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# Weber quoting Maxwell

**Zur Auseinandersetzung zwischen der Weberschen Theorie der Elektrizität und der aufkommenden Maxwellschen Elektrodynamik**

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## Zusammenfassung

Die Abhandlung setzt sich mit der Ablösung der älteren Elektrodynamik von Wilhelm Weber und Franz Neumann durch die Maxwellsche Theorie im letzten Drittel des 19. Jahrhunderts auseinander. Aufhänger für die Darstellung der Problematik sind die wenigen Zitate, die sich bei Wilhelm Weber finden. Die Diskussion wurde damals hauptsächlich durch Carl Neumann und Johann Karl Friedrich Zöllner geführt. Beide waren engagierte und leidenschaftliche Anhänger und Verteidiger der Weberschen Sicht und Darstellung der Theorie von der Elektrizität. Streitpunkte waren (1) die Nahwirkungstheorie, die mit dem Maxwellschen Feldkonzept identisch ist und im Gegensatz zur Fernwirkungstheorie (Prototyp: Newtonsches Gravitationsgesetz) stand, und (2) die Annahme der Existenz einer substantiellen Elektrizität. Weber beharrte bis zuletzt auf seinem Konzept und entwickelte ein Atommodell, das als Vorstufe des Rutherford-Bohrschen Atommodells angesehen werden kann. – Konsens bestand bei den absoluten elektrischen Maßsystemen. J. Cl. Maxwell las aus dem Kohlrausch-Weber-Experiment die Lichtgeschwindigkeit heraus, die für seine elektromagnetische Lichttheorie eine wichtige Stütze war. Das absolute elektromagnetische Maßsystem diente als Grundlage für die Internationalen Maßeinheiten 1881.

## Abstract

This article deals with the supersession of Wilhelm Weber's and Franz Neumann's older theory of electrodynamics by Maxwell's theory in the last third of the 19th century. Starting-point and basis for the presentation are the few quotations that can be found in Weber's works. The discussion was mainly performed by Carl von Neumann und Johann Karl Friedrich Zöllner. Both were engaged supporters and advocates of Weber's view of electricity. Points of controversy were: (1) The theory of close-range effects, which is identical to Maxwell's concept of field and which stood in contrast to the distant range theory (protoype: Newton's gravitational law), and (2) the assumption of the existence of an electrical substance. Weber persisted right to the end in his concept and developed an atomic model that can be regarded as an initial stage of the Rutherford-Bohr atomic model. Consensus existed in the absolute electrical measurement systems. J. Cl. Maxwell inferred the velocity of light from the Kohlrausch-Weber-experiment. Weber's absolute electro-magnetic system served as a basis for the international units of measure in 1881.

# 1 Introduction

Two of the leading figures of XIXth century electrodynamics were James Clerk Maxwell (1831–1879) and Wilhelm Eduard Weber (1804–1891), 27 years older than Maxwell (for a portrait of Wilhelm Weber see page 8). It is well known that Maxwell quoted in his papers on electromagnetism of 1855, 1864 and 1868 the works of Weber, see [1], [2], [3] and [4]. In Maxwell's *Treatise on Electricity and Magnetism* (1873), which introduced to Continental Europe a new epoch of research into electricity, Wilhelm Weber, next to Michael Faraday and William Thomson (Lord Kelvin), is most frequently quoted, [5]. What is almost unknown is that Weber also quoted Maxwell a few times in his works. Wilhelm Weber had already formulated a fullfledged theory of electrodynamics, which was acknowledged on the Continent until the 1870's as one of the leading ones, together with the studies of Franz Neumann. It dealt with the already well-known phenomena of magnetism and diamagnetism using as support the hypotheses of electrical molecular currents, Coulomb's law of electrostatics, Ampère's study of attraction and repulsion of two electrical currents, and Faraday's work on induction. The central point of Weber's theory was the basic law of electrical action, which he propounded in 1846, [6]. In Weber's writings Maxwell's name appears only six times. We give these instances below, and relate them to their historical context. This is the topic of this work, resulting from a systematic perusal of his papers. All of these citations are in the fourth volume (1894) of Weber's collected works, a set of 6 volumes published during 1892 and 1894, [7]. It should be observed that there are no index of names nor subject index in these volumes.

# 2 First and Second Quotations

The first quotation appears in a paper of 1871: "Electrodynamic measurements relating specially to the principle of the conservation of energy", [7, Vol. 4, pp. 247–299, see esp. p. 261]. This paper has already been translated into English, [8, see esp. p. 13]. It is only an indirect citation, as he is quoting Tait's work and it is Tait that cites Maxwell's name. In this work Weber shows the compatibility of his fundamental law of electricity describing the interaction between charged particles with the principle of conservation of energy. At the end of Section 6 Maxwell's name appears in a footnote:

> In Professor Tait's very instructive work, 'A Sketch of Thermodynamics' (Edinburgh, 1868), the following passage occurs at page 76, in reference to the investigations of Riemann and Lorenz which appeared in Poggendorff's *Annalen* for 1867 [Phil. Mag. S. 4, vol. xxxiv, pp. 368 and 287]: – "But the investigations of these authors are entirely based on Weber's inadmissible theory of the forces exerted on each other by *moving electric particles*, for which the conservation of energy is not true, while Maxwell's result is in perfect consistence with that great principle." This assertion of Professor Tait's seems to be in contradiction with the above. At page 56 of the same work Mr. Tait mentions that Helmholtz has based the doctrine of energy on Newton's principle and on the following postulate: – "Matter consists of ultimate particles which exert upon each other forces whose directions are those of the lines joining each pair of particles, and whose magnitudes depend solely on the distances between the particles." The contradiction between the fundamental law of electricity and *this postulate* is evident; but the contradiction between it and the *principle of the conservation of energy* is by no means evident, – a distinction which Professor Tait seems to have overlooked.

