Beyond Electromagnetic and Mechanical World-views: J. Larmor's Models of Matter and Energy in the Early 1890s

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Abstract. In the last decades of the nineteenth century, the relationship between matter and energy was widely debated, mainly in the context of electromagnetic theories. In the 1880s and early in the 1890s, Larmor swung between Helmholtz and Maxwell's theoretical models. In 1893, he put forward a renewed *Maxwellian* approach centred around the relationships between electricity and matter, and between electric and chemical phenomena. Both the electromagnetic theory and the theory of matter were based on the assumption of a rotationally elastic aether. In 1894, he introduced the 'electron', namely a subatomic unit of matter and electric charge, stemming from a continuous aether as a knot of rotational energy. He tried to connect continuous models to discrete models; he tried to connect the intimate nature of matter to the intimate nature of energy. In particular, he aimed at unifying physics, starting from a primitive medium, whose motions could produce regular structures and regular perturbations. New bold hypotheses, like electrons' 'steady motion' inside atoms, were the price Larmor had to pay for that integration. I find that Larmor's theoretical contribution cannot be qualified as an electromagnetic world-view, just because he tried to go beyond a purely mechanical or a purely electromagnetic foundation of physics.

Keywords. Matter, energy, continuous, discrete, electromagnetic, mechanical

Historians of science who have studied Larmor's theories and conceptual models in recent times have pointed out difficulties and obscurities in his theories (Darrigol 1994). Nevertheless, I find that some issues have not been sufficiently highlighted. In particular I would like to rephrase the conceptual context of Larmor's early theoretical researches, in order to stress the following points:

- he opened new perspectives to theoretical physics, even though he did not manage to fully develop them,
- his most meaningful achievements came before his famous *Aether and Matter*,
- his research programme cannot be enrolled in the so-called electromagnetic world-view.

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1. Matter and Energy in Late Nineteenth Century Theoretical Physics

In 1858, H. von Helmholtz, put forward a mathematical theory about vortex filaments and vortex rings, which could permanently last in a perfect fluid. In 1867, W. Thomson dared to identify vortex rings with atoms of ordinary matter, and developed the corresponding model[1]. W. Thomson's kinetic model of matter can be placed alongside a conceptual tradition wherein matter is not a fundamental entity but is derived from some kind of dynamism. In a *Friday Evening Lecture* held in 1860 before the Royal Institution, W. Thomson associated explicitly his new model of matter to Leibniz's conceptions. Moreover, he pointed out another meaningful link between the theoretical model of matter as a dynamical structure in a continuous medium, on the one hand, and the theoretical model of contiguous action, on the other. He claimed that the 'belief in atoms and in vacuum' had to be looked upon 'as a thing of the past', and that 'we can no longer regard electric and magnetic fluids attracting or repelling at a distance as realities'. According to W. Thomson, this was just the conception 'against which Leibnitz so earnestly contented in his memorable correspondence with Dr. Samuel Clarke' (Thomson W. 1860, in Thomson W. 1872, p. 224). Thomson's thesis is quite suggestive, even though whirling motions taking place in a medium seem to me to be a model of matter somehow different from Leibniz's conception of matter as endowed with a sort of intrinsic power.[2]

It is worth mentioning Maxwell's passages in support of the theoretical model of the atom as a hydrodynamic ring. In the 1875 edition of *Encyclopaedia Britannica*, he stated that, although the 'small hard body imagined by Lucretius, and adopted by Newton, was invented for the express purpose of accounting for the permanence of the properties of bodies', it failed 'to account for the vibrations of a molecule as revealed by the spectroscope'. On the contrary, 'the vortex ring of Helmholtz, imagined as the true form of atom by Thomson, satisfies more of the conditions than any atom hitherto imagined'. He found that the main satisfactory feature of the model was its 'permanent' and, at the same time, pliable structure.[3]

Nevertheless, that model was criticized both in Great Britain and on the Continent (Merz 1912, p. 64; Kragh 2002, pp. 88–9, 92 and 95). W. Thomson himself, in the already quoted 1860 lecture, remarked that 'electricity in itself' had 'to be understood as not an accident, but an essence of matter': the vortex-atom model, at that stage, could not account for that fundamental property of matter. Although the model was abandoned in the 1890s even by its author, the conceptual stream survived and found a new implementation in Larmor's electron.[4] The fact is that, in the last decades of the nineteenth century, the debate on matter and energy involved many characters, and different, independent points of view were put forward.

Tait, who held the chair of Natural Philosophy at Edinburgh, introduced a new couple of fundamental entities in physics, in his 1885 book on matter: he wrote that in the physical universe 'there are but two classes of things, Matter and Energy' (Tait 1885, p. v and p. 2). Among the different kinds of matter, Tait listed air and water, as well as luminiferous aether. Among the different kinds of energy he listed waves and heat, as well as electric currents. He pointed out that they were all ‘examples of energy associated with matter’. In many passages he emphasised what he considered the keystone of physics: the deep link between matter and energy. More specifically, he stated that ‘Energy is never found except in association with matter’ and probably ‘energy will ultimately be found . . . to depend upon motion of matter’. Nevertheless, this symmetry between matter and energy was broken for two reasons: matter consists of ‘parts which preserve their identity’ while energy ‘cannot be identified’; moreover, matter ‘is simply passive’ or ‘*inert*’ while energy ‘is perpetually undergoing transformations’.[5]

In the 1890s, on the Continent, W. Ostwald, one of the main upholders of *energetism*, starting from a different methodological perspective, advocated the exclusion of matter from the list of fundamental physical entities: ‘the concept of matter, which has become indefinite and contradictory, has to be replaced by the concept of energy’.[6]

In the same decade, Hertz took a different way: in Hertz’s physics, forces were replaced by hidden masses and by their hidden motions. He also criticized Newton’s dualistic conception of force: it was both an action on a given body, as expressed by the first two laws, and a relationship between two bodies, as expressed by the third law.[7] In the case of a stone tied to a string and moving along a circle, Hertz criticized the interpretation in terms of centrifugal forces balancing or opposing centripetal ones. He wondered what exactly was the physical meaning of those supposed centrifugal forces: were they ‘anything else than the inertia of the stone?’ In this case, he added, why should we take ‘the effect of inertia twice into account, firstly as mass, secondly as force?’ Moreover, forces were assumed to be the *causes* of a change in uniform motions, whereas the so-called centrifugal forces were looked upon as the *effects* of non-inertial motions. Hertz was dissatisfied with that clash between causes and effects, and stated that ‘centrifugal force is not a force at all’. He looked for ‘other representations’ of mechanics, ‘more closely conformable to the things which have to be represented’, where the concept of force was banned (Hertz 1894, in Hertz 1956, pp. 6, 13–14 and 25).

In 1887, when he held the chair of theoretical physics at Kiel University, Planck wrote a treatise on the conservation of energy. Three elements appeared tightly connected: the interpretation of electromagnetic phenomena, the interpretation of the conservation of energy, and the choice between the theoretical model of contiguous action and the theoretical model of at-a-distance action. The latter appeared to Planck as the more general, for it could take into account the whole universe. Actually, in the action-at-a-distance model, the force acting on a given body can be considered as the sum of all forces exerted by whatever distant source of the universe. On the contrary, contiguous action had a narrower scope, even though it appeared to Planck more suited to explaining electromagnetic phenomena. He decided to explore the consequences of contiguous action, even from the methodological point of view. He tried to combine contiguous action with the conservation of energy, and found for this combination the name ‘infinitesimal theory'. That *infinitesimal* approach involved all physics: every action on an infinitesimal volume could be transmitted, in a finite time, through the surface surrounding it (Planck 1887, pp. 244). Energy, electromagnetic or not, could be interpreted as something similar to matter. Not only could energy neither be created nor destroyed, but it could not disappear from a given place and instantaneously appear in another distant place. Energy could flow through the boundaries of a volume, just as matter did. The principle of conservation of energy became closely linked to specific ways of transfer of energy. According to this 'infinitesimal theory, energy, like matter, can change its place only with continuity through time'. The energy of a material system could be represented as a series of units or elements: 'every definite element approaches its place and just there can be found'. In brief, Planck claimed that the infinitesimal theory corresponded to the following conception: 'the energy of the whole system can be looked upon as the sum of the energies of every single system' (Planck 1887, pp. 245). The conception of 'elements' of energy travelling through space and time was an important contribution to the scientific debate in the late nineteenth century. Moreover, that conception helps us to better understand the conceptual roots of the theoretical researches Planck subsequently undertook on the electromagnetic and thermodynamic properties of radiation.[8]

Just how widespread the acknowledgement of a conceptual link between matter and energy was in the late nineteenth century is shown by Poincaré's representation of electromagnetic energy as something flowing as 'a fictitious fluid'. In 1900, what actually prevented Poincaré from the complete identification with 'a real fluid' was the fact that 'this fluid is not indestructible' (Poincaré 1900, p. 468).

