MAXWELL, MECHANISM AND THE NATURE OF ELECTRICITY

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Mechanical explanations

I remember being asked in the school playground "what is electricity?" I promptly, and smugly, replied, "electricity is the accumulation and flow of electrons". "What are electrons?" was the next question from my inquisitor. "Negatively charged particles" I replied. "Charged with what?" was the triumphant response from my adversary, who knew he had me, and didn't wait for a reply.

Had I had the experience then that I have now, I could have responded by saying that the charge on the electron is a primitive not to be explained, just like its mass. I doubt that this would have satisfied my schoolmate. There is a widespread disposition to the effect that the only kinds of explanation acceptable are mechanical explanations, explanations that appeal to pushes and pulls of a kind that are operative in the workings of a clock. My explanation of electricity was not acceptable because it was not mechanical. This predilection for mechanical explanations, widespread as it is within common-sense discourse, stretches far beyond that domain. The mechanical philosophers of the seventeenth century formulated a strict, philosophical version of the view that adequate explanations are to be identified with mechanical explanations, and many scientists have been attracted to the same view. Maxwell was one of them, as we shall see.

The conditions to be satisfied by mechanical explanations according to seventeenth- century mechanical philosophers such as Robert Boyle were very strict indeed. The only quantities allowed to figure in fundamental mechanical explanations were shape, size, and motion, together with some property that served to distinguish portions of matter from empty space. (Boyle chose impenetrability.) It is doubtful that any significant mechanical explanation meets the strict requirements of the mechanical philosophers. Clocks and watches do not qualify because they involve such things as the weight of the pendulum bob and the elasticity of the spring.[1] Subsequent to the seventeenth century, the demands of the mechanical philosopher were typically weakened to broaden the scope of what was to count as an acceptable mechanical explanation. The list of primitives was extended to include such items as mass, weight, and elasticity. After Newton, a mechanical explanation of a system came to be understood as an explanation that characterised the system in terms of a few mechanical primitives governed by Newton's laws of motion. Force itself was admitted by many as an acceptable primitive. To the extent that large numbers of forces were freely admitted into mechanical explanations, those explanations became extremely flexible and the demand that explanations be mechanical correspondingly weak. This is not to say that the search for mechanical explanations in the strict sense was completely given up. When Heinrich Hertz formulated his version of the principles of mechanics in 1894[2] he reverted to something like the strict sense of mechanical explanation insofar as he tried to reduce forces to the contact action between hidden masses.

James Clerk Maxwell sought to explain physical phenomena mechanically. In his view "when a physical phenomenon can be completely described as a change in the configuration and motion of a material system, the dynamical explanation of that phenomenon is said to be complete"[3] and he expressed the view that most of the sciences that deal with systems without life had either been reduced to mechanics or were in a fair state of preparation for such a reduction.[4]

None of the mechanisms that Maxwell appealed to qualified as mechanical in the strict sense of seventeenth-century mechanical philosophers such as Boyle. His electromagnetic ether was elastic as were the colliding molecules in his first version of his kinetic theory of gases, while in later versions of the kinetic theory molecular collisions were attributed to short-range repulsive forces. While Maxwell was relaxed about just which primitives were to figure in his mechanical reductions, he did insist that those primitives be few in number and not subject to *ad hoc* adjustment to adapt to the variety of observable phenomena. He was attracted to William Thomson's theory of the vortex atom because of its non-*ad hoc* character. In that theory the properties of atoms and of substances composed of them were to be explained in terms of vortex rings in an ether that possessed the properties of constant density and zero viscosity only, as compared, for example, to Boscovich's theory of point atoms in which one was free to add whatever forces proved appropriate to the atoms. It is worth quoting Maxwell on this matter in full:

> But the greatest recommendation of this theory, from a philosophical point of view, is that its success in explaining phenomena does not depend on the ingenuity with which its contrivers "save appearances," by introducing first one hypothetical force and then another. When the vortex atom is once set in motion, all its properties are absolutely fixed and determined by the laws of motion of the primitive fluid, which are fully expressed in the fundamental equations. The disciple of Lucretius may cut and carve his solid atoms in the hope of getting them to combine into worlds; the followers of Boscovich may imagine new laws of force to meet the requirements of each new phenomenon; but he who dares to plant his feet in the path opened up by Helmholtz and Thomson has no such resources. His primitive fluid has no other properties than inertia, invariable density, and perfect mobility, and the method by which the motion

1 Alan Chalmers, "The Lack of Excellency of Boyle's Mechanical Philosophy," *Studies in History and Philosophy of Science* 24 (1993), 541-564.

