FARADAY AND THE POWERS OF MATTER

The Role of Principles, Hypotheses, and the Interpretation of Experiment in the Development of Faraday's Field Theory, as presented in his Experimental Researches in Electricity, 1830-1855

A Thesis submitted to the Board of the Faculty of Literae Humaniores in the University of Oxford for the Degree of Doctor of Philosophy

by

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Conventions

References

Bibliographical details of a work will be given in the footnotes only if that work has not been listed in the bibliography, otherwise reference will be made only to the author, short-title, page or article number and where applicable, the edition cited and the volume number.

Citations

All references to the twenty-nine series of Faraday's Experimental Researches in Electricity will be identified by the paragraph numbers supplied by Faraday. These numbers are enclosed in parentheses and have been set into the text wherever possible. References to other papers by Faraday will be by page number (if no paragraph numbers are supplied). Thus, ERE I: 321 refers to page 321 of the first volume of the Researches and ERE I: (321) to paragraph (321) of a paper found in that same volume.

Only minor simplification of Faraday's punctuation has been made in quotations from his papers and letters. Spelling and the use of capitals have not been altered. All italics are Faraday's unless a note appears to the contrary. References to Faraday's Selected Correspondence will be by volume and page number.

Abbreviations of Book and Serial Titles

A. SERIALS

AHES	Archive for History of Exact Sciences
BJHS	British Journal for the History of Science
C. & D. Math. Jour.	Cambridge and Dublin Mathematical Journal
HSPS	Historical Studies in the Physical Sciences
Phil. Mag.	The Philosophical Magazine
Phil. Trans.	Philosophical Transactions of the Royal Society
RILS	The Royal Institution Library of Science. Physical Sciences
Sci. Mem.	Scientific Memoirs, selected from the Transactions of Foreign Academies of Science ..., R. Taylor and W. Francis, eds.
Sci. Mem. (1853)	Scientific Memoirs. Natural Philosophy, J. Tyndall and W. Francis, eds.

B. BOOKS

Faraday	Agassi, J., Faraday as a Natural Philosopher, Chicago and London (1971).
Fields of Force	Berkson, W., Fields of Force. The Development of a World View from Faraday to Einstein, London (1974).
ERE (I,II,III)	Faraday, M., Experimental Researches in Electricity. Reprinted from the Philosophical Transactions of 1831-1852, 3 vols., London (1838,1844,1855), facsimile reprint: New York (1965).
ERCP	------ Experimental Researches in Chemistry and Physics, London (1859), facsimile reprint: Bruxelles (1969).
Preliminary Discourse	Herschel, J.W.F., A Preliminary Discourse on the Study of Natural Philosophy, London (1830), facsimile reprint: New York (1966).
Forces and Fields	Hesse, M.B., Forces and Fields. The concept of Action at a Distance in the history of physics, London (1961).
Affinity and Matter	Levere, T., Affinity and Matter. Elements of Chemical Philosophy 1800-1865, Oxford (1971).
Aether and Electricity	Whittaker, E.T., A History of the Theories of Aether and Electricity, vol.1, The Classical Theories, London, revised and enlarged edn. (1951).
Michael Faraday	Williams, L.P., Michael Faraday, a Biography, London (1965).
Corr. (I,II)	------ (et. al., eds.), The Selected Correspondence of Michael Faraday, Edited on behalf of the Royal Institution of Great Britain, 2 vols., Cambridge (1971).

Introduction

Faraday's reasoning, unlike that of most theoretical scientists, was based almost entirely upon his own experience in the laboratory. It had to be so. As he explained in a letter of 1860,

> I could not imagine much progress by reading only, without the experimental facts & trials which could be suggested by the reading. I was never able to make a fact my own without seeing it;--and the description of the best works altogether failed to convey to my mind, such a knowledge of things as to allow myself to form a judgement upon them ... For the same reason I never could work ... by students or pupils. All the work had to be my own.[1]

No facts were as important to Faraday as those which he himself had observed, and the observation of an effect or process was often more important than the discovery of a fact.

Yet Faraday was aware that one's expectations or 'favourite notions' may influence what one believes one sees taking place and that the words one uses to describe the phenomenon may prejudice its interpretation. Consequently Faraday emphasizes the dangers of hypotheses and theoretical concepts as much as he does their uses. He devalues specific theories as belonging to the realm of 'speculation' or of 'doubtful knowledge': they can be regarded as true only when they have been shown to provide a unique or unequivocal interpretation of the facts.

Although he held that knowledge can originate only in direct

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1. Faraday to E. Becker, 25 October 1860, Corr. II:975.

perception and that scientific knowledge is of facts and of laws, Faraday was a scientific realist. He believed that no theory could be truly explanatory unless advanced as a causal theory. While Faraday often introduced new words in an attempt to make his descriptions theory-free and his theories themselves as non-committal as possible, and while he saw the task of science as the search for natural laws, he was convinced that this task could be complete only when the causes of the facts expressed in those laws had been found.

For these reasons Faraday's Experimental Researches in Electricity are of considerable interest to those concerned with the acquisition, development, and structure of scientific knowledge. Faraday's Researches are the record of the conscientious examination of natural phenomena by a man who shared many of the concerns of those who have traditionally regarded themselves as philosophers of science rather than of nature itself.

The three volumes of Faraday's Experimental Researches in Electricity contain the series of twenty-nine research papers on electricity, electro-chemistry, and magnetism, together with a number of expository papers and lectures. All were read or published between 1821 and 1855. These papers exemplify a particular view of nature, on which the key to an understanding of natural phenomena and their laws is the examination of changes in the condition and properties of matter. Faraday proves to have little interest in the motions of bodies, being all but entirely preoccupied with the discovery of relationships between their properties or 'powers'. The field theory emerges gradually as the set of laws which govern these relationships.

It is only in retrospect that Faraday's Researches, particularly the earlier papers, can be seen as the gradual accumulation of the premises, both factual and theoretical, which are to form his final

argument for the truth of the field theory. Consequently my analysis of the Researches is carried out on two levels. It is an exposition of the evolution of certain key concepts and of the postulates or principles which define those concepts. I will show how Faraday was able to refine his basic concepts to such a point that they could become the language both of description and of theory. But in order to show why Faraday reaches the conclusions that he does at any of the main stages of his career, an analysis must be made of the relationship between his principles or extra-theoretical postulates, his theoretical concepts and the statements in which they appear, and his interpretation of phenomena.

Principles, Hypotheses, and the interpretation of Experience

In this essay I will show how the field theory emerges from the interplay between a set of postulates and theoretical concepts, an epistemology or theory of knowledge, and experience--the interpretation of the results of Faraday's experiments. The main ingredients of Faraday's thought and work are summarized below.

(1) Principles. Though tacit in much of Faraday's reasoning, a set of regulative principles or postulates can be shown to be at work throughout the Experimental Researches, some of them being present from as early as 1831. These principles are statements about the way in which force must act and the way in which matter and force must interact. I shall subsequently identify them as the principles of equality of action and reaction (or of cause and effect), of polarity or induction, of the conservation of force, and of economy or of least action. Taken together these principles define Faraday's concept of force: force is a definite and indestructible quantity of polar or inductive action.

Faraday believes that all the forces of nature (as chemical, electrical, magnetic, cohesive, optical, thermal, and gravitational actions) are simply forms of a single fundamental power (which is probably electricity), and that all forms of this power are convertible into other forms. I will call this belief the principle or doctrine of the unity and/or convertibility of force. This principle may appear to be an hypothesis about the nature of force rather than a postulate like those listed in the previous paragraph, but like the latter, Faraday treats it as being beyond experimental disproof and uses it in his interpretation of experience.

When considered in the larger context of nineteenth century natural science this set of principles may be seen to have constituted a theory of the nature of force, one which was shared by many of Faraday's contemporaries but which was rejected by his successors and interpreters. However, Faraday himself does not treat these principles as a theory--as a set of hypotheses or possibly-true statements. We shall see that these principles govern the interpretation of experience (and, therefore, the use of phenomena as evidence for some theory) and that they are not themselves liable to experimental disproof.

(2) Theoretical Concepts. The most important of Faraday's theoretical concepts is force, by which he understands a quantity of power or action and which he represents with the well-known lines of force. The lines of force play a dual role, being used to represent force as a theoretical entity and to describe the actual distribution of force as an agent. Other concepts include that of a 'particle' or atom (a concept which does not include the substantiality of atoms) and of a 'mutual' or 'inductive relation' (a dynamical coupling or interaction whereby the active powers of one individual are opposed or reacted upon by those of another).

In this essay I will treat Faraday's concept of force as being defined by the principles or postulates. I will show that as his career progresses Faraday's basic concept of force becomes more and more precise; that this process corresponds to an increase in his explicit reliance upon the postulates described above; and that it involves the use of experiment not simply as a means of proving or disproving conjectures, but of refining the language to be used in describing and explaining the phenomena.

An indication of the close relationship between the postulates and Faraday's theoretical concepts is that by 1838 the lines of electrostatic force embody these postulates, i.e., the behaviour of the electrostatic field as represented by that of the lines is consistent with the truth of the postulates. Since the lines of force are used throughout to interpret and to describe the phenomena, it will become evident that it is through his use of these lines that Faraday imports the postulates into his interpretation of experience and, therefore, into his explanations of the properties and behaviours of matter.

(3) Faraday's Epistemology. In his well-known attack on atomism of 1844 Faraday announces the principle or precept that knowledge is perception, i.e., that what cannot be perceived (in principle) can neither be known nor conceived (imagined). It follows that matter (or any entity, including force) can be known only as its powers or manifest properties. Since Faraday applies this principle to the whole domain of real and possible entities it functions effectively as a check upon the positing of complex or structural entities and hence as a criterion of the admissibility of an hypothesis.

Faraday's epistemology requires an ontology of powers and the denial of the existence of substance as the bearer of such powers. What exists must be active, for what is not active cannot be perceived

(and is not a legitimate referent of a scientific hypothesis). Ultimately there are only powers and the laws of those powers.

A main conclusion of this thesis can now be stated. Faraday's epistemology requires an ontology of powers. The postulates or principles are the laws of those powers; the laws of the field. Nor is the field the abstraction that our experience of concrete, material objects would suggest. By identifying physical entities with their secondary or manifest qualities Faraday makes the conditions of knowledge his criteria of existence. He can therefore regard the field as real: it may not be actually seen, but it can be known through its effects.

(4) Hypotheses. Faraday makes use of a number of assumptions about the possible natures or structures of elementary atoms and about possible relationships between the known properties of matter. While the most important of these are those about the nature of atoms, it will become clear that these hypotheses cannot be considered in their own right in Faraday's work. The hypotheses specify only the elements of a theoretical conception or model of some process. The behaviours of that model--the laws of the interactions of its constituent parts--are determined by the postulates or principles.

Whereas Faraday never questions the truth of the principles, he usually feels obliged to justify the use of an hypothesis on instrumental grounds. Hypotheses can, of course, be confirmed or disproven by experiment.

(5) Experience. The actual nature of a particular phenomenon or process is often more important to Faraday than a 'fact'--a result which can be expressed as a set of data. The most important of Faraday's conclusions depend at least as much upon the observation and analysis of an effect as they do upon the discovery of or the attempt

to explain regularities of behaviour.

The relationship between experience and theory is one of the most interesting aspects of Faraday's work. In view of the range and complexity of his experimental analyses I have discussed only those observations or experimental trials which meet one or both of the following criteria: (1) that the trial had results which proved to be of crucial importance to Faraday's development of the field theory; (2) that Faraday's interpretation of the experiment is particularly relevant to the attempt to illustrate the relationship between postulates, theory, and experience in his work.

The interplay between Principles, Hypotheses, and Experience

Two general conclusions can be drawn from the present study of the relationship between theory and experience. First, that the most important 'relationship' is between experience and the principles--not between experience and the hypotheses. Faraday interprets the phenomena in terms of one or more of the principles or postulates. Thus interpreted the phenomena can be adduced as evidence for or against some hypothesis. The second conclusion is that the phenomena play two quite distinct roles in Faraday's Researches. They provide Faraday with certain basic 'facts' or 'natural truths' about the nature of force. It is such facts which are expressed as the principles of polarity, unity, conservation, and so on, even though Faraday does not allow that experiment could bring about the downfall of one of these principles. The second role of the phenomena is that they provide a necessary check upon theorizing, for it is by experiment that the truth or falsity of an hypothesis is determined.

Yet Faraday's response to experiments which produced unexpected

or unwanted results shows that he distinguished between results which tend to confirm or disconfirm some hypothesis and results which require the revision or redefinition of a theoretical concept. The important point here is not just that Faraday never allows mere experience to overthrow one of his postulates, it is that he regards negative results as a sign that the postulate--or the concept it specifies--is not quite adequate to the task of 'representing' what is actually the case. This is why we find Faraday inventing new words and new concepts. His is a search for an ever closer agreement between 'the natural truth and the conventional representation of it'.

1. THE POWERS OF MATTER

The ontological primacy of force or power in Faraday's later theories is due to the fact that it is the primary explanatory concept in his earlier theories. I will therefore consider Faraday's beliefs about the nature of the world insofar as these can be shown to have governed his conception of what constitutes an adequate scientific explanation.

Although Faraday never states them explicitly, it emerges that he had three main criteria for the adequacy of an explanation: (1) a theory is a possible or probably-true account if it is consistent with all of the postulates and precepts described above. A theory can be regarded as a true account if it meets two further criteria, viz., (2) that it provides an explanation of some phenomenon or process which cannot be explained on any other theory which also meets the first criterion, and (3) that it identifies and posits causes as sufficient conditions of the occurrence of an effect or of the truth of some law. In the course of this essay I will argue that these criteria are linked to a view of nature which I shall identify as Faraday's dynamism.

1.1 Metaphysics, Physics, and Historical Interpretation

I have drawn attention to the main elements of Faraday's thought and to the fact that he held certain beliefs about the nature of the world and of scientific explanation. Those scientists and historians who held that the mainstream of science between the seventeenth and twentieth centuries was newtonian mechanics have regarded Faraday's denial of substance as the bearer of primary qualities, his insistence on the ontological primacy of force, and his use of the concept of lines of force as the result of the fact that he was educated neither as a newtonian nor as a mathematician.[2] Thus Faraday has been regarded as something of an anomaly, a genius whose achievements were recognized only after they had been made respectable by his two main interpreters, William Thomson and James Clerk Maxwell.[3] The authors of more recent studies of Faraday have drawn attention to differences between Faraday's basic concepts or his ontology and those of his mechanically-minded contemporaries and successors. However, in recent studies Faraday's principles, his concepts, and his theories have either been lumped together as constituting his 'metaphysics', 'world-view', or his 'research programme'[4]--or they have been identified with his

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2. This was also the view of some of his contemporaries, such as G.B. Airy and John Tyndall. See, for example, Tyndall's Faraday as a Discoverer (London, 1868), reprinted in RILS 2:50-123.

3. Even though he regarded Faraday's theory as superior to any existing alternatives, Maxwell accepted neither Faraday's ontology nor his related conception of explanation. See Maxwell's articles on Faraday in his Scientific Papers, 2: 355 ff. and 768 ff.; William Thomson, 'On Atmospheric Electricity' (18 May, 1860), reprinted in RILS 1:334-347, at p.346; and E.T. Whittaker, Aether and Electricity (chapters 6-8).

4. E.g., J. Agassi, Faraday,and William Berkson, Fields of Force.

adoption of some specific theory of matter such as Boscovichean atomism[5] or the dynamical atomism of Joseph Priestley, Thomas Exley, and others.[6]

I believe that the existing studies of Faraday's work have failed on one or both of the following counts:

First, those historians who tend to follow a Popperian interpretation of science (on which metaphysics is distinguished from physics proper on the basis of a demarcation criterion)[7] have tended to treat Faraday's entire experimental career as a search for crucial experiments.[8] While I accept that Faraday may be described as having held a certain metaphysics, to describe his work as an attempt to confirm or refute certain consequences of the metaphysics is to provide neither an adequate description of the way in which experience is brought to bear upon theory by Faraday, nor, therefore, an adequate explanation of the way in which field theory emerges from the experimental side of

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5. L.P. Williams, Michael Faraday. This is the most comprehensive study of Faraday's life, work, and sources. It has been criticized by J.B. Spencer, 'Boscovich's Theory and its Relation to Faraday's Researches: An Analytic Approach', AHES 4 (1967): 184, and by P.M. Heimann, 'Faraday's Theories of Matter and Electricity', BJHS 5 (1971): 235. These interpretations, together with that of T. Levere, Affinity and Matter, are discussed below, in section 2.6, p.199 ff.

6. P.M. Heimann, op.cit., note 5.

7. K.R. Popper, The Logic of Scientific Discovery (London, 1959) and I. Lakatos, 'Falsification and the Methodology of Scientific Research Programmes', in I. Lakatos and A. Musgrave, eds., Criticism and the Growth of Knowledge (Cambridge, 1970): 91. The normative import of such a criterion for the scientist is that he seek crucial experimental tests of his metaphysics or of that set of beliefs or conjectures which has generated a certain area of enquiry. Although Popper introduced the demarcation criterion and the notion of falsifiability as a solution to the problem of induction (Popper, 'Conjectural Knowledge: My Solution to the Problem of Induction', in his Objective Knowledge [Oxford, 1972]: 1) the normative implications have sometimes been carried over into the history of science, so that the task of the historian is seen as the 'rational reconstruction' of science as the search by scientists for crucial tests of their research programmes.

8. Berkson, Fields of Force (passim), and Agassi, Faraday.

Faraday's work.[9]

Second, recent historians have tended to ignore certain fundamental differences between Faraday's meta-scientific beliefs, his basic concepts, and his ontological commitments, and the corresponding set of beliefs, concepts, and commitments of the newtonian or mechanical-corpuscular view of nature. Thus Williams has discussed Faraday's concept of lines of force without noticing that force in Faraday's Researches denotes a quantity of action rather than the intensity of a quantity at a point or the ratio of the products of two masses and accelerations,[10] and that Thomson and Maxwell did not (and could not) give to force the primary explanatory and ontological status that Faraday had done.[11] In one recent study of a native British tradition of newtonian dynamical atomism[12] it has been suggested that Maxwell may have taken force to be primary in the same way that Faraday had

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9. Although certain experimental results do prove to be crucial as tests of specific hypotheses, Faraday simply does not treat those results which are inconsistent with his principles in the way that a good falsificationist should have done. In Faraday's work experiment proves to be a determinant of the meaning of terms as well as of the truth of statements.

10. Williams does notice that Faraday treats force as a quantity of action (Michael Faraday:373) but explores the implications of this point only insofar as they bear upon Robert Hare's misunderstanding of Faraday's theory of electrostatics.

11. Force (in the mechanical sense) can be eliminated entirely from mechanics--it is not an essential explanatory concept. In 1856 Thomson suggested that the 'potential energy of gravitation may be in reality the ultimate created antecedent of all motion, heat, and light ...' ('The Origin and Transformation of Motive Power', RILS 1:196 ff., at p.201), but for reasons similar to those subsequently advanced by J.W.F. Herschel, Faraday clung to the idea that force, not energy, must be the basic explanatory concept of a physical theory. See: J. Herschel, 'On the Origin of Force' (1866), reprinted in his Familiar Lectures: 460.

12. P.M. Heimann and J.E. McGuire, 'Newtonian Forces and Lockean Powers: Concepts of Matter in eighteenth-century thought', HSPS 3 (1971): 233, at p.306. Faraday is identified with this tradition in Heimann, op.cit., note 5.

done.[13] Finally, although Berkson points out that Faraday denied and that Maxwell maintained a distinction between matter and the field, he fails to grasp the deeper reasons for this difference, treating Maxwell's interpretation of Faraday's work as a suppression of Faraday's metaphysics.[14] Thus we have two incompatible views: that Maxwell fully understood Faraday's theory of lines of force and that he assigned to force the same ontological primacy that Faraday had,[15] and that Maxwell accepted Faraday's field theory while rejecting (and suppressing) his view of nature.

While the present essay supports the findings of those recent studies in which Faraday is shown to have held certain principles in common with theorists of the non-mechanical or dynamical tradition of atomism,[16] my discussion of Faraday presupposes a more rigorous

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13. But see J.E. McGuire, 'Forces, Powers, Aethers, and Fields', Boston Studies in the Philosophy of Science 14 (1974): 119, esp. p.141.

14. Berkson, Fields of Force: 188. A similar failure underlies Agassi's treatment of the response of Faraday's contemporaries to his work.

15. Williams, Michael Faraday: 513. Maxwell did understand Faraday's theory of lines of force from an instrumental standpoint, but this standpoint was one which Faraday could not easily adopt. In the introductory pages which are all that remains of an early manuscript 'On the Mathematical Theory of Polar Forces' (University Library, Cambridge, Add. Mss. 7655, uncatalogued) Maxwell insists that although it contributes to 'the clearness of our conception' to 'direct our attention to the potential function as if it were a real property of the space in which it exists', we have no reason to believe that 'anything answering to this function has a physical existence in the various parts of space'. Compare Faraday's position as discussed in the last part of this thesis, sections 4.1, 4.2, 4.3.

16. See Heimann, 'Faraday's Theories ...' (op.cit., note 5); Heiman and McGuire, 'Newtonian Forces and Lockean Powers ...' (op.cit., note 12); and McGuire, 'Forces, Powers, Aethers, and Fields' (op.cit., note 13). However I will show that Faraday's thought cannot be identified with a native British dynamical tradition to the extent that Heimann has supposed.

distinction between mechanics on the one hand, and different forms of dynamical atomism on the other. This distinction (which is drawn below) is specifically tailored to the problem of describing Faraday's concepts and his ontological commitments. It is designed to catch what prove to be the main differences between Faraday's own theory of matter and the field and those which he criticized during his career.[17]

1.2 Mechanics and Dynamism: a working distinction

The ontology of those theorists who have traditionally been regarded as mechanical theorists[18] admits of two sorts of things: objects (as the bearers of properties) and changes. Specifically, it is supposed that there are entities having the following primary qualities: extension (shape, size, impenetrability), spatial location, and mobility (velocity). The explanation of phenomenal or secondary qualities and regularities of behaviour consists in attributing primary qualities to fundamental entities or substances and in positing or discovering laws which define changes in the relationships between these entities.

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17. The larger task of placing Faraday's ideas in the intellectual context of early nineteenth-century natural philosophy is beyond the scope of the present essay. A comparative study of Faraday's dynamism, that of his contemporaries and predecessors, and the mechanical-corpuscular view of his successors is made in my 'From Active Powers to Inertial Mass: Dynamical and Mechanical Theories of Matter and the Field, 1830-1880' [in preparation].

18. This group would include those followers of Boyle and of Newton who accepted the existence of substance (and of imponderables) and the distinction between primary and secondary qualities. See M.B. Hesse, Forces and Fields: 98 ff.; R.E. Schofield, Mechanism and Materialism (Princeton, 1970); and Heimann and McGuire, op.cit., note 12. For the distinction in the philosophical tradition see J. Bennett, 'Substance, Reality, and Primary Qualities', American Philosophical Quarterly 2 (1965): 1.

In order that the behaviours of bodies be described by the laws the bodies must have mass. While the primary qualities are necessary attributes of substantial or material entities, inertial and gravitational mass are not conceptually necessary attributes. Mass is introduced through and defined in terms of the set of laws which describe the way in which a body must behave under certain conditions. It is required not by those criteria which specify what it is to be a material object but for the explanation of change: an object must have mass if it is to behave in the way that the laws of motion require that objects do behave.

The ontology of mechanics therefore admits of entities having such properties as are required by the criteria of objecthood on the one hand and by the laws of motion on the other. Force does not belong in the ontology. It is neither a theoretical entity nor an essential explanatory concept.[19] In suggesting that force does not belong in the ontology of mechanics because it may be eliminated from explanations I am doing some violence to the subtleties and complexities of the history and interpretation of mechanics, but my point is that mechanical explanation does not necessarily commit one to an ontology of forces whereas dynamism does.[20]

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19. It is always possible to replace forces (as causes of change of position or of the rate of that change) by ratios of the products of masses and accelerations (as Mach argued) or by reducing all electric, magnetic, and other forces to the motions of extended inertial matter or to body-forces. The latter reduction is epitomized in the mechanical matter-field theories developed by Thomson and Maxwell in the 1860s. See, for example, William Thomson, 'On Vortex Motion', Transactions of the Royal Society of Edinburgh 25 (1869): 217, and J.C. Maxwell, 'On Physical Lines of Force' (1860-62), reprinted in his Scientific Papers, I: 451.

20. Cf. Max Jammer, Concepts of Force (Chapters 6-8), Hesse, Forces and Fields; esp. pp.157 ff., Levere, Affinity and Matter (Chapter 1), and McGuire, op.cit., note 13.

Dynamism[21] also admits of entities and of change, but in dynamism the ontology and the explanatory concepts may become conflated so that causes or agencies may appear in the ontology as ultimate entities. This conflation of substance and attribute (or of things and causes) comes about in the following way. Like the mechanical theorist, the dynamist recognizes certain rules about what it is to be an object, but his criteria of objecthood differ in one important respect: they are derived from a subjective or volitional notion of force (as the cause and perceptual basis of all qualities) rather than from the common-sense notion of what it is to be a material object.[22]

Dynamical theorists such as Joseph Priestley, John Herschel, and Faraday have denied that there is any distinction between what exists as the bearer of properties and what acts in manifesting those properties and that fundamental entities must have some primary qualities

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21. For a discussion of dynamism as a metaphysical system see M. Capek, 'Dynamism', in P. Edwards, ed., The Encylopedia of Philosophy (8 vols., New York and London, 1967) 2: 444 and Jammer, op.cit., note 20 (chapter 9). Main proponents of dynamism as a metaphysical theory include Leibniz and Kant, and main proponents of dynamical atomism as a physical theory include Kant, Boscovich, Priestley, Davy, J.W.F. Herschel, and Faraday. However, the term 'dynamical atomism' has also been used to refer to a tradition originating with the latter part of the 31st Query of Newton's Opticks (1730). For an account of these traditions see: Heimann and McGuire, op.cit., note 12 and A. Thackray, Atoms and Powers. For Boscovich and Kant and their influence on the nineteenth century see: Williams, Michael Faraday (Chapter 2); 'Kant, Naturphilosophie and Scientific Method', in R. Giere and R. Westfall, eds., Foundations of Scientific Method: The Nineteenth Century; 'Boscovich and the British Chemists', in L.L. Whyte, ed., Roger Joseph Boscovich; D.M. Knight, Atoms and Elements (Chapter 3); R.G. Olson, 'The Reception of Boscovich's Ideas in Scotland', Isis 60 (1969): 91; and Levere, Affinity and Matter (Chapter 1).

22. See Jammer, Concepts of Force (Chapters 1 and 9). Of Faraday's contemporaries, the most influential proponent of the view that knowledge is of forces as the causal basis of perception was J.W.F. Herschel. See his Preliminary Discourse (esp. pp.87-90); 'On Atoms', in Herschel's Familiar Lectures on Scientific Subjects (esp. p.458); and W.A. Wallace, Causality and Scientific Explanation, vol. 2: 98 ff.

which are identical to those manifested by bodies as secondary qualities (such as inertia and elasticity).[23] These denials turn upon an argument which may take two forms. It may be argued that essential attributes of matter (such as impenetrability and inertia) are not primary qualities (as the mechanical or corpuscular theorists maintained) but are caused by powers of attraction and repulsion. It may also be argued that matter (both bodies and elementary atoms) can be known only through (or as) its manifest or secondary qualities.

If only the first point is argued then ultimate entities may subsist independently of their properties as the bearers of those properties, as in Boscovich's theory[24] and in those theories which have been identified as 'newtonian dynamical atomism'.[25] If both points are argued then ultimate entities will be identified simply as the loci of forces or of quantities of action (as in the theories of W. Rowan Hamilton and of Faraday),[26] for it has been argued that atoms can be regarded as hard, extended, or inertial only in the sense that these properties are physical (perceptual) manifestations of the existence or exertion of repulsive forces.

1.2.1 Matter and its Powers: three forms of atomism

Faraday's field theory develops initially out of his attempts of 1834 and 1837 to explain the electrical and chemical properties of matter in terms of some definite relationship between elementary atoms and

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23. For the case against inertia see J. Priestley, Disquisitions Relating to Matter and Spirit (Birmingham, 1777): 1-7 and Herschel, Preliminary Discourse: 87 ff.

24. R.J. Boscovich, Theoria Philosophae Naturalis (Venice, 1763), trans. J.M. Child, A Theory of Natural Philosophy (London, 1922).

25. See, for example, Levere, Affinity and Matter (Chapters 1-3).

26. For Hamilton and Faraday see infra, section 1.4, esp. p.94 ff.

their forces of power and finally out of an attempt to explain the relationship between electrical and other powers without recourse to any particular atomic theory at all. In order to make my analysis of Faraday's use of the atomic hypothesis clearer I will introduce a distinction between three forms of atomism. The first is the corpuscular atomism usually attributed to Boyle and to Newton, and to those who followed the latter part of the 31st query of Newton's Opticks.[27] It is the view that atoms are solid spheroids which act by impact and/or by action at a distance.[28] The second is dynamical atomism, which has also been traced to Newton's 31st query,[29] in which the atoms may not be extended spheroids, and in which all interactions are by forces (and never by impact) or due to the mediation of imponderables (elastic fluids or aethers).[30] The third form of atomism is the fully-fledged dynamical atomism in which the distinction between substance and attribute is denied, and with it, the existence of material atoms and of imponderable fluids.

I shall refer to these three types of theory throughout this essay as (respectively) corpuscular atomism, point-atomism, and force-atomism. Whereas an individual point-atom or a corpuscular atom is assumed to exist as the locus of at least one essential or inherent

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27. Reprint of the 4th edition of 1730 (New York, 1952): 400 ff.

28. See W.L. Scott, The Conflict Between Atomism and Conservation Theory, 1644 to 1860.

29. Opticks; 371 ff. See: Thackray, op.cit., note 21; Heimann and McGuire, op.cit., note 12; and Levere, Affinity and Matter (Chapters 1-3).

30. In fact many dynamical atomists--whether they held that atoms are extended corpuscles or not--admitted the existence of imponderables as well (e.g. W.R. Hamilton, J. Herschel, R. Mayer, F.O. Mossotti, and Charles Babbage). For the background to this tradition see Schofield, op.cit., note 18; D.C. Goodman, 'Wollaston and the Atomic Theory of Dalton', HSPS 1 (1970): 37. For chemical atomism in the nineteenth century see: Knight, op.cit., note 21; 'The Atomic Theory and the Elements', Studies in Romanticism 5 (1966): 185; 'Steps Towards a Dynamical Chemistry', Ambix 14 (1967): 179; and W.H. Brock, ed., The Atomic Debates.

property, namely inertia,[31] an individual force-atom is something of a fiction because statements about it as an individual presuppose that it is in some physical (dynamical) relation to some other entity or observer. Thus inertia or elasticity are not inherent properties of individual force-atoms for they are manifested by those atoms as elements of a system or structure of relationships.

Force-atomism might more appropriately be called 'relational-atomism',[32] a term which would avoid the conceptual and etymological complications of the word force[33] while expressing the tension between the notion of an individual, persisting entity and that of an entity which (it is claimed) is just the locus of a set of properties which it owes entirely to the dynamical relationships which constitute the system of which the atom or point is a part.[34]

Force- or relational-atomism is the hypothesis of point-atomism together with the principle that all existents must be possible objects of knowledge, where knowledge can be of manifest qualities only.[35] If some thing is just its manifest qualities, and if those properties can be manifested only as a relationship between two or more entities, then properties may be construed as relations, i.e., as direct

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31. Thus Boscovich (op.cit., note 24, arts. 8-9) attributes inertia to points.

32. I owe this suggestion to Dr. J.D. North.

33. See: Levere, Affinity and Matter: 12. I give the term force-atomism a far more precise meaning than does Levere, who does not take the epistemological component of Faraday's dynamism to be an essential component of his later atomism.

34. See, for example, L.L. Whyte's interpretation of Boscovich, 'Boscovich's Atomism', in Whyte, ed., op.cit., note 21, esp. pp.109 ff.

35. Behind this claim lies the epistemological precept that knowledge is perceptual rather than inferential. The history of this view has been traced by R. Smith, 'The Background of Physiological Psychology in Natural Philosophy', History of Science 11 (1973): 75.

evidence for the existence of a physical relationship between what is perceived (is active) and what perceives (is acted upon). A further consequence is that since perceivability is the sole criterion of existence the properties or powers of a thing cannot all be dispositions. If atoms or points were merely the seats of dispositions, then they could be said to exist only while or when the conditions for the activation of one of those dispositions obtain.[36]

In his earlier theories Faraday does use the concept of an individual atom or particle as the seat of powers which may be dispositional but from as early as 1834 he is primarily concerned with relationships between powers or properties. The explanation of these relationships consists in positing or discovering the lawlike properties not of individual entities but of the relationships between them. Thus Faraday has no use for primary or essential qualities such as inertia and elasticity. He works entirely with the concepts of active powers and mutual relations. By 1837 we find Faraday treating elementary atoms or 'particles' as the original and terminal points of inductive relations (which he represents as the lines of electrostatic force). While the actual condition of these particles (and of masses generally) is caused by the electrostatic forces between them, the particles do have an apparently inherent or essential property--the disposition to resist the polarizing action of electrostatic forces.

Faraday's position until the 1840s is therefore best described as that of a point-atomist. His atomism is decidedly dynamical, but he has not yet come to view the properties of particles as being due entirely to the existence and condition of the dynamical relations. By the mid-1840s Faraday does adopt the position which I have described

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36. This could be denied only by introducing (tacitly or explicitly) the distinction between an entity and its attributes. It is precisely this distinction that the force-atomist denies.

as force-atomism, on which the properties attributed to individuals are supposed to be due entirely to the field--that is, to the existence, properties, and laws of the system of lines of force. The field emerges finally as the causal basis of the powers of individuals.[37] We shall see that the language of the field theory was more suited to the requirements of Faraday's epistemology than was the language of atomism; and that this was one of Faraday's reasons for developing and defending his physical theory of the field.

1.3 Electrical, Chemical and Magnetic Powers: 1831-1836

In this section I will discuss Faraday's use of the conceptions of lines of force and of the electrotonic state in the first nine series of his Experimental Researches in Electricity,[38] in order to delineate his views on the nature of matter and force prior to the development of his first comprehensive theory of the electrical properties of matter in 1837.

1.3.1 Magnetic Induction

In the first series of his Experimental Researches[39] Faraday describes his discovery of magnetic and electromagnetic induction. In the second series Faraday uses the concept of lines of force to state the law of

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37. While Faraday accepts that the properties of magnets and of magnetizable bodies may be described as dispositions he argues, in effect, that the possession of a disposition is a relational property of individuals as singularities in the field.

38. 3 vols., London (vol. I, 1839; vol. II, 1844; vol. III, 1855). For conventions concerning the identification of quotations and paraphrases see supra, p. v.

39. 'On the Induction of Electric Currents ...', ERE I: (1-139), read: 24 November, 1831.

magnetic induction, but is unable to explain to his own satisfaction the process of induction.

In 1820 H.C. Oersted had discovered that an electric current has magnetic properties.[40] In 1821 Wollaston and Davy believed that they had found that a live wire can be made to rotate about its axis in the presence of a current.[41] But where Wollaston had supposed helical currents within the wire, Faraday came to believe that the magnetic forces about the wire were circumferential. In 1821 he published a paper[42] in which he showed that there is no direct attraction between a magnetic needle and a current, and that the wire ought to revolve not about its own axis but about that of a magnet.[43] These results convinced Faraday that the forces between two currents or between a wire and a pole did not act in right lines. He regarded as an 'ascertained fact' that

> the connecting wire has different powers at its opposite sides; or rather, each power continues all round the wire, the direction of action being the same ... (ERE II: 132)

Where Faraday took the circumferential or rotatory nature of the magnetic force to be a basic observational fact, Ampère believed that simple facts could not be observed directly in such cases, and that the rotations therefore had to be analyzed in terms of forces acting

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40. For a discussion see: Williams, Michael Faraday: 137 ff.; R.C. Stauffer, 'Speculation and Experiment in Oersted's Discovery', Isis 48 (1957): 49; and for the philosophical context, B.S. Gower, 'Speculation in Physics: the History and Practise of Naturphilosophie', Studies in History and Philosophy of Science 3 (1973): 301.

41. Cf. Williams, Michael Faraday: 152 ff.

42. 'On some new Electro-Magnetical Motions, and on the Theory of Magnetism', ERE II: 127-147.

43. Ibid., pp.131-132. Cf. Williams, Michael Faraday: 151 ff. and 165 ff.

in right lines between the elements of the current(s).[44] For Ampère it was a basic ('simple') fact about nature that all interactions occur between points and by forces acting in right lines. Faraday's early rejection of this view is important because it underlies his definition of a line of force.[45]

Faraday did not read the requirements of the traditional mathematical analysis into the facts, but he did read the requirements of his own conceptual scheme into them. This is revealed by the nature of his initial attempts to discover the electrical (inductive) effects of magnetism. Faraday expected to find that magnetism can produce electric force as a reciprocal or reverse action. As we shall see, this idea is related to those of action and reaction and of convertibility.

Faraday's first attempts to detect an electrical effect of magnetic action reveal clearly that he was using some principle, however vague, of the equality of action and reaction. Williams has suggested that Faraday was reasoning from the hypothesis that magnetic action is just electric action (as Ampère had claimed),[46] and while I accept that Faraday does consider this possibility from time to time, I shall show that his first attempt to obtain an induced current

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44. A.M. Ampère, as cited by Williams, Michael Faraday: 167.

45. Infra, p. 30. The rejection of the direct action of forces and couples is implicit in Faraday's definition. This fact proves to be of greater significance to an understanding of Faraday's thought as a whole than are the various interpretations of his early experiments on the interactions of currents and poles. For a discussion of the latter see Williams, Michael Faraday: 152 ff.; Agassi, Faraday: 54 ff.; and Berkson, Fields of Force: 39-47 and 60-65.

46. Cf. Williams, 'Ampère's Electrodynamic Molecular Model', Contemporary Physics 4 (1962): 113.

was the result of his adherence to a more fundamental idea: that whatever its nature, the force or action (as a cause) must produce an equal and opposite reaction in the region around it. In the early researches this reaction occurs in the matter around a magnet or a live wire,[47] but in his later researches we find Faraday attributing this reactive property to space itself.[48]

In November of 1825 Faraday attempted to detect the induction of a current in one wire by a current passing through a second wire. A galvanometer included in the secondary circuit showed no indication of a current, hence 'no visible proofs of induction by the wire through which the current was passing upon its neighbour could this way be perceived'.[49] This experiment may be interpreted as a test of Ampère's theory of electric currents.[50] However, in the light of the fact that Faraday later expected a continuous current to be produced in the secondary circuit by a continuous current passing through the

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47. In noticing an early instance of the idea of action and reaction Berkson concludes immediately that 'Faraday ... already believed in the conservation of force' (Fields of Force: 63). However, the most that can be claimed on the basis of Faraday's use of this idea is that he adheres to a principle of equality of action and reaction from which the more general principle of the conservation of force emerges (as I shall subsequently show).

48. In arguing that the space around a magnet is essential to the existence of the magnetic powers Faraday appeals (in 1852) to a resistance or reaction of space to the passage of the lines of magnetic force (cf. (3277 ff.), esp. (3282-86). The link between the concepts of existence and opposition or reaction appears throughout the Experimental Researches and is indicative of more widely held ideas about nature (see infra, notes 101,148).

49. Davy's 'Laboratory Notebook', as cited by Williams, Michael Faraday: 174. Throughout this essay I will refer to the inducing current or active circuit as the primary current or circuit and to the induced current (or the circuit in which it appears) as the secondary current (or circuit). Faraday had earlier attempted to detect a 'reaction' of steady magnetic forces upon a continuous current (see ERE II: 162 (dated July, 1825)).

50. Williams, Michael Faraday: 174.

primary this attempt assumes a rather different aspect. Even after Faraday succeeds in demonstrating that the induction of a current requires that the secondary conductor be moving in the field of a magnet or a primary circuit, he continues to believe that a stationary conductor must be in a state of dynamical interaction with the source of magnetic force. I shall argue that he believes this for two reasons: first, he believes that to assume otherwise would be to take a position inconsistent with the principle of equality of cause and effect (or of action and reaction) and second, that relative motion between magnet and conductor cannot be a satisfactory causal basis for the production of a force. There must, he believes, be some conversion of the pre-existing static force into its dynamical form. Both ideas are to reappear throughout Faraday's researches on magnetic and electrostatic induction. The latter is to be the basis of his argument for the reality of the field in 1852.

1.3.1.1 Action, Reaction, and the Electrotonic State

When Faraday first succeeded in obtaining an induced current in November of 1831[51] he did not at first realize that a necessary condition for the production of the current is that the conductor be moving in the field. He was able to state that this is a necessary condition only after he had replaced his first theoretical interpretation of the effect by a descriptive account based upon the concept of lines of magnetic force.

Faraday opens the first series of his Researches by defining 'induction' as the power which static electricity has 'of causing an opposite electrical state in its vicinity' and by which currents can induce 'any particular state upon matter in [their] immediate

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51. Cf. Faraday to R. Phillips, 29 November, 1831, Corr. I: 209.

neighbourhood, otherwise indifferent' (1). This is no more than a description of what Faraday has observed that electrical powers do. That he treats this description as a definition of the action of this force is important, because it will subsequently become the basis for his theory of induction of 1837, of his denial of action at a distance and, finally, of his field theory of 1852.

Faraday has been struck by the fact that the inductive effects of currents have been restricted to conductors of electricity and to magnetizable metals, while the inductive effects of static electricity are common to all matter. To him

> it appeared unlikely that these could be all the effects which induction by currents could produce ... whilst yet an infinity of bodies, exhibiting definite phenomena of [static] induction ... still remain to be acted upon by the induction of electricity in motion (2).

He has also been puzzled by his earlier failure to find the effect of a current on a nearby conductor (3). Faraday expected moving or dynamical electricity to produce an effect not merely in conductors but in all matter. By analogy, all matter susceptible to electro-static action should also be susceptible to electro-dynamic (magnetic) action. But Faraday is not reasoning only that the effect of a current should be as universal as that of static electricity. He believes that where a current is not induced, this fact requires explanation as much as does the fact of induction itself. Although the non-occurrence of a current in non-conductors could readily be attributed to their lack of conducting power, the temporary nature of induced currents had been unexpected. It required explanation, and suggested that the appeal to conductivity (or lack of it) would be only a preliminary answer.

Faraday had found that a current is produced only when the conductor is moving near the magnet (6 ff.) or when the field of a

current is rising or falling in the region of a stationary conductor (17). Yet he was more interested in the fact that the current induced in the secondary circuit (when the primary is opened or closed) is a temporary effect. While the circuit is closed the magnetic forces continue to circulate about the wire and act upon the secondary conductor. Thus, if the induced current is the only effect of the magnetic force, it should continue to pass while the forces continue to act. Since it does not do so, some other (as yet unobserved) effect must occur because the effects do not seem to be equivalent (at least temporally) to the cause (as Faraday understood it). Faraday concludes that some unobserved reaction must occur in the secondary conductor. He supposes that the latter takes on a 'peculiar state' (i.e., a state which is peculiar to or characteristic of the matter of the conductor) which is the reaction of the matter to the initial action of the magnetic forces. The induced current is thus interpreted as the only observable effect of the interaction of matter and force, for it is produced not directly by the field but by the production and relaxation of this state. Since the matter reacts upon the force to produce a state of equilibrium, no current can pass once the reactive state has been set up.

Faraday believed that he had discovered 'a new state' of matter, which he called the electrotonic state. The temporary nature of the induced current is adduced as evidence for the existence of the electrotonic state (67). The matter of the conductor 'resists the formation of an electric current in it'(60), an action which does not occur in matter in the ordinary conducting state. The electrotonic state thus represents a reaction of the matter to a change of some kind in the region around it. This reaction is 'equal to [the current] produced either when the condition is induced or [when it is]

destroyed' (71). The induced current is therefore a measure of the electrotonic state. Yet the state is neither the same thing as a current nor is it simple resistance to the passage of a current: it is something which 'exert(s) a reaction upon the original inducing current, and produce(s) equilibrium of some kind' (72,74).[52] Faraday is careful to avoid equating the electrotonic state with some thing distinct from the matter. Since his results

> favour the notion that the electrotonic state relates to the particles, and not to the mass, of the wire or substance under induction, being in that respect different to the induction exerted by electricity of tension (73),

it is possible that such a state may be set up in non-conductors and other materials,

> the current itself, when it occurs, being as it were a contingency due to the existence of conducting power, and the momentary propulsive force exerted by the particles during their arrangement (73).

As we shall see, the theory of electrolysis which Faraday subsequently develops in 1833 is foreshadowed in this and the following passage:

> In the electrotonic state the homogeneous particles of matter appear to have assumed a regular but forced electrical arrangement in the direction of the current, which if matter be undecomposable, produces, when relieved, a return current ... (76)

Faraday has realized his 'hope of obtaining electricity from ordinary magnetism' (4) but his experiments have shown him that this effect is not as he had expected it to be. They have shown that unless some hidden reaction of the conductor is introduced, the conversion of magnetic into electrical force--as observed--is not compatible with the principle of the equality of cause and effect.

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52. 'But whether great or small, it is hardly conceivable that [this state] should exist without exerting a reaction upon' the primary current or the moving magnet (72, my italics).

Yet, unless the experiments are interpreted in terms of this principle they do not provide independent evidence for the existence of this state. When interpreted in terms of the principle, the temporary nature of the induced current requires that some reaction of the matter be posited.

Faraday was unable to detect any effects of this state other than the one which it had been introduced to explain. Consequently his attitude towards the electrotonic state is ambivalent. At first he regards it as an important discovery, essential to the further investigation of the relationship between electricity and matter. His own investigations, based upon the hypothesis that matter is capable of sustaining internal strains corresponding to such a state, are subsequently to prove him right. Here, however, the electrotonic state has been introduced primarily to explain a discrepancy between what Faraday's beliefs about the nature of force or action had led him to expect, and what his experiments had actually shown him to be the case.

1.3.1.2 The Lines of Magnetic Force

Faraday's first reference to the magnetic lines or 'curves' of force occurs in his application of the discovery of magnetic induction to Arago's discovery that a rotating conducting plate placed in a magnetic field will tend to produce a similar rotation in a magnet placed parallel to the plane of rotation of the conductor (89-139). In explaining Arago's result as being due to the induction of currents in the conductor (where it is the field of such currents which produces the effect in question) Faraday introduces the idea that the conductor must cross or cut a number of lines which represent the direction of the force produced by the magnet at any point in the vicinity of one of its poles. The production of a current can

therefore be described as a result of the fact that these curves are crossed or cut:

> By magnetic curves I mean the lines of magnetic forces, however modified by the juxtaposition of poles, which would be depicted by iron filings; or those lines to which a very small magnetic needle would form a tangent (114 n.).

Two points are of interest here. First, the 'curved lines' of magnetic force are defined in terms of the set of effects of a magnetic pole upon individual magnetizable filaments placed in the region of the pole. They describe a distribution of force which may be inferred from (and taken to be the same as) that which the forces have in the presence of iron filings or magnetic needles. I call attention to the inference from the actual distribution (as indicated by a magnetic needle) to the distribution which the forces are supposed to have (in the absence of magnetizable matter) because Faraday is eventually to reject the view that needles and filings can provide complete and unequivocal information about the magnetic field.

The second point is that Faraday makes no attempt to explain why or how the geometrical relationship[53] between the axis of the conductor and that of the lines of force bears upon the physical effect produced. The relationship is stated simply as a law which specifies the way in which the direction of motion of the conductor, that of the current produced in it, and that of the line of magnetic force, must be related (116). Yet the principle which led to the hypothesis of the electrotonic state does underly the explanation of Arago's effect, for Faraday supposes that the state is successively established, released, and renewed in the conductor as it rotates near the magnet (120-124). Here the lines of force play a descriptive rather than an explanatory role.

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53. Cf. (114). The conductor must not be parallel to the line(s) of force.

In the second series[54] Faraday dispenses with the electrotonic state, remarking that he has been persuaded both by his failure to demonstrate its existence and by the simplicity and sufficiency of the law of magnetic induction that the hypothetical state is no longer necessary (242). This is what Faraday says; it does not prove to be what he believes. First he restates the earlier law of induction (114,116) in terms of the motion of the wire, the direction of the magnetic force at a point, and a new power which causes the current in the matter. He shows that motion of a conductor through the magnetic curves is equivalent to motion of the curves past a stationary conductor (238-239), a point which depends upon his having also demonstrated that the lines of force are <u>independent</u> of the matter of the magnet (i.e., that they do not rotate in space when the magnet rotates (219-220)). Thus he is able to show that relative motion of conductor and lines need not involve changes in the intensity of the force in the region of the wire, and that relative motion of curves and conductor is a necessary condition for the production of a current in the latter (217).[55]

While this new mode of describing the relationship between electric currents and magnetic forces had enabled Faraday to see that relative motion of conductor and curves is a necessary condition of the effect,[56] Faraday did not believe that this could be taken as an

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54. <u>ERE</u> I: (140-264), read: 12 January, 1832.

55. A sufficient condition is that the conductor be moving <u>and</u> that it form a closed circuit. Motion is sufficient to produce only 'the power ... which tends to urge an electric current through [the conductor]' unless it is closed (256).

56. When self-inductive effects were brought to Faraday's attention by William Jenkins in 1834, Faraday first described the process in terms of the lines of force in order to <u>identify</u> it as an inductive effect (cf. <u>infra</u>, section 1.3.4.2).

explanation of magnetic induction. Certain unspecified 'powers' of the conductor had to be taken into account.

1.3.1.3 The Balance of Powers

Instead of resorting to hypotheses about the possible structure of the conductor Faraday introduces specific powers which are called into action when those conditions specified by the law of induction obtain. He also introduces a new form of the principle of equality of action and reaction, one which is to appear throughout his researches on electrochemistry and static induction, viz. that powers or actions generally are opposed by other powers, where this opposition always tends to produce an equilibrium condition or 'neutralization' of the two opposing actions.

Faraday had expected that different metals would exhibit different susceptibilities to magneto-inductive action (just as their conductivities are known to differ). He had realized that the variability of the latter property would mask any detectable variations in the former. Yet he was apparently not expecting to find that different metals, when connected in a single circuit, 'exhibit exactly equal powers with respect to the currents which are formed ... in them' by inductive action (201). Faraday explains this by first showing that induced currents are proportional to the conducting power of the matter in which they are induced. It follows that the forces which generate a current and those which obstruct it must be 'so perfectly balanced as to neutralize each other exactly' (213). As the obstruction is inversely proportional to the conducting power the tendency to generate a current must be directly proportional to the obstructive power. This must be supposed in order to explain the fact that no current is produced in a circuit consisting of metals having different

conductivities (193-201). Thus Faraday supposes that inductive action in such a circuit produces an equilibrium of the obstructive and generative powers. Here any reference to the actual state or structure of the matter has been made unnecessary through the introduction of an hypothesis which specifies both that there are three distinct powers at work and that these are related in a certain way.

Faraday has replaced the two actions of the electrotonic state by those of the three powers of the conductor. This move is important because it is the first instance of a technique which Faraday is to use throughout the Experimental Researches. Instead of talking about molecular tensions and reactions Faraday posits three powers: conductivity, a tendency to generate a current, and a tendency to obstruct or resist the generation of a current. It may appear that Faraday is being evasive and that he is substituting one ambiguous hypothesis for another. But two points should be noticed: first, by describing the conductor(s) in this way Faraday is describing what he sees with words which are as simple and as non-committal as possible. Thus he can now say that the induced current is produced by motion of the conductor across the lines, being the effect of some as yet unspecified interaction of certain powers of the matter with that power represented by the lines of force (256). The second point is that recourse to hypotheses about the actual nature of the interaction has been avoided. The electrotonic state has been supplanted as a cause by the simple requirement that the power(s) in question be called into play only when the conductor moves so as to cut the lines of force. In this way the temporary nature of the induced current is also explained.

Yet Faraday has been unable to show that some other effect will not occur when both magnet and conductor are stationary. That he still

believes that it should, and that he was unsatisfied with the law of induction as anything more than a description of the process shows that Faraday did interpret this process in terms of a principle of equality of cause and effect:

> Thus the reasons which induce me to suppose a particular state in the wire (60) have disappeared; and though it still seems to me unlikely that a wire at rest in the neighbourhood of another carrying a powerful electric current is entirely indifferent to it, yet I am not aware of any distinct facts which authorize the conclusion that it is in a particular state (242).

The preceding example is important not only because it shows how Faraday came to introduce his two main theoretical concepts but also because it shows that Faraday was able to move between the attempt to explain a process in terms of an hypothesis about the internal structure of matter and the attempt to give a more descriptive (but still causal) account of that process.

1.3.2 Chemical Powers and the Law of Electrolysis

In the third to the seventh series of his Researches Faraday is concerned with the experimental proof of the law of electrolysis.[57] The theories which he develops to explain this law involve his rejection of the then-accepted classifications of bodies as conductors or insulators, of electricities according to their sources,[58] and of the

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57. For the background to the discovery of this law see Williams, Michael Faraday: 218-223 and 241 ff., and for the historical context see Levere, Affinity and Matter (Chapters 3, 4).

58. Faraday had proven in his third series of January 1833 that different processes for producing electricity do in fact produce one and the same 'agent'. He refers to the current throughout the early Researches either as a 'wonderful and subtile agent' (361, cf. 564,705,855,873,877,995,1114) or as a set of two equal and opposed forces (517,667,891). These forces are 'progressive' in that they carry action from one place to another (being the forces of electricity in its dynamical state). None of the effects of the current support the inference that it is a substantial thing capable of motion--an inference that Faraday repeatedly rejects. (See section 1.3.4.2.1.)

view that there are three distinct states of matter. The fact that Faraday treats these distinctions as being merely phenomenal truths (justified as inductive generalizations, but not as fundamental truths) suggests that he was committed to some general theory of the nature of matter.

Faraday's doubts about the reliability of classifications based upon phenomenal differences between bodies prove to be typical of his approach to the problem of explaining nature, yet they do not appear to have been tied to any specific theory of the nature of matter. His rejection of the usual notions of 'conductor', 'insulator', etc. is related to an attempt to reduce the number of different fundamental entities or agents. He later demonstrates that the distinctions between conductors and insulators and between magnetic and diamagnetic bodies (both well-founded in ordinary experience) cannot be taken to be evidence of real differences in the natures of such bodies. These demonstrations are part of this same attempt to explain the obvious differences between the electrical, magnetic, and other properties of matter in terms of a simple theory of the properties of electric and magnetic forces. Faraday is eventually led to deny the validity of a distinction which is essential to the interpretation and explanation of nature on what I have called the mechanical or corpuscular view,[59] namely the distinction between matter and force.

1.3.2.1 The first theory of electrolysis: 1833

In January of 1833 Faraday reported that 'there is great reason to believe that the quantity of matter decomposed' by a current 'is proportional' not ... to the intensity [of that current] but to the

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59. Cf. supra, pp. 14 ff., and J.T. Mertz, A History of European Thought in the Nineteenth Century, I: 302 ff., II: 3-200.

quantity of electricity passed' through a conducting solution (329). Virtually all of the experimental work reported in the fourth to the seventh series is directed towards an experimental proof of the law implied by this statement and, with series eight, towards an experimental determination of the limits of its applicability. The statement itself could be justified as a generalization from the facts that the ratio of the quantities of the products of electrochemical action and the ratio of these quantities to the quantity of electricity passed through the solution are both constants. Yet to prove the statement as a law Faraday believed that he had to show that it is a consequence of a theory in which a specific connection is postulated between conduction as a variable property of all matter and some invariable power of the ultimate particles of matter (538,852).

In the fifth series Faraday develops a theory of electrochemical action in which matter is supposed to consist of discrete particles endowed with various powers of attraction and repulsion. In this and the following sections I will show that Faraday's first explanation of the law of electrolysis consists in showing how two of these powers interact with the electric forces which constitute the current, but that within a year he abandons the hypothesis of a complex interaction of two powers, basing his explanation instead on the principle that electrical and chemical powers are identical and the hypothesis that each particle of matter is the seat of a specific (definite) quantity of electric power.

In the course of his study of decomposition as one of the effects of electrical action[60] Faraday had discovered that both conduction and decomposition in liquids cease when they become solidified (394). In

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60. See the third and fourth series, ERE I: (265-449).

describing this discovery Faraday does not say merely that bodies generally become conductors as they are liquified or cease to conduct as they are solidified through cooling, he says that at some stage in the cooling process they lose a power, the ability to conduct. He describes his initial results with water as a 'law of the assumption of conducting power during liquefaction, and loss of it during congelation' (394) and later speaks of the conducting power as being 'conferred by liquidity' (410).

This discovery is both new and unexpected. Faraday proceeds to link conductivity with 'some properties and relations of the particles' of the matter (412). The fact that both conduction and decomposition cease when a fluid is solidified suggests both that these two processes are related and that they are related in some way to the internal condition of the matter. However, Faraday is not yet prepared to develop an explanation based upon possible relationships between the particles of matter. He proceeds instead to explore the relationships between the secondary qualities of the matter in these two states. He finds that as a solid is liquified it 'loses almost entirely the power of conduction for heat, but gains in a high degree that for [conducting] electricity' (416) and that the converse holds for a liquid as it is solidified. This suggests that there is what Faraday calls a 'natural dependence' of the two conductivities. This dependence permits the inference that there is a 'physical reason' for the 'very extraordinary relation of [these] two conducting powers'. Specifically, 'both ... appear to be directly connected with the corpuscular condition of the substances concerned' (416).

Faraday has at once suggested that an explanation might be sought in an investigation of the relationship between these variable powers of the matter and has avoided, for the time being, the need to develop

a specific theory of this relationship. On the assumption that there is some physical basis for the relationship between electrical and thermal conductivity Faraday goes on to deny that the apparent differences between the properties of matter in the solid, fluid, and gaseous states can be taken as evidence that there is a fundamental difference between matter in these three states. It is plausible to suppose that 'at that point where the liquid and the gaseous state coincide, the conducting properties are the same for both' and that these powers 'diminish as the expansion of the matter into a rarer form takes place' (442).[61] The import of this argument (or possibly a presupposition of it) is that we should not be led by the obvious or immediate differences between the properties of some substance in its three different states into concluding that all the properties which matter has in one state will be lost when it is made to change state.

Faraday's general conclusion is one which few, if any, experimentalists before him would have dared to assert: 'All bodies conduct electricity in the same manner from metals to lac and gases, but in very different degrees' (444). Faraday believes that there is some very general or universal interaction between electric force and matter, one which retains its identity regardless of differences in kinds and states of matter. It is probable that Faraday viewed the function ofthe matter as that of transmitting electric forces as vibrations, where static or inductive action is a necessary condition

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61. In fact he 'cannot but suppose that' this will be the case. For Faraday's early work on the properties of gases see 'On the Condensation of several Gases into Liquids' (1823), ERCP: 89; 'On the Existence of a Limit to Vaporization' (1826), ERCP: 199; and Corr. I: 139-41 and 159-62.

for and a continually recurring stage of this process.[62] Faraday's first two theories of electrolysis fail to provide him with a 'clear view' or model of this process, which he is able to develop only in 1837 and 1838.

Faraday's first theory of electrolysis appeared in the fifth series of June 1833.[63] Faraday begins by showing that the force which acts to decompose the particles of a solution must be the same at any point in the solution. This follows from his earlier discovery that the decomposing action of the current is directly related to the quantity of electricity which passes and from his rejection of the generally accepted idea that the poles act directly on the individual particles of the solution.[64] He had shown that metallic poles are not essential to the process of decomposition (461)[65] and now concludes that the action is

> an internal action of the parts suffering decomposition, [and] ... that the power which is effectual in separating the elements is exerted there, and not at the poles (471).

Thus Faraday denies that decomposition is the result of forces acting between poles (electrodes) and particles (493,518). No 'constant expression can be given as to the action on a single particle placed in the course of the current' (503) because there can be no experimental access to such a case, but Faraday realizes that the relationship between electric action and its effect can be stated as an

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62. When referring to the nature of electricity Faraday usually includes this as a possibility (along with the hypothesis that it is an active fluid). His later view of the current is that it is a form of vibration analogous to heat and light, and it is eventually described as a 'wave of power' (ERE III: 517).

63. ERE I: (450-563), read: 20 June, 1833.

64. Rejection of this idea was initially tentative. As Williams has shown, it was an hypothesis to be tested (Michael Faraday: 242).

65. For the proofs see ERE (461 ff.) and (493 ff.).

aggregate effect for given conditions:

> The sum of chemical decomposition is constant for any section taken across a decomposing conductor, uniform in its nature, at whatever distance the poles may be from each other or from the section ... (504)

The first version of the law of electrolysis is then stated:

> for a constant quantity of electricity ... the amount of electro-chemical action is also a constant quantity, i.e. would always be equivalent to a standard chemical effect founded upon ordinary chemical affinity (505).

This statement is presented as a summary of Faraday's experimental findings. The theory of this action is based upon the assumption that decomposition is an effect 'produced by an internal corpuscular action, exerted according to the direction of the electric current' and that this action involves the exertion of a force which is 'either superadded to, or [which gives direction] to the ordinary chemical affinity of' the elementary particles (518). The current, which is conceived as a line or 'axis' along which two equal but opposed forces are exerted (517) acts directly on the chemical affinities, increasing their intensity in one direction and decreasing it in others so that alternate particles are made to move towards and past each other, towards the poles (521).

Although Faraday says that the effect is considered to be 'essentially dependent upon the mutual chemical affinity of the particles of opposite kinds' (519) he also introduces longer-range attractive forces or 'mutual relations' which are non-chemical and which exist between every particle and every other. Thus,

> a particle of hydrogen in combination with oxygen is considered as not altogether indifferent to other particles of oxygen, although [the latter] are combined with other particles of hydrogen, but to have an affinity or attraction for them (523).

Faraday calls this relationship a 'general relation of particles already in combination [with] other particles with which they are not combined'. It is weaker than the affinity forces which exist between combined particles, and is an elective action because it exists only between unlike particles. Thus it is neither a chemical force (because it 'probably has a direct relation to and connexion with, attraction of aggregation in solids and fluids') nor--despite the supposition just quoted--is it an ordinary cohesive force, for it does not exist between like particles (e.g., the hydrogen particles).

On the basis of this distinction between two types of inter-particle 'relations' Faraday proceeds to give a more elaborate account of decomposition. He states that this longer-range attractive relation, 'though it does not at all approach in force ... to that by which [one particle is chemically bound to another], can, under the electric influence, be made even to surpass [the chemical affinities]' (523). The electric forces of the current are able to overcome the chemical affinities by enhancing the long-range attractions.[66] In view of Faraday's later position it is important to notice that the electric force interacts with both a chemical force (the affinities) and a non-chemical force.

Faraday introduces the latter forces because he wishes to explain not only how decomposition occurs but why it does not occur in gases

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66. Williams has argued that this theory (in which the affinities are enhanced or 'exalted' by the current forces) shows that Faraday was 'thinking in terms of patterns of force which ... were changeable and variable under different conditions' and that this involves 'the addition and subtraction of the forces represented by Boscovich's curve [as] a necessary concomitant of all chemical action' (Michael Faraday: 245). If this last point is accepted than it must follow that Faraday dispensed with a specifically Boscovichean view of this process within a few months of developing this theory. Cf. infra, section 1.3.2.3.

and vapours. Here the explanation consists in supposing that the long-range attractions are either very weak or non-existent between particles in the gaseous state, a supposition justified by the

> remarkable circumstance, that in gases and vapours, where the attraction of aggregation ceases, there likewise the decomposing powers of electricity apparently cease, and there also the chemical action of quantity is no longer evident (523).

Faraday's general view is that the effect is due to forces which 'are internal, relative to the matter under decomposition' (524).[67] He believes that it is 'more philosophical, and more directly expressive of the facts, to speak of the decomposing body, in relation to the current passing through it, rather than to the poles ...' (524)[68] and that such an account is sufficient on the assumption that 'the effect is ... <u>essentially dependent</u> upon the <u>mutual chemical affinity</u> of the particles' (519).

An explanation of this process consists in positing certain relationships or interactions between <u>forces</u> (or between entities which are <u>defined</u> in terms of those forces, <u>viz</u>., currents and particles).[69] Faraday had been able to distinguish between the lines of magnetic force and the lines of iron filings because the fact of

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67. The appeal to long-range forces leads to an ambiguity about the actual role of the current which is not removed until Faraday restates the theory in terms of the interaction and identity of chemical and electrical powers.

68. The most important of these facts include the <u>evolution</u> of products (as gases or precipitates) rather than their retention at the poles, and that decomposition can occur without poles (as, for example, at an interface between two chemically different solutions (493-498)). By rejecting the 'analogy with ordinary attractive forces, as those of gravitation, magnetism, cohesion, chemical affinity &c.' (537) Faraday has avoided one of the unconfirmed consequences of the accepted theories, <u>viz</u>., that the products of decomposition should be held at the poles.

69. The 'particles' of this theory are introduced as the loci of the chemical and aggregative <u>forces</u> which Faraday believes to be necessary to the theory.

magnetic induction showed that magnetic forces do exist independently of the presence of magnetic (or magnetizable) matter in the field. Here, however, the current or 'line of action' cannot be distinguished from the chain of affinity and long-range forces in the same way because the existence of such lines cannot be demonstrated independently of the decomposition process. Thus Faraday has defined the current as an agent (517) which may or may not exist independently of the matter in the way that lines of magnetic action had been shown to do.

In the sixth series Faraday reports his findings on the conditions under which platinum and other metals act as catalysts in inducing the chemical combination of mixtures of gases. His interpretation of this effect shows that Faraday is still thinking in terms of atoms or particles which have definite powers of attraction and repulsion. While these powers are dispositions, the theory is dynamical in the broader sense, for the process is explained in terms of force-relations between particles together with certain assumptions about the conditions under which these relations can be active.