2. *Larmor 1885–1892: from Helmholtz to Maxwell*

Formerly a fellow of St. John's College, Cambridge, then professor of natural philosophy at Galway's (Ireland) Queen's College, Joseph Larmor returned in 1885 to St. John's as a lecturer. In the same year he published a paper in the *Philosophical Magazine*, 'On the Molecular Theory of Galvanic Polarization', where he outlined a discrete theoretical model for matter and electricity. Larmor started from the analogy between 'the polarisation action of a galvanic cell' and 'an electrical condenser of very large capacity'. His theoretical reference was 'Clausius well-known molecular theory' and, in particular, the interpretation of electrolytic phenomena in terms of 'transfer through the fluid of the temporarily dissociated hydrogen and oxygen under the action of the electric force' (Larmor 1885, p. 422).

The theoretical framework of Larmor's paper could appear unusual to a British *mathematician* trained at Cambridge and interested in electromagnetism: apart from W. Thomson, he quoted Clausius and Helmholtz. A discrete model of matter was in prominence, and the approach to electric actions sounds more *Continental* than *Maxwellian*.[9] Nevertheless, Maxwell was not beyond Larmor's conceptual horizon.

After six years and some other short papers, Larmor published 'On the Theory of Electrodynamics' in the *Proceedings of the Royal Society*. The new theoretical framework involved contiguous action and continuous models for matter and electricity: the first words of the paper made reference to the 'electrical ideas of Clerk Maxwell'. Larmor appeared particularly interested in those 'mechanical models of electrodynamic action', which had led Maxwell to the conception of electric currents as closed paths. The peculiar entity of Maxwell's theory was the 'displacement current' in dielectrics, which prevented electric charge, whatever it was, from heaping up (Larmor 1891, p. 521).

However, he tried to insert those 'remarkable conclusions' in a more general theoretical framework or, in his words, 'a more general view of the nature of dielectric polarisation'. He thought he had found that framework in Helmholtz's theory: Helmholtz had put forward a theoretical model different from Maxwell's, a model which, as Larmor himself acknowledged, dated back to Poisson's theory of magnetisation. Not only did Larmor try to interpret Maxwell's *displacement* current in terms of matter polarisation, but he chose the conceptual reference frame of a Continental scientist who had re-interpreted Maxwell's theory in terms of polarisations *superimposed* to the action at a distance. In contrast to Helmholtz, Maxwell had imagined displacement currents in all dielectrics (aether included) in continuity with conduction currents, as a part of the same path.[10]

Larmor had started from *Helmholtzian* general conceptions and had therefore arrived at a *Helmholtzian* result: Maxwell's theory was a peculiar case of Helmholtz's general theory, corresponding to an endlessly high value of the dielectric constant. The theoretical difference between Helmholtz and Maxwell, specifically concerning the relationship between electric actions and matter (or media in general), was not pointed out by Larmor in this paper, apart from some hints in the last pages (Larmor 1891, p. 534). There was a sharp distinction between vacuum/aether and ordinary matter in Helmholtz's theory, whereas, in Maxwell's theory, there was only a quantitative difference (of inductive capacity) between aether (not vacuum) and matter. What Larmor called 'the transition to Maxwell's scheme' was, in reality, Helmholtz's representation of Maxwell's theory rather then Maxwell's original theory. The last sentence of the paper stated that electrodynamics was well expressed by 'Maxwell's scheme', and that that scheme 'has also so much to recommend it on the score of intrinsic simplicity'. Indeed, the appreciation of Maxwell's theory had filtered out from Helmholtz's theory. During that process, the comparison between the theories was restricted to the aspect of mathematical physics: at that stage, the more interesting comparison involving theoretical physics was completely overlooked by Larmor.[11]

The following year, in a short paper published in the same *Proceedings*, 'On the Theory of Electrodynamics, as affected by the Nature of the Mechanical Stresses in Excited Dielectrics', Larmor paid much more attention to theoretical issues. He took into account two historical-conceptual paths: the conceptual path which connected Faraday to Maxwell, and the conceptual path which went through the theories of Poisson, Mossotti and Helmholtz. He qualified the former as based on 'Faraday's view of the play of elasticity in the medium', even though the reference to the elasticity of a medium seems more suited to Maxwell's theory than Faraday's. The latter dealt with 'the picture of a polarised dielectric supplied by Mossotti's adaptation of the Poisson theory of induced magnetisation' (Larmor 1892, p. 55).

According to Larmor, the second view suffered a 'defect of circuital character' for it did not consider all currents as closed currents: it required 'the existence of absolute electric charges on the faces of an excited condenser'. In that view, every electric current made electric charges accumulate on the plates of a condenser, thus destroying the property known as 'circuital or solenoidal'. Nevertheless he found that the problem 'practically disappears in the limiting case when the constant ratio of the polarisation to the electric force is extremely great'. Here we see the same interpretation put forward in the previous paper: Maxwell's theory as a limiting case of Helmholtz's theory. The latter was considered by Larmor different from the former and more general, in fact so general as to include Maxwell's theory as a subset of the set of possibilities Helmholtz's theory could take into account. It seems that once again Larmor overlooked the deep theoretical differences between the two theories, limiting himself to the mathematical aspect of the comparison. Nevertheless, at the same time, he claimed to be interested in the foundations of Maxwell's theory: this was an issue definitely more theoretical than mathematical. In particular, he regretted that Maxwell's equations 'involve nothing directly of the elastic structure of this medium, which remains wholly in the background'. In this part of the paper, Larmor swung between different theoretical models and different methodological attitudes. In another passage he stated that Hertz's experiments had corroborated Maxwell's 'special form' of Helmholtz's theory, rather than supported Maxwell's theory *against* Helmholtz's theory (Larmor 1892, pp. 55–6).

Larmor thought that Maxwell's theory required further investigation, in particular the relationship between the electromagnetic actions and the structure of matter, or media in general. He criticised Maxwell for having not developed his theoretical foundations in a complete way: that criticism could explain, at least in part, his choice to confine the comparison to the mathematical side. Probably Larmor judged that Maxwell himself had not managed to make people appreciate the theoretical differences between the two theories, because he had not accomplished his theory, particularly with regard to the interactions between fields and matter, or aether.[12]

However, in the course of the paper, while taking into account some arrangements of condensers, wholly or in part filled with a fluid dielectric, Larmor pointed to the core of the theoretical difference between the two theories. In part explicitly and in part implicitly, Larmor singled out some elements for comparison:

- contiguous actions *versus* actions at-a-distance,
- open currents *versus* closed currents,
- electric charge as source of electric action *versus* electric charge as side-effect of the different reactions offered by media to the electric force,[13]

- electromagnetic energy placed on charged bodies *versus* electromagnetic energy stored in the media (Larmor 1892, p. 58).

After having displayed the different features of the two theories, he expressed his trust in Maxwell's theory.

