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Volta and the Strange History of Electromagnetism

1. Introduction

To build a physical theory of both electric phenomena and magnetic phenomena constituted a very difficult subject, since for the first time experimenters met entirely new classes of phenomena; the human body does not offer any sensation by which to directly evaluate the strength of a phenomenon under scrutiny – except for strong electric discharges, which are dangerous for human life – as well as to hypothesize about the nature of the new phenomenon. Thus, theory had the task of investigating about phenomena concerning a "phantom reality"; in philosophical words, it maybe had to investigate outside of those "pink glasses" which according to Kant bound human experience.

Surely, the dominant mechanistic philosophy offered a variety of suggestions – mainly interacting fluids, action at a distance, and the parallelism between Coulomb's law and gravitational law, – which at first glance appeared not at odds with the new phenomena. Yet, Volta's inventions apparently constituted a breakthrough in the philosophy which in his time dominated the theory of electricity. As Heilbron puts it: "It appeared that once again an instrument [the electrophorus] would overthrow electrical theory".[1, ‡]

The common historical appraisals on this episode[2, 3, 4, 5] – as well as the current account on the subsequent electromagnetic theory – overtly present theoreticians as meeting great difficulties in building what later constituted the electromagnetic theory. Rosenfeld stated (p. 1633)[2] that electromagnetism represents an interesting case study owing to the "winding path of [its] history…, [which includes at least two] main turnings which opened … unexpected vistas". Moreover, "It is noteworthy that [from the electromagnetic viewpoint] the conceptual frame of

[1] This breakthrough involved new chemistry too.[6]
‡ HEILBRON (1982), p. 211
[2] ROSENFELD (1957), sect. 3.
[3] BLIN-STOYLE (1959), pp. 5-29.
[4] HESSE (1965), ch. VIII.
[5] BERKSON (1974), p. 63
[6] WILLIAMS (1965), pp. 49-50.

classical physics is essentially dualistic. In the course of time the dualism of matter and force underwent curious vicissitudes, but in spite of repeated efforts, it could never be reduced to unity. During the mechanistic period, the aim [followed by several scholars] was, naturally, to eliminate the concept of [Newtonian] force ... The failure to account for electromagnetic phenomena in mechanical terms precipitated a dialectic reversal of dilemma: the field [of forces] concept was given the pre-eminence…" (p. 1631).[2] Rosenfeld (pp. 1639-42)[2] recognised three conflicting philosophical attitudes, underlying theorirists' activities.

Let us notice that electromagnetism plays the role of the first theory dismissing the mechanistic theoretical scheme. Truly, in 1822 Fourier's theory was not conjoint to mechanics; yet, it suggested radical variations in no more than mathematical techniques, i.e. differential equations. It was S. Carnot's results that radically changed theoretical physics; yet, they were not appreciated until 1850. Hence, thermal phenomena represented a radical variation in the mechanical picture of the world not before the second half of the century.

Moreover, an inspection of the variety of accounts by historians on electromagnetic theory manifests their embarrassment in proposing adequate categories to explain the erratic path leading at last to Maxwell equations. The common historical account – i.e. the triumph of the field notion over the previous notions, as in above mentioned Rosenfeld's account – constitutes more the retrospective view by winners than homage to that Faraday who actually conceived this notion in a very different way. In short, the history of electromagnetism presents several, specific problems; moreover, in the historiography of science this case study represents a methodological problem.

Here I will attempt to sketch a comprehensive view on the history of electromagnetism, by starting from the episode of Volta's innovations. Although a Newtonian theorist, Volta began the long struggle among very different ideologies on experimental phenomena which characterises the history of electromagnetism. This struggle – though in different terms – then involved the basic notions pertaining to electricity, magnetism and their mutual relationships, in particular their mathematical languages. After recalling Volta's inventions in Sect. 2, in Section 3 I will offer a synthetic list of the objective historical facts, representing the main fundamental advances in electromagnetism. Section 4 deals with interpretations of the history of electromagnetism by means of a single notion or at most some subjective notions; I will offer a new interpretation, improving previous ones. Section 5 suggests a new determination of the end of the process of elaboration of electromagnetic theory, according to which special relativity is the final step. Section 6 presents an interpretation of the foundations of a scientific theory, as well as an interpretation of the role played by electromagnetism in the history of physics. A new notion of incommensurability follows, which gives reason why the case study of electromagnetism is a hard subject, and yet a very interesting one within the development of theoretical physics.

