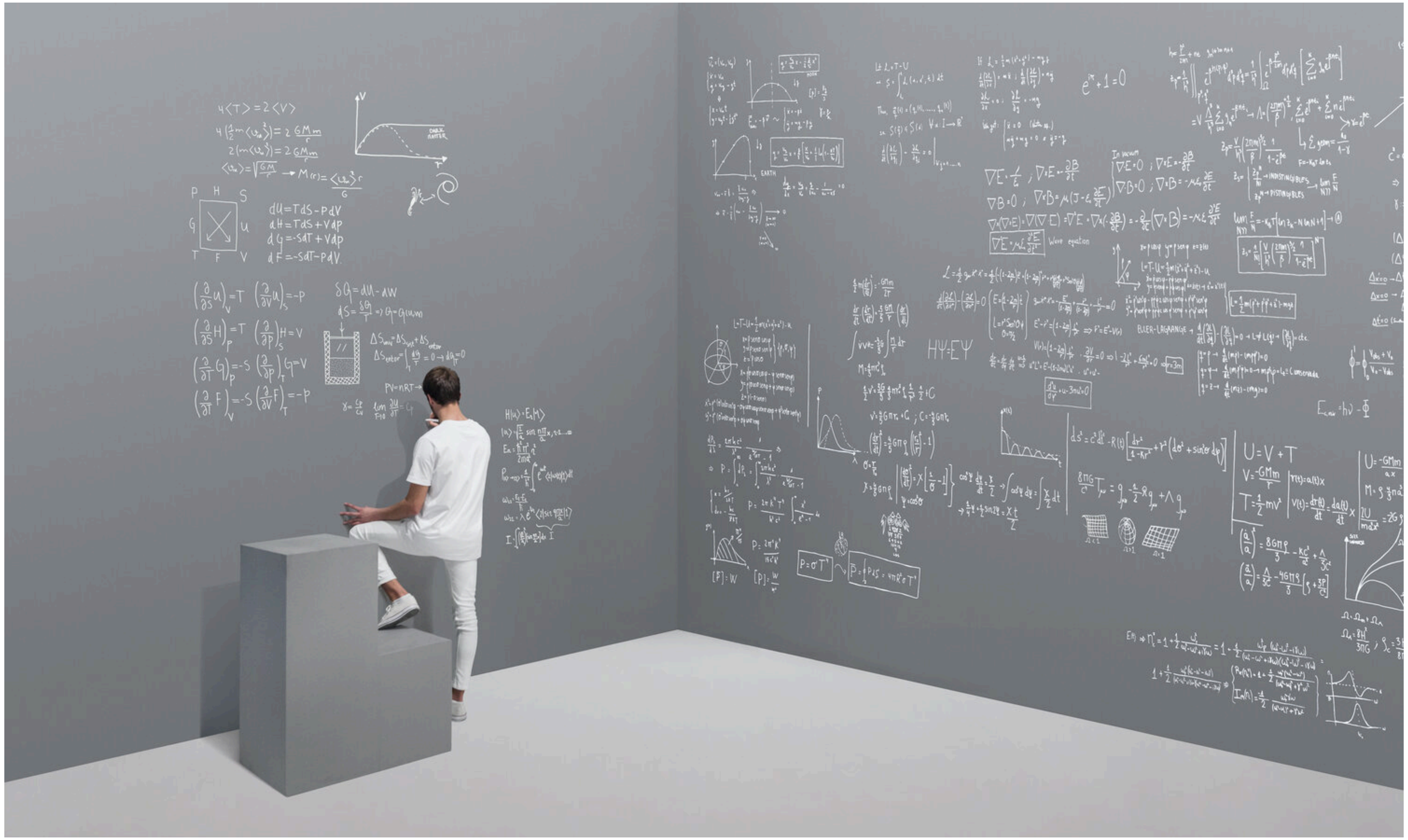
CERN

Art & Science ACROSS ITALY

3ª edizione

NOV 2020 MAG 2022

Giovanni Organtini - "Sapienza" Università di Roma & INFN-Sez. di Roma



INFN Istituto Nazionale di Fisica Nucleare

CERN

Giovanni Organtini - "Sapienza" Università di Roma & INFN-Sez. di Roma

If it disagrees with experiment it's wrong. In that simple statement is the key to science. It does not make any difference how beautiful your guess is. It does not make any difference how smart you are, who made the guess, or what his name is – if it disagrees with experiment it's wrong. That is all there is to it.

Now I'm going to discuss how we would look for a new law. In general we look for a new law by the following process. First we guess it. [...] Then we compute the consequences of the guess to see what, if this is right, if this law that we guessed is right, we see what it would imply, and then we compare those computation results to nature, or we say compare to experiment or experience, compare it directly with observation, to see if it works.

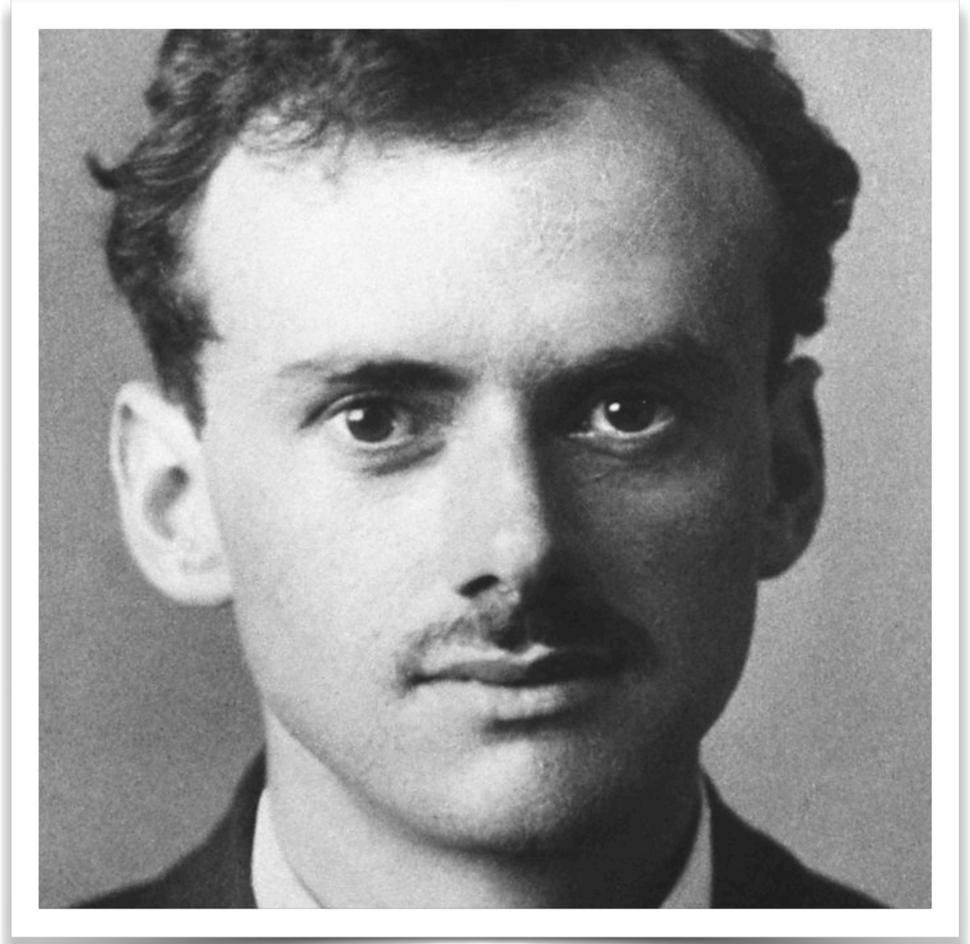
Giovanni Organtini - "Sapienza" Università di Roma & INFN-Sez. di Roma

