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Pierre Maurice Marie Duhem

The Electric Theories of J. Clerk Maxwell

A Historical and Critical Study

Translated by Alan Aversa

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Pierre Maurice Marie Duhem is deceased

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To my wife, who made this translation possible, and to the Holy Trinity, Who makes all things possible

Foreword

Pierre Maurice Marie Duhem[1] (1861–1916)—an accomplished physicist,[2] philosopher of physics,[3] and historian of physics[4]—ranked first in his class at the *École Normale Supérieure* (Jaki 1984, 36) France's most prestigious university, and first on the national physics *concours* exam for *agrégation* in 1885 (Chervel 2011). In his third year at the *École Normale,* he was the first student ever in France's *grandes ecoles* to present himself for the doctor's degree (Jaki 1984, 47). The thesis, later reprinted as *The Thermodynamic Potential and its Applications to Chemical Mechanics and to the Study of Electrical Phenomena*,[5] was rejected because it disproved the "principle of maximum work" of Berthelot, who had great influence over French academic politics. Undiscouraged, Duhem presented a second thesis, *On Magnetization by Induction* (Duhem 1988), this time in mathematics. It was accepted by a committee including Poincaré and Tannery. Tannery cataloged the thesis under the title: *A Novel Theory of Magnetization by Induction*

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[1]Jaki (1984); Maiocchi (1985); Miller (1970); Ariew (2011); Duhem (1936)

[2]Jaki (1984, 259–317). For a physicist's perspective on Duhem (1902), see de Moura and Sarmento (2013).

[3]Jaki (1984, 319–373). Duhem's greatest, most well-known work in the philosophy of physics is Duhem (1906), translated as Duhem (1991); it even influenced Einstein (Howard 1990). For a philosophical perspective on Duhem (1902), see Ariew and Barker (1986). For how Duhem's philosophy of physics relates to his cosmological, thermodynamical, and even religious views, see Kragh (2008).

[4]Jaki (1984, 375–436). Duhem (1990b) and Duhem (1990a) are his own summaries of his philosophy and history of physics for his candidacy in the Académie des Sciences, originally published as Duhem (1913, 151–157) and Duhem (1913, 158–169), respectively. Duhem's ten volume *Système du monde* (Duhem 1913–1959), partially translated as Duhem (1985), initiated the field of the history of medieval physics. It also demonstrates Duhem's "continuity thesis" of scientific development (Hannam 2009). For how Duhem's historiography influenced his epistemology, see Bordoni (2013b).

[5]*Le potentiel thermodynamique et ses applications à la mécanique chimique et à l'étude des phénomènes électriques* (Duhem 1886)

Founded on Thermodynamics[6]; by including the term "thermodynamics," he emphasized that this thesis is very similar in content to Duhem's rejected thesis.

The subject of Duhem's theses reflects his grand vision for physics: to subject all branches of physics—mechanics, chemistry, electromagnetism, etc.—to thermodynamic first principles.[7] Drawing inspiration from the "energetics program" (Rankine 1855) of Rankine (Parkinson 2008), Duhem subjected mechanics and chemistry to thermodynamic first principles in works such as his *Commentary on the Principles of Thermodynamics* (Duhem 2011), one of Duhem's few scientific works translated into English, and the *Treatise on Energetics or General Thermodynamics* (Duhem 1911), which Duhem considered his greatest scientific achievement.[8]

Duhem's Philosophy of Physics

Duhem was a moderate realist (Brenner et al. 2011, 7–12) who argued that physical theories are classifications of experimental laws. This is a key aspect of Duhem's philosophy of physics:

> A physical theory…is an abstract system whose aim is to *summarize* and *classify logically* a group of experimental laws without claiming to explain these laws.[9]

Duhem (1991 19) gives a more specific definition of physical theory in terms of the "abstract system" of mathematics:

> A physical theory is not an explanation. It is a system of mathematical propositions, deduced from a small number of principles, which aim to represent as simply, as completely, and as exactly as possible a set of experimental laws.[10]

Just as there are many ways to classify seashells or bodily organs, so there are also many ways to classify classification physical laws; and just as classifications *per se* do not explain what they classify, so also physical theories do not explain physical laws. Physical theories are not, as Newton thought about his theory of

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[6]*Théorie nouvelle de l'aimantation par influence fondée sur la thermodynamique* (cf. Jaki 1984, 79).

[7]For how Duhem partially accomplished this task, see Bordoni (2012a,b,c, 2013a). Needham (2013) is a review of Bordoni (2012a).

