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AETHER/OR: THE CREATION OF SCIENTIFIC CONCEPTS†

I. Concept Formation in Science

When we survey the history of science, no matter what our philosophical persuasions, it is clear that the formation of new ways of conceptualizing reality is a central feature of the scientific enterprise and of what we call 'scientific progress'. However, little attention has been given to the study of how these new concepts are actually formed. Indeed, until the last 20 years or so, the question of how new concepts are formed in science has been relegated to the status of 'mere' psychology — and not even done by psychologists! Concept formation has been seen by philosophers of such disparate views as Reichenbach, Popper and Feyerabend as incapable of rational analysis; as involving some 'creative leap'; as a matter of individual psychology; as lying within the 'context of discovery'. The proper concern of philosophers is that of legitimating the new conceptual structures once they are formed; i.e., it lies within the 'context of justification'.

Historians, on the other hand, have worked quite steadily within the context forbidden to philosophers, but have not attempted to formulate theories about how concept formation takes place. With a few exceptions, even those historically oriented philosophers, who have argued that certain aspects of discovery provide legitimate concerns for philosophers, have tended to focus on the transition from one 'completed' theory to another.

The general situation just characterized has, as I will argue, led to serious misconceptions concerning the way concepts are created in science. In this paper,
I wish to examine some of the factors involved in the formation of one scientific concept: 'electromagnetic field'. I have chosen this particular concept because the formation of the field conception of forces has proven to be one of the most significant innovations of 19th and 20th century physics. Its formation has also led to the alteration of many fundamental concepts. I will examine only the electromagnetic field and not the gravitational and quantum field concepts here, since the present conception of the field as a state of space is completed in the special theory of relativity. I will also only examine the works of Faraday, Maxwell, Lorentz and Einstein, since their contributions were the most significant. I, of course, realize that a more complete analysis would involve the works of others, e.g., Kelvin, but this is not necessary for my purposes here.¹

Stated most simply, the concept of field involves the notion that continuous physical processes take place in the region surrounding the bodies and charges in question; in particular, that electric and magnetic states characterize points in the space around charges and magnets. The major issues in the early stages of the development of electromagnetic theory were: (1) Are there such processes or are the actions transmitted at a distance? and (2) If there are such processes, do they take place in space free from all matter, ponderable or otherwise, or are they states of some material medium ('aether') filling all space?

The scientists considered here held that there are such processes and thus were concerned with the second question. They maintained that an adequate characterization of electric and magnetic actions must include the notion of continuous transmission of the action through the intervening space. They believed that such a characterization is not simply a mathematically convenient way of describing the actions, as, for example, the Laplace 'potential field' characterization was for gravitation. Rather, the electric and magnetic fields as conceived by Faraday, Maxwell, Lorentz and Einstein have physical existence (i.e., they are present even when no test body is present to detect them). The major problem they faced in formulating the field concept was how, or by what processes, such an entity could exist. In the solution of that problem radical revision of other concepts occurred. The concepts of 'space', 'time', 'mass' and, indeed, 'physical', itself, were altered to accommodate the dual conception of reality: matter and field.

In the following sections, I address specific problems encountered and methods utilized by each scientist in his attempt to formulate the concept of field. From an examination of this case, it appears that concept formation in science is a process, which divides into three stages. I shall call these stages: (a) 'heuristic

¹Let me state from the outset that I do not claim that the following historical analysis is complete. I am also aware of the controversies in the literature surrounding some of the points I make. These will be addressed, primarily in the notes, when I think it is necessary for the purposes of this paper. A more complete analysis of the views of the scientists considered here can be found in my forthcoming book: Faraday to Einstein: Constructing Meaning in Scientific Theories (The Hague: Martinus Nijhoff, 1984).
guide', (b) 'elaborational', and (c) 'philosophical'. Although the specific details of each case will vary, these stages do seem to characterize the important components of concept formation in science generally.

In stage (a), the new way of conceptualizing the phenomena in question is introduced primarily by borrowing analyses of similar problems in related or unrelated fields and/or insights from these fields. These are used as heuristic guides to explore the new conceptual possibility. In the physical sciences, this will primarily involve the use of analogy, but need not in general.2 In stage (b), the new conception is accepted as a fruitful way of comprehending the phenomena in question, and methods of analysis appropriate to the discipline are used to elaborate, clarify and extend it. In physics this usually involves a highly rigorous mathematical analysis, but in other sciences, and in the more experimental fields of physics, it may primarily involve experimentation and/or the collecting of more empirical data. In stage (c), the now highly developed conception is subjected to rigorous critical scrutiny. The foundations upon which the conception rests are reassessed, leading to varying degrees of clarification and reformulation of those foundations and, thereby, to the concept.

These stages should be taken as simply providing a general schema within which to discuss concept formation in science. They will be elaborated more completely, with respect to the concept of field, in the following sections. However, some possible apprehensions of the reader should be allayed at this

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2There is a rather large philosophical literature concerning what it means to be an 'analogy'. Some of the best discussions are to be found in: Rom Harré, The Principles of Scientific Thinking (London: Macmillan, 1970); Mary B. Hesse, Models and Analogies in Science (London: Sheed and Ward, 1963); and John D. North, 'Science and Analogy', On Scientific Discovery, M. S. Gremk, R. S. Cohen and G. Cimino (eds.) (Dordrecht: D. Reidel, 1980). In the rather ornate language of Harré, the analogies used here are 'paramorphs'. Also, Lindley Darden has been working on developing a notion of 'interfield connections' in theory construction; cf. Lindley Darden, 'Theory Construction in Genetics', Scientific Discovery: Case Studies, T. Nickles (ed.) (Dordrecht: D. Reidel, 1980) and Lindley Darden and Nancy Maull, 'Interfield Theories', Philosophy of Science 44 (1977), 43-64. An 'interfield connection' involves borrowing of insights and/or results from related, but different fields as an aid in theory construction. Some examples are: borrowing from cytology to help develop the theory of the gene and borrowing from X-ray crystallography to help construct a model of DNA. With respect to the analysis of concept formation, such connections only become useful, at the earliest, late in stage (a) and, most often, in stage (b), during the elaboration of the concept.

Finally, let me give a few examples of what I take to be 'uses of analogy' vs. 'borrowing insights', in connection with stage (a). In the example developed here, use of analogy ranges from the crude analogies implicit in Faraday's view that the lines of force 'vibrate' and 'shake' like ropes (unrelated) or 'wave' like light rays or are 'vehicles of transmission' like light rays (related, but not clearly so at the time), to the very sophisticated analogies of Maxwell between the motion of the electromagnetic field and fluid flow and heat flow (unrelated fields, but similar mathematical form to the problem). In contrast to the use of analogy, in his development of a mechanical model of the aether (which I, along with Maxwell, would call an 'analogy'), Maxwell borrowed insights from the mechanics of machinery construction (i.e., 'idle wheels'). In sciences other than physics, borrowing insights may be more common at stage (a) than the use of analogy.

It should be noted that I reserve the term 'model' for a 'proposed true representation of nature'. Though I realize this is somewhat unorthodox, I, nevertheless, find such a distinction between 'models' and 'analogies' to be useful here.
First, I do not claim that these stages occur at separate times; there can be, and usually is, interaction. These stages are successive, though, *i.e.*, (b) cannot occur before (a), but it is possible to *tentatively advance* to the next stage and return to the techniques of an earlier stage when certain types of problems arise. Second, the transition from one stage to another may take place within the theory of one scientist or may span several generations and theories. It would be highly unusual, though, for a concept to be taken through all of the stages in the work of one scientist. Third, the introduction of, or significant alteration in, a concept may occur in a false theory — as is the case here. Finally, the ‘ultimate refinement’ mentioned in stage (c) is not meant as necessarily the ‘final’ or ‘last’ word on the matter. We can only judge retrospectively at what point a concept received its ultimate formulation. For example, from the perspective of pre-relativistic physics, the concept of mass had received its final formulation.\(^3\) The process of articulating ways of conceptualizing reality is an ongoing enterprise in science and our concepts are interconnected. An accepted formulation of a concept may be altered in some unforeseen way in a future theory or it may keep that meaning, but be eliminated from our description of reality.

In the final section I discuss the relevance of the example developed here for the most influential philosophical views of concept formation in science. Throughout this introduction the expression ‘concept formation’ has been used, rather than ‘conceptual development’. This has been in order to avoid begging the issue between the continuous development view of positivist and neopositivist philosophers and the discontinuous, ‘no-development’ view of ‘Kuhnian’ (though perhaps no longer Kuhn himself) philosophers. I will refer to these views respectively as the ‘orthodox’ and the ‘radical’ views of the nature of concept formation in science. They can be characterized as follows.

The orthodox position is that conceptual development is continuous and cumulative. The radical position is that concepts do not develop, but arise in a discontinuous manner, completely replacing former concepts in such a way that there is an incommensurability of meaning between one period and the next in science. What the following analysis reveals is that neither of these views adequately characterizes the formation of the concept of field. Both are too simplistic. Rather, there is commensurable development of concepts, but it is not simply cumulative.

Let me illustrate this with respect to the question of the origin of the field concept. It has been argued by Stein that the concept of field is present in Newton’s thought in the form of such notions as ‘centripetal field’, ‘field intensity’ and ‘regions of impenetrability and inertia accompanied by interaction

\(^3\)As we will see later, it would be better to say ‘pre-Lorentzian’, since mass is dependent upon velocity in his theory of electrons.
fields'. It has been argued by Heilbron that it is present in the thought of many late 18th and early 19th century scientists concerned with electric and magnetic phenomena in the form of such notions as *sphaera activitatis* and *Wirkungskreis*. Agassi has argued that it originates with Oersted's notion of "electric conflict" existing in space. These analyses and others support the view that the field concept did not arise *ex nihilo* in Faraday's theory. Vague field speculations have a long history in science. This is a point in favor of the orthodox view.

However, the following can be said against the orthodox interpretation of such analyses. Newton may have utilized the concept of field in his analysis leading to the inverse-square law when he concluded that "accelerations toward the sun are everywhere — *i.e.*, even where there are no planets — determined by the position relative to the sun". He may even have held the view that bodies are "mobile regions of impenetrability" in space. However, as Laplace showed, the mathematical formulation of the fields of the *Principia* requires that they be considered what are called 'potential fields'. A 'potential field' description allows the derivation of the force which would act on a test body if it were placed in the space surrounding the body. The characterization of the actions is still as 'at a distance', *i.e.*, the force does not exist in space in the absence of a test body. The field is 'potential' in that it represents the potential instantaneous interaction between a test particle and the body. The same is true of the late 18th and early 19th century notions in electricity and magnetism. On the other hand, Maxwell's mathematical formulation of Faraday's concept of field revealed that such fields must exist even in the absence of a test particle. Finally, any Newtonian field concept would be *logically inconsistent* with the Einsteinian concept. Newtonian fields obey the Galilean transformation rules, while Einsteinian fields obey the Lorentz transformation rules. This point is in favor of the radical view.