1.3.2.2 The theory of catalytic action

Faraday's investigation of catalytic action was carried out as part of an attempt to determine the extent to which the catalytic action of platinum (which Faraday uses as one of the poles in his chemical cells) might distort the chemical data upon which he wished to base his experimental proof of the law of electrolysis. Faraday is able to show that this power of the platinum is incidental to the electrolytical process in that it is not an electrical action. A qualification which he introduces in his statement of this conclusion shows that he is using an assumption about the unity of force. The relevant

power of the platinum is

> not ... to be considered as of an electrical origin, otherwise than all attraction of particles may have this subtle agent for their common cause ... (564)

While Faraday is a long way from demonstrating that electricity is in fact the basic cause of all other powers of matter, he evidently wishes to leave open the possibility that such a demonstration will be found.

He proceeds to show that the catalytic power of platinum can be reduced to a joint action of the affinity forces and the long-range attractive relations, together with a new repulsive power of the particles. Indeed,

> all the phenomena connected with this subject press upon my mind the conviction that the effects ... are dependent upon the natural conditions of gaseous elasticity, combined with the exertion of that attractive force, possessed .... especially [by solid bodies] ... (619)

Faraday's explanation consists in showing that combination (the activation of mutual affinities) can occur just when those conditions under which the repulsive relations (peculiar to gaseous particles) are active do not obtain. The crucial assumption here is that the long-range attractive relations are opposed (in their consequences) to, but can act coextensively with the repulsive or 'elastic' relations. Faraday attributes three distinct powers to the atoms: (1) the chemical affinities, (2) the long-range attractive relations, and (3) the repulsive power to which the elasticity of gases is due. Three distinct powers are required because the result of the process is a chemical change (hence the first kind of power); because it occurs only in mixtures of gases and not in solids or liquids (hence the third power); and because it occurs at the surface of any clean metal (hence the second kind of power). If chemical combination is to occur the particles must be brought together to a point at which these short-range

forces (1) can come into operation. Only the forces (2) which oppose the action of the repulsive forces (3) can perform this function. The former are, however, weaker than the latter. Thus the forces (2) must be strengthened or enhanced by the platinum, for where the current fails to pass through or decompose gaseous matter, the platinum evidently succeeds in producing a chemical change.

Faraday therefore supposes that at an interface between two states of matter the attractive forces of aggregation of the solid are balanced on all sides of a particle except that side adjacent to the gas. Similarly, the mutual relations of repulsion of the gas particles are balanced on all sides except that side adjoining the solid. The platinum and the gases cannot repel each other because these forces (3) exist only in gases and only between particles of the same gas.[70] The attractive relations (2) of the metal combine in action with those of the gas particles so that together (and in the absence of an even distribution of repulsive relations (3)) the relations (2) are strong enough to overcome the repulsive forces. The particles of two or more different kinds of gas can thus be brought within the range of their affinities (1).

While Faraday is willing to attribute to the particles those powers which seem to be required in explaining this chemical change he does not wish to commit himself to a particular view of the way in which the particles interact:

> we may err in imagining each particle to be a little nucleus to an atmosphere of heat, or electricity, or any other agent, but we are still not likely to be in error in considering the elasticity as dependent on <u>mutuality</u> of action (626).

Hence his use of the term 'relations'. In the gaseous state, particles are 'influenced solely by relation to particles of their own kind' (627).

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70. Here Faraday cites the findings which led to Dalton's law of partial pressures (626-27,657).

A relation is an interaction or causal connection. By using this word Faraday is able to express what is required by his theory without prejudicing the question of how these elementary particles are able to influence each other in the specified ways.[71] Whether inter-particle action is mediated or occurs directly at a distance does not become a pressing question until 1838, when Faraday realizes that conduction and insulation may be reduced to a single process on the assumption that the difference between the two consists in the rate at which inductive action is transmitted through matter (1612).

Faraday's use of the idea of a 'mutual relation' between particles suggests that at this stage he did distinguish between the particles and their powers, and that he regarded the latter as dispositions which could be manifested under the appropriate conditions. He has shown that the platinum can act to 'suppress or annihilate a part of' the repulsive powers of the gas particles to a point where the attractive relations (2) and eventually the affinities (1) can take over (628).[72]

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71. Faraday never considers the possibility of action by impact, nor does he conceive of particles as extended corpuscles having definite bounding surfaces. He speaks of the 'approximation' of a gas particle to the platinum as being 'very great' (a distance at which they are in 'close contact' with the metal, but not yet close enough to be chemically combined either with it or with each other (625, 628,658)). Cf. Series 14 (1745-47).

72. Clearly the forces (2) and (3) can interact, and since only 'a part' of the repulsive action is removed these two forces coexist over a considerable range of distances. The repulsive forces coexist with the affinities (1) or are effective at distances at which (1) could operate since they prevent combination in (fluid) mixtures and in gases. So the forces (3) operate over a larger range of inter-particle distances than do the other two, ceasing only at the very short distances at which the forces (1) are effective. Whether one interprets these passages as indicating adherence to a specifically Boscovichean form of atomism will depend primarily upon whether one regards Boscovich's force-curve simply as representing the resultant action of a number of coexisting forces at a given distance (as, Williams, Michael Faraday: 245) or as representing the action of a single power whose character (sign) changes with distance (as Levere, Affinity and Matter 13).

A gas particle at the solid/gas interface is in a curious condition: it has neither repulsive powers nor is it in chemical relationship with any other particle. If the particle in question is an oxygen particle surrounded by other oxygen particles then repulsive forces will exist between these particles, but if the latter are hydrogen particles then the oxygen particle will be in what Faraday calls its nascent state (658).[73] It is isolated from any other particle of the sort that it could repel and is not yet able to combine chemically with the hydrogen particles (628,658):

> At the moment of separation of any such particle [from the mass of the gas in the case of catalysis or from the electrode in the case of electrolysis] it is entirely surrounded by other particles of a different kind with which it is in close contact, and has not yet assumed those relations and conditions which it has in its fully developed state, and which it can only assume by association with other particles of its own kind (658).

A particle in the nascent state is evidently not the same thing as a particle in the free or gaseous state. The 'elasticity' of the particle is 'for the moment ... absent' (658). Clearly, exercise of both the repulsive forces (3) and the attractive relations (2) depends upon the environment of the particle. From the standpoint of the corpuscular or kinetic theory of gases the assertion that a nascent particle has no elasticity is either false (for it is assumed on the latter theory that atoms are entities which possess at all times the disposition to repel each other) or it is trivially true (for the power of repulsion, as a dispositional property, is active only under certain conditions which do not obtain in the case considered by Faraday).

Faraday has adopted the position which I have identified as point-atomism, in which properties may be construed as dispositions whose manifestations or exercise constitutes a causal relation between

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73. It is not actually acting or being acted upon by any force or entity, hence if it does have any properties these must be dispositional.

entities. I have discussed it in some detail because comparison with Faraday's later position on the nature of properties reveals that an important change takes place in his underlying assumptions about the nature of force as a causal link between entities. Faraday has supposed that the repulsive relations can come into or go out of existence. He is later to deny that force-relations can be created or destroyed, whether by changes in distance between entities or by the interposition of certain kinds of matter. (I shall show later that this denial is directly related to the development of Faraday's ideas on the conservation of force as a quantity of action.) The present example is important because in the light of his later ideas it becomes clear that in 1833 Faraday did not believe that the conservation of force precludes the attribution of propensities or dispositions to fundamental entities.

This later position is foreshadowed in the second version of his theory of electrolysis and again in his 1837 theory of induction, in which he emphatically denies the possibility of there being latent (hidden) properties or states. While this denial is implicit in the 1834 theory of electrolysis, Faraday does not seem to have realized this--a point which needs to be emphasized just because Faraday does occasionally fail either to realize certain implications of his own position until some time after that position has first been stated, or to realize that certain implications of a given position are inconsistent with other beliefs which he held at the time. In interpreting Faraday's theories it is difficult to tell whether these inconsistencies are simply a function of the vagueness of his emerging ideas or whether they did not arise for Faraday because he had not yet grasped the belief or principle in question.

1.3.2.3 The second theory of electrolysis: 1834

Within eight months of his publication of the fifth series Faraday replaces the theory of electrolysis developed there by one based upon four assumptions: (i) that the atoms have only one power, the chemical affinities (1); (ii) that this power is electrical in origin; (iii) that this power is finite, consisting of a definite quantity of action; and (iv) that the quantity of action is different for and characteristic of each chemical element. These assumptions are introduced in the seventh and eighth series.[74] Faraday's earlier theory had explained the actual process of electrochemical decomposition, but he had been unable to explain the law of electrolysis, i.e.--to explain the facts which had led him to state it. Here he explains the law by showing that these facts are a consequence of these four assumptions.

Faraday's 1834 theory of electrolysis marks a definite shift away from hypotheses about the atom as a complex system of forces. Faraday dispenses with the long-range attractive and repulsive relations of the particles, primarily because these had been introduced as 'mechanical' (non-chemical)forces (656n). Although Faraday had been 'convinced' that

> the superficial actions of matter ... and the actions of particles not directly or strongly in combination, are becoming daily more and more important to our theories of chemical as well as mechanical philosophy (656)

he now wishes to reduce the chemical properties of matter to the action of just one kind of force, an electrical force (703). In this respect the doctrine of the unity of force (of which the first two assumptions just listed may be regarded as consequences) appears to have been a more important guiding principle than any specific model or theory of the atom. Although Faraday again introduces the idea of an atom or

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74. Series seven, ERE I: (661-874), read: 23 January, 1834, and series eight, ERE I: (875-1048), read: 5 June, 1834. Note that the final version of the seventh series (as published) was still being written in May of 1834 (see Corr. I: 272).

particle in which the electric forces reside, he does so only after stating the theory in terms of relationships between ions, and also feels obliged to justify his use of what he calls the 'atomic theory or phraseology'.

The change in Faraday's position occurs in two stages. In the seventh series he restates the earlier theory in his new terminology, emphasizing the quantitative aspects of the force-relations between dissociating particles. By treating electro-chemical changes as due directly to the interaction of the current and the affinities he is able to eliminate the ambiguous relationship between the current, the affinities, and the long-range forces (2). The second stage involves a re-development of the theory in order to show how the electric current can be produced by a cell. This is effectively an application of certain leading assumptions about the nature of force, together with the assumption that electrical and chemical forces are (respectively) converted forms of each other.[75]

By the spring of 1834 Faraday had realized that the differences between his own interpretation of electrochemical action and those of his predecessors necessitated the introduction of a new terminology (661). In spite of his disclaimer that he was 'fully aware that names are one thing and science another' (666) Faraday took great care in choosing terms which would be free from theoretical connotations. As this process typifies Faraday's approach to the problem of developing

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75. I shall refer to these assumptions collectively as the doctrine of the unity of force. For a survey of the forms that this doctrine took in the thought of Davy, Faraday, Whewell, and others, see Levere, Affinity and Matter: 27 ff., esp. 70 ff. and 122 ff. In a letter of 1834 Faraday cites (John) Playfair and J.J. Berzelius as having been proponents of the view that all the powers of matter are referable to 'one common principle'--remarking that 'I have been in the habit of supposing that [these] general views ... have long been as it were common property' (Corr. I: 276).

a theory-free description[76] of a process I shall draw attention to several points of interest.

As he had done in the third and fifth series (283,517), Faraday again avoids specifying the nature of the electric current. He rejects the usual notion of material fluids but has no 'clear view' or model to offer as an alternative. In April of 1834 Faraday wrote to Whewell that 'the idea of a current especially of one current is a very clumsy and very theoretical view of the state of electrical forces'.[77] Faraday had other reasons for avoiding either the 'usual notions'[78] themselves or words which connoted such ideas. His confidence in the new theory of electrolysis required that the theory be stated in a language which would be independent of ephemeral and mistaken views of the nature of the current:

> I have little doubt that the present view of electric currents and the notions by which we try to conceive of them will soon pass away and want therefore names by which I can refer to [the surface of action] without involving any theory of the nature of electricity.[79]

A second reason was that while it was evident to him that the current is the determining agent in the process of decomposition, he was unable to specify the nature of this agent or of its action upon the particles of matter.[80] As he explained to Sir Charles Lemen:

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76. The new terminology is 'theory-free' in that it does not suggest any particular view either of the nature of the action between particles and poles or of the nature of electricity. (Quasi-material or imponderable fluids, atmospheres, and aethers were widely admitted at this time as real entities; see, for example, T. Exley, Principles of Natural Philosophy: or a New Theory of Physics, founded on Gravitation, and applied in explaining the general properties of matter ... (Bristol, 1829).

77. Faraday to Whewell, 24 April, 1834, Corr. I: 264.

78. Ibid., 264-265.

79. Ibid.

80. This difficulty arose in connection with new discoveries which are reported in the eighth series.

> At present my mind is very unsettled with regard to the nature of the electric agent. The usual notions attached to positive and negative and to the term current I suspect are altogether wrong but I have not a clear view of what ought to be put in their places.[81]

Although Faraday had 'one idea' that a current might be 'a resolution and recombination of forces' between 'contiguous particles' he was unable to 'see clearly how these changes come about'.[82]

It appears that Faraday was unwilling to put forth a theory about the nature of the current until he could succeed in visualizing the process whereby the opposing forces are resolved and recombined while being transformed into electrostatic actions between the particles and back into current electricity. Although this problem became pressing only after his discovery that water and other solutions could conduct without decomposing (912,966 ff.), Faraday had realized as early as April of 1833 (413,444) that the relationship between conduction, decomposition, and the transfer of chemical elements would have to be explained in terms of some alternating sequence of electrostatic and electrodynamic actions.

In the seventh series Faraday solves this problem with the now familiar use of a description couched in terms of powers having certain relationships (which are defined simply in terms of their directions). He describes the current simply as a 'relation of powers' (663) and names the points at which electrochemical action occurs in terms of the directed (axial) nature of the current.[83] As he remarked to Lemen, the

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81. Faraday to Lemen, 25 April, 1834, Corr. I: 267.

82. Ibid.

83. This involves introducing a convention in terms of which Faraday can name those parts of the cell at which the current acts in distinct and opposite directions (i.e., has opposite chemical effects). See (663) and Whewell's letter of 25 April, 1834, Corr. I: 265-267.

idea of 'forces with certain directions' can serve as an 'abstract notion of electricity' for though such a description tells us 'little or nothing' about the nature of this agent it is still possible to account for 'all the phenomena ... in such a way'.[84]

Thus Faraday introduces terms which, he believes, will not 'tend in any way to support false views' regardless of 'changes which may take place in our views of the nature of electricity ...' (663). He describes the cell entirely in terms of the places at which the current enters, leaves, and appears to act. Yet Faraday has not set aside the view that 'it is the causes of the forces that one wants to lay hold of'.[85]

1.3.3 Electricity, Atomicity, and the proof of the law of electrolysis

In July of 1834, six months after the seventh series had been completed, Faraday wrote:

> I think more myself of the Seventh Series than of any other. In it I have determined and proved the definite action of Electricity.[86]

The experimental 'determination' of this law consists in taking into account various processes which could result in the ratios of the products of decomposition failing to be constant, and in showing that these processes are of a secondary nature. Having established the reliability of the instrument which he is to use to demonstrate the law (732-739) and having also distinguished between the secondary or chemical actions which occur at the electrodes and the primary or electrical action of the current to which the law applied (742-746) Faraday can state the law with confidence (764,783,791,821-823).

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84. Faraday to Lemen, 25 April, 1834, Corr. I: 267.

85. Ibid.

86. Faraday to R.W. Fox, 23 July, 1834, Corr. I: 277.

However, the law is at this stage still an experimental law in the sense that Faraday has not yet shown why the facts upon which it is based should be as they are: he has not yet 'proved the definite action of Electricity'.

Proving the law involves showing why the original law of electric action (377) should be true as a law of electrochemical action as well (505,821). Faraday has to demonstrate that although the affinities between the particles in a compound molecule may vary, this variability has no bearing upon what is implied by the truth of the law of electrolysis: that the quantity of action required to effect a given dissociation is always the same for a given kind of compound molecule.

Faraday has already proven experimentally that his original law of electrical action (377) is sound: 'the chemical power of a current of electricity is in direct proportion to the absolute quantity of electricity which passes ...' (821). Matter can now be classified according to whether or not it is decomposed by electric forces passing through it (822). Bodies which are both decomposable and which obey the law of conduction (394) are to be called electrolytes while all others are non-electrolytes. Electrolytes form an 'exceedingly important general class' because they are decomposed into ions. The word 'ion' refers to an entity which is 'not in combination with another' (826). Why this is so will emerge shortly. Ions each have 'a definite proportion, in which they are always evolved during electrolytic action' (824). But ions are also indifferent to the electric forces, having no tendency 'to pass to either of the electrodes' (826).

The ion is therefore a curious entity. It possesses no powers of the sort that can interact with the electric forces yet, since it is 'a combining body' it must possess affinity forces. Faraday states that the fact that the ions are indifferent to the current is a fact upon which

> is founded much of the proof adduced in favour of the new theory of electro-chemical decomposition, which I put forth in [the fifth] series of these researches (826).

The ions are the dissociated or 'nascent' particles of the earlier theory of electrolysis and catalysis (658). Those particles which do pass towards one of the electrodes are called anions and cations (accordingly as they travel to the anode or cathode, 826). Faraday now stipulates that only an anion (paired with a cation) or a cation (paired with an anion) can be chemically active:

> If one ion be combined in right proportions (697) with another strongly opposed to it in its ordinary chemical relations, i.e. if an anion be combined with a cation, then both will travel, the one to the anode, the other to the cathode, of the decomposing body ... (827)

This statement is introduced as a definition of the three terms. Faraday does not use the term 'ion' only as a generic term.[87] His stipulation that only cations and anions are involved in the process--as pairs-- is equivalent to the hypothesis that for every particle of one element which is dissociated and which eventually recombines at one electrode, there will be one other particle dissociated and recombined at the other. The supposition that ions do move in pairs (i.e., as cations and anions) may be regarded as an ad hoc assumption which conveniently accounts for the fact that the ratio of the products of decomposition is always definite. This could then be developed in terms of the further assumptions that the ions are endowed with equal and opposite quantities of electricity. Faraday does go on to suggest that if the atomic theory is adopted, then such an assumption becomes plausible (852-869).

To prove the law Faraday would have to show not that this hypothesis may be true, but that it is true. His experimental proof of the law of electrolysis has been taken to be the first sound evidence

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87. See note 92.

for the atomic(electronic) nature of charge[88] and this has led most scientists and historians to suppose either that Faraday did adopt the concept of the electron,[89] or that he should have deduced the atomicity of electricity from his results.[90] Various explanations have been offered of the fact that Faraday did not conclude that electricity really is atomic in nature.[91]

1.3.3.1 The proof of the law

I do not believe that Faraday based his proof of the law upon the concept of the atomicity either of matter or of its electrical powers. In fact, Faraday's distinction between a single ion and those ions which constitute a cation-anion pair suggests that he regarded the law as proven on other grounds and that the basis for his distinction

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88. This interpretation was first placed upon Faraday's results by Maxwell (Treatise on Electricity and Magnetism, 2: articles 255-260), an interpretation which Maxwell himself rejected, and by Helmholtz ('On the Modern Development of Faraday's Conception of Electricity', Journal of the Chemical Society 39 (1881): 277-304, at p.290). Neither Maxwell nor Helmholtz actually attribute the concept of electronic charge to Faraday.

89. Whittaker emphasizes the passage in which Faraday does appeal to the idea that a definite quantity of electricity is associated with each atom (Aether and Electricity: 179-180) while Hesse notices that Faraday was 'reluctant to have to consider atoms even as point-singularities in his continuous force-field', but cites the later 'Speculation' of 1844 (Forces and Fields: 219, note).

90. Williams states that the law of electrolysis was 'deduced from theory' but fails to explain how this was done (Michael Faraday: 255-256). Levere claims just the reverse--that the law was derived from quantitative data and that 'a further deduction from his quantitative results' led Faraday to the hypothesis of definite electro-chemical powers (Affinity and Matter: 87-88).

91. Levere explains that the 'deduction' of the existence of the electron' did not follow because Faraday was not a Daltonian (corpuscular) atomist (loc.cit. note 90). Berkson follows Williams in attributing Faraday's failure to reach the (apparently) obvious conclusion to his not having been a fluid-theorist (Fields of Force: 80), while B. Schonland, following Lord Rayleigh, attributes this failure to simple prejudice or to the vagueness of Faraday's ideas (The Atomists(1805-1933), Oxford (1968): 33).

between ions, anions, and cations was as follows: he combined what I described earlier as the essentially dynamical view that a property exists or is manifested only as a relation between entities with the supposition that for every particle of one element which is dissociated there must be one other particle which is dissociated.

From a non-dynamical point of view the latter supposition would account for the fact that the ratio of the products of decomposition is constant (which, together with the assumption that the particles bear a discrete unity of charge, would explain the definite action of electricity). From the latter point of view the explanation is plausible, but it is not necessarily true. However, Faraday's stipulation that ions must be paired can be construed as a consequence of the dynamical view that where an entity is introduced as having some explanatory function in a theory, that entity must have some relevant power and that it has that power only if it is in relation to some other entity. Single ions (i.e. entities which are not paired) are nascent or temporarily inert, having no properties or relations of the sort that could determine chemical decomposition in the way that the law suggests that it is determined. The 'determining factor' is the relationship between ions (as pairs), a relation which constitutes a definite quantity of electrical force. On my interpretation of this version of the theory it follows that Faraday has built into his terminological distinction between ions and ion-pairs[92] a stipulation

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92. During the course of his correspondence with Whewell on nomenclature Faraday had asked for words denoting the two members of an ion-pair (Faraday to Whewell, 24 April 1834, Corr. I: 264). Whewell eventually suggested that the term 'ion' be used to refer to the two kinds of ion (Whewell to Faraday, 5 and 6 May, 1834, Corr. I: 269-270 and 271-272). Faraday does use 'ion' as a generic term in the final versions of the seventh and eighth series (824-825, 832,925,943,946-947), yet in his last letter to Whewell on this subject Faraday informs him that his advice has been taken but that he will have 'little occasion' to use the term 'ion' (Faraday to Whewell, 15 May, 1834, Corr. I: 272). Together with Faraday's statement at (826), cited supra, p. 55, this suggests that Faraday regarded single ions as a dynamical improbability and as irrelevant to the explanation of the law of electrolysis.

which appears as a sufficient reason for the definite action of electricity in decomposing matter (rather than as a plausible or possible reason for the fact that electricity acts in the way it does).

Faraday's main objective in restating the theory in the new terminology is to stipulate what must be true of the powers of the elementary particles if the law is to be explained in terms of what he had earlier referred to as their 'properties and relations'. Hence the import of the statement that two ions must be combined even while each is passing towards an electrode (827,828) is stipulative rather than theoretical. The stipulation is not really 'theory-free'; it follows from what Faraday takes to be the physical (dynamical) **basis** for the observed constancy of the ratios of the masses (or volumes) of evolved products.[93]

Faraday believed that he had proven the law of electrolysis. I have suggested that he believed this because he had based his account on the idea of a force-relation between two members of an ion-pair, where the nature of that relationship (as a definite quantity of action) required that there be a one-to-one correspondence between each particle reaching the electrodes. On my interpretation the force-relationship was of greater theoretical importance than any properties which the particles might have been supposed to have as individuals. Whereas in the fifth series Faraday had stated that the transmission of the dissociated particles is due to the action of the mutual relations (2)

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93. As is clear from the theory of the voltaic cell which Faraday develops in the eighth series, the (paired) ions remain related to each other by a fixed quantity of electric force until each reaches an electrode and is precipitated or evolved (as part of a gas). The recombination results in the liberation of this quantity of force as the current (whereas decomposition by a current would require the exertion of this same quantity of force). It follows that decomposition by a current and the production of a current (by decomposition) are identical but reciprocal processes. See (855 ff.) and Series 8 .

which subsist between them at all times (523,538,542) he now uses the term 'relation' in such a way that it is possible to construe the word solely in terms of its quantitative connotation: for every particle reaching one electrode there will be another reaching the other electrode. The terms of the new theory are 'theory-free' to the extent that they do not imply the adoption of any particular hypotheses about the nature of matter or of electricity (as atomic) but they are 'theory-laden' to the extent that they reflect Faraday's views about the nature of force as a determining cause of the electrochemical process.

Faraday's restatement of the theory of electrolysis in the terminology of 'ions' meets several requirements: it has been presented in a form in which the quantitative relations between chemical elements have been emphasized; in which the most fundamental theoretical principles of the earlier version have been preserved, and in which a detailed account of the nature of the elementary particles is no longer required. In contrast with the earlier version of the theory in which no less than three different forces (both chemical and non-chemical) had been introduced, Faraday is now prepared to assert only that:

> ordinary chemical affinity is a mere consequence of the electrical attractions of the particles of different kinds of matter ... (850, cf.917)

This statement signifies an important shift away from specific hypotheses about atoms as complex systems of powers towards a simpler view of the problem of explaining the general relationship between electricity and matter.

While developing the final version of his theory of electrolysis during the early part of 1834, Faraday had realized that the current (conceived as a 'set of forces having certain directions' or as a 'relation of powers') does not exist independently of the electrolyte

as a separate agent. He comes to view the current as the resolution and recombination of the two opposed forces which constitute the (electrostatic) force between cation and anion. Thus the current is nothing other than the release of the state of electrostatic tension which is established as the opposing affinities of the particles. In this way Faraday can view the processes of electrochemical decomposition and of the chemical generation of the current solely in terms of the opposition or reaction of systems of forces and in terms of the transition of force from its static to its dynamical (progressive) state and back again.

Even more important is the fact that Faraday also begins to realize the theoretical significance of an idea which he had introduced in the first paragraph of the first series--that electric forces, whether in their static or their dynamical form, are inductive or polar in nature.

This idea is restated in the eleventh series as one of 'the first principles of [the] action' of electricity, 'the most extraordinary and universal power in nature' (1161). As a principle it has two important consequences. One is the impossibility of there being isolated, latent, or discrete electrical states or charges. The second is that action (and specifically action at a distance) can be defined in terms of the idea of polarity or induction. In the second part of this essay I will show that the denial of action at a distance as Faraday himself understood it, follows from his adoption of this principle.

The ideas that electricity acts inductively between entities rather than as discrete charges attached to them and that inductive relations are polar quantities of action are implicit in the theory of electrolysis as I have interpreted it. If Faraday did understand his theory as a force-atomist then we should expect that he did regard each ion-

pair as consisting of a force-relation which is equivalent to a fixed quantity of electrical (or chemical) action rather than as pairs of atoms attached to or associated with electronic charges.

Although the view I have attributed to Faraday does follow from the theory of electrochemistry as developed in his papers of electrostatic induction of 1837 and 1838, Faraday does now go on to develop a second account of electrolysis which is based upon the atomicity of electricity as well as of matter (852 ff.). He does so for two reasons. First, he has been unable to obtain what he repeatedly refers to as a 'clear view' of the way in which the forces and the particles are related. Even the model which he now develops proves to be inadequate, for it does not explain why an electrolyte can conduct electricity of low intensity without decomposing (966 ff., and ERE I: 321 (note)). The second reason is that by developing a visualizable model of the process Faraday hopes to lend weight to his attempt to show that the theory of electrochemistry can be generalized to cover all chemical processes--thereby showing that all are ultimately due to electrical powers of the particles (as Humphry Davy and J.J. Berzelius had suspected (703,870)).

In reintroducing the notion of an atom or particle Faraday first justifies his use of these terms. Although

> we know nothing of what an atom is ... [and are] in equal, if not greater, ignorance of electricity, so as to be unable to say whether it is a particular matter or matters, or a mere motion of ordinary matter, or some third kind of power or agent,

there are two other points to be considered (852). The atom itself is unknown (and as he is later to argue, unknowable), 'yet we cannot resist forming some idea of a small particle, which represents it to the mind'. Second, unless we do adopt some such representation we cannot deal with the information we do have, viz.:

> the immensity of facts which justify us in believing that the atoms of matter are in some way endowed or associated with electrical powers, to which they owe their most striking qualities, and amongst them their mutual chemical affinity (852).

Thus it is both 'impossible, and perhaps ... impolitic, not to reason upon' the possibility that the law is really a consequence of the fact that each particle of matter is endowed with a definite quantity of force or action (852). The argument is double-edged: on the one hand it is intended to justify the introduction of a basic theoretical entity (the atom) while on the other it involves the idea that the justification for the introduction of such an entity lies in the fact that it enables certain theoretical conclusions to be drawn.

Faraday has argued simply that some such interpretative device or model is necessary, but has conflated the necessity of its introduction with the plausibility of those hypotheses which its introduction makes possible. Faraday accepts at this stage a position which he is later to reject, namely, that the 'powers' to which atoms owe their 'most striking qualities' may be powers of things: the agencies to which chemical changes are due may be grounded in real entities (even if the latter are merely points).[94] On the basis of this atom-powers-relations ontology Faraday puts forth (as an hypothesis) the view that all the particles of each kind of matter are endowed or 'associated with' (869) a characteristic and definite quantity of force. He then asserts that this force is identical in nature to an electrostatic force, which enables him to reduce chemical action to electrical action. What Davy and Berzelius had believed as a general hypothesis, Faraday is able to state and use as a fundamental principle of a general theory of the electrical and chemical properties of matter:

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94. In 1844 he is to argue that the temptations alluded to here must be resisted because the atom itself (as distinct from its powers) is not a possible object of experience and is not, therefore, an object either of knowledge or of thought.

> As soon as we perceive, through the teaching of Dalton, that chemical powers are ... definite for each body, we learn to estimate the relative degree of force which resides in such bodies ...,

using the fact that electricity (as a set of opposed forces) can be 'conveyed from place to place, whilst it retains its chemical force' (852). Taken together, the definite action of a quantity of current electricity (as measured out by the volta-meter (721)) and the definite relations (which are, ex hypothesis, electrostatic forces) of the particles suggest that some definite quantity of force is 'the link' which

> connects the proportion of that [electricity] we have evolved to the proportion of that belonging to the particles in their natural state (852).

On my interpretation of this theory it is this definite quantity of force or action which Faraday has in mind when he stipulates that ions travel and are decomposed or recombined only as members of a cation-anion pair. On this interpretation Faraday's conception of what constitutes an explanation or proof of a natural law is seen to be directly related to his emerging conception of force as a definite quantity of action which may assume different forms--manifesting itself in this case as polar tension or relation between elementary particles, at one instant, and as the progressive forces of the current at the next.

Although Faraday is later to treat the 'action' as residing in a single field, it is difficult to tell at this point whether he really regarded these 'definite quantities' of force as the discrete fields of individual particles or whether the atoms are merely fictions or conceptual aids (852) in which we have a 'means of localizing as it were the force, identifying it by the particle and dealing it out in

successive portions ...' (1650).[95]

1.3.4 The unity and convertibility of the powers of matter

Faraday had believed for years that chemical and other forces might be reducible to (or merely converted forms of) the electrical powers of matter.[96] In addition to the assumption that the chemical forces are identical to the electrical forces, Faraday's explanation of the law of electrolysis has required the further assumption that the two forms of force are equivalent in their actions or effects. I will now show how, in the eighth series of the Experimental Researches, Faraday goes on to develop a general theory of the conversion of electrical and chemical powers but that he fails to achieve the necessary basis for a similarly general theory of the electric, magnetic, and thermal powers of matter.

The fact that Faraday had earlier introduced the non-chemical relations of attraction and repulsion suggests that he did not then suspect that a complete theory could be based upon the identity of

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95. In which case the power or action would reside in the field but would be localized in the particles. Faraday later suggests a similar view of magnets as regions of the field in which the lines of force are highly concentrated, but he never makes clear whether chemical atoms are real individuals or merely fictions. See, for example, the comments in the first version of his lecture on conservation of 1857 and compare the remarks added in 1859 ('On the Conservation of Force', ERCP: 454 ff. and 461).

96. In one of his first lectures to the City Philosophical Society (given between 1816 and 1818) Faraday had stated his belief that 'the attraction of aggregation and chemical affinity is actually the same as the attraction of gravitation and electrical attraction ...' ('Lecture Book', p.31, as cited by Levere, Affinity and Matter: 70). Cf. Williams, Michael Faraday: 85-89, and Corr. I: 276.

the electrical and chemical powers.[97] He has assumed that the chemical (i.e. electrical) action of matter is somehow associated with or a property of its atoms, an assumption quite in keeping with the then-current view that matter should be defined or described in terms of its manifest qualities or powers.[98] Although the latter view was closely associated with the doctrine of the unity of force (through theories such as that of Boscovich) and although the two views were probably not distinguished by their proponents, the distinction between the dynamical or 'powers' view and the doctrine of unity of force helps to account for the differences between Faraday's first theory of electrolysis (in which non-chemical powers are used) and the later version of the theory in which atoms have only one relevant power.

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97. This suggests that Faraday was not simply working out Davy's original hypothesis but that he adopted it (publicly) only after he had shown that it could succeed (870,965)--pace Whittaker, who supposes that Faraday had adhered to 'Davy's doctrine of the electrical nature of chemical affinity ... in its most direct and uncompromising form' (Aether and Electricity: 184). Compare the two earlier versions of the law of electrolysis (505,523) with the later statements of it (821,947).

98. See, for example, J. Herschel, Preliminary Discourse (esp. articles 27-28); W. Whewell, Astronomy and General Physics considered with Reference to Natural Theology (pp.211-12, 257-58, and 361 of the 4th ed. (London, 1834)); and for a historical account, R. Smith, 'The Background of Physiological Psychology in Natural Philosophy', op.cit., note 35. In a collection of essays written in 1829 at the request of the Royal Society, P.M. Roget remarks that 'we begin by classing the different agents in nature, designating them by specific names; we next endeavour to conceive these agents as possessed of certain powers or qualities adapted to the production of the observed effects' (Treatises on Electricity, Galvanism, and Electro-Magnetism, article 40 of the treatise on electricity). Where Whewell and Herschel emphasized that the explanatory status of laws required that there be efficient causes, Roget stressed that this 'mode of viewing' the facts leads to 'great facility in tracing the connexions of the phenomena' and that this advantage is 'not immediately dependent upon the truth of the particular hypothese we employ ...' (ibid.), words which could have been written by Faraday (who did not read Roget's work until 1840 (ERE II: 103, footnote)).

1.3.4.1 Electrical and Chemical Powers

In the remainder of the seventh series Faraday examines the implications of the hypothesis that the atoms of matter are endowed with a definite quantity of electric force. Drawing upon his earlier demonstration of the definite action of different kinds of electricity (366-67,367-68), Faraday points out that the quantity of electricity in one 'grain' of water will be 'equal to a very powerful flash of lightning' (353, cf. 860-1,873). Now if this quantity can be turned into a current, and if (as Faraday has concluded) the relationship between conduction and decomposition is so close that the former cannot occur unless the latter occurs (854-55) then it must follow that

> the agent, which is electricity, is simply employed in overcoming the electrical powers in the body subjected to its action ... [thus] it seems probable, and almost a natural consequence, that the quantity which passes is the equivalent of, and therefore equal to, that of the particles separated (855).

If chemical change is to be reduced to changes in the state of a single type of force then some account must be given of the way in which this force can assume the two states in question. Further, this account must be consistent with the facts since discovered by Faraday (887-91) that the affinity forces in one cell may be overridden by those in another (as is evidenced by a change in the direction of the current) and that solutions can be made to conduct electricity without decomposing.

While working with different chemical cells connected in series Faraday found that there is

> a most extraordinary mutual relation of the chemical affinities of the fluid which excites the current, and [those of] the fluid which is decomposed by it (887).

This discovery was not entirely unexpected (505) but it proves to be

of great significance for Faraday's theory of the conversion of electrical and chemical force. That different electrolytes exhibit different degrees of electrical-chemical power (when connected in a series by plates or wires (888-91)) indicates that

> we have ... the power of opposing the actions of the two fluids simultaneously to each other at the opposite ends of the plates, using each other as a conductor for the discharge of electricity which the other tends to generate ... (891)

Faraday's conclusion is that there is 'an opposition of forces', i.e. of the affinities of the two cells, and that this opposition will determine both the 'formation and direction of the electric current' (891). The source of the current consists in an inequality between two or more affinities which would produce 'such a condition of the electricity (or the power on which chemical affinity depends) as would produce a current if there were a path open for it ...' (893). This condition is the cause of the current, which can pass only if the circuit is closed. Faraday proves the existence of this strained condition of the particles (of their affinities) by showing that a wire attached to one of the electrodes of a cell will draw a spark when brought sufficiently close to the other (915,956). This proves that 'the power on which chemical affinity depends' exists prior to the current and is therefore independent of it. Similarities between this state, condition, or power of the matter and the electrotonic state (60) or inductive power (256) will become evident in what follows.

After showing that the intensity of the current in a voltaic circuit is related to the intensity of chemical action at that point of the circuit in which the affinities are most intense (prior to the passage of the current, 904-909) Faraday concludes that

> decomposition ... [is] ... the direct consequence of the superior exertion at some other spot of the same kind of power as that to be overcome (910).

The fact that two powers can oppose each other shows that they are 'of the same nature' (910). This is the first occasion on which this criterion of identity has been made explicit. It follows that there is a reaction, opposition, or 'antagonism of forces' (910) which precedes and determines actual decomposition and the creation of a current. The chemical forces which are strongest can react upon and have 'a power over' the forces which would ordinarily produce a current (in a second cell). The forces of the second cell react upon the stronger affinities producing a resistance 'to the original determining force, and consequently to the current' (910). Evidently the reaction is to the affinities rather than to the current as a distinct agent.

Faraday has come to view decomposition by a current and decomposition during the production of a current as a single process which can run, so to speak, in two directions. As his complete account of these processes is too complex to recount here I will discuss only those points which bear directly on his conception of force.

If the 'mutual relation and dependence' of two opposed sets of affinities are taken to be the essential or characteristic feature of the production of a current in a circuit containing two or more chemical cells, then

> there appears no necessity for using, in respect to such cases, any other term than chemical affinity, (though that of electricity may be very convenient,) or supposing any new agent to be concerned in producing the results (917).

The affinities of the chemical elements interact in a manner analogous to the generative powers of the different conductors connected in an inductive circuit (193-201),

> for we may consider that the powers at the two places of action are in direct communion and balanced against each other through the medium of [the connecting wires] ... in a manner analogous to that in which mechanical forces are balanced against each other by the intervention of the lever (1031) ... (917)

The 'direct communion' or connection is provided by the forces of electricity in its dynamical form (the current).[99]

Decomposition and recombination are not caused by the current as Faraday had supposed earlier. The current is now conceived to be a direct physical connection between the affinities in different cells. For example, if A, B, C, and D denote (respectively) oxygen, hydrogen, zinc and hydrogen in a cell consisting of water containing dilute sulphuric acid, a zinc electrode and a platinum electrode, then (to simplify Faraday's account) there will be a tension established between the oxygen A of the water and the zinc C (call this force F_{AC}) which is stronger than the binding force of the water molecule (F_{AB}). The molecules (AB) will not be decomposed by the forces F_{AC} unless the force liberated by the simultaneous formation of the products (AC) and (BD) is allowed to pass (outside the cell) as a current. Similarly, combination of A and C (oxidation of the zinc) cannot occur unless the force liberated by the dissociation of A and B is allowed to pass as a current (as a force in the opposite direction). In this simple cell oxidation of the zinc is the 'sole cause' of the current (930,949) which consists of two opposed forces, these being the tensions or strains set up originally by the inequality of the affinities F_{AC} and F_{AB}. The role of the current is to equalize this inequality; to bring the two into equilibrium.

We can now see just what Faraday means when he calls the current a set of two opposed actions or a relation of the powers of the chemical atoms. The inequality of the affinity of the oxygen (A) for the

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99. Action, reaction or opposition, and equilibrium are referred to throughout the eighth series, although no concise statement of the relationship between these concepts appears until (959) and (1031). See: (898,904,910,917,963,922) and for similar ideas about other molecular powers, Herschel, Preliminary Discourse, articles 81 ff. and 234.

hydrogen (B) and for the zinc (C) cannot effect a chemical change unless this tension is allowed to pass through the wires between the electrodes. To use the terms quoted earlier, the current is just a 'resolution and recombination of forces' which exist between the 'contiguous particles' of the electrolyte and the electrodes.[100]

In this explanation of the generation of a voltaic current and of its action in decomposing the chemicals of a second cell the causal status of the current has changed. Earlier Faraday had believed that the current simply acts upon the affinities and the long-range forces of the particles and that it is not necessarily identical to the line of attractive forces in a chain of decomposing particles (521,541). Faraday now regards the system of mutual affinity-relations as the physical basis both for the constant proportionality of the masses and volumes of the products of decomposition (AC) and (BD) and for the relationship between these quantities and the intensity and the direction of the current (923, cf.827). Although the electrolyte can conduct only while decomposing, and although decomposition involves the transfer of chemical elements (923,925) both are the result of the 'mutual relation and action' of the powers of the particles (925). There is no longer a real distinction between the two forces of the current (517) and the affinities of the particles, for the current is no longer distinct (either spatially or causally) from the powers of the particles of the electrolyte. Faraday's model of the current as a progressive modification or polarizing of the affinities has not changed (542,950) but he no longer regards the current as an agent in its own right.

Faraday could actually see only the evolution or precipitation of chemical products at the electrodes and the heating or magnetic effects of the voltaic current in the wire. How does he justify his

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100. Faraday to Sir Charles Lemen, 25 April, 1834, Corr. I: 267.

identification of the hypothetical affinities F_{AC} and F_{BD} within the electrolyte with the current which passes to and is active in a second cell? He does so by appealing to the principle of the equality of action and reaction.

Faraday says that the attractive power of the zinc for the oxygen (F_{AC}) can be 'communicated to a distance' through connecting wires, to be exerted at some point other than the one at which it is established (918, cf. 910,917,947,959,996), and that this communication is made through the current which is 'merely a mode of exertion, or exhibition, or existence of true chemical action, or rather, of its cause ...' (877).[101] But this power must be opposed by an equal quantity of action where the two must tend (through the neutralization or balance of their opposed actions) to produce an equilibrium condition. Prior to the closing of a circuit containing two cells (one as described above and a second, whose constituents have weaker affinities than those of zinc and oxygen) there will be a tension between the zinc and the oxygen which is such as to place the whole electrolyte 'in a peculiar state of tension or polarity ...' (949). In this state the 'force of chemical affinity' (F_{AB}) has been 'influenced or polarized in the particles of the water by the dominant attraction of the zinc for the oxygen' (950).[102] Now comes the crucial part of Faraday's argument: when contact is made between the electrodes this force F_{AB} is 'transferred ... through the two metals [connecting the electrodes], so as to re-enter upon the circuit in the electrolytic conductor ...'

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101. Notice the use of 'exertion', 'exhibition', and 'existence' as equivalent terms, and cf. note 148.

102. This is the first explicit reference to polarity in the Experimental Researches. That Faraday speaks of the influencing or polarizing of a force shows that he regards the particles as centres of force (i.e., as entities whose extension consists in force rather than in hardness as a primary quality).

(950). In other words this polarized force

> is exactly balanced and neutralized by the force [F_{AC}] which at the same moment completes the combination of the zinc with the oxygen of the water (950).

The principle requires that there be forces in the wires which balance and neutralize (and are quantitatively equivalent to) the chemical forces, and, as Faraday had stated at (910) the opposition of two forces shows that they are 'of the same nature'.[103] Thus the current in the wire is just a wave consisting of the two opposed sets of affinities. So the forces

> of the two particles which are acting towards each other, and which are therefore in opposite directions, are the origin of the two opposite forces, or directions of force, in the current (950).

These two opposed forces 'are of necessity equivalent to each other' (950). The importance of this example is that it shows that Faraday justifies his identification of chemical and electrical powers not by a direct appeal to the principle of the unity of force, but that his interpretation of electro-chemical phenomena involves an appeal to the principle of equality of action and reaction as well.

Faraday now attempts to detect the state of tension which is 'the first consequence of the affinity of the zinc for the oxygen' (950). This attempt typifies both his use of his postulates or principles as guides to research and his response to negative experimental results. Faraday first explains that

> conceiving that [the peculiar state] might produce something like structure, either before or during its discharge, I endeavoured to make this evident by polarized light ... (951)

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103. At (1031) he is more explicit: the decomposition of elements in one cell by a current generated in another demonstrates that either set of affinities 'can determine the other, thus making what appears to be cause and effect convertible, and thereby demonstrating that both chemical and electrical action are merely two single exhibitions of one single agent or power ...'

Although the beam was passed both along the axis of the current and transversely to it (951-55) Faraday could detect no rotation of the plane of polarization. He does not conclude that the state does not exist, but that it does exist and has no influence upon polarized light (for this 'new and extraordinary state ... must be assumed by an electrolyte ...' (955)). However evasive or ad hoc this response to the experiment may seem, the test for structure is plausible in the first place only on the assumptions that the whole series or sequence of inter-particle actions, tensions, resolutions and recombinations is conservative (i.e., that all forces neutralize or balance) and that these electric forces can interact with light. By rejecting the hypothesis that this 'state ... has [a] power of affecting a polarized ray of light' Faraday is merely minimizing his losses, for he preserves one of the most essential theoretical concepts of his theory (the 'peculiar' or electrotonic state) and the principles of unity and of equality of action and reaction.

I argued earlier that the electrotonic state had been introduced to explain a discrepancy between what Faraday's beliefs had led him to expect about magnetic induction and what his experiments showed to be the case, and that the most important of these beliefs was that force (or action) must have an equal and opposite reaction. A third example shows the same principle to be at work here. Faraday does cite one 'beautiful experimental proof of a state of tension', namely, that a spark can be drawn just prior to contact of a wire connected to one electrode with the other--'in fact, at that moment when chemical forces only are efficient as a cause of action' (956). The production of the spark is taken to be evidence for the prior existence of the state of tension. The evidential relationship of 'spark' to 'state of tension' is similar to that of the case in which the

temporary nature of the induced current had been taken as evidence for the existence of the electrotonic state. Faraday had not simply inferred from the fact that a spark can be drawn that a state of tension must exist, he had predicted the effect. This state of tension or polarization of the affinities can be built up only against the reaction of an opposing set of affinities and the spark is produced as a momentary imbalance of these two opposed forces--it is the effect produced as the two forces are resolved or neutralized (957, 957 note).

Despite the confirmatory nature of this effect, it led Faraday to doubt the adequacy of the theory he had developed. Although Faraday has been able to explain why a cell which produces a current running in one direction will, when a second cell is introduced into the circuit, carry a current in the opposite direction (910 ff.,989 ff.), and although he has been able to explain resistance to the current within a cell (1007 ff., esp. 1017-31), so that he now has considerable evidence for a general view of electrical and chemical forces, there was a problem with this account. This was that water and other electrolytes could conduct electricity of low intensity without decomposing (968-70) and, therefore, 'by the same kind of power which it possesses in common with metals and charcoal' (1017). It appeared that the affinities which could 'excite' a current could also conduct one (983-87½). Faraday does not believe that this fact represents a serious limitation of the law of electrolysis (988,1032), but he is puzzled by what these phenomena, together with the production of a spark, suggest. A note that Faraday appended to the eighth series suggests that he was unable to visualize this process and that he regarded the simple model of particles and forces as inadequate:

> ... I would rather defer revising the whole theory of electro-chemical decomposition until I can obtain clearer views of the way in which the power under consideration can appear at one time as associated with particles giving them their chemical attraction, and at another as free electricity ... (493,957) (ERE II: 321, my italics)

We shall see that this difficulty led Faraday to have doubts about the usefulness of hypotheses about the nature of atoms and that the comprehensive theory of induction developed in 1837 and 1838 is a renewed attempt to explain the relationship between atoms and the static and dynamical states of the electric force.

1.3.4.2 Electrical and Magnetic Powers

In the ninth series Faraday returns to the problem of electromagnetic induction.[104] He tries to show that the phenomenon of self-induction is due to the same cause or principle as that of magnetic induction between two separate conductors. His treatment of this effect is quite consistent with the theory of matter and force which emerged from the eighth series, and his tentative explanation of self-induction involves an appeal to principles which he has made use of throughout the first eight series: those of the equality of action and reaction and of the convertibility of forces through some power of the matter in which they exist or are generated.

The phenomenon of self-induction had been brought to Faraday's attention by William Jenkins.[105] It involved what Faraday at first to be two distinct effects. The first was that upon breaking a circuit consisting of a voltaic cell whose electrodes are connected

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104. ERE I: (1048-1118). This paper was completed in December of 1834, two months after the tenth series (which was apparently set aside by Faraday in favour of the investigation of self-induction).

105. See ERE II: 206 and series 9 (1048).

by a coil having a soft-iron core, a strong shock could be felt. No shock could be detected if the core were absent. The second effect was that a strong spark could be drawn upon breaking a circuit consisting of a voltaic cell whose electrodes were connected by a long wire. Only very small sparks could be drawn with shorter wires.[106]

It is evident from his description of the first effect that Faraday at first regarded the induction of a current as being due to a change in the magnetic power of the soft-iron core:

> The shock is not due to the electricity set in motion through the wire by the plates, but to a current in the reverse direction, induced by the soft iron electromagnet, at the moment when, from the cessation of the original current, it loses its power (ERE II: 206).

The coil and core therefore act as a transformer, converting the low-intensity voltaic current of the cell into a short-lived high-intensity current. The magnetic power lost by the iron core reappears in the form of the secondary current which produces the shock. Thus the iron, after it has been magnetized by the primary current, has the power to 'react upon the wire' (ibid., pp.207-8). This reaction depends upon the nature of the core (thus the reaction is reduced if the core is of hard steel (p.208)). The significant feature of this case is that increasing the length of the wire increases the spark produced on breaking contact but does not alter that drawn when the circuit is closed. Thus it appeared that the current passing through the longer wire had acquired a greater intensity.

Faraday admits that this second effect can be explained in an intuitively obvious way by 'assuming a species of momentum as being acquired by the electricity' which will, of course, be increased as the length of the conductor is increased (p.208). Yet he is unwilling

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106. 'On the magneto-electrick shock and spark, and on a peculiar condition of electric and magneto-electric induction' (October 1834), ERE II: 204.

to accept this explanation:

> it is evident that the similar effect produced by the soft iron ... cannot be explained in this way, i.e. by momentum; and as it does not seem likely that the effects, which in these cases are identical, should have two causes, I believe that both are produced in the same way ... (p.209)

To show that this apparent identity is a real identity Faraday re-introduces the concept of lines of magnetic force. When both experimental situations are re-described in terms of a quantity of inductive action exerted by the primary current and represented in terms of its lines of force, it becomes evident that in each case

> the direction of the magnetic curves, both of the wire so magnetized and of the soft iron magnet, in relation to the course which the current is persuing [in the conducting wire] is the same ... (p.209)

If the effect is referred to 'a peculiar effect of induction exerted by the magnetism over the passing electric current, all becomes consistent' because

> the longer the wire the greater the number of magnetic curves which can exert their inductive influence; and the effect in a wire of a hundred feet in length will be nearly a hundred times greater than in a wire of the same diameter only a foot in length (ibid.).

The effect of the iron core can be described in the same way.

Faraday has spoken here of the inductive 'power' or 'influence' of the magnetic curves. Although he refers to this description of their action as an 'assumed cause' it is clear that the lines of force have been introduced primarily to facilitate a description in terms of which two similar effects can be shown to have a common cause. He goes on to make clear that he still believes the explanation to lie in the notion of the electrotonic state:

> I think I see here some of those indications of an electrotonic or peculiar state ... for though I speak here of magnetism and magnetic curves for the sake of reference, yet allowing Ampère's theory of the magnet, all the effects may be viewed as effects of induction produced by electrical currents (p.210).

As certain remarks subsequently made in his ninth series indicate, Faraday believed that the process could be described without recourse to the notion of magnetic force as anything other than the 'lateral' or inductive aspect of an electric force.

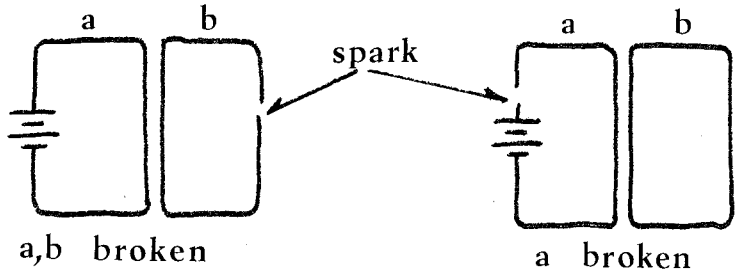
By the time Faraday had completed the ninth series (two months later, in December of 1834) he had realized that the two effects described in the earlier paper were in fact due to 'the inductive action of currents of electricity described in the first sections of the first series of my Experimental Researches' (1051). The ninth series is essentially the attempt to show that this is the case, viz. that the new phenomenon indicate that there is an 'immediate connexion' between electric induction and 'the direct transmission of electricity through conducting bodies' (1048). Faraday had demonstrated this graphically in the earlier paper by relating the quantity of inductive action to the number of lines of force generated by a conductor, and he now proves this experimentally. The fact that the effects can be varied by varying the length of the conductor (1067) and that the intensity of the effect varies with both the length and the form of the conductor (1062-63) shows that it is dependent upon both the quantity and the arrangement of the conducting matter (1059,1070) and not simply upon the quantity or intensity of the primary current (1071-72). Yet the inductive effects do in turn affect the primary current: as the size of the spark drawn on breaking contact is increased, so the 'permanent current loses in force' (1073).

In explaining these effects Faraday again rejects the possibility that 'the electricity circulates with something like momentum or

inertia in the wire' (1077). Faraday argues that the attribution of inertial mass to the current cannot lead to a plausible explanation because the effects can be modified as much by changes in the form of the conductor as by changes in its length (1070) and because the primary (inducing) current can be shown to be quite distinct from the secondary (induced) current (1089). But if one current is due to chemical action in the cell and the other to electromagnetic induction, should it not be possible to separate the two entirely? To do so would be to prove conclusively that the effects cannot be attributed to the inertial properties of a single (fluid) entity in the conductor.

Faraday 'separates' the secondary current from the primary by placing a wire forming part of a circuit parallel to a long wire through which a voltaic current could be passed (see figure 1.1).

FIGURE 1.1



When the latter was broken the effects which would normally have occurred at the point of disjunction appeared instead at a small gap in the former. It was evident that 'the extra current could be removed from the wire carrying the original current to a neighbouring wire' (1092).[107] Faraday concludes that this spark which had thus far been detected at the breaking point of the primary is really 'the equivalent of the current which would be produced in a neighbouring wire ...' (1092).

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107. The secondary current is just an induced current except that in the absence of a second conductor it will occur in the primary circuit.

1.3.4.2.1 Action and Inertia

Faraday again appeals to the principle of equality of action and reaction that had been the basis of his interpretation of the original experiments on magnetic induction, for he remarks that a current will act inductively 'with equal energy at the moment of its commencement as at the moment of its cessation (1926) ...' but in the opposite direction (1101). The fact that Faraday believes that this action can be transferred from one wire to another, and that he does not believe the current to be an imponderable but inertial fluid shows that his principle of the equality of action and reaction is not equivalent to Newton's Third Law.

What Faraday meant by the equality of action and reaction is revealed in his response to William Whewell's suggestion in a letter of 1835 that the effects should be explained in terms of the inertial properties of the current. Where Faraday took the 'causes' and the 'effects' to be active states or conditions whose behaviours could not be reduced to the laws of the motions of inertial masses or fluids, Whewell argued[108] that the model of electricity as an inertial fluid should be used because both mechanical interactions and the effects of self-induction could then be explained by the laws of mechanics.[109] On the basis of the analogy we have, according to Whewell,

> a full and exact account of the laws, alike, of electrical currents and mechanical collision. How then can I help identifying the two cases? (Corr. I: 293)

Modification of inductive effects by changes in the form or course of

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108. W. Whewell to Faraday, 9 September, 1835, Corr. I: 293.

109. 'A substance when put in motion by another substance, produces at the first instance and impulse opposite to that of motion; if the velocity be uniform, no further effect is perceived until the motion is stopped; and at that instant, an impulse is produced in the direction of the motion' (Corr. I: 293).

the conductor is analogous to changes or irregularities in the course of a pipe or tube through which water is passing. To Whewell the inductive effects are simply 'facts of instantaneous action', namely, the 'reaction of the current in which motion is produced by induction' (ibid., p.294). Whewell defines the word induction in terms of the analogy:

> The facts which occur at making or breaking contact are not induction, if induction means, as by analogy it should, the condition produced by the neighbourhood of an electric circuit. These facts mark the beginning and end of induction. Whether there is a permanent condition produced by a neighbouring circuit or not, this class of facts has no right to the name (Corr. I: 294).

Whewell has misunderstood Faraday, for he has interpreted the effects in terms of Newton's third law. What Faraday takes to be a dynamical and continuously active state of the current, Whewell sets aside as superfluous to those effects which should be expected when the process is interpreted in terms of the analogy:

> You say "a current sustains a state which when allowed to react at the cessation of the original current, produces a second current" [cf. 1114]. I think therefore that in accordance with your own views, all the facts produced by the beginning and end of electrodynamical proximity should be ascribed to electrodynamical reaction (ibid., 294).

Where Faraday had described the 'facts' in terms of a sustained inductive action of the primary (and a corresponding state of tension in the secondary conductor) Whewell explains them simply in terms of inertial properties of some substantial entity in the wire(s). He has evidently missed the point of Faraday's distinction between the inducing (primary) and induced (secondary) currents.

In his reply to Whewell[110] Faraday stresses the fact that strict adherence to the analogical argument not only leaves the transfer of

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110. Faraday to Whewell, 19 September, 1835, Corr. I: 294.

action from the primary to the secondary conductor (as at (1090) where the two are distinct wires) unexplained but leads also to an inconsistency. If the current momentarily induced in the secondary (when the primary current is cut) is simply a momentum-effect then it must be the effect of a current or substance which was not in motion while the primary continued to pass.[111] On Whewell's interpretation the 'momentum effect' could not be made to appear in a second conductor at all. Faraday suggests that the secondary conductor must assume the electrotonic state while the primary current continues to pass:

> if this second current had an existence during the time that the first current was continued I could have better conceived the notion of momentum. As the second instantaneous current does not exist I take it for granted you assume the electrotonic (60) or peculiar (1114) state ... (ibid.)

This serves to turn another of Whewell's objections, that the term induction should be applied only to the instantaneous effects and not to any process or continuous effect of the primary. To assume the electrotonic state will 'justify the application of the word induction to it either at its beginning its continuance or its termination' (ibid.). Thus Faraday also dissociates himself from Ampère's terminology, which Whewell had suggested that he use:

> let me remind you that I and Ampère use words, I.E. names, in very different ways. My words .... are merely intended to indicate how the effects included under them are obtained whereas Ampere by the word "Electro-dynamic" essentially implies a theory which may be wrong ... at all events [my words] pledge me to no theory ... (ibid., 295)

Although Faraday was prepared to 'accept Ampère's theory as the best present representation of facts' he still held it 'with a little reserve', for (like Whewell's interpretation) that theory involved positing qualities and structures which could not (in principle) be

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111. Ibid., pp.295-96.

perceived. Thus he explained that

> I cling to the relations of Magnetic & Electric forces as the simplest I can perceive; these again are readily distinguished in practise and hence the most convenient if not the best for an experimentalist to refer to.[112]

The significance of this exchange is that it reveals both that Faraday was unwilling to use the concept of inertia (even when pressed) and that his idea of a property or power is that of an active state or condition.[113]

1.3.4.2.2 The status of the lines of force

Faraday's interpretation and discussion of self-induction make clear that he still regards the state or condition of the conductors as the key to an explanation rather than the state of the region between them. Although the fact that the 'extra' or induced current can be transferred across space to a quite separate circuit shows that the secondary current is due to inductive action rather than to inertial effects, Faraday does not actually argue that the action must reside in or be transmitted by the lines of magnetic force generated by the primary current. This point is significant because it shows that Faraday is not yet prepared to assign an explanatory (i.e. causal) status to the lines of force.

In interpreting the self-inductive effects Faraday assumes that they depend not upon some permanent state of the conductor or of its field, but upon 'a change of state' of the former (1101). As he had made clear in his paper of October 1834, Faraday believes that a change of state of the matter (rather than a change in the distribution of

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112. Ibid., p.295.

113. Faraday later attempts to treat both inertial and gravitational mass as relational properties (i.e. as powers due to some property of the lines of gravitational force). See infra, section 3.4, p.298 ff.

the lines of force) will prove to be the cause of these effects (1100-01). Although the action may be described in terms of the lines of magnetic force it is not to be explained in terms of them.

The significance of this point and of the following argument is that although Faraday reaches his conclusion on the basis of reasoning which later leads him to assert that the action must reside in the field, this conclusion falls short of the assertion that the field of the primary is the cause of the inductive effects.[114] Nor is it equivalent to a denial of action at a distance,[115] (if such a denial is taken to follow either from the assertion that or from experimental evidence that an action takes time and that the action is transmitted through some medium).[116] When Faraday does deny that

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114. If Faraday did 'regard the effect as due to the collapsing lines of force of the primary current which intersected the wire as they fell' (Berkson, Fields of Force: 70) he certainly does not reveal this either in the ninth series or in the paper preceding it, in which the lines of force are used only to establish the identity of the action as an inductive one, i.e. one to which the law of induction (114,116) applies.

115. It is generally believed that Faraday either rejected action at a distance early in his career (Williams, Michael Faraday: 181, 223 and 302n.) or that he adopted a metaphysical stance which implied or entailed the denial of action at a distance (Berkson, Fields of Force: 51-52 and 70-71). These interpretations are misleading to the extent that they identify Faraday's rejection of action at a distance with his adoption of some definite set of criteria (Williams, op.cit. and Hesse, Forces and Fields: 203 ff.) or identify it as a metaphysical or aprioristic attitude (Berkson, op.cit., McGuire, op.cit. note 13, at p.137). Cf. sections 2.2 (p.117 ff.) and 2.2.1 (p.121 ff.).

116. Both Williams and Berkson reproduce the sealed note deposited by Faraday with the Royal Society in 1832, in which Faraday stated his belief that the transmission of magnetic action would take time (Williams, Michael Faraday: 181 or Berkson, Fields of Force: 73). Yet both overlook the significance of the fact that experimental evidence for this belief was not forthcoming: as late as 1852 Faraday was prepared to admit that both magneto- and electrostatic induction may occur instantaneously (e.g. (3249,3253)). It has not been recognized that evidence of a finite rate of propagation was neither the only criterion of action at a distance used by Faraday nor the most important; nor has it been realized that Faraday could admit instantaneous action while denying that it is action at a distance (as he understood this). Cf. infra, sections 2.2.1, 2.6, and 3.2.

electrostatic or magnetic action can occur at a distance he does so on the basis of the principles that (1) as polar actions and (2) as limited and definite quantities of action, these forces can act only between neighbouring or contiguous points.[117]

The conclusion reached by Faraday in the ninth series is that even if the magnetic or inductive forces of the current are assumed to be the direct cause of self- and of mutual induction, the account cannot thereby be made complete: '... still there appears to be a link in the chain of effects, a wheel in the physical mechanism of the action, as yet unrecognized' (1114). This passage is of considerable importance because it reveals Faraday's unwillingness to concede that this process involves nothing more than meets the eye, an unwillingness which is to lead him to argue for the reality of the lines of magnetic force in 1852. It is easy to see, with hindsight, that this 'missing link' is the field (as a quantity of action). But it is important to realize also that Faraday does not reach this conclusion in 1834 because he still identifies the cause with the electrotonic state, and this state with matter.[118]

Faraday's conclusion follows from his belief that the electric and magnetic forces are the 'results of'

> two forces of a physical agent, or of a peculiar condition of matter, exerted in determinate directions perpendicular to each other ... (1114)

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117. I.e., over the shortest possible distance, which is not necessarily an 'insensible' distance (1616). Faraday's 'denial' of action at a distance is therefore the consequence of a principle of local action, and this in turn is a consequence of his beliefs about the nature of force. Cf. infra, section 2.2.1.

118. This appeal to a 'missing link' is to reappear several times, and for the last time in Faraday's defence of the physical theory of the field (when it is identified as the electrotonic state--but as a condition in space as well as in ordinary matter (3269)). See infra, sections 3.5.3, and 4.2.2.

On this view the equality of action of the primary circuit when contact is made and of the reaction when it is broken (1106) requires that there be at least a partial conversion of the two forms or directions of the power (1109). Otherwise it would not be possible to explain how a current can, 'by its direct action', sustain

> a state which, when allowed to react, (at the cessation of the original current,) ... produces a second current, having an intensity and quantity far greater than the generating one ... (1114)

The difference in the intensity and quantity[119] of the primary and secondary currents 'cannot result from a direct reaction of the electric force' for this leaves no room for an explanation of the difference itself (1114).

Instead of concluding that the 'action' of the primary current exists as its field (as he is to do later) Faraday concludes that the two forms of power must be convertible wholly or partially[120] 'by a process or change of condition at present unknown to us' (1114). Faraday still believes that this conversion process can occur only in the presence of matter (as that which assumes the electrotonic state). Only in 1843 is he able to prove that the magnetic lines can exist in the absence of matter, and only then is he able to argue for the reality of the magnetic field as an entity in its own right.

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119. Faraday takes the difference in the duration of the primary and secondary currents to be evidence for a difference in the total quantity of action or power required to produce each.

120. In an ideal chemical cell the electrostatic (affinity) forces should be entirely convertible into the 'progressive' state (the current). Cf. series 10 (1000,1120 ff.); series 16 (1803); and Levere, Affinity and Matter: 102.

1.3.4.3 Magnetic and thermal powers

In the spring of 1836, a year after the ninth series had been completed, Faraday published a paper on 'The General Magnetic Relations and Characters of the Metals'.[121] In this paper Faraday reports an investigation carried out on the expectation that

> all the metals are magnetic in the same manner as iron, though not at common temperatures or under ordinary circumstances (ERE II: 217).

The experiments did not bear out this contention. Faraday's response to the failure of this attempt is as important (for our purposes) as the reasoning which led him to make it.

Faraday explains that 'general views have long since led me to the opinion' that all metals would prove to be magnetic (ibid., 218). His reasoning here is similar to that which had led him to conclude in April of 1833 that 'all bodies conduct electricity in the same manner ... but in very different degrees' (444). After having discovered the law of 'liquido-conduction' (380 ff.) Faraday had concluded that the 'law of the assumption of conducting power during liquefaction, and loss of it during congelation would [not] be peculiar to water ...' (394). He now wishes to establish a similar relationship between magnetic powers and temperature.