> We shall find reason to conclude that there is no superficial part in the distribution of energy; this would carry the result that the excitation of a condenser consists in producing a displacement across the dielectric which just neutralise the charge conducted to the plates; it would also carry the result that all currents, whether in conductors or in dielectrics, must flow in complete circuits, and would therefore confirm the Maxwell theory of electrodynamics (Larmor 1892, p. 58).

According to this view, Maxwell's theory could be compared to Helmholtz's theory on the grounds of theoretical physics: on that basis, Maxwell's theory and the *Maxwell-flavoured* mathematical limit of Helmholtz's theory appeared to Larmor quite different. The distinction between the mathematical side and the theoretical side of the comparison appeared in a subsequent passage, wherein Larmor specified that the limit of Helmholtz's theory 'which coincides with Maxwell's as to form must be abandoned' (Larmor 1892, pp. 55–6). Now, matter and energy were explicitly involved in the comparison. The experiments performed with electric waves had shown that the storage of the electric energy took place even in air or vacuum. Energy could not be split in two parts, one linked to stresses taking place in material media, and another linked to forces which acted independently from the medium.[14]

At this point the theoretical framework of Maxwell's theory was explicitly appreciated by Larmor, and he claimed that experiments had shown 'that at any rate the basis of electrical theory is to be laid on Maxwell's lines'. In the last passages of the paper, devoted to summarizing the 'principal conclusions', Larmor claimed that phenomena taking place between the plates of a condenser had to be explained in terms of stresses in the dielectric, consisting of 'a tension along the lines of force and an equal pressure in all directions at right angles to them'. We can easily notice that he used the same words Maxwell had used in the second chapter of his *Treatise* (Larmor 1892, p. 62; Maxwell 1881, vol. I, p. 153). Pressure and tension 'would exist in a vacuum' too, and they were 'the result of a uniform distribution of energy in the dielectric'. Now the key point was the distribution of energy: it was the link between energy and matter which qualified Maxwell's theoretical model. The *Maxwellian* limiting case of Helmholtz's theory led to a vanishingly small electric charge on the plates of a condenser: 'in that case a slight surface charge produces a great polarisation effect'. Nevertheless, from the theoretical point of view, this limiting case preserved the causal relationship between electric charge on conductors and polarisation in dielectrics: it was indeed a non-Maxwellian conception. Larmor acknowledged the difference and claimed that 'even this limiting polarisation theory must be replaced [...] by some dynamical theory of displacement of a more continuous character'.[15]

In the end, Larmor faced the query which Maxwell had not managed to solve: the interaction between aether and matter. To give 'a more vivid picture of it', he hinted at ‘a very refined aethereal substratum, in which the molecular web of matter is embedded’. Perhaps it could be imagined as a continuous aether, or endowed with a not specified structure, finer than matter, with the scaffolding of matter superimposed upon it. Matter seemed endowed with a discrete although interwoven structure. Larmor assumed that high frequency electromagnetic radiation could not affect the matter-web, probably because of the great inertia of its structure. On the contrary, it could affect the subtler structure of aether. At the interfaces between aether and dielectrics, or between two different dielectrics, or between aether and conductors, ‘the aethereal part of the distribution of energy in the medium’ should be ‘discontinuous’. In free aether, the electric action induced a strain which propagated ‘with the velocity of light’. He assumed that the presence of matter could modify this simple mechanism of ‘discharge of the system’, giving rise to the ordinary phenomena of induction and conduction.[16] At the beginning of the paper, Larmor had criticised Maxwell for the lack of a detailed account on the structure of aether, on the structure of matter, and on the interactions between those structures and electromagnetic actions. At that stage of his theoretical research, we can say that, apart from some vague hints, he had not been able to go far beyond Maxwell.

3. Larmor 1893–4: Attempts at Unifying Mechanics and Electromagnetism

From 1893 to 1897, Larmor, then fellow of the *Royal Society*, published in *Philosophical Transactions* three thick papers under the title ‘A Dynamical Theory of the Electric and Luminiferous Medium’. The title drew readers’ attention to aether, which represented the keystone of the whole project: it was the seat of electrical and optical phenomena, and it was involved in the constitution of matter. The first paper of the trilogy was received in November 1893, read in December, and revised in June 1894; some other sections were added in August.[17] Larmor immediately made known the mathematical and physical bases of his theory. He had tried ‘to develop a method of evolving the dynamical properties of the aether from a single analytical basis’, and this analytical basis of the theory dealt with energy. The starting point was ‘the mathematical function which represents the distribution of energy in the medium when it is disturbed’; then the mathematical *engine* would have developed ‘the dynamical analysis from the expression of this function’. This was the mathematical-physical aspect of the theory. Another aspect concerned theoretical physics, for an active interpretation was required or, in Larmor’s words, ‘the province of physical interpretation’ was involved. The process, consisting of combining mathematical procedures and physical interpretations, was not looked upon by Larmor as a new method: he noted that a ‘method of this kind has been employed by Clerk Maxwell’ (Larmor 1894, p. 719).

In the paper, the order of subjects began 'with the optical problem', and this problem would have 'naturally' led to 'the electric one'.[18] His previous reference to Maxwell appears a bit puzzling when compared with the order followed: first optics and then electromagnetism. A *Maxwellian* approach would have been more consistent with the opposite choice. Larmor's justification made reference to MacCullagh, whom he credited with having applied 'with success the pure analytical method of energy to the elucidation of optical phenomena'. Some decades before, that Irish scientist had developed an optical theory based on a model of aether endowed with rotational elasticity. The model had raised some debate but had not gained much success. Nevertheless, after some decades, in 1878, FitzGerald had tried to transform MacCullagh's optical aether theory into an electromagnetic aether theory.[19] Larmor re-evaluated that model and thought that it could account for optical as well as for electromagnetic phenomena. He acknowledged that MacCullagh had faced 'supposed incompatibilities with the ordinary manifestations of energy as exemplified in material structures'. However, he thought that those difficulties had been overcome 'by aid of the mechanical example of a gyratory aether, which has been imagined by Lord Kelvin'.[20]

The link between mathematical physics and theoretical physics was the 'Law of Least Action, expressible in the form $\delta \int (T - V)\, dt$', where T denoted the kinetic energy and V the potential energy. Larmor was confident that 'the remainder of the investigation' involved only 'the exact processes of mathematical analysis', provided that the energy was expressed in a physically suitable way (Larmor 1894, p. 720). In other words, once physics had warranted that energy was rightly specified, the mathematical procedures warranted that the corresponding phenomena were explained. The physical content was confined to the energy expression: additional phenomena could be described by simply adding other terms to the energy function.[21]

The actual physical world could be explained following a strategy of subsequent refinements, realized by means of subsequent additions of more specific terms to the energy function. This procedure appeared not so easy to Larmor, for we are dealing with 'a partly concealed dynamical system', and we should imagine 'some mechanical system which will serve as a model or illustration of a medium possessing such an energy function'. There was a problematic link, in general, between mathematics and physics, and, in particular, between the standard procedures of mathematical physics and the wider choice of the corresponding conceptual representations, concerning theoretical physics. More than one representation could be associated with a given mathematical model, and therefore the theoretical physicist had to decide which was the best among them. Larmor suggested that we should prefer the solution 'which lends itself most easily to interpretation', namely the solution which offers the closest relationship between representation and real phenomena. Nevertheless there was another requirement, which could have been in contrast with the former: the theoretical power, or the heuristic power of the representation. Larmor therefore thought that we should prefer a representation less close to phenomena, at least as they appear to us, if it shows to be 'distinctly more fertile in the prediction of new results, or in the inclusion of other known type of phenomena within the system' (Larmor 1894, p. 721).

