RE-READING THE PAST FROM THE END OF PHYSICS: MAXWELL'S EQUATIONS IN RETROSPECT

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I. Introduction

For the working physicist, the past and future of physics are thoroughly intertwined. With each set of goals the discipline has posed for itself comes a new gloss on prior accomplishments. As a result there is no unique or simple fashion in which the history of physics (as viewed by physicists) is related to their research priorities. In this brief essay I would like to illustrate some examples of the many ways in which the past is re-read, and then to speculate on some of the functions this constant reinterpretation plays.

By the 'history of physics' I am not referring to the relatively recent professional history of physics of the sort that appears in journals like *Historical Studies in the Physical Sciences*, *Archive for History of Exact Sciences*, and so on. Physicists as a rule do not read this literature and in any case it has not yet existed for a long enough time for there to be any meaningful assessment of their effect. Rather, I have in mind history as it appears in textbooks, as it is repeated from generation to generation of physicists, and in general the version of the past physicists learn from those primary and secondary sources they actually read.

I take the self-thematization (*Selbstthematisierung* as it appears in the original title of the conference in preparation of this volume) to mean the establishment of programmatic ideals for physics: the articulation of what it would take to provide an adequate account of natural phenomena. This articulation has occurred not once but several times within modern physics. The argument to be presented here is that each of these reorderings of explanatory ideals has been accompanied by a new perception of past accomplishments, at least in the minds of working physicists.

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poles; Ampère found the distant effects of current elements on other current elements. Maxwell, by contrast, formulated electrodynamics in such a way that he could maintain the precision of a Newtonian theory in a near-action form. Instead Maxwell proposed that charged objects act upon one another by first affecting states of an intervening substance which provided a continuum throughout space. For Maxwell his equations offered a comprehensive and quantitive measure of states of this continuum.

For example, in one formulation of his theory Maxwell represented the effects of magnetism as being analogous to an array of linked vortices through the ether. (See Figure 1.) Imagine a wire pq in which balls rotating clockwise in place represent a current. The current causes motion of the vortices on either side of the wire. These motions can then have physical effects on other wires (such as AB) just as a magnetic field induces currents in moving wires (3). Quite generally Maxwell felt the mechanics of the ether "must be subject

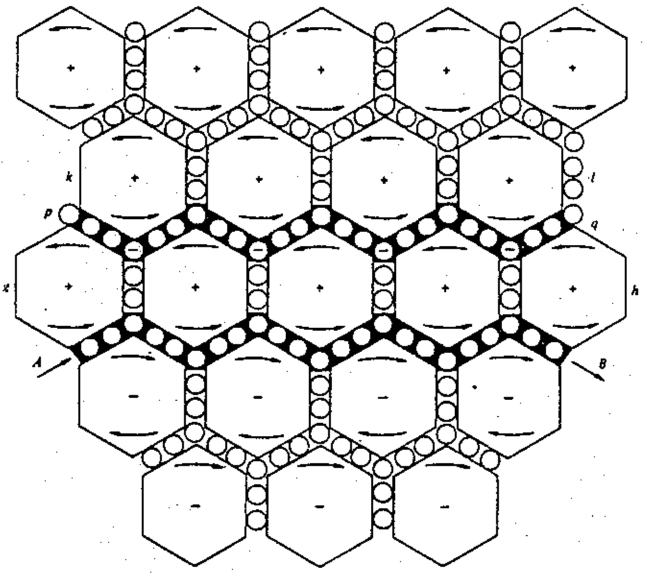

Fig. 1. Maxwell's Etherial Vortices (1861). Current in line pq causes vortices to form in the ether above and below the wire. Source: Maxwell, *Scientific Papers*, 489.

synthesis as a triumph of dynamics. Of course they recognized problems, but these were expected to be surmountable. Not everyone was of such a mind. In 1900 Wilhelm Wien became a spokesman for a new movement that hoped to reverse the effort to explain electromagnetic effects by the dynamics of the ether. Wien argued that,

> It is doubtless one of the most important tasks of theoretical physics to unite the up until now isolated fields of mechanics and electromagnetism, and to derive their relevant differential equations from a common foundation.

However Wien insisted that his predecessors' dream of finding a mechanically based synthesis was misguided.

> More promising as a foundation for further theoretical work is the opposite task: to derive the mechanical from the more general electromagnetic equations (10).