2. Volta's Innovations

Since the beginnings of the physical study of electricity or magnetism, it was impossible to guess the motion of mechanical particles as an explication of such phenomena. Yet, in order to interpret an entirely new field of phenomena, i.e., hydrodynamics, Euler had advanced a mechanist attitude by exploiting the mathematical notion of a fluid. In Volta's time, by means of a variety of intuitive notions of a hypothetical, imponderable fluid, theorists could explain all kinds of interactions at a distance. In particular, Volta followed the hypothesis of one electric fluid ("la nostra cara dottrina"). Although he was persuaded of an attractive, distance force of a Newtonian kind as an explication of electricity, Volta's experiments and moreover the invention of pile scientific community faced the s. c. with hard facts. By refusing to offer links with previous doctrines,[7] Volta undermined previous attempts to approach electric phenomena by means of a soft, cautious mechanist philosophy enlarging all suitable mechanist notions (force, fluids, etc.) to improve their interpretative capability. On the one hand, he greatly improved the methodology of specific, quantitative measurements on electric phenomena; on the other hand, Volta claimed to have obtained through his *elettroforo perpetuo*, since producing an *elettricità vindice indeficiente*; "an inexhaustible charge, a perpetual action or impulsion on the electric fluid".[8] His electrophorus was very impressive in his time; it puts a crucial question to the community of theoretical physicists.[9] It led to guessing that the very foundations of theoretical physics were maybe undermined.

Then, inventing the pile suggested to Volta he should reiterate a similar, astonishing claim: "This endless circulation or perpetual motion of the electric fluid may seem paradoxical, and may prove inexplicable; but it is none the less real, and we can, so to speak, touch and handle it".[10]

In fact, Volta's pile substantiated first the stationary motion of the electric fluid (or charges). That puts further problems to theoretical physics. The surprising fact was that the electric charges did not presented inertia. Moreover, the motion of electricity was not caused by any mechanical force – which, if recognised would directly introduce a physicist to the equation of motion and at last to the solution of the problem. One had to guess that electricity enjoyed a specific capability for moving its electric fluid (or elements). Indeed, Volta anticipated the notion of electric potential – and Ohm's law too.[11]

[7] GIGLI BERZOLARI (1993), p. 282.
[8] VOLTA (1918-29), I, p. 562.
[9] Even in 1824 S. CARNOT[46] echoed this polemics when founding his celebrated theorem on the impossibility of a perpetual mobile.
[10] VOLTA (1918-29), p. 576.
[11] In a previous paper I show the relevance of the double negated sentences for evidentiating the PO choice.[12] A cursorely scrutiny of their occurrencies in Volta's writings[13] shows that their

Although Volta's ideas about perpetual motion lost credit among physicists, after him electric currents suggested interpretations which were ever more at odds with the mechanical ones concerning static electric charges. After them, the theorists were aware that the theory of electricity had to investigate its phenomena in a new way.

By failing to give the correct emphasis to Volta's claims on both perpetual charge and perpetual motion, historians postponed the crisis of Newtonian paradigm in electrical theory to its most apparent event, Oersted's experiences.

3. A List of Historical Facts Concerning the Foundations of Electromagnetism

I think that the question of illustrating a chronology of the beginnings of electromagnetic theory at best by means of hard, objective historical facts deserves the attention of historians. Although at present to compile a list of the major advances in electromagnetic theory is not a matter of discussion, it is obvious neither which among the commonly considered advances played a fundamental role, nor which alternative developments have to be included. Hence, it seems relevant to offer an instance of this list by means of the following table.

Date	ELECTRICITY	MAGNETISM
1785	Coulomb's law $F=kQq/r^2$	
1799	Volta's pile	
1813	Poisson's equation for electrostatic potential: $\nabla^2 V = -4\pi\rho$	
1820	Oersted's experiment	
1820	Biot-Savart's law: $dB = i\, d\vec{l} \times \vec{r} / r^3$	
1821		Faraday's notion of lines of magnetic force
1825	Ampère's formalism for the interaction between magnetism and moving electricity	
1826	Ohm's law: $Ri = V$	
1831	Faraday's law: e.m.f. = $- d\Phi(\vec{B}) / dt$	
1832	Faraday's law on electrolytic conduction $m = MQ/Fz$:	
1834		Lenz' rule
1837	Faraday's relative dielectric constant: $\varepsilon = c/c_0$	

number is not great and moreover that VOLTA did not consistently used of them if not for supporting his idea od a perpetual motion.