Closely relevant is the second quotation, which appears in a paper of 1878, the seventh paper in the famous series of *Electrodynamic Measurements*, [9], see esp. p. 363 of Vol. 4 of Weber's *Werke*. This quotation deals with the same topic and appears in the first paragraph of this paper, our translation:

> Helmholtz maintained, and William Thomson, Tait and others agreed with him, that the general fundamental law of electrical action presented in the year 1846 in the Electrodynamic Measurements[1], to which was added in Poggendorff's Annalen 1848, Vol. 73, p. 229,[2] the derived *potential* of the electric force, was in contradiction with principle of the conservation of energy; however C. Neumann and Maxwell demonstrated the opposite, proving that an error was made in the presentation of the theorem by Helmholtz, that the principle of the conservation of energy is valid only for forces which depend *solely* on the distance.[3]

The start of the controversy between Wilhelm Weber and Hermann von Helmholtz (1821–1894) dates back to 1847. In his famous youthful study *On the conservation of force* Helmholtz maintained, when considering central forces, that the law propounded by Weber was at variance with the principle of the conservation of energy, [11], with English translation in [12]. The reason was that in Weber's force, beyond the $1/r^2$ Coulombian term, there were terms depending on the relative velocity and acceleration between the interacting electrical charges (or rather electrical particles)[4]. Weber had specified in 1848 a term for the potential of electrical energy, [16], with English translation in [10].[5] Hermann von Helmholtz continued to argue about this problem in several treatises from 1870-1875, trying to establish a distinction between the hitherto concurring electrical theories, essentially those of Weber and Maxwell, [17, see esp. pp. 545, 636 and 647] and [18, pp. 874–889]. Helmholtz tried to prove that two electrical particles, moving according to Weber's law, can attain an infinitely high speed, which would contradict the principle of energy conservation. The so-called "critical distance" (Weber's "molecular size, or dimension") plays the decisive role in this matter. Weber defended his position with his study of 1871, [19] with English translation in [8].

Peter Guthrie Tait now embraced in his "Sketch of Thermodynamics" (1868) the already obsolete point of view of Helmholtz of 1847, [20]. Also in the work "Treatise on Natural Philosophy" (1867) by W. Thomson and P. G. Tait this criticism of Weber's law was repeated, [21]. H. Helmholtz and G. Wertheim were responsible for the German translation published in two parts (1871 and 1874), [22] and [23]. Weber's law was described here as interesting and elegant, but also as a dangerous speculation (§385). Helmholtz wrote a preface to the translation. A close friend of Wilhelm Weber, Johann Karl Friedrich Zöllner

[1] See publication for the establishment of the Royal Saxonian Society of Science. Leipzig 1846. [Wilhelm Weber's Werke, Vol. III, p. 25, [7, Vol. 3, pp. 25-214].]

[2] [Wilhelm Weber's Werke, Vol. III, p. 245, [7, Vol. 3, pp. 215-254, see esp. p. 245] with English translation in [10, see especially p. 520].]

[3] See also Ad. Mayer: "Ueber den allgemeinsten Ausdruck der inneren Potentialkräfte eines Systems bewegter materieller Punkte, welches sich aus dem Princip der Gleichheit von Wirkung und Gegenwirkung ergiebt". Mathematische Annalen, Vol. 13, p. 20.

[4] Weber's force acting between the electrical charges $e$ and $e'$ separated by a distance $r$ is along the straight line connecting them and is given by $(ee'/r^2)(1 - \dot{r}^2/c_W^2 + 2r\ddot{r}/c_W^2)$. Here $\dot{r} = dr/dt$, $\ddot{r} = d^2r/dt^2$ and $c_W$ is Weber's constant. In 1855-1856 Weber and Kohlrausch found experimentally its value, $c_W = 4.39450 \times 10^{11} mm/s$, that is, essentially $\sqrt{2}$ times the light velocity in air, [13], [14] and [15].

[5] Weber's potential energy is given by $(ee'/r)(1 - \dot{r}^2/c_W^2)$.

(1834–1882), saw these claims as frivolous and irresponsible. In the introduction to his book "On the Nature of Comets" (Leipzig 1872), [24], he reproached Helmholtz for not having taken enough care to reach a more just evaluation of the ideas of a German scholar of such great merit as Wilhelm Weber. Maxwell, in his opposition to the earlier theories of electrodynamics, showed greater respect for the contributions of his predecessors, especially those of Wilhelm Weber.

The close rivalry between Weber and Helmholtz had other causes, however. The so-called "organic physicists", from the school of the physiologist Johannes Müller in Berlin, were: Ernst Wilhelm Ritter von Brücke (1819–1892), Emil Du Bois-Reymond (1818–1896), Hermann von Helmholtz, and, joining them, but not considering himself a student of Müller, Carl Ludwig (1816–1895). These men made it their task to establish physiology on a scientific basis of chemistry and physics. The pioneers in this project had indeed been the three brothers Weber: Ernst Heinrich (1795–1878), physiologist, Wilhelm Eduard, physicist, and Eduard Friedrich (1806–1871), physiologist. Wilhelm Weber, in particular, supported his two brothers in electrophysiology and in researching human walking activity, contributing precise methods of measurement and mathematical recording, [25] and [26, pp. 38–45]. Although the organic physicists built on the work done by E. H. and E. F. Weber, a certain spirit of rivalry developed. They believed that their work had not achieved the recognition it deserved. Emil DuBois-Reymond felt even that his work was actively suppressed. In a letter of 1849 to C. Ludwig he vented his feelings about it, expressing even a degree of hatred against the Weber brothers, [27, pp. 49–53]. Ludwig, who in 1865 became Ernst Heinrich Weber's successor at Leipzig, defended the Weber brothers in his letters. Ludwig saw in E. H. Weber the one researcher who had exercised the greatest influence upon his thinking, [28, p. 6]. The renown of the Weber brothers paled somewhat unjustly in face of the organic physicists, celebrated founders of modern physiology, and their contributions are for the most part undervalued in the historical accounts, [29] and [30].