The fact that the magnetic powers of the two known magnetic metals[122] depend upon temperature suggested that magnetism might prove to be as general to the metals as conductivity of a current

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121. ERE II: 217; dated January, 1836. Cf. also ERE II: 223 ff.

122. These being iron and nickel. The term 'ferro-magnetic' was not introduced by Faraday until September of 1846 (ERE III: 453). The distinction between para- and diamagnetic materials was discovered by Faraday in 1845, but was not expressed as such until 1850 (series 25 (2790)).

had been to electrolytes. There is a more important reason than the analogical considerations actually stated by Faraday.[123] This is that to develop a general theory of magnetism he has to show that this power is as general or as universal as electrostatic and chemical powers are.[124] The fact that iron, nickel and cobalt were then the only known magnetic metals would prove to be an accidental rather than a fundamental fact:

> In this view iron and nickel were not considered as exceptions from the metals generally ... any more than mercury could be considered as an exception from this class of bodies as to liquefaction (ibid.).

Faraday's trials were conducted during cold weather in December of 1836. Even at temperatures of about -60° F[125] Faraday could detect no indication of magnetic powers in any of the metals he tried. He attributes this to the fact that the temperature had not been made low enough, stating that the 'negative results ... could scarcely be allowed to have much weight in deciding the question under consideration ...' (ibid., 219). Faraday then compares the temperatures at which the known magnetic metals cease to be magnetic, finding that in each case the power is lost at a well 'defined and distinct' temperature (ibid.).

This showed that like the electrical conductivity of electrolytes, magnetic powers do depend upon temperature. Despite the failure of the initial experiments Faraday claims that

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123. The inference that one power will be as universal as another is underwritten by the principle of unity, for if all powers are merely forms of a single power then all matter should be susceptible or sensitive to every form of this basic power.

124. Cf. series 1 (1-4), where Faraday points out that the inductive action of electricity in its dynamical state (the current) should be as universal as its action in the static state. Faraday does not discover the 'universality' of magnetic action until 1845 (series 21 (2420)).

125. For details see the paper cited.

> the experiments, as far as they go, justify the opinion advanced ... that all metals have similar magnetic relations, but that there is a certain temperature for each beneath which it is magnetic ... and above which it cannot exhibit this property (ibid., my italics).

Instead of accepting the negative results as disconfirming the hypothesis, Faraday emphasizes that the two positive results confirm the principle which had generated that hypothesis, using the principle to explain why no general confirmation has been forthcoming.[126]

Here he uses the principle of unity in conjunction with an hypothesis about what determines the presence (manifestation) or absence of a power:

> The magnetic capability, like volatility or fusibility, must depend upon some peculiar [i.e. characteristic] relation or condition of the particles of the body; and the striking difference between the necessary temperatures for iron and nickel appears to me to render it far more philosophical to allow that magnetic capability is a general property of all metals, a certain temperature being the essential condition of this state, than to suppose that iron and nickel possess a physical property which is denied to all the other substances of the class (ibid., 220, my italics).

Out of seventeen metals, fifteen had not behaved as expected and the two which had were already known to be magnetic. The fact that iron and nickel lose their powers at different temperatures confirms the statement as applied to these two metals only; it does not justify Faraday's advancing it as a universal generalization (ibid., p.219). Yet Faraday chooses to overrule the 'evidence' because he believes not just that similar properties will be found to have similar causes but that similar groups of properties will be found to have similar causes. Thus it is not 'philosophical to allow' that substances

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126. For a discussion of principles and of confirmation in this context see, for example: H.R. Harré, The Principles of Scientific Thinking (Chapter 6, at p.172) and S. Bromberger, 'A Theory about the Theory of Theory and about the Theory of Theories', in B. Baumrin, ed., Philosophy of Science, The Delaware Seminar 2 (New York and London, 1963): 79.

which have been classified as being of a certain kind because they share certain properties (e.g. metals) do not also share some other property which has been shown to exist under certain conditions in some members of that class (e.g. magnetism).

This principle is used to govern the use which is to be made of experimental results--in this case to defend a reservation of judgement on the basis of unwanted results. It is really the expression of Faraday's conviction that all manifest properties (of bodies) depend upon the powers or secondary properties of elementary particles (though not upon particular structural properties which may be possessed only by matter of a certain kind).[127]

1.4 The Nature of Matter

Although he has attributed attractive and repulsive forces to the particles of electrolytes, solids, and gases in the fifth and sixth series of his Researches and has made rather guarded use of the 'atomic theory or phraseology' in the seventh and eighth series, Faraday has made no explicit assumptions about the actual structure of particles as entities distinct from their powers. At this stage of his thinking forces or powers are the concepts most important to the description and explanation of the relationships between the electrical, chemical, and magnetic properties of matter and these relationships are the main subject of Faraday's investigation.

Comparison of the first theory of electrolysis and of catalytic

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127. The theory hinted at here is not Ampère's theory of molecular currents (which Faraday categorically rejects at p.220) but a theory on which possession of magnetic power either as a permanent power or as a disposition depends upon the temperature (ibid., pp.220-21).

action with the second theory of electrolysis has shown[128] that by the spring of 1834 Faraday had adopted a more cautious and abstract approach to theory construction, defining his theoretical entities only in terms of those powers which had proven either to be founded in experience (e.g., the directed nature of the forces of the current) or to be essential to an explanation of the process in question. In Faraday's proof of the law of electrolysis the electrochemical process had been described in terms of (1) a single property or power of the particles and (2) the determinate (lawlike) nature of force as a definite quantity of action which exists as a relation or connection between particles. Matter as a system or structure of particles had been characterized in terms of its tendency to react upon or resist the passage of force in its static state, a disposition which Faraday believed to be possessed by all matter and to be manifested as the electrotonic state.[129] This is the only general disposition of all matter that Faraday continues to insist upon throughout his career.[130]

Powers, forces (relations), and the electrotonic state were not the only theoretical entities admitted by Faraday. Although the

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128. Cf. supra, sections 1.3.2.1-1.3.3.

129. After January of 1832 Faraday had dispensed with the term 'electrotonic state', replacing it by the term 'peculiar condition' (or state). In September of 1835 he wrote to Whewell that he had 'given up this electrotonic state for the time (242) as an experimental result (remember my researches are EXPERIMENTAL) because I could find no fact to prove it but I cling to it in fancy or hypothesis (242.1114) from general impressions produced by the whole series of results ...' (Corr. I: 296). On Faraday's view of force as an active state or tension the existence of this state (as a reactive state) is a necessity rather than a matter of 'fancy or hypothesis'.

130. In this respect it plays a role (in Faraday's thought) analogous to that of mass in mechanics (compare Faraday and Whewell's interpretations of self- and mutual-inductive effects as discussed, supra, section 1.3.4.2.1). Faraday finally identifies the electrotonic state as the condition of the field in space free of matter.

particles and the matter have been described solely in terms of some relevant power or condition, and although the current has been described just as a set of opposed forces which correspond to the two directions of action of the affinities, Faraday has admitted that the latter powers are 'associated with' or are properties of the particles of matter (852).[131] Faraday has made force the basic explanatory concept of his theories and has thereby minimized the explanatory role of atoms and of matter, but he has not yet made force the sole referent of his theories. He has interpreted virtually all of his major experiments in terms of a distinction between force (as that which acts) and matter (as that which reacts).

Faraday's interpretation of nature has not yet reached a level of sophistication at which the question of the ontological status of the 'particles' (as entities distinct from their powers) has become a pressing one. Between 1836 and 1840 this situation is to change. Faraday encounters two difficulties with the present view on which matter is identified as that which assumes the electrotonic state. The first had been apparent to him from as early as the spring of 1834, and will be discussed here. The second arises out of the 1837 theory of electrostatic induction which Faraday develops partly as a solution to the first problem: it is that the distinction between atoms and the powers to which their electrical properties are due leads to an inconsistency in Faraday's account of conduction and insulation as different aspects of a single property of matter.[132]

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131. Cf. supra, sections 1.3.2-1.3.3.

132. Cf. section 2.5.1 Faraday deals with this not by altering the model of the dielectric developed in 1837 but by insisting in 1844 that the interpretation of the model must be consistent with the principle that entities can be known only as their powers.

Faraday had been troubled by the fact that he had been unable to envisage how the powers of the elementary particles of a chemical solution can 'appear at one time as associated with particles giving them their chemical attraction, and at another as free electricity' (ERE I: 321 n.). He had been puzzled particularly by the distinction he had felt it necessary to draw between the two distinct conditions under which the electrotonic state (or polarized condition of an electrolyte) is created, viz., by the local action of an affinity at a point (as at an electrode) and by the exertion of such a force over a distance (as in a voltaic circle; cf. (910,917,947,959)). There was also the problem of explaining how the static state of the force could conduct the same force in its dynamical or progressive state.[133]

In a letter to F.C. Ward of June 1834, Faraday encourages Ward to experiment on a theory of atomic structure, 'for experimental philosophy ... is a great disturber of pre-formed theories'.[134] He then says this:

> I have thought long and closely about the theories of attraction and of particles and atoms of matter, and the more I think (in association with experiment) the less distinct does my idea of an atom or particle become.[135]

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133. Cf. supra, section 1.3.4.1, or (983-987½).

134. Faraday to Ward, 16 June, 1834, Corr. I: 274.

135. It is worth noticing that in his Preliminary Discourse Herschel had outlined a programme for the investigation of the atomic powers and structure of matter, concluding that the 'enquiry ... into the aggregation of matter resolves itself into the general question, What will be the behaviour of material particles under the mutual action of opposing forces capable of counterbalancing each other? and the answer ... can be no other than the announcement of the law of equilibrium, whatever that may be' (article 81). The 'law' is presumably a force-law of the kind proposed by Boscovich. For Faraday's approval of Herschel's Discourse see: Corr. I: 235. For a discussion of Herschel's methodology see: J. Agassi, 'Sir John Herschel's Philosophy of Success', HSPS 1 (1969): 1.

Two weeks later Faraday and William Rowan Hamilton met over breakfast at the Bilton Hotel in Dublin. In a letter written the same day Hamilton reported that Faraday, 'who had been proceeding entirely by induction and experiment ... has been led to almost as anti-material view as myself ...'[136] He went on to describe this view in the following terms:

> [Faraday] sees no proof from chemical facts ... for the existence of those little bulks or bricks, of which so many fancy the outward world to be built up. And as to his chief study, electricity, after having long given up the fancy of two fluids, he now sees no use for even one, and seems to regard the electrical current as only a transference of power--nearly as, in modern optics, we regard the transmission of light as consisting in the motion of a motion.[137]

This description reveals three aspects of Faraday's attitude towards theoretical explanation at this time (and towards the positing of entities in particular). They are significant because they are characteristic both of the anti-materialistic stance of the first nine series of the Experimental Researches and of the position which Faraday defends in 1844 and in 1846.

The first point is that Faraday does not believe that there are any facts which can prove the existence of atoms--a belief which was shared at this time only by theorists who rejected corpuscular or Daltonian atoms in favour of point-atoms or by those who took a positivistic attitude towards theoretical entities of any kind.[138] Although in 1844 Faraday is to produce facts which he shows to be inconsistent

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136. W.R. Hamilton to (Miss) Sydney Hamilton, 30 June, 1834, in R. Graves, Life of Sir William Rowan Hamilton II: 95-96.

137. Ibid., p.96. (Italics in the original.)

138. Faraday rejects corpuscular atomism but is far from being a positivist (in the sense that B.C. Brodie was). Cf.: D.M. Knight, 'Steps Towards a Dynamical Chemistry' (cited supra, note 30) and W.H. Brock, ed., The Atomic Debates.

with the assumption that certain properties of bodies depend upon the atomicity (finite extension) of their particles, he is to insist that there can be no experiential access to the actual nature of atoms. Second, Hamilton's description points to another of Faraday's criteria for the introduction of theoretical entities--that they be useful in developing and extending a theory. Clearly he had adopted his 'abstract' notion of the electric current because he found the fluid theories unhelpful (and, as his response to Whewell's interpretation of self-induction showed, misleading as well). It appears that by 1834 Faraday had adopted a simililarly abstract form of atomism, and for similar reasons. According to Hamilton,

> [Faraday] finds more and more the conception of matter an encumbrance and complication in the explanation of phenomena, instead of an assistance (ibid.).

I shall subsequently argue that this attitude is of particular importance to an understanding of Faraday's later development of the theory of magnetism and diamagnetism (in which the 'matter' is represented solely in terms of its ability to conduct or transmit the lines of force) for the field theory emerges from this theory as an attempt to give a general explanation of electrical and magnetic phenomena without recourse to any particular hypotheses about the nature of matter. The third point is that Faraday takes the electric current to be a vibration. In 1846 Faraday argues explicitly for the view that optical, thermal and electrical actions are transmitted as vibrations.

Hamilton does not indicate that Faraday had associated his position with that of any particular theorist. This position does appear to have emerged largely from Faraday's own attempts to deal with the problem of interpreting his own experiments. Yet by 1834 Hamilton had come to believe in his own brand of Boscovichean atomism, although, as he points out, his reasons for reaching an 'anti-

materialist' position differ from Faraday's. Since Faraday does not defend his own use of what he took to be a Boscovichean theory until 1844 it is worth examining Hamilton's position more closely.

On June 27, only three days before his breakfast meeting with Faraday, Hamilton had written to H. Logan that the views of Boscovich 'seem capable of being incorporated with high metaphysical idealism; and as such, I have long had a leaning to them ...'[139] The 'idealism' was that of Kant and the Naturphilosophen (as regards the status of laws) and of Berkeley (as regards the status of matter).[140] Hamilton had earlier described Dynamics 'or the science of force, as treating of "Power acting by Law in Space and Time"'.[141] He now says that

> Power, Space, and Time appear to me to constitute the elements of this language. Power, acting by law in Space and Time, is the ideal base of an ideal world, into which it is the problem of physical science to refine the phenomenal world, so that we may behold as one, and under the forms of our own understanding, what had earlier seemed to be manifold and foreign ...[142]

As conditions for the possibility of knowledge, space and time ('and Power localized in them') may have only 'a relative and subjective existence' (ibid.). To have objective reality they must be created

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139. Graves, Life of Hamilton II: 88.

140. In June of 1834 Hamilton had written to H. Logan that it 'has long been a fundamental article of my philosophical faith, derived perhaps from Berkeley ... that one Supreme Spirit excites perceptions in dependent minds, according to a covenant or plan, of which the terms or conditions are what we call the Laws of Nature. These terms or conditions it is the business of physical science to discover ... and ... to express ...' (letter of 27 June, 1834, Graves, Life of Hamilton II: 87). See also the letters from the period 1832-34 between Hamilton and Coleridge, Aubrey de Vere, Whewell, and Logan (Graves, Life, vols. I and II).

141. Hamilton to Whewell, 31 March, 1834. The comment appears in a reference to Hamilton's 'New Method of Dynamics' (published in the Philosophical Transactions for 1834 and 1835).

142. Hamilton to Logan, letter cited note 140.

and sustained by God. This is why Hamilton had insisted in an earlier letter to Coleridge that 'objectively, and in the truth of things, the powers attributed to atoms [by Boscovich] belong not to them but to God'.[143]

Hamilton also objects to the discontinuity presupposed by Boscovich's theory (in which the centres of forces are supposed to act at a distance):

> the discontinuity (though not the impenetrability) which Boscovich supposes, appears to me in some degree unsatisfactory; and I have speculated from time to time on the possibility of reviving the old idea of a plenum, but freed from some of the old clogs of matter.[144]

This was written only three days before Hamilton met Faraday. Hamilton's emphasis on powers (the source of events in space and time) and on laws (the conditions of the exercise of those powers) as joint conditions for the possibility of scientific knowledge is remarkably similar to the position outlined in Faraday's second lecture on the nature of matter of 1844.[145] There Faraday insists that atoms (as definite quantities of action) and laws are 'bound up with each other' because the constancy of the phenomenal properties of matter points to the existence of laws, and these in turn to the divine will which sustains the powers.[146]

It is unlikely that Faraday's 'Boscovichean' atomism was derived

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143. Hamilton to S.T. Coleridge, 3 October, 1832 (Graves, Life I: 593). Hamilton conflates Berkeley's and Kant's views on the basis of perceptual knowledge (cf. Life II: 87-88). The relationship between idealistic metaphysics and natural theology is discussed in Levere, Affinity and Matter: 75 ff.

144. Hamilton to Logan (letter of 27 June, 1834, cited note 140).

145. 'Matter' (dated 19 February, 1844). The manuscript of this lecture has been published in T. Levere, 'Faraday, Matter, and Natural Theology--Reflections on an Unpublished Manuscript', BJHS 4 (1968): 95, at pp.105-107.

146. Ibid.; cf. infra, section 2.7.3.

from Hamilton. Faraday would certainly have heard of Boscovich (through Davy and Herschel) before 1834. Yet Hamilton's views (and particularly his 'revelation' that Boscovich's theory (with modifications) could be the physical counterpart of Hamilton's own recently completed 'General Method of Dynamics' [147] suggest that he would have been enthusiastic about a dynamical version of Boscovichean atomism at the time that he met Faraday. Given the difficulties which Faraday had expressed to Hamilton about his own theoretical work, it seems likely that the two would have considered the relative merits of corpuscular or point-atomism and of force-atomism from both a theoretical and a theological standpoint. That Hamilton describes Faraday's view as having been 'almost as anti-material' as Hamilton's own suggests that while Hamilton himself tended not to distinguish between the atom or particle and its powers or manifest qualities,[148] Faraday still distinguished between the two. That Faraday had not yet adopted the principle which requires that the two be identified[149] would

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147. Cf. Graves, Life II: 88 and R. Kargon, 'William Rowan Hamilton, Michael Faraday, and the Revival of Boscovichean Atomism', American Journal of Physics 32 (1964): 792.

148. Cf. Graves, Life III: 176. In a memorandum of October 1831 Hamilton interprets Coleridge's interpretation of the 'universal Law of Polarity or essential Dualism' as stating that 'Power can be manifested only by its effects, that is by overcoming Resistance, which is Contrary Power. Existence is manifested by the struggle between the two opposite tendencies ...' (Graves, Life I: 439, my italics). The similarities between these ideas, those of the Naturphilosophen (and of scientific followers such as H.C. Oersted), and Herschel and Faraday's tendency to identify the concepts of existence, action (reaction or opposition), tension, and polarity deserve a closer examination than can be given here. They suggest that the influence of the Naturphilosophen may have been greater than has been admitted, for example, by B.S. Gower, 'Speculation in Physics ...' (op.cit., note 40) at p.302. The 'metaphysical element' of Naturphilosophie may not have been directly relevant to the development of science, but some of its most basic concepts evidently were. Cf. infra, sections 2.2.1, 2.3.1, and 4.2.2.

149. Cf. supra, p. 5 and section 1.2.1.

explain the fact that his two lectures on matter of 1844 are primarily devoted to an attack on the very distinction between atoms and powers which underlies the distinction between point-atomism and force- or relational-atomism as I have drawn it.[150]

We know from the note appended to the eighth series and from his letter to Ward that Faraday had been thinking 'long and closely about the theories of attraction and of the particles of matter' and that he had been unable to obtain a 'clear view' of the way in which atoms are related to electricity in both its static and dynamical states.[151] Another contribution to the subject which appeared at this time and which could hardly have escaped Faraday's attention was Whewell's Astronomy and General Physics considered with reference to Natural Theology.[152]

Although Faraday has not yet adopted the position described earlier as force-atomism it is clear that he is a dynamical atomist in that he takes forces or powers to be fundamental and defines atoms in terms of their manifest properties only. It is also evident that during the early 1830s Hamilton, Herschel, Faraday and Whewell had been thinking along lines which, though not necessarily similar on all points,[153] were converging over the question of the existence

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150. Cf. supra, section 1.2.1.1.

151. That Faraday was still concerned with the problem of thelocal and distant actions of affinities is clear from his reference to it in a letter on a discovery by Schoenbein, dated 16 June, 1836, ERE II: 248.

152. This was the third of the Bridgewater Treatises, first published in 1833. See esp. pp.211 and 361-68 of the 4th ed., London, 1834.

153. Whewell insisted that inertial mass is a primary quality of matter while Herschel and Faraday reduced it to force (to dynamical couplings between elementary particles). Compare, for example, Herschel, Preliminary Discourse: article 234 and Whewell, Philosophy of the Inductive Sciences (2nd ed., 1847), I: 433, or On the Philosophy of Discovery: 327 ff.

of substantial and extended (corpuscular) atoms. This coincidence of opinion came to a head at the meeting of the British Association at Liverpool in September of 1837, when Hamilton and Whewell objected to the use of the notion of atoms as real bits of substance[154] and Faraday is reported as having 'emphatically stated, that he was not an atomic chemist ...'[155]

Since the trend of Faraday's approach to theorizing has been to avoid the use of specific models and the positing of structured entities it is likely that his emphatic rejection of chemical atoms of 1837 was the outcome of his own predilection for the use of the 'abstract notions' of forces as theoretical tools[156] and of his doubts about the usefulness of hypotheses about atoms.[157]

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154. See the report of this discussion in the Athenaeum (1837): 747, (reprinted in D.M. Knight, ed., Classical Scientific Papers--Chemistry (Second Series): 134). While Whewell retained the concept of inertial mass as an essential quality (cf. note 153) he did appreciate that a decision on the propriety of the use of an atomic hypothesis (as distinct from a specifically corpuscular or Daltonian model of the atom) would 'depend, not upon chemical facts, but upon our conception of substance' (Philosophy of the Inductive Sciences (1st ed., 1840): 407).

155. I.e., not a corpuscular atomist (op.cit., note 154).

156. Cf. his letters to Lemen (of April 1834; cited note 81) and to Whewell (on Ampère's theory; cited note 112).

157. For further discussion of this point see sections 3.3.2.1, 3.5.2.1.

PART TWO

2. ELECTRICITY AND MATTER: 1836-1844

In the second part of this essay I will analyze the development of Faraday's first and only comprehensive theory of the relationship between electricity and matter, the molecular theory of induction of 1837 and 1838. I will examine Faraday's use of certain postulates and hypotheses and his attempts to justify them, and will show how these lead to the well-known challenge to the established theory of electrostatic action.

Faraday's theory represents both a refinement and an extension of certain ideas used throughout the first nine series of the Experimental Researches in Electricity. One of the most significant consequences of the theory is that in developing it Faraday was obliged to be more explicit about the nature and action of the elementary particles and their forces. Although Faraday does present the theory in terms of a model on which the particles are distinguished from their powers, he continues to treat the force-relations or dynamical interactions of the particles as the basic determinants of the properties of both the particles and of the masses they constitute. An analysis of the explanatory role of force in Faraday's theory shows that he does at times interpret his model of the dielectric as a force-atomist rather than as a point- or corpuscular atomist,[1] and that the

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1. For a definition of these terms see section 1.2.1.1.

epistemological and methodological position which he defends in his well-known 'Speculation' of 1844 is characteristic of his whole approach to the problems of acquiring and justifying scientific knowledge.

The theory of induction is both a retrospective theory and an attempt to extend the view of the relationship between matter and electrical action which had emerged from Faraday's investigation of electrochemistry. Faraday's first objective is the 'elucidation of inductive action'--the provision of a solution to the problem of explaining how both the static and the dynamical states of the electric force may have a quantitatively definite connection with the atoms of matter, one which is preserved through the conversion of affinities into the progressive forces of the current and back again. This problem had originally been stated in the note appended to the eighth series in March of 1834.[2] Faraday's second objective is what he calls the 'subjugation of many dissimilar phenomena to one law' (1164).

The former objective requires that a specific model of electrified matter (the dielectric) be developed while the latter requires an appeal to fundamental principles; statements which specify what is and what is not possible. Although the search for a model (a 'clear view') of the relationship between matter and its powers is a main object of his present investigation, the provision of a unified theory of the phenomena on the basis of a few principles continues to be

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2. '... I would rather defer revising the whole theory of electrochemical decomposition until I can obtain clearer views of the way in which the power under consideration can appear at one time as associated with particles giving them their chemical attraction, and at another as free [current] electricity ...' (ERE I: 321).

Faraday's most important general objective.[3]

The theory of electrostatic induction is presented and defended in the eleventh series of Faraday's Experimental Researches[4] and is developed in the following three series.[5] In the following discussion I will draw attention to four main aspects of this theory, its consequences, and Faraday's defence of them:

(1) While the theory does lead to certain important consequences which could not have been derived from its more loosely constructed predecessors, the theory of induction is the result of an attempt to consolidate the results of Faraday's earlier investigations on the basis of a single principle (that electric and magnetic forces are polar or inductive actions, consisting of two equal and opposed tendencies or actions) and an hypothesis (that there are elementary

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3. Faraday was far more at ease with the principles than with the hypotheses that had to be introduced to develop a model of the dielectric. This contrast in attitude can be seen in two comments which he makes much later in his career. In his lecture 'On Mental Education' of May 1854, Faraday states that 'before we proceed to consider any question involving physical principles, we should set out with clear ideas of the naturally possible and impossible' (ERCP: 478). We begin with such ideas and do not give them up. Such is not the case with hypotheses, as Faraday explained in a letter written that same month: '[theoretical ideas] serve to aid discovery & development by suggesting analogies and crucial experiments and other forms of test for the views which arise in the mind as vague shadows .... I have always a great difficulty about hypotheses from the necessity one is under of holding them loosely & suspending the mental decision ...' (Faraday to A. de la Rive, 29 May, 1854, Corr. II: 737).

4. 'On Induction', ERE I: (1161-1306); read: 21 December, 1837. For conventions and abbreviations used in the citations see supra, p.v.

5. The twelfth series was completed in December 1837and the thirteenth and fourteenth followed in February and June of 1838. Most of the results reported in the twelfth and thirteenth series were known to Faraday as he wrote the eleventh, and even those experiments reported in the fourteenth series were made before the final version of series eleven went to press. I will therefore discuss this series of four papers as a whole rather than in chronological order.

particles which have the disposition to polarize).

(2) The theory itself consists of the hypothesis that all electrostatic actions (and possibly all magnetostatic actions) are transmitted by the progressive polarization of consecutive or contiguous particles, together with the further hypothesis that the disposition to polarize will be characteristic of the particles of each kind of matter. On the first hypothesis matter should exhibit a capacity or ability to promote or retard the transmission of electrostatic action; on the second hypothesis this ability should be characteristic of each kind of matter.

(3) Both hypotheses are confirmed in the case of solid insulators or dielectrics. Faraday concludes that two premises of the then-prevailing theory of electrostatic action must be rejected, viz., that forces between charged bodies originate in electric fluids and that these forces act directly at a distance along a line joining the centres of the two electrified elements or masses. Faraday's primary objective is to establish the principle of induction as a 'first principle' of electrostatic action (rather than to explain how attractions and repulsions may be effected at a distance).

(4) The theory of electrostatic induction is one of the clearest and most detailed of Faraday's theories. Faraday achieves this clarity by stating his view of the way forces must act in terms of the principle of induction and by developing two models of the way in which the electrotonic state or polarized condition of a dielectric is produced. The exactness of these models underlines their limitations and leads to a consequence not foreseen by Faraday: he is obliged to assign to matter (the atoms) an ontological status consistent with its explanatory role in the theory, a role which is decidedly secondary to that of force or power.

2.1 The Principle of Induction

Faraday opens the eleventh series by stressing the need for a unified explanation of electrical phenomena:

> The science of electricity is in that state in which every part of it requires experimental investigation; not merely for the discovery of new effects, but what is just now of far more importance, the development of the means by which the old effects are produced, and the consequent more accurate determination of the first principles of action of the most extraordinary and universal power in nature ... (1161, my italics)

He is convinced that a comprehensive theoretical explanation of the properties of matter must be based upon the 'first principles' of the action of electric force:

> Chemistry and Magnetism have successively acknowledged its over-ruling influence; and it is probable that every effect depending upon the powers of inorganic matter, and perhaps most of those related to vegetable and animal life, will ultimately be found subordinate to it (1161).

Faraday arrives at the first and most important of these principles[6] by stating as a necessary truth about all electrical action what he had originally observed to be true of both electrostatic and electrodynamic actions in 1831 (1). For theoretical purposes electrical action is to be characterized simply as it is seen (through its effects) to act:

> In the long-continued course of experimental inquiry in which I have been engaged, this general result has pressed upon me constantly, namely, the necessity of admitting two forces, or two forms or directions of a force (516.517), combined with the impossibility of separating these two forces (or electricities) from each other ... (1163)

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6. The second and third become explicit only gradually. The second is the principle of conservation (which is implicit in Faraday's application of the present theory to convection currents and magnetic induction) and the third is that force or action (being a state of dynamical tension) always tends towards a condition of equilibrium or least action. I shall later identify this idea as the principle of economy or of least action. Cf. infra, sections 2.4.3, 3.3.2 (p.285 ff.), 3.5.2.1, and 4.3.1.

In 1831 Faraday had remarked that both the static and dynamical forms of electricity can be considered to act inductively because both cause or induce opposite states or changes of the electrical state in nearby matter, be it a current having a certain direction, chemical decomposition, or an induced charge. The effect is always qualitatively opposed to its cause (in direction or character). In August of 1836, several months before he began to work upon the problems discussed in his eleventh series, Faraday had written in his laboratory Diary that:

> There are ... evidently what I may call two elements of power or equal force and acting towards each other. These may conventionally be represented by Oxygen and Hydrogen, which represent them in the voltaic battery. But these powers may be distinguished only by direction, and may be no more separate than the North and south forces in the elements of a magnetic needle.[7]

These conclusions had been reached after 'much consideration ... of the manner in which the electric forces are arranged in the various phenomena generally'[8] and Faraday is about to argue (in the published paper) that the two 'elements' or 'directions' of the power cannot be regarded as being independent of each other. The next comment from his Diary shows that the lines of electrostatic tension were introduced to express or represent this polarity or relatedness of the effects of the electric force:

> [These elements] may be the polar points of the forces originally placed in the particles of matter, and the description of the current as an axis of power, which I have formerly given, suggests some similar general expression for the forces of quiescent electricity. Line of electric tension might do; and though I shall use the terms Pos[itive] and Neg[ative], by them I merely mean the termini of such lines.[9]

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7. Diary: (3423). I have added the second set of italics.

8. Ibid.

9. Ibid.

Thus Faraday takes the crucial step of making what had originally been a comment on his own use of the word 'induction' into the leading principle of his theory. Inductive action

> is of the most general influence in electrical phenomena, appearing to be concerned in every one of them, and has in reality the character of a first, essential, and fundamental principle (1162).[10]

Faraday's reference to appearances may be taken quite literally. He will argue that the conclusion follows from the fact that 'bodies cannot be charged absolutely, as far as my experience goes, only relatively ... All charge is sustained by induction ...'[11]

Faraday justifies the claim that all charge is the manifestation of an inductive or polar relation and that the principle of induction is as true of molecular interactions as it appears to be of interactions at sensible distances, in two ways. First he argues that the polar nature of electrical actions must be taken to be a basic principle of the theory because

> we cannot proceed much further in the investigation of the laws of electricity without a more thorough understanding of its nature; how otherwise can we hope to comprehend the harmony and even unity of action which doubtless governs electrical excitement by friction, by chemical means, by heat, by magnetic influence, by evaporation, and even by the living being? (1162)

Faraday's claim is just that if the laws of electrical action are to be found (and to be found to be simple) then some apparently basic and universal aspect of electrical action must be taken to be really basic and universal.

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10. It should be emphasized from the outset that by 'induction' or inductive action Faraday understands an action which is causally prior to electrostatic attraction (or repulsion)--the latter being just one of the possible effects of the former (and by no means the most important). See infra, section 2.5.1.

11. Diary: (3425). Of course the claim that absolute charge is an impossibility (or, conversely, that all charge must be sustained by inductive action) cannot be justified inductively (on the basis of experience alone); see infra, p. 114ff., esp. 117.

We have seen that in his earlier researches Faraday had proceeded by giving a minimal description of his theoretical entities. His comments to Lemen and to Whewell on the adequacy of the 'abstract notion' of the current as a set of directed forces showed that he regarded this approach as sufficient for theoretical purposes even though it fell short of providing a causal explanation.[12] Here he is making the further point that certain aspects of such a description can and must be taken as primary in order to develop a theory and to generate decisive experimental tests of it. Faraday replaces the earlier descriptions of the current and of the 'quiescent' affinities as powers which induce opposite states or reactions with the idea of an inductive relation or polar tension. He advances the apparently polar nature of electrical actions as a description to which all descriptions and all interpretations of electrical phenomena must conform. This is how Faraday does use the fact that electrical actions are inductive (at sensible distances) and it is for this reason that I have called it the principle of induction.

Faraday selected the inductive or polar appearance of electrical action as the key to its nature because this was closely related to another fact, viz., 'the impossibility, as yet, of absolutely charging matter of any kind with one or the other electricity only ...' (1163). This brings us to Faraday's second argument for the fundamental status of the principle of induction. As he explains, the 'necessity of admitting two forces' and the 'impossibility' of producing a single (isolated) electrical state

> dwelt upon my mind, and made me wish and search for a clearer view than any that I was acquainted with, of the way in which electrical powers and the particles of matter are related; especially in inductive actions, upon which almost all others appeared to rest (1163).

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12. Cf. supra, pp.53 and 82 ff.

All electrical states appeared to be causally related to other (equal but opposite) electrical states. The principle states that every electrical state must be causally related to another. Faraday believes that he can prove this by showing that an isolated electrical state (a discrete charge) cannot be produced in the laboratory.

In searching for what he calls 'an unexceptionable test' of his theory Faraday had been seeking both 'the accordance of known facts with it' and 'consequences which would flow from it if true; especially ... those which would not be consistent with the theory of action at a distance' of Cavendish, Aepinus, Coulomb, and Poisson (1165-6).[13] Faraday produces three consequences which, he believes, should occur on his own theory but not upon the rival theory of electrostatics. The first two are tests for the consequences of the hypothesis of contiguous molecular action and, therefore, of the principle of induction, while the third is a direct test of that principle itself.

Faraday believed that the 'received theories' would allow inductive action only in straight lines, while on his own theory it could and should proceed in curved lines.[14] Second, he believed that the hypothesis that induction is an action of contiguous particles[15]

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13. For a survey of the action at a distance and fluid theories of electricity see Whittaker, Aether and Electricity (Chapter 2) and Hesse, Forces and Fields (Chapter 7, pp.180 ff.); and for the mathematical theories of attraction, Whittaker, op.cit. (Chapter 7).

14. 'Could' because the action proceeds in steps from particle to particle and may therefore be transmitted in curved lines, and 'should' because for Faraday the curvature of a line of force is a measure of the tension or action it represents. Thus a field represented by straight lines is a field in its 'normal' or 'quiescent' state--a state of no action. Cf. sections 2.3.3, 2.4.3.

15. Note that this hypothesis follows from the principle: polar forces necessarily act locally (over the shortest possible distance only) because, as Faraday subsequently puts it, 'it is apparently of the nature of polar forces that [they act only between

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together with the hypothesis that the elementary particles of matter have a characteristic disposition to resist or react upon this action[16] entail that the degree of inductive action transmitted through a medium should be characteristic of each kind of matter. There should be 'something equivalent to a specific electric induction for different bodies' which, if detected, 'would unequivocally prove the dependence of induction on the particles' (1167).

Faraday's third test is derived directly from the principle of induction and appears to have been an attempt to justify the application of the principle to the unobservable realm of elementary particles--to show that the inductively justifiable generalization that all electrical actions over sensible distances are polar may also be held to be true of intermolecular actions as well. While Faraday's first two tests are for confirming instances (effects which he expects to detect as consequences of the hypothesis of contiguity), he presents the third as a deliberate attempt to find a counter-instance to the principle upon which the theory has been based: the production of an isolated or discrete state of charge.[17]

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contiguous particles] for the one force either finds or developes the contrary force near to it, and has, therefore, no occasion to seek for it at a distance' (1665, cf. 1628). It is important to realize that for Faraday forces act locally because they are polar--not because they are contact or body forces of the sort posited in the hydrodynamical or elastic solid theories of matter and aether which were current during and after his time. The actual distance over which such a force acts need not be insensible provided that it is the shortest possible distance. Williams has remarked that 'the most important part of [Faraday's] theoretical vision from 1832 onwards was his conviction that the transmission of force was an intermolecular process and not action at a distance' (Michael Faraday: 287). On my interpretation the basis for this conviction is Faraday's concept of polarity, expressed in 1837 as the principle of induction.

16. For a discussion of the probable origin of this hypothesis see infra, sections 2.2.2.1 and 2.3.

17. Not surprisingly, the possibility of such a test and the nature of its results prove to have been the original stimulus for Faraday's developing the hypothesis of contiguous action (1168). Cf. infra, pp.116 and 120.

2.2 The Principle of induction and the interpretation of experience

Faraday opens his 'proof and argument' for the theory with a discussion of the possibility of there being absolute charges and of the implications that such a discrete, isolated, or 'latent' electrical state is a 'natural impossibility' (1168 ff.). He first takes the facts that all electrical actions have been observed to be inductive (i.e. that no absolute or isolated electrical state has been produced by any means) as grounds for the assertion that all electrical states are and must be the observable effects of an inductive or polar relation between the points at which they appear. He then shows that since the accepted fluid theories of electricity do not preclude the possibility of there being discrete electrical states, they must be rejected as inadequate. Faraday effectively advances the principle as a constraint upon the acceptability of a theoretical interpretation of electrostatic phenomena.

Faraday begins his examination of the validity of the principle by asking whether there are any situations to which it would fail to apply:

> Can matter, either conducting or non-conducting, be charged with one electric force independently of the other, in any degree, either in a sensible or latent state? (1169)[18]

This possibility does arise on the fluid theories as Faraday understood them (1168), for if electricity does have 'an actual and independent existence as a fluid or fluids' then it should be possible

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18. Since Faraday regards the charged state as an active one in which a body possesses a certain tension or potentially exertible action (of which charge is the phenomenal effect), the expression 'charge with force' does not signify a confusion of terms on his part. There is no sense in which a body can be said to be charged and yet not be endowed with electric force.

to isolate and identify it. If, on the other hand, it is a 'mere power of matter, like ... the attraction of gravitation', then things should be as Faraday's principle requires that they be. The fluid theories do allow the possibility of

> cases in which an isolated portion of matter in one condition being uncharged, shall, by a change of state, evolve one electricity or the other: and though such electricity might immediately induce the opposite state in its neighbourhood, yet the mere evolution of one electricity without the other in the first instance, would be a very important fact ... (1175)

Faraday believes that such a state would be both uncaused and temporarily without effect (hence, 'latent' and unobservable). His objection is that the fluid theories '[assign] not the slightest reason why such an effect should not occur' (1175).

On Faraday's present view the production of an isolated charge is conceivable but not physically possible. Since isolated or latent electrical states do not occur in the best known instances of the generation of electricity, all of which 'give both forms of the power in equal proportion', Faraday concludes that all cases of the production of electricity 'are subject to the same law of limitation', viz., the principle of induction (1176). The deficiency of the fluid theories lies in the fact that they neither preclude the possible occurrence of an isolated charge, nor do they provide any explanation for the fact that such charges are not produced.[19]

The import of the principle of induction is that it is not possible to produce an isolated charge, i.e. to charge matter in such a way that it will act as if it possesses a force qualitatively identical in its action to that of its surroundings (or which will be

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19. Faraday apparently does not consider the principle that charge (qua quantity of electric fluid) is conserved as meeting this objection. Moreover, the conservation of charge follows from Faraday's principle of induction (1177) which therefore supplants the explanatory function of the fluids.

temporarily without effect at all). Thus where Coulomb believed that he could prove that an insulated conductor could be bodily charged with an even distribution of a single electric fluid over its surface, Faraday states that Coulomb's experiment 'upon the equality of action of conductors ... and the residence of all the electricity upon their surfaces' is 'sufficient, if properly viewed, to prove that conductors cannot be bodily charged ...' (1170). According to Williams it is curious that Faraday should cite Coulomb's experiment in support of his own (opposed) view.[20] Yet Faraday has reinterpreted Coulomb's result in the following way: the conducting sphere or wire is no different from a non-conductor because it is (must be) inductively related to its surroundings, including the source of inductive action. The electricity which Coulomb and others had supposed to reside upon the surface of the sphere is just one of the two equal and opposed forces which constitute any inductive relationship. Coulomb's experiments do not 'prove' what Faraday claims for them, for they are (if 'properly viewed' in terms of the principle) simply an instance of the principle.

The same is true of Faraday's own experiments (1169-74). These had shown that conductors and insulators are charged inductively and never absolutely (1171) because any charge produced on one body was always accompanied by an 'opposite and equivalent state' elsewhere on (or near) that body (1171). Faraday concludes that as matter has never yet been absolutely charged, 'to all appearances such a state of matter is impossible' (1174).

The appearances support this contention only if it is allowed

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20. Williams, Michael Faraday: 289. Berkson is mistaken in supposing that Coulomb had been testing for inductive capacitance in the insulator covering the conductor, for such a property was not admissible on Coulomb's theory. Cf. note 33 (p.121), Berkson, Fields of Force: 84, and Faraday's Diary: (3596).

that electrostatic action does not involve the redistribution of fluids on the surface of a body (1173-74). Yet this is one of the assumptions which was to have been proven by the experiments, while treating the facts (thus interpreted) as evidence for the assertion that absolute charge is a 'natural impossibility' (1177) is warranted only if it is accepted that any action as manifested by an effect (e.g., the appearance of charge) must have an equal and opposed cause. In short, Faraday appears to presuppose the principle in adducing the facts as evidence for the truth of that principle and as evidence against the theory of fluids.

Faraday now goes on to claim that what appears to be the case is in fact necessarily the case--that the production of a single electrical state is a 'natural impossibility' (1177). While a large number of instances in which a charge is shown to be determined by an equal and opposed charge elsewhere do constitute an inductive warrant for the generalization that all charge is just inductive action, the further claim that charge must be inductive and that a non-induced charge is a 'natural impossibility' cannot be proven (inductively). This is why I have singled out these claims as corollaries of the principle of induction rather than as law-statements. Although he would (presumably) have regarded the production of a discrete charge as refuting the principle, Faraday evidently attaches a greater degree of necessity to the relationship between the concepts of charge and induction than any that could be conferred (or justified) by experience alone.[21]

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21. As we shall see, the existence of a charge entails the existence of an inductive relation (hence, the existence of a second, opposed charge). This is, of course, the metaphysics of polarity translated into the language of electrostatics. Faraday's application of the concept of polarity to natural powers appears to have been gradual--at least in the published Researches. For example, he had concluded that magnetic force must act through

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Faraday's confidence in the principle appears to have been directly related to his conception of force as a dynamical relationship between agents or entities. This interpretation is suggested both by the fact that he has already justified the principle on heuristic grounds (1162,1165) and that he now goes on to state his experimental findings in terms of a definition of the concepts of charge, induction, and polarity:[22]

> As far as experiment has proceeded, it appears, therefore, impossible either to evolve or to make disappear one electric force without equal and corresponding change in the other (1177).

This much is just a statement that charge is conserved, presented appropriately enough as a generalization of Faraday's experimental results. Faraday advances this generalization as a statement about what is necessary because he interprets the failure to produce an absolute or isolated charge as being due to some fundamental property of forces, viz., that they are polar or inductive in nature. This is clear from the fact that he proceeds immediately to restate this conclusion as a conceptual point:

> Charge always implies induction, for it can in no instance be effected without [it]; and also the presence of the two forms of power, equally at the moment of the development and afterwards (1177).

Here the meaning of the word 'charge' (as a term which refers either to some physical state or to the operation by which such a state is produced) is tied directly to the fact that charges appear in or as

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the matter upon its particles and had distinguished this from electrostatic forces on this account in 1831 (73). The conclusion drawn there on the basis of the principle of equality of action and reaction is applied explicitly to electrostatic forces only now, in 1837. Faraday does not seek the polar or 'antithetical' effects of gravitational force until 1850, and never applies this line of reasoning directly to cohesive forces.

22. Similarities between Faraday's present position as to the existence of discrete charges (electrons) and that attributed to him in section 1.3.3.1 will become apparent in what follows. See section 2.3.

pairs, where each member of the pair is 'opposed' to the other in sign or in the 'direction' of its action.

The import of this restriction of the meaning of the word charge is that the word can no longer be used to refer to isolated or discrete electrical states. It now follows that there is 'no absolute charge of matter with one fluid; no latency of a single electricity':[23]

> This though a negative result is an exceedingly important one, being probably the consequent of a natural impossibility, which will become clear to us when we understand the true condition and theory of the electric power (1177).

It is possible that Faraday's claim that the existence of a discrete or isolated charge is a physical impossibility is based upon a position which he does not defend explicitly until 1844. This is the rejection of the distinction between existence and agency or between substance and attribute. Faraday's rejection of imponderable fluids turns upon his rejection of the position that the existence or manifestation of a property justifies an inference to the effect that that property inheres in some material or quasi-material entity.[24] Like those of his contemporaries who espoused or were influenced by Naturphilosophie, Faraday tends to identify existence with action

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23. The assertion that there is a latent charge could have no operational meaning. According to Faraday there is no operation by which it could be either produced or detected as such. Like the nascent particles and the ions of the theories of catalysis and electrolysis (658,824 ff.), such entities or states are simply irrelevant to the explanation of a law or process. Cf. sections 1.3.2.2 and 1.3.3.

24. We have seen that this was not an inference that Hamilton and Herschel, among others, were prepared to make (supra, section 1.4). Yet others of Faraday's contemporaries, notably Robert Hare and G.B. Airy, were to insist that secondary qualities cannot be explained in terms of active powers and that the existence of substance (inertial, if not ponderable) is a necessity. Cf. infra, pp.266 and 300.

and action in turn with tension or reaction, i.e. polarity.[25] As he had made clear in a letter to Whewell of October 1837, Faraday regarded the charged state as one which is actively 'sustained' and determined by the force-relation which must exist between it and an equal quantity of opposite charge.[26] Even though it appears only on the surfaces of discrete entities, charge is not seen by Faraday as a state of those entities as unrelated individuals.

A possible theoretical role can now be assigned to what I referred to earlier as the 'metaphysics of polarity'.[27] I suggest that Faraday has used the assumption that positive and negative states (charges) are the terminal points or states of polar relations as a premise in his deduction of the universal generalization (the principle of induction) from the experiments in which he showed that no absolute charge can be produced (that every electrical state produced was related to some other opposed state). The principle is therefore inferred from a few of its own instances with the help of the above

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25. While dynamists (specifically, force-atomists) would identify existents with their manifest attributes, the further identification of action with polarity or the opposition of powers suggests the influence of Naturphilosophie. Levere rightly distinguishes dynamism from Naturphilosophie but, underestimating the importance of the idea of polarity in Faraday's work, suggests that the latter school had little influence either on Faraday or upon Davy, and that both were unsympathetic to Naturphilosophie (Levere, 'Aspects of Chemical Affinity in the Nineteenth Century', Oxford D.Phil. Thesis (1968): 82 ff. and 165 ff.; Affinity and Matter: 25 ff. and 123 ff.).

26. '... can you give me a term to express the determining & sustaining influence of the [inducing] charge and the dependant & sustained condition of the [induced] charge' (Corr. I: 314). In 1855 Faraday states that 'the electric dualities are equal, equivalent, and mutually sustained ... a single state, i.e. an unrelated duality, cannot exist alone' (Lecture of 19 January, 1855, ERE III: 567).

27. Cf. p.114 (note 21) and ff.

assumption which it can then be used to explain.[28]

On this analysis it follows that Faraday's reference of August 1836 to the possibility that the 'two elements of power' are inseparable, that the relationship between them may be represented by lines of electric tension, and his remark that by 'the terms Pos[itive] and Neg[ative] ... I merely mean the termini of such lines'[29] are references to a theoretical premise which becomes, through the use of the above form of argument, the principle of induction. It is apparent that the lines of electrostatic induction represent what is arguably the most important element of Faraday's larger theory of nature: the concept of polarity.[30]

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28. As noticed on p.113-4, a second premise is that electrostatic action does not produce a redistribution of electric fluid(s) on the surface of bodies. As J. Dorling has shown, this is a valid form of inference provided that certain additional restrictions are imposed ('Demonstrative Induction: Its significant Role in the History of Physics', Philosophy of Science 40 (1973): 360). An important point about such a premise is that confidence in it (or the probability assigned to it) may depend upon what the scientist and his contemporaries take to be reasonable. Thus, according to Dorling, our assessment of the reasonableness of Cavendish's use of an assumption to the effect that the law of electrostatic attraction would be an inverse-square law turns upon an evaluation of the acceptability of such an assumption to his contemporaries ('Henry Cavendish's deduction of the electrostatic inverse square law from the Result of a single Experiment', Studies in History and Philosophy of Science 4 (1974): 327, at p.334). On this criterion Faraday's premise would appear unreasonable or implausible in the context of the mathematical theory of electrostatics, but quite plausible in the context of the vague but pervasive conceptual scheme of dynamical atomism and of Naturphilosophie.

29. Diary: (3423).

30. It need not be the case that Faraday deliberately adopted the form of inference just described. My point is that once the role of the premise (in which the concept of polarity is embedded) has been recognized, Faraday's inference from his failure to produce a disconfirming instance (an absolute charge) to the principle of induction no longer appears as a simple case of inductive inference. It follows that an analysis of the extent to which Faraday's principle is justified by his argument and his experiments must involve an examination of his reasons for attaching such importance to this premise. This calls for a more extensive study of the intellectual context and of possible influences upon Faraday than can be carried out here.

If inductive action is prior to the existence of an electrical state, it is also prior to the electrostatic forces which cause the attractions and repulsions by which charges are measured. It follows (as Faraday is later to argue of magnetic properties) that the disposition to become charged and to be attracted or repelled is a relational property--a property which exists or is possessed by an entity only if that entity is in dynamical relation with some other entity. The disposition could not be attributed to a truly isolated individual for it could not be manifested except as an interaction with some other entity, and unless the disposition is manifested then there are no grounds for positing it.

It is well known that Faraday was the first electrical theorist to take seriously the possibility that the region between two charged bodies may affect or determine their action upon each other. As he points out in the thirteenth series, the

> great point of distinction and power ... of the theory is, the making of the dielectric of essential and specific importance, instead of leaving it as it were a mere accidental circumstance of the simple representative of space, having no more influence over the phenomena than the space occupied by it (1666).

The importance that Faraday attached to the region between active entities was a consequence of his dynamical view of nature and of his adherence to the principle of polarity or induction. If all charge is just the manifest effect of an inductive relation then the properties of that relation and of the region in which it exists must be taken seriously. It follows that electrostatic action cannot be described (let alone explained) in terms of the properties, structure, or condition of the entities upon which (or the points at which) these effects appear.

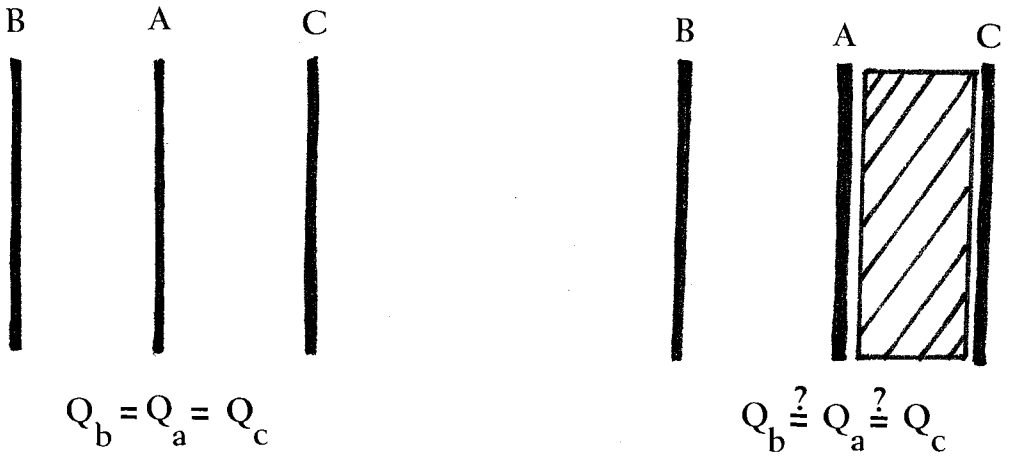
In the eleventh series Faraday presents a more direct version

of this argument: if electrostatic actions are polar then they must be local actions, transmitted step-by-step through the elementary particles of matter. It follows that inductive action is transmitted by the dielectric and may, therefore, be influenced by it.

2.2.1 Polarity, induction, and the hypothesis of contiguous action

That Faraday had adopted the position just described prior to his discovery of the existence of specific inductive capacity is clear from his own description of the course of his enquiry prior to his experiments on specific inductive capacitance. Faraday introduces these experiments[31] by stating his case in terms of a simple experiment which he had not even performed when he came to write the eleventh series.[32] If an electrified metal plate (shown as A in figure 2.1)

FIGURE 2.1



is placed between and parallel to two equidistant plates (B,C) then A will act equally on B and C (1252). On the accepted theories the charge on A will disturb the equilibrium distribution of electric fluid on B and C, polarizing them. The same result would be expected on Faraday's theory. However, if the interval between A and C is

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31. These are described infra, sections 2.2.2 and 2.2.2.1.

32. See the supplementary note to the eleventh series, (1307 ff.), and (1253).

filled by some material other than air (or whatever material fills the gap between A and B), then the 'relation of C and B to A' should be altered on Faraday's theory but on the received theory there should be no change in the electrical condition of the outer plates. Faraday had looked for earlier attempts to determine whether an insulator can influence inductive action, but had found only the experiment of Coulomb on an insulated wire, discussed above.[33] Coulomb's experiment offered Faraday 'no proof of the truth of the supposition' that 'no change will occur under such variation of circumstances, and that the relations of B and C to A depend entirely upon their distance' (1252).

Faraday was convinced that his principle of induction was true because he had been unable to produce an isolated charge (or portion of electric fluid).[34] Given the principle, all electrical actions had to be local, acting only over the shortest possible distance. Coulomb's conclusion (and the generally accepted one) had to be mistaken because it amounted to the assumption that a polar force could act inductively between two points or surfaces without affecting points in between. Faraday's well-known denial of electrostatic action at a distance and his experimental proof of this denial follow from his contention that a polar or inductive force cannot act as shown in figure 2.2a but must act as shown in figure 2.2b. Thus induction, if it is related to any particles of the surrounding

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33. Cf. supra, p. 113 (1252), and the Diary, (3596). Like Franklin and Aepinus before him and like Poisson after him, Coulomb had supposed that insulators are, by definition, impervious to the passage of the electric fluid. Hence there was no point in looking for differences of the sort that Faraday is seeking here.

34. Cf. (1168), the Diary, (3425), and my analysis in the preceding section.

FIGURE 2.2



dielectric,[35] must be 'related to all the particles of that dielectric inclosed by the surrounding conductors ...' (1254).

This is Faraday's denial of action at a distance. It is important to realize that Faraday claims no more than this until 1844, when he argues that the transmission of force 'between' particles is dependent upon their being infinitely extended (where extension consists in force; a position which is already implicit in his insistence here that charges are causally related to each other).[36] Faraday does not attempt to develop a theory to explain attraction and repulsion nor does he deny that action can occur over sensible distances between particles (1616,1628).

On these points he was misunderstood by his contemporaries (and by recent interpreters as well). Thus in 1840 Robert Hare objected to Faraday's admission that 'nothing in my present view forbids' that one particle should act over 'the distance of half an inch'

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35. On Faraday's view there is no real distinction between matter as something susceptible to electrical action and the supposed fluids as active sources of power. The only active (manifest) property of the fluids is attributed by Faraday to matter itself. (He subsequently presents a similar case for the reduction of the properties of the optical aether to matter.) As his arguments of January 1844 are to show, Faraday objects to hypotheses in which such entities are posited because they commit one both to more than is required for explanatory purposes and to more than one could ever know. Cf. sections 2.7.1-2.7.3 and 3.3.2.1 (p.291 ff.).

36. Faraday has only to add the hypothesis that the rate of communication of action is determined by some property of the lines of force which constitute that causal relation (1612).

(1616).[37] To Hare, Faraday had denied action at sensible distances through dielectrics only to reintroduce it at the molecular level.[38]

Faraday had not denied action at a distance, if by this is meant either that the action takes time or that it is a mediated process occurring in some material (substantial) fluid or aether. He had denied just that a polar force can be effective at points beyond the nearest possible point. Hence his wording of the claim: 'nothing ... forbids' that inter-molecular action may be at sensible distances and his use of the word 'contiguous'.[39]

It has been supposed, too, that Faraday introduced the dielectric as a possible mechanism for the explanation of attractions and repulsions.[40] This supposition has sometimes been linked with another, that Faraday had a metaphysical or aprioristic adversion to the idea of action at a distance (that is, attraction at a distance).[41] Here two points must be noticed.

First, Faraday demonstrates little interest in attraction and

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37. R. Hare, 'A Letter to Prof. Faraday on certain Theoretical Opinions', Phil. Mag. 27 (1840): 44, or ERE II: 251.

38. This objection is repeated both by Hesse (Forces and Fields: 199) and by Heimann ('Faraday's Theories of Matter and Electricity', op.cit. supra, p.11 (note 5). Cf. infra, section 2.6.

39. Not surprisingly, Hare's objections did not induce Faraday to alter his theory, which had been based partly upon an analogy with the transmission of light and radiant heat. See Faraday's 'An Answer to Dr. Hare's Letter ...' (ERE II: 262, especially p.267) and infra, section 3.2 (p.260 ff.).

40. This was William Thomson's original interpretation of Faraday's hypothesis of contiguous action ('On the Mathematical Theory of Electricity in Equilibrium ...', C. & D. Math. Jour. 1 (1846): 75, at p.92). Maxwell took the lines of induction to be lines of tension or pressure in an elastic medium, an interpretation advanced more recently by Whittaker, Aether and Electricity: 187.

41. Maxwell, 'Action at a Distance', Scientific Papers II: 311; Berkson, Fields of Force: 58. By contrast, Hesse places the origin of Faraday's denial in his study of static induction (Forces and Fields: 198) while Williams identifies it first in Faraday's early experiments on the chemical action of a convection current (Michael Faraday: 223). Neither they nor Berkson appreciate the connection between Faraday's denial of action at a distance and his concept of force as a dual or polar action.

repulsion, or what he later calls the 'dynamical' effects of the action of a force. He is primarily concerned with changes in state or structure: the state of reaction or opposition to action and/or the transmission of action.[42] He appears to have had little confidence in the idea that the dielectric could be treated as a physical cause of the observed motions of charged bodies. Four years earlier, in 1833, he had written to Mary Somerville that

> I think it very doubtful whether the attractions and repulsions can thus be referred [to] directly and mechanically to the pressure of the air which is of course implied by pressure [of the electric fluid] upon the air. I think electricians have hurried the science here & given a clumsy mechanical view because they could not perceive a better.[43]

Even in 1838 Faraday is not prepared to advance his theory of the dielectric as a structured system of lines of induction as a possible explanation of attractions and repulsions. These lines represent the properties of force or action, which Faraday takes to be prior to those effects to which his contemporaries and predecessors had devoted their attention (1161). He defines induction as 'consisting in a species of polarity' (1165), where the term 'polarity' means 'only a disposition [distribution] of force by which the same molecule [or mass] acquires opposite powers on different parts' (1304).

The second point is that Faraday's denial of action at a distance is not simply a consequence of aprioristic or metaphysical notions. Even if his concept of polarity is regarded as having its roots in a

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42. There are only two explicit references to electrostatic attraction in the four papers under discussion, and one of these occurs in the context of an aside on correct experimental procedure. See (1566 ff.), esp. (1575), and section 2.2.2.

43. Faraday to Mary Somerville, November 1833 [notes to the page-proofs of Mary Somerville, On the Connexion of the Physical Sciences, London (1834)], Somerville Papers (Bodleian Library), Dep. c. 370/MSF L/folio 36. The word 'to' (preceding 'directly and mechanically') has been deleted; the second interpolation is mine.

metaphysical tradition such as dynamism or Naturphilosophie, it is possible to show that Faraday's inference to the principle of induction involves an important empirical as well as conceptual premise:[44] had there been instances of absolute or discrete electrical states he would (presumably) have had to abandon the principle as anything more than a generalization of limited range.[45] As he himself has emphasized, it was the apparent impossibility of there being absolute charges which had led him to assert that this is a physical (and conceptual) impossibility (1163,1168, Diary: 3425). The denial of action at a distance had followed only after this principle had been deduced and defended.

2.2.2 Tests of the hypothesis

While Faraday's justification of the principle of induction depended upon his concept of force as a dual or polar relation between the points at which its effects become manifest, the two experimental tests which he now makes of the hypothesis of contiguous action involve the use of the idea of the curvature of lines of induction and the introduction of inductive capacitance as a 'conservative power' of the dielectric. This suggests that the idea that force is a conserved or indestructible quantity also contributed to this next stage of his defence of the theory of induction. Here, however, conservation is not advanced or defended explicitly as a criterion of the adequacy of an hypothesis or an interpretation of the phenomena. As yet this idea is still a presupposition of Faraday's thinking

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44. Cf. supra, p.117 ff.

45. --presumably, because it is not at all clear that Faraday would have accepted the verdict of nature even on this point, as his later response to the negative results of experiments on the magnetic analogue to inductive capacitance are to show (cf. section 2.3.4).

rather than an explicit premise in his arguments.[46]

Of the two consequences of the hypothesis that induction is an action of contiguous particles (1165-66), Faraday believed 'the expected action in curved lines' to be 'the most important at present' (1215). In his experiments on induction and discharge Faraday treats the curvature of the lines of inductive action not merely as a possible (and confirmed) consequence of the hypothesis, but as being necessary. It will emerge that the hypothesis of contiguous molecular action simply provides a model for a property which is necessary on Faraday's view of force: curvature is a measure of the quantity of action residing in the field (as represented by the lines). Thus if there is a sensible field at all, its lines must have some curvature.[47]

Faraday's first test involves charging a non-conductor, placing an uncharged conductor on or near it, and showing that the latter acquires an opposite charge on portions of its surface which cannot be connected to any portion of the former by a straight line (1217-19). As a sensor he uses a pith (carrier) ball, measuring with an electrostatic balance (1180) the 'force' acquired by the ball at different points in the region of the spherical conductor (figure 2.3; cf. ERE I: plate VII, figs. 106-108). He finds that the force varies for different points in the region (figure 2.3a).[48] It can be shown that

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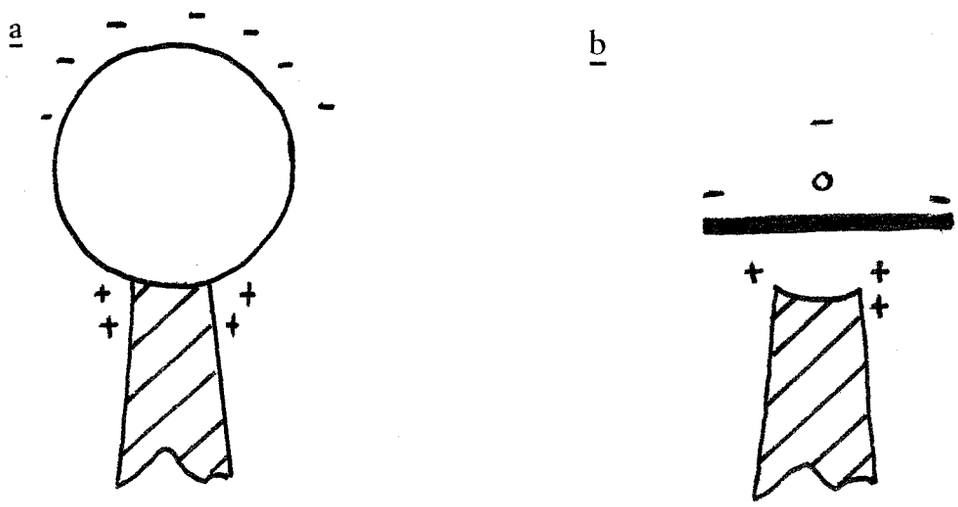
46. In fact Faraday does not distinguish between conservation and the principle of the equality of cause (action) and effect (reaction) until 1851. Cf. section 4.2.1.

47. At the molecular level the lines of no action would represent the electrostatic forces or affinities of the particles in their 'normal' or 'quiescent' form. This state is one of possible rather than of virtual action (tension). It is to emerge not as a disposition to act but as the basis of such dispositions (see sections 2.4.1-2.4.3, 3.5.2.1, 4.1-4.3).

48. Faraday's demonstration is a proof even on the supposition of electric fluids because he grounds ('uninsulates') the apparatus at the moment that the sensor is actually brought into contact with the conductor so that only that charge due to induction through the air remains on the latter (1219-20).

FIGURE 2.3

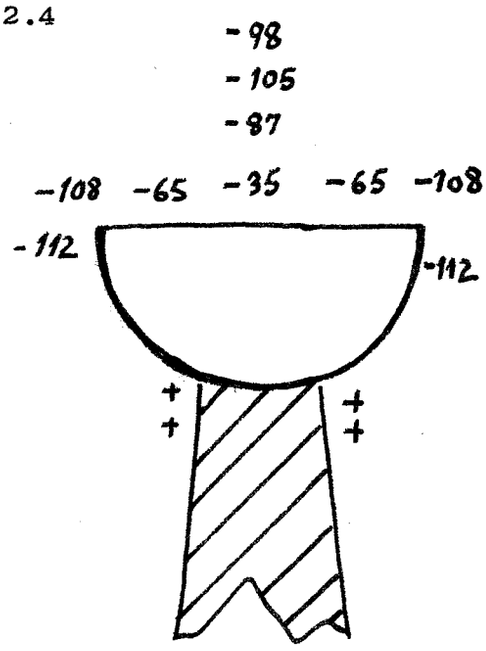


induction does not occur through the conductor by placing a metal disc above the charged insulator and testing for charge in the region above this disc (fig. 2.3b).