2 Heinrich Hertz, *The Principles of Mechanics* (reprinted New York: Dover, 1956).

3 W. D. Niven, ed.,*The Scientific Papers of James Clerk Maxwell*, Vol. 2 (Cambridge: Cambridge University Press, 1890), p. 418.

4 *Ibid.*, p. 592.

> of the fluid is to be traced is pure mathematical analysis. The difficulties of this method are enormous, but the glory of surmounting them would be unique.[5]

Maxwell sought to explain electromagnetic phenomena mechanically, in terms of the states of a mechanical ether possessing density and elasticity. Here there is an irony. For it was in electromagnetism that it first became clear that mechanical explanations could not be achieved universally. The charge on the electron is a non-mechanical primitive on a par with its mass, whilst the electromagnetic fields are not the mechanical states of an underlying ether. The energy associated with the magnetic field is not the kinetic energy of matter in motion. Maxwell's undoubted successes in electromagnetism were achieved in spite of his quest for mechanical explanations in that domain, while his approach led to mistakes and dead-ends that needed to be overcome by those taking a different approach. At least, that is what I shall argue. In the remainder of this paper I document the nature and fate of Maxwell's attempt to explain electricity mechanically.

Maxwell's Mechanical Model of Electromagnetism

In the study of electromagnetism, Maxwell took his lead from Michael Faraday. He aimed to interpret Faraday's lines of force as representing the mechanical states of an ether. By 1862 he had made substantial progress in that direction by constructing a mechanical-ether model of electromagnetism that was able to account for the major known electromagnetic phenomena and also contained the first hints of an electromagnetic theory of light.[6] This is not the place to consider the details of Maxwell's construction of his model. Our main concern is the conception of electricity contained within it.

In Maxwell's model, lines of magnetic field were identified with the axes of vortices in the ether. The vortices were made up of innumerable small ether cells separated from each other by small particles on their surface. These particles acted as idle wheels enabling neighboring vortices to rotate in the same sense. In conductors these idle wheels were able to move from vortex to vortex through the conducting material, thus constituting a conduction current. In insulators the particles could not leave the surface of the ether cells so that any movement on their part resulted in a distortion of the cells to which they were attached. These elastic distortions corresponded to an electric field. This difference between conductors and insulators opened the way for Maxwell to accommodate charged bodies, and electrostatics, into his model. In the body of insulators and conductors there would be no accumulation of particles, because in both cases just as many particles would enter a volume element from one side as leave it from the other. The exception to this takes place at the boundary between insulators, in which ether cells are distorted in an electric field, and conductors, in which they are not. The surplus of particles on the surface of an insulator bounded by a conductor constituted the charge on the conductor in Maxwell's model.

The details of Maxwell's model were able to accommodate the major electromagnetic phenomena known at the time, the magnetic field accompanying conduction currents, the interaction of currents and magnets, electromagnetic induction and electrostatics. Taking Maxwell's model seriously and literally for the moment, it is worth stressing the extent to which his model did indeed constitute a mechanical explanation or reduction of electromagnetism in a fairly substantial sense. The ether is a medium characterized in terms of two basic properties, its density and its elasticity. (It should be added that both of these characteristics were modified when the ether was in the presence of ordinary matter in a way that was assumed but left

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5 *Ibid.*, pp. 471 - 2.

6 *Ibid.*, Vol. 1, pp. 451-513.

unspecified in Maxwell's model.) A magnetic field is identified with rotating cells in that ether and an electric field with the elastic distortion of those cells. In addition to the ether cells we have the idle wheels that separate them. It is these that, in Maxwell's words, "play the part of electricity."[7] "Their motion of translation" Maxwell continued, "constitutes an electric current, their rotation serves to transmit the motion of the vortices from one part of the field to another, and the tangential pressures thus called into play constitute electromotive force." A conduction current involves the bodily motion of the particles through conductors, while the charge on the surface of a conductor is identified with the excess of particles on the surface of the adjoining insulator. It is important to realize that these particles that "constitute the matter of electricity"[8] are material particles that serve a purely mechanical function in the model. They are not charged. That two charged bodies attract or repel each other according to Coulomb's law is something that Maxwell had to, and did, derive within his model. Those attractions and repulsions arise from the distortions of the ether cells between charged bodies and not from any force exerted by the particles on one another. In Maxwell's model the electric field, in the form of distorted ether cells, leads to the accumulation of particles rather than an accumulation of particles giving rise to the field. Charge and the fields are mechanical states in Maxwell's model. It would be a mistake to think of his idle-wheel particles as anything resembling electrons.