[8]For a translation of the introduction of Duhem's *Treatise*, see Maugin (2014, 172–175).

[9]Duhem (1991, 7), a translation of Duhem (1906, 3):

> Une théorie physique. est un systéme abstrait qui a pour but de *résumer* et de *classer logiquement* un ensemble de lois expérimentales, sans prétendre expliquer ceslois.

[10]Original from Duhem (1906, 24):

> Une théorie physique n'est pas une explication. C'est un systeme de propositions mathématiques, déduites d'un petit nombre de principes, qui ont pour but de représenter aussi simplement, aussi completement et aussi exactement que possible, un ensemble de lois expérimentales.

gravitation or Amperé about his force law, "uniquely deduced from experience;" other theories (e.g., Einstein's theory of gravitation) can equally, if not better, "save the phenomena save the phenomena"[11] of experience. In the history of physics, Duhem sees—from as far back as Aristotle to the present day—a long, steady, and continuous process asymptotically approaching the best, "natural classification."

All of Duhem's philosophy of physics—the under-determination of theory by fact, confirmation holism,[12] the strict separation between physics and metaphysics,[13] and the continuity of scientific development—is rooted in his understanding of physical theory as a classification.

One reason Duhem preferred Helmholtz's electromagnetic theory over that of others,[14] in addition to its being in "continuity with tradition," is because of what Buchwald calls Helmholtz's "taxonomy of interactions" between "laboratory objects."[15] Helmholtz's approach to electromagnetism was to classify the unique interaction energies between the various combinations of charged and current-carrying "laboratory objects." Thus, Helmholtz explicitly classified experimental laws, forming a true theory in the Duhemian sense.

Reception of Duhem's Physics

Lorentz (1926, 65), an article on Maxwell's electromagnetic theory, cites Duhem (1902), of which the present work is the translation, and classifies Duhem's treatment of electrodynamics under the heading "43. *Thermodynamische Behandlung*" ("Thermodynamic Treatment"), saying: "*P. Duhem* represents, in particular, the thermodynamic viewpoint."[16] He cites Duhem's *Lessons on Electricity and Magnetism* (Duhem 1891–1892), his accepted thesis (Duhem 1888), and his article in the American Journal of Mathematics (Duhem 1895b); however, Lorentz thought it would take him too far afield to discuss Duhem's treatment in detail.

Louis Roy, a student of Boussinesq and Professor of physics at the University of Toulouse (Jaki 1984, 298), promoted Helmholtz-Duhem electrodynamics in great detail in a book (Roy 1923a) and several articles (Roy 1915, 1918, 1923b). He writes[17]:

[11] Duhem (1908), translated as Duhem (1969).

[12] i.e., that there are no "crucial experiments crucial experiment;" cf. the related Duhem-Quine thesis: Ariew (1984).

[13] Duhem (1893), translated as Duhem (1996, 29–49).

[14] See this volume p. xx.

[15] Buchwald (1994, 11–12); cf. Buchwald's article "Electrodynamics in Context: Object States, Laboratory Object States, and Anti-Romanticism" (Cahan 1993, 334–373).

[16] "Den thermodynamischen Standpunkt hat insbesondere *P. Duhem* vertreten." (Lorentz 1926, 140-1).

[17] Roy (1923a, 7; 87), translated in O'Rahilly (1938, 178).

> Maxwell kept his eyes fixed on his object, which was to establish a theory inclusive of electrical and optical phenomena; unfortunately none of the paths he successively followed could lead him thereto. Then, when logic barred the way, he evaded the inconvenient obstacle by a flagrant fault of reasoning or calculation, certain that his objective was true. … The best way of recording our admiration for such a genius, is to reformulate his work with the help of the ordinary laws of logic. … An excessive admiration for Maxwell's work has led many physicists to the view that it does not matter whether a theory is logical or absurd, all it is required to do is to suggest experiments. … A day will come, I am certain, when it will be recognised … that above all the object of a theory is to bring classification and order into the chaos of facts shown by experience. Then it will be acknowledged that Helmholtz's electrodynamics is a fine work and that I did well to adhere to it. Logic can be patient, for it is eternal.

> [The Helmholtz-Duhem exposition is] the only real demonstration of Maxwell's equations which has hitherto been given.