[12] DRAGO (1991b).

[13] GIGLI BERZOLARI (1993), pp. 228, 229 n r. 5, r.13, r. 14, 232 n, 259 r. 5-6, r. 7-8, 259 r. 19, 272 r. 4, r. 8b, 290 r. 1.

1839	Gauss' theorem: $\Phi_S(\vec{E}) = \Sigma q_i / \varepsilon_0$	
1843	Farady's experiment on electric charge conservation: div i + dρ/dt = 0	
1845	Neumann's potential funtion V and potential vector A for electricity	Faraday's notion of a "magnetic field"
1846	Weber's force: F = [1- $(\dot{r} - 2r\ddot{r}) / 2c^2$]ee'/r^2	
1847	Helmholtz: the energy of an electric work: eV=W	
1848	Kirchoff's laws: Σi = 0 (in a knot); ΣRi = Σ e.m.f.s (in a mesh)	
1850		Thomson: div B = 0; rot H = 0
1852	Thomson: Electric field's energy ∝ ∫εE^2dv	B = μ H Magnetic field's energy ∝∫μH^2dv
1861	Introduction by Maxwell of the word "field"	
1861-2	Maxwell's four equations for the electromagnetic field: div E = ρ/ε rot E = - ∂B/∂t div B =0 rot B = μJ + (1/c^2)∂E/∂t Wave equation: ∇^2 B = (1/c^2)∂B^2/∂t^2 ; ∇^2 E = (1/c^2)∂E^2/∂t^2; Velocity of light: c = 1/√εμ	

Table 1 The foundational advancements of the electromagnetic theory.

For brevity's sake, the suggestions by Riemann and some others – although very relevant in their times – are excluded. However, the well-known textbook by Whittaker is widely descriptive of such attempts.

4. Subjective Appraisals on the History of Electromagnetism

The surprising phenomena elicited by Volta's innovations led most theoreticians to dismiss the great tradition of theoretical mechanics for rather following new explicative notions which were induced from this new field of study. Of course, not all physicists renounced the framework of mechanical theory. That gave rise to a struggle between radically different conceptions on the same field of phenomena. It received a conclusive account not before the end of the 19th Century, when Helemholtz' theory and Poincaré's theory on electromagnetic phenomena were dismissed in favour of Maxwell's.

Even the nature of this long, theoretical conflict is not recognised. Commonly, historians refer philosophical mechanicism to Newton's mechanics only, according to which a perpetual mobile is not manifestly excluded, at least through its inertia principle. They ignore that at this time several foundations have already been recognised for mechanics. Beyond Newton's mechanics, Lagrange's mechanics was apparently a new foundation, not only owing to its new formalism but also for its basic notions. However, it influenced electromagnetic theory not before Maxwell's time.

NEWTON	Cou-lomb	Oer-sted	Am-père	Fara-day	Web-er	Kelvin	Maxwell	Her-mann	L. CARNOT
Theory as a philosophy too	~	~	~	C		N			Full experiment-al theory
Organisation by axioms-principles	N			C	N	N		C	Organisati-on based upon an universal problem
Infinite and absolute space	N			C		N		C	Relative and bounded space
Absolute time	N			C		N		N-C	Before and after
Mass-point-	N	C	N-C	C	N-C	N		C	Extended corps, machines
Movement as a property of corps	N	C	N-C	C	N	N		C	Communic-ation of the motion
Inertia as perpetual motion	N				N			C	Impossibili-ty of perpetual motion
Acceleration as basic concept	N		N-C		N	N		C	Quantity of motion
Force-cause, as a synthesis of the interaction	N		N			N		C	Work and energy
Infinitesimals	N		N	C	N	N		C	Geometrical motion

F=ma	N		N	C	N	N		C	Laws of conservati-on
Differential equations	N		N	C	N	N		N-C	Principle of virtual velocities
All trajectories		C						C	Invariants of motion
Machines as applications				C	N-C	N			Object of the theory
Infinite power of machines									Chimere of infinite power, machine as versatility

Table 2 Comparison of contributions by each author with those of either Newton or l. Carnot (Legenda: N = Newtonian; C = Carnotian; N-C =dubious; ~ = indifferent; void = to be studied).