$$(\not{\partial} - m)\,\psi = 0$$

Giovanni Organtini - "Sapienza" Università di Roma & INFN-Sez. di Roma

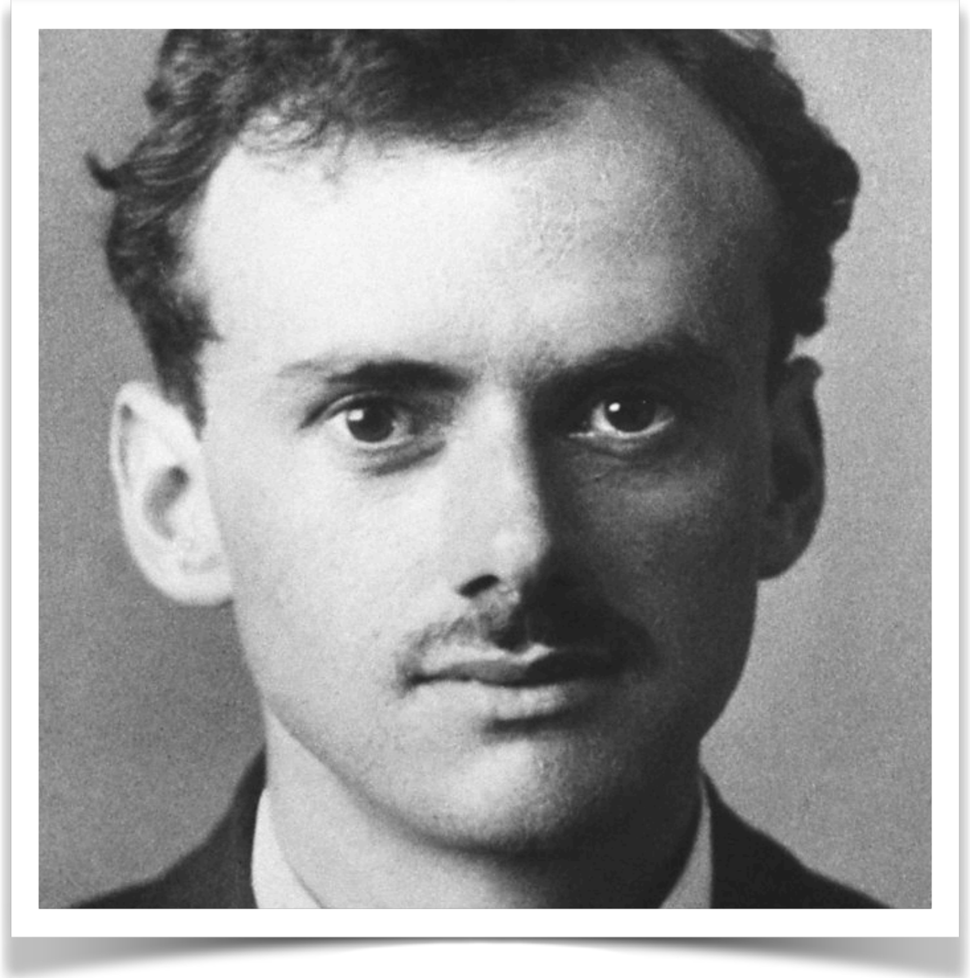
Giovanni Organtini - "Sapienza" Università di Roma & INFN-Sez. di Roma

[L'idea dello spin] è scaturita effettivamente solo grazie alle manipolazioni delle equazioni che stavo studiando; non stavo cercando di introdurre idee fisicamente plausibili. Gran parte del mio lavoro del resto consiste nel lavorare con le equazioni per vedere cosa se ne può ricavare. La seconda quantizzazione, per esempio, è nata così. Non credo che questo abbia senso per gli altri fisici; penso sia una mia peculiarità il fatto che mi piace lavorare con le equazioni, soltanto alla ricerca di relazioni matematiche interessanti che magari non hanno alcun significato fisico. Succede, però, che a volte ce l'hanno.



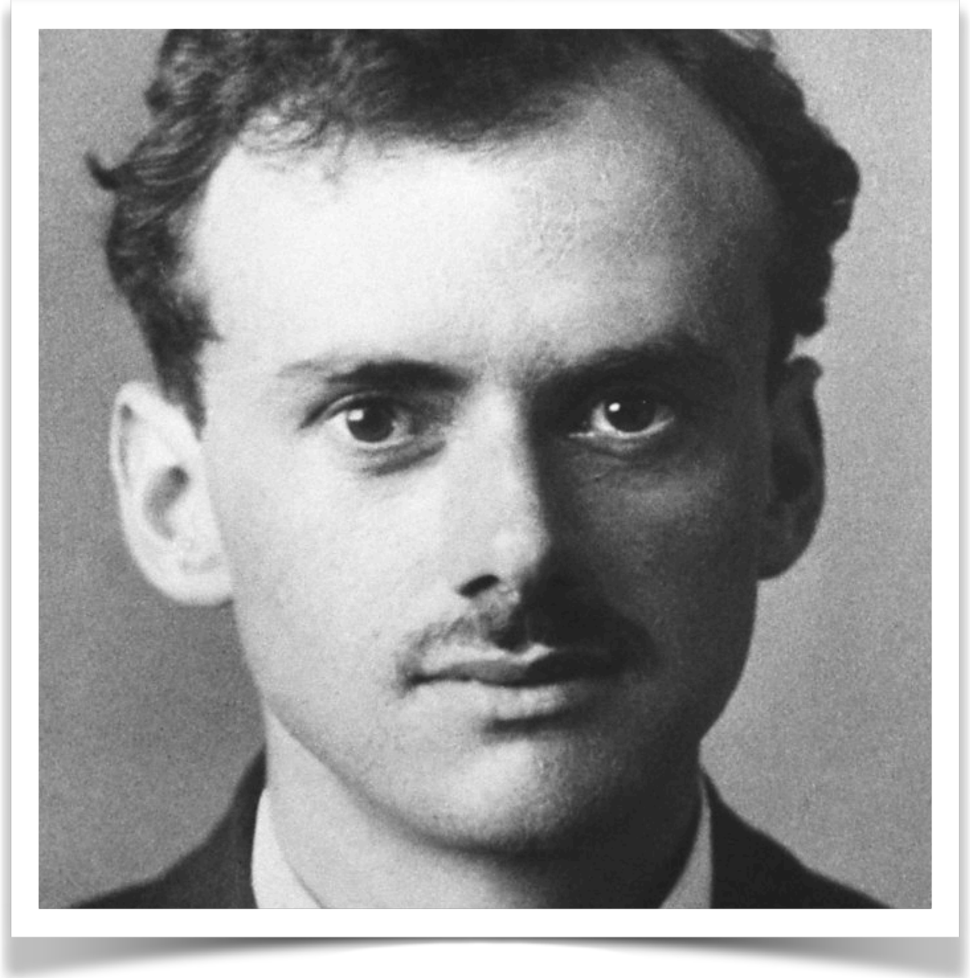
Interview of P. A. M. Dirac by Thomas S. Kuhn on 1963 May 7
Niels Bohr Library & Archives, American Institute of Physics
College Park, MD USA
www.aip.org/history-programs/niels-bohr-library/oral-histories/4575-3

Una delle caratteristiche fondamentali della natura sembra essere che le leggi fisiche fondamentali sono descritte in termini di una teoria matematica di grande bellezza e potenza. Potremmo forse descrivere la situazione dicendo che Dio è un matematico sopraffino, cui è piaciuto usare una matematica molto avanzata nella costruzione dell'universo. A me sembra che se si lavora allo scopo di perseguire la bellezza nelle proprie equazioni, con una buona intuizione, si è di sicuro sulla buona strada.