We must not leave Maxwell's model here because, after all, its main claim to fame is that, in the course of its development. Maxwell hit on the first hints of a displacement current and an electromagnetic theory of light. If it were the case that Maxwell's model played a

[7] *Ibid.*, p.486.

[8] *Ibid.*, p.490.

strong heuristic role in leading to that innovation, then this would have been a vindication of his attempt to offer a mechanical reduction of electromagnetism. However, there are strong reasons to doubt that mechanism played a productive role here, for two major reasons. First, I claim that the key move that led to Maxwell's innovation was made for electrical, rather than mechanical reasons. Second, while his model led to a hint of an electromagnetic theory of light, it did not yield that theory itself. The displacement current needed to be drastically modified before that could be achieved, and that move involved Maxwell abandoning the details of his model.

The terms in Maxwell's mathematical formulation of his model were subject to a double interpretation, a mechanical and an electromagnetic one. The links between the two sets of quantities opened up the opportunity to draw a link between his electromagnetic ether and the luminiferous ether that was presumed to be the seat of light waves. We have seen that a body was charged because the ether surrounding it was subject to elastic distortion. The links between the mechanical and electrical interpretation of that distortion enabled Maxwell to relate the elasticity of his electromagnetic ether to the ratio between the electromagnetic and electrostatic unit of charge. Since that ratio could be measured experimentally, this enabled Maxwell to evaluate the elasticity of the medium, which in turn enabled him to calculate the velocity at which transverse waves would be transmitted in that medium. This turned out to be equal to the velocity of light. As Maxwell remarked, "we can scarcely avoid the inference that *light consists in the transverse undulations of the same medium which is the cause of electric and magnetic phenomena,"* where the italics are Maxwell's own.[9]

A first step in getting this achievement in perspective is to note that the numerical value for the elasticity of the ether in Maxwell's

[9] *Ibid.*, p.500.

model depended on fine details of that model, details over which there was some flexibility. The best that can be said is that Maxwell's model yields a value for transverse waves in his electromagnetic medium that is within a factor of two or so of the velocity of light. As Daniel Siegel has shown,[10] Maxwell made a choice of detail which he thought would give him the simple result of a velocity equal to the ratio of the electromagnetic and electrostatic units of charge.[*]

A second step is to note that Maxwell's model fell short of giving an electromagnetic theory of light, as Joan Bromberg has observed.[11] There is no demonstration in the model of how transverse waves can arise electromagnetically. Indeed, insofar as Maxwell's model involves a displacement current, that current does not give rise to a magnetic field in the way that it must to yield electromagnetic waves.

The paucity of what Maxwell owed to his model is supported by his promptly dropping all of its details and endeavouring to develop an electromagnetic theory that would encompass optics in a way that bypassed those details. Already, in December 1861, before the final half of the paper that presented his mechanical model had even been published, we find him writing to his friend H. R. Droop at Cambridge, "I am trying to form an exact mathematical expression for all that is known about electromagnetism without the aid of hypothesis."[12] Afterall, Maxwell had made it clear that he did not propose his model seriously "as a mode of connection existing in nature, or even as one [he] would willingly assent to as an electrical hypothesis."[13]

Within a couple of years Maxwell had incorporated a form of displacement current into his electromagnetic theory in a way that had the consequence that all currents, conduction plus displacement currents, flow in closed circuits and that enabled him to derive an electromagnetic theory of light independent of a mechanical model. In "A Dynamical Theory of the Electromagnetic Field" in which he published this development, he introduced the displacement current as follows:

> In a dielectric under the action of electromotive force, we may conceive that the electricity in each molecule is so displaced that one side is rendered positively and the other negatively electrical, but that the electricity remains entirely connected with the molecule, and does not pass from one molecule to another. The effect of this action on the whole dielectric mass is to produce a general displacement of electricity in a certain direction. This displacement does not amount to a current, because when it has attained to a certain value it remains constant, but it is the commencement of a current, and its variations constitute currents in the positive or negative direction according as the displacement is increasing or decreasing.[14]

These are virtually the same words that Maxwell used to introduce displacement into his mechanical model in a way that he there described as "independent of any theory about the internal mechanism of dielectrics"[15] and where he acknowledged the

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[10] Daniel M. Siegel, *Innovation in Maxwell's Electromagnetism* (Cambridge: Cambridge University Press, 1991), Chapter 5.