Both points, taken together, are in favor of a new view: *commensurable, but not simply cumulative, development*. This new view of concept formation is strongly supported by the following analysis. The ramifications of the view are discussed in the concluding section.

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II. Lines of Force

Faraday was a great experimenter, but he was also a metaphysician, which makes him an ideal candidate for introducing a new ‘world-view’. Both qualities were vital to his attempts to explain electric and magnetic actions. Hopefully, through several recent books and articles, the picture of him as the paradigm inductivist has faded. This is not to deny that his experiments were crucial in his attempt to construct an alternative theory of electric and magnetic actions (i.e., alternative to the accepted action at a distance theory of Ampère et al.). However, one must also add that he openly and admittedly participated in a great deal of metaphysical speculation both as a result of his experiments and as a guide to experimentation. Together, experimentation and speculation constituted his research. His field conception developed through their interaction. It must be stressed though that he took great care to separate what was speculation and what his experimental data could support, believing that errors are due to judgment and not to perception.

With respect to the stages of concept formation introduced in the previous section, Faraday must be characterized as beginning his work in electricity and magnetism with a stage (c) analysis of the concepts of ‘force’ and ‘material particle’. He was influenced by Davy’s knowledge of the philosophical views of Boscovich, and indirectly by those of Kant, to speculate that material particles are point centers of converging lines of force and that there is a unity of all forces in nature. These speculations led to his initial hypothesis that electric and magnetic actions are transmitted continuously, rather than at a distance. He drew upon the well-known experiment with iron filings to illustrate his new conception. If iron filings are sprinkled around the magnet, they form discrete curves, originating at the poles and extending into the space surrounding the


10One particular comment he made on the heuristic value of speculation is worth quoting at length in that it is instructive as well as prophetic.

It is not to be supposed for a moment that speculations of this kind are useless, or necessarily hurtful, in natural philosophy. They should ever be held as doubtful, and liable to error and change; but they are wonderful aids in the hands of the experimentalist and mathematician. For not only are they useful in rendering the vague idea more clear for the time, giving it something like a definite shape, that it may be submitted to experiment and calculation; but they lead on, by deduction and correction, to the discovery of new phaenomena, and so cause an increase and advance of real physical truth, which, unlike the hypothesis that led to it, becomes fundamental knowledge, not subject to change.

From Michael Faraday, Experimental Researches in Electricity (New York: Dover, 1965), 3244; see also vol. III, p. 452.

11For a good discussion of Faraday’s problem situation and a discussion of the influence of Boscovich’s views on him, see Berkson, op. cit., note 9. A somewhat different view is presented in Williams, op. cit., note 9.
magnet. As the strength of the magnetic force is increased, new lines develop within and grow outward, causing the whole system to expand outwardly. For Faraday, this situation provided a graphic illustration of the actual transmission of electrostatic and magnetic actions. That is, contrary to the prevailing view that such actions are transmitted instantaneously and directly, Faraday held that they are transmitted continuously in the surrounding space, along their 'lines of force'.

He felt he had experimental reasons, as well, for introducing this new way of conceiving such actions. His early researches in chemistry, his redoing the classic experiments for his 'Historical sketch of electromagnetism' and his investigation of Oersted's discovery of 'electromagnetic rotations' all seemed to indicate to him the need for a new conception of such actions. However, it must be said that all the known phenomena and all of his subsequent discoveries could be accounted for in action at a distance terms. Thus, there was no 'crisis' in the scientific community at the time. The 'crisis' which precipitated the field conception of forces, and thus the 'revolution', was at most for Faraday himself. Indeed, many of the arguments he offered for the new field conception in his Researches are based upon the failure to distinguish between the actual path of transmission and the resultant path of transmission of forces. Perhaps this failure was not due to his lack of mathematical sophistication, but rather to his belief that electromagnetic actions involve non-central forces. From my reading of Faraday and of the Faraday literature, this remains questionable. In any event, he did not attempt to provide a mathematical analysis of the notion of non-central forces. His expositions relied upon his visual, intuitive, analogical way of thinking about the phenomena. Finally, his theological views may also have influenced him to deliberately attempt to deal with the 'facts' as experienced, rather than as reconstructed according to the needs of mathematical analysis.

The development of his lines of force concept took place in three periods of research: (1) research into and the discovery of electromagnetic induction; (2) research into electrochemical and electrostatic induction, from which came the discovery of the 'specific inductive capacitance' of dielectric media; and (3) research into magnetic induction, from which came many discoveries important to the development of his concept, in particular: the existence of diamagnetic and magnecrystalline media, the rotation of the plane of polarized light by magnetic action, and the essential dipolar nature of magnetism.

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12It should be noted that as early as 1832 he held that electric and magnetic actions should take time. This is supported by a letter he deposited with the Royal Society at that time.


15There is a fundamental disagreement in the literature as to when Faraday 'had' his field concept: Agassi, Berkson, Williams, Gooding, op. cit., note 9; also, Gooding, 'Final Steps to the Field Theory: Faraday's Study of Magnetic Phenomena, 1845 - 1850', Historical Studies in the Physical Sciences, 11 (2) (1981), 231-275 and Williams' review of Berkson and Agassi (British Journal for the
Faraday's seminal discovery of electromagnetic induction came in two steps. First, he observed that the switching on and off of a current in a loop induced a current in a nearby conducting loop. Second, he observed that, given a permanent magnetic source and a conducting wire, the motion of either produced a current in the wire. The problems Faraday grappled with at this stage were how change in a magnetic force could produce a current and how a current could arise in a conductor simply because of motion. His proposed solution was two-fold. The first problem could be solved if we assumed that there was a previously existing relationship between the conductor and the magnetic force. That is, the observed current is produced by a change in a previously existing, unobserved state. He called this “new condition of matter” the “electro-tonic state”. He speculated that the presence of a magnetic force produces a “state of tension” within a conductor and that the introduction or removal of the force builds up or releases the strain, allowing the production of a current. Just what this “state of tension” was posed a problem for him. He seems initially to have considered it a kind of ‘polarization’ of the particles of the conductor, though not ordinary electrical polarization. Later, in stage (3) of his research, the tension became a state of the lines of force themselves.

His actual introduction of the concept of lines of force into the explanation of electric and magnetic actions came in formulating a solution to the second of his problems, i.e., how motion could produce a current. He was able to show experimentally that it was not necessary for the conducting wire to pass into greater or lesser areas of magnetic force — simply “cutting” the lines was sufficient to produce a current. He even demonstrated a quantitative relationship between the number of lines cut and the induced force.16 He extended this

16Looked at mathematically, it is only in very rare circumstances that the lines of force are closed curves as Faraday assumed. In the usual case, the lines of force spiral infinitely in a finite volume. If we look at a finite surface, each line comes arbitrarily close to every other point on the surface, i.e., if a line crosses the surface once, it crosses it infinitely many times. Thus, because of the ‘spiraling’, as opposed to ‘closedness’, the same line may be cut repeatedly. (This would be so even if the lines were closed because the line might wind about before it closed on itself.) To remedy the defect, we should have to speak of ‘the number of cuttings’ rather than ‘the number of lines cut’. Another defect in this concept used as a quantitative measure is that ‘number of lines’ is an integer while ‘field intensity’ is a continuous function. We only are able to determine the approximate intensity of the force in terms of lines of force. This problem can be dealt with by replacing ‘number of’ with a discrete measure, which is essentially what Maxwell showed how to do in ‘On Faraday’s Lines of Force.’
conception to include the case where there was no motion, as in the two-loop, changing current case, by viewing the lines themselves as moving out from the loop carrying the initial current and passing over the second loop, thus being ‘cut’ by it; thereby producing a current.\footnote{Experimental Researches, op. cit., note 10, 238.}

He was particularly impressed by the case of the induction of a current in the metal of a rotating magnet itself. He conceived of the current as being produced by the magnet cutting its own lines of force. From this he was led to claim that “\textit{a singular independence} of the magnetism and the bar in which it resides is rendered evident”.\footnote{Ibid., 60.} Although he did not directly pursue it at this time, the question naturally arises as to where the magnetism does reside if not in the bar: quite probably in the space surrounding the bar.

The rest of his \textit{Researches} involved working out and extending, by experiment and by speculation, this initial hypothesis that electromagnetic induction involves a relationship between the conductor and the lines of force.\footnote{I differ with Gooding on this point. However, I do not claim that Faraday had fully worked out his lines of force conception at this point. I only claim that this speculation guided his research. That is, he used it heuristically. See note 15.} We must, however, be careful as to how much of an hypothesis we attribute to Faraday at this point. It is reasonable to assume that at this juncture he believed that: (1) induction was not an action at a distance, but a new action; (2) this new action required further study, which would yield a fresh understanding of electric and magnetic forces; and (3) the lines of force would quite probably be shown to be essential to the description of such actions.

Without going into stages (2) and (3) of his research in any detail, let me simply state the most significant discoveries and their effect on the development of the concept. With respect to electrostatic induction, his most significant discovery was that, contrary to accepted belief, there is a difference in the inductive capacity of different dielectric media. Here Faraday hypothesized that electrostatic induction takes place by polarization of “contiguous” particles of the medium by the charges, not by direct action.\footnote{I also disagree with Gooding with regard to his interpretation of Faraday’s use of “contiguous”. In ‘Conceptual and Experimental Bases of Faraday’s Denial of Electrostatic Action at a Distance’, Studies in History and Philosophy of Science 9 (1978), 117 – 149, he argues that Faraday simply meant the next particle in the medium. Thus, he simply trades action at large distance for action at a distance between consecutive particles of the medium. This would indeed be a new conception of electrostatic action, but I believe it is not Faraday’s. I see this problem as connected with an important distinction which Faraday made in his \textit{Researches} — that between electrostatic and magnetic lines of force. On the surface it seems odd that he would make such a distinction. The basis for the differentiation lay in his belief that electrostatic induction was a polarization phenomenon while electromagnetic induction was not. He conceived of electromagnetic induction as consisting of the polarization of “contiguous particles” of the intervening medium. By “contiguous particles” he meant “those which are next” (Experimental Researches, op. cit., note 10, 1164). With this definition of “contiguous” it may appear that Faraday was only replacing action at a distance at what he called “visible distances” with action at a distance between contiguous particles.} He maintained that the
difference in inductive capacitances could be due to the effect this state of polarization has on the number of lines of force able to pass through the medium.

With respect to magnetic induction, he first attempted to develop a similar line of reasoning, involving polarization of the particles of magnetic substances. But, with the discovery of the different properties of paramagnetic, diamagnetic and magnetocrystalline substances, he switched to the notion that the lines of force are "conducted" through these substances with greater or lesser ease, depending upon the substance. He left open just what the process of "conduction" itself involved.