P. A. M. Dirac "Pretty Mathematics"
Int. J. Their. Phys. 21, 603-605 (1982)

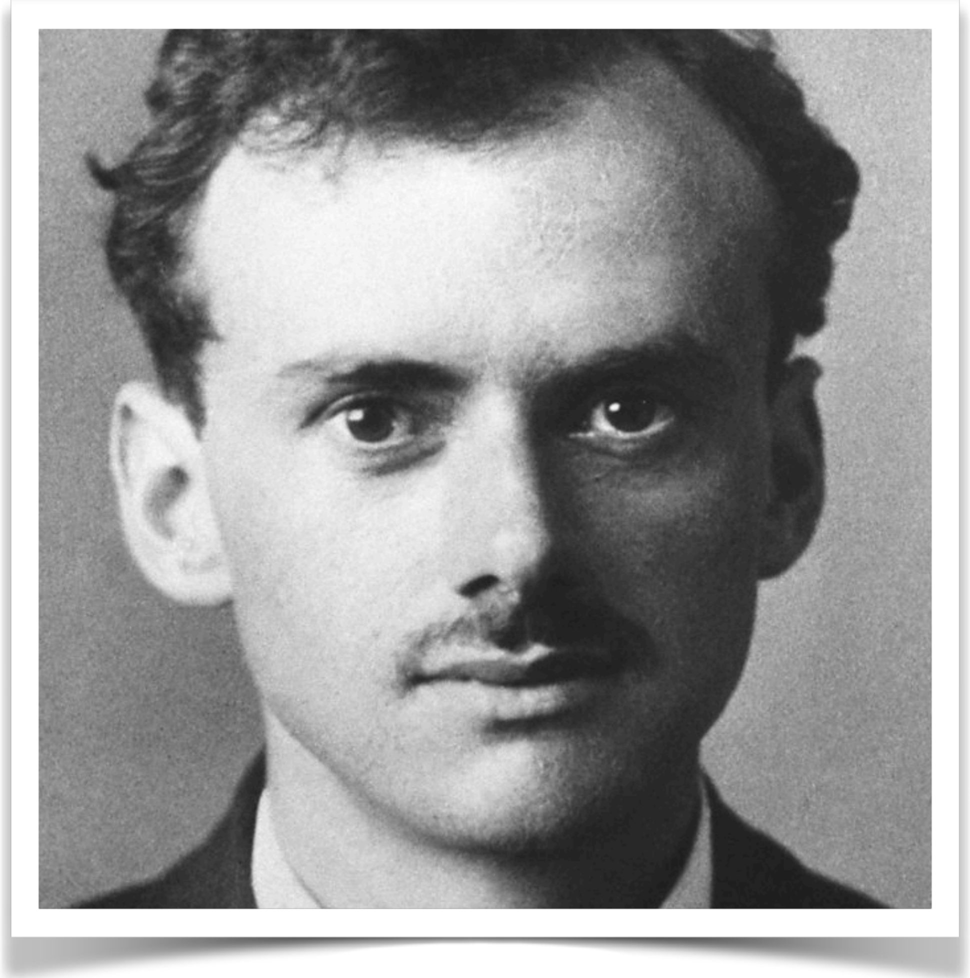
Si direbbe essere una delle caratteristiche fondamentali della natura che le leggi fisiche fondamentali siano descritte in termini di una teoria matematica di grande bellezza e potenza [...] si potrebbe forse descrivere la situazione dicendo che Dio è un matematico sopraffino, che ha usato una matematica molto avanzata nella costruzione dell'universo



P. A. M. Dirac
"The evolution of the Physicist's Picture of Nature"
Scientific American vol. 208, n. 5 (1963)

A me sembra che, se si lavora dal punto di vista di ottenere la bellezza nelle proprie equazioni, e se si ha davvero una solida intuizione, ci si trova senza dubbio sulla strada giusta.

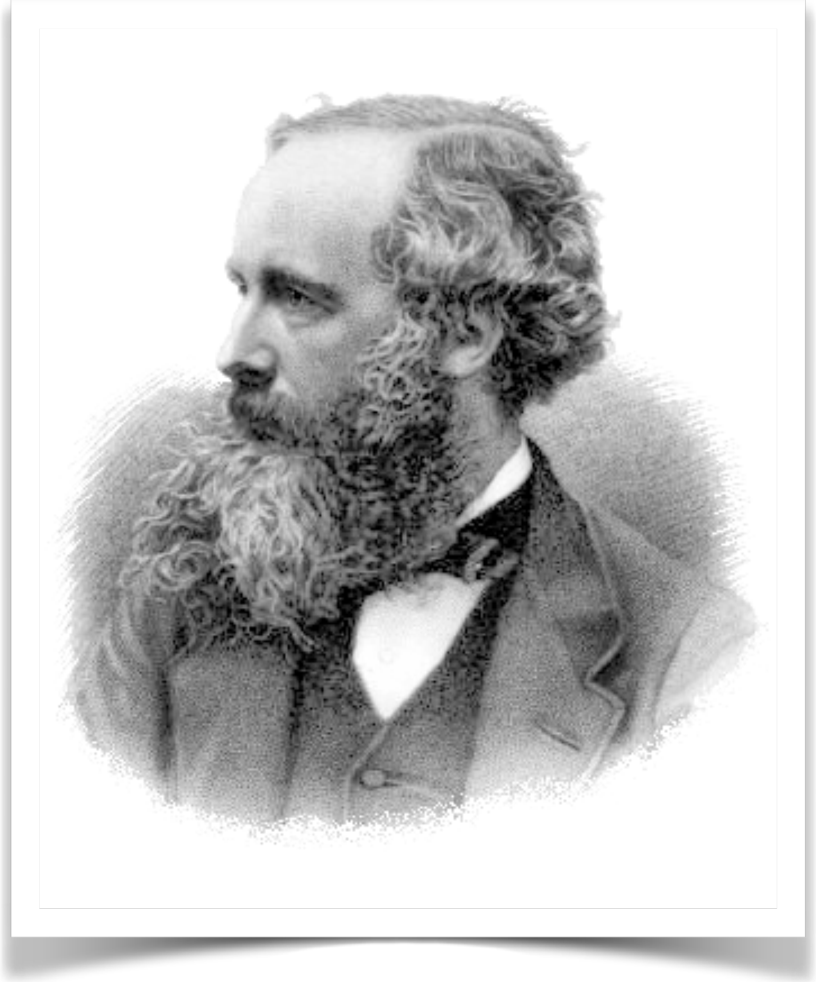
Giovanni Organtini - "Sapienza" Università di Roma & INFN-Sez. di Roma