In a final test for the distribution of inductive action Faraday shows that this action varies in a non-uniform manner above a hemi-spherical conductor (when charge is applied to the non-conductor on which it stands, as in figure 2.4):

> Here the induction fairly turned a corner. Nothing, in fact, can better show both the curved lines or courses of the inductive action, disturbed as they are from their rectilineal form by the shape, position, and condition of the metallic hemisphere; and also a lateral tension, so to speak, of these lines on one another ... (1224)

FIGURE 2.4



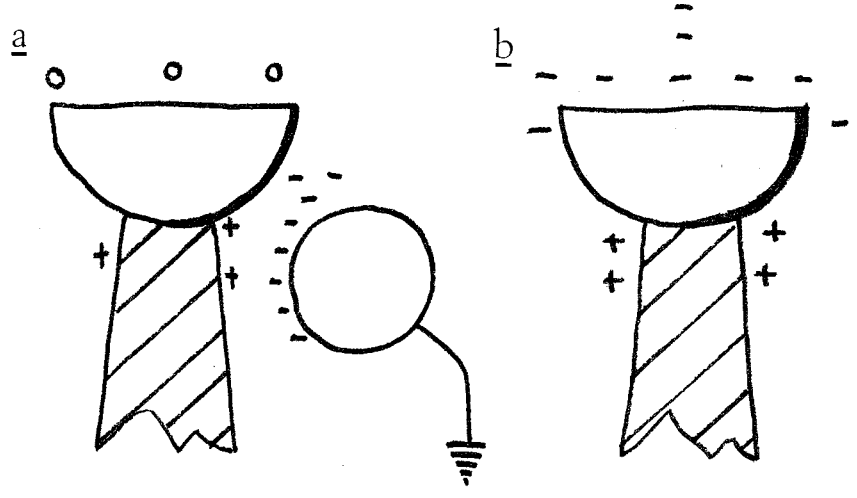
This is clearly more than a description of the distribution of the electrostatic potential in terms of its measured value at a number of points, it is an interpretation of the measured distribution (a set of numbers) in terms of lines of inductive action.

The most significant point is that Faraday regards the lines as being disturbed from their normal (rectilinear) form by the presence of electrified matter and as acting upon each other laterally when they are in such a disturbed condition. That Faraday is convinced that he has evidence of a lateral action is clear from the fact that he immediately provides a second test as a check upon the inference that he has made in interpreting the above experiment:

> if uninsulated conducting matter was brought round and near to the excited shell-lac stem, then the inductive force was directed towards it, and could not be found on the top of the hemisphere (1225).

Thus the distribution would have been as shown in figure 2.5a, where

FIGURE 2.5



the action of the charged shellac was directed to or absorbed by the grounded conductor. On removing the latter (fig. 2.5b),

> the lines of force resumed their former direction. The experiment affords proofs of the lateral tension of these lines ... (1225, my italics)

Differences in the degree of inductive action on the sensor at different points indicated that the force varied in a fairly uniform manner and that this distribution was drastically altered by the introduction of a grounded conductor and was resumed on removal of the latter.

Faraday has not been making the sort of tests which could provide information about the form and mutual interaction of lines of induction: the only data he has are sets of values of the charge induced on a carrier ball at various points (which can be compared with other sets obtained for different charges and arrangements of the conductors and insulators). How does Faraday justify this interpretation of experiments which reveal only changes in the intensity of the inductive action as the distribution of charge is changing? In particular, why does he attribute a disturbed state of 'lateral tension' to the lines which represent these distributions?

An immediate answer to the second of these questions is provided by Faraday himself. He states that the above experiment demonstrates both the curvature and the lateral tension of the lines,

> all depending ... on induction being an action of the contiguous particles of the dielectric, which being thrown into a state of polarity and tension, are in mutual relation by their forces in all directions (1224).

Given this model a lateral tension of the lines could be explained on the supposition that the lines consist of chains of particles acting inductively along the axis of the line and repelling the particles of other lines in planes perpendicular to this axis. Given the model, the experiments just described could be regarded as a test of a consequence of the model.

While this would explain how Faraday thought the lateral tensions andthe curvature of the lines to be <u>possible</u> it explains neither why he found it necessary to attribute a lateral action to the lines, nor

why he was led initially to interpret these experiments as proof of the disturbed or distorted state of the lines.

It subsequently becomes clear that Faraday expected the lateral action to be analogous to (if not identical to) a magnetostatic force. On this view the lateral action of the lines is the magnetic analogue to electrostatic action while the circumferential action of the current (also lateral) is the magnetic analogue to electric force in its dynamical or progressive state. Thus the two forces would be shown to have three corresponding states (normal or quiescent, static or inductive, and dynamical or progressive) and the way would be made clear for a unified theory of these two powers.[49]

A second reason which emerges only in the twelfth and thirteenth series, is that the lateral (magnetic) and the direct (electrostatic) actions are supposed to be partially inter-convertible, where their sum is a constant. A decrease in direct (inductive) action would produce an increase in lateral action, an inference justified apparently by the fact that the lines of a brush discharge diverge or bulge as the interval over which discharge occurs is made to vary.[50] Implicit in this view is the assumption that a system of lines of induction represents or constitutes a fixed quantity of electrostatic and magnetic action, a quantity of action which is converted into the magnetic field, heat, light, motion of charged particles, and sound when the inductive tension collapses or gives way to the progressive

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49. For the development of this line of reasoning see sections 2.3.3 and 2.4.1. This is one of the few occasions on which Faraday's adherence to an analogy (inferring static and dynamic states of the magnetic power from the static and dynamic states of the electrical power) leads him into an error which is not corrected by subsequent experiments. He never does observe the magnetic analogue of the electrostatic state, but continues to believe that it should exist (1734-35, 3269-70).

50. See sections 2.3.3, 2.4.3, and 2.5.2.

forces of the current during discharge (conduction).[51] Faraday never proves this experimentally because he has no concept of what was subsequently identified as the mechanical equivalent of electric, magnetic, and other forces.[52]

I have drawn attention to these two beliefs because they do play the role (respectively) of an heuristic and a regulative principle. This is evident in Faraday's subsequent interpretations of phenomena similar to those just described. It illustrates the complexity of the set of beliefs which Faraday brought to bear upon the problem of interpreting nature and his preoccupation with the nature of force rather than that of matter.

Although Faraday subsequently insists that the lines of induction merely represent the direction of the force at a given set of points (1304) it is evident that he tended to reify the lines, treating them as entities in their own right. For example, when repeating the above experiments in gases other than air Faraday finds that the experiments are best performed in a current of the gas (1226). If the action persists while the sustaining dielectric is moving (as it does) then the lines must subsist or persist even while their actual constitution is changing. This particular series of experiments (1226-28) requires that a distinction be drawn between the line as an interpretative device and the line as a theoretical entity (viz., an in-principle identifiable chain of particles along which force is transmitted). Faraday did consider the fact that the actual

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51. Thus the lateral (magnetostatic) actions of lines of induction would be the cause or prior condition of the lateral (dynamic) magnetic field of the current. See Section 2.4.1.

52. He does, however, have a very clear idea that the proof of the conservation of force will depend upon such a demonstration that each form of force has its equivalent in the action of some other form (1686). See section 2.4.3.

constitution of a line must be continually changing in a moving (fluid) dielectric, for he next replaces the fluid dielectrics by solids, remarking that

> it is thus very satisfactory to obtain the curved inductive action through solid bodies, as any possible effect from the translation of charged particles in the fluid or gases, which some persons might imagine to be the case, is here entirely negatived (1228).

I have emphasized this distinction between the line of force as a conceptual and interpretative device (a mere 'representation') and the line of force as a physically real chain of particles because Faraday subsequently assigns an explicit physical function to the former rather than to the latter,[53] and because the above example shows that he was less inclinced to distinguish between the two at this stage than he professes to be.[54]

It is evident that Faraday already regards the lines as constituting a system which reacts or responds to changes in the distribution of charged bodies by changes in form,[55] and that he interprets data about the distribution and 'direction' of inductive action in terms

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53. The reality (causal status) of the lines of electric induction is guaranteed, so to speak, by the fact that they exist as chains of material particles. Faraday has to be more cautious with the lines of magnetic induction because he finds (in 1838 and 1848) that magnetic force does not polarize matter as universally as the electrostatic force. Consequently he argues in 1851 that the physical existence of the lines cannot be tied to the presence of matter. This is, of course, why his final arguments for the reality of the field deal primarily with the magnetic lines rather than the lines of electrostatic induction.

54. Thus I do not accept Heimann's view that the lines of force assumed ontological primacy over matter only after 1844 ('Faraday's Theories of Matter and Electricity', op.cit. supra, p.11 (note 5) at p.256). Given the primary explanatory status of force ('action') in the present theory and in its predecessors it is unlikely that Faraday regarded the lines as only imaginary until 1846. See sections 2.6 and 2.7.4.

55. See especially his description of the experiments on the hemispherical conductor (1224), at (1231).

of his model of the dielectric as a structure of particles organized into a system of lines. The availability of such a model supports his contention that inductive action

> instead of being like that of gravity, which causes particles to act on each other through straight lines, whatever other particles may be between them, is more analogous to that of a series of magnetic needles, or to the condition of the particles considered as forming the whole of a straight or curved magnet (1231, my italics).

As an inductive action can be transmitted and sustained only as a series of polar relations between contiguous particles, the inference that a non-observable system of electrostatic lines is analogous to a visible system of magnetic lines is based not simply upon the hypothesis of contiguity but upon the more fundamental principle that both electrostatic and magnetic forces are inductive.[56]

Finally, it should be noticed that in denying that the accepted theory is a 'correct representation of that great natural principle of electrical action' (1231) Faraday is claiming not that the inverse-square law of attraction is invalid, but that the law does not describe correctly or completely the nature of inductive action. Faraday's lines of induction do not represent electrostatic attractions but something that he takes to be more fundamental, namely, that quantity of force or action which can produce attraction as just one of its effects.

If, as I am maintaining, Faraday does believe that he is measuring not the electrostatic forces as given by Coulomb's law but some other quantity, then his present challenge to the received theories is

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56. As forms of a single power these two forces should be analogous in all respects, and so (eventually) should other forces prove to be. For Faraday's response to experimental results which clearly disconfirmed this conclusion see section 2.4.2.

precisely that which he is to make to the inverse-square law of gravitation twenty years later: that the law merely describes one possible effect of a system of power whose primary action is inductive (the polarization of matter or the production of currents) rather than the production of attractions and repulsions.[57]

2.2.2.1 Specific inductive capacitance

If the principle of induction is true then inductive capacitance must exist. In the case of the three metal plates, one of which is separated from the other by a solid insulator other than air,[58] the centre plate must act equally upon the two outside plates. The principle of induction requires that the total action of the centre plate on each outer plate be the same while the hypothesis of contiguous action together with the hypothesis that the polarizeability of particles is specific or characteristic, suggest that more of this action will be stored as molecular tension in one case than in the other.[59]

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57. For further discussion of the distinction between inductive action and attraction, see section 2.5.1.

58. Cf. supra, p. 120 and (1252).

59. Williams has argued that the specificity of inductive action is an hypothesis which Faraday developed as a direct consequence of his adherence to Boscovichean atomism, on the grounds that Faraday's position is not explicable on any other (then-current) theory of matter (Michael Faraday: 291-94). Yet virtually all of the properties of matter that Faraday has so far investigated are specific or characteristic to each kind of matter--melting points, pressures and temperatures at which changes of state occur, temperatures at which electrical conductivity and magnetic powers are lost or acquired, and so on. There is no need to suppose that Faraday required a theory which posited such specificity (although it is evident that such specificity would support a theory such as Boscovich's). The problem with Williams's thesis is that if, as he maintains, Faraday predicted specific inductive capacitance on the basis of Boscovich's theory in 1837, we are left with the problem of explaining why Faraday did not anticipate in 1834 the characteristic differences in the intensity of a current necessary to produce decomposition (electrolyzation potentials). Cf. (984, 904,910,967,987).

The crucial assumptions here are: (1) that the total quantity of action represented by the lines of induction proceeding through the dielectric between the plates and through the air surrounding them, including the intermolecular tension of both mediums, will be a constant; and (2) that the dielectric is a medium which prevents the two equal and opposed forces of the polar relation from combining and neutralizing each other (as they would do if a conductor were introduced between the plates of the condenser). Without inductive capacitance no tension or polarity (and hence no charge) could ever be sustained; without specific inductive capacitance the equality of the two elements or directions of the force would not be preserved. Thus both the existence and the specificity of inductive capacitance are necessary properties of the medium between the points or surfaces on which charge appears.[60]

The instruments used by Faraday in testing for the existence of specific inductive capacitance are an elaborate form of the three-plate condenser described earlier. He uses two instruments each consisting of a small spherical conductor attached to an insulated stem which protrudes through a larger spherical conductor concentric with the first (figure 2.6). The expected differences (1195) are to be detected by the following procedure. A charge is applied to the ball on the stem of one of the instruments. This charge is then divided between both instruments by connecting the two stems with a conductor. (Thus the two inner surfaces have the same charge and correspond to the single centre plate A in figure 2.1.) All charges are measured by charging a carrier ball from the balls on the stems and determining

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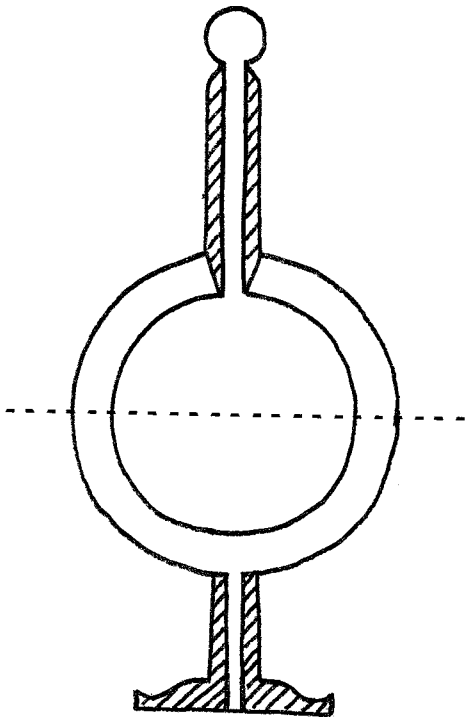
60. A similar (and necessary) property is attributed to space in 1852 on the grounds that the polarity of a magnet could not otherwise be sustained in a vacuum. See section 4.2.2.1.

FIGURE 2.6



the degree of repulsion exerted by the carrier on a torsion balance.[61] The two instruments are then discharged (grounded), their residual charge (if any) measured, connected together, disconnected, and, finally, tested for a difference in charge (1197). A difference in the insulating or inductive capacity of the region between the inner and outer surfaces would be observed as a difference in the final charge of the two instruments after division of their charges (at which stage in the procedure their outer surfaces now correspond to the two outer plates B and C in figure 2.1).

Such a difference would show that the charge originally divided between the two inner surfaces (which is equal at the instant of division) has been communicated to the outer surface of each instrument at a different rate. Since the only physical difference between the two instruments consists in the nature of the medium placed between the inner and outer shells, the observed difference must be due to some

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61. The quantity of charge is measured as the torsion required to bring the carrier ball and that of the electrometer (1180) to a fixed angular separation of 30 degrees (1184,1197).

property of this medium, namely specific inductive capacity.(1277).[62]

Although Faraday describes these instruments as Leyden phials (1195) he does not interpret their action in the way that his predecessors had done. Franklin and Aepinus had taken the glass between the inner and outer conductors (corresponding to the space between the two shells in Faraday's instruments) to be a perfect insulator (impervious to the electric fluid) and, although Franklin had been obliged to admit that the glass must transmit some sort of action,[63] this was not an anticipation of Faraday's concept of inductive capacitance (as distinct from his discovery that this is specific to different insulators). To Franklin the inference that there is action through the glass was required to explain the electrification of the inner lining of the jar,[64] yet the glass had to be impervious to the fluid because it effectively separated two electrical states or quantities of fluid. To Faraday such a situation is impossible: as active and qualitatively opposed conditions these two electrical states must be causally related.

This is best illustrated in Faraday's response to his discovery that the two instruments, which had been shown to be identical in respect of their ability to retain charge, subsequently lost charge at different rates. The rate of loss of charge appeared to depend upon which instrument had been charged initially (i.e., with a full- rather than with a half-charge (1207)), and to what extent it had

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62. As Faraday observes, this term denotes the ratio of the capacity of the test medium to that of air. (The term now refers to this ratio taken relative to the capacity of a completely evacuated condenser.) Note that this is not the dielectric constant, which has the same numerical value as the inductive capacitance only on an appropriate system of units.

63. The principle of the Leyden jar was that it could 'store' quantities of electricity.

64. Cf. Whittaker, Aether and Electricity: 49.

been charged (1234). This presented a major obstacle because Faraday's trials required that one instrument always be charged first and its charge divided with the second instrument. Equally puzzling was the fact that the charge 'which in these cases returned from an apparently latent to a sensible state, was always of the same kind as that which had been given by the [original] charge' (1235).

The immediate import of this discovery was that, like his discovery of secondary chemical actions and of the non-electrical nature of catalytic action, it enabled Faraday to avoid an experimental pitfall--it was now obvious that the measured charge of the instruments could not be taken to be a constant quantity over time (1233,1250).

The significance of this discovery (which confirmed Faraday's conviction as to the fundamental identity of conduction and insulation)[65] lies in the way in which Faraday investigated it. It could not be the case that there is a single, latent, temporarily hidden charge stored in the stem of one of the instruments or in the dielectric which it contains (1244). Faraday charged up one of the instruments containing a layered dielectric, removed the dielectric and separated the two halves. No charge appeared on the outer surfaces of the material until the two layers had been separated:

> Hence it is clear that, of the <u>forces sought for</u>, the positive was in one half of the compound plate and the negative in the other half; for when removed bodily ... from each others inductive influence, they appeared in separate places, and <u>resumed of necessity their power</u> of acting by induction on the electricity of surrounding bodies (1246, my italics).

This example shows the extent to which Faraday's principle of induction guided his interpretation of electrostatic phenomena--where he could not readily detect two equal and opposed forces or states

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65. Faraday did not at first realize that this is a case of residual polarization of the dielectric (1245). His final conclusion is that it involves slow conduction (1246-47).

he immediately set about looking for them.

Faraday could now proceed to determine 'whether different dielectric bodies actually do possess any influence over the degree of induction which takes place through them' (1252). The trials themselves are quite straightforward.[66]

Faraday first places a hemispherical piece of shellac in one instrument, leaving the other empty. He charges the empty instrument up to 297° of torsion on the electrostatic balance, then divides this charge with the instrument containing the shellac. Allowing some 7° of torsion for the action of the stem, '290° may be taken as the divisible charge' of the empty instrument and, if there is no inductive capacitance, the half-charge of each should be 145° (that amount being 'lost' by the empty appliance and 'gained' by the one containing shellac). Yet the measured charges (after correction) were 114° for the empty appliance and 113° for the one containing shellac. The inductive capacitance of the shellac relative to that of air would be

> inversely as the respective loss and gain indicated above; and assuming the capacity of the air apparatus as 1, that of the shell-lac apparatus would be 176/113 or 1.55 (1259).

After several repetitions Faraday obtains corrected values averaging 'close upon 1.5' for shellac (1266 , cf. 1270-76). He concludes that

> the experiments altogether fully prove the existence of a difference between dielectrics as to their power of favouring an inductive action through them; which difference may ... be expressed by the term specific inductive capacity (1277).

Faraday now turns to examine the gases of 'aeriform bodies', being convinced that because they are 'so peculiarly constituted, and are bound together by so many striking physical and chemical relations',

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66. See ERE I: (1252-92) or Williams, Michael Faraday: 292-94.

they should exhibit definite differences in inductive capacity (1283). No difference could be detected using the procedures he had designed; moreover, no change in the capacity could be detected on increasing or decreasing the density of a given gas (tested relative to air at atmospheric pressure). Faraday then tests different gases against each other in order that

> no difference might escape me, and that the sameness of result might stand in full opposition to the contrast of property, composition, and condition which the gases themselves presented (1290).

Still no difference in 'their capacity to favour or admit electrical induction through them could be perceived' (1292).

Despite this fact Faraday believed 'the point established, that in all these gases induction takes place by an action of contiguous particles' (1292). He had two reasons for concluding this. First, the experiments did show that gases have an inductive capacity--as would any experiment which shows that a medium is a non-conductor or a poor conductor (i.e., that it can sustain and separate the two opposed forces of the inductive relation).[67] The second reason is that Faraday remained convinced that some difference would be detected (1293). A month later he repeats these experiments (1361) and four months later we find him still concerned with the possibility that there are 'differences which have as yet escaped me ...' (1313).[68]

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67. See <u>supra</u>, p.135 and <u>infra</u>, section 2.3.1.

68. Williams suggests that Faraday did not really expect to find differences because he thought that the intermolecular forces must be the same for all gases (as implied by Boyle's law) (<u>Michael Faraday</u>: 293-94). In addition to his having overlooked the passages just cited (esp. 1283, 1290-92, 1313), Williams has overlooked the point that induction is an action of the <u>electrical</u> powers of the particles rather than of those forces which Faraday calls 'mechanical' (the cohesive forces (626,656,1596)). When Faraday does introduce non-electrical forces (which have been banished since the seventh series) he does so to explain not the <u>constancy</u> of inductive capacitance in gases but the <u>differences</u> in the critical point at which each ceases to insulate and becomes a conductor (1594).

Faraday concludes that inductive action is

> an action of contiguous particles, through the intermediation of which the electric force, originating or appearing at a certain place, is propagated or sustained at a distance, appearing there as a force of the same kind exactly equal in amount, but opposite in its direction and tendencies (1295).

Induction is not simply transmitted to a distance, it is sustained by the polar tension of the particles in the same way that the chemical affinities of a voltaic cell had been transmitted and sustained or 'balanced' against those of a second cell, through the wire joining the two (917,947,1031).

Induction 'requires no sensible thickness in the conductors which may be used to limit its extent' (1295). All that is required for the existence of the two opposed actions of a polar relation is a single interval, however small, of non-conducting material--material which resists the recombination, 'resolution', or neutralization (950) of the two actions. Charge is just the manifest effect of the strained or polarized condition of the matter which occupies the region between the points or surfaces at which it appears. Thus the appearance of charge is just a sign that the normal or 'quiescent' distribution of the interparticle forces has been altered so that they now possess an additional quantity of (possible) action.[69]

It is important to see how, and in what sense Faraday's present theory of the nature of charge is an extension of his earlier theories of the electrical and chemical powers of matter. Faraday can now explain why conductors can only be charged superficially:

> All charge of conductors is on their surface, because being essentially inductive, it is only there that the medium capable of sustaining the necessary inductive state begins (1301).

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69. Cf. series eight (esp. 950), series nine (1110), and note 47.

No appeal need be made to any property or power other than the polarizability of the particles of the conductor and the insulator (dielectric), for charge can exist only at a surface separating two mediums having a significant difference in inductive capacity. The particles of one of the mediums must be more easily polarized than those of the other.[70]

In the fifth series Faraday had shown that a material pole or electrode is not necessary to the occurrence of electrochemical decomposition: all that is necessary is an interface between two fluids or two mediums having different chemical constitutions (493-96). The surface of the 'pole' is just the boundary between two substances having different chemical affinities. Just as the poles are 'the limiting surfaces of the decomposing substance' (535) so the conducting surfaces of a condenser or Leyden phial are merely the 'limiting ... surfaces' of an inductive relation, at which the ability of the matter to sustain electric tension alters abruptly (1297).[71]

This capacity is defined as the polarizability of the particles, i.e. their ability to retain their normal, undisturbed condition under the action of the force and to transmit acquired tensions onwards by conduction. Faraday never does succeed in explaining this disposition of the particles, and although he suggests in the twelfth and thirteenth series that it might be determined by cohesive and other intermolecular forces (1575,1594), after 1838 he makes no attempt to explain it.

In 1848 (after finding that magnetic induction does not

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70. Here the polarizability of the metallic particles is negligible compared to that of the air particles. It follows that the difference between conduction and insulation is just a matter of degree (see section 2.3.1).

71. The idea of an interface had also been used in the sixth series to explain catalytic action (626-30) and had been central to Faraday's suggestion that similar explanations could be given of chemical changes which do not involve a current (e.g. combustion (656)).

necessarily produce polarization analogous to electrical polarization) Faraday dispenses with the idea of molecular polarization, replacing it with the more general concept of the conductivity of matter for the lines of electric and magnetic force. On this theory a good conductor (one which is easily polarized and whose particles would, on the present theory, transmit their acquired tensions onwards very easily) attracts the lines of force (because they find an easy passage through it) while a poor conductor repels the lines (because they find an easier passage elsewhere). In this way Faraday is able to preserve the generality of the present theory without having to develop a specific theory of the nature of matter or of the basis of the characteristic disposition of its particles to polarize or react upon force.[72]

The resulting picture (on the present theory) is of a structure of particles and lines; a system of tensions between particles. Although Faraday does refer to this as a 'corpuscular view' (1302) it is unlikely that he regarded the particles as anything other than the terminal points of inductive relations. If the particles are extended, then this property must consist in their having electrostatic powers which extend to the nearest neighbouring centre of force (or 'contiguous particle'). The inductive state (like the polarized state

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72. In fact the two ideas appear together in Faraday's description of the effect of a conducting sphere upon lines of static induction in air, at (1566). There he says that a small conductor in the region of a large charged conductor will assume a higher charge than the latter because more inductive action is 'directed towards it than would have passed across the same place if the ball had not been there'. The ball 'removes the resistance of the particles of the dielectric, which otherwise would have been there' acting (so to speak) as a sink for the action stored as polar strain in the surrounding dielectric. This is why a mass or particle can act as a 'centre of inductive force' upon nearby matter--it simply attracts the lines of action towards it so that more charge forms upon its surface than elsewhere (1331,1442-43,1562-66). For the later development of this idea see sections 3.3.2.1, 3.5.2, 3.5.2.1, 4.2.2, 4.2.2.1.

of the electrolyte)[73] is a 'forced one' which is

> originated and sustained only by force, and sinks to the normal or quiescent state when that force is removed ... (1298, my italics)

Charge is just the phenomenal effect of this forced state while discharge (conduction) is 'the return of these particles to their natural state of tension, whenever the two electric forces are allowed to be disposed of in some other direction' (1300).

In the eighth series Faraday had shown that the voltaic current can be considered as a particular condition of the affinities of the matter. Here he has shown that charge, too, is a state of the electrical forces of matter.

2.2.3 Theoretical terms and the role of experience

An important aspect of Faraday's method of defining new scientific terms was well described by Maxwell, who wrote that Faraday began by

> getting rid of those parasitical ideas, which are so apt to cling to every scientific term, and to invest it with a luxuriant crop of connotative meanings flourishing at the expense of the meaning which the word was intended to denote. He therefore endeavoured to strip all such terms as 'electric fluid,' 'current,' and 'attraction' of every meaning except that which is warranted by the phenomena themselves, and to invent new terms ... which suggest no other meaning than that assigned to them by their definitions.[74]

We have seen that Faraday has replaced 'current' and 'fluid' by 'axis of power'; 'pole' by 'electrode'; 'atom' by 'particle' or 'ion'; and 'attraction' and 'polar' by 'action' and 'inductive'.

In the conclusion to his eleventh series Faraday makes a remark which, in the light of later events, supports the view that Faraday

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73. In the eighth series Faraday had spoken of the polarizing of the forces of the particles (rather than of the particles themselves). Cf. (950).

74. 'Faraday', Scientific Papers II: 355, at pp.358-59.

regarded the development of his own theoretical vocabulary as a gradual process in which experimental inquiry leads to an increase in the precision of a term through a progressive restriction of what he calls its 'sense'. After having explained that the term 'line of force' refers to an imaginary or representational device and that the term 'polarity' indicates just a 'disposition of force' to which the polarity of a particle is due (1304), Faraday explains that

> the particular way in which this disposition is made will come into consideration hereafter ... All I am anxious at present is, that a more particular meaning should not be attached to the expressions used than I contemplate (1304).

It is likely that Faraday was not entirely clear about the exact details of his own theory (and was unwilling to commit himself to particular hypotheses about the nature and cause of the disposition to polarize). His habitual caution about hypotheses required that he use terms which carry as few theoretical connotations as possible, and preferably none at all.[75] Thus, the term 'polarity' is intended as a descriptive term:[76]

> Further inquiry, I trust, will enable us by degrees to restrict the sense more and more, and so render the explanation of electrical phenomena ... more and more definite (1304).

This comment points to an important aspect of Faraday's approach to the problem of developing a language adequate to the task of describing and explaining nature. It is evident that Faraday does not make experience the sole arbiter of the truth, falsity, or probability of an hypothesis or principle. Progress towards a 'more definite' explanation of the phenomena consists in a process by which the

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75. See his letters to Lemen and to Whewell, cited in sections 1.3.2.3 and 1.3.4.2.1

76. The extent to which it could be merely a descriptive term is apparent from Faraday's arguments as discussed supra, sections 2.1-2.2.1.

language of a science is made more and more precise.

In Faraday's Researches this process involves two sorts of restriction upon the 'sense' of a word. First, a word may be restricted so that (as Maxwell remarked) it expresses no more than what Faraday takes to be a primary fact: 'anode' and 'cathode' are terms defined in terms of the direction of action of a current entering and leaving a cell; while polar actions between charges and magnets and wires are termed 'inductive', and this word is defined in terms of the fact that such actions originate and terminate in qualitatively opposed states, effects, or conditions (1,1163). The term 'polar' is not used, because Faraday wants to avoid the connotation that poles are things between which forces act directly (in right lines)--hence the poles of a cell become 'electrodes' (493,661-62).

Examples could be multiplied, but there is one important instance that has yet to be encountered. Faraday has defined polarity as a state or condition of the particles of matter (albeit one intimately linked to, if not caused by, the field in which they exist (1304)). He is later to revise this term in the light of experiments which show that magnetic forces (which are polar) do not polarize all matter. His revision consists in restricting the term so that it denotes a property of force itself rather than a property which force may exhibit only in the presence of matter.

These examples show that for Faraday, experiment or experience was important as a guide to and as a check upon the use both of the accepted terminology and of his own newly-introduced terms. I believe that this was a far more important role than that of confirming or refuting hypotheses because Faraday rarely ever retracts an hypothesis in the face of recalcitrant experience, while he frequently introduces a new term or 'restricts' the meaning of an old one in such situations.

Generally this sort of restriction will not involve a radical change in the meaning of a term, since it is clear that both 'pole' and 'electrode' or 'atom' and 'particle' denote the same sort of thing (as defined in terms of the actual or possible function of that sort of entity).[77] Thus Faraday's terms are broader and less dependent upon a particular theoretical context than were their predecessors. The 'restriction' of the reference of such terms consists in the introduction of higher-order principles (as we saw in the case of 'charge' and 'induction')[78] and not necessarily in the development of some specific theory.

The second sort of restriction imposed by Faraday may lead to a more radical redefinition of a term--though here again this redefinition does not depend upon some theory. In 1844 Faraday argues that the reference of the word 'matter' (and of 'atom' or 'particle') be restricted so that the word shall refer only to the active or (in principle) perceivable qualities of things--just as he has so far used the words particle and current to refer only to powers (manifest qualities) or to the places at which they exist or are 'localized' (1650,852,517). Here the restriction is made to avoid ontological commitments of the sort precluded by Faraday's epistemology.[79] In

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77. Faraday's terms are intended to denote classes rather than specific entities. Thus 'electrode' may refer either to the interface between a chemical solution and the air (at which chemical products are evolved) or to a metallic pole; similarly his 'particles' may be atoms whose extension consists either in hardness (as a primary quality) or in repulsive force.

78. Supra, section 2.2. For Faraday's final statement of the relationship between principles (which define possibilities) and the role of 'clear ideas' in making judgements about matters of fact, see his 'Observations on Mental Education' (May 1854), ERCP: 463, esp. pp.468-69, 478.

79. For further discussion see section 2.7.1-3. In denying that 'matter' and 'atom' can refer to substance (or some thing distinct from its properties) Faraday is redefining that term on the basis of a theory of knowledge rather than of nature.

other words, it is advanced on the basis of a principle which stipulates what it is possible to know rather than one which stipulates what could or could not be the case (or hypotheses about what might be the case).

It is apparent that Faraday's development of a theoretical vocabulary and his use of experiment cannot be seen as a case of the generation of vague ideas by some metaphysics and their being made precise through the development of some theory, which is then either refined or refuted through experimental tests upon hypotheses formulated in terms of those concepts.[80] Faraday refines and redefines terms in conjunction either with experiment and his regulative principles (of induction and conservation) or on the basis of his epistemology (explicitly after 1844). To the extent that these principles are irrefutable, meta-theoretical postulates, it would be misleading to suggest either that there is a definite interaction only between theory and experience in Faraday's work, or that the primary function of his experiments is to confirm or refute the predictions of theories.[81]

The role of experiment will be examined more fully in the next sections, where it will be shown that Faraday uses experiment to illustrate and confirm his molecular theory of the dielectric but that he rejects experimental results that are not consistent with his principles of polarity and conservation.

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80. Cf. I. Lakatos, 'Proofs and Refutations', British Journal for the Philosophy of Science 14 (1963): 1, and Y. Elkana, 'Hemholtz' "Kraft": An Illustration of Concepts in Flux', HSPS 2 (1970): 263. A study of the introduction and definition of theoretical terms and of the viability of the distinction between theoretical and observational terms can be found in P. Achinstein, Concepts of Science (Chapters 3, 5 and 6).

81. Cf. supra, p. 11 ff., and section 1.2.

2.3 The molecular theory of induction

The twelfth and thirteenth series of the Experimental Researches contain Faraday's 'application of the theory' to the 'phenomena of conduction, electrolyzation, current, magnetism, retension, discharge ...' and an 'examination of' the theory in terms of these processes (1306). Faraday wants to show that conduction and insulation both depend upon a single power of the elementary particles (namely, that power which gives rise to inductive capacity) and that the lateral or transverse action of electrostatic forces is just a magnetic force. Both hypotheses are consequences of his predilection for unity both in the nature of these powers and in the processes by which they come to manifest themselves.

Faraday defines 'discharge' as a general 'action or effect' (1319) which includes (i) ordinary conduction (involving 'no chemical changes, and apparently no displacement of the particles concerned'); (ii) electrolytic discharge (in which chemical change occurs and the particles will be displaced 'to a certain degree'); (iii) sparks or brushes (which may involve a 'violent displacement of the particles of the dielectric' and are therefore called 'disruptive discharge'); and (iv) 'convection, or carrying discharge' (in which discharge is effected by the 'carrying power of solid particles').

Discharge is of crucial theoretical importance because it is the process whereby the two opposed powers or tendencies of a polar relation interact and neutralize. It is of particular importance in those forms (such as the brush) which can be directly observed, because here Faraday believes that he can actually see the transition of the electric power from its static (inductive) state into its progressive (dynamical) state.[82]

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82. Recall that obtaining a 'clear view' of this transition and the relationship of the two states of the power to the elementary particles had been a major problem left unsolved by the 1834 theory of electrolysis (ERE I: 321 n., (1163)).

2.3.1 The identity of conduction and insulation

Faraday now argues that although 'all these modes of discharge ... require to be considered apart', all will be shown to be 'the result of one common principle'--that of induction (1319). After noticing that 'neither Cavendish nor Poisson attempt to explain by, or even state in, their theories' the assumption that conduction and insulation are fundamentally different properties, Faraday states that 'according to my view of induction, insulation and conduction ... are only extreme degrees of one common condition or effect [of matter]' and that 'in any sufficient mathematical theory of electricity' the two 'must be taken as cases of the same kind' (1320).

On the accepted view the difference between these two properties had been taken much for granted. Faraday is soon to prove their identity by showing that both can be referred to the polarizability (reactivity) of the elementary particles of matter. Here he justifies this 'attempt to look at the highest cases of conduction as analogous to, or even the same in kind with, those of induction and insulation' with the following assertion:

> That in our attempts to penetrate into the nature of electrical action, and to deduce laws more general than those we are at present acquainted with, we should endeavour to bring apparently opposite effects to stand side by side in harmonious arrangement, is an opinion of long standing, and sanctioned by the ablest philosophers (1327, my italics).

While the first part of this passage may be read as a fairly typical appeal to the view that the value of a theory consists largely in its heuristic or reductive power, the italicized passage suggests the influence (however indirect) of the Naturphilosophen or of their scientific followers,[83] particularly when it is considered together

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83. In particular, Oersted. For an account of Oersted's speculative and scientific thought see B. Gower, 'Speculation in Physics ...', op.cit., note 40 (supra, p.22), at p.339 ff.

with Faraday's use of the concept of polarity, his tendency to identify the existence of a thing with its manifest qualities, and to identify these in turn with a state of tension or opposition.[84]

The 'reduction of conduction and insulation ... to an action of contiguous particles obedient to one common law' is a 'very important result'; moreover, the 'identity of character' of the two properties 'when viewed by the theory' is, according to Faraday, 'additional presumptive proof in favour of the correctness' of the theory (1338).[85]

How does Faraday's molecular theory provide for the identification of conduction and insulation? Faraday's researches on electrolysis (946-57) and his experiments on the combined effects of induction and conduction (1233-50) have convinced him that induction (the static state of the electric power) will be 'a necessary preliminary to conduction' (1323)--conduction being the dynamical or 'progressive' state of the power. Induction 'brings the contiguous particles of the dielectric into a certain condition, which, if retained by them, constitutes insulation, but if lowered by the communication of power ... constitutes conduction' (1323). In insulators (such as whale-oil, shellac, and glass (1233-47)) this 'communication will be slight or negligible, occurring by occasional 'discharge action' between particles (1324), whereas in metals and in carbon this discharge will occur readily.[86]

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84. Cf. notes 143 (p.98), 25 (p.117) and infra, section 4.2.2.

85. Faraday's attempt to identify such opposed qualities was soundly rejected by Robert Hare as a confusion analogous to that of identifying motion with rest or darkness with light ('A Letter to Prof. Faraday ...', op.cit., note 37 (supra, p.123), at p.255-56.

86. Even before his first attempt to develop an atomic theory of the structure of an electrolyte in April of 1834, Faraday had believed that conductors would insulate or exhibit inductive action. In November of 1833 he had remarked in a letter to Mary Somerville that 'There are probably no non-electrics'--i.e., no perfect conductors (Somerville Papers, cited note 43). Cf. (412,444).

On this view 'all the effects prior to' either a spark discharge or an ordinary case of conduction will be inductive. Consequently the electric tension built up prior to discharge (which is of sensible quantity and duration in the case of a spark) may be interpreted as

> the limit of the influence which the dielectric exerts in resisting discharge; it is a measure, consequently, of the conservative power of the dielectric, which in its turn may be considered as becoming a measure, and therefore a representative of the intensity of the electric forces in activity (1362, my italics).

Here the polarized state of the matter is identified as a 'conservative power', a power which is required on Faraday's view of force as consisting as a tension or opposition of two equal and oppositely-directed actions, each of which can exist (exhibit a measurable identity) only as it is built up against a resisting or reacting force--in this case the electric powers (affinities) of the particles (1298, 950).[87]

The theory suggests that the two crucial steps or states are the polarization of the particles (induction) and the subsequent discharge of the acquired polar forces (conduction). In addition to the ability to acquire a quantity of potential action, the particles also have a certain ability to communicate this additional action, 'by which [the tensions] are lowered, and discharge occurs' (1326).

However, this view is confused because the space between the particles must be capable both of insulating (preventing discharge while the tension is established) and of permitting the 'communication' of the tension. Yet Faraday attributes the latter ability to the particles (1326) and, on his later view that the particles are 'as wholes conductors' (1669,1674), it is difficult to see how this power

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87. The electrotonic state had been introduced in the first, eighth, and ninth series for a similar reason (cf. sections 1.3.1.1, 1.3.4.1, 1.3.4.2) and is to be reintroduced in 1852 as a property of space as well as of matter.

can be a power of the particles rather than of the space between them.

What Faraday says here is that 'the continuous particles have a power or capability of communicating their forces ...' (my italics). The italicized word should, perhaps, have been 'contiguous', yet the problem just described is later solved by Faraday on the assumption that the particles are continuous, being infinitely extended, mutually penetrable and, in effect, unit-fields capable of sustaining some maximum degree of distortion in the case of insulators or minimum degree in the case of conductors.[88]

Here, however, Faraday does tend to treat the particles as conductors and the region between them as an insulator, treating the dielectric as a structure analogous to a system of (macroscopic) conductors separated by a gas (or a non-ionizable fluid).[89] Thus, in applying the present theory to electrolytes as a special class of dielectrics which can conduct (either as metals do (910-12,1007) or by decomposing) or which can act as insulators (425 ff.,950-55), Faraday states that because the paired-ions (828) are inductively related while they are passing in opposite directions, the process depends 'of necessity, upon the non-conduction of the dielectric as a whole' (1348)--otherwise the polar forces acquired prior to dissociation would not be carried as fixed and definite quantities

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88. For further discussion of the problem and of its solution, see section 2.5.1 and p.218.

89. See his 'illustration' of the condition of an electroylte under static induction (1350), and cf. series 14 (1674-75).

of action to the next undissociated particle.[90] These quantities exist as inductive or polar relations, a state of the force which can be sustained only in a non-conductor.

2.3.2 Polarizability: the experimental evidence

In 1834 Charles Wheatstone had determined that a current does travel through a wire at a finite velocity, and had developed a method of analyzing a diffuse form of spark known as the brush.[91] Both the discovery and the method proved to be of crucial importance to Faraday, for (like W.S. Harris's paper on electrostatic induction and lightning discharge) they appeared in 1834--the year in which Faraday had determined that he would have to develop a more accurate account of electrical action.[92]

Wheatstone's results proved that '<u>time</u> entered as an element into the conditions of conduction', even in metals (1328, cf. 1248).

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90. Although Faraday notes that this action is a 'carrying one' he is not committed to the view that ions constitute or carry discrete (electronic) units of positive or negative charge. See section 1.3.3.1, (1621,1650), and (1245-47). Notice that this theory of the electrolyte (as a special class of dielectric) supports the electrochemical theory of the seventh and eighth series rather than that of the fifth and sixth, for it involves the stipulation that the whole action of a force be between members of an ion-pair (1348) rather than being exercised partly elsewhere. Thus Williams's comment that the theory of induction of 1837 must be understood in terms of the theory of catalysis is misleading (<u>Michael Faraday</u>: 291-92). In making inductive action the basic principle of this theory Faraday has <u>denied</u> one of the most important hypotheses of the earlier theory, namely, that non-polar forces relating every particle to <u>every</u> other determine electrochemical action (523,619,656-58).

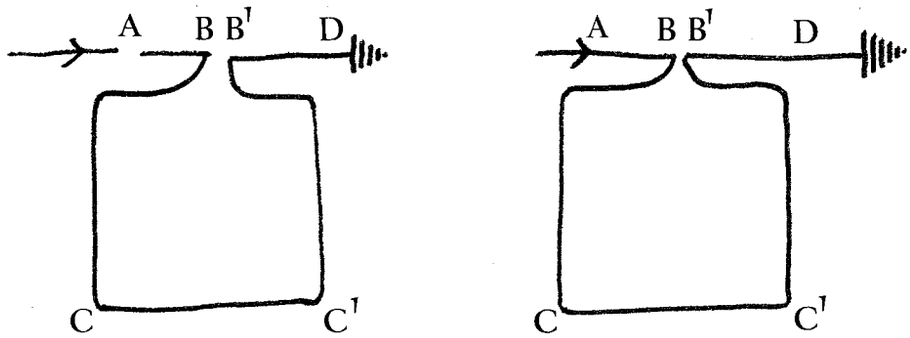
91. 'An Account of some Experiments to measure the Velocity of Electricity and the Duration of Electric Light', <u>Phil. Trans.</u> 124 (1834): 583. This investigation was a continuation of Wheatstone's earlier investigation of acoustical figures, and was carried out with Faraday's knowledge, if not with his assistance (<u>op.cit.</u>, p.583).

92. W.S. Harris, 'On some Elementary Laws of Electricity', <u>Phil.Trans.</u> 124 (1834): 213. Cf. <u>supra</u>, sections 1.3.4.1 and 1.4.

Although Faraday was never able to determine whether induction or discharge (or both) took time, this fact supported his belief in the identity of the two processes (1328). If the matter does not resist the passage of electricity (discharge) then conduction would have to be instantaneous.[93] The retardation of the current showed that some insulating or reactive property must be present even in metals. Thus Faraday could now insist that induction occurs in metals as well as in non-conductors (1328-29) and that the only difference between a metal and air or shellac lay in the rate at which molecular tensions are acquired and/or communicated.

It follows that there is no distinguishing in principle between conduction and insulation (1330,1327). Faraday drives home this point with an interpretation of one of Wheatstone's experiments, in which the discharge of a Leyden phial is applied to one end of a large copper loop having the configuration shown in figure 2.7. There

FIGURE 2.7



is initially a spark at A followed by a retarded spark at the interval BB'. Faraday believes that during this interval the wire is charged (i.e. that the inductive action is electrostatic rather than magnetic, (1331)). He defends this interpretation by showing that if the gap between B and B' is made small enough, the applied charge will jump this gap instead of being conducted through the metal ABCC'B'D. This shows that both the air in the interval and the

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93. Assuming, of course, that inductive tensions are established instantaneously, cf. (3249).

wire can be made to act either as insulators or as conductors. Prior to discharge there will be induction (polarization) both in the wire and in the air, but that in the wire must be greater than that in the air:

> Does not the middle part of the wire, therefore, act here as an insulating medium? ...
> If induction acts through the contorted lines of the wire, so it also does in curved and contorted lines through the air (1219,1224,1231), and other insulating dielectrics (1228); and we can apparently go so far in the analogy ... as to show that amongst insulating dielectrics some lead away the lines of [static induction] from others (1229), as the wire will do from worse conductors ... (1331)

In respect of their abilities to resist the formation of a current there is no real difference between a metal and a gas.[94] Thus both can be characterized in terms of their ability to lead away or provide an easy route for the discharge of the tension which exists in the lines of induction (1331).

This is an important instance of the way in which Faraday's theoretical assumptions and his predilection for unity at the most fundamental level[95] have (respectively) enabled and persuaded him to interpret this experiment in what was, for his time, a highly unorthodox way. It has also led him to an idea which is to become the basis of his final theory of the interaction of matter and the field, namely, that matter is just a region having a certain characteristic ability to transmit the action of the field.[96]

If the only difference between a conductor and an insulator consists in the conservative power (1362) or in the 'necessary degree

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94. Resistance to the formation of a current (polarization) is not identical to resistance to the passage of a current; cf. (74-75,213,1335).

95. The fundamentality of a theory is subject to certain theological constraints. See series 15, (1749,1791).

96. Cf. note 72 and sections 3.3.2, 3.5.2, and part IV.

of force or tension between the particles which must exist before the act of conduction' or intermolecular discharge takes place (1611), then there should be some 'mechanism' whereby this critical (and characteristic) degree of tension is determined. On this point Faraday's theory begins to break down, for it does not work as well for fluid dielectrics (in which the particles are mobile) as it does for solid and viscous dielectrics (in which the particles are 'constrained' or held in position).

Faraday suggests two possible determinants of the 'limiting condition between inductive tension and discharge (1612). The first is that discharge between polarized particles does not occur unless the electric intensity rises upon some critical value, which will be characteristic of each kind of material. In this case there will be perfect insulation between the particles until 'communication by discharge' takes place. The second possibility is that

> however small the difference [in potential] between [any] two such particles, if time be allowed, equalization of force will take place, even with the particles of such bodies as air, sulphur, or lac ... (1612)

Here it is important to notice that on either possibility the conditions required for discharge can obtain only if the particles are constrained (and cannot move so as to discharge their tensions by contact) and if the space between them (or whatever occupies it) has some insulating property.

The problem now facing Faraday is underlined by his conjecture that 'with regard to airs, one is almost led to expect a permanent difference of force ...' (1612). Yet in fluid dielectrics (especially in gases), we would expect the particles to move so as to discharge by convection and contact unless they are held in position in a manner

similar to the particles of solids and viscous fluids.[97] In short, Faraday has overlooked his own recent admission (1403) that the particles of a fluid dielectric will discharge by convection.

A second problem should also be noticed. Although Faraday had found the inductive capacity of all gases to be the same, he did succeed in showing that their abilities to prevent discharge differed (1385-89). The point at which the particles of each reach a maximum level of polar tension which is then released as an intermolecular discharge, proved to be characteristic of (though not definite for) each gas.[98] The results of Faraday's trials showed that the gases could be ordered as to their ability to prevent discharge, but did not support the view that there is a definite distance (and hence a definite level of molecular tension) at which each gas would become a conductor (1394-96).

These results posed the following problem: the fact that the conductivity or 'restraining ability' of gases varied while their inductive capacitances were all the same suggested that these two properties had to be distinguished. On the other hand, the characteristic nature of inductive capacitance of these same gases in the fluid state and the characteristic nature of their conductivity in the gaseous state suggested that the two properties were connected, or due to the same cause. Moreover, if all matter conducts as metals do

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97. In discussing the latter Faraday has introduced cohesive forces which, like those of the frozen electrolyte at (413), prevent the particles from moving, and may therefore oppose the action of an electrostatic force. Cf. (1572 ff., esp. (1575) and (1592).

98. Although this would appear to be a deduction from the theory, Faraday knew as early as 1834 that the relationship between potential difference, density, and the nature of the gas would vary (cf. Harris, 'On some Elementary Laws ...', op.cit., note 92, and (1363)). For Faraday's experiments see (1385 ff.) and ERE I, plate VIII, fig.127.

(444), then 'substances make but one series in this respect, and the various cases must come under one condition and law' (1336).[99]

As yet Faraday has no theory of the basis of the disposition to polarize, i.e. of why it is that the inductive capacitance and the resistance to discharge of a medium is characteristic; nor does he succeed in developing such a theory.[100]

2.3.3 Observation and interpretation: the role of the lines of force

Faraday now turns to a detailed analysis of the phenomenon of spark and brush discharge in gases, using Wheatstone's techniques. The significance of these researches lies in the way that Faraday uses the concept of lines of induction in interpreting these phenomena. Faraday believed that the brush discharge provided direct perceptual evidence of the existence and the lawlike behaviour of the lines of force.[101] I will now show that Faraday's use of the concept of lines of force is governed by his postulates of polarity (induction) and conservation, and that these postulates are imported into his interpretation of phenomena through his use of the concept of lines of induction.

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99. Faraday may well have been seeking evidence for an hypothesis such as Boscovich's, to the effect that properties such as conductivity are determined according to a force-law having a number of equilibrium-points or 'singular-points', as Babbage called them (The Ninth Bridgewater Treatise (2nd ed. 1838): 100 and 179 ff.; cf. Herschel, Preliminary Discourse, articles 90-91). Williams's thesis that Faraday uses Boscovich's theory is tenable, provided it is recognized that the hypothesis in question played a role secondary to that of the assumptions which I have identified as principles or postulates. See section 2.6, 3.1.3.1.

100. However, see section 3.2.1.2 and ERE III: 451, where the finite rate of propagation of certain actions is attributed to inertial behaviours of the lines of force.

101. His experiments on the curvature of the lines had not provided direct evidence of the sort that he believes that he now has. Cf. section 2.2.2.

Faraday first describes Wheatstone's method of observing the brush:

> If the eye be passed rapidly, not by a motion of the head, but of the eyeball itself, across the direction of the brush ... the general brush will be resolved into a number of individual brushes, standing in a row upon the line which the eye passed over ... (1427)

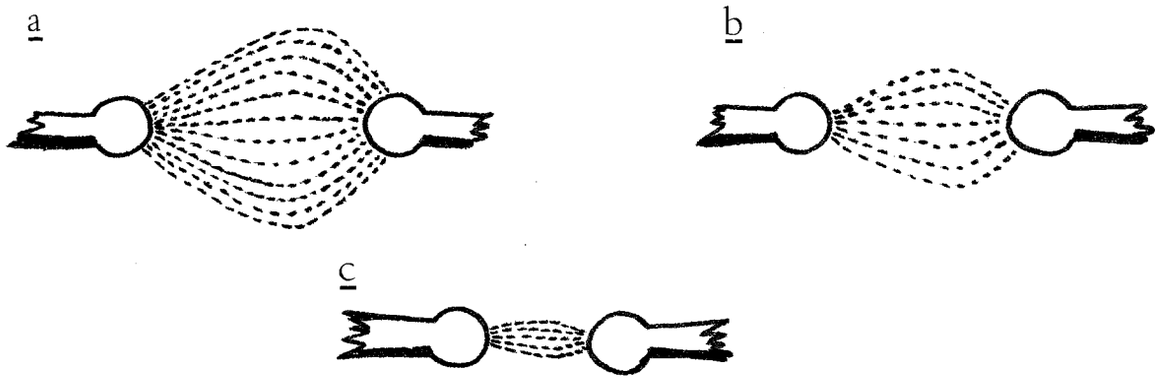
This much can be seen directly. Faraday takes each 'elementary brush' or filament to be 'the result of a single discharge, ... the space between them representing both the time during which the eye was passing over that space, and that which elapsed between one discharge and another' (1427). In this way it can be seen that the apparently continuous glow is in fact a structure of filaments each of which is 'instantaneous in its existence' (1428). Moreover, the sound produced varies in pitch as the interval (and hence the potential difference) is varied. This can be attributed to the 'recurrence of the noise of each separate discharge', an increase in pitch showing that 'we have increased the induction (1374), and by that means increased the rapidity of the alternations of charge and discharge' (1431).

Faraday also knew that a brush could be reduced to a single spark simply by bringing a grounded insulator near to the source of the brush. He regarded the brush as a diffuse and inefficient form of spark discharge ('a spark to air; a diffusion of electric force to matter' (1447)) in which the inductive power of the air both resists the discharge of the forces on the conductor and ensures that they are balanced by an opposed action (1443,1447). The spark, on the other hand, discharges 'the whole of the electricity' which has accumulated on a conductor (1448).

The brush can be transformed into a spark by decreasing the interval (increasing the inductive tension). As this happens there is a change both in <u>the form of the filaments</u> and in the <u>rate at which</u>

electricity is conducted across the dielectric (1448-49); figure 2.8.

FIGURE 2.8



The transition from the brush (fig. 2.8a) to the spark (2.8c) was of considerable importance because it provided a physical illustration of a relationship between severable variables: the form or curvature of the lines of induction (along which Faraday supposes the visible discharges to occur), the reactive capacity of the dielectric (insulation), and the tendency of the lines to contract or assume a less curved form at the moment of discharge (conduction). Insulation or reaction seemed to involve a bulging and lateral tension of the lines of action (2.8a) while conduction involved a collapse of the lines and a decrease in the lateral action (2.8c).

The importance of Wheatstone's technique (which was certainly known to Faraday by 1834) is that with it Faraday could have seen that the brush is a recurrent, apparently vibratory succession of inductive tensions and discharges. He could also have observed the relationship between induction (reaction) and the lateral action of the lines which had been introduced in the eleventh series (1224, 1231). This analysis of the brush may well have contributed directly to Faraday's development of a theory based upon curved lines of induction through a molecular dielectric, in which conduction (discharge)

involves a rapid succession of inductive tensions and intermolecular discharges.[102]

This phenomenon[103] was as important to Faraday as the use of iron filings had been to his original description of magnetic induction in terms of the lines or curves of magnetic force. The fact that the brush could be seen to be a series of lines whose form depended both on the distribution of matter and upon the inductive tension (or rate of conduction) would have suggested that the total insulating or reacting power of the dielectric is distributed partly as direct (inductive) action and partly as lateral (possibly magnetic) action, and that this distribution would vary throughout the dielectric:

> How beautifully does the curvature of the ramifications [filaments] illustrate the curved form of the lines of inductive force existing previous to [each] discharge! for the former are consequences of the latter, and take their course, in each discharge, where the previous inductive tension had been raised to the proper degree (1449).

The analogy between these lines or filaments and those formed by iron filings in a magnetic field turns upon the assumption that the 'visible effects in both cases [are] the consequences of the action of the forces in the places where the effects appear' (1449).

It is probable that Faraday's molecular theory was devised with this particular phenomenon in mind, especially so when it is realized that this is an instance of the conversion of electricity from its static state into its dynamical state--a process which Faraday had been unable to explain in March of 1834. Thus he announces that the phenomena

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102. This would not have been Wheatstone's first important contribution to Faraday's ideas. See Williams, Michael Faraday: 177-79.

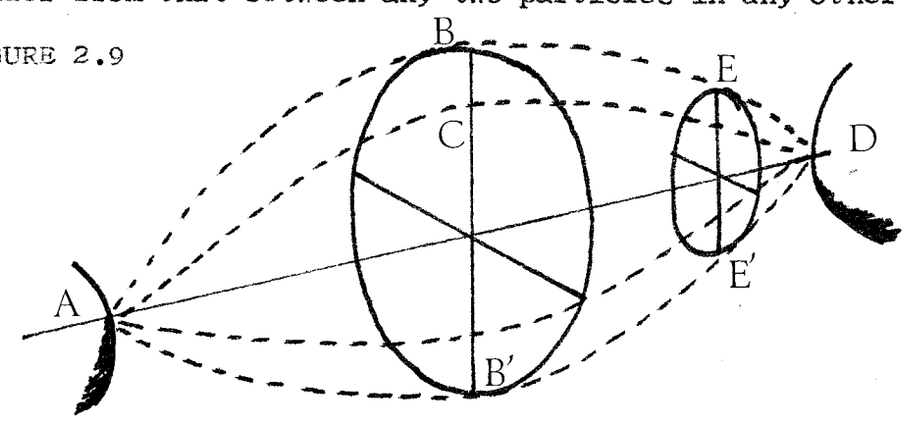
103. See ERE I, plate VIII, esp. figs. 117,119,120,121,122.

> constitute additional and powerful testimony ... in favour both of induction through dielectrics in curved lines (1231), and of the lateral relation of these lines, by an effect equivalent to a repulsion producing divergence, or ... the bulging form (1449).

The bulging or lateral expansion is seen by Faraday as evidence of a conversion of the inductive action into lateral (magnetic) action. The greater the lateral action (bulging), the less efficient the brush is as a discharge process; conversely, as the lines coalesce into a spark conduction increases (1447-49).

This provided the key to the solution of a problem posed by the facts that discharge initially occurred at one point in the dielectric and that the filaments are curved, and the assumption that all the particles of a uniform dielectric will have the same maximum polarizability or 'overturning' point (1361,1369). The action along any line should be the same as that along any other line, yet the curvature of the lines required that greatly curved lines incorporate a larger number of particles than would a straighter line. Thus if each line really does represent the same resisting or sustaining power (as a portion of the total 'action' sustained by the dielectric) then the actual tension between particles in any line ABD (figure 2.9) will differ from that between any two particles in any other line

FIGURE 2.9



ACD in a given section perpendicular to the lines (provided the two are not equidistant from the axis AD). The fact that discharge appeared to be confined initially to a small region ofthe dielectric

could be reconciled with the hypothesis that there is a characteristic maximum polarizability throughout the dielectric, and with the principle that opposed polar forces will be equal between any two points of the surfaces connected by any line (however long or short that line is), by supposing that the sum of all forces in any section is a constant (for given conditions) throughout the dielectric:

> The idea is, that in any section taken through the dielectric across the lines of inductive force, and including all of them [as section BB'] would be equal, in the sum of the forces, to the sum of the forces in any other section [EE']; and that, therefore, the whole amount of tension for each such section would be the same ... (1369)

Although the inductive tension along the lines will be greater in the region of the plane EE', the lateral (magnetic) action will be greater in the region of the plane BB'. Faraday believed that this lateral action would be the source of the magnetic field of the current produced as the lines collapse into the axis AD during discharge (1410-11,1634,1733-34).[104]

Faraday was aware that his interpretation of the form and behaviour of the lines of discharge would seem opaque to those who did not share his conception of the electric and magnetic forces as inter-convertible forms or directions of a single power. This is clear from his comments on an attempt to show that the lines of inductive action which exist prior to and in the same places as the luminous discharge filaments (1449) really do exhibit lateral effects (1412). Although he expected to find that two simultaneous sparks would actually unite before reaching the terminal conductor, he was unable to 'obtain sparks which ... conjoined into one spark before they

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104. This marks a significant step towards the later model of his electric and magnetic wave, on which there is a rapid succession of inductive (axial) tensions, magnetic (lateral) tensions, and discharges during which the lateral action becomes the magnetic field of the discharge current. Cf. series 23 (2700-01) and (3265-68,3270,3338).

reached ... the ball ...' (1416). However, 'though I think I saw a tendency in the sparks to unite, I cannot assert it as a fact' (1416, my italics).

Strictly speaking one cannot see a tendency, although given certain expectations about the nature of a process one might interpret the convergence or divergence of lines of discharge as evidence that these lines tend to attract each other during discharge (whereas they had been repelling each other just prior to discharge). That Faraday was aware that such 'tendencies' would not be seen by those who did not share his expectations is evident from a later comment on these experiments:

> The running together or coalescence of different lines of discharge (1412) is very beautifully shown in the brush in air. This point may present a little difficulty to those who are not accustomed to see in every discharge an equal exertion of power in opposite directions ... (1453)

The alternative interpretation (of those who believed the spark to be nothing other than the passage of surplus electric fluid through the air) would be that the brush is 'a breaking forth in different directions of the original force, rather than a tendency to convergence and union in one line of passage' (1453). Faraday was evidently aware that the initial interpretation of a process or effect will be governed by one's expectations about what is or what ought to be taking place.

Faraday believes that the divergence of the filaments of a brush discharging into air (1447), the bulging of the lines of discharge between two conductors (1448-49), and the fact that this divergence decreases as the rate of conduction increases (1448) are evidence for the view that the total quantity of action sustained by the dielectric consists both in direct (electrostatic) and lateral (magnetic)

tension.[105]

Although the evidential relation of the phenomena to the theory may seem suspect because Faraday has relied upon a number of the assumptions of the theory in interpreting these effects as 'powerful testimony' for the theory, the phenomena do support his theory rather than the only well-developed alternative. As Faraday himself puts it:

> ... how unlike the appearances are to any which would be deduced from the theory which assumes inductive action to be action at a distance, in straight lines only; and charge, as being electricity retained upon the surface of conductors by the mere pressure of the atmosphere! (1450)

Faraday may not have realized that curvilinear lines of induction are not precluded on the mathematical theory of attractions,[106] but he would certainly have regarded that theory as being fundamentally wrong had he attached to the lines of that theory the significance that he attaches to his own lines of force.[107]

In adducing his original experiments on induction as proof of the impossibility of there being absolute charges (1175 ff.) Faraday had adopted a similar appeal to the fact that alternative or rival interpretations of the phenomena had been eliminated. As he also refers to the present case (and specifically, to the form of long brushes (1450)) as constituting a 'proof deducible from' the <u>form</u> of the discharge, it would appear that for Faraday an 'illustration'[108]

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105. For the argument behind this see section 2.4.1.

106. Hesse, <u>Forces and Fields</u>: 204 n.

107. <u>Viz</u>., that a straight line is a line of no action. As indicated in figure 2.9, the lines represent a quantity of action consisting of electrostatic and magnetic tensions and pressures as well as those due to cohesive and other molecular forces (1404-05).

108. --i.e., an exact correlation or correspondence between the characteristic appearance of effects as <u>perceived</u> and of those effects as <u>deduced</u> from some theory.

becomes a 'proof' if it can be explained by or 'deduced from' only one theory.

Faraday's remarks are interesting in the light of the fact that the 'illustrations' he has used so far[109] have involved (1) showing that a medium undergoing action of some kind can be seen to be organized; (2) assuming that this organization (which is observed as a system or structure of lines) is produced by an action or set of actions existing 'in the places where [their] effects appear' (1449);[110] and (3) an argument to the effect that this organization cannot be explained on the accepted theory of electrostatics (1215,1450).

Faraday's lines of force have a dual status. They are seen to exist and to have certain definite behaviours: Faraday observes that there is a definite relationship between the form and distribution of the lines of induction and the distribution of charged matter (as in the case of the brush discharge, fig.2.8), or he observes that there is a similar relationship between the form of the lines andthe distribution of magnetic poles and currents (as shown by changes in the distribution of iron filings). That there are such lines of action is an inference drawn from observation of such phenomena. The lines are then endowed (implicitly rather than by definition) with those properties that Faraday's postulates require that force or

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109. Illustrations used so far in the Researches include the action of magnetic forces on iron filings and that of static induction upon silk filaments (1350). Although the Chliadni figures are not mentioned in the Researches in Electricity they were probably of equal importance in this respect, cf. 'On a Peculiar Class of Acoustical Figures; and on certain Forms assumed by groups of particles upon vibrating elastic Surfaces' (May 1831), ERCP: 314, at p.318, 357-38.

110. Whereas Faraday's experiments on the curvature of lines of induction did not produce evidence for the existence of lines, his analysis of the brush discharge does produce evidence analogous to that provided by the use of iron filings in a magnetic field.

action have.[111]

This provides an interpretative device which can then be used to interpret experiments which yield only sets of data, such as those on static induction (1224,1231). In this second role the lines have the status of theoretical entities. They are used in the interpretation of those processes or effects where the existence of lines of action cannot actually be illustrated.[112] With them Faraday interprets data about the intensity and direction of an action at different points in the region of charges as if there were a definite relation of the kind observed in the case of the brush discharge and other 'illustrative' experiments. In this way he is able to adduce observable processes and sets of data both as evidence for his own theory and as evidence against the rival theory of electrostatics.

2.4 Postulate versus Observation: the case of magnetic induction

The extent of Faraday's reliance on the postulates of the polar nature and of the fundamental identity of forms of force is clearly revealed in his response to the failure of his attempts to find a magnetic inductive capacitance (a property analogous to that of dielectrics). Faraday denies that the experiments can have provided evidence against a theory on which inductive capacitance is a susceptibility to both electric and magnetic action, and appeals directly to the

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111. --namely, polarity, indestructibility (except through conversion into an equivalent quantity of some other form of action), and causal efficacy. Any model of the dielectric which incorporates the lines of force will conform to the principles of induction and conservation because the lines guarantee that the constituents of that model (particles, powers, force) obey the same laws that Faraday takes to govern real processes.