The final, and to him, most conclusive stage of development concerned the essential dipolar nature of magnetism. He maintained that experiment showed a "true magnetic system" to be necessarily dipolar. This convinced him that the lines of force constituted an essential part of the magnetic system in that they related the polarities. Thus, they existed even when not acting upon any substance. Any action should, then, take place through them, rather than by the two separate poles acting at a distance on one another and the substance.

In his paper, 'On the physical character of the lines of magnetic force', he addressed the question of the nature of these lines of force and concluded that

The significance of such a distinction would be minimal. It is clear that Faraday wished a more significant contrast between his view and that of the action at a distance theorists. An understanding of his conception of particles affords such a contrast. Faraday entertained the notion that material particles are point centers of converging lines of force — an idea similar to, though not identical with, that of Boscovitch. Thus, action between "contiguous particles" would be action through lines of force, not at a distance. In addition to the speculation that all matter was reducible to lines of force, he also speculated that the actions of all forces, e.g., gravity, could be explained in terms of lines of force. How, or by what condition the lines exist was never clear to Faraday. They could be a substance themselves, or a property of "mere space", or a property of an aether. If the aether existed, it was definitely not ponderable matter, and in this case he saw no objection to extending the conception of "mere space" to include such an aether.

Given the above, we can see that the distinction Faraday made between electrostatic and magnetic actions is not one of kind and thus less peculiar. Both actions would be describable completely in terms of lines of force. Faraday, however, did not make his conception of particles clear until his 1844 ‘A Speculation Touching Electrical Conduction and the Nature of Matter’ (ER, vol. ii, pp. 284 – 293). Some people have interpreted this paper as his expression of a view he only developed at that time and, perhaps, in response to Hare’s criticisms of his views on electrostatic induction. (ER, vol. ii, pp. 251 – 61.) However, I think the only way to understand Faraday is by interpreting his earlier remarks in terms of the later expressed conception of particles. In addition to the evidence existing in his researches, prior to Hare’s objections, we must look at the nature of Faraday’s response to Hare (ER, vol. ii, pp. 262 – 74). There he maintained that perhaps Hare’s problems in understanding the notion of “contiguous particles” were due to the fact that Hare failed to grasp the meanings he attached to the words. Faraday clearly saw that he was creating new meanings for the "words of electrical science". He did not elaborate on the differences in meaning, though, since he felt that they should be evident from a reading of his researches thus far. They are not, and only the 1844 “Speculation . . . " resolves the issue, in the way I have indicated. I can only venture a guess that Faraday did not specifically state his views earlier because he considered his ideas on particles to be the most speculative of his speculations. Lacking experimental evidence for his view, he did not offer it as part of his main arguments against the action at a distance view, even after he had expressed it. Thus, he continued to note an apparent difference in kind between electrostatic and magnetic actions. These matters are all discussed more fully in my forthcoming book (op. cit., note 1).
they are states of static strain or tension. He appealed to his earlier notion of
the electro-tonic state as a way of conceiving this state of strain. At this point,
however, the notion is presented in a more developed form. Rather than being
a vague "new condition of matter", "such a state would coincide and become
identified with that which would constitute the physical lines of magnetic
force". Thus, the "electronic state" is used to characterize the state of strain
in the lines themselves. The lines of magnetic force cannot be composed of
polarized material particles, as is possible in the electrostatic case, but are
"conditions of mere space" itself. Thus the "electronic state", along with the
lines of force, has become disassociated from matter (at least ponderable matter
— this point will be addressed further on) and has become a "condition of space
free from material particles".

Faraday's conception of lines of magnetic force as conditions of space is
indeed a field concept. However, because such actions were held to be
instantaneous, the concept of field is not essential to the description of the
actions. Such a 'potential' field is completely determined by the arrangement
of the particles and charges and can thus be eliminated from the description.
Only the mathematical formulation of the field description of electromagnetic
actions by Maxwell introduced a time delay in their transmission — and thus
the concept of field — necessarily into the description of the actions.

Exactly how Faraday conceived of the lines of force and their manner of
existence remains, and will remain, somewhat of a mystery. Faraday ended his
researches maintaining that he had "no clear idea" of the actual physical process
by which the lines existed and transmitted the actions. From what he did say
in his attempts to "clarify" his ideas we can see that his 'lines of force'
conception has two fundamentally different forms: (1) the lines of force are
"representative" of the intensity and direction of the force at a point and (2)
the lines have actual physical existence as either the "paths" or "vehicles" of
transmission of electric and magnetic forces.

The "representative" form is a vectorial notion. Faraday considered this
conception to be a non-speculative view which was supported by his researches.
Moreover it protected those researches from the criticisms which may be offered
against his field speculation (2). Interestingly, Faraday viewed the
"representative" view as neutral between two speculations: his field speculation
and the action at a distance speculation.

His field speculation took two forms: (a) the lines of force have physical
existence as states of a material, though non-ponderable, medium, which "we
may call ether" and (b) the lines of force have physical existence as states of
"mere space". While Faraday considered both (a) and (b) to be real

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Experimental Researches, op. cit., note 10, 3258.

See note 12. He, of course, was never able to establish this experimentally.

See note 20. If force is itself a substance, then there would be no need for an aether. What
possibilities, conception (b) was his preferred and "most speculative" view. It was "most speculative" because it was linked to his other speculative conceptions of the interconversion of all forces and of material particles as point centers of converging lines of force.

Also, throughout his researches, even when he was attempting to clarify his ideas, he seems to have remained confused as to whether the physical lines are the paths of the force or the actual vehicles of transmission of the force. In the latter case they would be similar to light rays, which were all he had for comparison. I tend to think that he considered them more as vehicles, since he wrote of them as "moving," "shaking" and "undulating". In fact, in his "Thoughts on ray vibrations" he attempted to explain how one could view light waves as undulations of the lines of force.24 Also, he attempted to connect static and dynamic electricity by a 'wave' theory of their interaction via the oscillation of lines of force between strained (static) and collapsed (dynamic) states. All of these conceptions take the form of extremely vague analogies, but they are sufficient to support the vehicles interpretation.

In conclusion, with Faraday we have the initial introduction of the notion that electric and magnetic actions should be conceived of as continuous processes taking place in space. This introduction was based on a very powerful visual image of lines of force filling space, coupled with metaphysical presuppositions about the priority of experimental observations. In later stages of development, Faraday made use of vague analogies with 'known' wave phenomena. Except for some elementary calculations, it is a non-mathematical conception. In fact he indicated in 1854 that perhaps mathematics could not itself settle the issue between his conception and action at a distance. He was impressed, though, by Kelvin's mathematical analogy between heat flow and current flow and the electric and magnetic lines of force, maintaining that the mathematical analogy between the lines of force and actual physical processes provided evidence for their being physical processes also.25 The use of mathematical analogy was to be fruitfully exploited by Maxwell in the next stage of development of the field concept. However, at that stage the lines of force were considered to be states of stress in a mechanical (i.e., Newtonian) aether. Thus Maxwell focused on only one aspect of Faraday's views — that the field could be a state of a material, though non-ponderable, medium. His favored conception that the field could be a state of "mere space" would have to wait until Einstein.

Faraday meant when he said it was possible that the lines are a state of some medium which "we may call ether", is unclear. It was quite reasonable for Maxwell to have assumed he meant it in the customary sense: a mechanical (Newtonian) aether. One is led to wonder what the present state of affairs would be if Maxwell had "got hold" of Faraday's speculation that force is the only substance and had given it a mathematical formulation!


25Ibid., 3302.
III. The Aether-Field

In this section I will discuss the aether-field concepts of Maxwell and Lorentz. Maxwell succeeded in developing Faraday's vague speculations into a viable and testable theory of electromagnetic field actions. He did so by ignoring Faraday's favored conception (2b), considering the field to be a state of a mechanical aether, i.e., one which should obey Newton's laws. Lorentz, in his elaboration, clarification and extension of Maxwell's conception, developed his own conception in which the field is a state of a non-Newtonian aether, i.e., one which does not obey the fundamental law of action and reaction. What the analysis shows is that in Maxwell's contribution there is a progression from stage (a) of development to stage (b). This progression occurred in his own method of reasoning, once he had established the laws of electromagnetic field actions. Lorentz' contribution lies fully within stage (b).

3.1 Maxwell's mechanical aether

In his first article on electromagnetism, Maxwell attempted to show that Faraday's "representative" view of the lines was capable of mathematical formulation. He did so in the first part of the paper, by using an analogy between the intensity and direction of a line of force at a point and the flow of an incompressible fluid through a fine tube. His analysis provided what amounts to a vector representation of the lines of force in terms of the velocity field of a fluid. In the second part of the paper, he provided a mathematical formulation of Faraday's notion of electro-tonic state, by introducing a vector function (what we call the 'vector potential'), but was somewhat dissatisfied with his analysis in that he was unable to construct a mechanical analogue for it. He did achieve this in his second paper.

The specific details of his analysis are beyond the scope of this paper and are not essential to our purposes. What is important to discuss is the method he so successfully exploited in developing the field concept here and in his second paper — that of 'physical analogy'. In suggesting a means of approaching the development of a new scientific conception, Maxwell stated the following:

The first process therefore in the study of the science must be one of simplification and reduction of the results of previous investigation to a form in which the mind can grasp them. The results of this simplification may take the form of a purely mathematical formula or of a physical hypothesis. In the first case we entirely lose sight of the phenomena to be explained: and though we may trace out consequences of given laws, we never obtain more extended views of the connexions of the subject. If, on the other hand, we adopt a physical hypothesis, we see the

phenomena only through a medium, and are liable to that blindness to facts and rashness in assumption which a partial explanation encourages. We must therefore discover some method of investigation which allows the mind at every step to lay hold of a clear physical conception, without being committed to any theory founded on the physical science from which that conception is borrowed, so that it is neither drawn aside from the subject in pursuit of analytical subtleties, nor carried beyond the truth by a favourite hypothesis.

The new method which Maxwell proposed as a middle way between the sterility of a purely mathematical analysis and the excesses of speculation he called "physical analogy": "that partial similarity between the laws of one science and those of another which makes each of them illustrate the other". That is, he saw "physical analogy" as a way of graphically exploring the possible physical implications of an isomorphism between the laws of different phenomena, without making any actual physical hypothesis, though such exploration may in some cases lead to physical hypotheses which can be tested by experiment. The "physical analogy" used in the first paper did not lead to any physical hypotheses, since the vectorial representation of forces ("geometrical model of the physical phenomena") can be utilized by many theories. However, it did show that an alternative representation was possible, thus supporting Faraday's position that both action at a distance and the field conception are speculations. The various analogies in the second paper did lead to physical hypotheses: the crucial hypothesis that electromagnetic actions take time and the related hypothesis (made explicit in the third paper) that light is an electromagnetic phenomenon.