After his book on comets, Zöllner wrote several more articles in defence of Weber's viewpoints, intending also to reply in part to attacks made upon himself. The tone became sharper and more polemic, and took on, moreover, a nationalistic flavour. These were the years after the Franco-Prussian War, and the founding of the German Reich by Bismarck. Zöllner was a supporter of spiritualism, which came from England (séances with a medium, table-shaking, ghostly rapping noises etc.) and he had been deceived by a trickster. His opponents made rich use of this to defame his personal reputation. Zöllner's attacks were directed in particular against P. G. Tait, W. Thomson, E. Du Bois-Reymond and John Tyndall, and he even fell out with his old friend C. Ludwig. Thus Zöllner damaged himself. His work towards the development of lens-photography and the founding of astrophysics was thereby doomed to remain largely unknown to posterity, [31] and [32, pp. 194-205]. The cause of Wilhelm Weber was similarly not well served by all this.

Let us now look at Zöllner's work "Ueber Wirkungen in die Ferne" – only the relevant scientific part, [33]. It is to some extent a reply to Maxwell's dissertation "On action at a distance" (1873), [34] (see also the last Chapter of Maxwell's *Treatise*, [5]). In Zöllner's work it is featured the exchange of viewpoints – the for and against of Weber's electrodynamics and Maxwell's electromagnetic field theory. In Weber's writings one can find only a few references to what was then a most highly topical argument. Weber was shy about such disputes. Zöllner, however, was different. We can say he represented Weber, and was clearly master of the English language, having a good acquaintance also with the English publications relevant to this subject. Perhaps he may well have sometimes overshot his intended target. Of Wilhelm Weber we know that he had a good command of French, and

Fig. 1:
Johann Karl Friedrich Zöllner (1843–1882)
Deutsches Museum München, BN 25077.

wrote letters in French. Letters by him in English are not known to us. He must however had a certain knowledge of English, for in 1838 he went on a fairly long journey through England, and met a number of scientists. In his article, Zöllner reproduced Maxwell's work largerly in German. In order to defend his theory of action by contact (field theory), Maxwell offered in his address the thesis that Newton, while describing gravitation as subject to a law of action at a distance, yet had in mind action by contact, a transfer of force from one element of volume (particle) to the next. Zöllner maintained, however, in contrast, that the law of gravitation had been for Newton an absolute and fundamental law, not capable of further elucidation, and in this he echoed most of the 19th century physicists. Both Maxwell and Zöllner reinforced their viewpoints with quotations from Newton, and Zöllner also cited Immanuel Kant as chief witness. The problem is still being discussed today in the literature of historical physics. For Zöllner the views of Maxwell and also W. Thomson represent a step-back of more than two centuries, which earns them the nickname of "modern Cartesians".

For Maxwell, Faraday is the initiator of a concept of continuum. Zöllner, in contrast, seeks to claim that Faraday stood for an atomistic concept of electricity. In our opinion, and indeed that of most historians of physics, Faraday rejected the existence of a substantial electrical charge, and also the existence of atoms and molecules with mass. For him there were only force-fields, possibly bound to insubstantial nuclei, [35]. Maxwell also writes in his *Treatise* on the subject of electrolysis: "The electrification of a molecule, however, though easily spoken of, is not so easily conceived", [5, §260, p. 380]. The crucial point of Weber's concept is, in contrast, the genuine existence of two kinds of electrical atoms, one positive charge and the other negative charge. His concept was later on confirmed by H. A. Lorentz's theory of electrons.

When Maxwell began his study of electrical phenomena, he at first immersed himself completely in Faraday's reasonings. Finally, however, when writing his treatise "On physical lines of force" (1861), [2], he occupied himself more intensively with Weber's writings. He adopted the result of a measurement of the relationship between the absolute electrostatic and the absolute electromagnetic charge, as determined by Rudolf Kohlrausch and Wilhelm Weber. This was in fact the speed of light, and it was one of the main points helping towards the creation of the theory of the electromagnetic nature of light (1864), [3] and [36]. In the introduction to his treatise "A dynamical theory of the electromagnetic field", at the end of which he develops his electrodynamic theory of light, and also considers the (in his opinion) admirable writings of Wilhelm Weber, he only declines to accept the idea of action at a distance forces. In a postcard of 1871 addressed to Tait, Maxwell now speaks directly, saying that Weber's law is fully in accord with the theory of energy conservation, [37, pp. 96-97].

That Helmholtz, William Thomson and Tait were wrong in supposing that Weber's force was incompatible with the conservation of energy was shown not only by Weber in his paper of 1871, but also by Maxwell himself in the last chapter of the *Treatise*, [5, Vol. 2, Chapt. 23], [38, Chapt. 3] and [39, Chapt. 11]. Helmholtz in 1847 had considered central forces which depend on position and velocity, showing that they were incompatible with the principle of the conservation of energy. Weber's force law, on the other hand, depends not only on the distance between the charges and their relative velocity, but also on their relative acceleration. This more general case had not been considered by Helmholtz.

## 3 Third and Fifth Quotations

The same subject-areas are treated in the third (two citations in the same page) and fifth quotations, so that they should be discussed together. The third quotation comes from his work of 1878, [9] and esp. p. 395 of Vol. 4 of Weber's *Werke*. In Section 8 of this paper Weber is discussing the application to luminiferous ether and to gases of the theory of reflexion and scattering of electric rays according to his theory and also the works of Krönig and Clausius. A discussion of the works of Krönig and Clausius can be found in [40, Vol. 1, pp. 193-8], while comments about Weber's discussion about reflexion and scattering of particles can be found in [40, Vol. 2, pp. 77–79]. The third quotation runs as follows, our translation:

> It is possible to transcribe the laws found in the previous Section for the reflexion and scattering of rays composed of electric particles of the same kind also to rays of ponderable molecules, according to Mosotti's conception composed molecules. And when these ponderable molecules are now gas molecules, then a state of aggregation of the gas will be built by this means, which corresponds entirely to the state of aggregation according to Krönig-Clausius's theory of gases, without being necessary to ascribe to these ponderable molecules a special form and elasticity according to Krönig, or a repulsive force inversely proportional to a higher power of the distance according to Clausius and Maxwell in particular.
>
> When there is a place, for example the space, where there are no ponderable molecules, it is evident the possibility, that the particles of one of the both component parts of these ponderable molecules, that is, either the positive or the negative electric particles, which are in this place, that would form in projectile motion likewise a body of special state of aggregation, now however, as it is composed only of electric particles of the same kind, should not be described as ponderable bodies, but as imponderable *ether*, for which it would be valid the laws of motion developed equally by Maxwell (Phil. Transact. 1867) for *dynamic media*, namely, the laws for the propagation of waves agreeing with the laws for the propagation of light waves. Such conception of a place filled with a medium, composed of mutually repelling particles, appears to be possible without rigid borders only with the assumption of an extension unbounded to infinity, nevertheless it seems possible a limitation of such a medium in a finite place without a rigid border according to Mosotti, if this medium surrounds one of Mosotti's ponderable bodies, which would attract this medium and it would be held by this means.