[*] As a matter of fact, Maxwell made a slip of a factor of the square root of 2, as Pierre Duhem was the first to point out in his book *Les Theories Electrique de J. C. Maxwell* (p.62).

[11] Joan Bromberg, "Maxwell's Displacement Current and the Theory of Light," *Archive for History of Exact Science* 4 (1967 - 68), 218-234.

[12] Lewis Campbell and William Garnett, *The Life of James Clerk Maxwell* (reprinted New York: Johnson Reprint Corporation, 1969), p. 330.

[13] Niven, *Scientific Papers of Maxwell* (ref. 3), Vol.1, p.486.

[14] *Ibid.*, p. 531.

[15] *Ibid.*, p. 491.

electrical theories of Michael Faraday and Ottaviano Mossotti as his source of inspiration. That is, the key idea of a displacement current that Maxwell took from his mechanical model is something he had fed into that model for electrical rather than mechanical, reasons. Maxwell's model did not play the positive heuristic role in leading Maxwell to his innovations that it is typically assumed to have, although Daniel Siegel does not agree.[16]

The Lagrangian Formulation of Electromagnetism

Following the abandonment of his mechanical model of electromagnetism, Maxwell took a new tack as far as his mechanical reduction of electromagnetism is concerned, a tack that was already in evidence in his 1864 paper. Maxwell aimed to cast his theory in a mechanical form that would avoid commitment to mechanical details by exploiting the Lagrangian formulation of mechanics. A number of Maxwell's followers pursued this approach for a couple of decades after his death. I argue that all of these efforts were relatively unproductive.

The Lagrangian formulation of mechanics focuses on the energy of systems rather than the details of the forces at work in them. The Lagrangian equations of motion of a system, as alternatives to Newton's laws of motion, are differential equations involving the Lagrangian function, L, which is the difference between the kinetic and potential energies of the system. These equations can be specified provided L is known as a function of a set of independent coordinates of a system sufficient to fix the state of that system, the so-called generalized coordinates, together with their time derivatives, the generalized velocities. Forces that constrain the system without doing work do not need to be considered, and any

[16] Siegel, *Innovation* (ref. 10) and Alan Chalmers and Daniel M. Siegel, "Maxwell's Electromagnetism," New Series 4 (1993), 17-33.

coordinates on which the energy of the system does not depend are ignored. Maxwell himself illustrated the idea with characteristic clarity.[17]

We imagine a belfry containing a complicated interconnected piece of machinery. Motion can be imparted to the various parts of the machinery by means of ropes that pass through holes in the floor to the bell ringers' room below. We assume the number of degrees of freedom of the system to be equal to the number of ropes. Now, if the bell ringers know the values of the kinetic and potential energies as a function of the position and velocity of the ropes, which they could deduce from experiments performed on the ropes, then from a knowledge of the position and velocity of the ropes at any instant they could deduce the positions and velocities at any other instant using Lagrange's equations. This is possible without knowing anything about the details of the mechanism in the belfry.

Maxwell aimed to develop a Lagrangian formulation of electromagnetism in which the ether mechanism would be the analogue of the mechanism in the belfry, while the positions and velocities of the ropes would have their analogues in measurable charge and current distributions serving to determine the electromagnetic energy. Maxwell's most detailed efforts in this regard appeared in his *Treatise on Electricity and Magnetism* of 1873.

There are a number of reasons why the extent of Maxwell's achievement in this context must be seriously qualified. In his *Treatise*, Maxwell gave a detailed Lagrangian treatment for interacting closed conduction currents only. When, later in his *Treatise*, he came to build on his Lagrangian formulation to formulate the general equations of his electromagnetic theory, he

[17] Niven, *Scientific Papers of Maxwell* (ref. 3), Vol. 2, pp. 783-784.

simply added the displacement to the conduction current to give the total current. The justification he gave for this involved electromagnetic rather than mechanical reasoning.