In 1938, Alfred O'Rahilly devoted a whole chapter of his two-volume *Electromagnetic Theory: A Critical Examination of Fundamentals* to Helmholtz-Duhem theory (O'Rahilly 1938, 161–180), citing Duhem (1902) copiously.[18] He concludes (O'Rahilly 1938, 177):

> We have just shown that it is impossible to admit that Helmholtz's theory, as just expounded, really re-establishes the tradition of writers like Weber and C. Neumann, not to speak of the contemporary electron theory. Nevertheless Duhem's work is of permanent value, and his protest against the complaisant acceptance of contradictory standpoints is still apposite.

That it "is still apposite" is evidenced by the fact that, very recently, Maugin (2014, 104–107) discusses Helmholtz-Duhem theory in the context of "incorporating electricity and magnetism, including nonlinear dissipative effects such as hysteresis, in his broad energetic view." (Maugin 2014, 104). Duhem never accomplished this in his great *Treatise*; thus, it remains an open problem for young physicists to tackle (cf. Wipf 2011).

Note on the Translation

Page numbers in [•] brackets, refer to the pages of the original (Duhem 1902). Page numbers in [•] brackets in the citations in the footnotes refer to the page numbers of the English version of the citation.

Sierra Vista, Arizona — Alan Aversa
March 2015

[18] O'Rahilly (1938, 36; 79–80; 83; 90; 95–96; 177; 182; 210).

Acknowledgments

In September 2013, I asked Stefano Bordoni what would be a good journal to publish Duhem (1895a), but he suggested that it would be better to translate all of Duhem (1902). He was certainly right. I would also like to thank Stanley L. Jaki[19] for his tireless work in promoting Duhem's physics and Ryan Vilbig for introducing me to Alfred O'Rahilly,[20] an advocate of alternative theories of electrodynamics, such as Weber's theory, Ritz's ballistic theory of light, and the Helmholtz-Duhem theory.

[19]†2009, *requiescat in pace*. http://www.sljaki.com/.

[20]http://humphrysfamilytree.com/ORahilly/alfred.html.

Contents

Chapter 1
Introduction

In the middle of this century,[1] electrodynamics seemed established in all its essential parts. Awaken by the experience of Oersted, the genius of Ampère had created and brought to a high degree of perfection the study of forces acting between two currents or between a current and a magnet; Arago had discovered magnetization by currents; Faraday had highlighted the phenomena of electrodynamic induction and electromagnetic induction; Lenz had compared the sense of electromotive actions [2] of currents to the sense of their ponderomotive actions. This comparison provided to F.E. Neumann the starting point of a theory of induction. W. Weber proposed this theory, in relying on hypotheses of the general laws of electric forces. Finally, H. Helmholtz, then W. Thomson, attempted to pass from the laws of Ampère to the laws discovered by F.E. Neumann and W. Weber, taking the newly asserted law of the conservation of energy as an intermediary principle.

Only two objects seemed to offer themselves to the study of the physicist eager to work in the progress of electrodynamics and electromagnetism.

The first of these objects was the development of the consequences implicitly contained in the principles that had been posed. To pursue this object, the geometers employed the resources of their analysis; experimenters began implementing their most accurate measurement methods; industrials lavished their inventive ingenuity; and, soon, the study of electricity became the richest and largest chapter of all of physics.

The second of these objects, of a more speculative and more philosophical nature, was the reduction to a common law of the principles of electrostatics and electrodynamics. Ampère himself had proposed it to the efforts of physicists. He said[2]:

> It is therefore completely demonstrated that one cannot make sense of the phenomena produced by the action of two voltaic conductors, assuming that electric molecules acting

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[1] [The 19th century].

[2] Ampère. *Théorie mathématique des phénomènes électrodynamiques uniquement déduite de l'expérience*, Paris, 1826. Deuxième édition (Paris, 1883), pp. 96 et sqq. [English translation: Ampère (2015)].

P.M.M. Duhem, *The Electric Theories of J. Clerk Maxwell*,
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> inversely to the square of the distance were distributed on the conductive wires in such a way so as to remain fluxed and can, therefore, be viewed as invariably linked among themselves. It must be concluded that these phenomena are due to that the two electrical fluids roam continually the conductive wires with an extremely fast movement, [3] meeting and parting alternately in the gaps of the particles of these wires…
>
> It is only in the case where one assumes the electric molecules at rest in the body, where they manifest their presence through the attractions or repulsions produced by them between these bodies, that it is shown that a uniformly accelerated movement neither can result from the forces exerted by the electric molecules in this state of rest nor depend only on their mutual distances. When it is assumed, instead, that, put in motion in the wires by the action of the battery, they are continually changing place, gather at every moment in neutral fluid, separate again, and will meet in other fluid molecules of the opposite nature, it is not more contradictory to admit that from the actions in inverse ratio of the squares of the distances which exert on each molecule, a force can arise between two elements of conductive wires which depends not only on their distance, but also on the directions of the two elements whereby electric molecules move, gather in the molecules of the opposite species, and separate the next moment to unite with others…
>
> If it were possible, starting from this consideration, to prove that the mutual action of the two elements is, indeed, proportional to the formula by which I represented it, this explanation of the fundamental fact of the theory of electrodynamic phenomena should obviously be preferred to any other…