For those physicists after 1900 who sought a unified 'electromagnetic world picture', such as H. Minkowski, H. Poincaré, H. L. Lorentz, and M. Abraham, Maxwell's equations were a starting and not an ending point. No longer did they view the ether as a mechanical object (or as fundamentally analogous to a mechanical object) in which stresses and strains could be identified with electromagnetic fields. Instead, as reformulated by Lorentz, the ether was completely distinct from charge. Thus electrical current simply became the movement of charge instead of a complicated state of the ether. Furthermore, the mechanical models of the ether were entirely abandoned and electrical and magnetic fields simply became specifications of states of a purely electromagnetic continuum.

In the years following Wien's program of 1900, Lorentz and others hoped to eliminate the concept of mechanical mass as a fundamental concept. They sought to show that what we call mass is nothing more than the inertia associated with electric fields in the ether. The mass of an ordinary object was ascribed to the aggregate inertia of the object's constituent charged particles. This was what was meant by explaining mechanics in terms of electrodynamics (11).

The ambitious program of the electromagnetic world view found a fascinated observer in the person of the young Albert Einstein. Even in his days as a student at the Eidgenossische Technische Hochschule (and despite the lack of interest displayed by his teachers) Einstein felt that the general theory of relativity could not even get started without the idea of space-time. Eventually, the stunning success of general relativity made Einstein a thorough-going convert to the geometrical program.

From 1915 to the end of his life Einstein attempted to create an even more general geometrical theory that would incorporate both the general relativity theory of gravity and suitably generalized Maxwellian electrodynamics. Thus Einstein's vision of Maxwell's equations was of a component of a more general geometrical theory of space-time. Einstein even came to believe that such a generalized geometrical theory could be so formulated that quantum effects would be explained by a more fundamental physics of the continuum. As is well known, in this belief Einstein maintained a minority position against his contemporaries.

Some very interesting physics has been built upon the Einstein-Minkowski idea. One intriguing recent project has been the attempt by J. A. Wheeler *et al.* to pursue a 'geometrodynamics' in which all physics would be built upon the dynamics deduced from geometrical considerations. (They did not, however, expect to derive quantum effects as Einstein had hoped.) Part of their program included the writing of a now very popular text on gravitation which they began by summarizing their motives. First they wanted to display the results of much interesting astrophysics. They then added:

> Of quite another motive for the study of the subject, to contemplate Einstein's inspiring vision of geometry as the machinery of physics, we shall say nothing here because it speaks out, we hope, in every chapter of the book (17).

One of these chapters, naturally, is on Maxwell's equations which are interpreted as simple geometrical objects in space-time (akin to elongated wine bottle boxes). (See Figure 2.) Of course no physical object exists which looks like Figure 2; Wheeler and his colleagues are simply saying that such hypothetical objects can be used to calculate electrodynamic effects such as the force on a moving charged particle.

3. Histories and Futures: Maxwell's Equations and Quantum Physics

As discussed earlier, Einstein set his geometrical program against the view that held quantum mechanics to be the basis of a complete physical theory.

> the portion of the world's history. The total number of facts of geography required to determine the world's history is probably finite; theoretically they all could be written down in a log book to be kept at Somerset House with a calculating machine attached which, by turning a handle, could enable the inquirer to find out the facts at other times than those recorded. It is difficult to imagine anything less interesting or more different from the passionate delight of incomplete discovery. It is like climbing a high mountain and finding nothing at the top except a restaurant where they sell ginger beer, surrounded by fog but equipped with a wireless. Perhaps in the times of Ahmes the multiplication table was exciting (18).

For three years following Russell's prophecy there was extraordinary excitement in the physics community as it became clear that quantum mechanics was a very new kind of physical theory. Heisenberg, Schrödinger, and Max Born set out the elements of the new theory which was brought to what seemed a conclusion by Dirac in 1928. Dirac brought together relativity and quantum mechanics in the equation that bears his name. Max Born apparently was so exuberant over these heady developments that he announced to a group of visitors to Göttingen: "Physics, as we know it, will be over in six months" (19).

Part of Born's enthusiasm for the relativistic quantum mechanics was based on theoretical and experimental success that from the beginning promised to be spectacular. But another element of Dirac's theory that inspired statements such as Born's was grounded in a fundamental misunderstanding of what Dirac's equation meant. Dirac, it should be added, shared this misapprehension (20). The issue was this. Dirac's equation for the electron unambiguously also predicted the existence of a positively charged particle. This particle seemed to have the same mass as the electron (as well it should – we now call this particle the positron) but no such particle was known. It was thus widely assumed that someone would find a reason why this particle was the proton.