112. The most important instances being Faraday's interpretation of his experiments on static induction as proving both a 'lateral tension' of the lines and the impossibility of creating an absolute charge (1169 ff.,1215 ff.)).

principles underlying the heuristic and analogical considerations which had led him to make the experiments in the first place. Implicit in Faraday's rejection of these experiments is the view that to treat them as providing counterevidence would be to interpret them in a manner inconsistent with the principles of induction (polarity), unity, and conservation.[113]

2.4.1 The nature of magnetic force: towards a unified theory

By the end of 1837 Faraday believed that he could develop a unified theory of chemical, electrical, and magnetic powers. His experiments on the resistance of gases to discharge had led him to believe that the actual path followed by a spark is a line of particles in a condition identical to those of a metallic conductor and analogous to that of the particles of an electrolyte.[114] Close observation of the brush and spark discharges had convinced him that static electric induction is accompanied by a lateral repulsion of the lines, this action being transformed into the field as the static state of the electric force gives way to the progressive or dynamical state during discharge.[115] Further, the fact that the discharge point for each

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113. See section 2.4.3. This view is subsequently vindicated with Faraday's discovery (in 1845) of diamagnetism and of the rotation of the plane of polarization of light. See series 19 and 20, and infra, section 3.1.2. Those discoveries confirm the principles themselves rather than the molecular theory as advanced in 1838.

114. Along this line the inductive relations (i.e. the particles) cannot be further polarized and therefore can offer no additional resistance to the formation of a current (1407-09,1326-31). Cf. sections 2.3.2-2.3.3.

115. Faraday supposes that at the moment of discharge the axial and lateral forces (which may include molecular or cohesive actions (1410,1563-1600)) would be 'thrown into' the line or axis of discharge, while the 'lateral effect, equivalent to a repulsion ... would be relieved and, perhaps, followed by a ... collapse or attraction of' the lines (1411). As suggested earlier (p. 38) Faraday envisaged the current itself as an alternating series of static and dynamical states of both the magnetic and the electric powers. See (1224,1231,1304,1262-65,1373,1449); infra, pp. 171-73, and sections 2.5.3.1 and 3.2.1.

gas is definite (or nearly so)[116] suggested a link with the definite nature of electrochemical action.[117]

It appeared to Faraday that the various forms of discharge could be explained on a theory which would incorporate magnetic action as a quantitatively definite part of the action built up as intermolecular tension. Here it is important to realize that Faraday was looking for the lateral action not only as the static analogue to electrostatic tension but as an equivalent (1686) or definite quantity of action. While considerations of the unity and identity of the various forms of action are evidently at work, Faraday is seeking a theory on which the magnetic field of the current can be shown to be a converted (dynamical) form of a prior quantity of static magnetic action--just as he had shown in the seventh and eighth series that the dynamical or progressive form of the electric force (the voltaic current) is an equivalent quantity of that force in its static state (the affinities of the chemical elements).[118]

This reasoning leads Faraday to a conclusion that he regards as necessary rather than merely plausible: the static state of the electric force must have a static magnetic component, just as the dynamical state (the current) has a magnetic field--otherwise that field would arise out of nothing. By February of 1838 Faraday had become convinced that

> as the lines of discharge are associated with a certain transverse effect so it appeared to me impossible but that the lines of tension or of inductive action, which of necessity preceded that discharge, should also have their correspondent transverse condition or effect ... (1658, my italics)

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116. Cf. (1385-96) and supra, section 2.3.2.

117. Both the law of electrolysis andthe fact that there is a characteristic minimum intensity required of a current (before it will decompose a solution) are important here. Cf. (1354,1410).

118. See supra, sections 1.3.3 and 1.3.4.1, esp. pp.72-75.

Analogical considerations could have suggested the possibility that there is a lateral action of the lines and that this is magnetic in nature; a possibility which would have been supported by Faraday's observation of the behaviour of the lines of discharge in the brush.[119] These considerations would suggest that the absence of a lateral action (or one which is not magnetic) is an improbability, but they alone could not support Faraday's claim that the absence of a lateral magnetic action is an impossibility. The importance of this point is underlined by the fact that Faraday had already made experiments which did not support this contention (1662) and is to repeat it even after another unsuccessful attempt to demonstrate the identity of electric and magnetic actions within dielectrics.

In its final form the argument[120] involves an analogical inference from the existence of three states or conditions of the electric force to three corresponding states of the magnetic force (1731-35). This argument is set out in table 2.1. The important point about this argument is that it is based upon the principles of unity, induction, and conservation. Although analogical and heuristic considerations have led Faraday to search for lateral actions of sparks and of lines of induction and to make the experiments on magnetic inductive capacity,[121] it is to the principles supporting these inferences that he appeals when the experiments fail to confirm one of their main conclusions. The argument states that the three states of the electrical force will be matched by the magnetic actions shown under the column

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119. See supra, p. 160 and figure 2.8.

120. The argument is presented as such only after the report of the unsuccessful experiments (1731-35). I have reconstructed it on the basis of comments made in series 12, 13, and 14; specifically: (1406-12,1572-1600,1603-05,1617-34,1653-65,1686,1709-35).

121. See section 2.4.2.

TABLE 2.1

State of the electric force	Corresponding state of the lateral or magnetic force		Observational status of magnetic force
	(Theory A)	(Theory B)	
1. Normal or 'quiescent'	none	normal or 'quiescent'	none[122]
2. Static or inductive	none expected	radial expected	doubtful[123]
3. Dynamical or progressive	radial + couple	circumferential or tangential	observed as circumferential

headed 'Theory B' (rather than those under 'Theory A'). Theory A is an Ampèrian or Weberian theory on which all interactions are resolved into central forces, on which no magnetostatic analogue to the electrostatic force should exist, and on which the normal or 'undeveloped' state of the force would not be treated as a physical state of the force.[124]

According to Faraday 'the state of no lateral action is to static or inductive force the equivalent of magnetism to current force' only

122. This 'normal' or 'undeveloped' state of the force corresponds to the normal or 'quiescent' state of the chemical affinities. If Faraday does regard this as a real state of the force (in which the lines are straight, representing a field of no action), then he has adopted a field theory of the dielectric on which the active state of particles arises out of a permanently subsisting but 'undeveloped' state, although the latter would never be detected as such (cf. supra, section 2.2.2).

123. Faraday has not actually observed lateral actions of the lines of induction or discharge--certainly the evidence for their existence is far weaker than that for the existence of the lines of induction: I have called this action 'radial' to distinguish it from the only observed lateral action, which is circumferential. Faraday believed that the action which Ampère had taken to be radial could provide a precedent for his own view. Cf. series 9 (1113), 13 (1603), and 14 (1659).

124. --i.e., it could not be made use of in an argument of this type. See note 122.

if it is assumed that 'electric and magnetic action are in their nature essentially different' (1734). If, as Faraday believes (theory B), 'they are the same power' and if 'the whole difference in the results is the consequence of the difference in direction' (1734, cf. 1114), then the three states of the two actions will be as shown because

> the state of static induction which is between the normal condition and the current will still require a corresponding lateral condition in the magnetic series, presenting its own peculiar [characteristic] phenomena ... (1734)

Taken together, the presumed identity of the two actions, Faraday's literal interpretation of the action of a current as a circumferential action,[125] and the belief that neither the static nor the dynamical (lateral-circumferential) actions can arise directly out of nothing require that some lateral-radial action accompanies electrostatic induction:

> it can hardly be supposed that the normal electric, and the inductive or polarized electric condition, can both have the same lateral relation (1734, my italics).

Given Faraday's convictions about the identity and convertibility of electricity and magnetism as two forms of a single power, the inference just described must have seemed plausible enough, particularly in the light of his belief in the vibratory nature of electric and magnetic forces in (what he took to be) their dynamical states.[126]

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125. Cf. supra, pp. 21-23 and Faraday to G. de la Rive, 12 September, 1821, Corr. I: 122, esp. pp.123-24.

126. The earliest reference to a vibratory theory of the transmission of force which Faraday is known to have read is in James Tytler's article 'Electricity' in the 3rd edn. of the Encyclopaedia Britannica (18 vols., Edinburgh, 1797), 6: 440-567. Faraday had suggested that magnetic and electrical actions would both be transmitted as waves (analogous to those of sound and of light) in his sealed note of 1832 (reproduced in Williams, Michael Faraday: 181). Wherever he refers to the nature of the current he has included the possibility that it is a vibration (as at (283)). Cf. Agassi, Faraday: 32. The importance of the analogy with the transmission of light is discussed infra, section 3.2.

Evidently the heuristic potential of the theory provided a strong reason for Faraday's developing the argument just described. As Ampère had shown, similar currents attract while currents passing in opposite direction repel each other. If the lateral action of the lines of static induction should prove to be the static equivalent of the magnetic action of currents, Faraday would be a step closer to solving the problem that had confronted him in March of 1834--that of obtaining a 'clear view' of the transition of electric force from its static to its dynamic state,[127] but this time with respect to magnetic rather than chemical effects.

This leads immediately to a second objective, that of proving experimentally that different forms of discharge will always produce the same quantity of magnetic action. While Faraday had succeeded in showing that for some forms of discharge 'the amount of lateral or magnetic force is very constant',[128] he has not been able to show that 'the same amount of current will in its <u>different forms</u> produce the same amount of transverse action' (1665). This problem can be solved if some concomitant effect can be used as a measure of those forces which combine to form the state of tension or opposition which leads to discharge.[129]

Faraday also believed the lateral action to be missing 'link in the chain of effects' which connect a primary current with the induced (secondary) current. His examination of self-induction in October and November of 1834 had left him convinced that there was some 'as yet unrecognized' state or condition of the magnetic force (1114). Now, in 1838, he is still convinced that such a 'connecting

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127. <u>Loc.cit.</u>, <u>supra</u>, p. 75.

128. See series 2, 3, and 4 (216,366-68,376).

129. Cf. (1623,1634-52) and <u>infra</u>, section 2.4.3.

link in the series of effects' should be found (1660-62,1650).

Behind this reasoning lies Faraday's belief that magnetic action will be inductive or polar in the same way that electrostatic action had been shown to be. The magnetic force in both its static and dynamic states should be universal in its action, i.e. all matter should be as susceptible to magnetic action as it is to electrostatic action. Faraday is arguing, in effect, that magnetic action should produce the same state of tension that electrostatic action does--the electrotonic state (1661,1662).[130] Magnetic action should be transmitted as an action of contiguous particles, rather than as a 'higher quality and condition' (1663) of or within the dielectric:

> The transverse power has a character of polarity impressed upon it. In the simplest forms it appears as attraction or repulsion, according as the currents are in the same or different directions: in the current and the magnets it takes up the condition of tangential forces; and in magnets and their particles produces poles (1665).

His experiments on electrostatic actions have shown that electrical powers 'show effects at a distance only by means of the polarized contiguous and intervening particles'. It is to be expected that 'all polar forces act in the same general manner' because

> it is apparently of the nature of polar forces that [they act by contiguous particles], for the one force either finds or developes the contrary force near to it, and has, therefore, no occasion to seek for it at a distance (1665).

A polar force must act progressively or locally. It may act to a distance only indirectly, by polarizing the particles between the points at which it originates and terminates.[131]

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130. This had been stated originally in series 1 (1-4,73).

131. As pointed out earlier (section 2.2.1), polarity--as Faraday understood it--entails only that action be local. Thus he explains that in a vacuum a central particle will act directly on those forming the inner surface of the bounding sphere if there are no particles between it and the surface, but indirectly if the vacuum is not perfect (1616). For further discussion, cf. infra, section 2.6, p. 204.

Do both magnetic and electrostatic induction produce the polarized, 'peculiar', or 'electrotonic' state in all matter? If the dielectric can absorb or intercept some part of magnetic action in the same way that it has been shown to absorb a portion of the electrostatic inductive action then a long-standing problem could be solved: the facts that a magnetic field produces no detectable effect on a stationary conductor and that a secondary current differs in duration (and quantity) from the primary which causes it[132] can be explained on the assumption that this action is absorbed as a lateral and static relation of the lines of induction. It would be nothing other than the lateral or transverse component of the electrostatic action, absorbed by the dielectric as polar tension and observed through the bulging or lateral dilation it causes in the lines of static induction (1304,1362,1369-75,1449).

The extent of the rationale of Faraday's supposition that there is a lateral (static) action of the lines of induction and that it is magnetic in nature is now evident. It involves the postulate of the unity of force, the postulate that a force which acts inductively at sensible distances will do so at insensible distances, and the obvious appeal of the possibility that in this way a unified theory could be established.

2.4.2 The experiments and their interpretation

On this theory each of the two forms of force would be convertible, partially or wholly, into the other.[133] Convertibility implies the

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132. Cf. sections 1.3.1.1 (p. 26 ff.) and 3.4.2 (pp.85-86).

133. --as Faraday had supposed at (1114). This particular conclusion is restated after Faraday's discovery of diamagnetic action. See series 19 (2222-23) and infra, section 3.1.

identity of the two interconvertible forms of the force,[134] and identity requires that both forms of the force obey the same principles of action (1665,1731-34). The magnetic force should not be 'some higher quality and condition' of the particles of the dielectric, 'acting at a distance' and having, 'like the force of gravity, no relation to' the particles (1663).

In view of the fact that Faraday had first made this claim about magnetic action at a time when he did not believe it to be true of electrostatic action,[135] it is ironical that the experiments he now describes do not at all support the view that magnetic action is a progressive, polarizing action of contiguous particles.

In the thirteenth series of February 1838, Faraday explained that the 'feeling of the necessity of some lateral connexion between the lines of electric force' had led him to 'make many experiments' in which dielectrics of varying inductive capacity had been introduced between a magnet or a coil and a secondary circuit (1662). These experiments had not produced the expected effect upon the inductive action of the magnetic field. By June of 1838 Faraday has determined that dielectrics do not reduce the quantity of action passing between a magnet or coil and a circuit.

He places two coils provided with soft-iron cores along an axis. The coils are wired in series with a galvanometer (1711) so that currents can be induced in the coils (shown as A and B in figure 2.10) by the periodic motion of a magnet (C). Faraday then interposes various materials (both conductors and insulators) between the magnet

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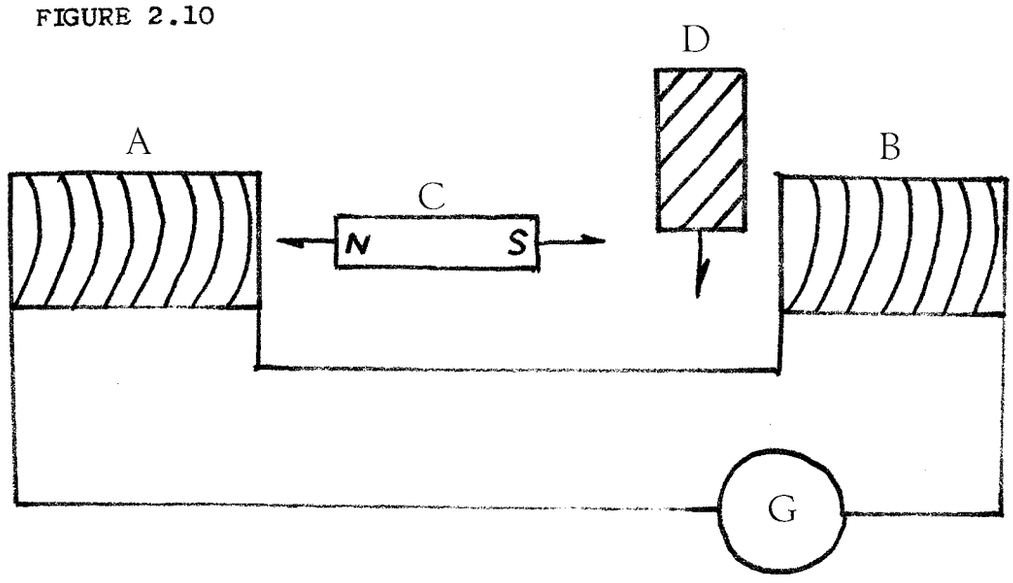
134. Cf. (910,917,1031) and supra, p.67 ff.

135. 'All the results favour the notion that the electro-tonic state relates to the particles, and not to the mass, of the ... substance under induction, being in that respect different to the induction exerted by electricity of tension' (73, my italics).

FIGURE 2.10



and one of the iron cores (1712). If the medium (D) does intercept or react upon the magnetic action of the magnet then the currents induced in A and B will be unequal and the galvanometer needle will be deflected less in one direction than in the other. However, 'not the least effect was observed on the needle', nor did the electrical conductivity of the medium seem to have any bearing on this result (1713).

Faraday believes that electrostatic induction must precede the formation of the induced current. If this static state does involve a lateral repulsion which is magnetic, then the dielectric should be susceptible to magnetic action.[136] Yet the experiments show that, 'judging by the amount of effect produced at a distance by forces transverse to the electric current' the intervening matter,

> and therefore the intervening particles, have nothing to do with the phenomena; ... though the inductive force of static electricity is transmitted to a distance by the action of the intermediate particles ... the transverse inductive force of currents ... is not transmitted ... in a similar way (1726).

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136. The expected effect was produced with only one material: soft-iron (1714). This demonstrated the 'perfection of the general arrangement' and so confirmed the absence of any effect in other materials. Faraday devised a more sensitive test (1720-25), but even using a coil in place of the magnet, no deflection occurred.

Having drawn this conclusion from his experiments, Faraday now asserts that it cannot be accepted:

> It is ... very evident that such a conclusion cannot be considered as proved (1727).

Faraday believes these results to be dubious because they are not compatible with the principles upon which the theory of the dielectric has been based.

If the principles are to stand, then the experimental results are in contradiction with each other. When copper is introduced between the magnet or coil (C) and one of the outer coils (A), 'we know that its particles are affected' because (as Arago had shown) currents are induced in the copper.[137] Yet it seemed 'impossible to consider this effect on the particles of the intervening matter as independent of that produced by the inductric coil or magnet C, on the inducteous coil or core A ...' (1727). How can the inductive action of (C) produce the same effect on both (A) and (B) when it is also inducing (or tending to induce) currents in the intervening medium (D)? The medium (D) should reduce the effect of (C) upon (A). The only alternative is to suppose that the action of (C) is not definite or 'limited'.[138]

As with each of his appeals to the principle that cause must equal effect, Faraday states his objection to the most obvious interpretation of these experiments in terms of the principle of equality of action and reaction:

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137. Cf. series 1 (81-139) and supra, p.29.

138. Thus it would differ both from chemical action and from electrical action (366,376-77,505). In 1852 Faraday states that the 'limited and definite' action of a force is one criterion of its being an action at a distance. Cf. (3255) and infra, section 4.2.1. Inductive action is identified as 'limited and exclusive' at (1681).

> Since the inducteous body [A] is equally affected by the inductric body [C] whether these intervening and affected particles of copper are present or not ... such a supposition would imply that the particles so affected had no reaction back on the original inductric forces (1727, my italics).

Nor does Faraday want to admit that the action of (C) on (A) is distinct from its action on the medium (D). He prefers to advance an ad hoc hypothesis to the effect that the particles of (D) are 'efficient in continuing the action onwards ... producing the effect of no loss of induced power' at (A).[139]

Faraday advances this hypothesis as 'the more reasonable conclusion' (1727). It is reasonable in that it is consistent with his belief that 'there must be a particular condition [of the medium (D)] corresponding to the state which causes currents in metals and other conductors ...' (1728,1733). Yet Faraday has never succeeded in demonstrating the existence of such a state (60,242,1114,1661-62). His confidence in his principles is such that he is prepared to set aside the results of the best experiments that he has been able to make, and to posit the ever-elusive electrotonic state in support of the very conclusion that these experiments have failed to prove:

> It appears to me possible ... and even probable, that magnetic action may be communicated to a distance by the action of the intervening particles, in a manner [similar] to the way in which the inductive forces of static electricity are transferred to a distance ... the intervening particles assuming ... a peculiar condition which ... I have several times expressed by the term electrotonic state ... (1729)[140]

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139. Faraday apparently did not notice that this simply raises the same problem again, for the medium (D) is now supposed to react upon the force of (C) yet still transmit the whole of the action of (C) on to (A).

140. For the development of this idea see sections 4.2, 4.3. Of Faraday's insistence on the existence of this state Maxwell wrote in 1855 that 'the conjecture of a philosopher so familiar with nature may sometimes be more pregnant with truth than the best established experimental law discovered by empirical

.../

2.4.3 Polarity, Induction, and Conservation

I suggested in an earlier section that a principle of conservation was implicit as a premise of Faraday's argument that matter should exhibit a property or action analogous to electrostatic inductive capacitance in the presence of a magnetic force.[141] The idea that force is not created or destroyed would appear to underly Faraday's contention that the circumferential condition of the magnetic force could not arise directly out of the normal or undeveloped state[142] and that both the normal and static or 'polarized' states of the electric force cannot have the same lateral action (i.e. none).[143] It is also apparent that Faraday takes the normal or 'undeveloped' state to be a real state of the force, out of which the active states (2 and 3) develop.[144]

Behind this view is the idea that the 'mutual relations' between particles are definite quantities of possible or of potential action, quantities which are indestructible and uncreatable.[145] This view

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enquirers, and though not bound to admit it as a physical truth, we may accept it as a new idea by which our mathematical conceptions may be rendered clearer' ('On Faraday's Lines of Force', Scientific Papers 1: 155, at p.187). On Maxwell's mechanical theory of the field an electromotive force is simply the concomitant of the rate of change of the angular momentum of molecular vortices having inertial mass. Cf. 'On Physical Lines of Force', Scientific Papers 1: 451, at pp.477 ff., and 'A Dynamical Theory of the Electromagnetic Field', ibid., at pp.537 ff.

141. Cf. section 2.4, pp. 168 ff.

142. --i.e., that state 3 cannot arise out of state 1 (supra, pp.171-73, table 2.1).

143. Loc.cit., supra, p. 173.

144. This is certainly a premise of his final defence of the reality of the lines of force. See sections 4.1, 4.2, 4.3. For a discussion of this idea in connection with the proof of the law of electrolysis, see section 1.3.2.2 (esp. p. 47 ff.), and 1.3.3.1 (pp.58-64).

145. In the ninth series Faraday had stated that the (induced) current is, 'as far as we can judge ... the electricity which before was quiescent in the wire; and ... we can easily recognize the two states' (1110, my italics).

has emerged only gradually in the published Researches and is barely distinguishable from the principles of the equality of action and reaction (cause and effect)[146] and of polarity,[147] but it differs from those principles in that it invokes the existence of force as a definite and indestructible quantity of something (action).

Views similar to Faraday's were widely held at this time.[148] Although this doctrine of the universal convertibility and indestructibility of the different forces or powers of matter falls short of being a doctrine of conservation of energy (because no standard for the comparison of the work done by different forces was available prior to 1843),[149] Faraday's work on electrolysis had led him to realize that the conversion process can be quantified (although he would not have chosen to adopt a standard unit of 'work' to effect this). In his fourteenth series Faraday shows that he is well aware of what is required for the enunciation and proof of a general doctrine of conservation:

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146. In 1839 Faraday bases his objections to the contact theory of the voltaic pile upon the principle that the conversion of force must be a conservative process, for if it is not then the equality of cause and effect would have to be denied (series 17, (2605 ff., esp. 2069-71). Faraday's first explicit reference to the 'principles of action and reaction' occurs in the context of his attempt to show that all the forces exerted by an electric eel must equal those exerted within it (series 15, (1772,1789-90)).

147. As remarked earlier (section 2.2) the conservation of charge follows from Faraday's principle of induction, where the equality of the two opposed 'forces' of anpolar relation entail the conservation of a quantity of action.

148. See, for example, P.M. Roget, 'Electricity', art. 113, op.cit., note 98 (supra, part I, p.65), and R. Mayer, 'Remarks on the forces of inorganic nature' (1842), trans. Phil.Mag. 24 (1862): 371.

149. T.S. Kuhn, 'Energy Conservation as an Example of Simultaneous Discovery', in M. Clagett, ed., Critical Problems in the History of Science, Madison (1959): 321. Cf. note 154.

> hereafter we may be able to compare corpuscular forces, as those of gravity, cohesion, electricity, and chemical affinity, and in some way or other from their effects deduce their relative equivalents; at present we are not able to do so, but there seems no reason to doubt that their electrical, which are ... their chemical forces ... will be by far the most energetic ... (1687, my italics)

Faraday's treatment of convective or carrying-discharge suggests that he was struggling towards but had not actually formulated a doctrine of the conservation of force. Faraday had realized in 1832 that the proof of the identity of the different forms of the current depended not merely on showing that electricity from a given source could be made to produce the same effects as electricity from some other source but also upon showing that the different currents all obey a law of definite action (265-67,361 ff.). To prove the identity of an ordinary conduction current or an electrolytical (voltaic) current and a convective discharge (in air) Faraday has to show that convection has the same definite quantitative character as the other forms of discharge.[150]

Faraday is now confronted with two aspects of a single problem: his theory has not been adequate to the task of dealing with the relationship between the forces present in the inductive (static) and dynamical (progressive) states of the electric force in both solid and fluid dielectrics. Convection occurs only in non-viscous or fluid dielectrics, in which part of the inductive or polarizing action produces the attraction or repulsion of the particles of the dielectric. Clearly the quantity of (inductive) action can no longer be identified with the degree of polar tension of the particles.[151]

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150. Faraday had shown in 1832 that 'travelling particles of air can effect chemical changes' (1623), cf. (461-69) and Williams, Michael Faraday: 221-23.

151. For Faraday's discussion of fluid dielectrics and of convection, see (1617-24,1632-34,1642-45,1703-08) and esp. (1575,1623).

The problem of explaining the relationship between polarizability and mobility is not solved by Faraday.[152] He is to deal with the second problem by appealing to first principles.

The current, as a cause, has a constant and definite effect throughout its course both 'on the bodies in which it exists ... [and] collaterally, as in inductive or magnetic phenomena' (1620). Proving the identity of electrolytical and convective processes involves proving that the force which makes the particles of a fluid dielectric 'travel for yards across a chamber' and 'produce strong winds ... so as to move machinery' is equivalent to that force 'by which a particle of hydrogen leaves one particle of oxygen to go to another' in an electrolyte (1622). The fact that the forces act over sensible distances in the former case and over insensible distances in the latter is unimportant: these are not 'essential differences' (1623).[153]

Yet it is evident that since the motion of particles has been introduced, the inductive tensions which precede the discharge must be convertible without loss into the discharge (including the motive or dynamical effects). Because he has no standard unit for the effect of an accelerative force Faraday cannot solve this problem. The best that he can do is to state that 'when the right limitations are applied, constant and definite [experimental] results will ... be obtained' (1626).[154]

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152. See infra, section 2.5.1.

153. In forging this analogy between conduction in air and in an electrolyte Faraday returns to a more mechanical conception of both processes. See section 2.5.2.

154. The 'right limitations' were arrived at by a number of scientists between 1840 and 1850. Cf. Kuhn, (op.cit., note 149); J.P. Joule, 'On the Calorific Effects of Magneto-Electricity, and on the Mechanical Value of Heat' (1843) in his Scientific Papers, London (1884): 123; 'On the Existence of an Equivalent Relation between Heat and the ordinary Forms of Mechanical Power', Phil. Mag. 27 (1845): 205.

Faraday bases his proof of the identity of convective and other forms of discharge upon his original model of the current, in which the principles of equality of action and reaction (and of cause and effect) are implicit. This was the view that the current is an 'axis of power having contrary forces, exactly equal in amount, in contrary directions' (517). Here the model is extended to include the lateral (magnetic) actions. Given the principle of induction (1162,1627-33), for every particle bearing (or being the 'localization' of) a certain quantity of charge and moving in one direction there must be an equivalent quantity moving in the other. Thus, the constancy of action (as one of the proofs of identity) must be sought in sections of the current (1634).

This is the basis of Faraday's earlier analysis of the dielectric into sections (1368-70, cf. 1703 ff.), in which each section contained or represented a definite quantity of action equal to that of every other section. The sum of all the sections (whatever the relative distributions of forces within each) can be taken as the volume enclosed by the lines of static or of magnetic induction and will be a constant quantity for given initial conditions. On this interpretation it is evident that the lines of induction must be curved if they are to represent a field capable of producing a sensible effect. Curvature is necessary because where the lines are straight there is no tension and therefore no action (potential).

This reasoning--and the principle of induction in particular--also underlies Faraday's proof that a charged body moving with respect to other charged bodies is equivalent to a current, when considered solely in terms of the effects it does or should produce on the latter (1642-45). In fact this is presented as a deduction from the principle of induction itself:

> as charge exists only by induction ... and a body when electrified is necessarily in relation to other bodies in the opposite state; so, if a ball be electrified positively in the middle of a room and be then moved in any direction, effects will be produced, as if a current in the same direction ... had existed ... (1644)

This 'startling result' supports Faraday's contention (which he has not been able to demonstrate experimentally) that a convection current will be identical in all respects to any other form of discharge (1642-45).[155]

My analysis of the development of Faraday's theory of induction and discharge supports the view that Faraday does treat force as a conserved quantity of action.[156] It also reveals that the idea of conservation emerges gradually from Faraday's attempts to explain electrical phenomena in terms of the principles of the equality of action and reaction (induction) and of the unity and convertibility of force. At this stage it operates as an implicit assumption rather than a higher-order principle like those of induction and unity.

Faraday does not begin to use the principle of conservation by that name until the early 1850s. This principle may have developed out of his work in two ways. Faraday may have taken the principle of equality of action (cause) and reaction (effect) as entailing

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155. Faraday's 'startling result' did not go unnoticed by W.R. Hamilton, who took the idea to be suggestive of an undulatory model of the transmission of force and of matter itself. In 1840 he wrote to Herschel that 'I like much the notion of motion of matter being perhaps a successive excitement of powers ... The definiteness and indeed existence of weights, corresponding to chemical and electro-chemical actions, seems to show that ponderable and imponderable agents must be more closely related in their essence than it is common to suppose ... And I have been struck by a remark of Faraday's which was somewhat to this effect, that the mechanical motion of an electrically excited body must be considered to produce, or be equivalent to, a current of electricity', R. Graves, ed., op.cit., note 136 (supra, part I, p.94), vol.2: 337-38. Cf. infra, section 3.2.

156. Cf. supra, section 2.4.1 and p.181 ff.

that conversion processes be conservative. Thus a force or power in one of its forms must produce an equal or equivalent effect. If the latter does not appear to be equivalent to the cause, then it must be supposed that the cause has been converted into or 'conserved' in some other form (e.g., molecular polarization (1362)).[157] Or Faraday may have assumed that the total quantity of action existing as intermolecular tension in the polarized dielectric (or electrolyte (950)) must be constant for a given system of charges or characteristic for a given chemical element. He would also have assumed that this quantity of tension or action is indestructible.[158] In either case it has been assumed that there is some indestructible quantity of action which is finite in its effects and which may be associated with (852) or localized as (1650) elementary particles of matter.

The atom or particle as a theoretical concept has not yet been displaced by that of a plenum of action in which atoms exist only figuratively as the points at which action is localized and between which forces act, yet Faraday is soon to argue for the abolition of the atom as a theoretical entity.[159]

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157. Faraday's interpretation of magnetic induction in series 1 and 9, and his interpretation of changes in the form of the lines of the brush discharge suggest that this was his view.

158. The proof of the law of electrolysis in the seventh series and the theory of electrolysis advanced in series 8 and 13 have been based upon the assumption that the quantity of action between two ions will not vary with distance (though the intensity evidently will).

159. The atom as a discrete entity is dispensed with on epistemological grounds in 1844, although Faraday never does succeed in dispensing with it as a theoretical concept. Cf. supra, pp.63-64 and infra, section 2.7.3 (p.224 ff.).

2.5 The Limitations of the Theory of Induction

By the spring of 1838 Faraday has developed a theory in which force, as a conserved quantity of action, may be converted from the static or inductive state into the dynamical or progressive state. The former state is that of the chemical affinities of the atoms of matter and of electrostatic induction between molecules and larger masses. The latter state constitutes the progressive actions of the current, including the production of magnetism, heat, light, and the motions of particles and masses. Faraday has identified the intensity acquired by the inductive state with the polarizability of a particle or system of particles, a characteristic property which he has called specific inductive capacitance. The quantity of action represented by this state is independent of the distance between two particles or masses (being determined by the number of lines of induction joining any pair of particles), and has a characteristic maximum for each material. Faraday has identified this as the 'conservative' or 'restraining' power of a dielectric. It marks the point at which a given material will permit the conversion of force in its static state into force in its dynamical or progressive state.[160]

There are three main limitations inherent in this theory. First, the conditions under which force is transformed from its static into the dynamical state appear to be determined by some property of the elementary particles of matter, rather than of force or of the lines which represent it. This raises a question as to the status of the disposition to polarize. Is this an inherent property of particles as individual entities or is it a property of the inductive-relations of which the particles are merely the original and terminal points?

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160. Cf. (1164,1277,1292,1338,1354,1362-76,1398,1403-10,1611-12).

The fact that no answer has been provided to this question leads to two other problems. These concern the distinction between conduction and insulation and an implicit distinction between polarizability and electrostatic attraction and repulsion.

2.5.1 A problem about polarizability

Faraday has introduced two distinctions whose consequences do not seem to have been apparent to him. He has distinguished between inductive capacitance (which constitutes insulation) and the conservative or restraining power of a dielectric (which constitutes a measure of its conductivity). This distinction has been introduced and adhered to in Faraday's discussion of gases, and it is problematic only in the case of gaseous or fluid dielectrics. The second distinction is that although Faraday has tended to identify the inductive action of an electrostatic force (i.e. its polarizing action) with its attractive and repulsive action, he has tacitly introduced a distinction between the two in his discussion of gaseous and fluid dielectrics. These distinctions conceal two related problems:

(1) Faraday has stated that particles have a tendency to retain or return to a normal, 'quiescent', or unpolarized state (1303,1683). A force which tends to polarize a particle should therefore repel the particle, because the particle should move in that direction in which the inductive or polarizing action decreases most rapidly. Yet according to the laws of electrostatics, a particle upon which charge is being induced will tend to move towards the source of inductive action, i.e. in that direction in which the polarizing action increases most rapidly. Evidently the laws of attraction of charged bodies do not apply to Faraday's elementary particles.[161]

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161. Faraday's assumption (1303,1683) is compatible with the behaviour of similar charges. However the action of a charge on a neutral body would always be to induce a dissimilar state and to attract the latter.

(2) Faraday has identified charge with polar (molecular) tension, and has maintained throughout the Researches that the presence or existence of a force entails that there be a reaction to it. The polarizing of a particle is this reaction to inductive action. However, charge can be induced in or on a particle or mass only if that body is unable to move or if it tends (initially) to resist the action of an accelerative force. If the body were entirely unconstrained or had no inertial mass it would be attracted as soon as a finite charge (or degree of polarization) had been induced in it. It follows that if particles are to be polarized to the degree at which discharge (conduction) can take place then they must be constrained within the dielectric.[162]

If, as Faraday has assumed, the particles of gases are unconstrained, how can they be polarized sufficiently to produce discharge? And, if they tend to resist being polarized, how is it that they move into regions of greater inductive (polarizing) action (1594)?

These problems arise out of the fact that on the one hand Faraday has taken inductive action--the tendency of one element of a polar relation to 'seek' or to create an equal quantity of opposed action elsewhere--as what he himself calls a 'primary fact' (1740),[163] while on the other hand he has attributed the essential property of

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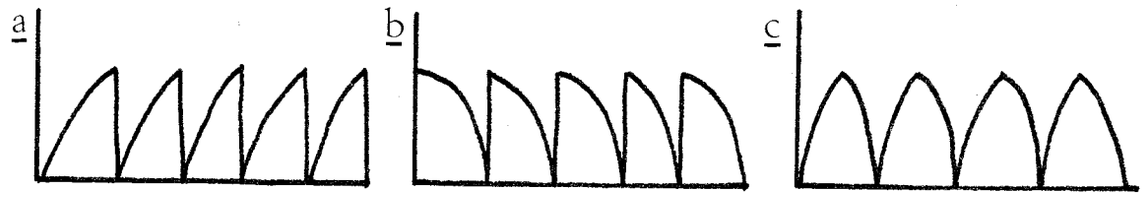
162. --otherwise that tension would be converted into kinetic and magnetic energy and all discharge would be convective. Constraints, in the form of cohesive or other 'mechanical' relations, are present in solid and viscous-fluid dielectrics (1573-1600).

163. This is a necessary property of polar or inductive actions and (as pointed out earlier, p. 107) it is prior to attractive and repulsive actions. Cf. (1,1162-63,1174-78,1443,1453,1615-16, 1628,1642-45,1665,1681,1739-40). If Faraday had taken the actual motions of charged bodies to be the primary fact he might not have been led to develop a theory on which the elementary particles will be repelled when they should be attracted.

polarizability to the particles of matter.[164] This is evident from the shortcomings of Faraday's attempt to reduce conduction and insulation to a single property of all matter.

In the thirteenth series Faraday had pointed out that the theory required that there be a 'limiting condition' between insulation (inductive capacitance) and conduction (discharge) at the molecular level. He had suggested that the communication of polar tensions could occur either as discharge across a perfectly insulating space, or as slow conduction or communication of these tensions between particles (which could occur at intensities much lower than those required for discharge).[165] These possibilities are shown in figure 2.11, where the vertical axis represents the intensity or potential, the horizontal axis the time, and the area under each curve the quantity of inductive action built up in any interval. If conduction occurs as a 'distinct act of discharge' between contiguous particles

FIGURE 2.11



(1333,1612) then it will appear as in fig. 2.11a, in which the build-up of tension takes time.[166] If conduction occurs as a gradual 'lowering of the tensions' of neighbouring particles, then the process will be as in fig. 2.11b or 2.11c, where the discharge or both the

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164. Cf. supra, section 2.3.1 (p.152-53).

165. Conduction without decomposition in an electrolyte, and conduction in metals being a case in point (911 ff.,916,1326-31,1354,1612).

166. This is required by the fact that the current has a finite velocity (cf. supra, pp.154-55).

build-up of tension and its discharge take time.

Taken together, the assumptions made by Faraday in formulating his theory of induction and conduction are inconsistent. He has treated the space occupied by the dielectric as an insulator (as in the case represented by fig. 2.11a)[167] and as a conductor (as in the case represented by figs. 2.11b,c). Faraday has stated that the particles of a dielectric are analogous to 'a series of small insulated conductors' (1679) separated by insulating space but has also assumed that completely evacuated space can conduct.[168] Yet two particles in a vacuum will act inductively even at sensible distances (1615). This means that the vacuum must not conduct.

The problem with this theory is not (as Robert Hare claimed in 1840)[169] that two elementary particles act over a distance through an intervening vacuum. The problem lies in the fact that in dispensing with the distinction between conduction and insulation as secondary properties (of systems of particles) Faraday has attributed both properties to the space between atoms. Having insisted that induction (the production of charge) requires the capacity to react upon or resist the combination of the two elements of the polar relation, Faraday has then overlooked the fact that this must be as true of the space between elementary particles as it has been shown to be true

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167. Cf. (1348,1441-42,1447,1679).

168. In series 11 he had remarked that minute cracks in the shellac stem of the differential electrometers (1177 ff.) would 'constitute vacua' and 'conduct away the electricity ... as fast almost as if a piece of metal had been introduced there' (1193). This is consistent with an implication of the fact that as a gas is rarified its resistance to the formation of a discharge current is reduced (1370-73,1381 ff.). A vacuum, being free of resisting (polarizable) particles, should be a perfect conductor.

169. Cf. supra, section 2.2.1, pp.122 and 175 (note 131).

of systems of such particles.

It is evident that if polarizability is a property of individual particles, the resistance to conduction by inter-particle discharge can be explained only by attributing a similar property to the region between individual particles.

The argument just presented is based upon Faraday's well-known reductio disproof of forms of atomism in which a distinction between matter (as the bearer of properties) and space (as the absence of any properties) is insisted upon.[170] In 1844 Faraday shows that the problem can be solved if it is assumed that the difference between conduction and insulation (i.e., the 'limiting condition' (1612)) is determined by some property of the region between atoms. He supports this assumption by arguing that the atoms of matter are infinitely extended and that this is the only view that is epistemologically sound.[171]

2.5.2 Two models of the dielectric

Although Faraday has used two quite different models of the dielectric, it can be shown that he tended to adopt a dynamical interpretation of these models. In the first place, he does not appear to have noticed or to have been concerned by the paradoxes presented by the theory.[172] The fact that the problems discussed in the preceding section can be resolved on a dynamical interpretation of the theory suggests that

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170. 'A Speculation touching Electric Conduction and the Nature of Matter' (January 1844), Phil. Mag. 24 (1844): 136, ERE II: 284, at p.286 ff.

171. These arguments are discussed in sections 2.7.1-2.7.3.

172. Apart from his reference to the problem of determining how 'insulation may be sustained, or conduction effected' as a point of 'great importance' (1612), there is no evidence either in the published papers or in the laboratory Diary to suggest that Faraday saw these as pressing problems.

Faraday did not advance it as a corpuscular theory (in which the distinction between matter and its powers is insisted upon).

Yet Faraday has been using conceptions appropriate to two models of the structure of the dielectric. The first, which I shall call the dynamical model, is closely related to the earlier accounts of electrolysis and catalysis of 1833 and 1834 and of inductive action in the eleventh series. Although Faraday's discussion of induction has been presented in terms of 'particles', 'dispositions of force', inductive and other 'relations', and 'localized forces' or 'centres of action', he has also presented his theory in terms of a second model, which I shall call the corpuscular model.

On the dynamical model the particles are just the sources and/or terminal points of inductive relations and of cohesive forces. The former, in their normal or quiescent form, are the chemical affinities (or the two 'forces originally placed in the particles of matter').[173] Induction occurs as a progressive distortion, 'influencing' or 'polarizing' of these forces (950,1303-04,1734). Conduction is a rapid alternating series of tensions and collapses in the lines of induction; it is a wave or vibration which progresses through the ordinarily 'quiescent' field of the particles. Every particle will tend to remain in position because, once polarized, every particle will attract every other along the 'axis of induction' (1658) and will repel particles lying in planes perpendicular to this axis (1304, 1369-70). The polarizability of the particles will be a function of the inductive and other relations which connect each to every other (1403,1410,1594). On this model the particles may tend to move, but can be displaced only slightly in solid or semi-rigid dielectrics.

Faraday introduces the corpuscular model by identifying the

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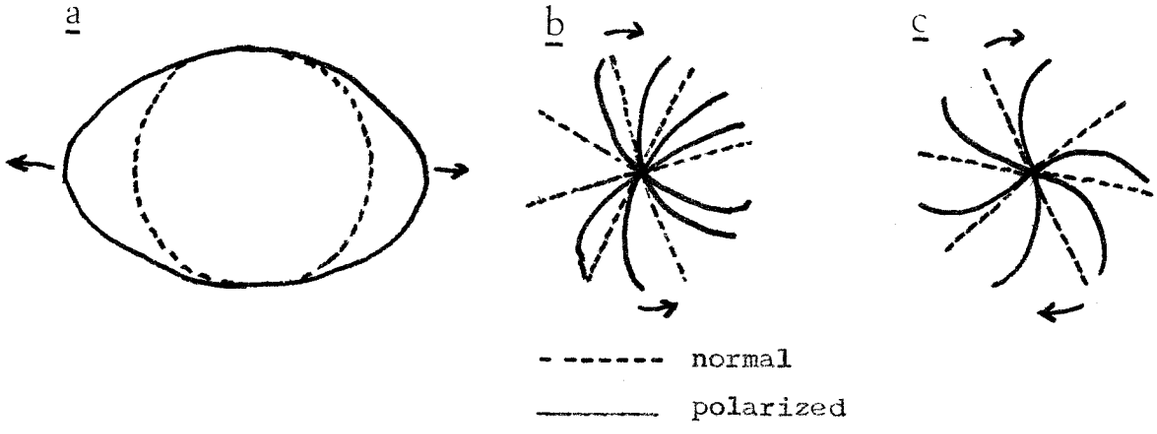
173. Loc.cit., supra, p.106.

dielectric with a system of extended corpuscles, spheres, or dipoles which, being 'as wholes conductors', accumulate charge upon their surfaces (1669,1679,1687). In this respect they behave just as the large spherical conductor described at (1564-66),[174] being regions in which the lines of induction are conducted more readily than elsewhere.[175] The polarizing of such particles would involve the creation of a disequilibrium condition of their electric forces (an idea quite consistent with Faraday's original definition of polarity (950,1304)) and would be sustained by forces acting inductively between the particles. Discharge would be instantaneous (analogous to the passage of a spark) and the fact that metallic conduction takes time would have to be referred to a finite rate of polarization of the particles.

If the dielectric is a structure of extended, elastic spheroids then polarization could resemble a deformation of the kind shown in figure 2.12a. If polarization consists in a distortion of the field of a particle as represented by the lines of force, then this state could be as shown in figure 2.12b. However, polarization need not be construed as a deformation of the field of the particle along the axis

FIGURE 2.12



174. Cf. supra, p. 143 (note 72).

175. Faraday does regard such spherical or extended bodies as being the products of chemical action (1739). It is possible therefore that he uses the term 'corpuscle' (1302,1686) to denote complex molecules rather than elementary particles.

of induction, for on the dynamical model it may be a rotatory displacement of the lines from the distribution which they have when the powers are in their 'undeveloped' or normal state (fig. 2.12c).[176]

On the dynamical model as represented in fig. 2.12c the characteristic disposition to polarize is a property not of an individual particle but of the lines of force. Faraday has stated that both particles and lines tend to retain or resist being 'disturbed' from a normal form or condition. On this view polarizability is a property 'of' the particle only in a figurative sense. The distinctions between polarizability, the limiting or maximum degree of tension which can be sustained prior to discharge, and the attractive (accelerative) action of an electrostatic force are no longer problematic. The first two properties will be aspects of the behaviour of the lines of force because the rate at which tension is built up and transmitted will be a function not of the conductivity of the space between the particles but of the rate at which the lines of induction can change form. As for the distinction between inductive action and attraction, it is apparent that the necessary constraints are provided by the lines of force which relate every particle to every other. The particles will exhibit inertial behaviour because they are 'in mutual relation by their forces in all directions' (1224,1304).[177]

However, on the corpuscular model the problems of distinguishing between conduction and insulation and between inductive and attractive

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176. Cf. supra, pp.171-72 and infra, pp.197-98.

177. To explain a finite rate of propagation of optical, thermal, and electrical actions Faraday attributes inertial behaviours to the lines of force in 1846. He never does attribute inertial mass to the particles as a primary quality, even after criticisms on this point by Robert Hare and G.B. Airy (cf. infra, sections 3.2.1.2 and 3.4).

action remain insoluble.[178] It is evident that the dynamical models (as represented in figs. 2.12b and c) either do not lead to certain problems or provide for a solution to them. Faraday has not made clear which of these models he takes to be the most plausible, and does not commit himself until 1844, when he defends the dynamical interpretation represented in fig. 2.12c, on which the particle is identified with its powers or its field.[179]

The Experimental Researches contain no conclusive evidence for the view that Faraday did interpret his theory of induction on the basis of the fully-dynamical model prior to 1844. However, there is a reason for believing that Faraday did work primarily within the context of the dynamical model rather than the corpuscular model. I have pointed out that on this model polarization of the particles (which are constrained or held in position) could involve a tendency to rotation about an axis. A consequence of this is that the polarizability of a dielectric should vary along different axes. In the fourteenth series Faraday reports the results of experiments intended to explore this very possibility.

In March of 1838 Faraday had announced his expectation that inductive capacity in crystals 'will vary in different directions'

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178. Cf. section 2.5.1, and Faraday's 'Speculation' (op.cit., note 170), p.286 ff.

179. This is similar to Maxwell's interpretation of Faraday's theory of the dielectric in 1861. However, Maxwell took the lines to represent the lines of tension in an elastic medium filling all space and did not accept Faraday's identification (in 1844 and 1846) of the materiality of the particles with their lines. See J.C. Maxwell to M. Faraday, 19 October, 1861, in L. Campbell and W. Garnett, eds., The Life of James Clerk Maxwell (2nd ed.), and for Maxwell's rejection of Faraday's identification of matter and the field, Treatise on Electricity and Magnetism, II: art. 529). Like Whewell, Airy, and others (including William Thomson), Maxwell did not accept that inertia could be treated as a relational rather than as a primary property. See his Theory of Heat, London (1871): 86.

depending upon the alignment of the lines of induction and the axes of the crystals (1317).[180] In the fourteenth series he states explicitly that the particles of non-crystalline dielectrics must be held fixed within the mass and that the equality of inductive capacitance in every direction shows that 'they can be polarized electrically in any direction' (1688). Contrary to his expectations, crystalline dielectrics did not reveal differences either (1688-96). Yet Faraday concludes that

> it does not follow [from these results] that each particle may not tend to polarize ... with more facility, in one direction than another; or that different kinds may not have specific differences in this respect, as they have differences of conducting and other powers ... (1689)

When considered in the context of Faraday's use of cohesive forces in the thirteenth series, this attempt to find a relationship between crystalline polarity and inductive action shows that Faraday tended to favour a model of the dielectric in which the force-relations between particles carry the main burden of explanation of the various powers of matter. This would help to explain the facts that his theory of the dielectric is far more successful when applied to solid dielectrics than to fluids and gases[181] and that Faraday does not appear to have been aware of the limitations of his theory in this respect.[182]

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180. Faraday had originally tested for electric polarization as a rotatory effect in 1834 (950-55). The connection between chemical and crystalline polarity had been emphasized by Whewell in a letter of 1835 (Corr. I: 300), and the need for such a test had been Faraday's reason for constructing in 1838 the three-plate condenser originally described in series 11 (1252,1307 ff.).

181. Cf. supra, sections 2.3.1-2.3.2 and 2.5.1.

182. Models of matter in which atoms are assumed to be held fixed and to vibrate about their normal positions were quite widely accepted at this time. For a survey see S.G. Brush, 'The Wave Theory of Heat: a forgotten stage in the transition from the caloric theory to thermodynamics', BJHS 5 (1970): 145, at p.155 ff.

2.6 Faraday's Atomism: an historical problem

It has been argued that Faraday developed his theories on the basis of a Boscovichean theory of matter, that he had been using this theory throughout his career, and that his failure to acknowledge this was due to his unwillingness to commit himself publicly to a theory which would be dismissed by the scientific community as 'metaphysics at best or as meaningless at worst'. This is one of the main theses of L. Pearce Williams's biography of Faraday.[183] A similar thesis has been advanced by Trevor Levere, who argues that Faraday was a dynamical atomist, though not necessarily a Boscovichean theorist.[184] It has been maintained, on the other hand, that Faraday worked on the basis of an atomic theory on which the atoms act at a distance (being separated from each other by empty space); that his references to Boscovich of 1844 and 1846 were made as part of an attempt to revise his theoretical approach; and that this need for a 'fundamental reconsideration of his basic concepts' had been brought about by Robert Hare's criticisms of his theory of induction in 1840.[185] Against Williams's interpretation it has been maintained that Faraday could not have been a Boscovichean because the only references to Boscovich made by Faraday occur in the context of a theory of matter which does not resemble that of Boscovich.[186]

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183. Michael Faraday. Cf. pp.78 and 292-94. Williams takes the Boscovichean force-curve to be the key to an understanding to Faraday's work. While Williams states (of the researches on static induction) that 'there is ... not one word even hinting at Faraday's deepest concepts' (op.cit., p.294) it will be apparent from sections 2-2.2.3 that Faraday had stated and defended his most fundamental concepts in the first seventeen paragraphs of series 11.

184. Affinity and Matter. Cf. pp.68 ff., esp. 86, 96, 99 ff.

185. P.M. Heimann, 'Faraday's Theories of Matter and Electricity', op.cit., supra, p.11 (note 5): pp.236, 243.

186. J.B. Spencer, 'Boscovich's Theory and its Relation to Faraday's Researches ...', op.cit., supra, p.11 (note 5), and Heimann, op.cit., p.235.

On the first interpretation Faraday's speculative papers of 1844 and 1846 would be statements of a position which he had held in some form throughout his career. On the second interpretation Faraday should have been aware of the paradoxical results of his theory as to the distinction between conduction and insulation. According to Heimann, he was made aware of a quite different problem by Robert Hare in 1840, namely that action at a distance--which had been denied for actions at sensible distances--had been reintroduced at the atomic level. Heimann has argued that the result of Hare's intervention was an 'intellectual crisis' leading to a 'critical examination' or 'fundamental reconsideration' by Faraday of his 'basic concepts'.[187]

I shall refer to the first interpretation as the continuity thesis, for on this view it is supposed that there is a demonstrable continuity between Faraday's earlier work and the ideas of his 'Speculation' of 1844, which consists in either his use of some particular theory of matter or his use of heuristic and regulative principles. The former version has been advanced by Williams.[188]

I shall refer to the interpretation advanced by Heimann as the intellectual crisis thesis, for on this view differences between Faraday's thought prior to 1844 and his work after that date are emphasized and his appeal to dynamical atomism is explained as an ad hoc response to a problem which became clear to him only by 1840.

In support of the intellectual crisis thesis it is argued that Faraday's theory of induction of 1837 was a theory of the propagation of electrical forces rather than a theory of matter, that Faraday

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187. Heimann, op.cit., pp.236, 243.

188. As Levere does not insist upon Faraday's having been a Boscovichean and as he emphasizes the role of the unity of force, his interpretation falls between these two versions of the continuity thesis. Cf. section 2.7.1.

had not been aware that this theory led to the reintroduction of action at a distance at the atomic level, and that Faraday could solve this problem only by adopting a theory of matter in which atoms are taken to be centres of force rather than corpuscles having finite extension.[189] It is then argued that this solution involved Faraday's adoption of an atomic theory belonging to a 'native British tradition of natural philosophy which ... went under the label of "Boscovich's theory"'.[190] In support of the continuity thesis it has been argued that Faraday did not acknowledge his commitment to Boscovichean or dynamical atomism because there was a general and united opposition to such theories at this time[191] and because Faraday was naturally reticent about committing himself on the question of the nature of atoms.

Each of these positions (as advanced by Williams and Levere, on the one hand, and by Heimann on the other) overlooks some aspect either of Faraday's theories and concepts or of his approach to the explanation of nature. I have maintained throughout this essay that while Faraday regarded specific hypotheses about the nature of matter as useful, the role of such hypotheses is of less importance to an understanding of his thought than the set of principles he has used both in the interpretation and in the explanation of experimental results.

For our purposes, therefore, the important question is not whether Faraday adopted some specific theory of matter, but whether he had been working on the basis of a dynamical form of atomism rather than

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189. Heimann, op.cit., pp.242-44.

190. Ibid., pp.247-53.

191. Williams, Michael Faraday: 78, 292-94, and Levere, Affinity and Matter: 70, 96-97.

a corpuscular theory.[192]

My answer to this question will be in two parts. First, I will discuss the problems which arise on the two main interpretations of Faraday's work given so far, and will show that each involves some assumptions which are implausible, if not untenable. I will then show that the solution to the problem of interpreting Faraday's defence of dynamical atomism in 1844 follows from a consideration of an aspect of Faraday's thought which has generally been overlooked, namely his beliefs about and his attitude towards the nature of scientific knowledge in general, and to the ontological status of the referents of theoretical terms in particular. I shall show that there is a continuity between the earlier theories and the 'Speculation' of 1844.

There are three main objections to the 'intellectual crisis' thesis.

(1) It is not at all clear that Faraday drew a hard and fast distinction between his theories of electrolysis and of induction and a theory of matter. Faraday has consistently identified atoms in terms of specific powers of attraction and repulsion and has justified his appeals to the concept of an atom on instrumental grounds (852,869,1703). Heimann would appear to be incorrect in maintaining that in 1834 and again in 1838 Faraday distinguished between his

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192. The question of similarities and differences between Faraday and Boscovich will therefore not be discussed. Since Faraday could not have had first-hand knowledge of Boscovich's theory, exact correspondences between the ideas of the two are hardly to be expected. Even so, the solution to the historical problem of Faraday's sources requires (at the very least) a concensus among historians as to the claims which various theorists would have been prepared to make about the ontological status of the points or centres of force, about the causal basis of the properties attributed to these points, and so on. Cf. supra, section 1.2.1.1 and infra, section 2.7.3.

theory of matter and his theory of the transmission of force.[193] In addition to the fact that Heimann himself identifies the theory of induction as a corpuscular theory of matter,[194] his interpretation involves supposing that Faraday did not attempt to develop a theory of matter until after 1840.

Yet Faraday's letter to Ward and his conversation with W.R. Hamilton[195] show that he had considered the problems of using an atomic theory in 1834, and we have seen that the 1837 theory of induction was developed as a solution to the problem of obtaining (what in 1834 Faraday called) a 'clear view' of the way in which the static and dynamic forms of the electric force could both be associated with the particles of matter.[196] Faraday's natural theology (as expounded in his second lecture on matter of 1844) would have precluded a rigorous distinction between a theory of matter and a theory of its powers.[197] It is also unlikely that Faraday would have dissociated himself from any specific model of the atom--as he had done in 1834 and 1837[198]--had he not been familiar with theories then current.[199]

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193. Heimann, op.cit., p.238.

194. Ibid., p.241 ff.

195. Cf. supra, section 1.4 and loc.cit. supra, pp.93, 94, and 95.

196. Loc.cit. supra, p.75; cf. sections 2.1, 2.2, 2.3.

197. Cf. infra, pp. 222-24. On Heimann's account we would have to assume that Faraday began to consider the theological implications of his (supposed) instrumentalism only after 1840. Yet such issues had been raised in Herschel's Preliminary Discourse and in Whewell's Astronomy and General Physics, and were of considerable importance to Hamilton (see supra, section 1.4). Their overtones are clearly present in Faraday's only published comments on the bearing of his researches on the question of the 'principle of life', series 15 (November 1838), (1749,1791).

198. Loc.cit., supra, pp.93 ff. and p.

199. Had Faraday looked to the opinions of and/or the approval of others for guidance he could hardly have reached any final decision on the basis of the large number of opinions then available to him. Support for dynamical atomism was strong among persons with whom Faraday had had contact (Davy, Herschel, Hamilton, Whewell, J.H. Green)--as was support for corpuscular atomism among chemists such

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(2) It is improbable that Faraday's 'Speculation' of 1844 (and the second lecture on matter) are part of an ad hoc response to criticisms made by Robert Hare in 1840.[200] The problem which Heimann supposes to have been crucial was a problem only for Hare--not for Faraday. Hare's criticisms of Faraday's theory of induction reduce to two main objections: that Faraday admits action at a distance between the elementary particles of the dielectric, and that Faraday does not make use of the hypothesis of quasi-material fluids.[201] The second objection carried no weight with Faraday, who had consistently rejected the validity of the inference from powers to imponderable but substantial fluids as the bearers of those powers. As for the first objection, I have shown that action between the particles of the dielectric is an integral part of Faraday's theory and that according to Faraday's own definition of action at a distance an action at sensible distance between particles is not inconsistent with his denial of action at a distance between bodies or systems of particles.[202] His original claim of 1838 that 'nothing in my present views forbids that the particles should act at the distance of half an inch' is literally true.[203] Faraday had argued only that inductive or polar actions are local actions, being confined wholly to the region between

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as Daubeny, Davies Gilbert, and Donovan. Cf. Levere, Affinity and Matter: 70,80,96 and M.A. Sutton, 'J.F. Daniell and the Boscovichean Atom', Studies in History and Philosophy of Science 1 (1971): 277, and note 21 (p.16).

200. 'A letter to Prof. Faraday on Certain Theoretical Opinions', Phil.Mag. 17 (1840): 44, ERE II: 251.

201. Op.cit., note 200, ERE II: 251-52, 254.

202. See supra, sections 2.2.1 and 2.4.1, esp. pp. 122ff., and section 3.2.

203. Hence Faraday's remark, in his reply to Hare, that 'with the meaning that I have carefully attached to the word contiguous ... I see no contradiction here in the terms used, nor any natural impossibility ... in such an action [at a distance]' (ERE II: 267).

two adjacent or 'contiguous' particles.[204]

Although Faraday does open his letter to Hare with the statement that the latter's comments 'have caused me very carefully to revise the general principles of the view of static induction which I have ventured to put forth',[205] the contents of that letter and of the published lecture of 1843 on the nature of inductive action show that Faraday has revised neither his concepts nor the principles which specify those concepts.[206] The lecture of 1843[207] was intended to clear up misunderstandings of his basic principles. As such it may be construed as an answer to Hare and to the 'many' who had failed to understand the original appeal to the fundamental role of induction as a polar action, but it reveals no change in Faraday's position as regards principles. In the light of this response to Hare's criticisms, and in the light of Faraday's later comments on this problem[208] I do

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204. That Faraday had not altered the meaning of this term is clear from his use of it in an unambiguous context in series 19 (1121,1124).

205. ERE II: 262.

206. In his reply to Hare Faraday simply repeats what he had stated in the first section of series 11. He does, however, introduce an analogy between the propagation of electrical action and that of heat and light (ERE II: 267). The significance of this is discussed in section 3.2 and 3.3.2.

207. 'On Static Electrical Inductive Action' (March 1843), ERE II: 279. Here Faraday discusses variations on an experiment which had been well-known since the publication of Priestley's History and Present State of Electricity in 1767. His purpose was to reinterpret this experiment as 'the expression and proof of certain parts of' his own view of induction (ERE II: 279-80).

208. Faraday develops the analogy between the propagation of electrical, optical, and thermal actions in his 1846 lecture on 'Ray Vibrations' (cf. infra, section 3.2,1. He also states--in the context of discussions of this analogy--that he is perfectly satisfied with the original theory of induction of 1837 (2443, 2446). This suggests that the possibility of a wave theory of electricity, light, and heat had occurred to Faraday long before 1840. Such a theory had been proposed by Melloni in 1837, and had been endorsed by Hamilton in 1840 (cf. supra, note 155, and infra, section 3.2, p.261.

not believe that Heimann's conclusion that Hare's criticisms led to a fundamental revision of Faraday's concepts can be accepted.[209]

(3) In addition to his suggestion that Faraday seriously considered the various speculative works on the nature of matter only after Hare's intervention of 1840,[210] Heimann has argued that 'Faraday's ideas must be seen as part of a native British tradition of natural philosophy' deriving from Joseph Priestley and others, rather than from Boscovich's Theoria.[211] Heimann suggests that Faraday referred to Boscovich rather than to Priestley in 1844 and 1846 because he did not wish to be identified with Priestley's theological views.[212]

While the case for the influence of this tradition is strong, it does not explain the importance of the concept of duality or polarity in Faraday's thought.[213] Faraday's tendency to identify substance with its manifest or secondary qualities may have derived from a tradition of this kind but his tendency to effect a further identification of existence with the opposition or reaction between two opposed forces or powers suggests the influence of ideas common to the

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209. Faraday certainly did not 'abandon his theory of the action of "contiguous" particles across insensible distances' for he had never understood action at a distance in the way that Hare (and Heimann) supposed that he had (Heimann, op.cit., p.244).

210. Heimann, op.cit., p.244 ff. and 249.

211. Heimann, op.cit., pp.236 and 253; cf. Heimann and McGuire, 'Newtonian Forces and Lockean Powers', op.cit., note 12 (supra, p.12).

212. Heimann, op.cit., p.253. This may be correct, yet two points should be noticed. First, Faraday had had no qualms about speaking at the centenary of Priestley's birth in 1833 when he had commended Priestley for his 'freedom of mind and ... independence of dogma' (Phil.Mag. 2 (1833): 382, at pp.390-91). The second point is that Faraday never does give precise indications of the sources of his main ideas--see, for example, (564,870,859, 1327,1739,2146) and Corr. I: 275-77 and 306.

213. For which see supra, sections 2.1-2.2.3, 2.3.1, and infra, section 4.2.2.

Naturphilosophen and their followers.[214] The concept of a polar or inductive relation (as used by Faraday) is not found in Boscovich, nor has it been identified in the tradition described by Heimann.[215]

The main objections to the continuity thesis have been that Faraday never refers to Boscovich prior to 1844 (and then only once afterwards, in 1846),[216] and that his theory of induction of 1837 is 'perfectly comprehensible' without recourse to Boscovichean atomism.[217]

Williams and Levere have appealed to Faraday's reticence or to his fear of opposition to explain the fact that Faraday mentions neither Boscovich nor any other dynamical theorist in his published Researches.[218] Yet both cite the fact that interest in the theories of Priestley and of Boscovich was aroused by the publication of F.O. Mossotti's theory of electricity and gravitation in 1837,[219] and both overlook the counterbalancing influence of people such as Hamilton, Herschel, and Whewell.[220] The problem with this interpretation is that evidence produced to show that Faraday was exposed to dynamical or explicitly Boscovichean influences immediately undermines the argument that Faraday could not acknowledge this influence because of a 'united opposition' to such theories.[221] Thus the fact that Faraday

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214. See supra, p.98 (note 148) and p. 117 (note 25). Heimann suggests the influence of J.J. Berzelius, but his ideas differ from those of Berzelius (who may have derived them from Naturphilosophie in any case). See Levere, Affinity and Matter: 141 and 155 ff.

215. Heimann, op.cit., p.247 ff.; Heimann and McGuire, op.cit., note 211.

216. J.B. Spencer, op.cit., note 186.

217. Heimann, op.cit., p.235.

218. Williams, Michael Faraday: 79,292, and Levere, Affinity and Matter: 70,96-97.

219. Williams, Michael Faraday: 296, Levere, Affinity and Matter: 97.

220. Cf. section 1.4.

221. Levere, Affinity and Matter: 97.

does not acknowledge his sources can be made to support two quite incompatible conclusions: that Faraday was a dynamical (and perhaps a Boscovichean) theorist throughout his career, and that Faraday did not adopt any particular form of atomism until 1844, when he adopted the dynamical theory of Priestley and others.

One important aspect of Faraday's willingness to make public pronouncements about his theoretical commitments has been overlooked by the proponents of both conclusions. This is that Faraday has not hesitated to challenge many of the most fundamental assumptions made by his contemporaries and predecessors, and that when Faraday does make such challenges public, he does so only when he is able to support his conclusion with experimental evidence and/or with an appeal to one or more of his principles of unity, induction, and conservation.

During the first eighteen years of his career Faraday has rejected Ampère's interpretation of the nature of the interactions of currents and Herschel's and Babbage's interpretation of Arago's discovery.[222] He has disproven the generally accepted belief that poles are essential to electrochemical decomposition and that they act directly upon the particles of the electrolyte according to an inverse-square law, and has consistently rejected the fluid theories of electricity and the then unquestioned distinction between conductors and insulators.[223] Faraday has argued that all metals should be magnetic even though he could not prove this experimentally,[224] and has argued that both electrostatic and magnetic actions should be actions of contiguous particles, even though he has been able to prove this only

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222. Cf. Corr. I: 130-32,134-35,138,209-11,214 and ERE I: (127-28, 183-242).