The fifth quotation is from the handwritten papers remaining after Weber's death, which were published at the end of Vol. 4 of his Collected Papers (1894). It is in the eighth and last work on the series of Electrodynamic Measurements, "Electrodynamic measurements, particularly in respect to the connection of the fundamental laws of electricity with the law of gravitation", [7, Vol. 4, pp. 479–525, see esp. p. 484]. In the second Section of this paper Weber is discussing the derivation of the gravitational law based on his fundamental law of electrical action, following to the work of Zöllner. Weber is then able to derive a law analogous to Newton's law of universal gravitation valid for all distances $r$ such that $r \gg \rho$, where $\rho$ is a typical distance appearing in his theory, characterized by Weber as a molecular distance. Only for distances of the order of $\rho$ there would be deviations from Newton's law. The quotation of Maxwell runs as follows, our translation:

> These molecular distances for ponderable gas molecules come especially into

question according to the dynamical theory of gases. Maxwell (On the Dynamical Theory of Gases, Philos. Transact. Vol. 157, Part. I, pp. 49) found already, that to explain the behaviour of gases according to this theory it is necessary to suppose a law for the reflexion and scattering of the gas molecules which are in projectile motion when they collide (which cannot be accounted for based on Newton's law of gravitation) especially for the purpose of this explanation, which can be accounted by a force of repulsion proportional to the 5th power of the distance between the molecules, supposition that however otherwise in no way would be justifiable. - Every arbitrary supposition like this will be totally eliminated, if all ponderable molecules, consequently also all gas molecules, are combinations of equal amounts of positive and negative electricities, as for these molecules the law of gravitation is valid only for great distances, for molecular distances on the other hand, arises similarly the law for the reflexion and scattering, as the theory developed by us for the collision of two electric molecules of the same kind which are in projectile motion, according to the 7th publication of the Electrodynamic Measurements, Art. 7. [6]

In the treatise of the third quotation Wilhelm Weber took issue with renewed objections by Helmholtz to his basic law of electricity, drawing support from arguments expressed by Carl Neumann. In addition to other matters, Weber wanted to say something about the structure of the luminiferous ether. It was supposed to consist only of one kind of basic electrical particle, moving about much like gas-molecules, and repelling one another because of their equal electrical charge (the same polarity – positive or negative – and the same magnitude), without touching one another directly. These particles are not subject to the law of gravitation; they are imponderable, even though they possess a very small inertial mass. According to the conceptions of Zöllner a ponderable particle will consist of an equal number of positive and negative basic electrical particles (the simplest electrical atoms). A positive basic electrical particle has an equal and opposite charge to a negative basic electrical particle, but the mass of one charge may differ from that of the other. Which of the two kinds of particle has the greater mass is left open by Weber. For particles in the ether the same laws of movement as were developed by Maxwell in his treatise "On the dynamical theory of gases" (1867) should apply, [41]. Weber considered the ether to be a dynamic medium occupying an infinitely large space, in which light-waves could also transmit themselves. Concerning the mechanism of repulsion amongst the particles, however, Weber had a different opinion from that of Maxwell.

In his work on the conservation of energy of 1871, [19] and [8], Weber had examined the laws of movement of two basic electrical particles subject only to their mutual interaction. These "molecular movements", according to Weber, resist all experimental examination. Because of this, any considerations and reckonings can be regarded only as tentative. Wilhelm Weber considered this movement of two particles both in the direction of the straight line between them and in the direction orthogonal to it, see [7, Vol. 4, p. 268 and following] and [8, p. 119 and following]. The size $\rho$, which Weber called a "molecular dimension" and Helmholtz the "critical distance", is here the decisive influence. The formula for this is:

$$\rho = 2\left(\frac{1}{\varepsilon} + \frac{1}{\varepsilon'}\right)\frac{ee'}{c_W^2} \ .$$

[6][Wilhelm Weber's Werke, Vol. IV, p. 389], [7, Vol. 4, pp. 361–412, see esp. pp. 389–394].