In the first part of the paper, 'Physical Optics', Larmor credited FitzGerald with having been the first to profitably combine MacCullagh's optical aether with Maxwell's electromagnetic aether. At the same time, MacCullagh was credited with having successfully applied dynamical methods to optics, although he had not managed to give a detailed physical representation of actions taking place in the aether (Larmor 1894, p. 723). He had assumed a kind of aether endowed with constant density but variable elasticity, which could resist rotations but not translations. To that aether MacCullagh had associated a potential energy depending on 'a quadratic function of the components of this elementary rotation'. From 'a purely rotational quadratic expression for the energy' MacCullagh had deduced 'all the known laws of propagation and reflexion for transparent isotropic and crystalline media' (Larmor 1894, pp. 727–9).

The optical equations, as re-interpreted by FitzGerald and Larmor, stemmed from a mathematical and physical entity $\boldsymbol{K} = (\xi, \eta, \zeta)$, representing 'the linear displacement of the primordial medium', and from the vector $\boldsymbol{D} = (f, g, h) = \nabla \times \mathbf{K}$, representing 'the curl or vorticity of this displacement'. The mathematical-physical strategy had already been outlined at the beginning of the paper: first to look for the mathematical expressions for potential and kinetic energy, and then to insert them in the Principle of Least Action.[22]

In a short section added in June 1894, Larmor outlined the correspondence between Maxwell's electromagnetic theory and MacCullagh's theory: when assuming that magnetic induction corresponds to 'the mechanical displacement of the medium, the electric theory coincides formally' with MacCullagh's theory. Indeed, if we consider the time derivative of $\boldsymbol{D} = \nabla \times \mathbf{K}$, we obtain

$$\frac{d\mathbf{D}}{dt} = \nabla \times \frac{d\mathbf{K}}{dt},$$

which becomes the well known circuital equation for the free aether $\frac{d\mathbf{D}}{dt} = \nabla \times \mathbf{H}$, provided that $\boldsymbol{H} = d\boldsymbol{K}/dt$. In other words, the magnetic force should correspond to the velocity of the medium. The medium would be endowed only with rotational elasticity, and would offer no resistance to translational motions.[23]

At that stage, the problematic link between aether and matter was no more satisfactorily explained by Larmor's theory than by Maxwell's theory. However, a detailed knowledge of the structure of matter and of the interaction between aether and matter was not at stake when only Lagrangian methods were involved.[24]

In a following section, dealing with electrodynamic effects of the motion of charged bodies, he tried to give a double representation, both in terms of displacement currents and in terms of electrified matter in motion. He thought that both representations could be reduced to a unified explanation, in terms of a chain of strains across the aether.

> When a charged body moves relatively to the surrounding aether, with a velocity small compared with the velocity of electric propagation, it practically carries its electric displacement-system

> (f, g, h) along with it in an equilibrium configuration. Thus the displacement at any point fixed in the aether will change, and we shall virtually have the field filled with electric currents which are completed in the lines of motion of the charged element of the body, so long as that motion continues. On this view, Maxwell's convection-current is not differentiated from conduction-current in any manner whatever, if we except the fact that viscous decay usually accompanies the latter (Larmor 1894, p. 763).

In the section 'On Vortex Atoms and their Magnetism', he tried to link magnetism to the molecular structure of matter. Larmor assumed that vortex-rings of aether with an empty core were the basic structure of matter, following a tradition going from W. Thomson to J.J. Thomson: 'a permanent electric current of this kind is involved in the constitution of the atom'. Whilst in magnetic matter all elementary vortices should have the same orientation, in ordinary matter they should have different orientations (Larmor 1894, p. 764). A theory wherein vortex-rings of aether represented atoms, and the velocity of the same medium represented a magnetic field, was a step towards the integration among different aspects of mechanics, electromagnetism and chemistry or, in Larmor's words, 'a step towards a consistent representation of physical phenomena'. Molecules were considered as sets of atoms which could be linked to each other by the magnetic forces they produced. Nevertheless, those magnetic bonds raised a query concerning the property of matter, for in that case all kind of atoms and molecules would have created a structure endowed with strong magnetic properties. In other words, all substances would have exhibited magnetisation: it meant, Larmor acknowledged, that his specific model failed, and he was forced to 'find some other bond for the atoms of a molecule' (Larmor 1894, p. 765).

In another page added in June 1894, Larmor tried to further clarify the relationship between electricity and structure of matter. The lines of twist starting from an atom and ending on another atom of the same molecule resemble the short tubes of force connecting the atoms in a molecule as suggested by J.J. Thomson some years before (Thomson J.J. 1891, p. 155). In both representations, the bonds between atoms were electric bonds, and a molecule became a charged fragment of matter, or ion, when some bond was free and the molecule looked for a partner. In that theoretical model, the transfer of electricity as pure propagation of breakdowns of elasticity across the aether appeared not completely satisfactory, for the seat of electricity could also be inside matter. To fill the gap, Larmor took a step forward: the transfer of electricity also consisted of the 'convection of atomic charges'. The electric charge became closer to matter, and endowed with a discrete rather than continuous structure. The unifying element was however the aether: the discrete structure of matter and electricity could be imagined as 'evolved from some homogeneous structural property of the aether'. Electric charge underwent a conceptual shift from a phenomenon connected to the distribution and transfer of energy to a phenomenon connected to the distribution and transfer of matter. Conversely, matter became a peculiar entity, stemming from dynamical actions taking place in the aether. However, a sort of conceptual continuity was assured, for the transfer of particles, represented as dynamical structures of the aether, was not so different from the transfer of *pure* energy. In other words, in Larmor's general framework, matter and energy, in their intimate nature, were not radically different from each other.[25]

According to Larmor, there was a fundamental unit of matter, or 'monad', stemming from the continuous structure of aether, and a hierarchy of discrete entities: at the more elementary level we have the monad, then collections of monads, corresponding to the different elements, and, eventually, the molecules, corresponding to the ordinary substances. To be more precise, the model required two kinds of monads perfectly symmetric: positively charged monads and negatively charged ones, the latter being 'simply perversions or optical images' of the former. Although the symmetric monads were welcome from the theoretical point of view, that symmetry did not match up with the known chemical properties of substances. In nature, Larmor remarked, $H^+ Cl^-$ really exists, but its electrically symmetric $H^- Cl^+$ does not exist. Chemistry broke the electromagnetic symmetry between positive and negative electric charge. Larmor acknowledged that, at that stage, neither the present theory nor 'any dynamical theory' could account for that asymmetry (Larmor 1894, pp. 771–2).

Another flaw in the foundations of the theory came from the motion of matter through aether. In Larmor's theory, an irrotational flow of aether corresponded to a magnetic field. As a consequence, if material bodies in motion had dragged away the inner and the surrounding aether, a magnetic field would have come out. Some effects would have followed, including perhaps an 'influence of magnetization on the velocity of light'. Those effects could not be accepted: therefore the hypothesis that aether was not dragged by matter in motion was assumed.[26]

However, another query emerged: the hydrodynamic basis of the model of vortex-atoms put in danger the physical consistency of the whole theory. The model required that 'a rise of temperature is represented by increase of the energy, and that involves an expansion of each ring and a diminution of its velocity of translation'. The first consequence concerned the wrong dependence of velocity from temperature, from the point of view of the kinetic theory of gases. The second consequence concerned the change in the dimensions of atoms: how could the model assure that the frequency of radiation did not change? (Larmor 1894, p. 782) At that stage, the attempt to unify, or at least put together without any mismatch, a kinetic theory of gases, properties of electromagnetic radiation and hydrodynamic models was probably a too demanding theoretical task. The theory lacked new general principles and innovative mathematical approaches, and could not realize that great unification involving mechanics, electromagnetism and thermodynamics.[27]