P. A. M. Dirac
"The evolution of the Physicist's Picture of Nature"
Scientific American vol. 208, n. 5 (1963)

Giovanni Organtini - "Sapienza" Università di Roma & INFN-Sez. di Roma

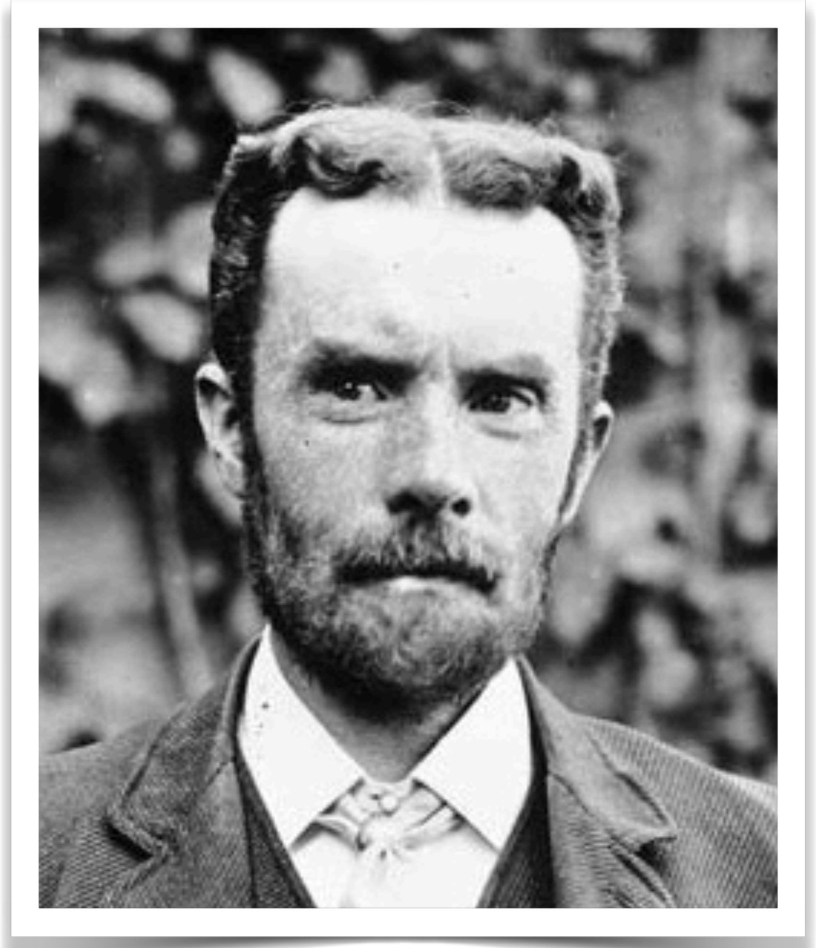
$$\Phi_S(\mathbf{E}) = 0 \qquad \Gamma_\gamma(\mathbf{E}) = -\frac{\Delta\Phi(\mathbf{B})}{\Delta t}$$



$$\Phi_S(\mathbf{B}) = 0 \qquad \Gamma_\gamma(\mathbf{B}) = \mu_0\epsilon_0\frac{\Delta\Phi(\mathbf{E})}{\Delta t}$$

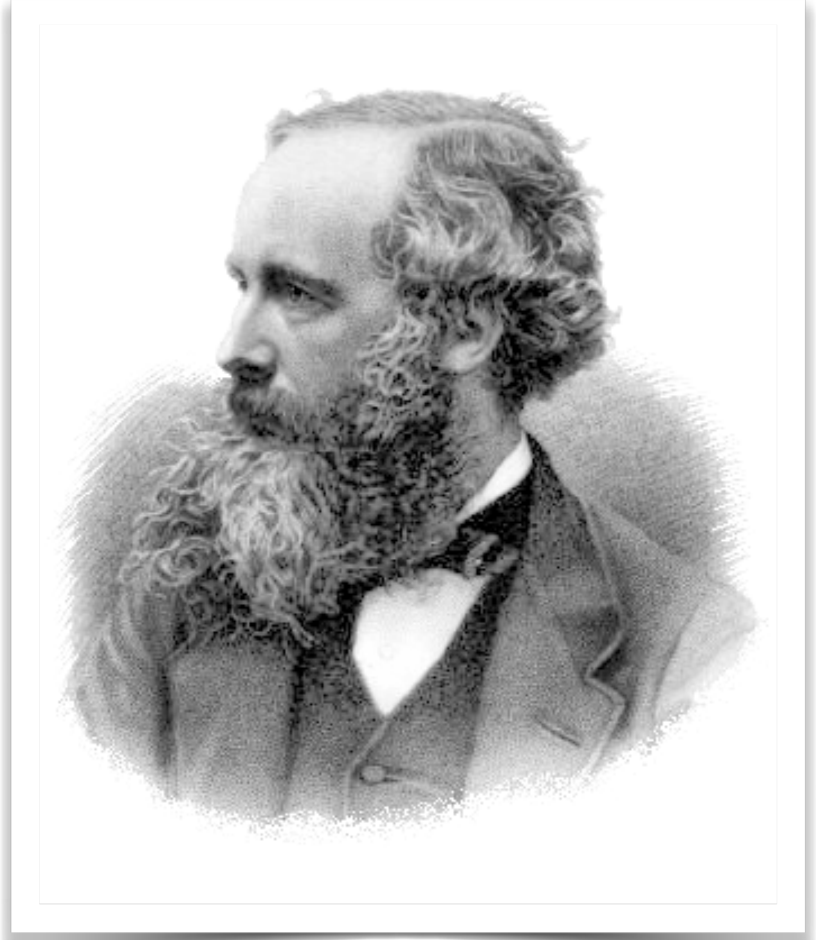
Giovanni Organtini - "Sapienza" Università di Roma & INFN-Sez. di Roma

$$\nabla \cdot \mathbf{E} = 0 \qquad \nabla \wedge \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$



$$\nabla \cdot \mathbf{B} = 0 \qquad \nabla \wedge \mathbf{B} = \mu_0 \epsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$

Giovanni Organtini - "Sapienza" Università di Roma & INFN-Sez. di Roma



will be limited sheets, terminating in the electric circuit as their common edge or boundary. The number of these will be equal to the amount of work done on a unit pole in going round the current, and this by the ordinary measurement $=4\pi\gamma$, where γ is the value of the current.

These surfaces, therefore, are connected with the electric current as soap-bubbles are connected with a ring in M. PLATEAU's experiments. Every current γ has $4\pi\gamma$ surfaces attached to it. These surfaces have the current for their common edge, and meet it at equal angles. The form of the surfaces in other parts depends on the presence of other currents and magnets, as well as on the shape of the circuit to which they belong.

PART III.—GENERAL EQUATIONS OF THE ELECTROMAGNETIC FIELD.

(53.) Let us assume three rectangular directions in space as the axes of x, y, and z, and let all quantities having direction be expressed by their components in these three directions.

Electrical Currents (p, q, r).

(54) An electrical current consists in the transmission of electricity from one part of a body to another. Let the quantity of electricity transmitted in unit of time across unit of area perpendicular to the axis of x be called p, then p is the component of the current at that place in the direction of x.