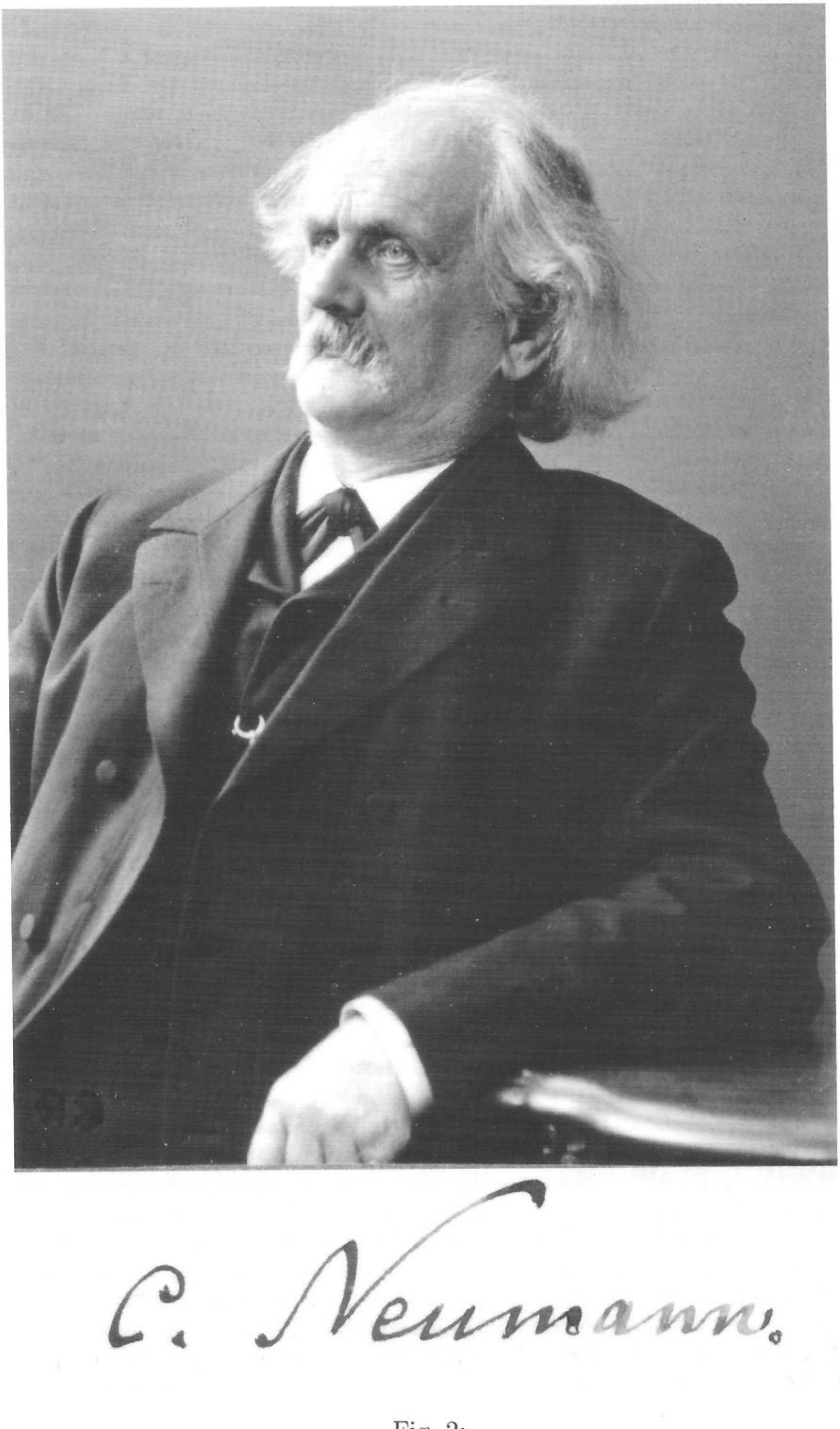


Fig. 2:
Carl Neumann (1832–1925)
Deutsches Museum München, BN 14785.

In this, $e$ and $e'$ are the charges, $\varepsilon$ and $\varepsilon'$ the associated inertial masses and $c_W$ the Weber constant. The absolute value of $\rho$ is very small, nevertheless a finite value. By means of $\rho$ "molecular movements" and "long-range movements" are distinguished from one another. Over distances larger than $\rho$ long-range movements occur; over distances shorter than $\rho$ molecular movements take place. From Weber's law there follows what seems to be a curious fact, namely, that two electrical particles of the same sign by no means always repel one another, but will even attract each other when at distances closer than $\rho$. We shall return to this when we deal with Weber's visionary thoughts on the structure of chemical atoms and molecules, [42, pp. 211-220] and [26, p. 169].

The particles of the ether, according to Weber, realize only long range motions; they can approach one another only until a distance that is close to $\rho$ because the value of the repulsion at $\rho$ would grow to infinity. Weber also leaves the question open, as to whether ether particles are simple basic electrical particles, or molecules comprising several identical basic particles closely enclosed in the molecular distance, [7, Vol. 4, p. 383].

To treat mathematically the repulsion of ether particles in projectile motion, Weber introduced the term "electric rays", and he pointed out that when such a "ray" collided with a single particle, reflection and scattering would occur. When examining the principles of motion of electrical particles carrying charges of opposite polarity, Weber found that here a rotational motion of particles around one another can also occur. Thus he can actually explain the existence of Ampère's molecular currents. Such molecular currents may generate to some extent magnetic dipoles, which impart magnetic properties to substances, [7, Vol. 4, p. 281] and [8, p. 132]. The participation of a particle in the motion depends on its mass. When the mass of a particle is so large that the mass of another particle in comparison to it is extremely small, then the first particle remains motionless. One can picture such a particle when a basic electrical particle merges with a molecule of ponderable mass. This second particle then moves in a circle around the first. With this realisation Weber had transformed Ampère's molecular current into a planet-like formation. With Ampère one must still imagine a single molecular current as a double current moving in two circular rings around the ponderable nucleus. Weber now merges the first ring with the ponderable atom or molecule, and the second ring he confines to a single particle. In a graphical representation, the ring around the planet Saturn becomes a moon. Thus a formation similar to Bohr's model of the hydrogen atom was now evident. Already in 1862, in his treatise about galvanometry, [43], Weber had expressed in conclusion the thought that such encircling particles, moving in an adjacent stratum of the ether, will give rise to light waves, and could generate frequencies matching the rotations of the particles, [7, Vol. 4, pp. 95-96].

To be precise, these ideas of Weber reach back to 1846, when he took issue with Faraday's concept that the ether was a mediating medium and also indeed with Faraday's discovery of 1845 of the magnetic rotation of the plane of polarization of light, [6, pp. 213–214 of Weber's *Werke*]. One should not feel surprised that Wilhelm Weber concerned himself in the 1870's with problems of the ether, even though his basic thinking concerned action at a distance forces. Consider the trend of research in physics at that time. A great expectation was placed on a mechanical ether, which would be the key to understanding most, perhaps even all, physical phenomena. Ideas such as the imponderable, and special fluids such as the light-stuff, heat-substance and the magnetic fluids were all thrown aside. There only remained the electrical fluids, regarded, however, by many physicists as superfluous hypotheses. Even the idea of ponderable atoms and molecules was interpreted by William Thomson as molecular vortices. In the 1860's Maxwell had created with his electromagnetic theory of light the picture of an elastic ether in which, however, even the small-sized ether particles rotated. W. G. Hankel wanted to transfer the electrical phenomena to the ether, and Erik Edlund developed in 1872 an ether theory of electricity. In contrast to all this, Wilhelm Weber stood firm on the acceptance of two kinds of electrical entities with atomic structure, and all chemical atoms and molecules were to be based on these (for references about the ether theory of electricity, see [18, p. 921]).