All these difficulties did not discourage Larmor, and did not prevent him from outlining a physical theory of *everything*. Could he leave gravitation out of the door? Could he give up looking for an explanation of the intimate nature of mass? He proposed new, bold hypotheses and, at the same time, he relied on already existing theories of gravitation and their corresponding hypothesis. For instance, he wrote that it was *proved* by Laplace that 'the velocity of gravitation must be enormously great compared with that of light'. He went on writing that 'gravitational energy, whatever its origin, must preserve a purely statical aspect with respect to all the other phenomena that have been here under discussion'. It was a theoretical approach not consistent with any theory of contiguous actions. He insisted that 'mass is a dynamical conception', but he associated this bold statement with the formalistic remark that 'the ultimate definition of mass is to make it a coefficient in the kinetic part of the energy function of the matter' (Larmor 1894, p. 794). Nevertheless, I think that it would be a mistake to underestimate Larmor's ambitious project. He tried to link the old concepts of mechanics to new concepts emerging from the more recent tradition of electromagnetic theories; he tried to connect continuous models to discrete models; he tried to connect the intimate nature of matter to the intimate nature of energy. In particular, he aimed at unifying physics, starting from a primitive medium, whose motions could produce regular structures and regular perturbations. On these grounds, I do not see Larmor at ease inside the boundaries of the so-called electromagnetic world-view. His world-view was at the same time mechanical and electromagnetic or, better, he pursued the foundation of a sort of proto-physics, from which mechanics and electromagnetism should have been deduced. I would like to quote the next passage concerning the nature of mass, in order to show the net of concepts, hints and hypotheses which was the hallmark of his 1893 theoretical project.

> To make a working scheme we must suppose a layer of the medium, possessing actual spin, to cover the surface of each coreless vortex-atom; we might imagine a rotationless internal core which allowed no slipping at the surface, and this spin would be like that of a layer of idle-wheels which maintained continuity between this core and the irrotational circulatory motion of the fluid outside. A gyrostatic term in the kinetic energy thus appears to introduce and be represented by the kinetic idea of mass of the matter; it enters as an aelotropic coefficient of inertia for each vortex, but when averaged over an isotropic aggregate of vortices, it leads to a scalar coefficient for a finite element of volume. (Larmor 1894, p. 796)

From 'Atoms' to 'Electrons'

Immediately after the last lines of Larmor's 1893 text, *Philosophical Transactions* reported some pages which Larmor had added in June and August 1894. He drew attention to the conception of the electric current as convection of atomic charges. He remarked that an electric current should involve two kinds of convection: a 'circulation of the medium ... around the conducting part of the circuit', and 'the convection of charged ions' (Larmor 1894, p. 798). Nevertheless, this interplay between aether flows and ions flows could account, Larmor noted, for ordinary currents but could be unsuitable to account for microscopic currents or 'molecular circuits'. On that scale of length, 'in a molecular circuit', electric convections could not take place, 'but only permanent fluid circulation through it'. This difference led to an asymmetry between the magnetism stemming from macroscopic electric currents, and the magnetism stemming from permanent magnets, due to microscopic or molecular circuits. In ordinary currents, a continuous flow of aether was associated to a flow of discrete entities; in magnetic matter, only the continuous flow was involved (Larmor 1894, p. 800).

The introduction of discrete units of matter and electric charge in a *Maxwellian* context led Larmor to the theoretical re-valuation of the *old* potentials and Helmholtz's *old* approach. He found 'the lines of Helmholtz's theory of 1870' acceptable, and claimed that the physical meaningfulness of potentials 'would not be inconsistent with general principles' (Larmor 1894, pp. 803–4). The conceptual tension between fields and potentials was at the core of British physics, namely the theoretical model of contiguous action. Nevertheless, in the 'Conclusion' of the section added in June 1894, Larmor came back to the foundation of what he called his 'present view': a medium which is 'a perfect incompressible fluid as regards irrotational motion' but is endowed with rotational elasticity. The medium was 'the seat of energy of strain', and 'undulations of transverse type' were propagated throughout it. The design for a great unification was still at stake: both matter and electricity were permanent dynamical effects taking place in that kind of aether. The discreteness of matter stemmed from the continuity of the medium and the tension between continuous and discrete representations seemed thus overcome.

> A cardinal feature in the electrical development of the present theory is on the other hand the conception of intrinsic rotational strain constituting electric charge, which can be associated with an atom or with an electric conductor, and which cannot be discharged without rupture of the continuity of the medium. The conception of an unchanging configuration which can exist in the present rotational aether is limited to a vortex-ring with such associated intrinsic strain: this is accordingly our specification of an atom. (Larmor 1894, p. 805)

The motion of a charged particle through aether produced an 'elastic effect of convection through the medium', consisting of 'a twist round its line of movement'. The effect was not so different from the propagation of elastic actions in *displacement* currents: such a twist was just the common feature of every kind of electric current. At the same time Larmor acknowledged that he had not managed to enlighten what he considered the core of every electromagnetic theory: 'the detailed relations of aether to matter'. Moreover, the theory tried unsuccessfully to cope with some difficulties concerning magnetism and the already mentioned asymmetry between macroscopic and microscopic electric currents.[28] Nevertheless Larmor had in store other hypotheses and remarks.

The pages added in August 1894 consisted of two sections; the second was devoted to optical phenomena, already discussed in the first part of the 1893 paper, whereas the first dealt with 'atomic charges', or 'primordial atoms', or 'monads', the concepts he had introduced in the middle of the paper, in June 1894. In the first section, the elementary units of electric charge were named 'electrons', a name recently used by J. Stoney, and the section was entitled 'Introduction of Free Electrons'.[29] The new electrons were different from the previous atomic charges, for they were placed at a different level in the structure of matter. Atoms were no longer the elementary building blocks of matter: they became complex structures and, with these structures, electrons were involved. Even molecular currents became convective currents; he assumed that the core of vortex-rings consisted of 'discrete electric nuclei or centres of radial twist in the medium'. Nevertheless, the discreteness was of a particular kind: these nuclei consisted of dynamic structures emerging from the continuous medium itself. The new solution, the 'electron', confirmed the integration between the continuous *substratum* and the discrete unit, in some way a *particle*, of electric charge (Larmor 1894, p. 807). The specific unifying element of the new theory was the convective nature of all kind of electric currents, both macroscopic and microscopic.

> A magnetic atom, constructed after this type, would behave like an ordinary electric current in a non-dissipative circuit. It would for instance be subject to alteration of strength by induction when under the influence of other changing currents, and to recovery when that influence is removed; in other words, the Weberian explanation of diamagnetism would now hold good. (Larmor 1894, p. 807)

A planetary structure and a statistical approach were the main features of the molecular model which Larmor attempted to outline: a magnetic molecule 'composed of a single positive or right-handed electron and a single negative or left-handed one revolving round each other'. He made use of the analogy between planetary motions and electronic motions, but he gave up localising the position of the electron over time. He looked upon the mass of a planet as 'distributed round its orbit': at any point of the orbit, we should imagine a mass density 'inversely proportional to the velocity the planet would have when at that point'. He interpreted the measurable effects as a statistical result, reckoned over a large number of microscopic events.[30]

At that stage, however, the model was roughly outlined and Larmor did not inquire into the intimate structure of the atom. The statistical nature of electronic motions made them different from the previous flow of aether, for those motions underwent a sort of fluctuation.[31]

Independently from their peculiar nature of dynamical singularities in the aether, electrons were electric charges in motion along closed paths, therefore undergoing an accelerate motion. Consistently with Maxwell's electromagnetic theory of radiation, accelerated electric charges would have sent forth electromagnetic waves. That effect was in contrast with Larmor's atomic model, for a swift damping of electronic motion would have followed. To save the model, Larmor introduced (*ad hoc*, indeed) the concept of 'steady motion', and the concept of perturbation of a steady motion. Electric waves could stem only from those perturbations.