We shall use the letters p, q, r to denote the components of the current per unit of area in the directions of x, y, z.

Electrical Displacements (f, g, h).

(55) Electrical displacement consists in the opposite electrification of the sides of a molecule or particle of a body which may or may not be accompanied with transmission through the body. Let the quantity of electricity which would appear on the faces $dy.dz$ of an element dx, dy, dz cut from the body be $f.dy.dz$, then f is the component of electric displacement parallel to x. We shall use f, g, h to denote the electric displacements parallel to x, y, z respectively.

The variations of the electrical displacement must be added to the currents p, q, r to get the total motion of electricity, which we may call p', q', r', so that

$$\left.\begin{aligned} p' &= p + \frac{df}{dt}, \\ q' &= q + \frac{dg}{dt}, \\ r' &= r + \frac{dh}{dt}, \end{aligned}\right\} \quad \ldots\ldots\ldots \quad (A)$$

Electromotive Force (P, Q, R).

(56) Let P, Q, R represent the components of the electromotive force at any point. Then P represents the difference of potential per unit of length in a conductor

Art & Science across Italy — 3ª edizione — NOV 2020 MAG 2022

Giovanni Organtini - "Sapienza" Università di Roma & INFN-Sez. di Roma

Coefficient of Magnetic Induction (μ).

(60) Let μ be the ratio of the magnetic induction in a given medium to that in air under an equal magnetizing force, then the number of lines of force in unit of area perpendicular to x will be $\mu\alpha$ (μ is a quantity depending on the nature of the medium, its temperature, the amount of magnetization already produced, and in crystalline bodies varying with the direction).

(61) Expressing the electric momentum of small circuits perpendicular to the three axes in this notation, we obtain the following

Equations of Magnetic Force.

$$\left.\begin{aligned} \mu\alpha &= \frac{dH}{dy} - \frac{dG}{dz}, \\ \mu\beta &= \frac{dF}{dz} - \frac{dH}{dx}, \\ \mu\gamma &= \frac{dG}{dx} - \frac{dF}{dy}. \end{aligned}\right\} \quad \text{(B)}$$

Equations of Currents.

(62) It is known from experiment that the motion of a magnetic pole in the electromagnetic field in a closed circuit cannot generate work unless the circuit which the pole describes passes round an electric current. Hence, except in the space occupied by the electric currents,

$$\alpha dx + \beta dy + \gamma dz = d\phi \quad \text{(31)}$$

a complete differential of ϕ, the magnetic potential.

The quantity ϕ may be susceptible of an indefinite number of distinct values, according to the number of times that the exploring point passes round electric currents in its course, the difference between successive values of ϕ corresponding to a passage completely round a current of strength c being $4\pi c$.

Hence if there is no electric current,

$$\frac{d\gamma}{dy} - \frac{d\beta}{dz} = 0;$$

but if there is a current p',

$$\frac{d\gamma}{dy} - \frac{d\beta}{dz} = 4\pi p'.$$

Similarly,

$$\left.\begin{aligned} \frac{d\gamma}{dy} - \frac{d\beta}{dz} &= 4\pi p', \\ \frac{d\alpha}{dz} - \frac{d\gamma}{dx} &= 4\pi q', \\ \frac{d\beta}{dx} - \frac{d\alpha}{dy} &= 4\pi r'. \end{aligned}\right\} \quad \text{(C)}$$

We may call these the Equations of Currents.

Istituto Nazionale di Fisica Nucleare

Giovanni Organtini - “Sapienza” Università di Roma & INFN-Sez. di Roma

Art & Science ACROSS ITALY — 3ª edizione — NOV 2020 MAG 2022

will be increased by the following increments,

$$a\left(\frac{dF}{dx}\frac{dx}{dt}+\frac{dF}{dy}\frac{dy}{dt}+\frac{dF}{dz}\frac{dz}{dt}\right), \text{ due to motion of conductor,}$$

$$-a\frac{ds}{dt}\left(\frac{dF}{dx}\frac{dx}{ds}+\frac{dG}{dx}\frac{dy}{ds}+\frac{dH}{dx}\frac{dz}{ds}\right), \text{ due to lengthening of circuit.}$$

The total increment will therefore be

$$a\left(\frac{dF}{dy}-\frac{dG}{dx}\right)\frac{dy}{dt}-a\left(\frac{dH}{dx}-\frac{dF}{dz}\right)\frac{dz}{dt};$$

or, by the equations of Magnetic Force (8),

$$-a\left(\mu\gamma\frac{dy}{dt}-\mu\beta\frac{dz}{dt}\right).$$

If P is the electromotive force in the moving conductor parallel to x referred to unit of length, then the actual electromotive force is Pa; and since this is measured by the decrement of the electromagnetic momentum of the circuit, the electromotive force due to motion will be

$$P=\mu\gamma\frac{dy}{dt}-\mu\beta\frac{dz}{dt}. \qquad (36)$$

(65) The complete equations of electromotive force on a moving conductor may now be written as follows:—

Equations of Electromotive Force.

$$\left.\begin{aligned} P&=\mu\left(\gamma\frac{dy}{dt}-\beta\frac{dz}{dt}\right)-\frac{dF}{dt}-\frac{d\Psi}{dx},\\ Q&=\mu\left(\alpha\frac{dz}{dt}-\gamma\frac{dx}{dt}\right)-\frac{dG}{dt}-\frac{d\Psi}{dy},\\ R&=\mu\left(\beta\frac{dx}{dt}-\alpha\frac{dy}{dt}\right)-\frac{dH}{dt}-\frac{d\Psi}{dz}.\end{aligned}\right\} \qquad (D)$$

The first term on the right-hand side of each equation represents the electromotive force arising from the motion of the conductor itself. This electromotive force is perpendicular to the direction of motion and to the lines of magnetic force; and if a parallelogram be drawn whose sides represent in direction and magnitude the velocity of the conductor and the magnetic induction at that point of the field, then the area of the parallelogram will represent the electromotive force due to the motion of the conductor, and the direction of the force is perpendicular to the plane of the parallelogram.

The second term in each equation indicates the effect of changes in the position or strength of magnets or currents in the field.

The third term shows the effect of the electric potential Ψ. It has no effect in causing a circulating current in a closed circuit. It indicates the existence of a force urging the electricity to or from certain definite points in the field.

INFN Istituto Nazionale di Fisica Nucleare

CERN

Giovanni Organtini - "Sapienza" Università di Roma & INFN-Sez. di Roma

Electric Elasticity.

(66) When an electromotive force acts on a dielectric, it puts every part of the dielectric into a polarized condition, in which its opposite sides are oppositely electrified. The amount of this electrification depends on the electromotive force and on the nature of the substance, and, in solids having a structure defined by axes, on the direction of the electromotive force with respect to these axes. In isotropic substances, if k is the ratio of the electromotive force to the electric displacement, we may write the

Equations of Electric Elasticity,

$$\left.\begin{aligned} P&=kf, \\ Q&=kg, \\ R&=kh. \end{aligned}\right\} \qquad \text{(E)}$$

Electric Resistance.

(67) When an electromotive force acts on a conductor it produces a current of electricity through it. This effect is additional to the electric displacement already considered. In solids of complex structure, the relation between the electromotive force and the current depends on their direction through the solid. In isotropic substances, which alone we shall here consider, if ϱ is the specific resistance referred to unit of volume, we may write the

Equations of Electric Resistance,

$$\left.\begin{aligned} P&=-\varrho p, \\ Q&=-\varrho q, \\ R&=-\varrho r. \end{aligned}\right\} \qquad \text{(F)}$$

Electric Quantity.