To the question that Ampère only posed, Gauss[3] formulates a response that he did not publish: the mutual repulsive action of two electrical charges does not only depend on their distance, but also on the speed of relative motion of the one with respect to the other; when two charges are at relative rest, this action reduces to the force inversely proportional to the square of the distance, known since Coulomb; when, on the contrary, two conductive wires are, the one and the other, the seats of two electrical currents leading in opposite directions, with equal [4] speed, one the positive electricity and the other the negative electricity, these two wires attract one another according to Ampère's law.

Gauss merely put on paper a formula that answered the question of Ampère; his illustrious pupil, W. Weber,[4] imagined a similar formula and deduced all the consequences. According to Weber, the mutual action of two electrical charges depends not only on their distance, but also on the first two derivatives of this distance with respect to time. Reproducing Coulomb's law when applied to electrostatic phenomena, the formula of Weber indicates that both current elements attract according to the formula of Ampère. In addition, it provides a complete mathematical theory of electrodynamic induction, a theory consistent at all points to that which F.E. Neumann discovered at the same time, inspired by the methods of Ampère.

The doctrine of Weber was, first of all, great; most physicists considered, according to the words of Ampère, that "this explanation of the fundamental fact of the theory of electrodynamic phenomena should be preferred to any other."

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[3] C.F. Gauss, *Werke*, Bd. V, p. 616.

[4] Weber, *Elektrodynamische Maassbestimmungen*, I, Leipzig, 1846.

However, this doctrine did not justify the hopes it first raised, although G. Kirchhoff[5] deduced, for induction within conductors of finite extent in all dimensions, a theory that served as a precursor to the research of Helmholtz, it did not lead to the discovery of any new fact; and, little by little, desperate by the sterility of the speculations regarding the actions that carry electric charges in motion, physicists diverted their attention, which could not be brought back by the hypotheses of B. Riemann, nor by the researches of R. Clausius. [5]

So, electrodynamics appeared in 1860 as a vast country whose daring explorers recognized all the frontiers; the exact scope of the region seemed known. It only remained to study carefully each of its provinces and exploit the riches it promised for industry.

However, in 1861, to this science that seemed so completely master of its domain, a new and vast area was opened; and so one could believe, many think today, that this sudden extension should not only increase electrodynamics, but also upset parts of this doctrine that are regarded as established in an almost final manner.

This revolution was the work of a Scottish physicist, James Clerk Maxwell.

Taking up and developing the old ideas of Aepinus and Cavendish, Faraday created, besides the electrostatics of conductive bodies, the electrostatics of the insulating body or, in the words he introduced in physics, *dielectric* bodies; but no one had taken these bodies into in account in the speculations of electrodynamics. Maxwell created the electrodynamics of the dielectric body. He imagined that the properties of dielectrics, at any given time, depended not only on the polarization of this body at this moment, but also on the speed with which the polarization varies from one moment to the next; he assumed that this speed causes ponderomotive and electromotive forces similar to those that cause the flow of electricity. To the *conduction current* he compared the *polarization current* or, in his words, the *displacement current*.

Not only do displacement currents exert, in conductive bodies, inducing actions similar to those of the conduction current, but also the electromotive forces of these two kinds of current, giving rise to a current in a conductive body, polarize the dielectrics in which they act. The equations, which derived from these hypotheses a method where only the electrodynamic properties of the body come [6] into account, offer surprising characteristics. According to these equations, the laws that govern the propagation of displacement currents in a dielectric medium are exactly those which obey the infinitely small displacement of a perfectly elastic body; in particular, uniformly moving currents behave absolutely like vibrations of the ether which optics then attributed to the light phenomena.