> We have very little experimental evidence relating to the direct electromagnetic action of currents due to the variation of electric displacement in dielectrics, but the extreme difficulty of reconciling the laws of electromagnetism with the existence of electric currents which are not closed is one reason among many why we must admit the existence of transient currents due to variations of displacement. Their importance will be seen when we come to the electromagnetic theory of light.[18]

This move by Maxwell in fact undermined the major attraction of his Lagrangian method that he illustrated with his analogy of the belfry. Whereas the conduction currents were measurable generalized velocities analogous to the velocities of the bell ropes, the displacement currents were not, for Maxwell, observable. (The first direct experimental evidence for the existence of displacement currents, by their magnetic effects, emerged only with Hertz's experiments culminating in the production of radio waves in 1888.) It is as if Maxwell's belfry now included undetectable ropes influencing the energy of the mechanism in the belfry. Maxwell's introduction of the hypothetical displacement current undermined the major epistemological attraction of the Lagrangian method as Maxwell had presented it, the extent to which it enabled one to avoid hypotheses about hidden mechanisms. Maxwell's treatment of interacting closed conduction currents merely reproduced known results, allowing them to be viewed from a fresh angle. The novel results were due to the displacement current. That current was postulated for electromagnetic rather than mechanical reasons, as we have seen, while its introduction ran counter to the epistemological attraction of the Lagrangian method.

[18] James Clerk Maxwell, *A Treatise on Electricity and Magnetism*, Vol. 2 (reprinted New York: Dover, 1954), p. 252.

A quite different mode of application of the Lagrangian, or the related Hamiltonian formulation of mechanics was initiated by George Francis FitzGerald, drawing on the work of his compatriot, James MacCullagh.[19] The latter had devised a Hamiltonian formulation of wave optics in 1839 that yielded equations describing the main optical phenomena, including reflection, refraction, and double refraction. FitzGerald, by drawing correspondences between the terms in MacCullagh's theory and electromagnetic terms, was able, in 1879, to translate MacCullagh's theory into an electromagnetic theory of light that was able to include reflection, refraction, and double refraction in a way that had eluded Maxwell. It should be noted, however, that MacCullagh's theory suffered from serious mechanical difficulties, pointed out by George Stokes.[20] MacCullagh's theory implied attributing elastic properties to the ether that were quite unlike those of any known substances and that, since they implied restoring torques proportional to absolute rotations of the ether, entailed non-conservation of angular momentum. FitzGerald's translation of the theory into electromagnetic terms did nothing to overcome those difficulties. It could even be said that this mode of theorizing made headway in spite of mechanical difficulties rather than because of mechanical virtues of the approach.

FitzGerald's Lagrangian formulation of the electromagnetic theory of light, rather than Maxwell's treatment of conduction currents, formed the model for further work by Maxwellians in the

[19] George Francis FitzGerald, "On the Electromagnetic Theory of the Reflection and Refraction of Light," *Philosophical Transactions* 171 (1880), 691-711, and James MacCullagh, "An Essay Towards a Dynamical Theory of Crystalline Reflection and Refraction," *Transactions of the Royal Irish Academy* 21 (1839), 17-50.

[20] G. G. Stokes, "Report on Double Refraction," *British Association Report* (1862), 253-82.

decade or two after Maxwell's death. However, FitzGerald's theory and later extensions of it differed in character from what Maxwell had illustrated with his belfry analogy. They applied to electromagnetic fields in source-free regions, with changing electric fields causing magnetic fields and *vice versa*. There were no empirically accessible levers, as it were, controlling the system analogous to the bellringers' ropes. Insofar as, with the analysis of Maxwell and FitzGerald taken together, we have Lagrangian formulations for closed currents and for source-free regions, we still lack a Lagrangian formulation for the distinctively Maxwellian case, the case of unclosed conduction currents rendered circuital by displacement currents. The problem of uniting the two treatments required a characterization of conduction and displacement currents in terms of some common generalised coordinates. This problem was to prove intractable, as Jed Buchwald has discussed.[21]

Subsequent extensions of the Lagrangian formulation of electromagnetic optics appear, on the surface, to be a success for, and vindication of the Lagrangian method. R. T. Glazebrook, building on earlier efforts by FitzGerald and Henry Rowland, showed how the Faraday effect, together with the newly discovered Hall and Kerr effects, could be accommodated into the Lagrangian treatment by adding a suitable term to the kinetic energy.[22] One can see how this apparent unification might be employed as an exemplar of the way in which the Lagrangian method could bear fruit. Starting with the Hall effect, say, we use it to construct the necessary addition to the kinetic energy. We then trace the consequences of the Lagrangian equations containing the new term to predict the Faraday and Kerr effects. Alternatively, we use the Faraday effect to suggest the addition to the kinetic energy (as FitzGerald had initially done) and then predict the Hall and Kerr effects in a similar way.