Just what did the method of "physical analogy" consist of? I would say that it was not a form of analogical argument, though it is possible that some of the analogies used could provide the basis for such arguments. John North makes a similar point in his article 'Science and analogy'. I find his characterization of the use of analogies in science quite apt and useful. He maintains that analogies "have two sides to their nature: they are instruments of argument, prediction and validation and they are instruments of cognitive meaning, understanding, formalization and classification".
The predominant use of analogy by Maxwell was as "instruments of cognitive meaning". That is, he used analogies as heuristic devices for exploring unknown phenomena. He had been greatly impressed by Kelvin's analogies between heat and electrostatics and between light and the vibrations of an elastic medium. In seeking a mathematical representation of Faraday's conception, Maxwell felt the most viable means of exploration to be by analogy with known phenomena. He believed Kelvin had shown that it is possible to transfer the solution of a mathematical problem from one branch of physics to another; that is, from an established branch of science to a newly developing one. Such analogies provide only partial solutions of the problems, though. In attempting to extend an analogy and complete the solution, one may and, hopefully, would be directed to new theoretical and experimental inquiries. Thus, particularly in Maxwell's second paper, the method of "physical analogy" provided a means of exploring the conceptual possibility that electric and magnetic actions are continuous actions taking place in a mechanical medium. They provided a concrete, visual image for the mechanism, where there was none.

Maxwell did not explicitly use his analogies as "instruments of argument". Indeed, he emphasized their "provisional and temporary character" repeatedly. He maintained that one must always be ready to abandon an analogy and replace it with a better one. This is possible, since such an analogy does not contain "even a shadow of a true theory; in fact, its chief merit as a temporary instrument of research is that it does not, even in appearance, account for anything". That is, it does not tell us how electric and magnetic actions are actually transmitted. In the first paper, the mathematical representation given admits of many theories. The mathematical field equations derived in the second paper admit of many underlying mechanisms. The particular mechanical analogy used there was not "brought forward as a mode of connexion existing in nature".

However, there does seem to be an underlying analogical argument strongly implicit in his first paper, based upon his and Kelvin's analogies between electromagnetic and continuous phenomena. That is, the similarities between the two, supposedly disparate, types of actions lend support to the conclusion method of physical analogy is designed to avoid the making of physical hypotheses. Second, if Maxwell could deduce his equations from the experiments in the way she suggests, there would be little need for the analogy in the first place, which is not what she wants to maintain. I think, in interpreting Maxwell in this instance we have to understand what he saw as the Newtonian method of "deduction from experiments". I do not have a full answer to this, but with respect to his use of the method of physical analogy, he saw the experiments as providing the basis for constructing the initial analogy and for making alterations to it as he went along. This in no way denies the crucial role played by the experiments in the formulation of his equations. I agree with her that, as Maxwell explicitly states, his model in no way constitutes a physical hypothesis, so his use of it is not hypothetico-deductive. However, I also deny that his use of it is as the basis for an inductive argument. I, with Maxwell, have argued that it functioned simply as a guide to his thinking.

that electromagnetic actions are continuous. One catches a glimmer of this argument in a key passage in which Maxwell discussed Kelvin’s analogy:

Now the conduction of heat is supposed to proceed by an action between contiguous parts of a medium while the force of attraction [electrostatic] is a relation between distant bodies, and yet, if we knew nothing more than is expressed in the mathematical formulae, there would be nothing to distinguish between one set of phenomena and the other.32

The natural conclusion for Maxwell to have drawn is that electric and magnetic forces involve contiguous actions of a medium — i.e., are continuous phenomena.33 This conclusion may of course be false. However, Maxwell, in his second paper, attempted to give the continuous action conception a mathematical formulation.

The second stage of Maxwell’s formulation of Faraday’s ideas concerns the conception that the lines of force actually exist and are essential to the description of electric and magnetic actions.34 Thus, Maxwell’s analysis does involve a “physical hypothesis” at this point: the lines are states of a mechanical medium. At the outset he expressed his dissatisfaction with the action at a distance explanation, attributing his dissatisfaction partially to the same vivid image of the iron filings that so influenced Faraday. The question addressed in this paper was by what mechanism the lines could exist. In attempting an answer to this question he was led to hypothesize the existence of new phenomena, and his characterization of the field takes us far beyond Faraday’s speculations.

In this analysis he made use of several mechanical “physical analogies”, involving the assumption of an elastic medium filled with ‘vortices’ and ‘electrical particles’. I find this paper remarkable in that Maxwell, through the use of a mechanical analogy which is itself not consistent and which probably could not work even locally — to say nothing of globally — (1) found the correct field equations for electrodynamic phenomena consistent with all known results; (2) showed that if the equations were correct, there is a time delay in the transmission of electromagnetic actions; and (3) calculated the velocity of transmission of such actions to be approximately that of light.35 If (2) and (3) were correct, they should lead to the discovery of new experimental results, which would prove anomalous for action at a distance theory. (So, for the first time the field

33Maxwell did not draw this conclusion explicitly. He went on to say that other considerations make the cases different. However, that my own conclusion could not have escaped him is evident from his second paper.
34Op. cit., note 31, vol. 1, pp. 451–513. He even wrote to Faraday concerning this paper in order to ask whether he had “got hold” of Faraday’s ideas.
formulation of the actions definitely indicates the possibility of evidence which could lead to the breakdown of that view!

The very title of the second paper demonstrates Faraday’s influence, since when the term ‘physical’ was added to ‘lines of force’, the assumption of their reality was also added. Thus, the purpose of the analogy in this paper was different from that in the first. The distinction is between a ‘kinematical’ formulation, allowing a spatial representation of the intensity and direction of the lines of force; and a ‘dynamical’ formulation, giving an analysis of the generation of the field.

Maxwell maintained that a suitable analogy had to be able to account for four things: (1) a tension along the lines of force; (2) a lateral repulsion of the lines of force; (3) the occurrence of electric actions at right angles to magnetic; and (4) the rotation of the plane of polarized light by magnetic action. Only the latter two conditions had been experimentally established; while the former two, which led to the consideration of the medium as in a state of stress, were suggestions made by Faraday. Maxwell showed that a mechanical analogy consistent with these constraints is that of a fluid medium, composed of elastic cells (‘vortices’ capable of rotation), separated by ‘electrical particles’ (to function as idle wheels between the cells), under a state of stress. We do not need to analyze the details of the model here. It suffices to say that the attempt to ascertain what the mechanical cause of the stress could be led Maxwell to the correct equations of the electromagnetic field.

Interestingly, despite Maxwell’s cautionary remarks about his method of “physical analogy”, the analogy developed here led to considerable misunderstanding and criticism of his work. The model is problematic and not necessarily consistent from section to section within the paper. But, whether the total model itself actually represented a working system was not important. As Maxwell repeatedly insisted, he used it as a guide to explore the conceptual possibility that electromagnetic actions are due to stresses and strains in a mechanical medium filling space. This is precisely the function he allocated to the method of “physical analogy”. Certainly, it should not be claimed that Maxwell believed the aether to be actually composed of the vortices, particles, etc., as suggested by the analogy. The various analogies were helpful in thinking out the problems, even if in the end the mechanical system taken as a whole was not functional. Once he had obtained the equations, he ‘scrapped’ the analogy, and, though making reference to it in the Treatise, made no further use of it. At this point, he made the transition to the elaborational stage of development (b), characterized in Section 1.

In the third paper and in a “Note”, he regarded the laws as representing the phenomena, no matter what the underlying mechanism.36 From known

36A Dynamical Theory of the Electromagnetic Field’, Scientific Papers, vol. 1, pp. 526 – 597 and ‘On a Method of Making a Direct Comparison of Electrostatic with Electromagnetic Force; with
experiments and relations he was able to: (1) re-derive the equations; (2) establish the electromagnetic theory of light independent of any assumptions concerning the nature of the medium of transmission; and (3) demonstrate, with the derivation of the wave equation, that highly complex interactions take place between electric and magnetic actions in space — all subject of course to experimental confirmation.

In the Treatise he reformulated the theory in general dynamical, i.e., Lagrangian, terms. He felt that this was sufficient to establish his theory as 'mechanical', in the absence of a mechanical model for the production of the electric and magnetic forces, since Newtonian mechanics can also be reformulated using the Lagrangian formalism. He believed that the Lagrangian method had the advantage of ‘presenting to the mind in the clearest and most general form the fundamental equations of dynamical reasoning’. However, his reformulation actually helped to mask the fact that the laws he had discovered were those of a non-Newtonian dynamical system, since the abstract mathematical formalism of generalized dynamics turns out to be 'mechanical' in a wider sense. Because of the customary association of ‘mechanical’ with Newtonian mechanics, it might be better for us to characterize the Lagrangian formulation of the theory as constituting a transition from a 'mechanical' representation of the aether to a 'dynamical' one. This leaves open the possibility of a non-Newtonian aether — such as Lorentz was to develop — while still maintaining a dynamical theory, i.e., one that ‘assumes that in space there is matter in motion by which the observed electromagnetic phenomena are produced’.

It must be stressed, though, that for Maxwell there was no possibility that the aether could be a non-Newtonian substance. Also, we cannot claim that with the dynamical formulation it was no longer important to him what kind of mechanical system constituted the aether. It remained a major concern throughout his life. However, he maintained that his laws were valid regardless, of the nature of the mechanism which actually produced the phenomena. Indeed, the laws acted as a constraint on any acceptable mechanism; but knowledge of that mechanism was an essential part of a complete dynamical theory. Thus Maxwell always regarded his theory as incomplete.

In conclusion, with Maxwell we have the mathematical formulation of the field conception of electric and magnetic actions. However, the concept of field...
is not fully articulated in that the field is conceived as a state of an unknown
dynamical system. What we can say, though, is that the concept of field is
indispensable for description of the actions in Maxwell’s theory.39 Unlike the
situation with Faraday’s conception, a complete inventory of bodies, charges
and their motions is inadequate to give a complete characterization of the nature
of electromagnetic interactions. The field enters essentially into the description
because of the time delay in transmission. That is, physical processes must be
taking place in the intervening space. Also, the dynamical properties of energy
and momentum, formally reserved for matter (ponderable) are attributed to
the field. However, it is important to understand that in Maxwell’s conception,
the field does not have an ontological status co-equal with matter, but is a state
of a material substance, the aether.40

By way of summary we can say that Maxwell took one aspect of Faraday’s
conception of electric and magnetic actions as involving continuous transmission
through space, gave it mathematical formulation and, in so doing, developed
a powerful alternative to action at a distance. The mechanical representation
Maxwell wished for the underlying processes was not possible because he had
discovered the laws of a dynamical system which did not fit into the Newtonian
schema. It is important to note that the mathematical formulation of both the
representative view and the physical lines view altered them. In the former
respect, Maxwell altered the relationship formulated by Faraday between the
intensity of the force and the number of lines cut by replacing ‘number of’ with
a continuous measure. In the latter respect, Maxwell’s electromagnetic field is
not propagated along its lines of force and thus the lines are neither ‘paths’
or ‘vehicles’ of transmission of the action. These changes, however, do not
place Maxwell’s conception outside of Faraday’s framework. I think it can be

39It should be noted that there is a formulation of electromagnetism in which electromagnetic
actions are not instantaneous, yet the field is not essentially involved in the description of the
phenomena, i.e., the Wheeler – Feynman formulation. It, however, has two objectionable
components: (1) the use of ‘advanced potential’ solutions (What are called ‘advanced’ and ‘retarded’
potential solutions are both consequences of Maxwell’s equations. However, the use of ‘advanced’
solutions is problematic because with them the effects of events preceded the events themselves.);
and (2) the assumption that all radiation emitted is eventually absorbed. Also, this formulation
is not in accord with Maxwell’s views.