223. Cf. series 5 (460 ff.), (444,1164-65,1320-38), and Corr. I: 264-67.

224. Loc.cit., supra, p.89.

in the case of electrostatic actions in solid dielectrics.[225]

Where Faraday has been unable to find experimental evidence in support of a conclusion, he has still insisted upon that conclusion wherever he believed that to abandon it would be inconsistent with his principles. Faraday's defence of dynamical atomism in 1844 fits this pattern exactly. In 1844 Faraday presents a reductio disproof of corpuscular atomism based upon the fact that there is no correlation between the specific gravity of a substance, the number of atoms a standard volume contains, and the conductivity of that substance. This defence is also based upon a new principle, an epistemological principle which requires that scientific discourse be restricted to talk of powers or secondary qualities and that atomic units of matter be abandoned as theoretical entities.

Given Faraday's willingness to challenge established assumptions and opinions it seems unlikely that he would have been in awe of opposition to dynamical atomism. As it is also unlikely that Faraday had no theory of matter prior to 1844, it follows that Faraday simply did not see fit to enter the debate until he could bring arguments to bear that he took to be decisive.

2.6.1 A solution to the problem

I have pointed out that Faraday's response to Hare's criticisms of 1840 did not involve a change in his conception of the nature of inductive action. Insofar as Faraday's two lectures on matter of 1844 can be considered as a response to objections of the sort made by Hare,[226] a similar case can be made for these lectures. On the basis

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225. Loc.cit., supra, p.180.

226. 'A Speculation touching Electric Conduction and the Nature of Matter' (cited note 170); 'Matter ' (February 1844), published in T. Levere, 'Faraday, Matter, and Natural Theology--Reflections on an unpublished Manuscript', BJHS 4 (1968): 95, at pp.105-07.

of the analysis of the development of Faraday's theories presented so far it can be shown that the intellectual crisis interpretation of Faraday's lectures of 1844 is inadequate. These lectures can be regarded neither as the products of a 'fundamental reconsideration' of his basic concepts nor as part of an attempt to deal with the problem of action at a distance.[227]

I shall defend a modified version of the continuity thesis which does not involve supposing that Faraday came to terms with the problem of the ontological and explanatory status of atoms only in 1844, and which escapes the objections raised against Williams's interpretation of Faraday. I will show that these lectures contain ideas which were already present, implicitly or explicitly, in Faraday's earlier theories of electrolysis, catalysis, and induction, and will argue that in 1844 Faraday defends that form of atomism which I have identified as force- or relational-atomism.[228]

The solution to the problem of Faraday's reliance upon an atomic hypothesis prior to 1844 involves showing that the two lectures of 1844 contain the elements of a theory of knowledge and of a methodology of science, and that Faraday's approach to the interpretation and explanation of nature between 1831 and 1840 exemplifies this theory.

2.7 Matter and the Nature of Scientific Knowledge: the lectures of 1844

In his lectures on the nature of matter of 1844 Faraday defends a position which is characteristic of his earlier work in three respects.

(1) The atomic theory defended in 1844 is essentially the same as that used in the 1833 and 1834 theories of electrolysis and in the theory of induction as developed in the eleventh series of the

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227. Action at a distance is not mentioned by Faraday in 1844, and is alluded to only indirectly in series 21 (2443,2446) and in the lecture on 'Ray Vibrations' of 1846 (ERE III: 452). Cf. section 3.2.

228. Cf. section 1.2.1.1 (p. 18 ff.).

Experimental Researches. The most important point of similarity is that of the explanatory status of the forces or powers of the particles. Throughout the first fifteen years of his career Faraday has consistently made the powers or 'mutual relations' of entities (whether atoms or masses) the primary subject of his investigation and the primary explanatory concept of his theories.

The explanatory status of forces or powers is the same in these lectures as it had been in Faraday's earlier work, the difference being that Faraday now argues that the particles or material bearers of these powers have no explanatory function in a theory, i.e. that there is no need to appeal to atoms or ultimate individuals as theoretical entities. By appealing to an epistemological principle to the effect that knowledge must be of perceivable entities, Faraday shows that the atoms have no ontological status as entities distinct from their powers.

(2) Faraday argues that laws are the keystones of scientific knowledge and that assumptions about the natures of the powers of the elementary constituents of the world are to be confined to what is consistent with the truth of the laws. Such assumptions involve specifying that these powers are limited and definite (conserved quantities), that they are polar, and so on. This position is evidently an articulation of Faraday's whole approach to the problem of interpreting and explaining nature.

(3) Finally, Faraday had justified his use of the atomic 'theory or phraseology' on instrumental grounds in 1834 (852,969) and again in 1838 (1703). In 1844 he concedes that the atomic concept is useful and therefore necessary, but insists that the materialist connotations of the word 'atom' be dispensed with because statements about atoms are statements which refer to entities that are not possible

objects of experience. In short, he admits the need for the theoretical concept, 'atom', but denies that this word denotes a real individual as distinct from a localized set of properties--just as he has treated the electric current as a relation of powers rather than as an entity.

2.7.1 Explanation and ontological commitment

During the latter half of January 1844, Faraday opened one of the weekly meetings at the Royal Institution with a lecture on his own views of the nature of matter.[229] Faraday first describes that 'most prevalent' view of the atomic constitution of matter, which

> considers the atoms as something material having a certain volume, on which those powers were impressed at the creation, which have given it ... the capability of constituting, when many atoms are congregated together into groups, the different substances whose effects and properties we observe (ERE II: 284-85).

In such a system the atoms, 'though grouped and held together by their powers, do not touch each other, but have intervening space' (ibid.). If this view is correct, then the particles of matter and the space between them are 'two different things'. On Faraday's account this atomic doctrine has three main features:

(i) the atom is a material entity which bears properties or powers and which is, qua property-bearer, distinct from those powers;

(ii) matter, as comprised of 'congregations' of atoms, is distinct from space, for though the atoms are 'related to each other by their powers' even in gases, the atoms are separated from each

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229. This was published in the Philosophical Magazine as 'A Speculation touching Electric Conduction and the Nature of Matter' (cf. note 170). References will be to the reprint in ERE II: 284.

other by space, which is 'the only continuous part' (ibid., p.286);

(iii) those properties of matter which we observe are due to the powers or inherent properties of the atoms.

Faraday is to argue for the denial of (i) and, therefore, for a quite different interpretation of (ii) and (iii).

It is important to notice that this is not a description of the kinetic or corpuscular atomism of the Bernoullis and Herepath.[230] Since Faraday could hardly have been unaware of the former sort of theory[231] it is significant that he chooses to attack what appears to be a dynamical form of corpuscular atomism in which the atoms even of gases are 'still related to each other by their powers' (p.285).[232]

This suggests that Faraday was not considering corpuscular or hard-bodied atomism as a real alternative to dynamical atomism, but was making a more specific comparison between what I have called point-atomism and force- or relational atomism.[233]

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230. For the history of the kinetic theory and its temporary demise in the early part of the nineteenth century, see W.L. Scott, The Conflict between Atomism and Conservation Theory, C.T. Truesdell, Essays in History of Mechanics, Berlin (1968), essay VI, and S.G. Brush, 'The Wave Theory of Heat', op.cit., note 182.

231. Herepath had published papers on the kinetic theory in Thomson's Annals of Philosophy between 1818 and 1822--Faraday's 'Historical Sketch of Electro-Magnetism' was published in this same journal in 1821. In 1837 Babbage had written to Faraday describing a theory in which radiation is explained in a manner analogous to G.L. LeSage's emission theory of gravitation (Corr. I: 308).

232. The manuscript lecture notes suggest a greater emphasis on the distinction between atoms and the void than between atoms and powers acting at a distance (H. Bence-Jones, Life and Letters of Faraday 2: 177, or Agassi, Faraday: 216-18). In this respect the published paper is more dynamical than the lecture appears to have been. We shall see that Faraday's second lecture is even more dynamical (cf. section 2.7.3).

233. This interpretation is consistent with Levere's remark that prior to 1837 there is 'nothing in the Faraday corpus to indicate anything more specific than Newtonian dynamism' (Affinity and Matter: 99). Cf. supra, section 1.2.1.1.

Faraday now makes a critique of the use of the theory in which atoms are distinguished from their powers. His main complaint is that the doctrine is 'not so carefully distinguished from the facts', so that it 'often appears ... as a statement of the facts themselves' (ibid.). Unlike B.C. Brodie,[234] Faraday is quite prepared to countenance talk about atoms provided that assertions about them are made subject to certain constraints. In 1859 Brodie wrote to Faraday, reminding him of a

> conversation which I had with you long ago, in which I believe that you ... [agreed] with me in the opinion that of the ultimate structure of material bodies we neither have, nor can have any actual knowledge, & that neither the ordinary hypothesis of solid impenetrable molecules, nor Boscovich's hypothesis of solid impenetrable mathematical points, ... is anything more than a contrivance for bringing these things down to the level of [our] limited comprehension.[235]

Faraday's 'agreement' would have been tempered by the fact that, whereas Brodie believed the danger of the notion of atoms to lie in its not being subject to any objective rules,[236] Faraday believed that certain epistemological constraints could be placed upon the use of such theoretical terms.

Faraday's main objection to the use of the atomic hypothesis is that it is 'an assumption; of the truth of which we can assert nothing, whatever we may think of its probability' (p.285). This is a strong claim, and it is important to see just what Faraday is denying. Faraday is uneasy about the misleading connotations of the word atom, which 'can never be used without involving much that is

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234. Cf. Brodie, 'Ideal Chemistry' (June 1867), Chemical News 15 (1867): 295, and W.H. Brock, ed., The Atomic Debates.

235. Brodie to Faraday, 14 January, 1859, Corr. II: 920.

236. See D.M. Dallas, 'The Chemical Calculus of Benjamin Brodie', in W.H. Brock, ed., op.cit. note 234.

purely hypothetical' (ibid.). As his later arguments are to make clear, Faraday is attacking not the use of hypotheses about individuals,[237] but the tendency to hypostatize words which appear in such hypotheses. Thus, while

> the word atom ... is often intended to be used to express a simple fact ... good as the intention is, I have not yet found a mind that did habitually separate it from its accompanying temptations ... (ibid.)

In view of a remark made by Faraday much later in his career about the difficulty he himself had felt in 'suspending the mental decision' as to the truth or plausibility of an hypothesis,[238] this remark and those which follow may reflect his own attempts to deal with this problem.

Words such as 'definite proportions, equivalents, primes &c. which did and do express fully all the facts' of the (chemical) atomic theory were 'dismissed because they were not expressive enough ... they did not express the hypothesis as well as the fact' (ibid.). Since there is a 'constant tendency of the mind to rest on an assumption, and when it answers every present purpose, to forget that it is an assumption', Faraday is convinced that to use a single word to express both 'hypothesis' and 'fact' is dangerous; an obstacle to 'clear-sighted judgement' (ibid.).[239] The solution, according to Faraday, is twofold: first, to adhere to a distinction between 'that knowledge

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237. He has himself used the concept of ultimate individuals such as 'ions' as what he has called a 'means of localizing as it were the [chemical] force, [and] identifying it by the particle ...' (1650).

238. Loc.cit., supra, p.103 (note 3).

239. For a later view of judgement and of prejudice, see Faraday's essay on 'Mental Education' (1854), ERCP: 463. Faraday certainly shared Joseph Priestley's view that preconceived ideas or 'prejudices' could 'not only influence our judgement but even the perceptions of our senses ...' (Faraday on Priestley, op.cit., note 212, at p.390).

which consists of assumption, by which I mean theory and hypothesis' and 'that which is the knowledge of facts and laws' and second, never to raise 'the former to the dignity or authority of the latter, nor to confuse [the latter] more than is inevitable with the former' (pp.285-86).

Faraday has recognized that theorists are likely to be misled by the connotations or 'accompanying temptations' of words (such as 'atom', 'current', 'pole', etc.). But he wants to retain both the conceptual utility and the explanatory power of scientific theory. Consequently he cannot seek a solution by denying (as Brodie and Mach were to do) that scientific theories are ever really about anything, being merely useful tools for organizing data.

Faraday's solution requires that a theoretical term can be 'separated from its accompanying temptations'--i.e., that the reference of a term can be suitably restricted to include just the powers or properties and to exclude the superfluous and unknowable entity which is supposed to bear those properties; be it a point, a corpuscle, or a fluid. This restriction is necessary because, as Faraday is to argue, hypotheses are admissible only if they do not incorporate assumptions about the existence of things that are not possible objects of perception.

It is clear that Faraday's solution to this problem turns upon his adoption of an epistemology on which knowledge of anything other than active powers is denied. Before discussing Faraday's epistemology I want to point out that the solution now proposed by Faraday is precisely that which he himself has used throughout the first eighteen series of the Experimental Researches in Electricity. He has defined the current as 'something progressive' and as an 'axis of power' and has stated his preference for the abstract notion of

forces as directed quantities. He has defined 'atoms' as 'particles' or as 'ions'.[240] When the argument of the present lecture is considered in the context of this aspect of Faraday's Researches it becomes evident that Faraday is simply making explicit a method that has been used throughout his earlier papers. While it is not possible to prove that Faraday's earlier 'restriction' of terms had been motivated by adherence to the doctrine that knowledge is perceptual, his earlier work certainly conforms to the point he now makes, that 'real knowledge' consists in facts and in laws, where laws are statements about relationships between manifest qualities.[241]

2.7.2 Faraday's epistemology

Faraday now argues that although some form of atomic hypothesis is indispensible, that hypothesis should commit its user to no more than is necessary for the articulation of an explanation. Thus, 'the safest course appears to be to assume as little as possible, and in that respect the atoms of Boscovich appear to me to have a great advantage over the more usual notions' (ibid., 289-90). The advantage of Boscovich's theory, as Faraday understood it, is that atoms are described in terms of a single property (or set of properties). No assumptions need be made about the nature or structure of the atom as a hard corpuscle (or as an Ampèrian electrodynamic molecule):[242]

> its secondary qualities are its only properties and these are to be reduced directly to the possession of attractive and repulsive forces.

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240. For further discussion and references see supra, section 2.2.3.

241. ERE II: 293; cf. supra, p. 215-16.

242. This same idea lies behind Faraday's response to W. Weber's claim (of 1848) that Faraday's researches on diamagnetism support a modified form of Ampère's molecular theory of magnetism. See infra, section 3.3.2.1.

Dynamical atomism therefore commits one to less than do the 'more usual notions' in which the atom is taken to be some thing distinct from its properties:

> If, in the ordinary view of atoms, we call the particle of matter away from the powers a, and the system of powers or forces in and around it m, then in Boscovich's theory a disappears, or is a mere mathematical point, whilst in the usual notion it is a little unchangeable, impenetrable piece of matter, and m is an atmosphere of force grouped around it (p.290).

Why did Faraday regard this approach as superior, and why did he object to the distinction between atoms and their powers? In this first lecture we find two main answers. One involves an appeal to a constraint upon what can or need be said about things like atoms. Here Faraday defends an epistemology on which the inert nuclei or bearers of properties must be excluded because they are not possible objects of experience. The second answer is an argument which is meant to show that adherence to such a constraint will remove a paradox which arises on the corpuscular version of atomism.

Faraday first presents the paradox, which is that on the view that the matter (the material nucleus, a) is distinct from the space which separates it from other atoms, there is no way of explaining both conduction and insulation of electricity.[243] Faraday shows that if matter is held to be individuated as atoms having finite extension and being separated by space (as the absence of matter) then two quite incompatible properties must be attributed to space.[244] Although this objection might be countered by allowing that the atoms move so as to communicate their powers by contact, Faraday undermines this

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243. In the light of later comments it is likely that Faraday believed this paradox to apply to the conduction or transmission of heat and light as well. Cf. notes 155 and 208.

244. Ibid., p.287. For a more detailed discussion see section 2.5.1.

assumption by showing that it is incompatible with the fact that the conducting power of metals bears no simple relation to the number of atoms contained in a unit volume of each.

Faraday now shows that if the distinction between matter and its powers is abandoned, the paradox does not arise. If we construe the matter simply as its powers or forces, then the 'matter will be continuous throughout'. He then states that

> the powers around the centres give these centres the properties of atoms of matter; and these powers again, when many centres by their conjoint forces are grouped into a mass, give to every part of that mass the properties of matter ... (p.291, my italics)

Here Faraday clearly states that the properties of atoms (as supposed individuals) are due to the powers or force-relations between them. It follows that these properties are relational rather than inherent or essential qualities.[245] The relevant property of a piece of matter can be explained solely in terms of powers or force-relations:

> Thus, referring back to potassium ... how can we for a moment imagine that its conducting property belongs to it, any otherwise than as a consequence of the properties of the space, or as I have called it ... the m? (p.290).

Similarly, any property we seek to explain may be referred directly to the powers rather than to the atom or nucleus:

> so all its other properties ... must belong to it, in consequence of the properties or forces of the m, not those of the a, which without the forces, is conceived of as having no powers (ibid.).

Faraday's account of the 'usual notion' of atomism is something of a caricature, for he describes the corpuscularist as having only two weapons in his explanatory arsenal: the material corpuscles, and space. He ignores the fact that many atomists (whether they held

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245. See infra, pp.224 ff. and section 4.2.2.1.

that atoms have finite extension or not) resorted to a compromise between kinetic or hard-bodied atomism and action at a distance on the one hand, and dynamical or force-atomism on the other, which involved introducing imponderable fluids or atmospheres.[246] Despite his appeal to the 'facts' (p.284) Faraday has tailored his account to support a specific point, that the matter cannot be distinguished from its powers, which occupy space.[247]

Yet such appeals to aethers or elastic fluids are ruled out by Faraday's next argument. This is that in explaining some property or process we should posit only those things that are in principle perceivable. On this criterion aethers and fluids (whose existence is inferred from the existence of certain properties)[248] must be abandoned along with the atomic nuclei.

So far Faraday has argued that reference to powers is sufficient and that the atoms or nuclei have no explanatory role. He now argues that they can have no ontological status either. This argument is based upon the claims that nothing can be known except as its manifest properties and that things which do not have manifest qualities are not legitimate subjects of a scientific hypothesis. Since an atom could be known in principle only through its relations with other atoms (perceivers), all that we can know are the relations. While

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246. For example, Dalton's atmospheres of caloric, Babbage's streams of particulate but imponderable fluids, Exley's 'atmospherules', and the optical-thermal aether of those such as Melloni who sought the unification of the theories of light and heat (cf. infra, p.261).

247. For the status of space as the presence of powers and as the absence of sources of power, see infra, section 3.5.3.

248. A consistent proponent of the inference from attribute to sustance was Robert Hare. See his 'Letter to Prof. Faraday ...', op.cit., note 200, and 'Dr. Hare's remarks ... on a recent speculation by Faraday on Electric Conduction and the Nature of Matter', Phil. Mag. 26 (1845): 602; esp. pp.603-04.

Faraday's earlier argument may be interpreted as supporting the claim that an entity which plays no causal or explanatory role can and should be dispensed with, the present argument is stronger: existence claims turns upon (and must be stated in terms of) property ascriptions.

This argument follows immediately upon Faraday's claim that the conducting property of an atom 'is a consequence of the properties of the space ... the m' and that the space (filled by the powers) is therefore the matter. Faraday then states that

> the a or nucleus vanishes, and the substance consists of the powers of m; and indeed what notion can we form of the nucleus independent of its powers? (p.290)

Now comes the major premise:

> all our perception and knowledge of the atoms, and even our fancy, is limited to ideas of its powers: what thought remains on which to hang the imagination of an a independent of the acknowledged forces? (p.291)

The 'thought which remains' is, of course, that tendency to treat the statement that there are properties as the assertion that there are bearers or possessors of those properties.

Faraday rejects this inference from the existence (perception) of an attribute to the existence (perceivability) of substance. He offers two arguments. First, that however difficult it may be to 'think of the powers of matter independent of a separate something to be called the matter' it is 'certainly far more difficult, and indeed impossible, to think of or imagine that matter independent of the powers' (p.291).

This is a conceptual point. It turns upon Faraday's identification of knowledge with perception and of conceivability with perceivability. In imagining an inert corpuscle to which powers are

then attributed, we are tacitly supposing that it has certain properties that make it a possible object of perception (e.g., that it is opaque or will resist penetration).

Faraday can now launch the second stage of his argument. We cannot infer the existence of substance (individuated as atoms) from attributes (powers) because the inferred entity can neither be perceived nor conceived:

> the powers we know and recognize in every phenomenon of the creation, the abstract matter in none; why then assume the existence of that of which we are ignorant, which we cannot conceive, and for which there is no philosophical necessity? (p.291)

Even if individuals are required (as atoms or ions are required in the explanation of the law of electrolysis), such individuals can be introduced and described only in terms of a relevant property or set of properties.

2.7.3 The ontology of powers

Faraday read a second lecture on the nature of matter within a few weeks of his reading of the 'Speculation'.[249] In this lecture we find a shift in the emphasis of Faraday's argument, towards the theory of knowledge which had been hinted at in the earlier lecture.

Faraday opens by stating that he has felt 'constrained to form some idea of matter' (p.105). This confession appears in a paragraph in which two restraints are placed upon this sort of endeavour. First, he tells us '[I am] purposely limiting my object to the investigation of the phenomena presented by the material creation'. Second,

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249. 'Matter' (op.cit., note 226). References will be to the pages of the manuscript as reproduced in Levere's article.

> whilst marshalling my thoughts into that order or condition which is least inconsistent with the phenomena, it seems to me very important that we assume as little as possible, since all that we assume may be wrong (ibid.).

Although the first point has not been made explicitly in any of Faraday's research papers, the distinction between the material creation and the living world had been implicit in Faraday's remarks on his attempt (of 1838) to apply the laws of electricity to nervous or vital powers.[250] The latter point is certainly not new.[251]

Faraday now presents a defence of dynamical atomism. This involves showing that atoms must be taken to be active centres of power, each of which is definite in amount:

> God has been pleased to work in his material creation by laws, and these laws are made evident to us by the constancy of the characters of matter and the constancy of the effects which it produces (ibid.).

The constancy of the effects points to a constancy of matter itself:

> Matter, as far as we can observe it, is invariable in itself; and it acts by forces impressed upon it which, as far as we can judge, are also invariable; having undergone no change ... from the first moment of their creation ... (ibid.)

Yet the invariability of the impressed forces is not a matter of judgement or of supposition--the forces must be invariable because 'their integrity & the integrity of the laws which govern the material universe are bound up with each other' (ibid., my italics). The constancy of the properties and effects of matter suggests that the

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250. Cf. series 15 (1749,1791).

251. It bears comparison not just with a similar comment in the earlier lecture (in support of Boscovichean or point-atoms) but with Faraday's comment in series 6 that 'although we may err in imagining each particle to be a little nucleus to an atmosphere of heat, or electricity, or any other agent, we are still not likely to be in error in considering the elasticity [of gas particles] as dependent on mutuality of action' (626, my italics).

powers of the atoms are definite and constant, but the existence of the laws requires that these powers be definite. The laws, in turn, point to the work of a creator.[252]

All the laws which Faraday has so far discovered or attempted to explain govern processes in which a quantity of electric, chemical, or other forces is transformed into an equivalent and definite quantity of action, which is taken to be this same force in another form.[253] Thus, whatever we assume about the nature of the material universe, we must start from the assumption that both its constituents and their behaviours are constant, i.e. subject to laws of this kind.

Prior to 1844 Faraday may be read as a point-atomist. But in arguing that atoms can be known only as their powers, that these powers 'give these centres the properties of atoms',[254] and that no other entities are to be countenanced, Faraday has adopted what I defined earlier as force- or relational-atomism.[255] Faraday has evidently decided that his earlier, instrumentalist approach to the justification of the use of the atomic concept is no longer adequate, and is now making explicit his use of a causal theory of the properties of matter.

On this view one is committed not to the existence of atoms as discrete entities, but to the existence of relationships or interactions in virtue of which the supposed atoms manifest their powers. Rigorous adherence to the principle that all knowledge is perceptual

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252. As Levere has pointed out, 'God's activity in the universe was not restricted to an initial creation, but was rather a constant presence' (op.cit. note 226, pp.101-03). Cf. supra, section 1.4.

253. See series 3 and 7. This point applies equally to future discoveries; see series 19, 28, and 29.

254. 'Speculation', p.291.

255. Cf. section 1.2.1.1.

rather than inferential requires the abandonment of atoms as theoretical entities. To be identified as individuals some manifest or detectable property would have to be true of them (thus we would have to ascribe at least one monadic predicate to such an entity). But monadic predicates such as 'inertial mass', 'elasticity', or 'finite extension' can only be inferred of such an entity as an individual. On Faraday's criterion of knowledge the attribution of a property presupposes a relationship between at least two entities.

To the objection that to recognize or even to conceive of a relation or interaction between entities we must be able to identify those entities in terms of some inherent property,[256] Faraday would, presumably, have acknowledged this as a conceptual necessity, but would have denied the ontological status of such individuals as ultimate particulars.[257] It follows that there are no ultimate

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256. --i.e., we must be able to identify them as individuals. Cf. M.B. Hesse, The Structure of Scientific Inference, chapter 1, p.28 ff. Faraday denies not that monadic predicates can be ascribed to ultimate particulars in theoretical statements, but that the individuals to which such predicates are applied can have the status of theoretical entities. Cf. note 257.

257. Whereas in the earlier lecture Faraday had been prepared to state the view that an individual atom is something distinct from its powers, he is now unwilling even to state this view without the qualification that to do so is to 'speak absurdly' (loc.cit., infra, p226). While atomic entities are shown to be fictions, Faraday cannot do without the concept of an individual or a singularity; a persisting point at which various properties exist. This was the import of his argument of series 7 (loc.cit., supra, pp.61-62). The difficulty is illustrated by the fact that in a lecture of 1840 he states that during chemical combination the 'acting particles are not altered in themselves ...' (R.I. Ms., as cited by Levere, Affinity and Matter: 100), yet he claims in his 'Speculation' of 1844 that two atoms may be mutually penetrable 'to the very centres', coinciding in the way that two waves may coincide (ERE II: 292-93). The two would lose their individuality while combined, yet still reappear as individuals having the same chemical properties as before (as Faraday is to claim in 1857; cf. supra, pp.63-64 and ERCP: 455 and 461: 'we cannot clearly explain what the chemical force is doing ... ... what are its effects during the three periods before, at, and after the combination ...').

particulars to which monadic predicates describing dispositional properties can be ascribed, and that ultimately all properties are relational properties.[258] Faraday's theory of the field is to emerge as the set of statements which describe these relations or interactions.

In defending this view Faraday first argues that possession of a property, whether a general property such as hardness or a specific property such as translucency of conductivity, indicates possession by the matter of the relevant forces:

> Then as to the nature of matter--take a piece of wood or iron or stone, I believe it to be matter as any other person would do, and I believe it to be manifested to our senses as a particular kind of matter by its properties; for we have no way of knowing matter, either generally or specifically, than by the properties which it exhibits (ibid.).

To ascribe a property is to ascribe a specific kind of force to the atoms which constitute the matter. Since we can know matter only by its properties and atoms by their forces, it cannot be otherwise. All property ascriptions are causal:

> But these properties belong to it by virtue of the forces which belong to it and in no other way; for, by the consent of all natural philosophers, the word force or forces is used to express that which gives them their properties and powers (ibid.).

We may say that 'the weight or gravitation of a body depends on a force which we call attraction', but this force

> is not something away or separate from the matter, nor is the matter separate from the force; the force is an essential property or part of the matter &, to speak absurdly, the matter without the force would not be matter (ibid.).

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258. For a discussion of the problem of ultimate particulars see: H.R. Harré, The Principles of Scientific Thinking (chapter 11, p.301 ff.); E.H. Madden and M. Sachs, 'Parmenidean Particulars and Vanishing Elements', Studies in History and Philosophy of Science 3 (1972): 151; H.R. Harré and E. Madden, Causal Powers (chapters 5-6); and H. Post, 'The Problem of Atomism', British Journal for the Philosophy of Science 26 (1975): 19.

Matter is identical with its properties in the sense that it consists of the powers which cause them:

> if we recognise matter by its hardness, what to we other than recognise by our sensations a force exerted by it? I press my finger against a piece of glass, and, because my finger is resisted by it I say it is hard ... (ibid.).

'Hardness' is not to be understood simply in terms of the sensation of touch: for Faraday it includes the immediate cause of that sensation, namely the force which makes the sensation possible:

> but how does this hardness or resistance arise? by a force of repulsion which existing in the particles of the glass & in the particles of my finger prevents their coming nearer to each other than a certain distance, fixed for the circumstances but varying if the circumstances vary (ibid.).

So to say that something is hard is just to say that it is a region or system of forces, each of which acts according to some determinate law:

> I say again that the glass is hard because its particles resist displacement; not that they are touching by any imaginary surfaces ... but because the forces of the particles hold them under the circumstances at a given distance & in a given position (ibid.).

Faraday's point may be put in two ways: he is asserting that a property such as hardness has an immediate cause in the powers of the matter. He is also claiming that this is the meaning of the words 'hard' and 'hardness'. To ascribe a property is to posit a cause of that property. Inert corpuscles and quasi-material or substantial fluids cannot be causes of properties because they are, by definition, inactive. In identifying matter (that which has properties) with force Faraday has taken the argument of the first lecture on matter a stage further.

In his first lecture the distinctions between matter and space

and between atomic individuals and their powers had been presented as an objection to the usual view. Here Faraday has isolated what he takes to be the central metaphysical problem posed by the distinction between an entity and its properties.

Having argued that the nuclei have no explanatory role and can have no epistemological status, Faraday points out that an atom is just the cluster of phenomenal properties which identify it as a specific kind of matter. Without the forces there would be no properties, 'there would be no more gravitation, no more reflexion of light, no more chemical action' (ibid.).

Faraday concludes by stating his own view of the nature of atoms. In contrast with the earlier lecture, this statement is unusually emphatic:

> That an atom of matter is an unchangeable amount of power, I believe; and as indestructible as any of those atoms which Newton and others may have imagined as consisting of nuclei; and that this power is grouped round & attached to a center, I believe, just as others suppose it associated with a nucleus (ibid., p.107).

This is all that one is entitled to believe--'abstracted from the properties, no thought remains in my mind on which I can found the idea of a nucleus'. There is, according to Faraday, no 'real reason ... for supposing that there is [a] nucleus in a particle of matter'. It would appear that a 'real reason' for supposing the existence of something is that the entity or property posited be an efficient cause of the property to be explained.

Hypotheses about such entities would automatically meet the following criterion: that an hypothesis specify only causally relevant attributes and commit its user to the existence only of those entities that are possible objects of experience.

2.7.4 The laws of Force

Taken together, the arguments of the two lectures of January and February 1844, show that centres of force are necessary and sufficient for the purposes of the explanation of the properties of matter. The theological overtones of Faraday's argument and his emphasis of perception as the basis of knowledge are new, but the emphasis is that of Faraday's Experimental Researches. It is an emphasis both on laws, statements about the relationships between things or their properties, and on efficient causes. As Faraday had remarked in his notes for a lecture of 1837 on Mossotti's theory:

> Now want experimental proof of the general law [of electrical, cohesive, and gravitational attraction]-- Mossotti's words not impossible--... Nature of a thing the answer both of the ignorant and the philosopher-- search for laws.[259]

The whole course of Faraday's experimental work has been a search for those laws which govern the action and conversion of force--the laws of electric and magnetic induction, conduction, and chemical action. This work has been carried out under the auspices of a small number of principles about the way in which forces must act.

I have shown in earlier sections that Faraday's theories of electrolysis and electrostatic induction have been based upon these principles, which specify the concept of force and which specify the nature of force as a theoretical entity. The actual and possible behaviours of force are those of the lines of force, and it is in their dual role as observed and as theoretical entities[260] that the lines confer upon force the properties that Faraday's principles

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259. R.I. Ms., as cited in Levere, Affinity and Matter: 97.

260. Cf. section 2.3.3.

require that it have.[261] In addition to his emphasis on the relationship between the definite nature of the powers of matter and the determinacy of laws, it is significant that Faraday applies the epistemological constraint upon the positing of entities, to hypotheses about power or force itself:

> Matter acts & is acted upon only by its force, and the atoms of matter are to my imagination centres of force. What force is I know not; the nature of our existence gives us only to recognize and to estimate it by its effects.[262]

Matter and force have the same ontological status because neither can be known except as their powers or effects. The laws of nature are the laws of these powers. In part III I will show how these laws of force become the laws of the field theory.

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261. Despite his claims that the lines merely represent the forces, it is clear that they embody the emerging laws of the field. In series 12 Faraday had stated that the interactions between the particles of a dielectric will be 'governed by, or [be] in conformity with' the lines of induction (1442). In series 14 Faraday had emphasized that his theory of induction performed 'the important office of stating how the powers are arranged ... to trace them in their various relations to the particles of matter, [and] to determine their general laws ...' (1667-68).

262. 'Matter', p.107 (my italics). Both J. Herschel and W.R. Hamilton believed that nature is comprehensible to us only through our subjective understanding of force and cause as volitions. Cf. Herschel's Preliminary Discourse, pp.36-37, 86-91, 198; and Hamilton, loc.cit. supra, p.96ff.

PART THREE

3. FROM FORCE-ATOMISM TO THE FIELD THEORY: 1845-1850

Prior to 1844 Faraday had been prepared to introduce atoms as bearers of powers. In 1844 he had adopted an epistemological position whose main consequence was that atoms could be supposed to exist only as localized sets of powers. It followed that hypotheses about atoms as discrete bearers of primary qualities are unwarranted. Faraday's work between 1845 and 1850 is consistent with the epistemological position defended in 1844. He gradually dispenses entirely with references to elementary particles, basing his theory upon properties of the lines of induction and upon assumptions about the properties of matter as a system of powers.

In order to develop a general theory of magnetic induction Faraday believed that he would have to show that the magnetic forces are as universal as the electric force, that they are capable of interacting with other forms of force, and that they are polar or inductive at all orders of magnitude. In 1845 Faraday makes two discoveries which confirm his expectation that all matter is susceptible to the action of magnetic forces and which show that there is a definite relationship between magnetism and light. If the discoveries of electromagnetic induction, of the law of electrolysis, and of specific inductive capacitance were the first three experimental

steps towards the field theory, then these two discoveries of 1845 must be taken to be the fourth and fifth. They convince Faraday both of the truth of his fundamental assumptions about the entity, universality, and conservative nature of force and of the possibility of developing a general theory of magnetism to match the theory of induction of 1837.

The unified theory of electricity and magnetism was not to be realized as readily as Faraday had hoped. While the discovery of diamagnetic action did show that some general theory could be developed, the nature of diamagnetic action presented an immediate obstacle: this action was not inductive in the way that ordinary electrostatic and magnetic actions are. In order to develop a theory based upon his principles of unity, polarity, and conservation Faraday mounts an extended experimental and theoretical analysis of the nature of the interaction of matter with the magnetic field. By 1848 he is able to show that the polar or dual nature of the power can be construed as a property of the lines of induction rather than of a matter-force interaction. In this way Faraday reconciles the observed non-polarity of diamagnetic bodies with all three of his postulates about the nature of force. By 1850 Faraday can unite the theories of electrostatic and magnetic induction and can turn, finally, to a defence of the view that the referent of this unified theory must be taken to be a real, active entity.

3.1 The Universality of Magnetic Action

In the first series of his Experimental Researches, of 1831, Faraday had suggested that the inductive action of a current should be as universal in its action as the inductive action of electricity in its static state,[1] and had supposed that non-magnetic metals, even

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1. ERE I: (1-4, 60 ff.). For conventions and abbreviations used in the citations see supra, p.v.

insulators, assume a condition of molecular strain when in the presence of a magnet or a current.[2] In September of 1845 Faraday found that a strong magnetic force could, under certain conditions, rotate the plane of polarization of a polarized ray of light passing through a transparent medium. Less than two months later he had shown that a wide variety of materials could be affected by magnetic action, but in a manner quite different from that which he had expected in 1835 and 1838.[3]

The assumption that magnetic force will be universal in its action follows from Faraday's postulate of the unity and convertibility of force. Matter is a system of centres of electrical and other powers.[4] These powers should be capable of interacting with the magnetic force which is (as Faraday explains in the opening paragraph of the nineteenth series)[5] just a <u>form</u> of a single 'great power'.[6]

> I have long held an opinion, almost amounting to conviction, in common I believe with many other lovers of natural knowledge, that the various forms under which the forces of matter are made manifest have one common origin; or ... are so directly related and mutually dependent, that they are convertible ... one into another, and possess equivalents of power in their action (2146).

Here is an explicit statement of the assumptions which I have called

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2. Cf. section 1.3.1.1 (<u>supra</u>, p.25 ff.).

3. Cf. sections 1.3.4.3 and 2.4 (esp. p.128 ff.).

4. Cf. sections 2.7.1-2.7.3; 'Light and electricity are two great and searching investigators of the molecular structure of bodies ...' (<u>ERE</u> II: 286).

5. 'On the Magnetization of light and the illumination of magnetic lines of force', <u>ERE</u> III: (2146-2242), read: 20 November, 1845.

6. <u>Loc.cit.</u>, <u>infra</u>, p.239.

the principles of unity, convertibility, and conservation of force.[7] Referring to his earlier attempts to detect a relationship between electricity and the 'powers of light' (2147) Faraday remarks that these 'ineffectual exertions' had not convinced him that the expected effects could not be shown to occur (2148).

3.1.1 Magnetism and Light

Using a strong magnetic field and a piece of glass having a high refractive index Faraday succeeds at last in 'magnetizing and electrifying a ray of light, and in illuminating a magnetic line of force' (2148).[8] Faraday's unwillingness to accept the results of his experiments on the magnetic analogue of inductive capacitance in 1838 has been vindicated. Although he has not shown that magnetic force is transmitted as an action of contiguous particles, he has shown that the matter does absorb or react upon the force acting through it. This satisfies the principles of unity, convertibility, and conservation, leaving only the inductive or polar nature of magnetic action at intermolecular distances to be determined.

In his successful trial[9] Faraday placed a piece of optical glass

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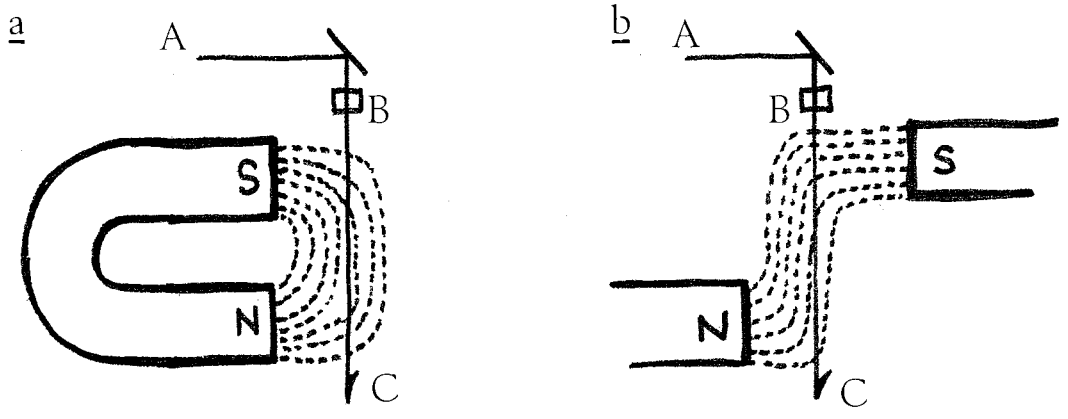
7. For an earlier instance of the use of these principles, see sections 2.4.1-2.4.3. The contention that magnetism can interact with light predates the electrical Researches by nearly a decade. See Williams, Michael Faraday: 175 or the laboratory Diary, I: 71.

8. The observed rotation of the plane of polarization of the ray is visual evidence of the presence of magnetic forces at the place at which this effect occurs. This is all that Faraday means by 'illumination' of a line. Cf. (1449) and ERE III: 1 (note 2). The term 'line of magnetic induction' refers to 'that exercise of magnetic force which is exerted in the lines ... which equally exist as passing from or to magnetic poles, or [as] forming concentric circles round an electric current' (2149). The term diamagnetic refers to 'a body through which lines of magnetic force are passing, and which does not by their action assume the usual [polarized] state of iron or loadstone' (2149, cf.2227,2270).

9. For the background to this discovery see Williams, Michael Faraday: 383 ff.; W. Thomson to M. Faraday, 9 November, 1845, and Faraday's reply of 13 November (Corr. I: 461 ff. and 463 ff.).

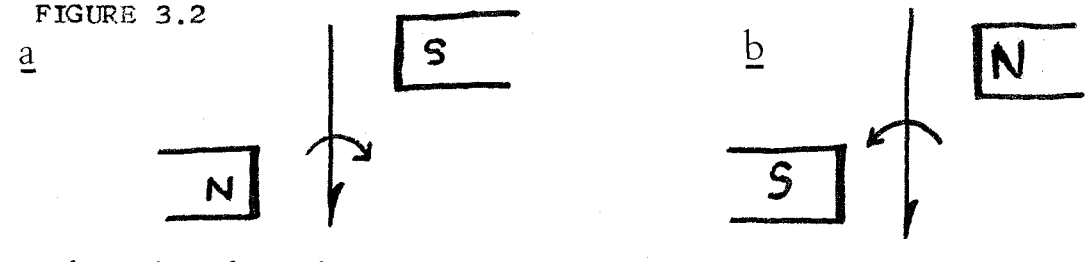
between the poles of an electromagnet, as shown in figure 3.1. The ray of light had been polarized by reflection before being passed through an eyepiece and the glass block. Faraday found that the essential condition was that both the polarized ray and the lines of magnetic action must be parallel (2151), as shown in figs. 3.1a and 3.1b. Arranging the electromagnet (inactive), the diamagnetic (D),

FIGURE 3.1



the light source (A) and the eyepiece (B) as in fig.3.1b, Faraday rotated the eyepiece so that the image of the lamp as seen at (C) is extinguished. When the electromagnet was activated 'immediately the image of the lamp-flame became visible, and continued so long as the arrangement continued magnetic' (2152). When the current activating the electromagnet was stopped, 'the light instantly disappeared'. Since the effects 'could be renewed at pleasure, at any instant ... and upon any occasion' they indicated to Faraday 'a perfect dependence of cause and effect' (2152).

FIGURE 3.2

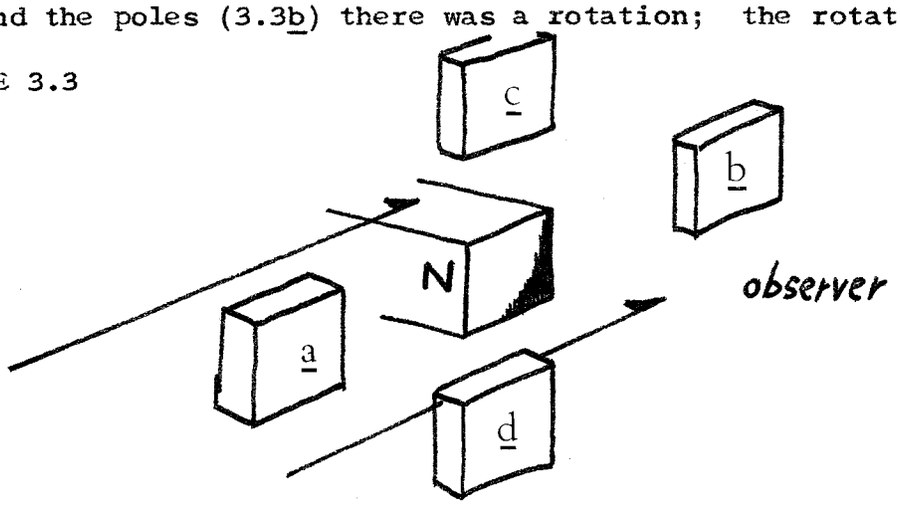


When the situation was as shown in fig. 3.2a, the 'rotation of the ray was right-handed, for the eyepiece had to be turned to the right hand ... to ... restore the image to its first condition' (2155).

If the direction of the current (hence, the polarity of the magnet) was reversed then a left-handed rotation resulted (as in fig. 3.2b). This showed that 'the direction [of rotation] was always the same for the same line of magnetic force' (2155).

Using a single pole Faraday found that when the glass was placed first between the pole and the source of the ray (figure 3.3a) and then beyond the poles (3.3b) there was a rotation; the rotation at a

FIGURE 3.3



being the opposite of that at b. When the glass was placed at c and d, where the magnetic curves are passing 'perpendicular to' the ray, no effect could be observed (2159).

It was evident that the magnetic action involved a rotation of the plane of polarization of the ray, that it occurred only if the line of force was parallel to the ray,[10] and that the direction of rotation depended upon the direction (sense) of the ray rather than upon the orientation of the matter in which the action occurs. Faraday states the law of the action as follows:

> if a magnetic line of force be <u>going from</u> a north pole or <u>coming</u> from a south pole, along the path of a polarized ray coming to the observer, it will rotate that ray to the right-hand; or ... if such a line ... be coming from a north pole ... it will rotate such a ray to the left-hand [as in fig. 3.4] (2160).

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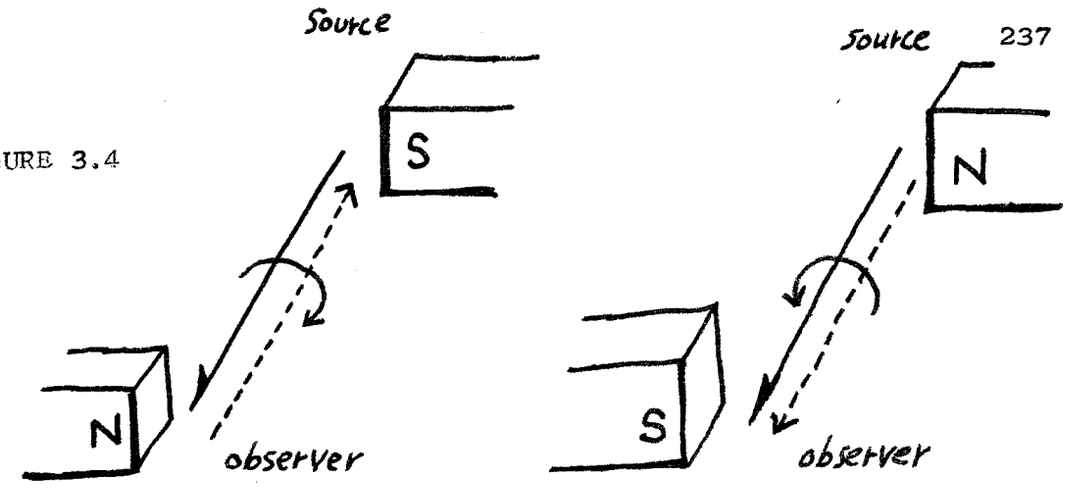
10. --or more generally, if the component of the force parallel to the ray has a value (2160).

FIGURE 3.4



Faraday now determines the 'different circumstances which affect, limit, and define the extent and nature of this new power of action on light' (2162). These are that:

(1) for a constant magnetic force, the degree of rotation is exactly proportional to the distance over which the ray travels through the diamagnetic (2163);[11]

(2) for a given thickness of the diamagnetic, the 'power of rotating' the ray is directly proportional to the intensity of the magnetic force (2164,2170), but is also relative to the natural rotative power of certain organic compounds;[12]

---

11. In the first part of a paper 'On the Magnetic Affection of Light, and on the Distinction between the Ferromagnetic and Diamagnetic Conditions of Matter' (published in September 1846, ERE III: 453 ff.) Faraday shows that when a ray is reflected back and forth across a transparent medium the degree of rotation will be increased by a unit quantity for every traversal when the rotatory power is superinduced, but that where the power is natural (as in oil of turpentine) the rotations will cancel out. While the matter may be a necessary link between the magnetic and optical forces, the law of rotation involves only two variables: the direction and the intensity of the magnetic forces. Cf. Corr. I: 496.

12. In organic substances the 'effect of the magnetic force is to add to, or subtract from, their specific force, according as the natural rotation and that induced by the magnetism is right- or left-handed' (2187). Faraday's findings suggest that the induced power is not as strong as the strongest possible force of natural rotation (cf. 2187-88, 2231-32). William Thomson sought to explain these phenomena in terms of a model also incorporating the thermal and gyrostatic (inertial) properties of matter. See Thomson's 'Dynamical Illustrations of the Magnetic and the Helicoidal Rotatory Effects of Transparent Bodies on Polarized Light', Proceedings of the Royal Society 8 (1856): 150 or Baltimore Lectures (London, 1904), appendix F; a paper that was to have an important influence on Maxwell's theory of the field in 1861.

(3) the power is not affected either by motion of the diamagnetic relative to the lines of force (2166) or by interposition of non-magnetic substances between the diamagnetic and the source of the field (2167);

(4) different (transparent) media 'possess the power of exhibiting the action ... in very different degrees' (as with electrostatic inductive capacitance). Yet the direction of rotation is not affected by the nature of the substance (again, with the exception of certain organic substances (2173, cf. 2215)).

(5) Finally, the power is common to bodies 'that are exceedingly different to each other in chemical, physical, and mechanical properties ... [e.g., solids liquids, acids, alkalies, oils, water, [chemical] aether], all possess the power' (2174).

Faraday had not been able to detect any effect of magnetism upon light passing through gases (2186,2212). Although he remained convinced that such an effect should exist (and succeeded in demonstrating it at the end of 1847)[13] the absence of any effect in gases had an important influence upon Faraday's theory of diamagnetism until 1848.[14]

Faraday now shows that a current in a helical conductor will rotate the plane of polarization of a ray passing along the axis of the helix when a diamagnetic substance is aligned along this axis (2190-95). Here, however, the image of the source of the light did not appear gradually (as with the electromagnet, (2170)) but appeared at the instant that the circuit was closed.[15] The relationship between

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13. 'On the Diamagnetic Conditions of Flame and Gases' (December 1847), ERE III: 467.

14. Cf. infra, sections 3.1.3.1 and 3.5.1.

15. 'In this experiment we may ... justly say that a ray of light is electrified and the electric forces illuminated' (2195). Faraday has always believed that magnetic forces are merely a transverse or lateral form of electric force. Cf. ERE II: 131-32; series 9 (1108-15), series 12 (1411-12), series 13 (1653-62), and series 14 (1733-35).

the direction of the current, that of the ray of light, and the direction of rotation can be expressed as in fig. 3.2, where the arrow denoting the rotation also represents the direction of the current circulating through the helix (2199-2200).[16]

Faraday concludes that he has established

> for the first time, a true and direct relation and dependence between light and the magnetic and electric forces; and thus a great addition [has been] made to the facts and considerations which tend to prove that all natural forces are tied together, and have one common origin ... (2221)

Faraday now gives the most precise statement that he is ever to make of the doctrine of the unity of force:

> It is ... difficult ... to express our expectation in exact terms; and, though I have said that another of the powers of nature is, in these experiments, directly related to the rest, I ought, perhaps, rather to say that another form of the great power is distinctly and directly related to the other forms; or, that the great power manifested by particular phenomena in particular forms, is here further identified and recognized, by the direct relation of its form of light to its forms of electricity and magnetism (2221, my italics).[17]

Faraday immediately draws attention to the polar nature of the powers concerned, pointing out that the new relationship has been shown to obtain for 'light made, in a certain respect, more precise

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16. Faraday notices that this law corresponds to the rule by which, on Ampère's theory, the direction of the molecular currents of the particles of a magnetic metal will be related to that of the magnetic force originating in or passing through it (2200), but he is willing to accept this only as an indication of the truth of the law rather than of Ampère's theory. Cf. infra, section 3.3.2.1.

17. In a letter to Maxwell of 13 November, 1857, Faraday explains that he uses the word force to denote not the 'tendency of a body to pass from one place to another' but 'the source or sources of all possible actions of the particles or materials of the universe; these being often called the powers of nature when spoken of in respect of the different manners in which their effects are shown' (L. Campbell and W. Garnett, eds., The Life of James Clerk Maxwell, 1st edn. (1882): 289). See loc.cit. supra, p.50 (note 75), p.65 (note 98), and p.105.

in its character and properties by polarization' and that the effect 'collates and connects' polarized light with electricity and magnetism 'in the duality of character which they possess' (2222, my italics).[18] The polar nature of these three powers is thus shown to be related, and

> yields an opening, which before was wanting to us, for the appliance of these powers to the investigation of the nature of this and other radiant agencies (2222).

This discovery has confirmed Faraday's basic ideas about force. As a conversion of magnetic into optical action, the effect shows that the unity of force holds for these two powers. It shows, too, that the magnetic forces do act upon the matter (as Faraday has supposed since 1831) and thus that this force does not act without effect upon non-magnetic materials. Finally, it shows that the relevant property of the force is its duality or polarity.

Faraday now draws three conclusions from this discovery. First, in terms of the 'conventional distinction' (2149) between lines of electric force and lines of magnetic force, it is clear that only the latter are 'effectual on the rays of light' (2223). Here Faraday compares the respective abilities of the two directions or components of a power--namely the direct (electrical) and the lateral (magnetic) components.[19] In non-magnetic matter, the occurrence of electrostatic induction and electrochemical action indicates 'a vast superiority in the energy with which electric forces can act as compared to magnetic

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18. He is also convinced that the 'relation ... cannot but extend to common light' as well (2222) and that magnetic forces will be found to act upon 'the other forms of radiant agents, as heat and chemical force' (2241). The identity of light and heat was widely accepted during the 1830s and 1840s. Faraday's discovery of the rotation of the plane of polarization of light led some to look for a similar effect of magnetism upon heat. See Brush, 'The Wave Theory of Heat' (op.cit., note 182).

19. For the distinction see the passages cited in note 15 (p.238).

forces'. But in the present case the action of the lateral or magnetic force is much greater (2223).[20] The results of Faraday's experiments on magnetic inductive capacitance of 1838 still require explanation, but this new effect does show that this explanation may lie in the fact that the magnetic component of the electrical power differs in 'energy' from the direct (electrical) component.

This leads Faraday to a second conclusion, viz., that whereas the electric forces do act directly upon those of the particles of matter to polarize them, the magnetic forces do not act directly on the ray of light 'without the intervention of matter'. Magnetic forces act 'through the mediation of the substance in which they and the ray have a simultaneous existence ...' (2224). The 'power of acting upon the light' arises from a mutual interaction of the magnetic forces and those of the matter, 'the substances and the forces giving to and receiving [this power] from each other'. Evidence for this conclusion consists in the 'special degree in which different matters possess the property'[21] and in 'the non-action of a vacuum, or of air or gases' (2224).[22]

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20. I.e., the comparative 'energies' or 'equivalents of action' (2223) of the magnetic component are greater than those of the electrical component--'here, in another direction ... [the magnetic forces] are shown ... to possess great superiority, and to have their full equivalent of action on the same kind of matter' as that which is affected by electrostatic forces (2223).

21. Faraday had believed that the magnetic force gives the matter the power of rotating the ray (2160,2224) but was in the process of abandoning this idea as series 19 was being written. Cf. J. Herschel to Faraday, 9 November, 1845 and Faraday's reply of 13 November (Corr. I: 461,463); Faraday to Whewell, 22 November, 1845 (ibid.: 466); Herschel to Faraday, 20 December, 1845 and Faraday's reply (ibid.: 473-75). By December of 1845 Faraday had begun to suspect that the magnetic force acts directly upon the light, although none of his correspondents appears to have shared this view; see A. de la Rive to Faraday, 25 December, 1845 (ibid.: 476) and Faraday to J.B. Dumas, 9 January, 1846 (ibid.: 481).

22. This conclusion proves to be premature in the light of Faraday's discovery of the diamagnetic properties of gases. See section 3.5.1.

The characteristic nature of the effect implies the necessary presence of 'substance' of a certain density.[23] 'Substance' is, of course, a spatial distribution of powers:

> Recognizing or perceiving matter only by its powers, and knowing nothing of any imaginary nucleus, abstract from the idea of these powers, the phenomena described in this paper much strengthen my inclination to trust in the views I have on a former occasion advanced in reference to the [nature of matter] (2225).

Faraday's third conclusion is that polarization effects are independent evidence for the creation of that 'peculiar condition' of matter which he had originally christened the 'electrotonic state'. Although the effect is observable only in transparent substances,

> it cannot be doubted that the magnetic forces act upon and affect the internal constitution of the diamagnetic, just as freely in the dark as when a ray of light is passing through it ... (2226).

Since Faraday has already demonstrated that all non-magnetic bodies are diamagnetic (i.e., susceptible to magnetic action), he can conclude that 'any such change' as that indicated by the rotation of the plane of polarization of light 'must belong to opake bodies ... for as diamagnetics, there is no distinction between them and those which are transparent ...' (2226).

This discovery represents a most important triumph for Faraday. He has finally shown that magnetic forces do indeed produce an effect upon non-magnetic materials, producing a 'molecular condition' which must be 'specifically distinct from that of magnetized iron ... and must be a new magnetic condition ...' (2227). The fact that there is an 'instantaneous return to the normal state [of a diamagnetic] when the magnetic inductionis removed' proves that thisis a state of tension. Consequently the force which rotates the ray in the matter 'must be

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23. Thus the ability to take on the rotatory power would be specific or characteristic--as have been all the properties so far examined except inductive capacitance in gases.

to us a new magnetic force or mode of action of matter' (2227). This new property is both perceptible and lawlike:

> it is impossible ... to observe and see the action of magnetic forces, rising in intensity, upon a piece of heavy glass or a tube of water, without also perceiving that the latter acquires properties which are not only new to the substance, but are also in subjection to very definite and precise laws ... (2228, my italics)

In order to show that this 'new magnetic condition' is the state he had failed to detect in 1838[24] Faraday now draws an analogy between the induced rotatory power and the natural rotatory power of certain compounds[25] and between natural and induced magnetism. Instances of substances having the former (natural) power include oil of turpentine and quartz ('which rotates only in one plane'), while magnetized metals may be supposed to have the latter power as a natural power. The condition of optical glass or of water in the field is analogous to that of soft-iron in the field; thus,

> the natural condition of the magnet and quartz, and the constrained condition of the helix and heavy glass, form the link of the analogy in one direction; whilst the supposition of currents existing in the magnet and helix, and only a tendency or tension to currents existing in the quartz and heavy glass, supplies the link in the transverse direction ... (2236, my italics)

On a unified theory of electrostatic and magnetic induction, the dielectric (even if it is a good conductor) must be placed in a state of tension by both an electrostatic and a magnetostatic force. If the same theory is to account both for magnetic and optical phenomena, the succession of static and dynamical states which constitutes the current[26] should correspond to different magnetic and optical conditions.

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24. Cf. (1662, 1709 ff.) and sections 2.4.1-2.4.2.

25. Cf. (2187 ff. and 2131 ff.) and supra, note 12 (p.237).

26. Cf. section 2.4.1.

Faraday believes that he can explain both natural and induced magnetism and natural and induced rotatory power in terms of a two-fold distinction between electric and magnetic force as components of a single power and between the static and dynamic states or conditions of these powers.[27] Faraday classifies the powers according to form, nature, and supposed state. The analogy between these classes is shown in table 3.1.

TABLE 3.1

State of primary power (electricity) in the matter	Form of secondary power as present in matter	Status of secondary power	
		Natural	Induced
1. normal or quiescent	---	---	---
2. static or inductive (electrotonic state)	optical (rotatory polarity)	quartz, oil of turpentine	optical glass
3. dynamical (current)	magnetic (linear polarity)	iron, nickel	copper (helix), soft iron

The analogy expresses hypotheses about the relationship between forms of the electrical power and the state of the electrical force which is supposed to cause or give rise to the other powers. (This is how Faraday had originally conceived the problem of explaining the conversion of electrical and chemical powers in March of 1834.)[28] It shows how the new effect may be interpreted as the effect Faraday had been seeking in 1834 (when he had attempted to detect a polarizing action of electrostatic tension in an electrolyte) and the effect that

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27. Cf. table 2.1, supra, p.172.

28. Loc.cit. supra, p.75, or p.102. This is consistent with the theoretical method of the earlier Researches, in which Faraday had stated hypotheses in terms of the forms, states, and directions of powers, rather than in terms of structures or properties of atoms. Cf. supra, pp.51-53, 82-83, 144ff. and 214 ff. As Williams has pointed out (Michael Faraday: 388-91), Faraday now relies increasingly upon the lines which represent these powers.

he had failed to obtain in 1838.[29]

The importance of this argument is that it enables Faraday to adduce the new effect as evidence for the original set of hypotheses even though he has not actually obtained the effects which (if those hypotheses were true) should occur:

> I could not then [in 1838] discover any peculiar condition of the intervening substance or diamagnetic; but now that I have been able to make out such a state, which is not only a state of tension, ... but dependent entirely upon the magnetic lines ... I am more than ever encouraged to believe that the view then advanced is correct (2240).

If this theory of matter as a spatially distributed set of electrical and other powers is correct, then gases, vapours, and crystals--(those bodies that have as yet given 'no indication of the power over light')--should also assume this 'new magnetic condition'. Independent evidence for this in the case of crystals appears in Faraday's next paper. As for gases, Faraday believes that the power exists but may be nearly insensible (2237).[30]

3.1.2 Diamagnetic Action

On 4 November, 1845, less than two months after his discovery of magnetic action upon light, Faraday made a discovery which was to underlie the development of a unified theory of electricity, magnetism, and matter. He found that the ability to assume the new magnetized state (2227-28) is a general property of all matter, 'including a vast number of opake and metallic bodies, and perhaps all except the magnetic metals and their compounds ...' (2243). Whereas this condition had been manifested as an optical effect in transparent bodies, it is exhibited in opaque materials as a specific form or attractive and

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29. Cf. (950-55, 1688 ff., 1709 ff., 2240), and section 2.5.2.

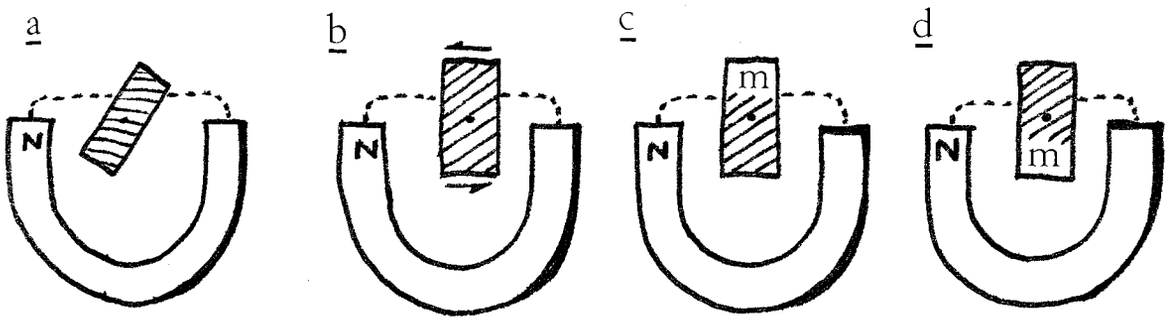
30. But see infra, p. 255 ff. and section 3.5.1.

repulsive action. In his twentieth series, Faraday shows that magnetism is a universal power of matter, and that the optical action described in the previous paper is--as he had suspected (2224-27)--a special case of this.[31] Having demonstrated the universality of magnetic action, Faraday can now attempt to place the theory of magnetism upon the same general basis as the theory of electrostatics.

Faraday had never doubted that opaque materials (in which the rotatory action of magnetic force could not be observed) would be shown to be affected by these forces. By analogy with the action of magnetic forces on iron filings, some alignment or tendency to motion of the matter should occur.[32]

Taking a bar of the optical glass in which the rotation of the polarized ray had first been detected, Faraday suspends it between the poles of an electromagnet and allows it to assume a stable position before activating the electromagnet, as shown in figure 3.5a. When

FIGURE 3.5



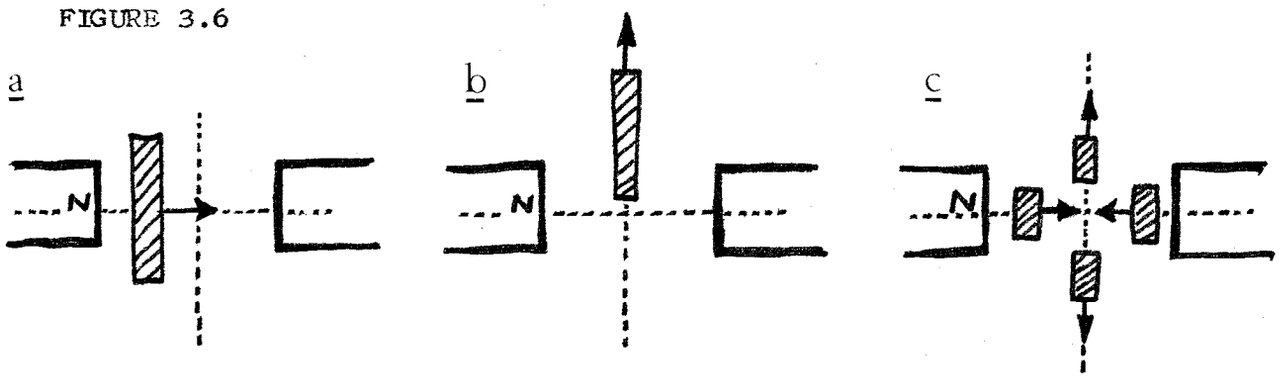
31. 'On new magnetic actions, and on the magnetic condition of all matter', ERE III: (2243-2342), read: 18 December, 1845. His belief that the optical (rotatory) effect is just a specific form of the diamagnetic action sought in 1838 had led Faraday to search for other effects. See Williams, Michael Faraday: 390-94.

32. This is one of the few cases in which Faraday sets out with a body which is free to move and in which he is actually looking for attraction or repulsion as a sign that a change of condition or structure is being produced in that body. Even so, he is soon to deny that there are direct attractions or repulsions between the matter and the magnetic poles and to insist that such 'dynamic effects' (i.e. motions (2441)) are not the best indicators of the action.

the magnet was activated 'immediately the bar moved, turning round its point of suspension, into a position across the magnetic curve or line of force ...' (2253), as shown in figure 3.5b. This appeared to be a stable position, and the bar always returned to it if displaced from it. Faraday defines this position as the equatorial position.[33] The way in which the bar moved seemed to depend upon its position prior to the instant at which the magnet was activated, for it could be aligned across the lines of force with its marked end in either of two positions (as in figures 3.5c and 3.5d, in which 'm' is the marked end). Faraday also found that the bar could be made to lie along the lines of force if it was aligned along them before the magnet was activated. Faraday defines this position as the axial position.[34] While the bar normally assumed the equatorial position, it could assume the axial position, and was clearly not polarized as a soft-iron bar would be.