> It may be objected that a rapidly revolving system of electrons is effectively a vibrator, and would be subject to intense radiation of its energy. That however does not seem to be the case. We may on the contrary propound the general principle that whenever the motion of any dynamical system is determined by imposed conditions at its boundaries or elsewhere, which are of a steady character, a steady motion of the system will usually correspond, after the preliminary oscillations, if any, have disappeared by radiation or viscosity. A system of electrons moving steadily across

> the medium, or rotating steadily round a centre, would thus carry a steady configuration of strain along with it; and no radiation will be propagated away except when this steady state of motion is disturbed. (Larmor 1894, p. 808)

This new condition of 'steady motion' broke the symmetry between macroscopic and microscopic level, for the condition of *steadiness* appeared suitable only for the latter. Unfortunately, the tension between *macroscopic* and *microscopic*, which seemed to have been overcome by the attribution of a convective nature even to microscopic currents, re-appeared once again. In Larmor's theoretical research, the boundary between microscopic and macroscopic level was continuously crossed but, in the end, he did not manage to remove the gap. There was a difference between the intimate nature of matter, concerning microphysics, and its visible features, concerning ordinary physics.[32]

Larmor took into account the steady motion of a microscopic electric charge and the field spread from the electric charge itself. J.J. Thomson and subsequently O. Heaviside had faced the same issue, giving solutions qualitatively akin to each other.[33] He seemed specifically interested in the relationship between the velocity of the electric charge and the velocity of radiation, and in the interpretation of the limiting case, when fast electrons approached the velocity of radiation.

> As the velocity of the electric system is taken greater and greater the permeability, in the direction of its motion, of the uniaxial medium of the analogy becomes less and less, and the field therefore becomes more and more concentrated in the equatorial plane. When the velocity is nearly equal to that of radiation, the electric displacement forms a mere sheet on this plane, and the charge of the nucleus is concentrated on the inner edge of this sheet. The electro-kinetic energy of a current-system of this limiting type is infinite (..) and so is the electrostatic energy; thus electric inertia increases indefinitely as this state is approached, so that the velocity of radiation is a superior limit which cannot be attained by the motion through the aether of any material system. (Larmor 1894, p. 809)

The velocity of an electron affected the geometry of its electric field, as well as its inertia and its energy. Larmor wondered whether the inertia of matter could be split into an *electric* inertia and a *material* inertia; if the latter could be associated to thermal kinetic energy of the molecules, the former could be associated to phenomena taking place inside the atom. Electric inertia could be the kind of inertia involved in the motions of electrons in the atom and, in particular, in those periodic motions which gave rise to atomic radiation (Larmor 1894, p. 809).

Indeed, the August 1894 addition to the 1893 paper is full of queries and suggestions, which are as interesting as generically sketched. One of them concerns the ultimate constitution of aether: was its intimate structure discrete or continuous, was its elasticity intrinsic or a consequence of some molecular structure? A page of cogitations led to the logical, rather than physical, conclusion that 'there must be a final type of medium which we accept as fundamental without further analysis of its properties of elasticity or inertia'. Electrons themselves were the discrete structure of aether, a structure of dynamical origin, as they were centres of rotational strains. Nevertheless, once electrons had been shaped, they became individual and self-contained entities: Larmor remarked that the 'fluidity of the medium allows us to apply the methods of the dynamics of particles' to describe their motions and interactions. But the energy of 'a system of moving electrons' was in some way the energy of aether, for potential energy consisted of 'the energy of the strain in the medium', and kinetic energy 'was that of the fluid circulation of the medium', although associated to 'a quadratic function of the velocity-components' of the individual electrons (Larmor 1894, p. 811).

The double nature of electrons, as individual building blocks of matter, on the one hand, and as dynamical structures of aether, on the other, affected their behaviour with regard to velocity. As long as their velocity remained far less than the velocity of radiation, their dynamical properties could be expressed 'in terms of the position of the electrons at the instant'. When their velocities approached that of radiation, Larmor suggested that they were 'treated by the methods appropriate to a continuum' (Larmor 1894, p. 811). In other words, low velocity electrons behaved like particles, whilst high velocity electrons behaved like radiation. Electrons could be described either like particles or like radiation, and the choice depended on their energy: the transition from the first description to the second took place in some unspecified way. The old clash between continuous and discrete models faded into a new representation, where *continuous* and *discrete* became complementary aspects of an entity endowed with an intimate double nature.

Phenomena taking place in conductors could be explained either in a simplified way, assuming the conductor as a continuum and taking into account the streams of energy coming from the surrounding dielectric, or in a more detailed way, taking into account the motion of charged ions. According to Larmor, ions, rather than electrons or monads, were involved in conductors: the average effect of their motions corresponded to the discharge of the electric stress in the conductor itself. The *Maxwellian* model of the loss of elasticity in the transition from dielectrics to conductors had its counterpart in the microscopic route of ions through the structure of the conductor.

> In the general theory of electric phenomena it has not yet been necessary to pay prominent attention to the molecular actions which occur in the interiors of conductors carrying currents: it suffices to trace the energy in the surrounding medium, and deduce the forces acting on the conductors, considered as continuous bodies, from the manner in which this energy is transformed. The calculations just given suggest a more complete view, and ought to be consistent with it; instead of treating a conductor as a region effectively devoid of elasticity, we may conceive the ions of which it is composed as free to move independently, and thus able to ease off electric stress; the current will thus be produced by the convection of ionic charges.[34]

Larmor acknowledged that the query concerning the nature of inertia was not completely solved by his theory. Ordinary matter was made of molecules, molecules were made up of atoms and atoms contained electrons: could inertia of matter be brought back to electric inertia of electrons? He was unable to answer in a definite way: he was forced to accept a sort of dichotomy between ordinary matter and *electric* matter, which corresponded to the distinction between material energy and electric energy.[35]

4. Concluding Remarks

Larmor did not manage to accomplish his great unification. He did not manage to overcome the asymmetries between mechanical and electromagnetic entities, or between macroscopic and microscopic levels. But he showed a way. The search for an intimate link between matter and energy, in particular between the structure of the electromagnetic field and elementary corpuscles, survived, and would have found new implementations in twentieth century physics. The more general commitment to integrate continuous and discrete representations of the physical world survived as well.[36]

Larmor envisaged a world which, at its fundamental level, consisted of aether and its dynamical structures. This was different to Lorentz, who imagined a world consisting of two distinct entities, aether and ions (later *electrons*), Larmor imagined his *electron* as nothing else but a rotational strain in the aether. His representation of the physical world can be looked upon as *electromagnetic* only in a very broad sense, for those structures were both mechanical and electromagnetic. I do not find that Larmor overturned the relationship between mechanics and electrodynamics. In particular, I find that an aethereal conception of matter cannot be identified with the attempt to pursue that overturn.[37]

I find Larmor's aether no less mechanical than Thomson's. I find that the most interesting feature of Larmor and J.J. Thomson's theories is exactly their commitment to overcome the distinction between what we nowadays call *mechanical* and *electromagnetic* world-views. Both Larmor and J.J. Thomson criticized Maxwell's concept of 'electric displacement', and put forward a more effective representation of electromagnetic fields: translations and rotations in McCullagh's aether for the former, and Poynting's tubes of force for the latter. In both models, units of energy were tightly linked to units of electric charge and these, in their turn, were tightly linked to units of matter. According to J.J. Thomson, bundles of aethereal structures, namely units of tubes of force, could propagate throughout aether in the form of electromagnetic radiation, or could link units of matter and electric charge. What both theories had in common was the resort to discrete, dynamical structures, either translational or rotational, emerging from a continuous, universal aether.[38]

I find in Larmor the convergence of two different theoretical traditions, corresponding to W. Thomson and Maxwell. I see in W. Thomson the pursuit of an ultimate mechanical explanation, and an attempt to outline a kinetic origin of matter. I see in Maxwell a complex interplay between electromagnetic phenomena and mechanical explanations. Seemingly, the electron Larmor introduced in 1894 represented an alternative to both Maxwell's leading theoretical model and Lorentz's particles (1892) and ions (1895). Nevertheless Larmor's electron as a rotational stress in the aether led to a model of electric current not so far from Maxwell's: an electronic flow could be looked upon as a motion of some kind of aethereal perturbation. I find that, beyond some specific, important features, which differentiated Larmor's electrons from J.J. Thomson's tubes of force, both entities consisted of dynamical and aethereal structures propagating through aether itself.[39]

In brief, I think that these British theoretical physicists cannot be easily classified: this is what makes them so interesting from the point of view of the history of science. The sharp distinction between mechanical and electromagnetic world-views seems not suited for them. J.J. Thomson and Larmor's theoretical models were based at the same time on mechanical and electromagnetic foundations. Aether and elementary structures *in* aether, or *of* aether, were the common root for both mechanical and electromagnetic entities, in particular matter and fields. They tried to bridge the gulf between mechanics and electromagnetism in an original way.