40Cf. the statement Maxwell made at the conclusion of his Treatise:
If something is transmitted from one particle to another at a distance, what is the condition
after it has left the one particle and before it has reached the other? If this something is the
potential energy of two particles, as in Neumann’s theory, how are we to conceive this energy
as existing in a point of space, coinciding neither with the one particle nor with the other? In
fact, whenever energy is transmitted from one body to another in time, there must be a medium
or substance in which the energy exists after it leaves one body and before it reaches the other,
for energy, as Torricelli remarked, “is a quintessence of so subtile a nature that it cannot be
contained in any vessel except the inmost substance of material things”. Hence all these theories
lead to the conception of a medium in which the propagation takes place, and if we admit this
medium as an hypothesis, I think it ought to occupy a prominent place in our investigations,
and that we ought to endeavour to construct a mental representation of its action, and this
has been my constant aim in this treatise (Op. cit., note 37, vol. II, p. 493).
said that Maxwell’s theory and its subsequent confirmation vindicated Faraday’s speculation in its general form, *i.e.*, that the lines of force represent some state of, or are due to some process in, the intervening space and that process may be of fundamental importance for the theory of electric and magnetic actions.

### 3.2 Lorentz’ non-mechanical aether

One major problem in Maxwell’s theory is that there is not a clear separation between the aether and other dielectric substances in that the aether is considered a special instance of a dielectric body. This led to a problem of how to conceive of the electromagnetic fields within matter. The field is a state of a dielectric substance, and is thus not clearly separated from states of ‘ordinary’ matter. Another significant problem is how to conceive of charge. The major contribution of Lorentz was to make a definite separation between aether and matter. This separation led to a clear understanding of ‘field’ and ‘charge’. In his conception, the aether, in matter and in a vacuum, has the same properties, and the electromagnetic field, in bodies and in a vacuum, is a state of the aether.\textsuperscript{41} In the process of working out this conception, Lorentz arrived at the conclusion that the aether is a *non-mechanical* substance.

The details of the process by which Lorentz arrived at his conception of the field as a state of a non-mechanical aether are not easy to render in a comprehensible form to the reader without sufficient technical background.\textsuperscript{42} The primary reason for this difficulty is that at stage (b) of development, the systematic use of visual images and ‘physical analogy’ was no longer necessary since the conception of electric and magnetic actions as field actions had been given sufficient mathematical formulation — *i.e.*, electromagnetic field theory was now a scientific domain in its own right and did not need to borrow insights from other scientific domains. What was required now was the clarification, elaboration and extension of the mathematical formulation developed by Maxwell. This stage of development brought about changes in the theory, but largely as the result of the solution of mathematical problems posed by various constraints, mathematical and physical.

We saw the transition from stage (a) to stage (b) take place in Maxwell’s analysis: from the heavy use of ‘physical analogy’ of the second paper to the use of the principles of generalized dynamics of the *Treatise*. Lorentz, himself, discussed this transition in his inaugural address at Leiden:

\textsuperscript{41}For a detailed analysis see, T. Hirosige, ‘Origins of Lorentz’ theory of electrons and the concept of the electromagnetic field’, *Historical Studies in the Physical Sciences*, 1 (1969), 151 – 209. I disagree with his conclusion concerning the status of the field in Lorentz’ theory. This will be discussed later in the section.

\textsuperscript{42}There are some excellent technical analyses, such as Hirosige. In particular, see, A. I. Miller, *Albert Einstein’s Special Theory of Relativity* (Reading, Mass: Addison – Wesley, 1981).
But one can also have too much of a good thing and, so, one can also . . . be all too graphic, overshoot the mark, and place so much emphasis on what should serve as a picture, that it is taken too much for the thing itself . . .

Now one must especially guard oneself against a similar excess of visualization when one is concerned with forces in physics.  

He went on to say that "the word 'force' is just a name for some quantities which occur in our mathematical formulae".  

It should not be thought, though, that this stage of development involves only the manipulation of mathematical formulae. As we will see, Lorentz did construct a "picture" of reality, but not one intended as simply a "mental picture". It was now possible, given the status of electromagnetism as a 'developed' science, to attempt a 'real' picture — i.e., a 'model'. His conception of electromagnetic actions as involving the interaction of a stationary aether with charged particles was not a "physical analogy" because, unlike Maxwell, he did bring it "forward as a mode of connexion existing in nature". That is, he made a physical hypothesis and thus we should consider it as a model, whereby what is meant here by 'model' is 'a proposed representation of reality'.

In developing this model, Lorentz affected a rapprochement between the action at a distance and the continuous action conceptions of electromagnetic actions. He actually began as an advocate of action at a distance. He had studied Maxwell's Treatise, but like most Continental physicists, found crucial parts of it rather incomprehensible. He therefore took Helmholtz' reformulation of Maxwell as the starting point for his own work in electromagnetism (1875), becoming converted to continuous action later (1891). Helmholtz had provided an action at a distance/aether reformulation of Maxwell's equations. Broadly characterized, electromagnetic actions were held to take place through the polarization of aether particles, which acted on one another at a distance. In his discussion of Maxwell's theory, Helmholtz had stated that one of the greatest problems of electromagnetic theory concerned the reflection and refraction of light. Lorentz took this as the starting point for his dissertation, the major conclusion of which was the superiority of the electromagnetic theory of light over the elastic solid theory.
and the vacuum are nearly the same. He then extrapolated the conclusion to liquids and solids. In his next paper, he made a clear distinction between the role of the aether in optical and electromagnetic phenomena in bodies and the role of the particles which constitute bodies.\textsuperscript{46} There he put forth the view that material bodies are systems of charged particles — tiny harmonic oscillators — which are the cause of dispersion. Concerning the aether he put forward "the very simple supposition that — except in the immediate neighbourhood of the particles — the properties of the aether are the same as in a vacuum".\textsuperscript{47} But he did not make the nature of the aether/particle interactions clear.

By the time he again took up problems of electromagnetic theory, he had accepted the continuous action view. In a paper of 1892, he developed the first version of his "theory of electrons".\textsuperscript{48} This paper is significant for the problem of concept formation in two respects. First, he constructed his complete model and, second, he attempted, for the only time, to give a 'mechanical' explanation for the electromagnetic equations.\textsuperscript{49}

His model consisted of the following: (1) material bodies are systems of microscopic, charged "ions" (with assumptions about how they bind to make macroscopic bodies); (2) "ions" are in part mechanical bodies to which Newton’s laws apply; and (3) the aether is everywhere locally at rest (a view arrived at earlier because he felt Fresnel’s stationary aether best explained stellar aberration) and perfectly transparent to uncharged matter. An important feature of this work is that no assumptions about the structure of the aether were made, only of matter. Given this model, what was required was to re-establish a relationship between matter and the aether, since bodies in motion may have currents and other electromagnetic phenomena taking place within them, and these result from the interaction of ‘ions’ with the aether.

The \textit{rapprochement} was brought about with the solution of this problem in that (1) changes in states of the aether are brought about only by the presence and motion of "ions" and (2) "ions" interact with one another only by changing the state of the aether, thus altering the force with which it acts on other "ions" at a \textit{later} time. So, here we have both the charged particles of action at a distance and the delayed, contiguous actions of the continuous action view. The ‘ponderomotive’ force with which the aether acts on the "ions" is a new force ('Lorentz force'), derived from the model, utilizing ‘mechanical’ considerations.

In our terms, Lorentz' attempted 'mechanical' explanation of the electro-

\textsuperscript{46}'Concerning the Relation between the Velocity of Propagation of Light and the Density and Composition of Media', \textit{Collected Papers}, 2, pp. 1 - 119.
\textsuperscript{47}'Ibid., p. 24.
\textsuperscript{48}'La Théorie Électromagnétique de Maxwell et son Application aux Corps Mouvants', \textit{Collected Papers}, 2, pp. 164 - 343.
\textsuperscript{49}Also, as Berkson has pointed out (\textit{op. cit.} note 9, pp. 273 - 274), this paper was significant for the physics community at the time because it presented the first explanation of the Fresnel dragging coefficient and provided the only derivation on it from an electromagnetic theory.
magnetic equations can be seen, rather, to be ‘dynamical’, according to the distinction made in the previous section, where we saw that ‘dynamical’ encompasses a wider scope of mechanical systems than simply Newtonian. Lorentz began this paper by criticizing Hertz for simply assuming Maxwell’s equations and not concerning himself “with the relation between electromagnetic actions and the laws of ordinary mechanics” (though he noted the method had advantages — and would revert to it himself after this paper). However, in his own analysis he applied the principles of generalized dynamics to the system of “ions” and aether, and thus did not even attempt a ‘mechanical’ explanation in the sense Maxwell had desired. Using general dynamical considerations he was able to assume both of Maxwell’s divergence equations and the equation for the circulation of the magnetic field. He then derived the equation for the circulation of the electric field (which completed Maxwell’s equations) and his new force equation. After this paper, he simply assumed all of the equations as the fundamental starting point for his theory.

The distinction between ‘mechanical’ and ‘dynamical’ is crucial here, since Lorentz’ aether turns out to be a non-mechanical, dynamical system. That is, it is non-Newtonian in that it violates the fundamental law of action and reaction. Lorentz derived the ‘ponderomotive’ force with which the aether acts upon the “ions”, but the aether does not experience any mechanical reaction from the “ions”. This is necessary in order to maintain the stationary aether hypothesis. So, the field is a state of a non-Newtonian dynamical system. Lorentz explicitly acknowledged this in his 1895 paper and defended his position in a 1901 letter to Poincaré, who had severely criticized his theory for violating this law. In the paper he said:

> Admittedly this conception would violate the law of equality of action and reaction — since we have reason to say that the aether exerts forces on ponderable matter — but, as far as I see, there is nothing to compel raising that law to a fundamental law of unlimited validity.

That is, he had arrived at the conclusion that electromagnetic theory need not conform to the laws of classical mechanics. In response to Poincaré’s criticism he said, “But why must we, in truth, worry ourselves about it [the violation of the third law]?”