Faraday now notices that if the bar is not equidistant from both poles it tends to move away from the nearest pole (as shown in figure 3.6a). If the bar is equidistant from both poles but is held slightly away from the axis, as in fig. 3.6b, then it tends to move away from

FIGURE 3.6



33. Generally, it is that position in which the longest diameter of an asymmetrical diamagnetic body is perpendicular to the lines of magnetic force (2252).

34. It is that position in which the longest diameter of an asymmetrical body (normally magnetic rather than diamagnetic) is parallel to the lines of force (2252).

the axis. Generally, the bar would both recede from the nearest source of magnetic action and tend to set across the lines of action (2263). Using small glass cubes and two poles, Faraday found that the diamagnetic matter tended to move in the directions shown by the arrows in figure 3.6c (2265).

Taking a small cube as a sensor, it became clear that the behaviours of this 'indicating particle' had one thing in common: 'its tendency was to move from stronger to weaker places of magnetic force' (2267).[35] Although Faraday had first described the effect as a pointing or alignment of the bar with respect to the lines of force, he now explains this behaviour as a secondary effect of a general tendency of the diamagnetic matter:

> the cause of the pointing of the bar ... is merely a result of the tendency of the particles to move outwards, or into the positions of weakest magnetic action. The joint exertion of the action of all the particles brings the mass into the position which, by experiment, is found to belong to it (2269).36

Faraday soon shows that the property is general to all non-magnetic matter (2276 ff.), including crystals (2278). His results disprove his earlier contention that all metals are susceptible to magnetic action as magnetic bodies[37] but confirm the broader principle that all bodies are susceptible to magnetic action:

> The new facts give ... an affirmative as to the existence of [magnetic] forces in all ordinary bodies, directly the opposite of those existing in magnetic bodies ... (2286)

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35. That is, into regions in which the density of the lines of magnetic force is lower.

36. The later theory of magnetism rests upon the assumption that both magnetic and diamagnetic matter tend to assume a position of least action or of least constraint within the field. See section 3.5.2.1.

37. Cf. supra, section 1.3.4.3. While metals can be examined for attractive and repulsive effects, solutions of their salts can be examined optically for the rotatory effect (2287 ff.). In this way Faraday shows that palladium, platinum, and titanium are also magnetic (2282 ff.), while the salts of manganese, cerium, chromium, and some other metals behave as magnetic metals would (2252,2290).

After an extensive examination of the magnetic properties of metals, their salts, and various other materials Faraday concludes in the twenty-first series[38] that all matter

> appears to be subject to the magnetic force as universally as it is to the gravitating, the electric, and the chemical or cohesive force; for that which is not affected by it in the manner of ordinary magnetic action, is affected in the manner [of diamagnetic action] ... (2420).

Faraday distinguishes between magnetic and diamagnetic action with respect to what he calls their 'dynamic effects' (2422).[39] Dynamic effects are attractions and repulsions (tendencies to motion). In respect of these 'the properties of magnetic and diamagnetic bodies are in opposition', for magnetics are always drawn into the axial line and attracted by the nearest pole while diamagnetics tend to recede from the axial line and are repelled from the nearest pole.[40]

3.1.3 Towards a theory of Diamagnetism

Faraday is eventually to provide an explanation of these 'dynamic effects' on which the contrast or opposition is shown to be apparent rather than real. Here he sets out by considering the plausibility of an atomic model of the diamagnetic as the basis for such an explanation (no doubt with the success of his molecular theory of

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38. 'On new magnetic actions ... continued', ERE III: (2343-2453), read: 8 January, 1846.

39. --as distinct from thermal, optical, or other effects. Faraday later states that diamagnetic actionis much weaker than magnetic action when 'estimated by its dynamic effects' and is convinced that this effect ('the motion which [such an action] can generate') is not 'the most striking measure of its force' (2441). This is to be expected, for Faraday has consistently sought changes in condition (chemical, electrical, molecular) rather than tendencies to change in position as evidence for the existence of a power (and as measures of its 'force').

40. Cf. supra, pp.246-47 (figs. 3.5, 3.6); and (2290,2304).

induction and with the analogy between the transmission of heat, light, electric, and magnetic action in mind).[41] A molecular theory of magnetic action would make a unified theory of electricity and magnetism possible. Thus, Faraday states that he is 'now even more content' with the molecular theory of induction 'founded on the action of contiguous particles' than he had been 'at the time of its proposition' (2443), and points out that

> It requires mere observation to be satisfied that when a magnet is acting upon a piece of soft iron, the iron itself ... carries on the force to distant points, giving it direction and concentration ... So also here the condition which the particles of intervening diamagnetics acquire, may be the very condition which carries on and causes the transfer of force through them (2443).

The fact that magnetic action has been shown to affect the matter it passes through renews the possibility that the transmission of magnetic force is an action of contiguous particles (2443).[42]

Faraday believes that he is now in a position to develop a general theory of electricity and magnetism which will incorporate the earlier theory of static induction, conduction, and electrolysis.[43] The importance of these difficulties is that both Faraday's speculative paper of 1846 (the 'Thoughts on Ray Vibrations') and his theory of the field as developed between 1848 and 1850, are responses to them.

Faraday had found that a solution of the salt of a magnetic element can be made to behave either as a diamagnetic or as a magnetic body would. This behaviour depended upon the nature of the medium in

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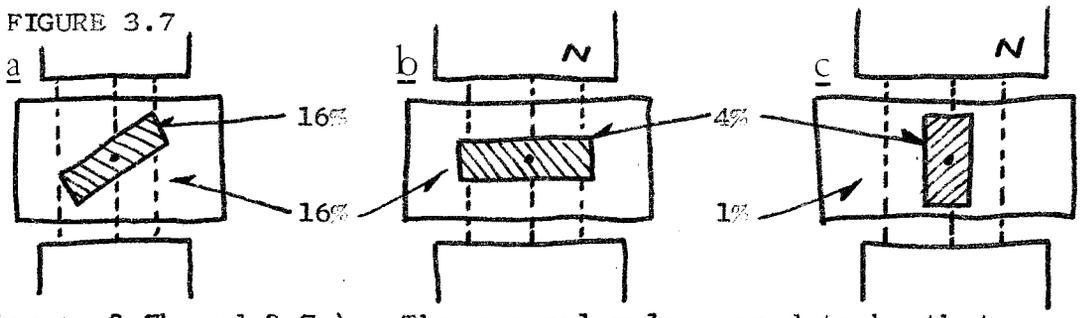
41. As the analogical argument at (2236) had shown the new phenomena could be adduced as evidence for Faraday's original contention that magnetic force, as a polar power, must be transmitted by an action of contiguous particles (73,1665,1709-35).

42. By 'an action of contiguous particles' Faraday intends a progressive action analogous to that by which light, heat, and electricity are transmitted. See infra, p. 261 ff. and supra, p.120 ff.

43. For Faraday's first attempt, see sections 2.4.1-2.4.2.

which the vessel containing the solution is suspended (2357-67). For example, a tube containing a 16% solution of protosulphate of iron ($FeSO_4$) would not point or set at all if placed in a solution of similar strength (2365) while a 4% solution would point equatorially (as a diamagnetic) in the 16% solution (figures 3.7a and 3.7b). The same 4% solution would point axially (as a magnet) in a 1% solution

FIGURE 3.7



(figures 3.7b and 3.7c). The general rule seemed to be that

> any tube pointed axially if the solution in it was stronger than the surrounding solution, and equatorially if the tube solution was the weaker of the two (2367).

If the magnetic properties of metals are preserved through chemical change,[44] should it be expected also that materials which are magnetic or diamagnetic in the solid or liquid states will also have that property in the gaseous state? Here Faraday stresses the influence of 'theoretical views' (about 'the mode of action of the bodies') on the experimental investigation of this question (2400). These views included three hypotheses: (1) that properties possessed by matter in one state will be present in other states;[45] (2) that the interaction of matter and magnetism is a differential effect, being an interaction of field, matter in the field, and the test body (rather

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44. These tests rest upon the assumption that the characteristic quantity of magnetic power of a given element is preserved through chemical change (the formation of metallic salts): 'it seemed very likely, from analogy, that every metal well magnetic per se would be magnetic in its compounds ...' (2370). Thus the property must be an unalterable property of the metal atoms. See supra, p. 306 (note 197).

45. --and conversely, that a certain minimum density of matter is necessary for some properties to become sensible. See infra, pp. 259-60.

than direct action at a distance); and (3) that the elementary particles may be electrodynamic molecules (as Ampère had supposed).[46]

At the end of 1845 Faraday believed the first hypothesis to be suspect because throughout his trials he had found that tubes containing air and other gases behaved in the same way as evacuated tubes (2400-16). Not only were gases indifferent to the field, this 'indifference' did not appear to be related to the density of the gas. Contrary to his earlier expectations,[47] Faraday had to conclude that gases are equivalent to space free of matter (2416).

As for the second hypothesis, Faraday is inclined to interpret the observed attractions, repulsions, and axial or equatorial setting of matter as a result of the interaction of the field with the matter occupying it and with the test body. But these behaviours could be interpreted equally well in terms of direct attractions and repulsions between the poles and the particles of the matter, so Faraday states what he has observed in the form of a general law. Yet his actual statement of this law is revealing:

> By the exertion of this new condition of force, the body moved may pass either <u>along</u> the magnetic lines or <u>across</u> them; and it may move along or across them in either or any direction. So that two portions of matter simultaneously subjected to this power, may be made to approach each other as if they were mutually attracted, or [to] recede as if mutually repelled (2418).

Faraday <u>does not say</u> that the matter is <u>actually</u> attracted or repelled, he says just that the matter <u>appears</u> to have a <u>tendency</u> to move in

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46. For Weber's application of Ampère's theory to diamagnetism, see <u>infra</u>, pp.253 and 290 ff.

47. 'At one time I looked to air and gases as the bodies which, allowing attenuation of their substance without addition [dilution], would permit of the observation of corresponding variations in their magnetic properties ...' (2433). Cf. Faraday to Whewell, 9 November, 1844 and 5 October, 1846 (<u>Corr</u>. I: 427 and 498).

certain ways under certain conditions:

> All the phaenomena resolve themselves into this, that a portion of such matter, when under magnetic action, tends to move from stronger to weaker places or points of force (2418).

Here the law of diamagnetic action (2268-69) is stated not in the terminology of forces, attractions, and repulsions, but in terms of the action existing at a point and of a fundamental disposition of the matter to respond to this action in a certain way.[48]

According to the third hypothesis the observed behaviours are due to some property or power of the particles of the diamagnetic (which is opposed to that of the particles of a magnetic material). It is possible that currents exist around the particles of matter.[49] The direction (sense) of these currents in diamagnetic matter would be the opposite of those induced (or existing) around the particles of magnetic matter (2430).[50] Faraday is later to provide an experimental disproof of this hypothesis. Here he admits only that an explanation could be provided on the more general supposition that 'magnetic induction caused in [the particles of diamagnetics] a contrary state to that which it produced in magnetic matter' (2429).[51] In addition to the fact that Faraday had denied the appeal to structures as ultimate entities in 1844,[52] an Ampèreian theory could not explain the

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48. The observed motions are subsequently explained on the basis of these two concepts. See infra, sections 3.5.2.1 and 4.3.1.

49. For Ampère's theory see his Mémoires sur l'électrodynamique (2 vols.), Paris (1885-87), L. Pearce Williams, 'Ampère's Electrodynamic Molecular Model', Contemporary Physics 4 (1962) or Michael Faraday: 143 ff.

50. This hypothesis was later advanced by Weber in 1848. See section 3.3.2.1.

51. Despite its plausibility the use of the Ampèreian model involves introducing a number of ad hoc hypotheses about the nature of the molecular currents in order to apply Faraday's law of magnetic induction (114-16) to both magnetic and diamagnetic matter (as Weber found in 1848; see his 'On the excitation of Diamagnetism According to the Laws of Induced Currents' (January 1848), Sci.Mem. 5 (1852): 477, at pp.485-88.

52. Cf. supra, sections 2.7.1-2.7.3.

'exceedingly remarkable' fact that all gases and vapours stand in 'a position intermediate between the magnetic and diamagnetic classes', and that rarefaction even to the vacuum state produces no change (2430-34). A dynamical or force-atom theory would provide for an explanation in terms of powers which decrease and become ineffective at interparticle distances characteristic of the gaseous state (2435).[53]

Faraday appears to have such a theory in mind. Having arranged different materials in a series from iron and nickel (as the most actively magnetic) through osmium, air, and the vacuum (as being magnetically indifferent) to phosphorus and bismuth as the most actively diamagnetic substances (2424), Faraday states that these differences in degree do not imply a fundamental difference in the natures of these elements. There is no general correlation between magnetic properties and electrical conductivity. Those elements which are most magnetic and most diamagnetic are both metals and poor conductors (2425). Yet Faraday is unable to deal with this information using the theoretical tools available to him at this stage.[54] A further problem is that the 'antithetical relation' of magnetic attraction and diamagnetic repulsion (2419) is not matched by a similar difference in the action of magnetism on polarized light (2427). While the dynamical effects point to a difference in the reaction or response of the elementary particles to the force, the optical effects point to a lack of difference (or else to a difference

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53. Faraday does still expect to find a relationship between rarefaction (density) and magnetic properties. Cf. (2433-35), Faraday to Whewell, 5 October 1846 (Corr. I: 498), and (2723 ff.).

54.--or rather, those that he is willing to take seriously. The 'strikingly distinct' dynamic effects of magnetic attraction and diamagnetic repulsion should be referred to 'an action of the molecules of the mass' (2427), but see sections 3.3.2.1 and 3.5.2.

in the nature of the ray of light).[55]

In the course of this initial attempt to develop a theory of diamagnetism three things have become clear to Faraday. First, that he does not have enough experimental information to develop a general theory of both magnetic and diamagnetic action; second, that in the absence of such a theory the interpretation of certain actions (such as the attraction and repulsion of matter in the field) will be equivocal;[56] and third, that the key to the further development of the theory lies in the absence of magnetic properties in gases and in the polar nature of the magnetic rotation of the plane of polarization of light.

3.1.3.1 The interpretation of diamagnetic action

It seemed clear that the behaviours of air and gases in the field were directly related to the magnetic properties of the medium occupying the field in which containers of those gases were placed (2405,2414). Yet this relationship had to be distinguished from the supposed absolute nature of attraction (as of iron) and repulsion (as of bismuth). The fact that the behaviour of air in the field (or of a magnetic solution of a given concentration) depends upon the surrounding medium could be explained on three assumptions: (1) that 'bismuth and its congeners are absolutely repelled by the magnetic poles' and would be repelled regardless of the presence or absence of other matter in the field; (2) that iron would be absolutely attracted 'as a direct result of the mutual action of

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55. Cf. Faraday to J.B. Dumas, cited note 21 (p.241).

56. It will not be evident simply from the observation of an effect whether it is an action at a distance, a differential action, or due to some other cause. Cf. section 3.1.3.1.

[magnetic matter] and the magnets', and (3) that the observed motion of air in the field be 'considered as due to the travelling of the air to those positions which the magnetic or diamagnetic bodies tended to leave' (2437).[57]

Thus there is no action of the field on a gas. However, in the case of solutions of different strengths[58] the magnet acts directly but unequally on the test body and upon the medium surrounding it (2438). This immediately raises another question: is the behaviour of diamagnetic bodies in air due to 'any other reason, than that the air is more magnetic than they are, and tends to occupy the axial space'? (2438). In other words, could it be the case that air is really magnetic and that diamagnetic behaviour (so-called) is just a differential magnetic effect?

> It is easy to perceive that if all bodies were magnetic in different degrees [there being no diamagnetic bodies], forming one great series from end to end, with air in the middle of the series, the effects would take place as they do actually occur (2438).

On this interpretation the distinction between magnetic and diamagnetic materials would be abolished and the law of diamagnetic action would be explained on the assumption that the 'degree' of magnetism is just the strength of a tendency to move into regions of stronger magnetic action. Thus bismuth,

> goes from a strong to a weak point of action ... because that substance which is already at the place of weak action, tends to come to the place where the action is strong; just as in electrical induction the bodies best fitted to carry on the force are drawn into the shortest lines of action (2438, cf.1331,1566).

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57. Thus air (and other gases) would not be acted on by the field, and the observed motions would be explained by an application of Archimedes principle of hydrostatics to gaseous media (Williams, Michael Faraday: 421). This proves to be a secondary assumption which Faraday subsequently explains, cf. section 3.5.2.2.

58. Cf. supra, p.251 (fig.3.7).

As his reference to the analogy with electrostatic action suggests, Faraday does not take direct attractions and repulsions to be fundamental.[59]

There is one main obstacle to this interpretation. If all matter really were magnetic it would follow that air would have 'such power amongst other bodies to stand in the midst of them' and that rarefaction (or compression) of the air should render it 'more diamagnetic or ... altering its situation in the list' (2439, cf. 2424). Yet this is not the case. Further, 'such a view also would make mere space magnetic, and precisely to the same degree as air and gases' (2440).

Faraday's objection to this consequence is not that air, gases, and the absence of any matter 'have the same general relation to magnetic force'.[60] It is that

> it seems ... a great additional assumption to suppose that they are all absolutely magnetic, ... rather than to suppose that they are in a normal or zero state (2440).

The 'zero state' is a state of matter in which there is no disturbance of the normal distribution of the lines of force, i.e. no disposition to react upon that force by polarizing. Faraday rejects the possibility that all matter is magnetic, and inclines

> to the opinion that diamagnetics have a specific action antithetically distinct from ordinary magnetic action, and have thus presented us with a magnetic property new to our knowledge (2441).[61]

In August of 1846 Faraday defended this interpretation against E. Becquerel's claim that the repulsive action that Faraday had distinguished as a diamagnetic action is really just the result of a

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59. Cf. supra, pp.142-43 (note 72), and infra, sections 3.5.2.1, 4.3.1.

60. Space is the absence not of properties but of the (active) sources of those properties. See infra, section 3.5.3 (p.324 ff.).

61. But see infra, p.306.

differential action (of the sort discussed and rejected by Faraday in his twenty-second series (2438)).[62] He repeats his objection that if all matter is magnetic and the action is a differential one, then there will be no 'zero point' between magnetic and diamagnetic matter. It would follow that space must have some magnetic properties, and Faraday 'cannot help looking upon a vacuum as presenting a zero point in the phaenomena of attraction and repulsion', where space--the absence of matter--is that state or condition of things in which the lines of the field have their normal or 'quiescent' form.[63]

Here two points must be made. First, when Faraday does discover that gases do have magnetic and diamagnetic properties, he does not abandon his present position as regards the condition of space as the 'zero point'. This suggests that he had not really been convinced that gases are really equivalent to space in this respect. Hence the second point: whereas in 1838 Faraday had refused to accept the verdict of experiment on the question of the magnetizable nature of various materials[64] he has apparently been prepared to accept the fact that gases exhibit no magnetic or diamagnetic properties--i.e., that they have not been proven to be absolutely magnetic or diamagnetic in the way that iron and bismuth are.

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62. For Becquerel's work see Williams, Michael Faraday: 420-22. Becquerel's father (Antoine Becquerel) had observed the effect which Faraday calls diamagnetic repulsion in 1827 but had, in Faraday's opinion, missed 'the discovery of the great principle and fact, and ... fall[en] into old and preconceived notions' (Faraday to C. Wheatstone, 5 December, 1845, Corr. I: 471). Faraday's response appears in the second part of the paper cited supra, note 11 (p.237), at p.457 ff.

63. His stated reason for believing that this question cannot be considered open is the 'remarkable relation of a vacuum, and with it of those attenuated forms of matter, air, gases, and vapours ...' (op.cit. note 62, p.465).

64. Cf. section 2.4.2.

Faraday's main reason for supposing that gases would prove to have the same properties as matter in its denser states seems to have been his adherence to what he calls a law of continuity.[65] This may have been a rule of reasoning (to the effect that properties found together in a material in one state should be found together in other states of that same material),[66] or it may have derived from Faraday's inclination to accept an hypothesis such as Boscovich's (on which each atom has a characteristic force curve such that the presence or absence of certain properties is a function of interparticle distance).[67] Yet it is clear that his adherence to this principle (or the hypothesis which may have been behind it) was not unwavering. After stating his belief that gases may prove to be capable of assuming the 'new magnetic state' (2237) Faraday had remarked that

> we ought not too hastily to assume that the substances which in the solid and liquid state, possess properties even general in character, always carry these into their gaseous condition (2237).

The identity of the inductive capacitance of all gases, together with the hypothesis that 'magnetic action may be considered as a mere function of electric force' leads to the conclusion that the magnetic properties of all gases will be the same (if they exist at all (2445)). These considerations apparently outweighed Faraday's law of

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65. Cf. the 'Speculation' of 1844 (ERE III: 284, at p.290) and Faraday to Whewell, 9 November, 1844 (Corr. I: 427). By this law of continuity Faraday understood that properties could change only gradually, either in quantity or in nature.

66. Cf. section 1.3.4.3, esp. loc.cit. supra, p.89, and compare Faraday's letter to Whewell cited note 65.

67. Faraday's unwillingness to accept the identity of the inductive capacitance of different gases, his subsequent analysis of the conductivity of gases (supra, p. 159) and his present doubts about the magnetic indifference of gases (2237) suggest that this is the case.

continuity.[68]

This contrast between Faraday's conviction that gases would prove to have different inductive capacitances and his ambivalence on the question of their having any magnetic properties at all supports a general contention of this thesis: that Faraday's commitment to assumptions about the nature of force (the principles of unity, convertibility, polarity, and conservation)[69] was far greater than his commitment to assumptions about the nature of matter.[70]

3.2 Aether, Matter, and the Transmission of Force

When Robert Hare had objected in 1840 that Faraday's theory of electrostatic induction entailed the re-introduction of action at intermolecular distances[71] Faraday had responded by reaffirming his earlier position (of 1837), pointing out that

> with the meaning which I have carefully attached to the word contiguous ... I see no contradiction here in the terms used, nor any natural impossibility or improbability in ... an action [at sensible distances across a vacuum].

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68. This is not to say that he abandoned it. According to an account of 1854, Faraday had been impressed by the fact that electrolytes in the solid form can conduct electricity very slightly and had supposed that this power should exist in the fluid state as well--it being 'rather unphilosophical to admit it for the solid and then, without proof, to assume that it is absent in the liquid ...' (Faraday to A. de la Rive, 1 March, 1854, Corr. II: 718).

69. The supposed indifference of gases is compatible with conservation (for the gas is in a state of no action) and with polarity (because the interparticle forces are not supposed to be polar).

70. The former set of assumptions gradually displace the latter as Faraday treats matter more and more as a mere modification of the field. This can be seen most clearly in Faraday's final statement on the attempt to explain chemical change ('On the Conservation of Force', ERCP: 454 ff., esp. 461); cf. sections 3.5.2-3.5.3.

71. R. Hare, 'A Letter to Prof. Faraday ...', op.cit. note 37 (supra, p.123). For discussion see supra, pp.123-24 and 204 ff.

Faraday had also appealed to 'the modern view of the radiation and conduction of heat' as an illustration of his point that static induction at sensible distances could 'come under the same principles of action' as ordinary induction through a dielectric.[72] Faraday certainly believed that his own theory of induction and the transmission of electrical action was no less consistent on the question of intermolecular action than the then-accepted theories of light and heat,[73] and that the effects of the conduction and radiation of heat would prove to have the same 'principle of communication'.[74]

In 1845 Faraday gave a series of lectures on the theory of heat,[75] in which he emphasized that ignition is an action of contiguous particles,[76] that rays of heat and light produce effects (heat, light) only when they are stopped,[77] and the 'probability' of the analogy between the rays of light and of heat as suggested by Melloni.[78]

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72. 'Answer to Dr. Hare's Letter', op.cit. note 205 (supra, p.205). Faraday is probably referring to Melloni's theory of heat, on which the analogy between heat and light was emphasized (and their identity hinted at) and on which both are transmitted as vibrations in an intermolecular aether ('Memoir on the Free Transmission of Radiant Heat through different Solid and Liquid Bodies ...', Sci.Mem. 1 (1837): 1,39 and 'Observations and Experiments on the Theory of the Identity of the Agents which produce Light and Radiant Heat', Sci.Mem. 1 (1837): 388. Melloni's views were shared by Herschel, Mateucci, and others. See S.G. Brush, 'The Wave Theory of Heat', op.cit. note 182 (supra, p.198).

73. 'Answer to Dr. Hare's Letter', p.267.

74. Ibid. As Hamilton and Herschel realized in 1841, the analogy could be extended to the transmission of electrical action and even of matter itself (Hamilton, loc.cit. supra, p.186 (note155).

75. 'Professor Faraday on Heat. A course of four Lectures delivered at the Royal Institute', The Magazine of Science and School of Arts 6 (1845): 126,131,139,151,215.

76. Ibid., 131.

77. Ibid., 215. Thus they are just like lines of inductive action, which produce charge only at an interface (cf. supra, pp.141-43).

78. Ibid., 216.

Faraday's discovery of diamagnetic action in 1845 increased his confidence in the original theory of induction as much as it increased his hopes of developing a unified theory of electricity, magnetism, heat and light. In the concluding paragraphs of the twenty-first series he states that

> In reference to the manner in which ... electric force, either static or dynamic ... [is] transferred from particle to particle ... or across a vacuum, I have nothing to add to what I have said before (1641 &c) ... (2446).[79]

As he had done in his reply to Hare of 1840, Faraday adds that the possibility of action at a distance between particles 'can present nothing startling to the mind of those who have endeavoured to comprehend the radiation and the conduction of heat under one principle of action' (2446).[80]

These references to the wave theory of heat and of light in 1840 and 1845 suggest that there was a continuous development of Faraday's ideas between 1837 and 1848 and that during this period he was attempting to develop a wave-theory of the transmission of electrical force.[81] They are important because they foreshadow Faraday's later theory of the field, in which matter is defined simply as a region in which the lines of magnetic action are bent or refracted, (these lines being analogous to the rays of heat or of light). Between 1846 and 1848 Faraday develops the earlier idea that conductors and insulators are (respectively) regions in which the lines of electrostatic

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79. The reference to series 11 shows how little weight Hare's criticisms had carried.

80. Cf. loc.cit. note 73.

81. There is hardly any doubt that Faraday regarded the dynamical state of the electric force (the current) as a wave (cf. supra, sections 1.3.4.1, 2.4.1, 2.5.2). That there was a continuous development of his ideas during this period is argued in sections 2.6, 2.6.1, 2.7.

induction are made to converge or diverge by drawing an analogous distinction between (para) magnetic and diamagnetic bodies as regions of high and low conductivity for magnetic action.[82]

However, before making these final steps towards the unified theory of matter and the field Faraday has to come to terms with two problems. The first concerns the ontological status of the aether.[83] The second is the apparently anomalous nature of diamagnetic action. The fact that diamagnetics are always repelled and are never polarized suggested that this action is of a different nature or of a different order (2419) than ordinary magnetic action.

3.2.1 Faraday's 'Thoughts on Ray Vibrations'

Faraday deals with the first of these two problems in an impromptu lecture given early in April of 1846.[84] Whereas the intent of the lectures of January and February 1844 had been to show that force-atomism is superior to corpuscular- or point-atomism,[85] the present lecture is an exploration of the implications of this view. Faraday sets out to show that the transmission of forces of all kinds may be nothing other than a function of the lines of electric, magnetic, or other forms of power, and that the aether has neither explanatory nor ontological status as an entity distinct from matter.[86]

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82. Cf. supra, pp.141 ff. for the electrostatics case.

83. Faraday appears to have been the only leading scientist of the nineteenth century who was really unwilling to admit the existence of the aether; see infra, p. 268.

84. For the circumstances, see Williams, Michael Faraday: 380. The published version was requested of Faraday by the editor of the Philosophical Magazine, in which it first appeared. References will be to the reprint in ERE III: 447.

85. Cf. sections 1.2.1.1, 1.4, and 2.7-2.7.3.

86. Thus Faraday proves in 1846 what W.R. Hamilton had suspected in 1841 (Hamilton, loc.cit. supra, p. 186(note 155)).

On the dynamical view of matter the introduction of a separate medium for the transmission of force is unnecessary. This notion 'will dispense with the aether, which, in another view, is supposed to be the medium in which these vibrations take place' (ERE III: 447). On Faraday's view the 'ultimate atoms' of matter are centres of power and not 'so many little bodies surrounded by forces and capable of existing without them' (ibid.). Faraday's atoms do not have a definite form and finite extension, for

> that which represents size may be considered as extending to any distance to which the lines of force of the particle extend: the particle indeed is supposed to exist only by these forces, and where they are it is (ibid.).

Extension is identified with the ability of an entity to act (either by attraction or repulsion) and is represented by the lines of electrostatic or magnetic induction and of other powers of which it is an original and/or terminal point.[87]

Faraday now argues that it can be supposed that these lines are 'the seat of the vibrations of radiant phenomena' (just as they had been supposed to be the seat of the transmission of electrical action in the 1837 theory of induction).[88] The coincidence between the velocity of light and that of the transmission of electrical force could be seen as evidence for the identity of the two forms of force, but here Faraday argues for a more restricted point, that the mode of transmission of the two powers is the same:

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87. The lines of inductive or polar powers such as electricity (including chemical affinities) and magnetism will extend only as far as the nearest neighbouring particle (1616,1665), while those of cohesion, gravitation, and any non-polar powers may extend beyond such particles. See supra, p.114 (note 21) and section 2.2.1, esp. pp.121-22.

88. Cf. sections 2.3.1, 2.4.1, and 2.5.2.

> the light is supposed to be transmitted by vibrations through an aether ... the electricity is transmitted through a small metallic wire, and is often viewed as transmitted by vibrations also (ibid.: 448).

Faraday's theory of electric induction had incorporated a vibratory model of the current and thus supports the view that conduction is dependent upon 'the forces or powers' of the matter. Can light be shown to be 'existent in' the properties of the matter, or must the existence of an imponderable medium distinct from matter be admitted?

Faraday believes that the aether is unnecessary because its explanatory role in optical theory can be performed by matter itself. He shows first that the accepted distinction between manner (as something ponderable) and aether (as an imponderable) is an illusory one. The aether is simply an attenuated form of matter, a system of centres of force having fewer properties than those of a material (ponderable) system of forces.

3.2.1.1. Aether and matter

Whichever theory of matter one adopts, the 'matter of the aether' and that of an ordinary electrical conductor are 'alike in their essential constitution'. Both should consist of 'little nuclei, considered in the abstract as matter, and of force or power associated with these' or both should consist of 'mere centres of force, according to Boscovich's theory and the view put forth in my speculation ...' (ibid.). According to Faraday each of these models is applicable to both aether and matter because 'there is no reason to assume that the nuclei are more requisite in the one case than in the other'. But if, as Faraday had argued in 1844, the atoms can be known only as their powers, both aether and matter must be systems of centres of force.[89]

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89. By 'force' Faraday understands a quantity of action and he takes this to be causally prior to force in the mechanical sense. Cf. sections 1.3.3.1,1.3.4.1.2, 1.4, 2.2.2, 2.5.1, 2.7.3, etc.

While it is true that 'the copper gravitates and the aether does not, and that therefore the copper is ponderable and the aether is not' this difference 'cannot indicate the presence of nuclei in the copper more than in the aether' (ibid.). In addition to their chemical, electrical, thermal, optical, and other properties, material particles have inertial and gravitational powers. Those of the aether possess only that power which produces infinite elasticity. Thus, if both matter and aether consist of (extended) atomic nuclei, those of the aether must 'have in this respect proportionately more of the nucleus and less of the force' (ibid.: 449).[90]

This argument is meant to show that ponderability cannot be taken to be a criterion of materiality. It is aimed, apparently, at those like Robert Hare who had objected (to Faraday's argument of 1844) that his unwillingness to admit one or two 'imponderable principles' had led him to admit 'a much greater number' by denying the distinction between material powers that are imponderable and those that are not.[91]

Faraday holds that 'materiality' consists in the forces or powers rather than in substantial bearers of those powers.[92] Thus properties such as elasticity, inertia, gravitational mass and cohesive powers are not inherent or essential qualities. They are 'due not to the nuclei, but to the force superadded to them, if the nuclei exist at all' (ibid.). The fact that matter has more properties than aether does not entail any difference in the materiality (ponderability) of each: the imponderable aether is just as material as matter:

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90. If the distinction between atoms and their powers is maintained then the aether atoms are 'more material ... than the matter of [the earth]' because their powers are fewer and less extensive than those of ponderable matter (ibid.: 448-49).

91. 'Dr. Hare's Remarks ... on a recent Speculation by Faraday ...', op.cit. note 248 (p. 220): 604 ff., esp. 607.

92. Cf. section 2.7.1.

> the infinite elasticity assumed as belonging to the particles of the aether, is as striking and positive a force of it as gravity is of ponderable particles, and produces in its way effects as great; in witness whereof we have all the varieties of radiant agency as exhibited in luminous, calorific, and actinic [photo-chemical] phenomena (ibid.).

Faraday is simply adhering to the epistemological position defended in 1844, on which phenomenal or secondary properties can be taken as evidence for the existence of forces or powers as the immediate causes of those properties. Thus, optical, thermal, and photo-chemical phenomena are taken to be effects of particular kinds or forms of force or power.[93] The conclusion of this line of reasoning is that even on the 'received notion' of the aether, the aether is 'but force or centres of force' (ibid.: 449).[94] The fact that the aether does not have 'gravitation or solidity' is not to the point:

> but what are gravitation and solidity? Certainly not the weight and contact of the abstract nuclei. The one is the consequence of an attractive force, which can act at distances as great as the mind of man can estimate or conceive; and the other is the consequence of a repulsive force, which forbids forever the contact or touch of any two nuclei ... (ibid.)

If all properties are the manifest effects of active powers, then the aether differs from matter only in respect of the number of powers that it has. That matter has a larger number of properties

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93. 'In experimental philosophy we can, by the phaenomena presented, recognize various kinds of lines of force; thus there are the lines of gravitating force, those of electro-static induction, those of magnetic action, and other partaking of a dynamic character might perhaps be included' (ibid.: 450, my italics).

94. In the Queries to the Opticks, Newton had introduced two conceptions of the aether. In the 21st query of the second edition (1717) he describes an aether composed of mutually repulsive particles (pp.251-52 of the 4th edn. (1730)) and, in the 28th query, compares this 'rare Aetherial medium' favourably with a 'dense Fluid' which 'can be of no use for explaining the Phaenomena of Nature ...' (ibid.: 368).

> should not ... lead those persons who conceive of the aether as a thing consisting of force only, to think any otherwise of ponderable matter, except that it has more and other forces associated with it than the aether has (ibid.).

Here Faraday has applied to the aether the same reasoning that he had applied to 'abstract' matter in his speculative lectures of 1844: he has argued not for the elimination of a theoretical concept but for the elimination of the aether as a theoretical (or real) entity distinct from matter.

This last point is important in view of the fact that Faraday subsequently refers to the aether on several occasions, particularly in the context of discussions of the ability of empty space to conduct the lines of magnetic induction.[95] Although these later references have been interpreted as indicating a shift towards the notion of the aether (as an entity distinct from matter),[96] it is probable that Faraday continues to use the term as defined here: as having the same sort of referent as the word matter.[97] In this respect his references to the aether are like his references to action at a distance: they imply neither his abandonment of an earlier position nor his adoption of concepts appropriate to rival theories. Faraday has clearly redefined these terms (or 'restricted' their sense) in the

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95. Cf. (3263,3301) and Corr. II: 780,805,876.

96. See, for example, Maxwell's Treatise on Electricity and Magnetism II: 432 n.; Whittaker, Aether and Electricity: 194; and Williams, Michael Faraday: 470 ff.

97. Williams overlooks the fact that Faraday's rejection of the aether involves identifying aether and matter as systems of force-atoms and consequently misinterprets Faraday's investigation of the interaction of aether and matter of 1856 (Michael Faraday: 471-72; cf. Berkson, Fields of Force: 99). The manuscript on 'The Hypothetical Ether' which Williams reproduces at pp.455-56 (and which he dates at 1850 or later) is remarkably similar to the 'Ray Vibrations' of 1846. Faraday's later investigations on the optical properties of colliodal suspensions only reconfirmed his conviction that the elementary particles must be 'likened rather to centres of force than solid atoms' (Diary: (14407) or Williams, op.cit., p.472).

way that his epistemological and regulative principles require.[98]

3.2.1.2 The transmission of force

Having shown that from an epistemological standpoint aether and matter must be supposed to be the same sort of thing, Faraday now shows that the explanatory function of the aether can be fulfilled by the lines which represent the active powers of the centres of force. There will be a set of lines for each form of power.[99] As the electric current may be regarded as a vibration in a line of electrostatic induction, so light and heat may be explained as vibrations in the lines of electric, magnetic, or gravitational force.

The lines may exist as a series of centres of force, or may be independent of centres, proceeding 'through space' where those centres are absent.[100] There are two possible situations in which such lines would exhibit a lateral vibration. Taking two bodies 'under mutual action, and therefore connected by lines of force' and fixing 'our attention upon one resultant of force, having an invariable direction as regards space', it is evident that a lateral excursion of a point on the line may consist either in the lateral motion of a centre of force or in a lateral shift of the power (field) of that centre (ERE III: 450). A vibration is the periodic variation of the value of some quantity with time (as observed at a fixed point and measured relative to the values of that same quantity at neighbouring members of a series of points). This variation may consist either in the the motion of force-atoms in planes perpendicular to a line drawn through their centres (as shown in figure 3.8a) or in a similar change

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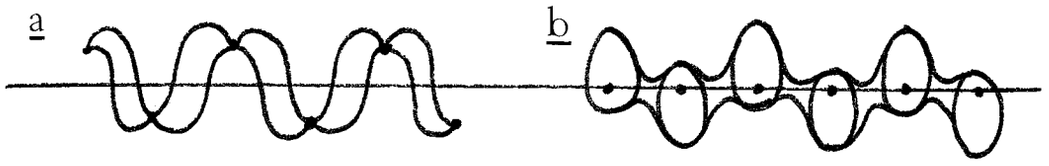
98. Cf. sections 2.2.1 and 2.2.3.

99. Loc.cit. supra, note 93.

100. For the development of this idea see infra, section 3.5.3.

FIGURE 3.8



in the distribution of force about centres which are supposed to be fixed (as in figure 3.8b). In either case the 'lateral disturbance' consists in a lateral excursion of the normal distribution of force about a centre, and 'the resultant upon which we are fixing our attention ... will [either] increase in force whilst the neighbouring resultants are diminishing, or it will fall in force as they are increasing' (ibid.). Faraday's point is that from the standpoint of what it is possible to know, the two models are equivalent: both processes can be defined in terms of what would happen at a specified set of points, at 'resultant(s) of force, having an invariable direction as regards space'.

Faraday now turns to the problem of specifying a physical basis for this lateral action of the lines of force. This can only be force itself:

> I do not perceive in any part of space, whether (to use the common phrase) vacant or filled with matter, anything but forces and the lines in which they are exerted. The lines of weight or gravitating force are ... extensive enough to answer in this respect any demand made upon them by radiant phenomena; and so, probably, are the lines of magnetic force ... (ibid.)

Radiant phenomena could be reduced to the original theory of induction as the phenomena which accompany vibrations (successions of inductive tensions and discharges) in the lines of force. Thus heat and light will not be as fundamental as the electric and magnetic forces of the particles of matter,[101] but can be explained without introducing any

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101. The secondary status as modifications in the form of the lines of electric or other forces would be consistent with the fact that while they can effect chemical and other changes in the state of a body, they do not (apparently) produce the 'dynamical effects' that electrical, magnetic, and gravitational forces can.

new entities or powers into the theory.

The lines of force must have some property corresponding to the 'assumed high elasticity of the aether' for they must be equivalent to the aether ('in respect of the time known experimentally to be occupied in the transmission of radiant force'). To be functionally equivalent in this respect the lines would have to be 'sluggish enough in their action' that lateral excursions of any point of the line would occur at a finite rate (ibid.: 451).

By introducing the idea of 'sluggishness' Faraday sidesteps the problem of having to decide whether or to what degree the lines are elastic, but does appear to attribute inertial mass to the lines themselves.[102] However, the inertial behaviour of an element of the line could be attributed to the elementary force-relations that exist between all points of the field as the normal or 'undeveloped' state of the powers.[103] Such behaviours (as inferred from a finite rate of propagation of an action) are due to a relational property, viz. a property which a point 'possesses' in virtue of its being part of a system of dynamical couplings between itself and other points.[104]

The main advantage of Faraday's proposed theory is that it promises to incorporate a whole range of radiant phenomena into a theory which has already been successfully applied to the chemical, magnetic, and inductive effects of electric forces. Faraday believes that any 'satisfactory' theory of radiation must explain the optical, thermal,

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102. --or perhaps, to force itself.

103. Cf. supra, p.126, sections 2.4.1 (table 2.1) and 2.7.3.

104. For Faraday's response to G.B. Airy's criticism that inertial behaviour can be explained only if inertial substance is assumed to exist, see section 3.4 (infra, p.300).

and photo-chemical effects of radiation.[105] Hence his own view

> which is in some degree founded upon the ordinary forces of matter, may perhaps find a little consideration amongst the other views that will probably arise (ibid.).

A theory based upon the 'ordinary forces of matter' has a better chance of proving to be a unified theory of the particles of matter. It has the advantage, too, of being a theory about a single fundamental entity whose laws are readily accessible to experimental investigation (in a way that those of the hypothetical aether are not).

3.3 Matter and the Magnetic Field: the problem of polarity

In his 'Thoughts on Ray Vibrations' Faraday has indicated the direction which physical theory should take. In view of the development of his own unified theory of the electric and magnetic field and Maxwell's application of it to light, that paper proves to have been an accurate proposal. Yet the proposals made there are far in advance of the actual state of theory in Faraday's Experimental Researches. He has still to explain how it is that magnetic action, which is polar or inductive at sensible distances, does not polarize diamagnetic materials. Only by 1850 does Faraday acquire enough additional experimental information about the nature of magnetic action to develop a theory on which this problem is solved and on which the interaction of matter with the field can be explained without

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105. M.A. Sutton has pointed out that Herschel (who was a point-atomist and probably a Boscovichean) and Faraday were silent about the problem of explaining spectral phenomena on such a theory ('Sir John Herschel and the Development of Spectroscopy in Britain', BJHS 7 (1974): 42, esp. 54 ff.). Hamilton had attempted to explain these on the basis of a force-atomistic model in 1839 (Hamilton to Herschel, 8 February, 1839, in Hamilton's Mathematical Papers 2 (London, 1940): 599). For Herschel's endorsement of Hamilton's 'metaphysical' atomism see Phil.Mag. 21 (1842): 409, at 410-11, the Athenaeum (30 July, 1842): 687, or Graves, op.cit. note 136 (supra, p.94), II: 389-91.

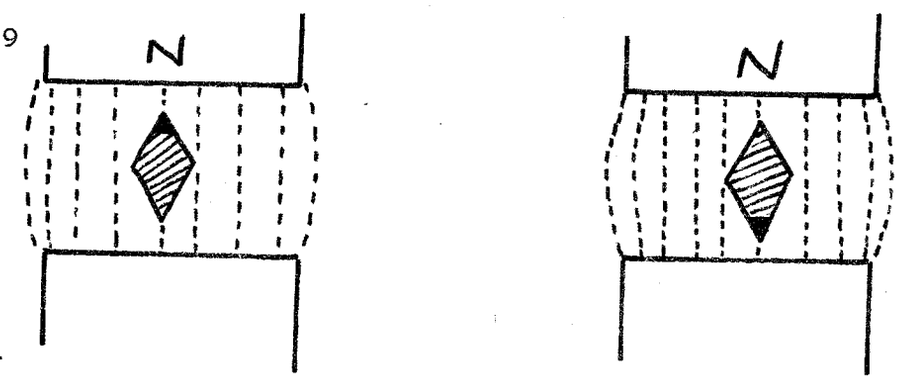
recourse to hypotheses about interactions between the field and individual elementary particles.

3.3.1 Postulate versus Observation: diamagnetism and molecular structure

In the twentieth series Faraday had pointed out that in diamagnetic action there is always a repulsion of the matter without the induction of poles, for 'either pole will repel the substance, and both poles will repel it at once' (2274). There is no molecular polarization of the matter and diamagnetic action does not involve the attraction and the repulsion of poles that is characteristic of ordinary magnetic action. In the opening paragraph of the twenty-second series of October 1848,[106] Faraday confesses that he has been 'embarrassed' by the behaviour of bismuth and other diamagnetic materials, and has been either 'contented with an imperfect explanation, or have left them for a future examination' (2454).

Cylinders of bismuth had been found to point or set either axially or equatorially when suspended horizontally in the field, but all were repelled from the nearest pole when suspended vertically (2456-57). Whereas Faraday had originally found that a crystal of bismuth could be made to align itself across the lines of force in either of two directions[107] he has since found that a crystal of bismuth may also assume a stable position along the lines of force in either of two positions (see figure 3.9). Faraday calls this a 'diametral' set or

FIGURE 3.9



106. 'On the Crystalline Polarity of Bismuth (and other bodies)', ERE III: (2454-2638), completed October 1848; read: 7 December, 1848.

107. Cf. (2253 ff.) or **Supra**, pp. 246-47.

position (2461) and is convinced that this behaviour 'is dependent on the crystalline condition of the substance' (2460).

He is led to this conclusion because 'amorphous' (non-crystalline) bismuth behaves simply as a diamagnet (setting across the lines of force) while the metal in its crystalline form can set along the lines of force in either of the two positions shown (fig. 3.9).[108] Evidently it is neither magnetic nor simply diamagnetic (2464). Faraday believes that such differences in behaviour must be attributed to some new power possessed by the metal only in its crystalline form. He posits a 'new force, or a new form of force, in the molecules of matter' which, 'for convenience sake' he designates as 'the magnecrystallic force' (2649).

Why is crystalline bismuth affected in a uniform field while non-crystalline bismuth is not? How can it set as a magnetic material would, yet in either of two positions and without being polarized? This new phenomenon is consistent neither with the law of diamagnetic action (2269,2418) nor with Faraday's concept of force as an inductive action.[109] Whereas in his Researches of 1833 and 1837 Faraday had been guided in his interpretation of experience by the principle that force is a quantity of power consisting of two equal and opposed actions or tendencies, the phenomena do not appear to admit of an interpretation in terms of this principle here.

Yet Faraday does attempt to interpret phenomena such as these in terms of the concept of polarity. This attempt lasts for two years. During this period Faraday is able to show that the polar or inductive

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108. Faraday takes the field to be a uniform field. The surfaces of the poles of the electromagnet are large relative both to the distance between them and to the dimensions of the test bodies. Cf. (2464).

109. See part II, esp. sections 2.2.1 and 2.4.2.

nature of magnetic action can be preserved, provided that the field is supposed to interact with the matter as a whole rather than upon each individual particle of the matter.

3.3.1.1 Magnecrystallic action

Faraday had been obliged to suppose that the new crystalline force is non-polar (and, therefore, capable of acting at distances greater than those which separate elementary centres of force).[110] The 'magne-crystallic' power had been posited as the outcome of a long series of experiments that Faraday had been led to make by applying the principles of unity and of the equality of action and reaction to the magneto-optic and diamagnetic effects discovered in 1845.[111]

First, since diamagnetic repulsion indicates an interaction of magnetic action and matter (in which a state of strain is produced) there should be both a reaction of the diamagnetic matter on the magnet and the production of an induced current in the diamagnetic as this state of strain is established or relieved.[112] Second, since the magneto-optic effect shows that there is a direct interaction between magnetism and light (and since magnetism is simply a 'function' of electric force (2445)) light passed through a helix should induce a current and, since the rays are polar, two rays having opposite

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110. Cf. infra, p.282 (note 131).

111. These experiments were not reported in the Experimental Researches. For the background see Williams, Michael Faraday: 408 ff.

112. Williams, Michael Faraday: 412. As pointed out in section 1.3.4.2.1 (p.83) Faraday tends to identify the possession of a power with the assumption by matter of an active state of tension equivalent to a quantity of motion. In other words, a body may be attracted or repelled by a force, or it may be polarized (or both; cf. section 2.5.1 and (2417-19, 2447)).

polarities should cancel or neutralize each other's action when passed in opposite directions along the axis of the helix.[113] Finally, since certain crystals and certain organic compounds can rotate the plane of polarization of light, there should be some connection between the molecular forces which produce this effect naturally and the magnetic forces which can create or 'superinduce' the same action in transparent diamagnetics.[114]

From the negative results of experiments on these possibilities[115] it seemed to follow that the natural rotation of a polarized ray could not be due simply to molecular currents or to some power of the elementary particles, since it was accompanied by diamagnetic repulsion only in crystals. The term 'magnecrystallic' force is introduced to distinguish the possible cause of the 'diametral' setting of crystals (2460) from both the rotatory power induced in diamagnetics and from a new force discovered by J. Plücker in 1847.[116]

Plücker had shown that the optic axis of the crystal[117] is 'repelled' but that the mass of the crystal is not attracted or repelled.[118] Plücker also believed that he had shown that the same

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113. Williams, Michael Faraday: 411, Faraday to Herschel, 22 December, 1845 (Corr. I: 475), and series 21 (2428).

114. Cf. Herschel to Faraday, 9 November, 1845, Corr. I: 461. An attempt to detect a relationship between molecular tension and optical action (performed on Herschel's behalf) did not yield positive results (Corr. I: 473 and 483).

115. Faraday succeeds in obtaining only the first effect, and then only with crystalline dielectrics (2564-68).

116. 'On the Repulsion of the Optic Axes of Crystals by the Poles of a Magnet' (1847), trans.: Sci.Mem. 5 (1852): 353. In November of 1847 Plücker sent Faraday this and a second memoir, 'On the Relation of Magnetism to Diamagnetism' (trans. Sci.Mem. 5 (1852): 376). See Corr. I: 511, 513.

117. --that is, the line or plane in which double refraction does not occur. Faraday takes this to be an axis or plane of no action in which the powers of the matter do not interact with the action carried by the ray(s) of light. Cf. section 3.3.1.1.

118. 'On the Repulsion of the Optic Axes ...' (op.cit. note 116): 353 ff.

piece of matter could behave either as a magnet or as a diamagnet, depending upon its distance from the two poles of a magnet.[119]

The importance of Plücker's discovery is that in rejecting Plücker's interpretation of it Faraday is to appeal to an idea which later emerges as a fundamental assumption about the nature of matter-field interactions: that matter always moves or aligns itself in the field so as to produce the minimum degree of distortion of the lines of force from their normal (equilibrium) form.

Plücker visited Faraday at the Royal Institution in August of 1848, one month before Faraday completed the twenty-second series of his Experimental Researches. They repeated the experiments[120] but Faraday was unwilling to interpret the results as Plücker did. He continued to reject the idea of a differential action resulting from a combined magnetic attraction and diamagnetic repulsion of each particle of the mass.[121] He supposed instead that because the optic axis is a line in which light is not doubly-refracted in a crystal, it is a line of inaction or of least action along which the magnetic action of the field would not be conveyed as readily as it would be in other lines or planes: hence a crystal in a uniform field aligns itself so that this line or plane is perpendicular to the

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119. 'On the Relation of Magnetism to Diamagnetism' (op.cit., note 116): 378 ff. Plücker subsequently identifies magnetic, diamagnetic, and the repulsive action ('On the Theory of Diamagnetism ...', Sci.Mem. (1853): 332).

120. Cf. (2594) and Corr. I: 526.

121. He wrote to Whewell in December of 1848 that 'I have formed no final opinion on [Plücker's] conclusion ... But this I think I know as a fact that no degree of power can make the magnetic & diamagnetic bodies change places or the individuals of the one class into the other' (Corr. I: 535).

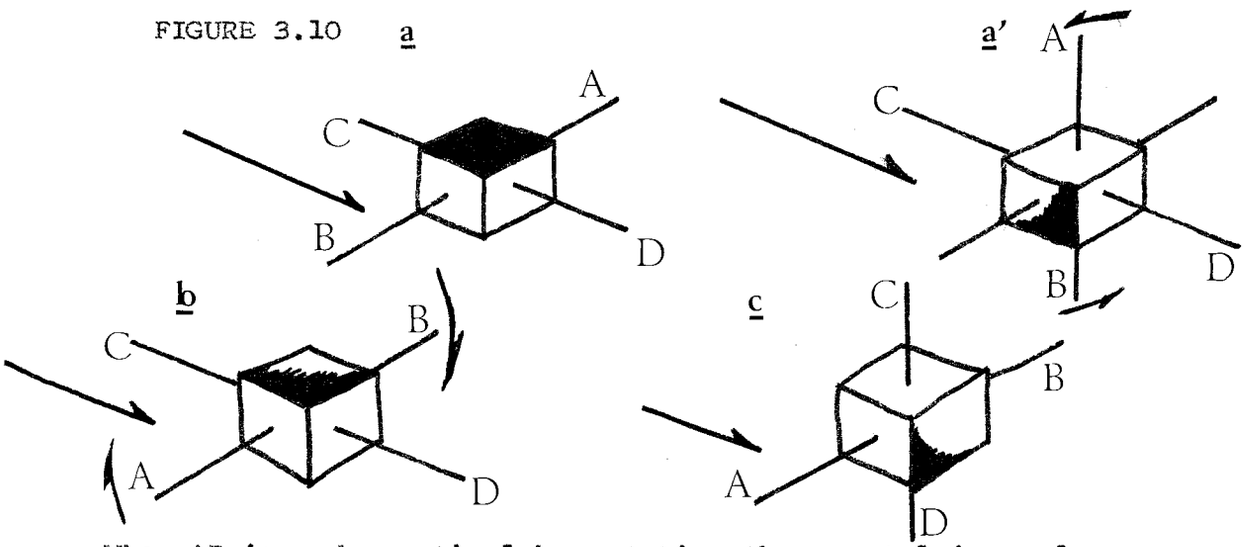
lines of magnetic force.[122]

The effect is complex. Faraday's clearest description of it appears in a letter to Whewell of 7 November, 1848:[123]

> If a crystal of bismuth be suspended by a filament of cocoon silk between the horizontal poles of a horseshoe magnet ... the crystal vibrates and points [as shown in figure 3.10a]. If the line through the crystal which is then horizontal and equatorial [AB] be made vertical the crystal again points & now with its maximum degree of force [fig. 3.10b]. If the line which is now horizontal and AXIAL [CD] be made vertical, the crystal is indifferent or it is simply repelled as a diamagnetic body out to be [fig. 3.10c]. The form of the piece of bismuth goes for nothing in this experiment the effect depends altogether upon the crystalline structure.

Faraday first allows the crystal to align itself so that the axis CD is along the lines of force and AB is perpendicular to them (a).

FIGURE 3.10



When AB is made vertical by rotating the crystal in a plane perpendicular to the lines, the crystal will tend to turn in this plane until AB is again horizontal (b). However, if the axis CD is now made vertical the crystal will not point, but will be repelled as any non-crystalline material is.

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122. Cf. infra, p. 281, Williams, Michael Faraday: 413, and entries from the laboratory Diary cited there. It would follow that crystalline and electrical forces are definitely related (as Whewell had suspected in 1835, Corr. I: 299).

123. Corr. I: 528, cf. (2470-71).

This suggested to Faraday that there is an axis in the crystal which tends to align itself along the lines of force: 'the line [CD] ... may now be taken as a line of force' (2470) along which the magnetic action passes most easily. The crystal is repelled when the line CD is not parallel to the lines of the field because the field acts either upon the crystal as a whole or else induces some force in the crystal which causes it to point.

Faraday concludes that the determining or 'directing force' is along the lines of magnetic action (i.e. along the axis CD), and that it is 'resident in the particles of the crystal' (2472). Since the crystal can point about the axis CD in either direction it appeared that

> either end of the mass or of its molecules is ... both in these phaenomena, and in the ordinary results of crystallization, like the other end ... (2472)

Faraday chooses to call this directive force an axial force rather than a polar one, because it leads to an alignment or set without either the induction of poles in the crystal or the repulsion or attraction of the crystal as a mass (2472).

These effects suggested a further coincidence between magnetic, optical, and crystalline powers. The optic axis is that line in which no double refraction occurs but is also in the plane in which no rotation of the plane of polarized light will occur.[124] Faraday had shown that magneto-optic rotation will occur only when the rays of light are parallel to the lines of magnetic force (2159). He had found that the crystals almost always aligned themselves so that their longest diameter is parallel to the lines of force (2474-76). This

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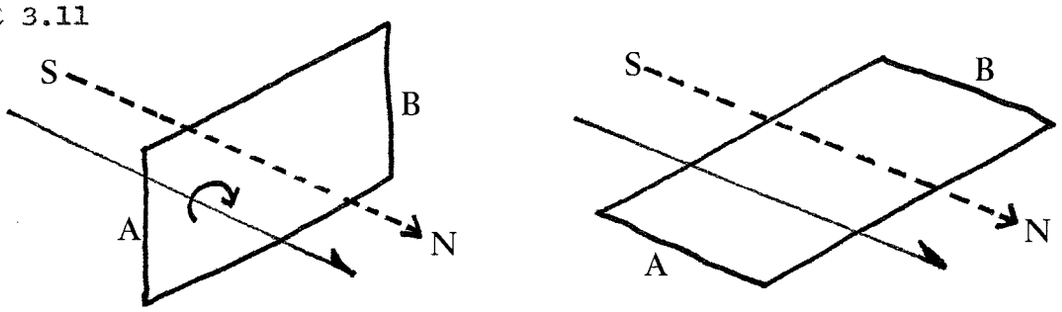
124. The plane perpendicular to the lines of force in a piece of optical glass is a plane of 'no action of light' while the optical plane of a crystal is a line or plane of 'no action' (Diary: (9385)).

line is the line of magnecrystallic force, and is perpendicular to the optical axis or plane of the crystal.

The facts may be summarized, with the help of figure 3.11, as follows: (1) a crystal aligns itself in the field so that its optical axis (line or plane of least action upon light, AB) is perpendicular to the lines of force; (2) magneto-optical rotation occurs only if the rays are passing parallel to the lines, well out of the plane AB. This suggested first that the pointing of the crystal and

FIGURE 3.11



the magnetic rotation induced in it are connected, and second, that in non-crystalline bodies the magnetic field creates or induces an optical plane.[125] Thus Faraday is led to identify the magneto-optic and diamagnetic effects, but to distinguish their immediate causes: in crystals the rotatory effect 'is not an optic force ... dependent on the direct action of light, but a physical force existent in the crystal' which is independent both of light and of a magnetic field.

Both the law of rotation (2160) and the pointing of crystals can be explained on the assumption that the crystalline strain which produces double refraction and which is least (or non-existent) along the optic axis is identical to the condition induced by a magnetic field in non-crystalline bodies, where the latter will have a maximum in a plane parallel to the lines of force. It follows (as Faraday had realized in August of 1848) that

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125. 'Hence the phenomena are probably one in their general nature, i.e. the magnet induces an optic plane, whereas crystals have naturally optic axes ...' (Diary: (9386)).

> both the magneto-optic and the induced optic forces are in their most natural position when in the equatorial plane, for the one which is not induced takes that plane and the other, which is induced, is induced in that plane.126

The observed behaviours of all diamagnetics could now be explained on the assumption that they tend to assume a position in which the action of the field (which is to increase the crystalline strain or to induce one where none exists) is minimized.[127]

In the twenty-second series Faraday summarizes the behaviours of crystalline diamagnetics in terms of a law of action. Given that the magnecrystallic forces interact with the field to produce an alignment rather than a repulsion (where the optic axis or its equivalent in an opaque body is not parallel to the lines of force), the law is that

> the line or axis of MAGNECRYSTALLIC force ... tends to place itself parallel, or as a tangent to, the magnetic curve or line of magnetic force, passing through the crystal ... (2479)

In other words, the crystal will move so that its 'final position ... in the magnetic field may be considered as that of the least constraint' (2502, my italics).

Faraday has now made explicit an idea which had been hinted at in the theory of electrostatic induction[128] and which is to become one of the main explanatory assumptions of his general theory of electric and magnetic action.[129] The problem had been to explain how an axial set can occur without either the induction of poles or the apparent exertion of an attractive or repulsive force. Although

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126. Diary: (9442, my italics).

127. Cf. Williams, Michael Faraday: 415.

128. Cf. supra, pp.141-43 and 156.

129. Cf. infra, pp.309 ff. and section 4.3.1.

in the explanation that Faraday gives here the interaction is supposed to involve the creation of a state of molecular strain in matter (if one does not already exist), Faraday later redescribes this interaction in terms of the ability of the matter to bend or refract the lines of force.

Faraday believes that he has found an avenue which may lead to a theory which incorporates both magnetic and cohesive or crystalline forces. Yet he is still confronted by the fact that while magnetic forces are polar actions at sensible distances (and should therefore act only between contiguous particles), crystalline forces are non-polar and may therefore act over distances greater than those separating contiguous particles.(2563,2472).[130] It follows that the crystalline molecules cannot be represented by 'the condition of a parcel of iron filings between the poles of a magnet' (2563). Moreover, the crystal can 'react upon and affect the magnet at a distance' (2567,2565-66).[131]

While demonstrating the existence of this ability of the crystal to repel the magnet Faraday had asked:

> How are the lines of magnetic force affected backwds. in this action and what are these lines? Are they lines of contiguously acting particles?--or are they like lines of gravitating force or rays of light?[132]

Williams has suggested that this reference to optical and gravitational

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130. Cf. (1628,1665) or supra, section 2.4.2.

131. This is an 'action at a distance' in two respects. First, the crystalline forces are effective at a place some distance from their point of origin (in the arrangement of the elementary particles 'and their forces' (2576)). Second, the crystalline force is non-polar and can act over distances greater than those separating contiguous particles, being in this respect like those of cohesion and gravitation (523,1231). Faraday had been persuaded of this by his observation of the formation of crystals in a supersaturated solution (2578, cf. 2568).

132. Diary: (9912), cited by Williams, Michael Faraday: 418.

actions signifies an important shift in Faraday's thinking away from the idea that the transmission of force is necessarily an inductive action between contiguous particles.[133] Yet Faraday has always admitted that cohesive and gravitational forces may not be polar and may, therefore, act at a distance by non-contiguous action (and without polarization).[134] He has tended to deny action at a distance only in those cases where he has been able to prove that the action in question is polar or inductive at all orders of magnitude.[135] That Faraday does not give up the notion of polarity or induction is clear from the fact that his attempt to detect a relationship between gravitation and electricity presupposes that the former force will act inductively as the latter does.[136] Thus I do not believe that Faraday's reference to gravitational action signifies that he is about to modify his ideas on force 'to a considerable extent' between 1848 and 1850.[137] This is supported by the fact that Faraday relies heavily upon the concept of polarity in his final defence of the physical theory of the field in 1852.[138]

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133. Williams, ibid.: 419.

134. E.g., (523) and (1231); loc.cit. supra, p.133.

135. Thus even electrostatic forces were not assumed to act by contiguous particles in 1831 (73). Cf. note 21 (supra, p.114).

136. Cf. infra, section 3.4.

137. Williams, Michael Faraday: 418-19.

138. He does, however, distinguish the concept of polarity from that of contiguity (local action). Cf. section 3.5.2.2 and part IV.

3.3.2 Towards a solution

In October of 1848 Faraday is confronted with an action which does not admit of an interpretation in terms of magnetic force as an essentially inductive action: the alignment of a crystal in the field does not involve the creation of poles, nor does it involve any attraction or repulsion of the centre of mass of the crystal. Faraday's solution to this discrepancy between his principle of induction and the fact of magnecrystallic action emerges from his attempt to provide an unequivocal interpretation of the magnecrystallic effect, i.e. to show that Plücker's and Weber's interpretations of this action and of diamagnetic action generally cannot be correct.[139]

Faraday does not want to admit that there is a direct attraction or repulsion either of the mass of the crystal or of the individual particles; nor does he admit that diamagnetics really are polarized in the way that an application of Ampère's theory would suggest.[140] Instead of appealing to the idea of molecular polarization (which cannot explain magnecrystallic action (2562-63,2586-90), he now suggests that the analogy between the transmission of light and heat and the conduction or transmission of magnetic force may provide a final solution:

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139. For Plücker's interpretations see the papers cited supra (notes 116 and 119) and his letter to Faraday of 8 December, 1849 (Corr. II: 567). For Weber's theory of diamagnetic action see infra, section 3.3.2.1.

140. In his reply to Plücker's claim (in the letter cited, note 139) that he had 'new proofs of diamagnetic polarity' and that Ampère's theory could explain diamagnetic polarity, Faraday stated his belief that the susceptibility of a crystal to magnetic action 'depends upon its internal structure--or rather on the forces which give it its particular structure' (Faraday to Plücker, 11 December, 1849, Corr. II: 569, Faraday's italics). Again the emphasis is on powers rather than upon the use of structural models (cf. section 3.3.2.1 and supra, p.244 (note 28).

> I cannot resist throwing form another view of these phaenomena which may possibly be the true one. The lines of magnetic force may perhaps be assumed as ... resembling the rays of light, heat, &c.; and may find difficulty in passing through bodies, and so be affected by them, as light is affected (2591).[141]

Thus in crystals the magnecrystallic axis is the line or plane in which lines of force 'pass more freely, or with less disturbance, through' the matter than they would do in other directions.

> In that case, the position which the crystal takes in the magnetic field with its magnecrystallic axis parallel to the lines of magnetic force, may be the position of no, or of least resistance; and therefore the position of rest and stable equilibrium (2591).

There is no 'mechanical force' (2586) acting upon the mass or upon its individual particles, as Weber and Plücker supposed. The 'cause' of the alignment is the tendency of the matter to assume that position of least interaction or reaction upon the lines of force; i.e., that position in which it can most easily conduct or transmit the lines of force. The explanation of the observed behaviours therefore consists in supposing:

(1) that crystalline (and possibly other materials) have axes of greatest and of least conductivity for magnetic as well as for optical actions, and

(2) that they will tend to assume a position such that the interaction of matter with the field (viz. the disturbance of the field by the matter) is at a minimum.[142]

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141. Cf. (2446) and supra, section 3.2.