But there is more. The velocity of the displacement current in a vacuum can be measured by purely electrical experiments; and this speed, thus determined, is numerically equal to the speed of light in a vacuum. Therefore, it is only a simple analogy between uniform displacement flux and luminous vibration which imposes itself on the spirit of the physicist; immediately, he is led to believe that light vibrations

[5]G. Kirchhoff, *Ueber die Bewegung der Elektricität in Leitern* (POGGENDORFF'S ANNALEN, Bd. CII, 1857). [English translation: Graneau and Assis (1994)].

do not exist. To periodic displacement currents, he attributes the phenomena that these vibrations were used to explain, often in a less than fortunate way; thus creating the *electromagnetic theory of light*, Maxwell made optics a province of electrodynamics.

Surprising for its consequences, the electrodynamics that Maxwell inaugurated was even more so by the unusual way that it followed its author into science.

Physical theory is a symbolic construction of the human mind intended to give a representation—a synthesis as complete, as simple, and as logical as possible—of the laws that experience has discovered. To each new quality of bodies, it matches a quantity where the various values are used to identify the various states, the various intensities of this quality. Among the different quantities that he considers, he establishes connections using mathematical propositions that seem to translate the simple properties and most essential qualities of which these quantities are the signs; then, deducing from these *hypotheses*, by rigorous reasoning, the consequences that they implicitly contain, he compares these consequences to the laws that the experimenter has uncovered. When a large number of these theoretical consequences represent, in a very approximate way, a large number of experimental laws, the theory is good. [7]

The theory must give of the physical world a description as simple as possible; it must therefore restrict as far as possible the number of properties that it regards as irreducible qualities and that it describes by means of particular quantities, the number of laws it regards as primary and of which it makes hypotheses. It must appeal to a new quantity, accept a new hypothesis, only when inescapable necessity compels it.

When the physicist discovers facts unknown to him, when his experiences have allowed him to formulate laws that the theory did not foresee, he must first search with great care if these laws can be presented, to the required degree of approximation, as consequences of the accepted hypotheses. It is only after having acquired the certainty that the quantities previously handled by the theory can serve as symbols to the observed qualities, that the received hypotheses can result from the established laws, that he is allowed to enrich physics with a new quantity, to the complicating of a new hypothesis.

These principles are the essence itself of our physical theories. If one were to miss it, the difficulty which is often encountered is whether or not a law, discovered by observation, following accepted hypotheses or not, too frequently attached to a laziness of the mind, would lead physicists to look at each new property as an irreducible quality, each new law as a first hypothesis, and our science would soon deserve all the reproaches that contemporaries of Galileo and Descartes addressed to the physics of the School.[6]

The founders of electrodynamics are carefully conformed to these principles. To represent the properties of electrified bodies, it was sufficient for Coulomb and Poisson to make use of a single quantity, electric charge, to impose on electric charges a single hypothesis, Coulomb's law. When Ampère discovered that attractive or repulsive actions are exerted between wires carrying electric currents, physicists

[6][Who, for example, explained why a sleeping pill makes one sleep by saying it has the "irreducible quality" of "*vis dormitiva*" or "sleeping power"].

sought first whether they could represent these actions by electrical charges properly distributed on wires and repelling each other according to [8] Coulomb's formula. Ampère attempted this. He did not deny that some facts of experience, and in particular the phenomena of electromagnetic rotation, discovered by Faraday, were proof that he could succeed; then he only wanted that the intensity of the electrical current take place with the electric charge. So, he only proclaimed the laws of electrodynamics were first laws, in the same way as Coulomb's law.

To create the electrodynamics of the dielectric body, Maxwell took a back-step.

At the time when Maxwell introduced in electrodynamics a new quantity, the displacement current, at the moment where he marked, as key hypotheses, the mathematical form of the laws to which this quantity should be submitted, no duly observed phenomenon required the extension of the theory of currents. It was enough to represent, if not all phenomena until then known, at least all those whose experimental study had arrived at a sufficient degree of sharpness. No logical necessity urged Maxwell to imagine a new electrodynamics. For guides, he had only analogies, the desire to provide the work of Faraday with an extension similar to what the work of Coulomb and Poisson received from the electrodynamics of Ampère, and possibly also an instinctive sense of the electrical nature of light. It took many years of research and engineering for Hertz to discover phenomena that reflected his equations, so his theory happened to be a form devoid of any material. With incredible imprudence, Maxwell reversed the natural order according to which theoretical physics evolves; he did not live long enough to see the discoveries of Hertz transform his imprudent boldness in prophetic divination.

Entering into science by an unusual route, Maxwell's electrodynamics does not seem less strange when one follows the developments in the writings of its author. [9]

We note at the outset that the writings of Maxwell describe not a single electrodynamics, but at least three distinct electrodynamics.