There were to be further non-Newtonian consequences of Lorentz’ electron

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theory, which will only be mentioned here, since they are not directly related to our purposes: the velocity dependence of mass and the restriction of the applicability of the laws to systems with velocities less than that of light. With hindsight, we can see the non-Newtonian consequences of his theory as necessary, since the rapprochement he attempted incorporated into his model the fundamental conflict between particles obeying Newton's laws, and fields (electromagnetic forces) obeying Maxwell's laws. In Lorentz' solution it turned out the particles violated Newton's laws. Clearly a new mechanics was needed — one which Lorentz attempted and which Einstein finally provided. Since Einstein's theory of relativity finally 'eclipsed' Lorentz' theory of electrons, there has been a general failure to recognize the radical nature of Lorentz' conception and its influence on the scientific community of his time — especially on Einstein. What Einstein said of Lorentz' conception is worth noting:

The physicist of the present generation regards the point of view achieved by Lorentz as the only possible one; at the time, however, it was a surprising and audacious step, without which the later development would not have been possible.\(^{53}\)

It should also be mentioned that others took Lorentz' work as providing a transition from a mechanical to an electromagnetic 'world-view' — a conclusion Lorentz himself was careful to avoid — where all inertial masses, laws of motion and forces of interaction would be reducible to properties of an electromagnetic aether as defined by the electromagnetic field equations. That is, many physicists shifted to attempting to provide an electromagnetic foundation for mechanics.\(^{54}\)

Let us now conclude with an examination of the status of the field in Lorentz' theory. For Lorentz, as for Maxwell, the field is a state of a material substance — the aether. However, Lorentz' aether is a non-mechanical substance. This is the fundamental contribution of Lorentz to the development of the field concept. Lorentz did not, as Hirosige has argued, make the final transition to our conception of field (i.e., as ontologically on a par with matter). The aether is a necessary constituent of Lorentz' field concept. From his analysis of Lorentz' work, Hirosige concludes that as of 1895:

... we can see the modern concept of the electromagnetic field definitively settled. Though Lorentz still uses the expression 'a state of the aether' instead of 'a state of the electromagnetic field,' his aether is no longer a dielectric medium conceived


in analogy with ponderable matter; it is an independent reality which supports all electromagnetic action. Apart from the name, it is equivalent to our notion of electromagnetic field.55

But, there is more at stake here for Lorentz than a "name". "The modern concept" of field — which will here be credited to Einstein — is that it is a state of space and is ontologically on a par with matter. For Lorentz, it is essential that space be filled with a substantial aether (even if it is not "conceived in analogy with ponderable matter") and that the field be a state of that aether. As Lorentz himself said, in a note added to the 1916 edition of Theory of Electrons:

I cannot but regard the aether, which can be the seat of an electromagnetic field with its energy and its vibrations, as endowed with a certain degree of substantiality, however different it may be from all ordinary matter.56

As a state of the aether, the field is not an "independent reality"; which I interpret to mean: it is ontologically on a par with matter. The aether may be an independent reality, but then it is not equivalent to our concept of field, because it plays a different role in Lorentz' conception. In saying that Lorentz' conception is "equivalent to our modern concept", one loses sight of his crucial contribution to the development of the field concept — that of the conception of a non-mechanical aether. From there it is, as Illy has said, "only a step — not only psychologically or logically but also historically — to the assertion that the aether is equivalent to a vacuum".57 But Lorentz never made that step.

There is evidence to support the claim that Lorentz believed in the existence of the aether throughout his life. Certainly, he needed it as long as his electron theory was viable (at least 1910), for the following reasons. First, motion through the aether was thought to be responsible for the 'Lorentz—Fitzgerald contraction' of matter, hypothesized to explain the conflict between the experiments of Michelson and Morley and the stationary aether hypothesis. Although Lorentz' initial arguments for the purported contraction are ad hoc and geometrical, it became a central hypothesis of his theory that the contraction occurs because the molecular forces in matter are affected by their motion through the aether, as are electric and magnetic forces. This hypothesis is needed because, unlike in the special theory of relativity, the length contraction in Lorentz' theory is an actual physical contraction of matter, due to the circumstances of motion through the aether. Second, a further consequence of

his theory is that the mass of a body is dependent upon its motion through the aether.

Perhaps in the final analysis, though, Lorentz retained the notion of aether because in one important respect he remained a Newtonian — he believed in the absolute character of space and time. These concepts, which were to be so acutely criticized and altered by Einstein, were left untouched by Lorentz. Although we credit Lorentz with the discovery of the transformation rules of special relativity, Lorentz' interpretation of these equations is significantly different from that of relativity theory. For Lorentz: (1) the transformations are non-reciprocal, e.g. inverse spatial transformations produce a dilation effect (rather than a contraction) and (2) "local time" is simply a mathematical coordinate transformation, with no physical significance. Also, unlike in special relativity, Lorentz held that, in principle at least, it should be possible to determine "true time" (correct universal time) and correct length. These correct measurements are determined with respect to the aether reference system — where clocks and rods are at rest with respect to the aether. Also, in his conception, the velocity of light is constant only with respect to the aether frame — it appears constant in other inertial frames because of the contraction effect.

Lorentz established the aether as the universal reference frame in his 1895 paper. Though not necessarily in absolute rest, it functions as an absolute reference system in that it is at rest with respect to all other reference systems. He continued to retain this view long after his theory of electrons had become clearly distinguished from Einstein's theory of relativity. (This did not happen until about 1910, cf. Miller.) By 1910 he had come to the conclusion that, "Finally, there is only so much substantiality left to it [the aether] that through it one can determine a reference system". That is, it is the rest system which gives the correct measurements of length and time.

He continued to argue with Einstein on this point, even after the development of the general theory of relativity. In 1915, in a very interesting and, because of its 'speculative' content, rather uncharacteristic letter to Einstein, Lorentz objected to the latter's claim in his article on relativity in Die Kultur der Gegenwart that he had looked "in vain for sufficient reason" why a system

"That is, space and time provide an absolute reference frame for all motions in the universe; see note 60. S. Goldberg comes to a similar conclusion in 'The Lorentz Theory of Electrons and Einstein's Theory of Relativity', American Journal of Physics, 37: 10 (1969), 982 – 994.

"Discussion of these points would lead us to far afield. For a good analysis of the specific details on how Lorentz' conceptions differ from those of Einstein, see Miller, op. cit., note 42. See also, K. Schaffner, 'The Lorentz Theory of Relativity', American Journal of Physics, 37 (1969), 498 – 513.

"Op. cit., note 52, p. 4; "That there can be no talk of absolute rest of the aether is self-evident; the expression would not even make sense. When for brevity I say that the aether is at rest, I mean that each part of this medium does not move with respect to the others and that all perceptible motions of celestial bodies are relative motions with respect to the aether"."

‘at rest’ is preferable to a rotating system for the formulation of the laws of physics and that he thus “felt compelled to postulate the equality of both systems”. Against this, Lorentz stated that he could find “sufficient reason” for the distinction — “the two systems move in different ways with respect to the aether”. He acknowledged that Einstein’s conclusion was correct, given his denial of the aether. But he suggested that Einstein had perhaps gone “too far” in that he “put forward a personal view as self-evident”. Later, in the same letter, in discussing simultaneity and the possibility of determining correct time, he maintained that he preferred “to decorate, or should I say disfigure” one of the systems he had described with an aether, with respect to which clocks would be at rest.62

As stated previously, it thus appears that the discomfort Lorentz had with Einstein’s elimination of the aether from the field concept was connected with his reluctance to give up the notions of absolute space and time. Although he expressed gratitude to Einstein for his theory, which would not have been possible if he had “gone along old fashioned roads” and retained the aether, he never fully accepted its consequences.63

One further point of contention with Einstein, which leads us to the analysis of the last stage of the development of the concept of electromagnetic field, is that Lorentz fundamentally disagreed with Einstein’s way of doing physics. He stated in many places that Einstein simply assumed as principles what he had “with difficulty and not altogether satisfactorily” deduced. But, as we will see in the next section, this ‘postulational’ method, which affected the final refinement in the concept of field, was in this particular example a direct consequence of what we have called stage (c) of development — philosophical analysis and critique of existing conceptions.

IV. The Field

As was noted in the previous section, it is only a short step from Lorentz’ conception of field to the contemporary conception. However, it is one which could not be made without major revision of the very foundations of physics. Lorentz began that revision by maintaining that Newton’s laws need not have universal validity. However, he retained the notion of an absolute reference frame and, thus, the aether. For Einstein, the aether was “superfluous” — the electromagnetic field is simply a state of space and ontologically on a par with matter. This follows from the two postulates assumed by him in the third

62Lorentz to Einstein, January 1915.
paragraph of his famous relativity paper of 1905. Since the change in the concept of field occurred so swiftly and simply there — with the statement: “The introduction of a 'luminiferous ether' will prove to be superfluous” — we need to set the stage for this paper by examining what prior considerations led him to this position.

We have just seen that Lorentz had criticized Einstein for simply assuming what he had first attempted to deduce. What lay behind Einstein's audacity? In attempting to answer this question I will make use of Einstein's “Autobiographical notes” and of recent works by Miller, Holton and Klein. It will be demonstrated that Einstein was led to eliminate the aether from the definition of field through a process of philosophical critique and reassessment of the foundations upon which the aether and, thus, the field rested. That is, we have now reached stage (c) of development.

Einstein maintained that fundamental problems in science require epistemological analysis, which should lead to a new understanding. We see this in the relativity paper, where his preliminary analysis of the meanings of the concepts of space and time led to new kinematics, a new interpretation of Maxwell's equations and a new formulation of the laws of mechanics. His continued use of such analyses reflects his view that science without epistemology is “primitive and muddled.” Things were certainly muddled when Einstein began his study of physics.

On the one hand, in the attempts to reduce electromagnetism to mechanics:

One got used to operating with these fields [electric and magnetic] as independent substances without finding it necessary to give oneself an account of their mechanical nature; thus mechanics as the basis of physics was being abandoned, almost unnoticeably, because its adaptability to the facts presented itself as finally hopeless.

We saw this abandonment in the move from mechanical to dynamical explanations and, finally, to the assumption of the validity of the electromagnetic laws, regardless of their underlying explanation. However, explicit acknowledgment that the desired reduction was “hopeless” could not be made because:

... dogmatic rigidity prevailed in matters of principles: In the beginning (if there was such a thing) God created Newton's laws of motion together with the necessary

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64 On the Electrodynamics of Moving Bodies, all references will be to the translation by A. I. Miller, op. cit., note 42, pp. 392 – 415.


masses and forces. That is all: everything beyond this follows from the development of appropriate mathematical methods of deduction.67

As we saw, the aether was needed in order to leave open the possibility of an explanation of the field as a state of Newtonian masses and forces. Even those who did not accept the God-givenness of Newton’s laws (e.g., Lorentz) failed to challenge the Newtonian concepts of space and time. The aether was needed as an absolute reference frame. It was the philosophy of Ernst Mach which “shook this dogmatic faith” in the young Einstein. Mach maintained that no scientific principles can be regarded as established truths. They are always subject to the control of experience and are thus alterable.