Such a favorable interpretation of the Lagrangian method in this context is unjustified for a range of reasons. Edwin Hall had detected the effect that bears his name for conduction currents. We have already seen that the Lagrangian formulation of electromagnetism in source-free regions could not accommodate conduction currents. What the Maxwellians did was to assume that the Hall effect applies to displacement currents also. This hypothetical Hall effect they then incorporated into their Lagrangian analysis. Glazebrook's assertion that the extra term in the kinetic energy "was a direct consequence of Hall's experiments"[23] is a gross distortion of the situation. Quite apart from this theoretical difficulty, as a matter of historical fact the route to the discovery of the three effects in question did not result neither from Lagrangian nor from any other mechanical considerations. The Lagrangian formulations were retroactive attempts to accommodate results obtained by other means. It is appropriate, at this point, to review how the Faraday, Kerr and Hall effects were indeed discovered.

Faraday was convinced that all the forces of nature have a common source and are therefore interrelated. This vague notion was transformed into something precise in various ways in experimental situations. On three separate occasions, in 1822, 1833, and 1845, Faraday attempted to detect a relationship between light and electricity.[24] In 1822 he passed polarized light in various directions through solutions carrying electrolytic currents, but detected no

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[21] Jed Z. Buchwald, *From Maxwell to Microphysics: Aspects of Electromagnetic Theory in the Last Quarter of the Nineteenth Century* (Chicago: University of Chicago Press, 1985), pp. 65-70.

[22] R. T. Glazebrook, "On the Molecular Vortex Model of Electromagnetic Action," *Philosophical Magazine* 11 (1881), 397-413.

[23] *Ibid.*, p. 413.

[24] J. Brookes Spencer, "On the Varieties of Nineteenth-Century Magneto-Optical Discovery," *Isis* 61 (1970), 34-51.

change in the light. In 1833 he repeated similar experiments, this time extending his investigation to electrified solids, again with negative results. He tried again during a four-day period in September 1845, and then, a week later, decided to try applying a magnetic rather than an electric field and, of course, the result was positive. A rotation in the plane of polarization of the light was detected. No Lagrangian nor any other mechanical considerations are in evidence here.

On the opening page of the paper in which he reported the discovery that the plane of polarization of light is affected by reflection from the pole of a magnet, John Kerr, Mathematical Lecturer of the Free Church Training College, Glasgow, listed the "known facts on which [his] expectation" of the effect was founded.[25] They included the Faraday effect, the interconnection between the reflective and refractive properties of bodies, the "enormous differences" between the magnetic behavior of iron and steel, on the one hand, and transparent diamagnetics, on the other, the reversal of the direction of the Faraday rotation in solutions of salt and iron, and the known laws of metallic reflection. No trace of mechanical considerations here either.

One of the factors that put Edwin Hall on the path towards his discovery that a transverse electromotive force is generated when a magnetic field is applied across a conduction current was his puzzlement at a claim he encountered in Maxwell's *Treatise.* According to Maxwell, "the mechanical force which urges a conductor carrying a current across the lines of magnetic force, acts, not on the electric current, but on the conductor which carries it."[26] From Maxwell's field point of view the force on the conductor was understood in terms of the variation of the energy stored in the

25 John Kerr, "On the Rotation of the Plane of Polarisation by Reflection from the Pole of a Magnet," *Philosophical Magazine* **3** (1877), 321-343.

26 Niven, *Scientific Papers of Maxwell* (ref. 3), Vol. 2, p. 157.

magnetic field with the position of the conductor. As Buchwald suggests,[27] when Hall first read this passage he had not really assimilated Maxwell's theory, and thought of the force on a current-carrying conductor in a magnetic field due to a second current-carrying conductor in terms of the action of one current on another, a natural consequence for the Continental electrical-fluid theorists with whom Hall was familiar. The experiment that Hall carried out to settle the matter, which led eventually to his famous discovery, in effect refuted Maxwell's claim that in a current-carrying conductor in a magnetic field "the distribution of the current will be found to be the same as if no magnetic field were in action." Once again, there is no scope for any suggestion that the Maxwellian formulation of electromagnetism in a Lagrangian framework in some way contributed to the discovery of the Hall effect.