Naturally this would have been a success beyond anyone's expectation: a single equation would have accounted for both known particles and simultaneously reconciled quantum mechanics and relativity. It seemed obvious to many research physicists at the time that Maxwell's equations would easily be integrated into this system. Leon Rosenfeld later recalled that,

> After Dirac's great paper on the theory of the electron one had the impression that all the fundamental features of atomic physics had been neatly incorporated into the new conceptual structure, and with characteristic eagerness the other pioneers of the atomic

e^+e^- which then annihilates creating a second photon which is absorbed by electron 2.

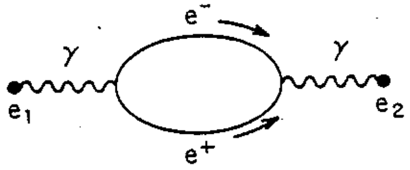

Fig. 4.

Indeed there is an infinite series of such possible processes which grow less probable as they grow more complicated. Adding together all possible diagrams gives us the total probability of electron 1 bouncing off electron 2. Maxwell's equations are thus given by infinite series, like the one just sketched of possible quantum exchanges between electrons.

Inspired by the success of quantum electrodynamics, physicists hoped that by analogy a quantum theory of the weak and the strong nuclear forces could be formulated. Some new particle or particles would take the place of the photon as carrier of the force. In 1967 S. Weinberg and A. Salam proposed a theory along these lines that explained both the weak and electrodynamic forces. They did so by making use of a new kind of symmetry.

The coordinate system in which one studies a phenomenon seems extrinsic to the phenomenon itself. For this reason Einstein postulated that it should be a goal of physics to make physical laws independent of changes of coordinate systems, even as one passed from a still to a moving system. Because coordinates are external to the objects of study, equations that remain unchanged when one changes coordinates are said to have an *external* symmetry.

Other kinds of symmetries are possible. For instance in the 1930's it was discovered that for some nuclear physics experiments nuclear effects were the same if one switched every neutron with a proton. This is an operation affecting the objects under study themselves. There the equations that remain unchanged even when one switches neutrons for protons are said to have *internal* symmetry.

Internal symmetries had been explored ever since Weyl's work in the

But even before the grand unified field theories were developed it was clear that the basic machinery of quantum field theory, together with the new ideas about internal symmetries offered a profound new insight into the nature of matter. For the first time, in the early 1970's there was a real hope that a unification of all the fields could be accomplished without reducing physics to electrodynamics or geometry.

The pedagogical organization of physics has begun to reflect the new ideal of the gauge theorists. In his text on gravity and general relativity Weinberg, like Wheeler, began by acknowledging the intrinsic interest of astrophysical phenomena. He added that it was true that the geometrical approach,

> .... *was* Einstein's point of view, and his preeminent genius necessarily shapes our understanding of the theory he created. However, I believe that the geometrical approach has driven a wedge between general relativity and the theory of elementary particles. As long as it could be hoped, as Einstein did hope, that matter would eventually be understood in geometrical terms, it made sense to give Riemannian geometry a primary role in describing the theory of gravitation. But now the passage of time has taught us not to expect that the strong, weak, and electromagnetic interactions can be understood in geometrical terms, and too great an emphasis on geometry can only obscure the deep connections between gravitation and the rest of physics (24).

Stephen Hawking, whose work lies on just this boundary between gravity and particle physics has helped advance physics towards the still distant goal of uniting gravity with 'the rest of physics'. In fact he (more than some particle physicists) is concerned that any 'final' theory of physics include gravity. Nonetheless Hawking expects that GUTS can be expanded to do the job. In his inaugural lecture as Lucasian Professor at Cambridge University Hawking began by discussing,

> The possibility that the goal of theoretical physics might be achieved in the not too distant future, say, by the end of the century. By this I mean that we might have a complete, consistent and unified theory of the physical interactions which would describe all possible observations (25).

After cautioning that such hopes have been raised before he added:

> "Nevertheless, we have made a lot of progress in recent years and, as I shall describe, there are some grounds for cautious optimism that we may see a complete theory within the lifetime of some of those present here (26).

goals of the mechanical and electromagnetic world pictures as misguided; nonetheless, we can recognize that these older interpretations of Maxwell's equations led to much productive physics. To give another example: in later life Einstein commented that Lorentz's reformulation of Maxwell's equations in terms of charges and fields in the ether "simply had to lead to the special theory of relativity" (29). Elsewhere Einstein asserted,

> The special theory of relativity owes its origin to Maxwell's equations of the electromagnetic field. Conversely, the latter can be grasped formally in a satisfactory fashion only by way of the special theory of relativity (30).