(68) Let e represent the quantity of free positive electricity contained in unit of volume at any part of the field, then, since this arises from the electrification of the different parts of the field not neutralizing each other, we may write the

Equation of Free Electricity,

$$e+\frac{df}{dx}+\frac{dg}{dy}+\frac{dh}{dz}=0. \qquad \text{(G)}$$

(69) If the medium conducts electricity, then we shall have another condition, which may be called, as in hydrodynamics, the

Equation of Continuity,

$$\frac{de}{dt}+\frac{dp}{dx}+\frac{dq}{dy}+\frac{dr}{dz}=0. \qquad \text{(H)}$$

(70) In these equations of the electromagnetic field we have assumed twenty variable

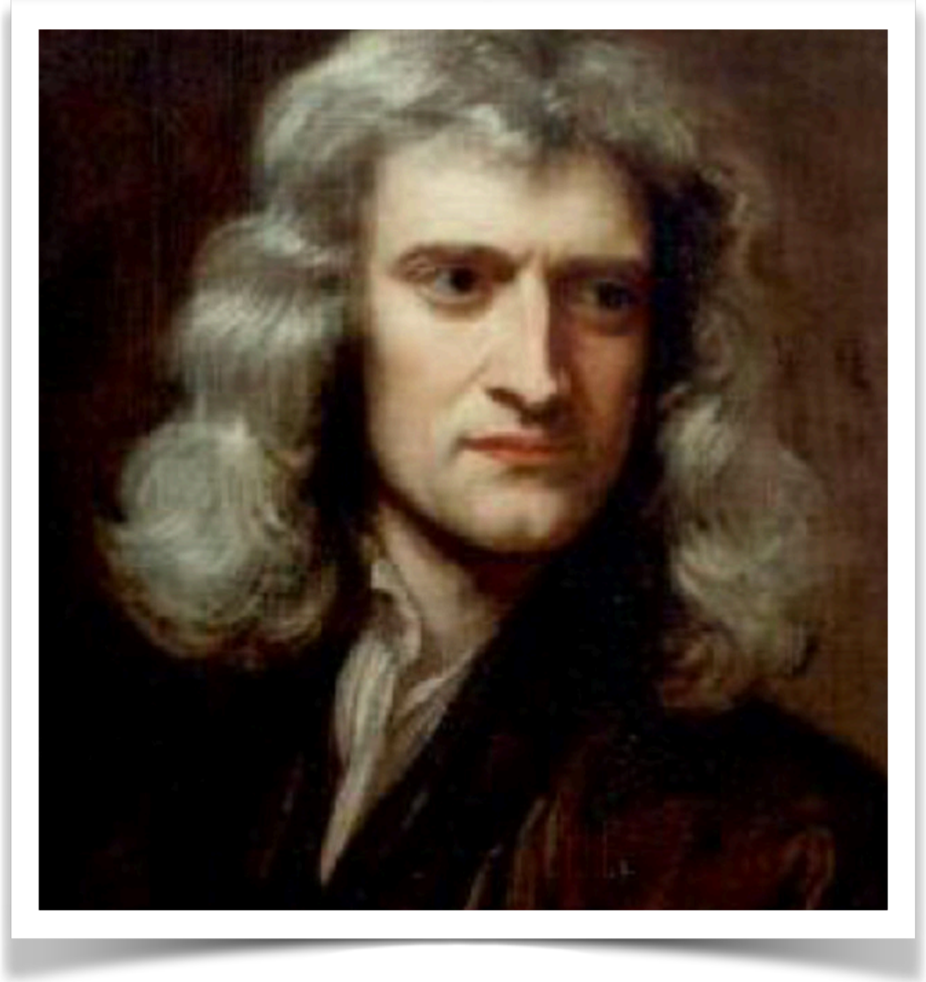
Istituto Nazionale di Fisica Nucleare

Giovanni Organtini - "Sapienza" Università di Roma & INFN-Sez. di Roma

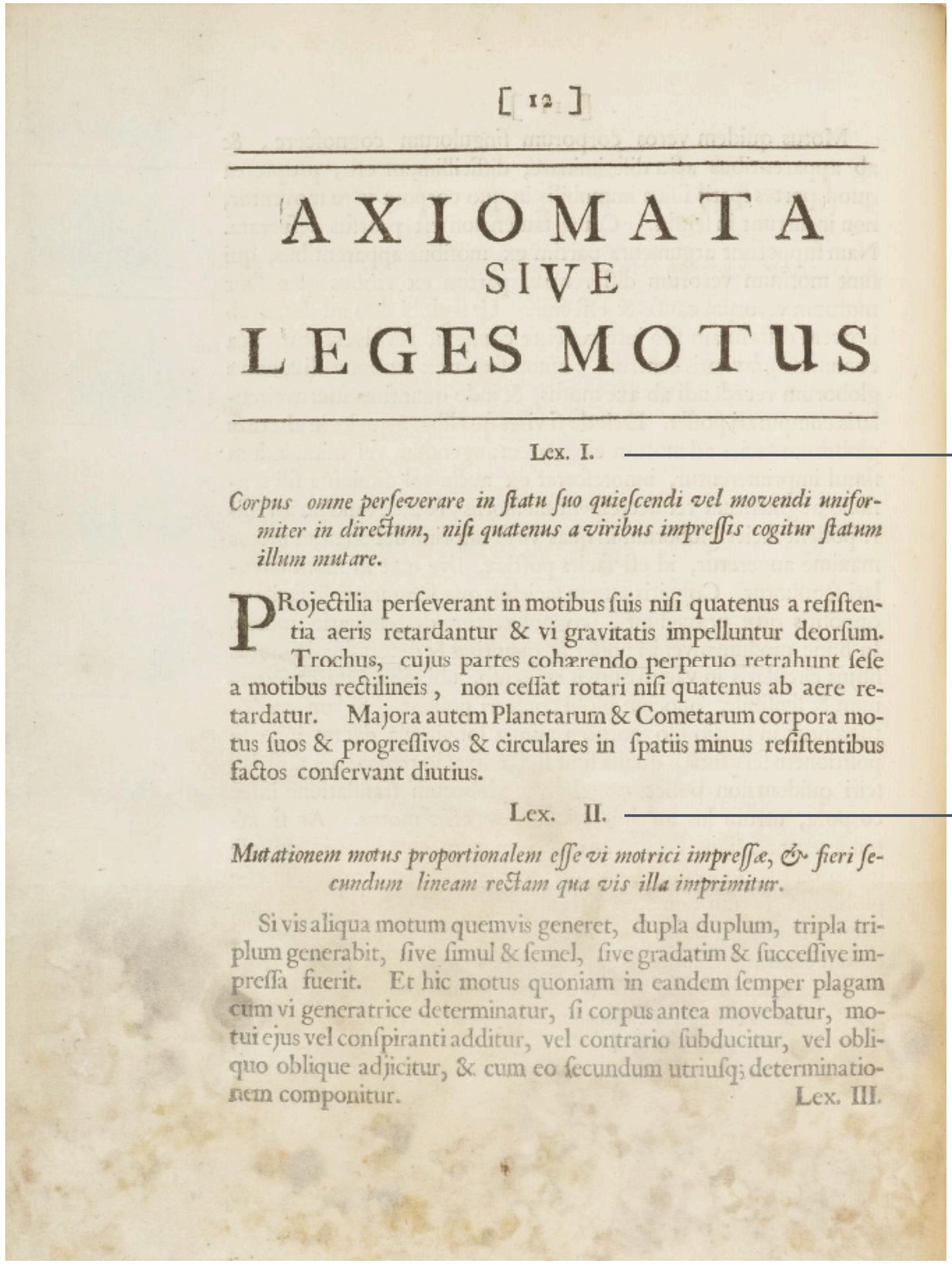
Between these twenty quantities we have found twenty equations, viz.