Beyond Mechanism

Maxwell's electromagnetism was the mechanics of an ether in a strong sense. Matter, as opposed to ether, entered into the theory in an indirect way, its presence modifying the properties of the ether. Some mechanical interaction between ether and matter , for example, accounted for some dielectric media being more polarizable than others and for some materials being insulators and others conductors. Maxwell's theory gave no hints whatsoever about what the details of that interaction might be. Consequently, that theory offered little by way of an understanding of the electrical, magnetic and optical properties of gross matter. The Continental approach understood electricity as the accumulation and flow of an electric fluid, the theory to which Maxwell offered his own as an alternative. It was that theory that showed the way to opening up a path that led to the electron theory by the end of the century.

27 Buchwald, *Maxwell to Microphysics* (ref. 21), pp. 78-79.

Before Maxwell embarked on his researches Andre-MarieAmpere had already postulated that permanent magnetism might be due to molecular currents. The laws of electrolysis pointed strongly in the direction of a unit of charge associated with the molecules transmitted through electrolytes, a fact that Maxwell acknowledged, although he insisted that the phrase "one molecule of electricity" was "out of harmony" with the theory presented in his own *Treatise*.[28] In 1878 we find H. A. Lorentz attributing optical dispersion to the vibrations of particles that are both massive and charged, while the idea that oscillating charged particles within molecules are the sources of molecular spectra became highly persuasive once Hertz had demonstrated by 1888 that oscillating charges do indeed radiate. By the early 1890s experiments in magneto-optics left little option but to acknowledge the existence of charged particles at the molecular level,[29] while experimental work in this area paved the way for the detection of the Zeeman effect in 1896. Around the same time, experiments on cathode rays had established those rays to be beams of sub-molecular charged particles. The electron theory was to find an anchorage in all of these developments during the 1890s.

By the end of the century, the electron, with a charge as well as a mass, was here to stay. In another decade or so, the mechanical ether became obsolete in light of special relativity, leaving the electromagnetic field as a primary entity not to be explained mechanically at all. While conduction currents in metals were understood as a flow of electrons, the displacement current in a vacuum was not a flow of anything, but simply a varying electric field. Maxwell's assertion, that "whatever electricity may be, and whatever we may understand by the movement of electricity, the phenomenon which we have called electric displacement is a movement of electricity in the same sense as the transference of a definite quantity of electricity through a wire is a movement of electricity" turned out to be plain false. This major ontological revolution, which saw Maxwell's fields, minus the ether, grafted on to charged electrons, amounting to a definitive rejection of the mechanical philosophy, took place somewhat surreptitiously, to such a degree that Alfred North Whitehead was able to describe the period in which it occurred as "an age of successful scientific orthodoxy undisturbed by much thought beyond the conventions" and "one of the dullest stages of thought since the time of the first crusade"[30] To some extent, this vindicated Ernst Mach's expressed opinion that the "view that makes mechanics the basis of the remaining branches of physics, and explains all physical phenomena by mechanical ideas is—a prejudice."[31]

I have argued that the attempts to reduce electromagnetism to mechanics by Maxwell and his followers were, as a matter of historical fact, not particularly productive. It would be a mistake to regard this as something that could, or should have been anticipated at the time. There is a very good reason why we should resist a generalization of the case I have made with respect to electromagnetism to conclude that searching for mechanical explanations is necessarily a methodological mistake. The reason lies in the nature of Maxwell's other major achievement on a par with his major innovations in electromagnetism. By adding statistics to the mechanics of colliding molecules, Maxwell gave us a mechanical theory of heat. Indeed, the key quotation I used to exemplify

[28] Maxwell, *Treatise* (ref. 18), Vol. 1, p. 380.

[29] Buchwald, *Maxwell to Microphysics* (ref. 21), Part V.

[30] Alfred North Whitehead, *Science and the Modern World* (reprinted Harmondsworth, Middlesex: Penguin, 1938), p. 123.

[31] Ernst Mach, *The Science of Mechanics* (La Salle, Illinois: Open Court, 1960), p. 596.

Maxwell extolling the virtues of mechanical explanations was taken from one of Maxwell's major papers on the kinetic theory. This successful reduction of one field to another, which was a mechanical reduction, parallelled another major reduction that took place round about the same time, also pioneered by Maxwell. That reduction was not a mechanical reduction at all. It was the reduction of optics to electromagnetism.