On the other hand, in the attempts to reduce mechanics to electromagnetism, it was necessary to retain the aether, since all mechanical phenomena were to be reduced to states of the electromagnetic aether. However, Einstein knew quite early, from his research into the nature of radiation, that this approach would not work. This research led to what he called “the second crisis” in physics. It should be noted that at the time it was a “crisis” for him, personally, and not for the physics community as a whole. The significance of Planck’s paper on black-body radiation (a problem in classical thermodynamics) went largely unnoticed by the community. Indeed, Einstein seems to have been alone in his recognition of the full significance of Planck’s quantization of the energy of radiation. Einstein’s realization of its significance led to his first two papers of 1905 — the first on the photo-electric effect and the second on Brownian motion — and to the relativity paper.

He saw that both mechanics and electrodynamics are inadequate in regions small enough for fluctuation phenomena to count. “The contradiction with dynamics was here fundamental; whereas the contradiction with electrodynamics could be less fundamental.”68 That is, if radiation possesses discrete energy, it is in contradiction with mechanics; if it possesses an atomistic structure, it is in contradiction with mechanics and with electromagnetism (though he saw the possibility of reconciliation here). Additionally, he saw that Lorentz’ electron theory led to the prediction of the wrong amount of energy for black-body radiation. These conflicts between the various domains of physics were very apparent to Einstein, since he saw physics as one grand unified scheme.

The skepticism awakened by the recognition of these inconsistencies led him to attempt a new foundation for physics, beginning with the consideration of electromagnetic and mechanical phenomena on a macroscopic level. However, he found that all of his attempts:

67Ibid., p. 19.
68Ibid., p. 45.
... to adapt the theoretical foundations of physics to this knowledge failed completely. It was as if the ground had been pulled out from under one, with no firm foundation to be seen anywhere, upon which one could have built.69

From these attempts he "despaired of the possibility of discovery of the true laws by means of constructive efforts based on known facts". Thus, the stage was set for a more daring approach. "The longer and more despairingly I tried, the more I came to the conviction that only the discovery of a universal formal principle could lead us to assured results." Thus, "constructive theories" (such as Lorentz') cannot resolve foundational problems. Resolution can only be achieved by "theories of principle" — a very Kantian reaction to his Humean dilemma!

He used another great theory of principle as a model for his third paper: classical thermodynamics and the impossibility of a perpetuum mobile. He assumed what seemed the obvious principles needed to clear up the "muddle". The first postulate — "for every reference system in which the laws of mechanics are valid, the laws of electrodynamics and optics are also valid" — eliminates the need for the aether as a preferred reference system for the formulation of the laws of electromagnetic theory. Thus, he considered electrodynamics and mechanics on equal footing: neither is to be reduced to the other. The second postulate — "light is always propagated in empty space with a definite velocity $c$ which is independent of the state of motion of the emitting body" — eliminates the role of the aether as the only frame with respect to which the velocity of light is truly $c$ (recall that for Lorentz it only appeared to be $c$ in all inertial frames because of the contraction effect). Given these two postulates, the aether is of course "superfluous".

Einstein then proceeded to show how it would be possible to unify mechanics and electrodynamics on the basis of these two postulates. If we assume the Galilean transformation rules, the postulates are incompatible. This incompatibility is eliminated with the recognition of the arbitrary character of our definition of simultaneity (time). Einstein's kinematical analysis began with an epistemological analysis of this concept.

The description of the motion of a material particle requires values of the coordinates as functions of time. What Einstein pointed out is that all judgments of time are actually of simultaneous events. e.g., the arrival of a signal and the position of the hands of a clock. There is no problem with assuring ourselves that events at the same location are simultaneous, but judgments of simultaneity at distant points are dependent upon the existence of synchronous clocks at distant points. What we assume to be synchronous in this case is a matter of

69Ibid.
70Ibid. p. 53
definition. This provided the key to the resolution of the apparent conflict between the postulates. Einstein claimed: "The type of critical reasoning which was required for the discovery of this central point was decisively furthered, in my case, especially by the reading of David Hume's and Ernst Mach's philosophical writings." 71

With the new conception of simultaneity in hand, Einstein proceeded to derive the transformation rules for events described with respect to inertial systems. These turned out to be the Lorentzian transformation rules, rather than the Galilean. However, unlike with Lorentz' interpretation of these rules, here they are completely reciprocal: the contraction in length is not an actual physical foreshortening of bodies and there is no correct length and no true, universal time. Again, let me emphasize that Einstein derived these rules free from any assumptions about an aether and free from any particular electromagnetic or mechanical theory.

Einstein went on to show Maxwell's equations to be invariant with respect to the transformation rules. He thus provided a new interpretation for them, rather than a reformulation of them. One important consequence of this reinterpretation was that the electric and magnetic fields should be viewed as one electromagnetic field. In the old electrodynamics, the electric and magnetic fields, though interrelated, were viewed as separate fields. In the new relativistic electrodynamics, what may appear as a magnetic field with reference to one system will appear as both an electric and magnetic field with respect to a system in motion relative to the first. Thus, it is best to view the situation in such a way that an electromagnetic field exists in both systems. This resolves the problem of the asymmetrical description of the production of a current in a conducting wire when the magnetic source is moving and when the conducting wire is moving, with which Einstein began the paper.

Given the anisotropic nature of the Lorentz transformations, it was obvious that a reformulation of the laws of mechanics was necessary, since the relationship between force and acceleration is now dependent upon whether the force acts in the direction of the velocity of the system or in some other direction. Einstein derived the new equations of motion and concluded the paper by listing some new empirical consequences of these equations. What remained was a field description of gravitation, consistent with the new equations. This led to a more radical revision of the concepts of space and time; a topic which does not belong to the present paper. Let me conclude this section by briefly discussing two aspects of Einstein's own style of stage (c) analysis and by discussing the nature of the field in the special theory of relativity.

In all of his work, Einstein made heavy use of Gedanken experiments and

71Ibid. Note that with the elimination of the notion of absolute simultaneity the final blow was dealt to instantaneous action at a distance.
what could be called ‘logico-aesthetic’ considerations. His *Gedanken* experiments reflect his predilection for ‘visual’ thinking. Since his childhood, he framed problems in physics in terms of such questions as: ‘What would an observer at X see?’ ‘How would an observer in X circumstances explain Y?’ That is, he would visualize a particular situation and reflect upon its consequences. Such experiments were for him another type of experience, on a par with, perhaps even superior to, sensory experience, when one was concerned with foundational problems. He, of course, had a venerable predecessor in the use of this method, who was, I suspect not coincidentally, also concerned with foundational problems — Galileo (with a little help from Archimedes!).

Einstein’s ‘logico-aesthetic’ considerations primarily centered on the notion of symmetry. He had a profound distaste for asymmetrical descriptions and explanations of physical phenomena. He often began his papers with the formulation of an asymmetry which “disturbed” him, such as the one mentioned above and that mentioned in the section on Lorentz. His wish to rid the aether frame of its special status resulted from such considerations. The matter/field duality he claimed “disturbing to every orderly mind”. Indeed, the primary importance of ‘logico-aesthetic’ considerations in his work is reflected in his life-long attempt to present a unified view of nature through a “unified field theory” in which all physical phenomena would be represented as structural properties of the space-time continuum. Such a theory, as he conceived it, would have been the epitome of a logically simple, consistent, coherent and symmetrical theory (one is tempted to say ‘beautiful’, as Einstein would have done). His ‘logico-aesthetic’ considerations shape much of the character of contemporary physics in the overwhelming emphasis on symmetry, the intense concern over possible violations of symmetries (*e.g.*, charge conjugation — parity) and the continued attempts to develop a unified field theory (*e.g.*, ‘supergravity’).

In conclusion, given the special theory of relativity, what can be said about the aether and the field? First, with respect to the aether, if all inertial frames are equivalent for the validity of the laws of electrodynamics, it is not possible to attribute any state of motion, even rest, to the aether. Thus, there is no possibility of giving a mechanical description of the aether particles — the aether is “superfluous”.

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73See Holton, *op. cit.*, note 65, for an interesting discussion of Einstein’s predilection for visual thinking.

74The removal of the aether concept from the description of electromagnetic processes is not required by the special theory. It is simply “superfluous”, as has been discussed. In a later paper, “Ether and Relativity”, Einstein stated what he believed the special and general theories indicated about the aether hypothesis:

The special theory of relativity forbids us to assume the ether to consist of particles observable through time, but the hypothesis of ether in itself is not in conflict with the special theory of relativity. Only we must be on our guard against ascribing a state of motion to the ether.
The removal of the aether from the description of electromagnetic actions marks the final and most profound change in the concept of field. The energy and momentum of electromagnetic actions must be in the field during the time delay in transmission, in order that these quantities be conserved. Thus, the electromagnetic field is the seat of very complex processes, as it was for Maxwell and Lorentz, with one crucial difference: the electromagnetic field of relativity is no longer a state of a material substance, rather, it is an independent reality, which possesses energy and momentum, like ponderable matter.

We saw that the concept of field is indispensable for description beginning with Maxwell’s theory. The important difference with the current conception is that the pre-relativistic field is not ontologically on a par with matter, but is a state of a material substance. Thus, being indispensable for description in a physical theory is not sufficient for claiming status as an independent reality (see my remarks concerning Hirosige’s views in the previous section). In Einstein’s theory, the concept of field is not only indispensable for a theory of electromagnetic actions, it is an irreducible element of description, in the same sense as the concept of matter in Newtonian mechanics. It is independent of matter and is free to interact with it. The electromagnetic field interacts with matter by receiving energy and momentum from matter and transferring these quantities to it. In order that these quantities be conserved, it is necessary to attribute the same dynamical properties of energy, momentum and angular momentum, attributed to matter, to the field. Thus, since the field is no longer a manifestation of processes taking place in an underlying medium, it has ontological status co-equal with matter. Now that we have arrived at the conception of the field as a state of space, the historical dimension of this paper is complete.

Certainly from the standpoint of the special theory of relativity, the ether hypothesis appears at first to be an empty hypothesis. In the equations of the electromagnetic field there occur, in addition to the densities of the electric charge, only the intensities of the field. The career of electromagnetic processes in vacuo appears to be completely determined by these equations, uninfluenced by other physical quantities. The electromagnetic fields appear as ultimate, irreducible realities, and at first it seems superfluous to postulate a homogeneous, isotropic ether-medium, and to envisage electromagnetic fields as states of this medium.