Three equations of Magnetic Force	. . . .	(B)
,, Electric Currents	. . . .	(C)
,, Electromotive Force	. . . .	(D)
,, Electric Elasticity	. . . .	(E)
,, Electric Resistance	. . . .	(F)
,, Total Currents	. . . .	(A)
One equation of Free Electricity	. . . .	(G)
,, Continuity	. . . .	(H)

Giovanni Organtini - "Sapienza" Università di Roma & INFN-Sez. di Roma



$$\mathbf{F} = m\mathbf{a}$$



[12]

AXIOMATA SIVE LEGES MOTUS

Lex. I.

Corpus omne perſeverare in ſtatu ſuo quieſcendi vel movendi uniformiter in directum, niſi quatenus a viribus impreſſis cogitur ſtatum illum mutare.

PRojectilia perſeverant in motibus ſuis niſi quatenus a reſiſtentia aeris retardantur & vi gravitatis impelluntur deorſum. Trochus, cujus partes cohærendo perpetuo retrahunt ſeſe a motibus rectilineis, non ceſſat rotari niſi quatenus ab aere retardatur. Majora autem Planetarum & Cometarum corpora motus ſuos & progreſſivos & circulares in ſpatiis minus reſiſtentibus factos conſervant diutius.

Lex. II.

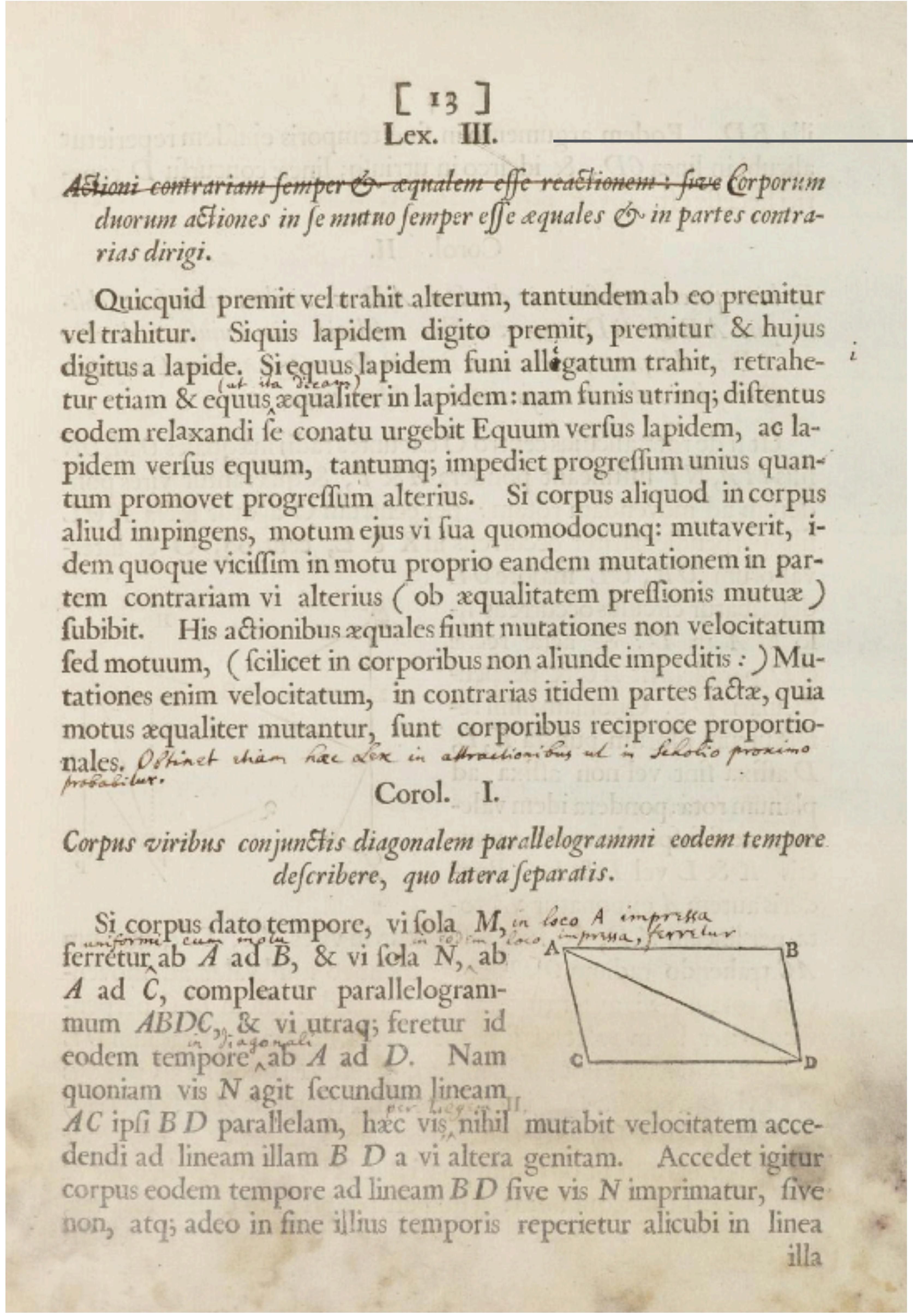
Mutationem motus proportionalem eſſe vi motrici impreſſæ, & fieri ſecundum lineam rectam qua vis illa imprimitur.

Si vis aliqua motum quemvis generet, dupla duplum, tripla triplum generabit, ſive ſimul & ſemel, ſive gradatim & ſucceſſive impreſſa fuerit. Et hic motus quoniam in eandem ſemper plagam cum vi generatrice determinatur, ſi corpus antea movebatur, motui ejus vel conſpiranti additur, vel contrario ſubducitur, vel obliquo oblique adjicitur, & cum eo ſecundum utriuſq; determinationem componitur.

Lex. III.

Corpus omne perseverare in statu suo quiescendi vel movendi uniformiter in directum, nisi quatenus a viribus impressis cogitur status illum mutare.

Mutationem motus proportionalem esse vi motrici impressæ, et fieri secundum lineam rectam qua vis illa imprimitur.


[13]

Lex. III.