Since 1783 L. Carnot's mechanics represented a real alternative to Newton's mechanics owing to the following characteristic features.[14] As widespread opinion recognises it, this mechanics formulation originated technical physics.[15] Although its technical features, its theoretical level was not lower than Newton's. It was the first formulation whose principles are fully experimental in nature.[16] It states the impossibility of perpetual motion as its basic principle. It constituted the first complete theory of the impact of bodies. This contact interaction – rather than motion subject to continuously variable forces – is meant as the basic phenomenon for the development of the theory. The basic notion of the theory is the notion of work. Its space is a relative one. For the first time it introduced in theoretical physics a mathematical technique of symmetries.[17] It was shown that this formulation accomplished Leibniz' reform of dynamics,[18] as well as d'Alembert's program.[19]

One may show that this mechanical theory is a true alternative by means of a table illustrating how the basic notions suffer radical variations in meaning when considered either in Newton's mechanics or in L. Carnot mechanics.[20] This table suggests an easy way for improving the interpretations on the birth of electromagnetism. In Table 2 I list the basic notions suggested by each relevant scholar of electromagnetism according to two polarities; these polarities are

[14] CARNOT (1783).
[15] GILLISPIE (1971).
[16] DUGAS (1950), p. 509.
[17] DRAGO (1989).
[18] DRAGO (1994a).
[19] HANKINS (1970), pp. 174-6.
[20] DRAGO (1990).

constituted by respectively the set of basic notions of Newton's mechanics and the set of basic notions of L. Carnot's mechanics.[21] Maybe, authors stood unaware of L. Carnot's influence, yet they were motivated by the similar search for an alternative attitude to the Newtonian one.

According to Rosenfeld (p. 1641),[2] through both Oersted's and Faraday's experiences, "central forces physics was doomed to ultimate failure in the domain of electromagnetic phenomena". Moreover, the most relevant advances in suggesting the basic notions pertaining to electromagnetic theory were achieved by Faraday, whose attitude turns out to be an essentially Carnotian one, since his basic notions agree with the notions of L. Carnot's formulation. Both authors shared beyond the mathematical tool – i.e. vectorial calculus, not differential equations – the opposition to the concept of Newtonian force

Recently, the relevance of an alternative attitude – to Carnot's – for the whole development of electromagnetic theory has been furtherly emphasised by a new formulation of electromagnetic theory by Hermann and others.[22] The change suggested by these authors in the basic notions amounts to as almost the same of that between Newton's and L. Carnot's.[21]

After Faraday, a new basic attitude won. His "step-by-step action" was changed by Maxwell at "at distance, instantaneous action". Although Maxwell's work interpreted electromagnetic phenomena through wrong mechanical analogies – i.e vortices – surprisingly he was successful in achieving correct local equations. At this time Newtonian attitude appeared to prevail again. Commonly, the historiography of electromagnetism stops here, by glorifying the notion of a field.

In which way may one further improve previous accounts of the whole development of this suffered theory? In a previous paper I interpreted characteristic statements constituting Koyré's historiographic categories: "Dissolution of the finite Cosmos and geometrisation of space". Moreover, I suggested that these subjective notions constitute efficient interpretative categories for Newtonian theories, whereas the alternative theories – born around the time of French revolution – may be interpreted by means of two analogous categories: "Evanescence of force-cause and discretisation of matter".[23]

In fact, the latter ones have been closely approached by P. Williams' categories for interpreting Faraday's crucial works.[24] Moreover, the whole history of electromagnetism may be interpreted by means of a conflict between the two polarities represented by these two characteristic statements. The former emphasising an attitude – e.g. Ampère's – for progressively introducing higher mathematics in order to formalise any new knowledge on both electric or magnetic phenomena, and so to get a great extension of common experience to include even extrasensorial experiences.