J. K. F. Zöllner had stated in his "Principles of an electrodynamic theory of matter" (Leipzig, 1876), [44], that all ponderable particles were based solely on the two kinds of basic electrical particles already described. One year later he wrote a treatise about the derivation of Newton's gravitational law from the static action of electricity, [45]. Already in 1876 he had the idea that gravitation might be due to electrical forces. Thereafter, however, he had to admit that the Italian astronomer, Ottaviano Fabrizio Mosotti (1791–1863) had previously had the same idea in mind, [45, pp. 424 and 429], [46] and [47]. Wilhelm Weber refer to this in the third quotation we had commented on, when dealing with the forces of repulsion between gas particles. These forces arise when the (neutral) gas particles in their projectile motion draw near to molecular distances.

Zöllner considered two simple ponderable molecules which are formed from the basic electrical particles, respectively $+e_1$ and $-e_1$, and $+e_2$ and $-e_2$. According to Coulomb's law, there are the repulsive forces $(+e_1)(+e_2)$ and $(-e_1)(-e_2)$, and the forces of attraction $(+e_1)(-e_2)$ and $(-e_1)(+e_2)$. Previously it had been accepted that the repulsive force between two equal basic particles is equal to the force of attraction between oppositely charged basic particles. Zöllner now maintained that there was a tiny difference between these forces: the force of attraction was very slightly greater than the force of repulsion. The difference is so small that it cannot be detected experimentally. In this difference, however, Zöllner saw the source of gravitation between the two ponderable particles. Gravitation, then, is a resultant – a residue of electrostatic forces. As the basic electrical particles also possess a mechanically inertial mass, this residual force is also proportional to the product of the masses, and inversely proportional to the square of the distance between the two ponderable molecules, as Newton's law of gravitation requires. One should note accordingly that inertial and gravitational masses are proportional to one another.

Wilhelm Weber already states, in the third quotation that when two such ponderable particles are in projectile motion – moving like gas particles – and approach one another, a repulsive force arises. This is shown in mathematical terms in the treatise from which the fifth quotation is taken. This treatise is the last one in the series of "Electrodynamic measurements".

Wilhelm Weber deduces the residual force of attraction of the two simple ponderable molecules situated at a distance $r$ from one another, but must do so in accordance with his basic law of electrical action, [48, pp. 481-483]. The distance between the two basic electrical particles within the ponderable molecules is assumed to be infinitesimally small in comparison to $r$. Following Zöllner, [45], Weber assumes that all ponderable molecules are composed of an equal amount of positive and negative charges. If the elementary charges are $+e$ and $-e$, the simplest ponderable molecule would be composed of these two charges together. Weber represents the inertial mass of $+e$ by $\varepsilon$ and the inertial mass of $-e$ by $a\varepsilon$, where $a$ is an numerical coefficient (Weber does not impose that both elementary charges must have the same mass, that is, he does not impose that $a = 1$, mentioning that future research can lead to the determination of the value of their masses). He then assumes with Zöllner that the attraction between opposite charges $+e$ and $-e$ is $(1+\alpha)$ times greater than the repulsion between $+e$ and $+e$ (or between $-e$ and $-e$), where $\alpha$ is a numerical factor to be determined by this derivation of the gravitational force from pure electromagnetic force. Utilizing these two suppositions he calculates the electromagnetic force between two ponderable molecules, that is, the sum of two attractions and two repulsions between the charges $+e$ and $-e$ of one molecule, and the charges $+e$ and $-e$ of the other molecule. The net result (assuming his fundamental law to be at work here) is given by, [48, p. 483]:

$$-2\alpha\frac{ee}{r^2}\left(1-\frac{1}{c_W^2}\left(\frac{dr}{dt}\right)^2+\frac{2r}{c_W^2}\frac{d^2r}{dt^2}\right) .$$

This would be the equivalent to a gravitational attraction between the molecules, derived only from electromagnetic forces. When the ponderable particles come into very close proximity, repulsive forces arise, which can be formally estimated in accordance with the laws already developed for the two basic particles, [7, Vol. 4, pp. 385 and 389], giving the resultant value $\rho$ for the molecular size. The formula previously given for $\rho$ had simply to be modified in order to obtain these molecular distances, which we will call $\rho^*$. We need only to multiply $\rho$ by the factor $2\alpha$ and substitute to $\varepsilon'$ the value $a\varepsilon$[7]

This force of repulsion, arising from Zöllner's law of gravitation and by Weber's law, made, according to Wilhelm Weber, the acceptance of a particular repulsive force between gas molecules superfluous. August Karl Krönig (1822–1871), in his basic kinetic theory of gases, had treated gas-atoms as solid, completely elastic spheres. So also did Rudolf Clausius, who continued Krönig's work. In 1860 Maxwell turned to this area of study. His efforts finally helped to establish the kinetic (or dynamic) theory of gases. In his treatise of 1866 (published in 1867), referred to by Wilhelm Weber, and entitled "On the dynamical theory of gases", [41], he supposed a repulsive force between gas molecules inversely proportional to the fifth power of the distance between them, see also [49, p. 569].

In reviewing the developments and results mentioned already, we have limited ourselves to the case of the simplest ponderable molecule. Gas-molecules are for the most part more complex in construction - according to Zöllner they consist of $+ne$ and $-ne$ basic electrical particles, $n$ being the number of charges of one sign. The previous thoughts about gravitation and repulsive forces over molecular distances can apply without complication to molecules of this kind. Weber indicates this towards the end of the fifth extract.

Mentioning $ne$ is not all that can be said about the structure of the ponderable molecule – about chemical atoms and molecules in general. In Weber's opinion, the structure of such a molecule is indeed much more complex. Let us now briefly summarize his visionary thoughts on the inner structure of ponderable molecules. They are to be found in [48], published in his posthumous works in 1894.

In the ponderable molecule with $+ne$ and $-ne$ basic electrical particles, the basic particles are always separated from one another, and occupy a certain space through their rotations and vibrations. The hydrogen atom with $n = 1$ is for Weber the most simply constructed atom. He gave it the symbol $\left[\begin{array}{c}+1\\-1\end{array}\right]$. The two particles rotate around one another.