~~*Actioni contrariam ſemper & æqualem eſſe reactionem: ſive*~~ *corporum duorum actiones in ſe mutuo ſemper eſſe æquales & in partes contrarias dirigi.*

Quicquid premit vel trahit alterum, tantundem ab eo premitur vel trahitur. Siquis lapidem digito premit, premitur & hujus digitus a lapide. Si equus lapidem funi allegatum trahit, retrahetur etiam & equus (ut ita dicam) æqualiter in lapidem: nam funis utrinq; diſtentus eodem relaxandi ſe conatu urgebit Equum verſus lapidem, ac lapidem verſus equum, tantumq; impediet progreſſum unius quantum promovet progreſſum alterius. Si corpus aliquod in corpus aliud impingens, motum ejus vi ſua quomodocunq; mutaverit, idem quoque viciſſim in motu proprio eandem mutationem in partem contrariam vi alterius (ob æqualitatem preſſionis mutuæ) ſubibit. His actionibus æquales fiunt mutationes non velocitatum ſed motuum, (ſcilicet in corporibus non aliunde impeditis:) Mutationes enim velocitatum, in contrarias itidem partes factæ, quia motus æqualiter mutantur, ſunt corporibus reciproce proportionales. Obtinet etiam hæc Lex in attractionibus ut in Scholio proximo probabitur.

Corol. I.

Corpus viribus conjunctis diagonalem parallelogrammi eodem tempore deſcribere, quo latera ſeparatis.

Si corpus dato tempore, vi ſola *M*, in loco *A* impressa, ferretur uniformi cum motu ab *A* ad *B*, & vi ſola *N*, in eodem loco impressa, ferretur ab *A* ad *C*, compleatur parallelogrammum *ABDC*, & vi utraq; feretur id eodem tempore in diagonali ab *A* ad *D*. Nam quoniam vis *N* agit ſecundum lineam *AC* ipſi *BD* parallelam, hæc vis per Legem II nihil mutabit velocitatem accedendi ad lineam illam *B D* a vi altera genitam. Accedet igitur corpus eodem tempore ad lineam *BD* ſive vis *N* imprimatur, ſive non, atq; adeo in fine illius temporis reperietur alicubi in linea

illa

Actioni contrariam semper et æqualem esse reactionem; sive corporum duorum actiones in se mutuo semper esse æquales et in partes contraries dirigi

Giovanni Organtini - "Sapienza" Università di Roma & INFN-Sez. di Roma

Giovanni Organtini - "Sapienza" Università di Roma & INFN-Sez. di Roma

$$\frac{ds}{dt} = np\frac{t}{M}$$

Quel ramo del lago di Como, che volge a mezzogiorno, tra due catene non interrotte di monti, tutto a seni e a golfi, a seconda dello sporgere e del rientrare di quelli, vien, quasi a un tratto, a ristringersi, e a prender corso e figura di fiume, tra un promontorio a destra, e un'ampia costiera dall'altra parte; e il ponte, che ivi congiunge le due rive, par che renda ancor più sensibile all'occhio questa trasformazione, e segni il punto in cui il lago cessa, e l'Adda rincomincia, per ripigliar poi nome di lago dove le rive, allontanandosi di nuovo, lascian l'acqua distendersi e rallentarsi in nuovi golfi e in nuovi seni

Alessandro Manzoni
I Promessi Sposi (1825)

Che luna!
Il ladro si ferma per cantare.

Yosa Buson
~1700

Giovanni Organtini - "Sapienza" Università di Roma & INFN-Sez. di Roma

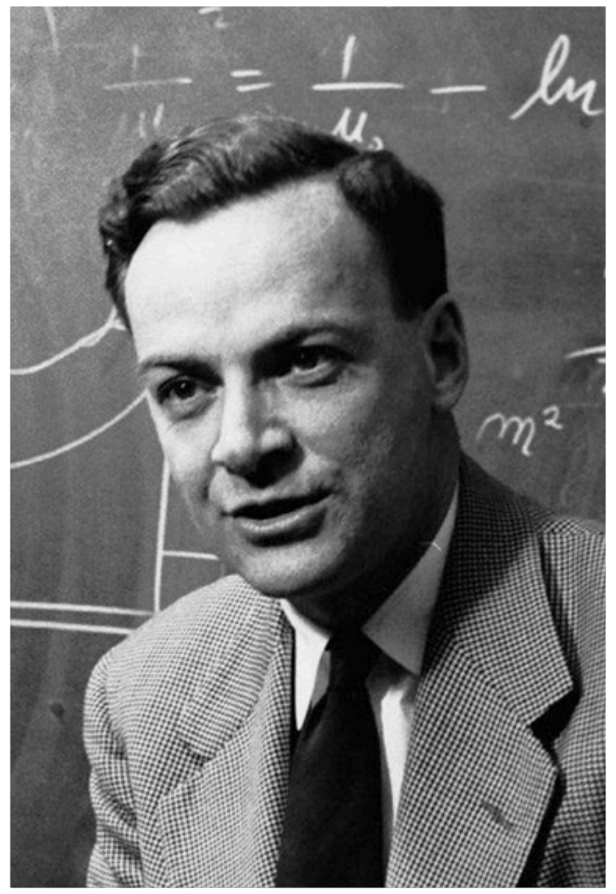
Giovanni Organtini - "Sapienza" Università di Roma & INFN-Sez. di Roma

The minimum could be defined as the perfection that an artefact achieves when it is no longer possible to improve it by subtraction.

Giovanni Organtini - "Sapienza" Università di Roma & INFN-Sez. di Roma

John Pawson
Minimum (1996)

Giovanni Organtini - "Sapienza" Università di Roma & INFN-Sez. di Roma



Let us show you something interesting that we have recently discovered: *All of the laws of physics can be contained in one equation*. That equation is

$$U = 0$$

What a simple equation! Of course, it is necessary to know what the symbol means.

U is a physical quantity which we will call the "unworldliness" of the situation. And we have a formula for it. Here is how you calculate the unworldliness. You take all of the known physical laws and write them in a special form. For example, suppose you take the law of mechanics, $F = ma$, and rewrite it as $F - ma = 0$.

Then you can call $(F - ma)$—which should, of course, be zero—the "mismatch" of mechanics. Next, you take the *square* of this mismatch and call it $U1$, which can be called the "unworldliness of mechanical effects." In other words, you take $U1 = (F - ma)^2$.

Sitografia

Giovanni Organtini - "Sapienza" Universitá di Roma & INFN-Sez. di Roma

J.C.Maxwell - A Dynamical Theory of the Electromagnetic Field - Part III
https://royalsocietypublishing.org/doi/pdf/10.1098/rstl.1865.0008

I. Newton - Philosophiæ Naturalis Principia Mathematica - pag. 46
http://cudl.lib.cam.ac.uk/view/PR-ADV-B-00039-00001/

Euler E842: An Introduction to Natural Science, Establishing the Fundamentals for the Explanation of the Events and Changes that occur in Nature
http://www.17centurymaths.com/contents/euler/e842/842trch7.pdf

Sitografia

P.A.M. Dirac Session III - AIP Oral History Interviews
https://www.aip.org/history-programs/niels-bohr-library/oral-histories/4575-3

P.A.M. Dirac, "Pretty Mathematics," Int. J. of Theor. Phys., Vol. 21, N. 8–9, 1982
https://link.springer.com/article/10.1007/BF02650229#page-1

The Evolution of the Physicist's Picture of Nature
https://blogs.scientificamerican.com/guest-blog/the-evolution-of-the-physicists-picture-of-nature/

R. Feynman - The essence of science in 60 seconds
https://www.youtube.com/watch?v=5v8habYTfHU

The Feynman Lectures on Physics - chap. 25
http://www.feynmanlectures.caltech.edu/II_25.html

Giovanni Organtini - "Sapienza" Università di Roma & INFN-Sez. di Roma