Yet another example comes from the case of weak interactions. Weinberg recalls being very impressed by the possibility of deriving Maxwell's equations from a symmetry constraint. This contributed to his hope that some analogous constraint might prove productive in finding a theory of nuclear interactions.

Finally, there is a justificatory role played by re-reading the past. It always gives added weight to a current research program if older, established theories mesh with the new theories in a natural way. For the late nineteenth century ether-mechanicians Maxwell's equations fit into a larger mechanical world view. For the reductionist electromagnetic program of the early 1900's the history of physics was up until then a series of fortunate approximations, the true basis of which was only beginning to be understood. In their eyes there was an ever decreasing number of fundamental entities – they hoped to show ultimately that there would only be electricity in the world. When Einstein was developing the special theory of relativity, Maxwell's equations represented but one of several physical theories which, when properly reinterpreted, would co-exist with (not replace) relativistic mechanics.

In recent times we see the progress of physics very differently – as a long road marked by ever increasing symmetry. We have in mind an inexorable climb up a ladder of symmetries: Galilean, Lorentzian, global gauge, local Abelian gauge, local non-Abelian gauge. The study of the reinterpretation of the past in physics is therefore integrally linked to the ideal of progress in the physical sciences.

The example I have given here of Maxwell's equations is of course not typical of all older physical theories. But I do hope to have left the reader with some sense of how the past feels to working physicists. It is certainly

11. For more on the electromagnetic world view, see items in Note 15 and 'R. McCormmach, Einstein, Lorentz and the Electron Theory', *Historical Studies in the Physical Sciences* 2 (1970), 69–81; Tetu Hirosige, 'Theory of Relativity and the Ether', *Japanese Studies in the History of Science* 7 (1968), 37–58; P. Galison, 'Minkowski's Spacetime: From Visual Thinking to the Absolute World', *Historical Studies in the Physical Sciences* 10 (1979), 85–121.
12. A. Einstein, 'Autobiographical Notes', in P. A. Schilpp (ed.), *Albert Einstein: Philosopher-Scientist* 1, La Salle: Open Court, 1969, 32.
13. *Ibid.*, 47.
14. *Ibid.*, 53.
15. There is a vast literature on the history of special relativity. The reader should refer to A. I. Miller, *Albert Einstein's Special Theory of Relativity: Emergence (1905) and Early Interpretation (1905–1911)*, Reading: Addison Wesley, 1981, and G. Holton, *Thematic Origins of Scientific Thought*, Cambridge: Harvard University Press, 1973 for further references.
16. See P. Galison, 'Minkowski', (Note 11).
17. C. W. Misner, K. S. Thorne, and J. A. Wheeler, *Gravitation*, San Francisco: W. H. Freeman, 1973).
18. B. Russell, 'What I Believe', reprinted in R. E. Egner and L. E. Denonn (eds.), *The Basic Writings of Bertrand Russell*, New York: Simon and Schuster, 1961, 367–370, on 367–8.
19. Stephen Hawking, *Is the End in Sight for Theoretical Physics*? Cambridge: Cambridge University Press, 1980, 1.
20. See for example, P. A. M. Dirac, *The Principles of Quantum Mechanics*, Oxford: Clarendon Press, 1930, 236.
21. L. Rosenfeld, 'Niels Bohr in the Thirties', S. Rozenthal (ed.), *Niels Bohr: His Life and Work as Seen by His Friends and Colleagues*, New York: Wiley, 1967, 118–119.
22. S. Weinberg, 'Conceptual Foundations of the Unified Theory of Weak and Electromagnetic Interactions', *Reviews of Modern Physics* 52 (1980), 515–523, on 517.
23. S. L. Glashow, 'The New Frontier', from *First Workshop on Grand Unification*, Brookline, Massachusetts: Math. Sci. Press, 1980, 3–8, on 3.
24. S. Weinberg, *Gravitation and Cosmology: Principles and Applications of the General Theory of Relativity*, New York: John Wiley, 1972, vii.
25. S. Hawking, 'End in Sight?' 1 (Note 19).
26. *Ibid.*, 2.
27. *Ibid.*, 26.
28. E. S. Abers and B. W. Lee, 'Gauge Theories', *Physics Reports C* 9 (1973), 1–141, on 10.
29. A. Einstein, 'H. A, Lorentz, His Creative Genius and His Personality', in H. A. Lorentz, *Impressions of His Life and Work*, Amsterdam: North Holland, 1957, 5–9, on 7.
30. A. Einstein, 'Autobiographical Notes', 62 (Note 12).