Basic particles of one sign can be enclosed within the close confines of a sphere with diameter $\rho$. The original repulsive force is here changed to a force of attraction. The particles execute a vibrational motion against one another. In this instance Weber talks of an inseparable group of particles, forming a world of their own. Such groups can consist of positive and negative basic particles. Rotational motion can occur between individual positive and negative single particles, or between groups of particles. According to the

[7]For the basic electrical particles: $\rho = 2\frac{\varepsilon+\varepsilon'}{\varepsilon\varepsilon'}\frac{ee'}{c_W^2}$. For ponderable particles: $2\alpha\rho^* = 2\frac{(1+a)\varepsilon}{a\varepsilon\varepsilon}\frac{ee'}{c_W^2}$; or $\rho^* = \frac{1}{\alpha}\frac{(1+a)\varepsilon}{a\varepsilon\varepsilon}\frac{ee'}{c_W^2}$.

Fig. 3:
James Clerk Maxwell (1831–1879)

Campbell, L. and W. Garnett: The Life of J. Cl. Maxwell with selections from his correspondence and occational writings. New edition. London 1884.

number $n$ there will be several possible ways of constructing a ponderable molecule. As the number $n$ increases, so also will the number of possible ways increase: For $n = 2$, there are four possibilities, namely:

$$\begin{bmatrix} -2 \\ +1 \\ +1 \end{bmatrix}, \begin{bmatrix} -2 \\ +2 \end{bmatrix}, \begin{bmatrix} +2 \\ -1 \\ -1 \end{bmatrix}, \begin{bmatrix} +1 \\ +1 \\ -1 \\ -1 \end{bmatrix}.$$

For greater $n$ let us select just one of the many possibilities, namely, with the $n$ positive unities together and $n$ separate negative unities:

$$\begin{bmatrix} +n \\ -1 \\ . \\ . \\ . \\ -1 \end{bmatrix}.$$

Here one is reminded of the atomic model of Bohr and Sommerfeld. If we ascribe a very large inertial mass to a positive basic particle, $+ne$, we have then the atomic nucleus. The $n$ negative particles $-e$ with their very much smaller mass now rotates round the heavy nucleus. A particle such as the neutron was not known to Weber.

## 4 Fourth Quotation

The fourth quotation appears in a joint paper by W. Weber and F. Zöllner, [7, Vol. 4, pp. 420–476]. It was published in 1880 and is the last paper published by Weber during his life. The motivation to cooperate was to establish a practical value for the absolute unit of resistance, the Ohm. They discuss the absolute system for magnetic and electromagnetic unities introduced by Gauss and Weber, concentrating on the absolute unit for electrical resistance. Weber had presented four different practical methods for reducing the unit of resistance to absolute measures. Due to the practical and scientific importance of this topic, the British Association for the Advancement of Science (BAAS) created in 1862 a Committee coordinated by William Thomson to deliberate about it. To produce a standard resistance determined in absolute measure they chose in essence Weber's fourth method. Their task was to establish a standard value for resistance which would have a practical application. They decided in favour of Weber's electromagnetic system. The Commission was mentioned in a footnote by Weber, being Maxwell one of its members, [7, Vol. 4, pp. 420–476, see esp. p. 426], our translation:

> About the members of the Committee reported the *Report*, p. 111, literally: "The Committee consists of - Professor Wheatstone, Professor Williamson, Mr. C. F. Varley, Professor Thomson, Mr. Balfour Stewart, Mr. C. W. Siemens, Dr. A. Matthiessen, Professor Maxwell, Professor Miller, Dr. Joule, Mr. Fleeming Jenkin, Dr. Esselbach, Sir C. Bright."

A general discussion of the formation and results obtained by this Committe on electrical standards can be found in [50, pp. 687–698]. Some information about the members of this Committee: Charles Wheatstone (1802–1875), for a short time professor of experimental physics at King's College in London, was a distinguished inventor of apparatus and measuring instruments for accoustics, optics and electricity. He constructed several instruments for telegraphy and was an early advocate for the installment of submarine cables. Alexander Williams Williamson (1824–1904), professor of chemistry at the University College in London, worked in the area of electrolysis, about diamagnetism and its meaning. Cromwell Fleetwood Varley (1828–1883), ingenious English electrician. Simultaneously with W. von Siemens he discovered the self-regulation of a dynamical machine.

William Thomson (Lord Kelvin), (1824–1907), famous British scientist which developed fundamental works in the areas of electromagnetism and thermodynamics. Excellent biographical works with many relevant references can be found in [51] and [50]. Balfour Stewart (1828–1887), teacher at the Scottish Owens College, conducted relevant preparatory work for the Kirchhoff's law of absorption and emission of spectral lines, dealt with all natural phenomena from the point of view of the energy principle and was the first to recognize the connection between the solar radiation and the variations in the terrestrial magnetism. Carl Wilhelm (William) Siemens (1823–1883), physicist, engineer and brother of Werner von Siemens, directed the London branch of the company Siemens & Halske. W. von Siemens suggested in 1860 pure mercury as a standard measure of resistance. Augustus Matthiessen (1831–1870), professor of chemistry at St. Mary's Hospital in London, occupied himself especially with thermoelectricity, the conductivity of metals and their variations, and with the production of standard resistances obtained from appropriate metals and alloys. William Hallowes Miller (1801–1880), professor of mineralogy in Cambridge, introduced notations and symbols in cristallography which are utilized even today. He was a member of the international metric commission. James Prescott Joule (1818–1889), discovered the law of heat dissipation, estimated experimentally the mechanical heat equivalent and discovered together with W. Thomson the effect which carries their names, which is utilized in the liquefaction of gases. Henry Charles Fleeming Jenkin (1833–1885), professor at the University College in London. In an article of 1865, [52], he gave initially an overview about the historical development of the concept of "resistance", beginning with a work of Humphry Davy of 1821. Beyond Jacobi's etalon, he mentioned also the trials of other physicists to create a standard for resistance. With the installation of telegraphic conductors and submarine cables arose an urgent necessity to create a standard measure of resistance. With the recommendation of W. Thomson a Commission was appointed in 1861 by the British Association for the Advancement of Science, which decided for the absolute electromagnetic system of measures created by Weber. The experiments were performed by Jenkin utilizing instruments according to W. Thomson and J. C. Maxwell. Details can be found in the Reports of the Meetings of the British Association for the years 1862, 1863 and 1864. In a letter of 25th May, 1865, sent Jenkin to Wilhelm Weber a standard resistance, exhibiting 1/10 of the British's Ohm (Ohmad), [42, p. 104]. Ernst Esselbach (1832–1864), studied with W. Weber and H. von Helmholtz. He was employed by Siemens in London, lastly as "Chief Superintendent" by the installation of the telegraph to India. He died during a trip by ship. Charles Bright, gave a procedure of how we could find defects in a long conductor wire (to look for the so called "faults") and patented this method in 1852. For his connection with the Committee, see [50, pp. 668-669 and 687].