The first writing by Maxwell[7] is intended to establish in clear light the analogy between the equations that govern various branches of physics, an analogy which seemed to suggest new inventions. "By a physical analogy I mean that partial similarity between the laws of one science and those of another which makes each of them illustrate the other."[8] The analogy, already noticed by Huygens, between acoustics and optics, contributed greatly to the progress thereof. Maxwell takes as his starting point the theory of heat conductivity, or rather the theory of the motion of a fluid in a resistant medium, a simply changing the notation, which does not alter the form of the equations. From these equations, by way of analogy, Ohm had earlier derived the laws of electric motion in conductive bodies; by a similar process, Maxwell deduced a theory of polarization of dielectric bodies.

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[7] J. Clerk Maxwell, *On Faraday's Lines of Force*, read at the Philosophical Society of Cambridge on 10 December 1855 and 11 February 1856 (TRANSACTIONS OF THE CAMBRIDGE PHILOSOPHICAL SOCIETY, vol. X, part. I, pp. 27–83.—THE SCIENTIFIC PAPERS OF JAMES CLERK MAXWELL, t. I, pp. 156–219; Cambridge, 1890).

[8] [*ibid.* p. 156].

The first memoir of Maxwell intended only to *illustrate* the theory of dielectrics by comparing the equations that govern it with the equations that govern other parts of physics. The second[9] aims to be a *mechanical model* that *describes* or *explains* (for an English physicist, the two words have the same meaning)[10] electric and magnetic action.

We know the constitution that, in this memoir, Maxwell [10] assigns to every body: *cells*—whose very thin walls are formed from a perfectly elastic and incompressible solid and contain a perfect, equally incompressible fluid—that animate rapid vortical movements. These vortical movements represent the magnetic phenomena; at each point, the instantaneous axis of vortical motion marks the direction of magnetization. The live force[11] of the rotational motion of the fluid that fills a volume element is proportional to the magnetic moment of this volume element. As for the elastic solid that forms the walls of the cells, the forces acting upon it distort it in various ways. The *displacements* that the various parts experience represent the *polarization* introduced by Faraday to account for the properties of the dielectric media.

To leave aside any presumption on the mechanical constitution of media where electric and magnetic events occur; to take as a unique starting point for the laws that experience has firmly established and that all physicists accept; to transform, then, by mathematical analysis the consequences of these laws so that the formulas are, so to speak, modeled on the equations to which the hypothesis of cells led; thus, to highlight the absolute equivalence between this mechanical interpretation and the commonly accepted electrical theories; to admit this doctrine to the highest degree of likelihood that can attain such an explanation: this appears to have been the purpose of Maxwell in his later publications concerning electricity. Likewise, it seems to be the main purpose of the large memoir entitled: *A Dynamical Theory of the Electromagnetic Field*[12] and of the *Treatise on Electricity and Magnetism*[13] which, in a certain way, this memoir outlines. [11]

He writes in the preface of the first edition[14]:

> In the following Treatise I propose to describe the most important of these phenomena, to shew how they may be subjected to measurement, 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 a light as I can the relations between

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[9] J. Clerk Maxwell, *On Physical Lines of Force* (PHILOSOPHICAL MAGAZINE, 4th series, t. XXI, pp. 161–175, 281 291, 338 à 348; 1861. Tome XXIII, pp. 12–24, 85–95; 1862.—THE SCIENTIFIC PAPERS OF JAMES CLERK MAXWELL, vol. I, pp. 451–513; Cambridge, 1900).

[10] *L'École anglaise et les Théories physiques* (REVUE DES QUESTIONS SCIENTIFIQUES, 2e série, tome II, 1893).

[11] [*Force vive* or mv^2, related to the kinetic energy $mv^2/2$].

[12] J. Clerk Maxwell, *A Dynamical Theory of the Electromagnetic Field*, read at the Royal Society of London on 8 December 1864 (PHILOSOPHICAL TRANSACTIONS, vol. CLV, pp. 459 à 512; 1865.—THE SCIENTIFIC PAPERS OF JAMES CLERK MAXWELL, t. I, pp. 526 à 597; Cambridge, 1890).

[13] J. Clerk Maxwell, *Treatise on Electricity and Magnetism*, 1st edition, London, 1873.—2o edition, London, 1881.—Traduit en français par G. Seligmann-Lui, Paris, 1885–1889.

[14] [*ibid*. p. v–vi].