NOTES

1. For an account of W. Thomson's theories, see Siegel 1981, pp. 241–2, and Darrigol 2000, pp. 77, 114–15, 117 and 133. A short account of Helmholtz's results can be found in Siegel 1981, pp. 255–6. In 1883, J.J. Thomson tried to apply W. Thomson's model to the kinetic theory of gases (Thomson J.J. 1883, p. 109). Giusti Doran pointed out that W. Thomson got involved in dynamical structures in aether two years before Helmholtz's paper on vortex rings (Giusti Doran 1975, p. 189).
2. According to Leibniz, the 'monad' was the basic entity in nature, and it was a dynamical entity. It would undergo transformations under the effect of an 'internal principle' ('un *principe interne*'): it would be the seat of actions and connections ('une pluralité d'affections et de rapports'). Every monad would be influenced by every action taking place in every side of universe ('tout corps se ressent de tout ce qui se fait dans l'univers'). Nothing is passive or idle in the universe ('il n'y a rien d'inculte, de stérile, de mort dans l'univers'). See statements 10, 11, 13, 15, 21, 61 and 69 in Leibniz's *La Monadologie*.
3. See Maxwell 1875, in Maxwell 1890, vol. II, pp. 470–1. Giusti Doran reminded us that, before 1875, Maxwell did not trust in a dynamical model of matter. (Maxwell J.C. 1873, p. 437; Giusti Doran 1975, p. 192).
4. Whereas Kragh saw 'if only indirectly, a kind of revival' I see a subsequent stage in a long-lasting conceptual stream (Kragh 2002, pp. 34 and 71). In the course of the twentieth century, historians have widely analysed what they looked upon as a 'kinetic theory of matter', or a 'physical picture in which force is more fundamental than matter', or 'the basis of a unified field theory of matter' (Merz 1912, pp. 62 and 64–6; Hesse 1961, p. 166; Giusti Doran 1975, pp. 140 and 142, footnote 2). More specifically, others have described in detail nineteenth century vortex-atom theory (Kragh 2002).
5. In that conceptual context we find a sharp statement against action at a distance, which was qualified as 'a very old but most pernicious heresy, of which much more than traces still exist among certain schools, even of physicists' (Tait 1885, pp. 3–6).
6. See Ostwald 1896, pp. 159–60. On Ostwald's *energetism* see McCormmach and Jungnickel 1986, Vol. 2, p. 220, and Harman 1982, p. 147. Ostwald held the sole German chair of physical chemistry, at the University of Leipzig, from 1887 until his retirement.
7. See Hertz 1894, in Hertz 1956, p. 6. Miller pointed out an interesting analogy among Hertz's concealed masses, Newton's concealed forces and energetists' concealed energies (Miller 1984, p. 78).

8. Even recently, in a historical survey of the light-quantum hypothesis, S. Brush pointed out that Planck's 1900 assumption of 'an integer number of energy elements was only a mathematical device'. Although I agree with Brush and 'Kuhn and other historians' on 'the evidence that Planck in 1900 did not propose physical quantisation of electromagnetic radiation', I do not find any evidence that Planck had previously refused the physical concept of 'energy elements', or that 'energy elements' were beyond his theoretical horizon. (Brush 2007, pp. 212–14) Planck's 1887 treatise shows his commitment to look for new models for the transfer of energy. That general theoretical commitment is however consistent with his subsequent refusal of Einstein's 1905 specific theoretical model of quantisation.
9. The fact is that different interpretations of Maxwell's *Treatise* were offered by different teachers and coaches in Cambridge. Around 1880, students could be introduced to electromagnetism by W.D. Niven lectures or by E. Routh training for the Mathematical Tripos. As Warwick pointed out, if Niven probably made reference to Maxwell's contiguous action, Routh made reference to 'an action-at-a-distance theory of electrostatics and, quite probably, a fluid-flow theory of electrical conduction' (Warwick 2003, p. 333). Both J.J. Thomson and Larmor were trained by the coach Routh. Niven was the scholar who took care of the second edition (1881) of Maxwell's *Treatise*, after Maxwell's death.
10. The question was: could the displacement current 'make all electric currents circuital'? (Larmor 1891, p. 522). The problem had been explicitly analysed by J.J. Thomson in his 1885 paper (Thomson J.J. 1885, pp. 127–8 and 133–5).
11. See Larmor 1891, pp. 534–6. For a detailed analysis of Helmholtz's *constants* and their relationship with Maxwell's *constants*, see Bevilacqua 1983, pp. 112–17, and Darrigol 2000, pp. 227–9 and 232–8.
12. On the reasons for Larmor's dissatisfaction with Maxwell's theory, see Darrigol 2000, p. 334.
13. It is worth mentioning that, besides Maxwell's leading representation of electric charge and electric current, there are other representations in his *Treatise*. They were put forward for specific purposes: the explanation of electrolysis, for instance (Maxwell 1881, vol. I, pp. 347–51). See, in particular, p. 351: 'This theory of molecular charges may serve as a method by which we may remember a good many facts about electrolysis. It is extremely improbable that when we come to understand the true nature of electrolysis we shall retain in any form the theory of molecular charges, for then we shall have obtained a secure basis on which to form a true theory of electric currents, and so become independent of this provisional theories.' For a wider analysis of Maxwell's different representations see Darrigol 2000, pp. 173–4.
14. See Larmor 1892, p. 62: 'Now the propagation of electrical waves across air or vacuum shows that even then, when there is no ponderable dielectric present, there must be a store of statical energy in the dielectric; and this fact appears to remove the only explanation which seems assignable for the division of the energy into two parts, one located in the dielectric, and the other located on the plates and absolutely independent of the dielectric, viz., that the latter might be the energy of a direct action across space which is not affected by the dielectric.'
15. See Larmor 1892, pp. 64–5. See, in particular, p. 65: 'The stress which would exist in a vacuum dielectric is certainly due in part to a volume distribution of energy, as is shown by the propagation of electric waves across a vacuum. There is thus no reason left for assuming any part of it to be due to a distribution of energy on its two surfaces, acting directly at a distance on each other. There is therefore ground for assuming a purely volume distribution of energy in the vacuous space, leading to a tension $F^2/8\pi$ along the lines of force, and a pressure $F^2/8\pi$ at right angles to them.'
16. See Larmor 1892, pp. 65–6. See, in particular, p. 66: 'At an interface where one dielectric joins another, the aethereal conditions will somehow, owing to the nature of the connection with the matter, only admit of a portion of the stress being transmitted across the interface; and there will thus be a residual traction on the interface which must, if equilibrium subsist, be supported by the matter-web, and be the origin of the stress which has been verified experimentally. Inside a

conductor, the aether cannot sustain stress at all, so that the whole aethereal stress in the dielectric is supported by the surface of the matter-web of the conductor'.