[21] DRAGO and FEDELE (1993).
[22] HERMANN and SCHMIDT (1985).
[23] DRAGO (1994 b).
[24] WILLIAMS (1971), pp. 530-1.

The latter one – e.g. Faraday's – emphasising a different, common attitude to rather disregard any "fable" about pre-conceived beings – as for instance force-cause, infinitesimals, etc. – for giving reality to hard facts of the matter when conceived as constituted by the more simple entities, i.e. indivisible particles. An account following these interpretative lines – to be performed by a careful revisitation of the original texts – would improve common historical accounts, mainly because it illustrates a conflict between the constitutive notions of this case-study.

Among previous historical accounts, Rosenfeld's approaches the above suggestion. In the development of electromagnetism in 19th Century physics, he sees a dialectical movement – a notion implying an intrinsic conflict – by means of the dialectical interaction of two notions. These notions – i.e. "force" and "matter" – are the same as those I suggested previously; yet, he lacks the notion of "discretisation", which in the electromagnetic context may be considered to mean a choice for the most naive mathematics possible.

5. When the Process of Birth of Electromagnetic Theory Ended

It is debatable whether Maxwell's theory represents a victory of the mechanic paradigm or rather the birth of a separate, incompatible theory. Maxwell had worked within the framework of Newton's mechanical philosophy by embracing the notion of absolute space. Having ignored even Galileian transformations, then the aether notion seemed unavoidable. That started a long process of crisis, culminating in the final reformulation of an already "accomplished" theory. This process ended by the introduction of special relativity in the old electromagnetism. That turned up previous evaluation on the philosophical attitude of the theory, which turned out to be no more in agreement with the Newtonian paradigm.

Moreover, since Maxwell's theory solved the manifest conflict between action at a distance and the notion of a step-by-step field, it appeared to represent a definitive solution to a long conflict between opposite attitudes. Yet, this conclusion too is debatable. In a previous paper, I showed evidence that Einstein's special relativity corresponds to the above-mentioned, minoritarian tradition of L. Carnot's theoretical mechanics; in particular, the formalism of the latter theory being independent from the fifth postulate of Euclidean geometry, it may belong to hyperbolic geometry (representing the velocity space), whose group of transformations is larger than the Minkowsky group.[25] Although Newtonian mechanics resulted as incompatible (or incommensurable) with special relativity – owing to the radical variations in meanings of the notions of acceleration, force, force at distance, energy and mass; and overall, the change in the basic mathematical tool, i.e. from the differential equations to the group theory –, historical accidents favoured its relationship with Minkowsky's geometry, whose

[25] DRAGO (1999).

space is again the position space (plus time dimension), instead of velocity space – as Sommerfeld (1909) quickly suggested – which is a hyperbolic one.

All the above suggests conceiving a different path for the mathematical development of electromagnetic theory in the period after 1860, which includes the fiasco of the aether notion. Indeed, there exists a legion of spontaneous attempts for bypassing Maxwell's original derivation of his equations for rather deducing them from a reduced number of electric or magnetic laws, via the Lorenz group.[26]

In particular, a recent suggestion by Jammer and Stachel (1980)[27] is relevant. They emphasised that in Faraday's time electromagnetic theory could follow an alternative development to Maxwell's, anticipating special relativity. Indeed, in the framework of Maxwell's local equations, it is Faraday's term which suggests just Lorentz' group instead of Galilei's group, and in particular it suggests that symmetrical description of the phenomenon which Einstein puts at the starting point of his illustration of special relativity.[28]

6. Basic Choice of a Physical Theory and Incommensurability

Let us now investigate the foundations of electromagnetism. In previous studies I suggested that the foundations of a scientific theory are constituted by two options. There is the option about the kind of infinity, either potential infinity (PI) or actual infinity (AI); this option may be formalised in mathematical terms as the option between constructive mathematics and classical "rigorous" mathematics. Then, there is the option on the kind of organisation of the theory at issue, either a problem-based organisation (PO) or an entirely deductive organisation from some axiom-principles, as Aristotle theorised it (AO); this option may be formalised by means of the option between either classical logic or non-classical logic, in which the law of the double negation fails.