But on the other hand there is a weighty argument in favour of the ether hypothesis. To deny the ether is ultimately to assume that empty space has no physical qualities whatever. The fundamental facts of mechanics do not harmonize with this view. (Sidelights on Relativity (London: Methuen, 1922), pp. 15—16.) Thus, in the special theory the aether hypothesis is “empty” since there are no physical properties associated with empty space itself. The “weighty argument” in favor of the aether hypothesis alluded to here comes from the general theory. In the general theory Einstein showed that physical processes take place in ‘empty space’, i.e., space free from matter and electromagnetic fields. These processes are associated with the gravitational field and there is a possibility, given the theory, that there is no such thing as truly empty space (no fields or matter). In some places Einstein maintained that the name ‘ether’ could be associated with these processes, but the issue is really a matter of semantics. Actually, since the address was given at Leiden, Einstein may have just been paying respect to Lorentz. The essential point is that with the special theory, the fundamental character of the aether hypothesis is changed.
V. Conceptual Development

In light of the historical analysis, we can now examine my initial contention that there is commensurable, but not simply cumulative, development of concepts in science. The analysis presented in the preceding sections supports the claim of continuous development for the concept of field. The conceptual 'revolution' usually credited to Einstein was dependent upon the work of Faraday, Maxwell, Lorentz and others not considered here. This 'revolution' and, I believe, all 'revolutions' in science are long processes, not sudden Gestalt switches. Although a change in Gestalt certainly took place here, it was a gradual process, begun at stage (a) and only completed at stage (c) of development.74 I prefer to characterize conceptual change in science as 'evolutionary', i.e., as a process whereby radical change can occur in a continuous context.75 Einstein clearly saw himself as continuing changes in our conception of physical reality begun by Faraday. Our analysis shows him to be correct in his belief. He credited Faraday with an "intuitive grasp" of the new physical conception and Maxwell with the "lion's share" of the revolution which he, himself, brought "to some degree of completion". Completing the revolution, however, meant abandoning the Newtonian framework into which Maxwell had attempted to fit his field conception.76 Lorentz' work made it clear that the Newtonian framework was inadequate.

It must be stressed, though, that in each of the views presented, the various field concepts differ in important respects. The lines of force are neither the vehicles nor the paths of transmission of force in the Maxwellian field concept. Lorentz argued that the field was not a state of a Newtonian dielectric substance. Einstein argued that the aether was superfluous to the concept of field. He and Lorentz both argued that Maxwell's wish for a mechanical description of the motion of the aether particles could not be fulfilled, though for different reasons. Einstein also argued that Lorentz' belief in the absolute character of space and time could not be part of the new world-view.

Einstein, himself, did not view these changes as representing a serious break with the "Faraday - Maxwell program". To a significant extent he was correct in maintaining this. The essential ingredient of that program is the field description of electromagnetic actions. As we saw, Maxwell viewed the field

74It is interesting to note that the concept of field spans several 'paradigms'. As conceived by Faraday it could have been either part of the Newtonian paradigm or a new 'lines of force' paradigm. As conceived by Maxwell it was part of the Newtonian one. As conceived by Lorentz it was part of the theory of electrons. As conceived by Einstein it was part of the relativistic paradigm.

75Note that I do not mean this in the sense of S. Toulmin, Human Understanding (Princeton: Princeton University Press, 1974). Although the evolutionary model presented there is interesting, I find it too problematic.

76For Einstein, completing the revolution meant representing matter and electromagnetic fields as part of the structure of the space-time continuum, as he did for the gravitational field.
equations as valid, regardless of the structure of the underlying mechanism. Lorentz assumed his modified version of them as fundamental and regarded the aether as stationary. For both, the laws governing electromagnetic actions are not dependent upon any particular hypothesis about the structure of the aether.

Finally, I think it can be said that when the material aether was at last abandoned, the preferred aspect of Faraday's "intuitive grasp" — the field is a state of "mere space" — acquired a new significance, though Faraday's conception of the lines of force as states of space and Einstein's conception of the field as a state of space are not identical. So one can only claim that Faraday's view that the field could exist independent of all matter, ponderable or otherwise, was made credible. Also, one cannot help but note the similarity between Einstein's hope for a unified field theory and Faraday's hope to describe all physical phenomena in terms of the lines of force — though it would be very misleading to claim them to be the same hope. Einstein, himself, believed that a unified field theory would be the culmination of the "Faraday – Maxwell epoch". I find no reason to dispute this belief.

Thus far we have shown the continuous development aspect of the orthodox position to be correct and the discontinuous, 'no-development' aspect of the radical position to be incorrect. Turning now to the other aspects of these positions, as stated at the outset, I think it can be said that the historical data support the view that at least in the case of the formation of the concept of field there is commensurable development, but that it is not simply cumulative. I suspect that the same can be shown for the development of other concepts as well. However, this case is sufficient to provide a counterexample to both the orthodox and the radical positions and thus to cast doubt upon them. In order for either position to claim support the history would have to be recast. To illustrate this, let me briefly sketch possible orthodox and radical interpretations for only the Faraday – Maxwell portion of my analysis and show their incorrectness.

The orthodox recasting of the history could go in either of two ways. First, Faraday's speculative views could be ignored, with only his experimental data, and possibly the 'representational' lines of force conception being considered. It could then be claimed that Maxwell derived his equations from the data of Faraday and others. The field concept would then originate with Maxwell. The second possibility would be to acknowledge Faraday's speculations about the physical lines of force, but only the aether aspect. It could then be claimed that Maxwell gave mathematical formulation to Faraday's aether-field concept.

"To say more than is said in the present analysis about the difference would require a discussion of the field in general relativity. See the discussion by Berkson, op. cit., note 9, for an interesting analysis of the differences."
In contrast to these recastings we have seen the following. Faraday's field speculations were an integral part of his *Researches* and they had significant influence on Maxwell. Maxwell, however, ignored Faraday's favored and possibly non-Newtonian speculation that the lines of force could be states of space. Finally, Maxwell did not simply mathematically formulate the aether aspect of Faraday's view. He developed a field concept that differs significantly from the conception of the lines of force as the *vehicles* or *paths* of transmission of electromagnetic force. Here we see development that is not simply cumulative.

Developing a possible radical recasting is more difficult. If one adheres strictly to that position, it is difficult to say anything more than that Faraday's real view was that the physical lines of force are states of empty space and that Maxwell developed a radically different aether-field concept. One of the problems with the radical position is that although it claims to be supported by the history of science, if one takes its tenets seriously, it should be impossible to do *historical* analysis in any usual sense!

In contrast to the radical recasting we have seen the following. Faraday was himself unsure which of the physical lines of force conceptions might turn out to be 'correct'. Maxwell started with the aether aspect of Faraday's conception and attempted to incorporate it into the Newtonian framework, although he ended with a significantly different conception. Here we see commensurable development.

In conclusion, I want to indicate briefly what I believe to be the two chief reasons for the failure of the orthodox and radical views to present an adequate theory of concept formation in science. They fail, first, because of their respective attitudes towards the history of science and second, because of a particular philosophical prejudice they both, perhaps unknowingly, share. The orthodox attitude is *ahistorical*. Its proponents have attempted to develop a theory of how scientific knowledge ought to be rather than paying attention to how actual science is. A certain amount of this kind of development is necessary to the philosophical enterprise. Philosophers cannot and should not simply accede to reporting what it is that scientists do in developing theories. However, we cannot simply ignore the historical data either. A philosophical theory of concept formation in science must illuminate actual cases of concept formation.

While orthodoxy fails partly because of its ahistorical attitude, the radical view fails partly because it is *unhistorical* in its attitude. The actual process of concept formation is not examined over an extended period of time, since concept formation is not seen as a process. Thus, *e.g.*, Faraday's concept of field would be compared with Einstein's concept of field, but the intervening history would not be considered. An adequate theory of concept formation requires a 'fine structure' analysis of the history — even finer than the one presented here. We have to start, *e.g.*, with Faraday, analyze his lines of force...
conceptions in detail, analyze Maxwell's aether-field concept, see if there are relationships between them, etc. The case presented here is even more damaging to the radical view because, by its own standards, philosophical theories about science must square with the actual historical data.

A discussion of the philosophical prejudice shared by both views sheds some light on what has been called the 'incommensurability problem'. 'Commensurability', for orthodoxy, is defined in terms of a particular philosophical theory about meaning in scientific theories: the 'reductionist theory of meaning'. What this theory maintains is that concepts in different theories can be compared by 'reducing' their content to shared theory-neutral observation sentences. There is a substantive history of critiques of this theory, among them those presented by the radical view. The radical view maintains that since the reductionist theory fails, concepts in different theories are not commensurable. That is, the radical view at least tacitly assumes that the reductionist theory of meaning is the only theory possible. In essence it shares the orthodox philosophical prejudice. I have argued elsewhere that, given the historical data, the course of wisdom is to consider the 'incommensurability thesis' as providing a reductio ad absurdum of the reductionist theory of meaning.78

What is required is that we redefine 'commensurability' in terms of a new theory of meaning in science, which is beyond the scope of this paper. However, a few remarks on this subject are perhaps in place. I believe the analysis given in this paper indicates that a realistic conception of the nature of meaning in science must depend significantly upon 'context of discovery' analyses. That is, I wish to argue, in line with the argument presented by Shapere in a recent paper, that a theory of meaning in science must have its origins in an analysis of scientific practice, rather than in the philosophy of language.79 Thus, I am advocating a significantly different approach to the development of a theory of meaning in science than is traditional. From my research thus far, I have formulated an hypothesis, which both resolves the 'problem of incommensurability of meaning' and provides the basis upon which to formulate a new theory of meaning. Scientific concepts are best characterized as explanatory schemata. The nature of the connection between related concepts in successive theories can be shown by an analysis of the chains of reasoning relating successive schemata. These chains can be traced through the stages of development characterized here. Let me again stress the tentative nature of this hypothesis; it is not the prime purpose of this paper to develop or defend it.

What I have tried to show is that concept formation in science is a process, capable of rational analysis and not simply the result of some inexplicable 'creative leap'. I have tried to show that, at least on the basis of the present

case-study, the process takes place in stages: (a) heuristic guide, (b) elaborational and (c) philosophical. This is a simple, but hopefully not a simplistic, schema. It may possibly provide a general characterization of concept formation in science, though more analyses will be necessary to show if this is so. Obviously, the particulars of each case will differ. They will depend upon the nature of the science and upon the state of its development at the time; e.g., use of analogy depends upon what are considered to be the "known" phenomena at the time. Again, the specific details of the methods utilized will bear the imprint of the particular science and scientist. Finally though it is still an open question whether the schema provided here is generalizable, at the very least my analysis of the formation of the concept of field provides an important counter-example to the views considered.

What has been shown here is that at each stage of development it is possible to trace a chain of reasoning concerning the problem of how electric and magnetic forces can be continuously transmitted through space, despite the differences in conception. The exploration of the possibility of such continuous actions began with Faraday's vague analogy between the lines of force and light rays and culminated in the sophisticated, highly mathematical use of 'physical analogy' by Maxwell. During the elaboration of the conception, the Lagrangian formalism was employed and 'dynamical' considerations replaced 'mechanical'. The concern for an understanding of the 'mechanism' producing electric and magnetic fields waned. Nevertheless, the field conception continued to develop, partly because the Lagrangian formalism masks the underlying physical situation. It was possible for Lorentz simply to proceed without considering the structure of the aether. Upon philosophical reflection, Einstein realized that not only were scientists not concerning themselves about the mechanical structure of the aether, but that it was not necessary to consider it at all. The notion of the aether had become superfluous because it rested on untenable assumptions. The field is simply a state of "mere space".