17. As reported by Buchwald and subsequently by Hunt, J.J. Thomson read Larmor's paper as reviewer of the Royal Society. Thomson wrote to Rayleigh that the paper was 'exceedingly long' and dealt with 'a very large subject being a kind of Physical Theory of the Universe'. See *Referee Reports*, Library of the Royal Society, London, 12.160 (5 February 1894). J.J. Thomson's appraisal is quoted in Buchwald 1985, p. 162, and Hunt 1991, pp. 215–16.
18. See Larmor 1894, p. 719: 'We shall show that an energy-function can be assigned for the aether which will give a complete account of what the aether has to do in order to satisfy the ordinary demands of Physical Optics; and it will then be our aim to examine how far the phenomena of electricity can be explained as non-vibrational manifestations of the activity of the same medium.'
19. See MacCullagh 1848, in Schaffner 1972, pp. 187–93. On the role of FitzGerald in the development of a dynamical theory of the electromagnetic field, see Stein 1981, pp. 312–13, and Hunt 1991, pp. 15–19.
20. See Larmor 1894, pp. 719–20. MacCullagh's model, FitzGerald's subsequent reinterpretation, and Larmor's reference to it have already been analysed by historians. See, for instance, Darrigol O. 2000, pp. 334–5.
21. See Larmor 1894, p. 721: 'In each problem in which the mathematical analysis proceeds without contradiction or ambiguity to a definite result, that result is to be taken as representing the course of the dynamical phenomena in so far as they are determined by the energy as specified; a further more minute specification of the energy may however lead to the inclusion of small residual phenomena which had previously not revealed themselves'.
22. After a series of mathematical steps, Larmor obtained an 'equations for elastic vibrations in the medium' (Larmor 1894, pp. 729–30).
23. See Larmor 1894, p. 735. A medium endowed with those peculiar qualities, which offered 'no resistance whatever to irrotational distortion' but resisted elastically 'nondistorting rotation', had already been criticized short after MacCullagh paper was published (Stein 1981, pp. 314–5). A similar theoretical model had put forward in 1891 by Heaviside, and then published in the first volume of his *Electromagnetic theory* (Heaviside 1893, pp. 127–8).
24. See Larmor 1894, p. 758. See also p. 759: 'The electrodynamic forces between linear current-systems are thus fully involved in the kinetic-energy function of the aethereal medium. The only point into which we cannot at present penetrate is the precise nature of the surface-action by which the energy is transferred (. . .) from the electric medium to the matter of the perfect conductor; all the forces of the field are in fact derived from their appropriate energy-functions, so that it is not necessary, though it is desirable, to know the details of the interaction between aether and matter, at the surface of a conductor.'
25. See Larmor 1894, p. 771: 'The charged atoms will tend to aggregate into molecules, and when this combination is thoroughly complete, the rotational strain of each molecule will be self-contained, in the sense that the lines of twist proceeding from one atom will end on some other atom of the same molecule. If it is not the case, the chemical combination will be incomplete, and there will still be unsatisfied bonds of electrical attraction between the different molecules. A molecule of the complete and stable type will thus be electrically neutral; and if any cause pull it asunder in two ions, these ions will possess equal and opposite electric charges.'
26. Larmor also quoted the negative results of experiments recently performed by Lodge, devoted to checking 'the effects produced by a magnetic field on the velocity of light'. This section of the paper contains very general cogitations on kinetic energy of aether, aether inertia, and the relationship between its density and elasticity (Larmor 1894, pp. 772, 774–5 and 778–9). On the problems arising from the identification of magnetic *force* with a flow of aether, see Hunt 1991, p. 215, and Stein 1981, p. 332.

27. Some historians have described Larmor's theories as too hard to understand, only roughly sketched, and pretentious (Buchwald 1985, p. 141–2, and Darrigol 2000, p. 332). My appraisal is more positive: in 1893–4, Larmor's sketch consisted of a net of interesting remarks, acknowledged failures, and new physical concepts.
28. See Larmor 1894, pp. 805–6. At that stage, the model of electric charge associated to atoms was only roughly outlined in Larmor's theory. This led Buchwald to qualify the model as 'mysterious' as Poynting and J.J. Thomson's *dissolution* of tubes of force (Buchwald 1985, p. 152). I think that Larmor's conceptual path, when set in its historical context, appears at least as fertile as 'mysterious', because of its power of unification. Furthermore, it seems to me that Larmor's *atomic electricity* was not in competition with Poynting and J.J.Thomson's theoretical models: it was a model able to explain what would happen *after* tubes dissolution.
29. On the use of the word 'electron' from Stoney to Larmor through FitzGerald, and the role of FitzGerald in the emergence of Larmor's new theory (August 1894), see Hunt 1991, p. 220. G.J. Stoney, secretary to Queen's University in Dublin, had introduced a basic unit of electric charge in the paper 'On the Physical Units of Nature', presented at the 1874 meeting of the British Association. In 1891 he introduced the word 'electron' for that fundamental unit.
30. See Larmor 1894, p. 807: 'Just in same way here, the steady flow of the medium, as distinguished from vibrational effects, is the same as each electron were distributed round its circular orbit, thus forming effectively a vortex-ring, of which however the intensity is subject to variation owing to the action of other systems.'
31. See Larmor 1893–4, p. 807, second footnote. See also p. 808: 'This mode of representation would leave us with these electrons as the sole ultimate and unchanging singularities in the uniform all-pervading medium, and would build up the fluid circulations or vortices—now subject to temporary alterations of strength owing to induction—by means of them.'
32. It is worth mentioning that, since the dawn of natural philosophy, two general conceptions on the link between *macroscopic* and *microscopic* world had been on the stage. On the one hand, the conception of an invisible small-scale structure as a tiny copy of the large-scale world; on the other hand, the conception of an invisible small-scale structure endowed with specific features, following different laws. The main hallmark of ancient atomism was the physical gap between the ordinary, visible world, and the invisible world of atoms: the latter was an *explanation* of the former.
33. On the modified inertia of *electric charges* in motion, see Thomson J.J 1881, pp. 229–34, and Heaviside 1889, pp. 325–6. On the geometrical shape of their electric field, see Heaviside 1889, p. 332.
34. See Larmor 1894, p. 814. Once again, in August 1894, Larmor tried to overcome the conceptual tension between two different representations of conduction: either a side-effect of the waste of electric displacement, in the passage from dielectrics to conductors, or a flow of microscopic electric charges.
35. See Larmor 1894, p. 818: 'In the absence of any such clue, a guiding principle in this discussion has been to clearly separate off the material energy involving motions of matter and heat, from the electric energy involving radiation and chemical combination, which alone is in direct relation to the aether. The precise relation of tangible matter, with its inertia and its gravitation, to the aether is unknown, being a question of the structure of molecules; but that does not prevent us from precisely explaining or correlating the effects which the overflow of aethereal energy will produce on matter in bulk, where alone they are amenable to observation.'
36. As E. Giannetto recently remarked, nature and origins of quantum physics' had meaningful roots in Larmor's theoretical researches (Giannetto 2007, pp. 178 and 181).
37. I share McCormmach's interpretation of British theories as a combination of mechanical and electromagnetic features: I see an alliance, rather than a competition, between mechanics and electromagnetic conceptions (McCormmach 1970, pp. 460–61). For different points of views, see Giusti Doran 1975, p. 206, Warwick 1991, pp. 33 and 369, and Kragh 2002, p. 69 and

p. 112, footnote 76. The fact is that historians have given slightly different version of what the electromagnetic world-view should be. The so-called mechanical and electromagnetic world-views are under review in Bordoni 2008, pp. 49–57.

38. See, for instance, Thomson J.J. 1891, pp. 149–50, and Thomson J.J. 1893, pp. 2–4 and 43. In 1880, Larmor and J.J. Thomson had qualified respectively first and second in the Cambridge Mathematical Tripos. For a different point of view on J.J. Thomson see Topper 1980, p. 50.
39. It seems to me quite debatable that Larmor's aether was 'nonmechanical' (Giusti Doran B. 1975, p. 206). On the influence of Maxwell's electromagnetic theory and W. Thomson's theory of matter on both Larmor and J.J. Thomson see Darrigol 2000, p. 333.

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