This Commission exerted an authoritative influence on the "Committee for the Selection and Nomenclature of Dynamical and Electrical Units", set up some ten years later to promote the development of electrical units, and to choose effective systems of measurement. At their "Electrical Congress" in Paris (1881), there followed the establishment of practical electrical units, based on the absolute electromagnetic system of measurement. Our modern International System of Units MKSA is derived ultimately from these units.

The Commission of the British Association adopted, however, as a basis, not only the electromagnetic system of measurement; it also chose for practical investigation a method

Fig. 4:
William Thomson (Lord Kelvin) (1804–1907)
Thompson, Silvanus: The Life of William Thomson, Baron Kelvin of Largs. 2 Vols. London 1910, Vol. 1, p. 535.

of Wilhelm Weber's, which Thomson improved. This method, or procedure, was based on the "induction inclinatorium", which Weber constructed in 1837, [53] and [18, p. 113]. It had originally been devised for measuring the inclination of the earth's magnetic field. In the apparatus used by Thomson a self-contained coil is turned at constant speed around a vertical axis by a system of gearing. As this proceeds, the horizontal intensity of terrestrial magnetism has an inductive effect. The induced current deflects a small magnet hanging centrally in the coil. Essential to the calculation of the coil's resistance is a knowledge of the horizontal intensity. In the electromagnetic system of measurement, resistance is measured in terms of speed. To interpret this, the speed of rotation of a particle in the rotating coil was taken into consideration.

The undertaking of the British Association to create definitions for the absolute Ohm and for standard resistance did not meet with complete success. In the tables of measurements, the individual values varied too large a percentage, according to Wilhelm Weber and Friedrich Kohlrausch (son of Rudolf Kohlrausch, and a pupil of Weber's, [40, Vol. 2, pp. 72–74]), [54]. Weber and Zöllner therefore took up the task again, hoping to establish, by means of another method (the first of Weber's four methods) a more exact value for standard resistance. In the following account of the procedure we touch upon the problematic nature of measuring absolute resistance.

Moritz Hermann von Jacobi (1801–1874), who developed electrotyping - he was brother to a well-known mathematician, Karl Gustav Jacobi - believed in 1846 that he had discovered a standard measurement for resistance, by producing a copper wire embedded in mastic (Jacobi's etalon). To Wilhelm Weber, however, this was not an absolute measure in the sense of Gauss' definition. The reason was that in this definition was included a special constant of the material, namely, the specific resistance of copper. Thus it became evident that an alteration in the inner structure of the wire would change its resistance. An arbitrary constant would also affect the definition of Ohm's law. Weber defined resistance as the quotient of electromotive force and current, [55], [56] and [42, pp. 91–92]. This demanded, however, that precise units of measurement be established for electromotive force and current. For the unit of electromagnetic current this had been achieved in 1841–1842 with the so-called tangent galvanometer, a device for measuring the effect of electrical current on magnetised needles, [57] and [58]. The unit for electromagnetic force was defined by Weber in 1851-1852, when he studied induction in a geomagnetic field, [55, p. 277] and [56, pp. 321 and 361–363]. Weber and Zöllner used in their project two large coils, with multiple windings of copper wire. In one coil, rotating in the terrestrial magnetic field, a surge of current is induced; in the other coil a magnet fixed in the centre is deflected from its North-South direction by the effect of the current-surge. As the horizontal component of the magnetic field vector is active both during the induction and also during the measurement of the current-surge, it is not at all necessary to include the electromotive force in the formula for calculating the resistance.

Unfortunately it emerged that in the place chosen for setting up the two coils (at the Pleissenburg in Leipzig), the temperature did not remain sufficiently constant. Thus the precise measuring that was sought could not be achieved. Gustav Wiedemann repeated the attempt ten years later, using the same apparatus, and reached a satisfactory conclusion. He improved parts of the equipment and also found a more suitable location, [59].

The creation of a more exact value for standard resistance held the attention of numerous physicists from various countries, even after the Paris Congress. New and varied methods were devised, [18, pp. 643–712].

## 5 Conclusion

While interpreting and commenting on the excerpts from Weber's writings, we have taken the opportunity to present some major points of interest in the different interpretations of electricity adopted by two great scientific researchers of the nineteenth century.
From Maxwell we have his action by contact (field theory), the finite limit to the speed of propagation of electric and magnetic effects, ideas of continuum, and the rejection of electrical substances.
From Weber the action at a distance, forces which depend also on velocity and acceleration of the interacting bodies, as well as the acceptance of two kinds of basic electrical atomic particles. Considerable parts and features of Weber's collected writings are to be found even today in the studies of electricity and its applications. To show that his points of view were not the last word in this area of knowledge, one might remember Weber's conclusion of his treatise on 1846. He writes that should new revelations follow from further study of Faraday's discovery of the influence of electric currents on the oscillations of light, then his force law which had been expressed without relation to an intervening medium (ether) might be expressed in a new form depending on this intermediary medium, [7, Vol. 4, p. 214]. And Maxwell says in the Preface of his "Treatise" that he would take the part of an advocate (presenting and defending his views and those of Faraday), instead of that of a judge. That is, he exemplified one method instead of attempting to give an impartial description of both, [5, p. xi]. These are surely the hallmarks of genuine scientific research.

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