Since the basic choices by Newton result to be AI and AO whereas the basic choices by L. Carnot are PI and PO,[29,30,31] their respective attitudes result to be the most divergent as possible. Previously, I suggested that two theories are incommensurable when they differ in at least one basic choice.[32] Clearly, the above

[26] See, for example, KOLBE (1986) and its bibliography.
[27] JAMMER and STACHEL (1980)
[28] One may suggest that a recent formulation[11] represents at best a mathematical foundation in agreement with L. Carnot's mechanics.[25] One more formulation[34] would be considered as a possible bridge, yet it is a less direct one. Ehlers[35] offers one more bridge between classical mechanics and special relativity, yet inside an affine space, which constitutes a restriction of the hyperbolic group pertaining to L. Carnot's formulation.
[29] DRAGO (1988).
[30] DRAGO (1991a).
[31] DRAGO and MANNO (1783).
[32] DRAGO (1987).
[33.] LÉVY and LEBLOND (1976).

two attitudes represented an incommensurability phenomenon which troubled the whole development of electromagnetism. All that give an account of the twisting path represented by the development of electromagnetic theory which had to speculate upon a field of odd phenomena by means of incommensurable theories.

That gives reason for the previous table on the beginnings of electromagnetic theory. The electromagnetic theoretists could refer to intuitively expressed, basic choices, which actually have been surrogated by the new basic notions for the new theories. In particular, one may recognise that the above mentioned notion of "force" actually surrogates in subjective terms an AO; further, the notion of "matter" surrogates a PO.[36]

Their recognised relevance for theorising upon the field of both electric and magnetic phenomena – which escape from all sensations, anthropomorphism, metaphors – shows that theorists indirectly referred to the basic options, although through their respective surrogatory notions pertaining to the subjective realm. For instance, a detailed analysis of Faraday's basic choices shows that they are the same as L. Carnot's.[37] On the contrary, Ampère's choices – at least in the classical papers on his law - adhere to Newtonian ones.

The one who first achieved a mathematical, electromagnetic theory, i.e. Maxwell, shared Newton's choices. That shows that Maxwell's solution for the intrinsic conflict within electromagnetic theory was of a Newtonian nature .Yet, subsequently special relativity gave a new solution. By dismissing absolute space, it attacked the AO of Newtonian mechanics. Moreover, it introduced a PO in a sensational way, through its main problem of conciliating the two principles – of relativity and of constant *c* – or even its problem of finding the covariance of all laws of theoretical physics. Furthermore, by introducing a group as the foundation of a theory, it conformed to the typical fundative role played by this mathematical technique in PI and PO theories.[38] In sum, though ignoring the basic choices determining the conflict,[39] Einstein turned up previous choices by Maxwell.

In particular the choice of PO is equivalent to the choice of a non-classical logic,[12] evintiated by the occurrences of double negated statements in the writings of the corresponding authors. In this light, one remarks that Volta started the first of the three changes in the dominant logic during the development of electromagnetic theory. Whereas Coulomb's law introduced in certain statements about phenomena, Volta stirred up logical trouble by claiming by means of a single negated sentence – there exists a motion *without* an end – the existence of an undecidable phenomenon.

[34] DAVIDON (1975).
[35] EHLERS (1983).
[36] DRAGO (1994).
[37] DRAGO and MANCINI (1993).
[38] DRAGO (1996).
[39] Actually, EINSTEIN[40] (KLEIN,[43] MILLER,[44] DRAGO,[41] ESPOSITO[42]) closely approached a characterisation of the option about the kind or organisation of a theory.
See for instance NERSESSIAN[45] whose interpretative analysis relies upon few basic notions.

Then, Faraday focussed the attention of the theorists upon a double negated sentence – it is *impossible* that electricity is *not* magnetism, and viceversa – which pertains to non-classical logic. Maxwell then came back to classical logic, although impossible vortices. At last, Einstein[40] introduced anew double negated sentences – "only *apparently* the two principles are *irreconciliable*" – for founding his theory.[41,42]

All that gives further evidence of the twisted path followed by the development of electromagnetism, which more than the development of whatever classical theory approaches closely the subsequent tortuous development of quantum mechanics.

40 EINSTEIN (1905).
41 DRAGO (1995).
42 ESPOSITO (1997).
43 KLEIN (1967).
44 MILLER (1981), pp. 123-41.
45 NERSESSIAN (1984).
46 CARNOT (1824), p. 21

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