142. I shall refer to this supposition as a principle of economy or of least action. This assumption is made not about an individual (the diamagnetic bar) but about the interaction of two individuals. The field tends to take the path of least resistance (viz., through that line or plane in which the matter does not react upon the force by polarizing) while the matter tends to assume that position in which the path of least resistance is parallel to the lines of force. See section 3.5.2.1.

The first supposition is based upon an analogy between the optic axis and the magnecrystallic axis and between the rays of light and the lines of force, respectively. The optic axis of a crystal is to a polarized ray of light what the magnecrystallic axis is to a line of magnetic force. Faraday's use of the analogy with light enables him to develop a general theory of magnetism which does not involve recourse to hypotheses about the structure of matter or the natures of the elementary particles.[143] On this theory the properties of force are attributed to the lines of force, the properties of matter are reduced to a single power (its ability to conduct the lines of action), and the observed behaviours of magnetic and diamagnetic bodies are explained in terms of the principle of economy or of least action.[144] However, Faraday first has to show to his own satisfaction that the appeal to the structures or natures of elementary particles is unworkable.

3.3.2.1 Particles and the field

Because of the success of his earlier theory of electrostatic induction (in which the polarizability of elementary particles had provided a basis for a general theory of electrical and chemical

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143. The theory is developed in series 26, in which Faraday dispenses entirely with assumptions about particles and their dispositions to polarize or react upon the magnetic force. It is applied to a general theory of atmospheric magnetism in series 26 and 27, in which Faraday supposes that the atmosphere acts as a lense or set of lenses upon the earth's magnetic field, its power of refracting the rays being a function of the heating effects of the sun. See (2847-3069).

144. While it is generally recognized that the lines of force become the primary explanatory concept in Faraday's thought after 1846 (Williams, Michael Faraday: 388 ff., and P.M. Heimann, 'Faraday's Theories of Matter and Electricity' (op.cit. note 5 , supra, p.11) the role of this principle of least constraint or least action has been overlooked. It enables Faraday to retain the idea of tension or strain as a causal factor without having to introduce specific assumptions about the molecular basis of that strain.

properties) Faraday is still unwilling to abandon the idea of atomic or molecular polarization.[145] The first step away from a theory in which such hypotheses play an essential role appears in his attempt to explain both the distinction between ordinary diamagnetic and the axial or directional nature of magnecrystallic action and Plücker's observation that there is a neutral distance at which a crystal will behave indifferently between two poles. The second step is not a theoretical one: it results from Faraday's unease about the fact that both Plücker and Weber took his researches on diamagnetism as providing experimental evidence for Ampère's theory of molecular currents.[146] The third step appears in Faraday's interpretation of the magnetic induction of a current in a diamagnetic metal (copper)--an interpretation advanced in support of his experimental disproof of Weber's application of Ampère's theory to diamagnetism.

In a note appended to the twenty-second series[147] Faraday shows that Plücker's observation that a crystal will behave either as a magnetic or as a diamagnetic material (depending upon its distance from each pole) can be explained in terms of the cause of magnetic and magnecrystallic action, 'namely the polarity belonging to the magnetic condition and the axiality belonging to the magnecrystallic condition' (2628).[148] Faraday now appeals not to the possible

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145. In October of 1848 he writes that the 'full understanding and true relation' of magnetic and crystalline forces will require an adequate theory of 'the polar (or axial) condition of the particles of the masses' (2604), cf. (2562,2588-90,2611-14).

146. Against the plausibility of the Ampère-Weber theory Faraday weighs his conclusion that only powers (as possible objects of perception) are legitimate theoretical entities (cf. supra, section 2.7 and infra, p.292.

147. 'On the position of a crystal of sulphate of iron in the magnetic field' (December 1848), ERE III: (2615-39).

148. The axial condition is that which allows a bar to set axially in either of two directions, cf. (2472) or supra, p. 247.

polarity of the molecules of the crystal, but to the axial condition as a basic fact, given in experience. This step is to lead directly to the theory of matter and magnetism from which Faraday's final theory of the field is to develop.

The fact that a system of iron cubes placed in a uniform field have 'terminations of different qualities' (2624) while similar cubes or crystals of bismuth will not (2625) may be explained as follows: The iron in the field acts

> as it were, as a conductor for the lines of magnetic power, for many of [the lines] concentrate upon the iron, and the intensity of power is much stronger between the ends of the iron ... and the magnetic poles, than it is in other parts of the magnetic field ... (2626)

The polarity of the iron in the field is a function of its ability to conduct the lines of force. The iron will

> by virtue of the polarity it acquires ... point axially, and carry on, or conduct, with its mass, the magnetic force, so much better than it was conducted in the same space before ... (2628)[149]

The force with which the bar sets is directly related to the proportion of the force conducted by it to that conducted elsewhere. As the distance between the poles is increased, the 'proportion of force carried on by the bar becomes greater as compared to that conveyed onwards by an equal space in the magnetic field at its side' (2628). Since a diamagnetic body does not tend to attract the lines of force (being a poor conductor of them), an increase in the distance between poles will not have the same effect for a diamagnetic in the field.

Faraday can now explain both Plücker's observation that there is a 'neutral point' at which the two actions appear to balance, and Plücker's interpretation (that the magnetic force decreases less

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149. Cf. (1566) or loc.cit. supra, p.143 (note 72).

rapidly with distance than the diamagnetic force). Since a bismuth bar does not appear to affect the normal distribution of the lines, 'at least as far as experiments have yet gone' (2626) a magne-crystallic or diamagnetic body will not have its 'power' raised by approximation of the poles, for its conductivity for the lines is apparently the same as that of an equivalent volume of the surrounding field (2628-29). Thus, while a decrease in the distance between the poles will produce an increase in the 'intensity of the magneto-crystallic state' (the induced state equivalent to the natural state of crystalline diamagnetics) the quantity of power conducted through the diamagnetic does not change. However, the conductivity of a magnetic material is much greater than that of an equivalent volume of the field and will therefore attract the lines of force to it.[150] The effects of the matter-field interaction will therefore be enhanced by a decrease in the distance between the poles and will decrease less rapidly with increased distance than the diamagnetic effects.

Faraday has effectively made the first major step towards the theory of magnetism and diamagnetism in its final form. He has only to realize that diamagnetic bodies have a conductivity for the lines of action which is less than that of free space (the field)[151] and that diamagnetics do therefore disturb the distribution of the lines of force by decreasing the concentration of the lines.

In this explanation of Plücker's discovery[152] Faraday has treated the conductivity or ability to transmit magnetic action as a property

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150. --figuratively speaking, for the lines converge upon or are concentrated in the region of a good conductor of action. They are attracted to it but not by it.

151. Here he has assumed that the diamagnetics have the same ability to transmit magnetic action as does the surrounding space.

152. Faraday had, of course, repeated the experiments himself (2594).

of matter as a system of particles. This marks an important shift away from appeals to hypotheses about the powers (and the induced polarity) of particles within the matter. Faraday was obliged to make this shift when, for the second time in his career, he found that his experimental discoveries were being adduced as evidence for a theory which he was unable to accept because of its speculative character.[153] In support of his application of Ampère's theory to diamagnetism Weber had cited Faraday's discovery of diamagnetism and his reference (in the twenty-first series) to Ampère's theory (2429-30).[154] Weber had, therefore, drawn upon Faraday's work as support for a theory about which Faraday had always had reservations[155] and which, according to Weber, implied the truth of the two-fluid theory of electricity as well.[156]

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153. In January of 1848 W. Weber published a paper in which Ampère's theory of electrodynamics was applied to Faraday's discovery of diamagnetism ('On the Excitation of Diamagnetism ...', op.cit., supra, p.253 (note 51)). Weber showed that the direction of currents induced in bismuth was 'constantly the reverse of those induced in iron ... precisely as it should be if bismuth contained magnetic fluids or their equivalent, Ampère's currents' (ibid.: 483). But to reconcile Faraday's law of magnetic induction with the fact that diamagnetics are always repelled by poles (a problem that arises only if magnetic and diamagnetic actions are taken to be similar (ibid.: 485-86)), Weber assumes that permanent currents are created (ibid.: 486-87).

154. Weber, op.cit., note 153, p.478 ff. Weber was claiming on behalf of Ampère's theory just what Ampère himself had claimed on learning of Faraday's discovery of the rotation of a magnetic pole about a current in 1821: that the new effect(s) confirmed the hypothesis of electrodynamic molecules. See Ampère to Faraday, 10 July 1822, Correspondance du Grand Ampère, ed. L. Launay, 3 vols., Paris (1936-43), II: 586, Faraday to Ampère, 3 September 1822, Corr. I: 134, and Faraday to G. de la Rive, 12 September 1821, Corr. I: 122.

155. Cf. the letters cited in the previous note and Faraday to Whewell, 19 September, 1835, Corr. I: 294.

156. Weber, op.cit. note 153, at p.481 and passim. In a second paper Weber advances a theory of electrodynamics in which currents are supposed to consist of elements or electronic units of electric fluid--another concept that Faraday found unacceptable ('On the Measurement of Electrodynamic Forces' (January 1848), trans. Sci.Mem. 5 (1852): 489, esp. 513-18.

Despite his earlier comment that he had 'had great hopes that' the application of Ampère's theory to diamagnetism would bear fruit (2620) it is clear that Faraday does not accept Weber's theory. It required that there be a polarity induced or existent in the particles of a crystalline diamagnetic, and Faraday had not been able to detect this experimentally (2642).[157] Where Faraday had insisted that diamagnetic action is distinct from ordinary magnetic action, Weber and Plücker identified both with the induction of currents in electrodynamic molecules. Faraday was unwilling to accept the idea that there is a direct action of the inducing pole(s) upon the individual particles of the matter.[158] He was also aware that the observed behaviours of diamagnetics in the field could be interpreted in three ways: as the differential effect of attractive and repulsive forces between the poles and currents induced around elementary particles; as a differential effect in which some matter is displaced more forcefully than other matter,[159] and in terms of a principle of economy combined with the assumption that diamagnetics have axes of least constraint that are either induced by the field or exist naturally (as in crystals).[160]

Given Faraday's unwillingness to admit hypotheses about structural entities and substantial fluids (which could be known only as their

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157. Becquerel, Reich, Weber and Plücker believed that a 'reverse polarity' did exist in diamagnetics (cf. Williams, Michael Faraday: 420 ff.). Faraday was in the process of dispensing with induced polarity as a necessary result of magnetic action. Cf. Faraday to J. Plücker, 11 December, 1849 (Corr. II: 569) and 8 January, 1850 (ibid.: 577-78).

158. The appeal to the structure of the particles could not explain the diamagnetic properties of gases as determined by Faraday late in 1847 (infra, section 3.5.1.).

159. Cf. supra, p. 255-56.

160. Cf. supra, pp. 281, 285.

manifest qualities and whose supposed structures or constitutions could never be known),[161] the fact that the observed behaviours could be interpreted in more than one way could only diminish their cogency as evidence for a theory as speculative as Weber's. This is clear from the opening remarks of the twenty-third series of Faraday's Experimental Researches.[162] Faraday states that

> in every endeavour to proceed by induction of experiment from that which is known in this department of science to the unknown, so much uncertainty, hesitation and discomfort arose from the unsettled state of my mind on this point, that I determined, if possible, to arrive at some experimental proof either one way or the other (2641).

The problem was to determine whether diamagnetic actions do involve the induction of molecular currents (and, therefore, the creation of a polarized state in the matter) or whether (as Faraday believes) the observed behaviours of diamagnetics follow simply from his original law of diamagnetic action together with certain subsidiary assumptions. Faraday's 'discomfort' derives from the fact that hypotheses of the sort that he had rejected upon epistemological grounds in 1844 and 1846 have been advanced on the basis of what he takes to be insufficient and equivocal experimental evidence:

> This [experimental proof] was the more needful, because of the conclusion [that diamagnetics do polarize] in the affirmative to which Weber had come in his very philosophical paper ...

and because

> I think it [so important] for the progress of science, that in those imperfectly developed regions of knowledge, which form its boundaries, our conclusions and deductions should not go far beyond, or at all events not aside from the results of experiment (except as suppositions) ... (2643, my italics)

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161. Faraday had distinguished between knowledge (as of facts and of laws) and 'doubtful' or 'hypothetical' knowledge in his two lectures on matter of 1844. See sections 2.7.1-2.7.3.

162. 'On the polar or other condition of diamagnetic bodies', ERE III: (2640-2701), read: 7 & 14 March, 1850.

These remarks may be seen as a rejection of Weber's hypothetico-deductive view of theory, on which a hypothesis (Ampère's) is confirmed when some known or some new effect can be deduced from it (Faraday's discovery of diamagnetic repulsion).[163] While Faraday might have been prepared to accept hypothetical structures or entities as 'suppositions' and on sufferance, his theory about the nature of scientific knowledge requires the elimination of such entities from scientific hypotheses. Yet Weber had claimed that the application of Ampère's theory to diamagnetism served to prove that there are electrodynamic molecules and electric and magnetic fluids.

At the end of 1849 Faraday showed that a consequence of Weber's theory--that currents be induced around the particles of matter moving in a field as well as through its mass--does not occur. The most important aspect of his experimental proof is that his theory of the experiments reveals that he has adopted the idea that diamagnetics repel the lines of force or cause them to diverge. As the experiments themselves reinforce Faraday's doubts about the possibility of explaining magnetism and diamagnetism on an atomic theory, they leave Faraday no option but to pursue his earlier suggestion that the 'true view' of magnetic action would involve treating magnetic force and its transmission in terms of an analogy with light and the optical properties of matter (2591).[164]

On Weber's theory the polarity induced in the molecules of the diamagnetic should be permanent and should therefore be 'distinguishable from the momentary polarity of the mass due to induced temporary currents' and from ordinary (para-) magnetic polarity (2642). Faraday's first trial involves the rapid oscillation of a core of

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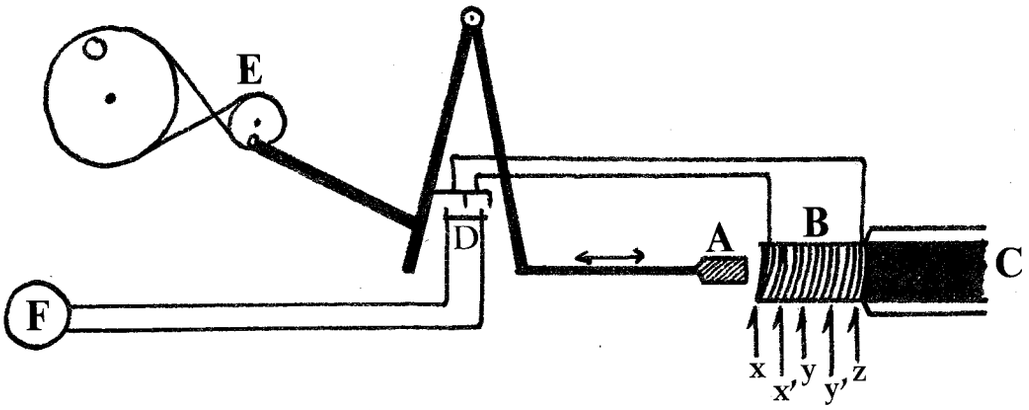
163. Cf. Weber, op.cit., note 153, passim.

164. Cf. section 3.2.

diamagnetic matter (shown as (A) in figure 3.12) in a coil (B) attached to the core of an electromagnet (C). The currents produced are rectified by a commutator (D) before passing on to the galvanometer (F).[165]

FIGURE 3.12



Faraday does not believe that the core acts directly upon the coil. An iron core will cause 'a strong convergence and concentration of the lines of magnetic force upon itself' and this change in the distribution of the lines will induce a current in the coil as the lines move across it (2696). As the iron recedes the lines will return to their normal (undisturbed) condition, inducing an opposed current (which is rectified and added to the first by the commutator). Faraday deems it unnecessary 'to suppose any direct action of [the core] on the helix' (2696).

If Weber's theory is correct then part of this indirect action should be absorbed in the production of molecular currents or in the alignment of already existing currents. But this action will be observable only if it is assumed that the field of the electromagnet constitutes a limited and definite quantity of action (for a given interval of time). Faraday expects to observe that part of the action

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165. The commutator is connected directly to the driving mechanism (E) and its contacts can be made to touch while the core is at any point of its path along the axis of the coil. The coil is a detector of the disturbances of the field of the electromagnet produced by the motion of the core (2643-52).

which goes to produce or to align molecular currents and to distinguish this from that part of the action that produces ordinary (linear) currents in the mass of the metal. Each action will reach a maximum at a different point of the path of the core along the axis of the coil. If the total possible action of the field were not definite (or finite for a given interval of time (2681)) then the possibility of distinguishing experimentally between the two kinds of inductive action would not arise.[166]

Faraday obtains a consistent deflection of the galvanometer needle in one direction when iron is used, and in the other direction when copper, silver, and other diamagnetics are used. Because he also finds that the current strength is proportional to the conducting power of the materials rather than to their 'strength' as diamagnetics (2655) Faraday concludes that he is obtaining only the effects of linear currents. If the currents were really formed around the molecules then the electrical conductivity of the metals as a whole would have no bearing upon the results. Thus, the effects were not produced 'by any polarity of their particles' (2656,2663).

Faraday now arranges a second test, reasoning that if iron and bismuth do have opposed polarities (as induced by the magnet) the current induced in the coil (B) will be at a maximum as the core reaches that point at which the product of its velocity and the field intensity is a maximum (2665). If the commutator is made to change as the core reaches either of two points equidistant between the end- and mid-points x', y', then the two opposed currents will be 'added'

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166. Faraday later proves experimentally that the magnetic field is a definite (limited) quantity of action. See series 28 and 29 and infra, section 4.2.1.

by the commutator and the galvanometer should not be deflected (2667-70).[167] His results confirm his contention that the diamagnetic action does not involve either an inherent or an induced polarity of the particles of the matter.

This lends plausibility to his view that diamagnetic action does not involve a direct action of the magnet upon individual particles of the mass, but that the interaction is between the field and matter as a system of particles having (collectively) a certain ability to distort the field. Faraday has assumed that the interaction of the field and the moving core is the only action that occurs--i.e. that currents induced in the core do not act directly on the coil and that the action of the induced currents is equal to that of the field in inducing them, and is absorbed entirely by the field (2696-97).[168] Thus, as the diamagnetic (a copper core) moves into the helix it makes the lines of force diverge 'or ... drives them before it' (2701). This conclusion is introduced as part of a description of the nature of the induction of currents, yet it is of considerable importance.

Where iron, a magnetic material, causes the lines to converge

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167. With a diamagnetic core the maximum effect should occur at the mid-point y (as with iron) or at the end points x,z (where the field is most intense but the velocity of the core is momentarily zero) and not at the points x',y' (2673). But Faraday finds that the maximum inductive effect of the disturbed field upon the coil occurs as the core is passing the points x' and y' (2667-75). Since the supposed molecular currents should be steady at this point, the results prove that the effect is due to linear currents induced in the mass, not to an action exerted in inducing or aligning molecular currents (2675-76,2693).

168. '... the currents which are produced in [the core] are caused by the direct influence of the magnet, and must react equivalently upon it' (2697). It could be argued that currents induced in the core act directly on the coil (as Weber had assumed). In this case, Faraday argues, all the matter present 'must ... be in a state of tension, each part acting on every other part, being in what I have ... elsewhere imagined as the electro-tonic state' (2700).

to become concentrated in the region that it occupies (2696) so 'by all parity of reasoning' copper will cause the lines to diverge or move away from the region it occupies (2696,2701). Faraday has evidently reached the conclusion that a general explanation of the differences between magnetic and diamagnetic bodies may lie in a theory about the effect that each sort of body has upon the normal distribution of a field.

What, then, is the causal status of the field if its action is to produce this reaction in the moving magnetic or diamagnetic matter? While there must be a 'reaction' of the lines 'upon the advancing copper' which results in the induction of currents,

> it does not seem logical to say that the currents which the lines of force cause in the copper are the cause of the divergence of the lines of force (2701).

While the inductive action must be equivalent both as an effect and as a concomitant of the divergence of the lines, Faraday wants to insist that the action of the lines is causally prior to the reaction of the currents:

> It seems to me, rather, that the lines of force are ... diverged, or bent outward by the advancing copper ... and that the reaction of the lines of force upon the forces in the particles of the copper cause them to be resolved into a current, by which the resistance [reaction] is discharged and removed, and the line of force returns to its place (2701).

Clearly Faraday assumes that the lines tend to resist deformation, remaining fixed in space until displaced by the forces of the particles of a moving piece of matter. Inductive action is just the product of the interaction and mutual disturbance of the magnetic field and the fields of the elementary particles.[169] Although this

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169. Electrostatic induction had been envisaged as a similar process in 1837. Cf. part II, esp. sections 2.5.2, 2.6, and 2.7.1.

account (the clearest that Faraday ever gives of magnetic induction) ends abruptly with the claim that 'no other meaning' is attached to 'the words line of force' than that they denote the direction and distribution of the forces (2701,2149) it is clear that Faraday treats them as being or as representing a spatial distribution of power whose interaction with the powers of the particles of the conductor creates the electrostatic tension necessary for the production of a current.

The significance of this description lies in the fact that in describing the copper, a diamagnetic, as causing a divergence of the lines of force or a decrease in their concentration Faraday has effectively made a general theory of magnetism possible. To develop a unified theory of both magnetic and diamagnetic action Faraday no longer has to develop a specific theory about the presence or absence of individual dipoles in magnetized or diamagnetized matter: he has only to realize that both actions may be explained in terms of the ability of matter to conduct or transmit magnetic action. Faraday is soon to argue that the properties acquired by bodies in the field are just the manifest effects of their powers of increasing or decreasing the density of the lines of force in the region of the field that they occupy.

3.4 Inertia and Gravitation

Faraday does not advance the completed theory of magnetism, in which the symmetry between the converging and diverging powers of para- and diamagnetic matter is exploited, until October of 1850. On this view the equatorial set of a diamagnetic and its tendency to recede from both poles of a magnet are due not to the direct action of exertion of forces but to a matter-field interaction which obeys certain laws.[170]

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170. Cf. infra, sections 4.2.1, 4.2.2, 4.3.1.

Matter acquires a disposition to move when placed in a field, a disposition manifested only when matter is in the field. I believe that Faraday regarded this disposition as a relational property (a property of a condition or system of relationships rather than of any individual) and that he held a similar view of inertial and gravitational mass.

Faraday has tended to identify theoretical and observable entities with properties and the properties in turn as manifest effects of a state of constraint (polar tension) or of the release of that state (discharge).[171] A property exists if it is manifested, and its manifestation signifies that the normal or equilibrium distribution of force (the field) at that point has been disturbed. These disturbed states exist only as they are sustained by or causally related to opposite states elsewhere.[172] The field (the set of force-relations between the points at which properties are localized and manifested) is the causal basis of such properties as can be known[173] to exist.

Immediately following his earlier suggestion that magnetism may be regarded as being analogous to light in respect of the way in which it acts and is acted upon by matter, Faraday had remarked that

> In making this supposition, I do not forget the points of inertia and momentum; but such an idea as I can form of inertia does not exclude the above view as altogether irrational (2591).

According to Faraday, inertia is just a form of power, the manifestation of a state or condition, which must (like any other power) be conserved.[174] It is a relational rather than a primary or essential quality of

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171. Cf. sections 1.3.1.1, 1.3.3.1, 1.3.4.1, 1.3.4.2.1, 2.2. (esp. p.116 ff.), 2.3, 2.7.3 and 3.2.1.2.

172. Loc.cit. supra, p.117; cf. Corr. II: 580, ERE III: 567.

173. I.e., seen to exist; cf. loc.cit. supra, p.267 (note 93).

174. Cf. (1623). It is manifested as momentum, with which Faraday tends to identify (e.g. ERCP: 451).

matter and can be manifested only as an active state or condition.[175] Faraday's next remark is all but incomprehensible unless this point is taken into account:

> I remember, too, that when a magnetic pole and a wire carrying an electric current are fastened together, so that one cannot turn without the other, if the one be made the axis the other will revolve round and carry the first with it; and also, that if a magnet be floated in mercury and a current sent down it, the magnet will revolve by the powers which are within its mass (2591).[176]

Faraday now knows also that magnetic action in any plane other than the plane or axis of least action of a diamagnetic will result in the motion of that body (2470-79), but does not believe that there is a direct action of the magnet upon the matter.

The objection had been put to Faraday that the dynamical theory of matter as a system of lines of force could not be accepted because on this theory the inertial mass of matter cannot be explained.[177] The analogy between magnetism and light that Faraday wants to make use of here (2591) had originally been advanced in connection with such a theory in his 'Thoughts on Ray Vibrations'.[178] Thus the objection that inertial mass cannot be explained amounts to the objection that the analogy between magnetism and light is incomplete:

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175. Thus it is a property of force (action) rather than of substance. This reduction of mass to dynamical interactions was unacceptable to Whewell, Thomson, Airy, Maxwell and others.

176. Faraday had shown in 1821 that the field of a current passing through a magnet and the field of that magnet will interact to produce the rotation of the matter of the magnet, and had concluded that the field of the latter remains stationary in space (ERE II: 127 ff., esp. p.129; series 1 (75)).

177. G.B. Airy, 'The Astronomer Royal's Remarks on Dr. Faraday's Paper on Ray-Vibrations', Phil.Mag. 28 (1846): 532, at 535 ff. Where Herschel had argued that inertia must be understood in terms of a subjective (volitional) notion of cause (Preliminary Discourse, articles 80,234) and must therefore consist in force (action), Airy insisted that 'the general notion of substance is really founded upon the perception of inertia (op.cit., p.535). He admitted that inertia might be explicable on the theory of centres of force (provided a finite rate of propagation is supposed) but concluded that the concept of substance provided a simpler solution (ibid.: 536). Cf. Whewell, op.cit. supra, p.99 (note 153).

178. Cf. supra, sections 3.2, 3.2.1.

some direct action must occur such that the inertial tendencies of the matter in the field are overcome.

Faraday's response is to argue that inertial mass is not a property that can exist independently of a system of electric, magnetic, or other relations between bodies, and that it is analogous in this respect to that property of the magnet by which it is rotated in the presence of the field of a current passing through it or near it.[179]

In the case of diamagnetic action there can be a 'set' without attraction or repulsion--just as in the case described there is a tendency in the magnet to rotate even though no force originating outside the system is exerted on the magnet. Faraday's point is that in these cases there is a motion or a tendency to motion which has been generated within a system. Thus he states that there 'seems as much difficulty in these motions as in the one I am supposing' (2591).[180]

On my interpretation of this passage Faraday treats inertia as a relational property, in a manner consistent with his treatment of other supposedly primary or inherent qualities.[181] He appears to have adopted a relational view of gravitational mass as well, on which gravitational mass ('weight') is convertible into (and therefore an

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179. Faraday's reference to the interaction of the field of the magnet and that of the current is meant to show that the observed motion of the magnet does not involve the exertion of direct forces originating outside the system. (There is, of course, a supply of action (energy) in the form of the current.) For the status of the magnet as a source of action see infra, section 3.5.3.

180. He continues: 'the hope of a polarized bundle of magnetic forces is enough of itself to make one work earnestly with such an object before us' (2591); cf. sections 3.5.3 and 4.2.2.

181. Thus I do not accept Agassi's statement that the passage cited (2591) 'hardly indicates a view concerning inertia and momentum' (Faraday: 232).

effect of) an inductive or polar relation between entities. In March of 1849 Faraday wrote in his laboratory Diary that gravity 'must be capable of an experimental relation to Electricity, Magnetism, and the other forces, so as to bind it up with them in reciprocal action and equivalent effect'.[182] In the twenty-fourth series[183] Faraday explains that 'if such a relation existed, there must be something in gravity which would correspond to the dual or antithetical nature of the forms of force in electricity and magnetism' (2703).[184]

It appeared possible' that as two bodies approach under gravitational attraction there would be a 'ceding to the force', and a 'reversion' of that force as they are separated. 'Quiescence (as to motion)' would be the 'neutral condition' (2703), in which no electrical action occurs in either body.[185] Gravitational power is manifested as the weight of a body. Faraday believes that the body should weigh less while falling and more while rising than it does when stationary because part of the power will go to produce induced currents in the matter.

This supposition makes sense only if it is supposed that the body represents or causes a distortion of the normal distribution of

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182. Diary: (10018); my italics. Cf. (1686,2146,2614) and supra, p.134.

183. 'On the possible relation of Gravity to Electricity', ERE III: (2702-2717), read: 28 November, 1850.

184. Faraday had been encouraged by his discoveries of the universality of magnetic action and of a relationship between magnetic and crystalline forces (which resemble those of aggregation and gravitation). Cf. (2614), the Diary: (10032), and Williams, Michael Faraday: 466.

185. The polar or inductive nature of the force (which is always attractive) would consist in the fact that while the direction of the induced currents would be constant with respect to the direction of motion, the currents would be opposed 'as to space generally' (2704).

the lines of force and that propagation of changes in the form of the lines has a finite velocity.[186] If the velocity of the matter is very large relative to that at which disturbances can be transmitted along the lines of force,[187] then the condition of constraint which constitutes the matter would momentarily be reduced or increased, depending upon the direction of motion. This should be manifested as a change in weight or, if gravitation is a convertible form of electric or magnetic force, as a current induced in a coil surrounding the moving body.[188]

Faraday now makes a direct test of the original assumption. Whereas he had been seeking effects due to differences in the weight of a moving body and that same body at rest, he now attempts to detect the effects of a rapid acceleration of a body, reasoning that

> [given that there is] a relation between the forces, and [that the effects sought are] consequent upon a condition of tension in and around the particles of the body, which, as we know, are at the same moment the residence of both gravitating and electric forces ... it seemed probable that the stopping of the up and down motion ... in the line of gravity would produce contrary effects to the coming on of the motion ... (2711)

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186. --as Faraday had argued of the lines as the functional equivalents of the elastic aether in 1846. His interpretation of the present experiments is similar to that of the action of magnetic and diamagnetic cores on the field as described supra, p. 294 ff. (cf. 2696-2701).

187. Yet in series 27 (October 1850) Faraday suggests that magnetic disturbances may travel with the velocity of light 'or even with that higher velocity or instantaneity which we suppose to belong to the lines of gravitating force ...' (2958). On this supposition inertial and gravitational mass would have to be attributed either to the lines of force or to the centres of force.

188. Taking the earth as one of the two interacting bodies and a cylinder of copper as the other, Faraday does at first detect small but regular currents (2705-6) but soon traces these to the action of the earth's magnetic field upon the connecting wires (2706). Other trials provided 'no positive or favourable evidence' for the 'original assumption' (2706-10).

By modifying the apparatus used in his tests for the induced polarity of diamagnetic materials,[189] the test body can be made to oscillate rapidly up and down over a distance of 3 inches (2712). Faraday expects that this motion will produce 'minute units of inductive action' (which will be detected by the coil). Just as motion of the matter had been supposed to disturb the magnetic field in the earlier experiment on Weber's theory, motion of the matter is here supposed to disturb the gravitational field sufficiently that the electric powers of the particles will induce currents in the coil as they interact with the gravitational field. All trials led to the same result (2714-16): the supposed interaction of electrical and gravitational powers did not produce any sensible effects upon the detector.[190]

It is significant that in seeking a relationship between electrical and gravitational action Faraday has assumed that this will be manifested only if gravitational action has the same dual or polar character as electric and magnetic actions. Equally important is the fact that he has placed gravitational powers on the same ontological footing as inertial, electrical, optical, and magnetic powers: as the manifest qualities of matter, all are due to the existence of matter as a distortion or state of constraint in the appropriate system of lines of force. From the standpoint of Faraday's epistemology matter should be identified not as that which <u>has</u> the power to react upon the lines of force but as <u>being just that power</u> or set of powers.

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189. Cf. figure 3.12 (p.294).

190. However, this did not alter Faraday's conviction of 'the existence of a relation between gravity and electricity' (2717). In 1859 and 1860 he returned to this problem, possibly as a result of Maxwell's encouragement (Maxwell to Faraday, 9 November, 1857, <u>Corr</u>. II: 881). Cf. Williams, <u>Michael Faraday</u>: 467-69.

3.5 Matter, Magnetism, and Space

Faraday had not expected (and had not entirely accepted) the fact that gases do not exhibit any form of diamagnetic action.[191] Yet this fact had played an important part in his interpretation of the diamagnetic behaviours of matter in its solid and fluid states.[192] In November of 1847, following a report by Zantedeschi on the repulsion of a flame by a magnetic pole,[193] Faraday shows that the magnetic field does produce a deflection of a flame or of a stream of smoke, where the deflection is such as to indicate a repulsion of the gas by the magnet.[194] Nearly two years later Faraday presents the twenty-fifth series of the Experimental Researches in Electricity,[195] in which he provides decisive experimental evidence for the magnetic or diamagnetic natures of different gases and explores the experimental and theoretical implications of this discovery. Having determined that all matter in all three of its states is susceptible to magnetic action, Faraday is able to advance the general theory of magnetism from which his physical theory of the field is to emerge in 1851 and 1852.

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191. Thus in December of 1847 he denies that he had ever denied that gases may have magnetic properties (ERE III: 488).

192. Cf. sections 3.1.3, 3.1.3.1.

193. This is reproduced at the end of Faraday's paper 'On the Diamagnetic conditions of Flame and Gases' (December 1847), ERE III: 467-83, at p.490 ff. References will be to the page numbers of Faraday's paper.

194. Ibid.: 469-70.

195. 'On the magnetic and diamagnetic conditions of bodies ...', ERE III: (2718-2796), read: 28 November, 1850.

3.5.1 Magnetism and Gases

In his investigation of 1847[196] Faraday had found that all gases appear to be strongly diamagnetic except two, oxygen being the least diamagnetic of all. Although he suspected that 'it may be as low as a vacuum, or may even pass to the magnetic side of it', his experiments had not been decisive enough.[197] Faraday had concluded that it is 'almost proved that many gaseous bodies are diamagnetic in their relations'. However, an important element of a final proof was still missing:

> I say almost proved; for it is not as yet proved in fact. That many, and most, gaseous bodies are subject to magnetic force, is proved; but the zero [point] is not yet distinguished (ibid.: 488).

Proof involved showing not just that matter is susceptible to magnetic action in the gaseous state, but that gases really are either magnetic or diamagnetic. While there was 'evidently no natural impossibility' that some gases may prove to be (para)magnetic rather than diamagnetic, or prove to be neutral as space is, Faraday had 'always believed that the zero was represented by a vacuum, and that no body really stood with it' (ibid.).

Faraday returns to the problem of the 'zero point' in the twenty-fifth series, completed in August of 1850. He explains that his re-examination of the magnetic properties of gases is the outcome both of his researches on the 'antipolarity' or reverse-polarity which

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196. Op.cit. note 193.

197. Ibid.: 476-80. Oxygen appeared to make air and compounds containing oxygen less diamagnetic, but Faraday concluded not that 'oxygen is really magnetic, but that a compound body possesses a specific diamagnetic force, which is not the sum of the forces of its particles' (ibid.: 480). This is a reversal of his earlier assumption about the retention of magnetic properties through chemical change (cf. supra, p.251 (note 44).

Weber had assumed to be induced in the particles of diamagnetics and of his desire to obtain an experimental determination of the zero point, which should exist if Faraday's theory of magnetism is correct.

If the law of diamagnetic action is true of gases, there should be a measurable expansion of diamagnetic gases when they are placed in the field (2721) and a contraction of magnetic gases under similar conditions, because

> the amount of power by which the particles would tend to recede from the axis of the magnetic field, would be added to [or subtracted from] the expansive force by which they before resisted the pressure of the atmosphere ... (2721)

The magnetic and diamagnetic action should, according to the law (2418) counter or enhance the repulsive powers of the atoms of the gas. More generally, any body should expand or contract unless it is truly at the zero point (2722).

Here we find Faraday attempting to prove the existence of a neutral or zero point by means quite independent of those that had failed him in 1847.[198] Faraday encloses various gases in an iron cube to which a sensitive pressure gauge is attached (2731-32) and the cube is placed between the poles of a magnet so that the cavity containing the gas has its greatest area perpendicular to the lines of force. No effects were produced in any of the gases tested (2734-36,2750). The results do not support Faraday's inference from the law of diamagnetic action (2721,2418) but they do support his earlier proof that Weber's theory is untenable. They show that individual 'particles do not tend to separate either parallel to the lines of magnetic power, or in a direction perpendicular to these lines' (2750).

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198. ERE III: 488.

Faraday's rejection of the idea that the phenomena could be interpreted and subsequently explained on a molecular theory did not follow from these experiments alone. While the individual particles may not be governed by the law of action which applies to masses, the motions of the latter have still to be explained. Faraday still suspects that the 'diamagnetic change of place' of the masses is due to the differences between magnetic and diamagnetic materials and that the latter 'must no doubt owe their differences to the qualities of the particles composing them' (2757). But his next discovery enables him to set this idea aside as a necessary part of an explanation.

Faraday re-examines the differential action on volumes of gases, using soap bubbles to contain the gas which is to be tested and compared with the gas occupying the field (2758-63). He finds that nitrogen is diamagnetic (or nearly neutral) and that oxygen is strongly magnetic. He then devises a test by which the strength of the tendency of each gas to move towards or away from the axis of the field can be measured.[199]

Faraday finds that oxygen at a pressure of one-third atmospheric pressure is more magnetic than the vacuum (2780-81,2786), and that generally

> any one of the tubes, if associated with another having a rarer atmosphere, passed inwards or magnetically, whilst if associated with ... denser atmospheres, it passed outwards [as a diamagnetic would] (2782).

This is an important result because it proves not only that oxygen is really magnetic (with respect to space made as free of matter as possible) but also that this magnetic power decreases with

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199. This test involves measuring the tension (torsion) required to restore two pieces of matter (or two volumes of a gas) to the position they had taken before the electromagnet was activated, thus it is really a measure of the 'relative diamagnetic intensities' of these materials (2771). Cf. Faraday to Whewell, 10 October, 1850 (Corr. II: 593), for a description of the balance.

rarefaction, ultimately disappearing in the vacuum state (2786).[200] It supports Faraday's contention that magnetic and diamagnetic actions are quite distinct, being 'separated' by the 'zero state'--the magnetic condition of free space.[201] It follows too that his original division of matter into two distinct classes had been sound (2399, 2424) and that all matter is susceptible to magnetic action, while space free of matter is not. Thus Faraday distinguishes between the term 'magnetic' as a general term referring to all forms of magnetic phenomena, defining those bodies that set axially and which tend to move from places of weaker to places of stronger force as paramagnetics and those which do the reverse and tend to set equatorially as diamagnetics (2790).

Faraday is finally in a position to develop a general theory on which the behaviours of these two classes of matter may be explained without recourse to hypotheses about the way in which masses of each kind 'owe their [powers] to the qualities of the particles composing them' (2757).

3.5.2 The theory of magnetism

The idea that matter interacts with the lines of force in such a way that they are attracted to it (tend to converge upon it) or else are repelled from it had been hinted at in Faraday's theory of static

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200. With Weber and Plücker's theories in mind, Faraday rejects the possibility that this decrease in power may be explained on the assumption that dense oxygen is less diamagnetic than rarified oxygen or the vacuum. This 'would imply that the acting force of a substance ... could increase ... as the quantity of the substance is diminished, which is not ... a philosophical assumption' (2782). Thus oxygen must be magnetic and space neutral (cf. 2440).

201. Cf. (2300,2399,2420,2420). Bodies such as nitrogen, which 'produce no effect when added to space, appear to me to be neutral or to stand at zero' (2789). Cf. section 3.5.3.

induction.[202] The related idea that the transmission of electrical and other powers is analogous to that of light and heat had been put forth both in Faraday's reply to Hare's criticisms and in his 'Thoughts on Ray Vibrations' of 1846.[203] The analogy had been applied to magnetism in the twenty-first series (2445-46), developed further in the twenty-second (2591), and had been applied in a theoretical account of the interaction of magnetic and diamagnetic matter with the field in the twenty-second and twenty-third series (2626-29,2696-97). By 1850 Faraday had reached the conclusion that the action of a diamagnetic upon the field can be supposed to be just the opposite of that of a paramagnetic body. Now, at the end of 1850 he can announce that all the observed behaviours of matter in the field may be explained in terms of the idea that bodies have an ability to effect the transmission of magnetic force (2797). His hypothesis is that each kind of matter will have a characteristic ability to transmit ('conduct') the action that exists in the magnetic field:

> if bodies possess different degrees of conducting power for magnetism, that difference may account for all the phaenomena; and further ... if such an idea be considered, it may assist in developing the nature of magnetic force (2797).

This is possibly the most important theoretical manoeuvre made by Faraday in the latter part of his scientific career. While the problem of explaining the specificity of this conducting of transmitting power remains, it is now the problem of explaining one assumption which is justified on other grounds--notably the explanatory power of the theory Faraday now develops from it. By characterizing all matter in terms of a single property or power--its conductivity of the lines of force relative to that of empty space--Faraday is

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202. (1566), cited supra, p.143 (note 72).

203. Cf. section 3.2.

able to place the burden of explanation upon the properties of force itself.

The advantages of replacing assumptions about the possible structures and natures of the elementary particles of matter by a single assumption about the conductivity of systems of such particles become evident when it is remembered that for Faraday the lines of force represent the existence, distribution, and behaviours of an entity which is both manifest and lawlike.[204] Faraday has assumed throughout that force has those properties which his fundamental principles ascribe to it. From the standpoint of Faraday's epistemology it is the proper referent of a physical theory, for its laws of action can be known and it is (by definition) a perceivable entity. By characterizing matter in terms of its ability to interact with force, Faraday can base his theory of magnetism upon the properties of force (which can be known) rather than upon suppositions about the internal constitution or structure of matter.

That Faraday made this manoeuvre deliberately and with these considerations in mind is evident from the introductory remarks to the twenty-sixth series of the Experimental Researches.[205] Having definedthe term 'conducting power' as denoting the 'capability which bodies may possess of effecting the transmission of magnetic force', Faraday immediately points out that

> thus limited in sense, the phrase may be very useful, enabling us to take, for a time, a connected and general view of a large class of phaenomena; may serve as a standard of meaning amongst them, and yet need not necessarily involve any error ... (2798)

Once again we find Faraday restricting or 'limiting' the sense of a

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204. For parallels with the 1837 theory of induction see sections 2.5.1, 2.7.4, and 3.2.

205. 'Magnetic conducting power', ERE III: (2797-2968), read: 28 November, 1850.

word so that it expresses only as much as the theory requires, on the one hand,and as much as the observed properties and behaviours of matter will support, on the other.[206]

This restriction is designed to permit the statement of the theory without committing Faraday to any specific theory of 'the principles and condition of [magnetic] conduction' itself. It is possible because whatever the actual nature of this conducting power proves to be, 'the phaenomena dependent on it must consist among themselves', and it is these phenomenal behaviours only that the theory professes to explain. The restriction is necessary because Faraday has to sidestep the problem of explaining conductivity without relying upon the concept of molecular polarization.[207]

Faraday begins by defining matter in terms of its ability to affect the distribution of the lines of force which represent the magnetic field. Paramagnetic matter is a region of high conductivity for the lines of force, having a conductivity greater than that of empty space. Diamagnetic matter is a region of low conductivity, having a conductivity which is less than that of empty space (2802-08). This property is manifested[208] as a concentration of the lines of force in the region of a paramagnetic and as a decrease in the concentration of these lines in the region of a diamagnetic (2807-08). The degree of action of the matter would be a function of the degree of distortion of the density of the lines of force, where this would

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206. Cf. section 2.2.3, and compare (1304) and (2797).

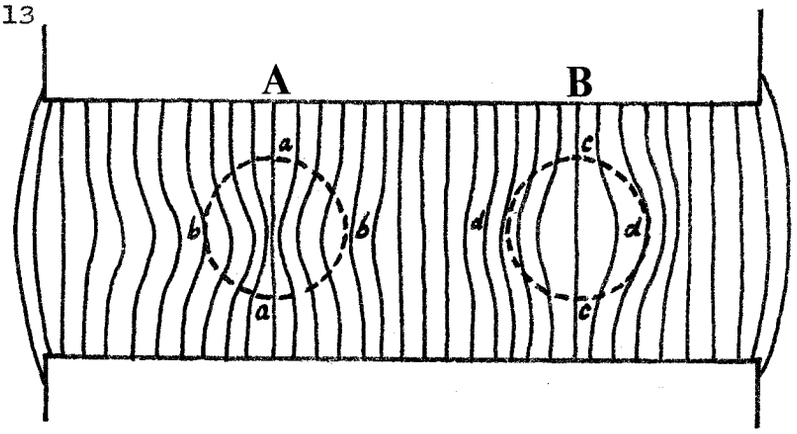
207. Cf. section 3.3.1 and infra, p. 319 ff.

208. This concentration could be observed through the use of iron filings. See ERD III: (3234-39), plates III and IV. It should be noticed that these illustrations alone could not have proven Faraday's case because he has still to deal with the problem of explaining polarity. See section 3.5.2.2.

(in principle) be measurable relative to the normal distribution of the lines.[209] The normal distribution is that which exists in the absence of matter (2802,2806). The magnetic field is any 'portion of space traversed by lines of magnetic power' (whether occupied by matter or not).[210]

Matter introduced into the field will affect the field by altering the density of the linesof force both within the volume it occupies and in the region of that volume, and, therefore, will also alter the direction of the lines (though not their sense). In figure 3.13, (A) is a paramagnetic and (B) a diamagnetic. The space

FIGURE 3.13



'occupied by' A 'transmits more magnetic power than before' while 'less magnetic power will be transmitted through the space [B] occupies than if it were away' (2807). Because every 'section of the line of such a magnetic field must be definite in amount of force, and be in that respect the same as every other section'[211] it will be

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209. Both the intensity of the field and the conductivity are represented in terms of the density of lines in the region of a point. Conductivity would be measured as the change in the density of lines caused by the introduction of a piece of matter into an evacuated field (2804).

210. --and there is 'probably no space without such lines' (2806).

211. (2809); cf. sections 2.4.1, 2.4.3.

> impossible to cause a concentration within the sphere of [the paramagnetic (A)] without causing also a simultaneous concentration in the parts axially situated as a a outside of it, and a corresponding diminution in the parts equatorially placed, b b ... (2809)

The effect of the diamagnetic body (B) will be just the reverse, there being a divergence or 'diminution of the magnetic force' at c and c and a concentration of the lines at d and d. If 'matter' or 'body' is identified with its sensible (magnetic) action then the bodies A and B have no precise bounding surfaces.

This description of the interaction of matter with the field was intended to deal with several problems. Faraday wished to explain (1) how magnetic action could occur without the actual attraction or repulsion of crystalline diamagnetics or the formation of poles (2470-73,2589);[212] (2) how diamagnetics generally could be made to set equatorially with no overall repulsive action upon their masses or upon the individual particles in the case of a gas (2570,2799-2800), and, finally, (3) why diamagnetic masses are always repelled (and never attracted) under the appropriate conditions.

3.5.2.1 The explanation of magnetic phenomena

Faraday's explanation follows from the concept of conductivity together with two other assumptions. The first defines the behaviour of force (as represented by the lines of force).[213] The second

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212. These ideas had formed the basis of the theory of induction of 1837 and could be applied in a theory of ferromagnetic materials, but the idea of molecular polarization cannot be applied either to paramagnetic or diamagnetic materials. Oxygen is the only paramagnetic substance that Faraday examined in detail, and he had shown that its volume is not affected by a strong magnetic field (hence, that its individual particles are not polarized (2721-50,2799-2800)).

213. Force is conserved, being indestructible and finite in its action; the existence of force is manifested in the production and/or mutual action of opposed but quantitatively equal effects at those points between which it exists.

assumption defines the interaction of matter with force. It states that bodies will tend to move in such a direction that their interaction with the field (the mutual distortion of magnetic and matter-fields) is a minimum.[214] A second and related assumption which has been implicit throughout Faraday's work since 1831 is that a condition of tension or (molecular) constraint is equivalent to a quantity of 'dynamical' action (motion). Matter appears to be attracted or repelled in the field because it tends to move so as to reduce or to alleviate the condition of constraint; this it does by moving in the field.

Given these assumptions and given Faraday's theory of conductivity (that paramagnetic matter tends to increase the density of the lines of force in the region it occupies while diamagnetic matter tends to decrease the density of the lines)[215] all the observed motions and behaviours of matter may be explained. For example, a sphere of iron midway between two poles is found to be in a position of unstable equilibrium. On the theory this is because the density of the lines between the point a (figure 3.13) and one pole and a and the other pole is the same. If the sphere is not at the midpoint the density will be greater on one side than the other, and the sphere will move into that region in which the lines are more concentrated.

Why does it move into regions of greater field-intensity? According to Faraday it will move in that direction or to that position in which it can 'determine the greatest amount of magnetic

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214. This has been described earlier as the principle of economy or of least action (supra, p. 285). Faraday uses it to explain the observed motions of para- and diamagnetic bodies, i.e.--to explain the laws of their motion given at (2269,2418-19).

215. In fact this is later identified as the only action of matter on the field, cf. (2933-34).

force' (2810) or, in the terms of the original law (2418-20), towards places of stronger magnetic force. Paramagnetic matter simply moves in such a way that its conducting power (ability to concentrate the lines of force) is used to best effect.[216]

This account evidently has teleological overtones. The field intensity at a point is determined or caused by the matter, while the matter tends to move in such a way as to perpetuate or to increase that very condition of the field which (according to the law) determines its direction of motion.[217] The sphere appears to be attracted towards one of the poles,[218] but it is in fact interacting with the field to produce changes in the distribution of the lines which in turn cause the matter to move in the direction that it does. The result is an acceleration of the matter towards one of the poles. But it is difficult to assign causal priority either to the matter or to the field if the interaction is as Faraday describes it.

In fact, Faraday may not have been thinking in terms of a cause-effect sequence at all, for the principle which underlies his explanation of para- and diamagnetic phenomena is a teleological and atemporal one: the matter will always move into regions in which the lines are most concentrated 'because' its conductive function or power of concentrating the lines is exerted least if it moves in this

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216. It would (so to speak) have to do more work on the lines of force in regions where they are not concentrated. Thus it takes the path (assumes a position) of least action.

217. Faraday had encountered the difficulty of assigning causal priority to one of the two interacting entities at (2701), cited supra, p. 297.

218. Hence the wording of the original law of magnetic and diamagnetic action, loc.cit. supra, p.252.

direction.[219] Conversely, a diamagnetic will move in that direction in which the lines diverge most rapidly, i.e. in that direction in which its diverging powers will be exerted least. For its part the field tends to take the path of least resistance, this being through a paramagnetic when one is present, and free space when only diamagnetic matter is present.

Faraday had observed that paramagnetics move or tend to move into regions of greater field intensity and that diamagnetics tend to do the reverse, and that the lines of force (as illustrated by iron filings or by powdered bismuth) appear to be concentrated in the region of the former and less concentrated in the region of the latter. The inference from these behaviours to a principle of least action appears to have involved a further assumption about the nature of force or action: that it tends always to produce or return to an equilibrium condition.[220] Thus motion, discharge and all events or processes signify the return of a system of lines from a state of tension to their normal form.[221]

That Faraday is using a principle of least action (rather than the generalization expressed by the laws of motion of para- and diamagnetic bodies (2418)) is clear from the way in which he explains

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219. Hertz had objected to Hamilton's principle on the grounds that it makes the 'present motion dependent upon consequences which can only exhibit themselves in the future, thereby attributing intentions to inanimate nature ...' (Principles of Mechanics: 23; cf. D.W. Theobald, The Concept of Energy: 43,49). Herschel described the laws of elementary atoms in teleological terms, and was prepared to admit the simultaneity of cause and effect. See R. Graves, The Life of W.R. Hamilton, II: 337 and Herschel's Familiar Lectures (1871): 458 and 473 ff.

220. (2831). Faraday later makes an exception of vital and organic forces (3317-18).

221. A similar assumption had been implicit in Faraday's interpretation of the behaviour of the electrostatic lines in 1837 (cf. sections 2.4.1 and 2.5.1), or (950,1224,1231,1298,1300-04).

other behaviours of matter in the field. An asymmetrical piece of iron will set axially[222] because this position is 'most favourable for the concentration of force in the axial line' (where concentration can occur only in the axial line because the lines can only move laterally in a uniform field). Two iron spheres aligned along the same equatorial line will repel each other while they remain in that plane but will become indifferent to each other as the line drawn between them becomes parallel to the axial line (2813,2830). Their apparent repulsion is really due to their tendency to move out of the region of low intensity which they create between them.[223] Faraday states that the motion is such as to 'fulfil the requisite condition of equilibrium of forces' (2831, my italics) and draws attention to the analogy with 'the phaenomena produced by electric induction' (2798).

This shows that Faraday did regard the law of para- and diamagnetic action (and possibly the laws of electrostatics as well)[224] as a consequence of some more fundamental principle which specifies a necessary property of both matter and the field (i.e. of all fields): that while the magnetic field tends to assume or to retain an equilibrium condition matter moves in such a way that this condition is most rapidly or most closely approximated.[225]

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222. Cf. supra, p.247.

223. Similarly, two diamagnetic spheres will appear to repel each other for both will tend to move out of the region of higher field intensity created between them.

224. But see supra, section 2.5.1.

225. 'We find no remainders or surpluses of action in physical forces. The smallest provision is as essential as the greatest. None are deficient, none can be spared' (2968).

3.5.2.2 The nature of polarity

Faraday now shows that polarity of matter is also a product of this matter-field interaction. Here he is able at last to explain how magnetic action may produce temporary or even semi-permanent poles in ferro-magnetic materials yet induce no poles at all in diamagnetics.

Faraday had been obliged to abandon the idea that polarity consists in a relationship or tension between points or particles because this was evidently not the case in crystals and diamagnetics generally. But he had found that like bodies will repel each other under certain conditions while a diamagnetic will attract a para-magnetic (2814-17). Thus diamagnetics proved to be analogous to magnetic bodies in that they could be the objects of both attractive and repulsive behaviours. It became evident that even though the diamagnetics are not polarized as ferromagnetics are, the power at work is a polar power rather than a non-polar power like cohesive or gravitational attraction.[236]

Faraday's solution to the problem of reconciling what he takes to be the fundamentally polar nature of magnetic action with the observed non-polar condition of diamagnetics in the field is a simple one: like the observed tendencies to motion of the two kinds of matter, this polarity can be construed as a product of the mutual action of matter and field--of that power which the matter has of disturbing the equilibrium of the field. The word polarity therefore refers to

> the condition of the mass as a whole, in respect of the state into which it is brought by its own disturbance of the lines of magnetic force; and that, both in regard to its condition with respect to other bodies similarly affected; and also in regard to differences existing in different parts of its own mass (2818, my italics).

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226. This shows that diamagnetics have a polarity of sorts, but in using this term Faraday now does not wish 'to indicate any internal condition of the substances or their particles' (2818).

This condition 'may be called conduction polarity' (2818). In its simplest form this is just the condition of a mass which is either conducting (concentrating) or resisting (repelling) the lines along which magnetic action is transmitted.

The polarity of a mass is defined with respect to the convergence or divergence of the lines. Though symmetrical for a symmetrical mass, this convergence or divergence will be opposite in 'quality' if considered with respect to the direction of the lines of force.

The only truly polar entities are the lines of force, for the polarity of the matter is a function of its conductivity, of the polar nature (directedness) of the lines of force, and of their tendency to concentrate in regions of high magnetic conductivity. A property which Faraday had formerly attributed to (paramagnetic) matter is now attributed to 'the known difference of quality in the two opposite directions of the lines of magnetic force' (2819). Thus diamagnetic bodies do acquire a polarity of sorts when in the field, which consists in

> a divergence of the lines of power on to, or a convergence of the parts, which being opposite, are in the direction of the magnetic axis; so that these poles, having the same general and opposite relations to each other, which correspond to the differences in the poles of paramagnetic bodies have still, ... that striking contrast and difference from the latter bodies ... (2820)[227]

Faraday can now explain both the differential relationship between paramagnetic and diamagnetic bodies and the behaviour of

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227. However, polarity cannot be defined just with respect to the convergence or divergence of the lines of force, for if this were the only criterion the diamagnetic body (B, figure 3.13) could be made equivalent to the paramagnetic body simply by rotating one of the other through 180° (2821). Polarity must be defined also with respect to the direction (sense) of the lines of force. The field must be taken as a frame of reference (2822).

crystalline diamagnetics.[228] A diamagnetic in a region more diamagnetic than itself will behave as a paramagnetic (and a paramagnetic will behave as a diamagnetic in a medium more paramagnetic than itself) because their behaviours are a function of the differences between the conductivities of the test body and the medium filling the field.[229] In this way Faraday can explain the original hypothesis that magnetic action is a differential action.[230]

The most striking achievement of his theory of magnetism is that Faraday has been able to explain all magnetic phenomena (including those in which matter does not assume or retain a sensibly polarized state) without abandoning the concept of polarity itself. He has achieved this by distinguishing between the idea of a polar relation or tension between two material (active) points or particles and the idea of a polar or inductive action. In effect Faraday distinguishes between the concepts of polarity and of contiguity (or local action).[231] Inductive action is no longer tied physically or conceptually to molecular polarization: the tension represented by the lines of electrostatic and magnetic induction may be transmitted and sustained as a series of actions between contiguous particles, but this is no longer necessarily the case. An inductive or polar relation may exist in the absence of matter or of particles which necessarily become polarized. It may therefore exist in free space, and may pass

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228. Cf. supra, p.251 (figure 3.7) and p.278 (figure 3.10).

229. For the analogy with the electrostatic case see supra, pp.141-43.

230. Cf. supra, p. 255ff. This explanation applies equally to the vacuum, which is supposed to have a characteristic conductivity having a value between that of the weakest paramagnetic and the weakest diamagnetic.

231. These two concepts have been identified throughout the Researches, see, for example, sections 2.1, 2.2.1, 2.4.1.

through a body without polarizing it, because the polarity has been made a property of the lines themselves.[232]

Polarity is now defined as 'the known difference of quality in the two opposite directions of the lines of magnetic force' (2819, cf. 2822). What we observe as a polar condition of a piece of matter is due to the fact that the matter is causing the lines to converge or diverge as they are transmitted through it (2818-20). Thus it is a necessary property of the lines of force and an accidental property of matter: like electric charge it is just the manifest effect of inductive action as this has been defined in the first series of the Experimental Researches (1, cf. 1304).

Faraday has distinguished the line of force as a line representing the direction of action of a force at a series of points in space and the line as a series of polar or inductive actions between material points or centres of force. This distinction has two important consequences. First, it leads directly to a problem about the causal status of sources of the field and about the ontological status of true magnetic poles. How can the polarity of permanent magnets, electromagnets, and ferromagnetic materials be distinguished from the 'conduction polarity' of para- and diamagnetic bodies in the field? Second, if the reality of the lines of force is no longer tied to the presence of real, polarizable particles, how is it to be defended without identifying the field with space?[233]

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232. Diamagnetics may be polarized, but in the absence of experimental evidence Faraday can now leave the possibility open.

233. It might be thought that, having argued in 1844 that matter or materiality consists in action or power, Faraday need only identify the lines of power with matter (as he had done in his 'Ray Vibrations' of 1846). But this does not solve the problems described in section 3.5.3.

3.5.3 The Powers of matter and the Power of space

Faraday has defined a field as 'any portion of space traversed by lines of magnetic power' and has supposed that all space is filled with such lines (2806). But a force can exist or be manifest only if it is built up against a reaction: it can exist only as a state of tension between mutually opposed tendencies.[234] It follows that if the field exists in free space (the absence of matter) then space must be capable of conducting the lines of force, i.e. of offering some resistance to or reaction upon their passage.[235] A separate line of reasoning has led to the same conclusion. If a paramagnetic is a better conductor than the space it occupies and if a diamagnetic is a worse conductor than the space (2818,2843) then empty space (the 'zero point') must be analogous to matter in that it can conduct or transmit the lines of force, having a greater reactivity than that of paramagnetic matter! But how, and in what respect, is matter to be distinguished from space if the relevant property of each is the same? And how can sources of the field be distinguished from ferromagnetics which acquire active powers in the field, and these in turn from para- and diamagnetic materials which acquire properties only in the field and lose them immediately on being removed from it?

Faraday is well aware that he has to distinguish between (1) ferromagnetic matter which is polarizable and may be a source of a magnetic field; (2) para- and diamagnetic matter which conducts the lines of force but without becoming polarized; and (3) space, which also conducts but in which there is nothing that could be polarized. As he had remarked in the twenty-fifth series:

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234. Cf. sections 1.3.4.2, 1.4 (p.98), 2.2 (p.117 ff.), 2.2.2.1.

235. Throughout the Researches conductivity has been linked with the ability to react or to insulate.

> this character of space is not of the same kind as that which, in relation to matter, we endeavour to express by the terms magnetic and diamagnetic. To confuse them together would be to confound space with matter, and to trouble all the conceptions by which we endeavour to understand and work out a progressively clearer view of the mode of action and the laws of natural forces (2787).

Para- and diamagnetic materials are more like space than ferromagnetic matter, which polarizes and can remove or extract power from the field (2504,2580). Like space and unlike ferromagnetics they have a specific influence on the direction and concentration of the lines but do not alter the total quantity of magnetic action in the field. Space differs from magnetizable (ferromagnetic) matter in the same way that para- and diamagnetic bodies do. Yet to identify these with space would be to identify 'the particles acting upon each other with the space across which they are acting' (2787).

This problem is set out as table 3.2.[236] The first three columns describe the action upon the field of the active, inductive (sustained) and passive states of matter (respectively), and the fourth describes the condition of the field in space (not occupied by matter in the first or second state). The action or effect of each on electric and magnetic lines of force (as described by Faraday) reveals that while the distinction between polarizable matter (I,II) and space (IV) is unproblematic, para- and diamagnetic materials (III) occupy an anomalous position between the two.

Faraday distinguishes matter having the properties described in columns I and II from matter having the properties described in column III without dispensing with the distinction between matter (I,II,III) and space (IV). He first points out that space is inactive or inert: 'space cannot act as matter acts, even though the utmost latitude be allowed to the hypothesis of an aether ... space ...

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236. This is my interpretation of Faraday's discussions at (2787-90) and (2832-35).

TABLE 3.2

FORCE Form and State	MATTER I. Active Matter	 II. Induced Active State	 III. Induced Passive State	SPACE
	Determines:	Determines:	Determines:	Determines:
magnetic (static)	sense (polarity) direction quantity intensity (both polarization and the conversion of force)	- direction quantity intensity	- direction - - (no polarization)	- normal distribution of field is that of free space
electric (static)	as for magnetic	as for magnetic	no analogue	as for magnetic
electric (dynamic)	as for magnetic	as for magnetic	no analogue	undetermined[237]
Causal status	source (active)	sustained (reaction, conversion)	reaction only[238]	reaction only[238]

237. Faraday has reached no definite conclusion about the electrical conductivity of free space (see supra, sections 2.5.1-2.5.2).

238. Cf. supra, p.135 (note 60) and infra, section 4.2.2.

comports itself independently of matter ...' (2789). In keeping with the ontology defended in 1844 and 1846 Faraday replaces the old distinction between matter (substance) and space (the void) with a distinction between matter (active powers) and space as the absence not of power but of centres or sources of power.[239]

Armed with this distinction Faraday can now say that bodies such as nitrogen 'which produce no effect [upon the field] when added to space' are 'neutral or stand at zero' (2789). Nitrogen has the same conductivity as space. The distinction takes care of the unwanted implications of Faraday's conclusion that both matter and space must conduct the lines of force.

Faraday then distinguishes between the active powers of permanent magnets and electromagnets (sources of a field (I)), the induced powers of ferromagnetics (II) and the temporary powers of para- and diamagnetic bodies (III). Here again Faraday appeals to a distinction between power as the ability to originate and sustain an action or state and power as the ability to alter or affect an action originating elsewhere. The fact that paramagnetics do not retain any magnetic properties when removed from the field suggests to Faraday that there is a 'distinction ... with regard to the polarity of a magnet, and the polarity ... due to mere conduction' (2832). The powers of the magnet are permanent; those of a ferromagnetic material semi-permanent, and both are therefore quite distinct from the powers of para- and diamagnetics and of space.[240] The polarity of a conductor

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239. --and without committing himself to the existence of the aether (cf. section 3.2.1.1).

240. The polarity of a magnet is such that 'we cannot conceive a mere space void of matter to possess either [polarity or the power producing it], whatever form that space may be supposed to have, or however strong the lines of magnetic force passing across it' (2832).

(columns III,IV) is not due to any arrangement or enhancement of the powers of elementary particles (2832, cf.2788). It is 'simply a consequence of the condensation or expansion of these lines of force' accordingly as the matter (or space) is 'more or less fitted to convey their influence onwards' (2832).

Here Faraday distinguishes between the possession of a property (such as conductivity; the ability to transmit action) and the possession of an active or causal power (such as electric or magnetic force). Both matter and space may have properties of the former sort, but only matter as defined in 1844 may be the seat of the latter.[241] Since iron in the field can become a semi-permanent source of the lines and can determine their polarity, Faraday concludes that iron in the field (matter as in column II) is really a magnet rather than a 'mere paramagnetic conductor with conducting powers of the highest possible degree' (2833). Thus the problem of distinguishing between all matter and space, and between ferromagnetic and other types of magnetic materials has been solved.

Faraday has relied upon a three-fold distinction between (1) the possession of a property or power, (2) having a disposition or susceptibility to action of a certain kind, and (3) having a power which causes such dispositions to be activated or manifested. To distinguish matter from space, both of which have a property in the sense of (1), Faraday distinguishes between (1) and (3). As not all matter has the ability to act (magnetically) upon other matter in the absence of a source of action (the field), he introduces a distinction between matter which causes properties (2) to be manifested and matter which

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241. 'It is evidently a very different thing to originate such lines of power and determine their direction [sense or polarity] on the one hand, and only to assist or retard their progression without any reference to their direction on the other' (2832).

possesses only properties of type (2). In the terms of Faraday's argument of 1846 about matter and aether it is apparent that space (or the aether as defined by Faraday) has only one power (of type (1)). Matter as in column III of table 3.2 has powers of type (2), while matter as in column I has all the powers that matter could have: it determines the sense (polarity), direction, distribution, and quantity of the lines of force, for it causes them.[242]

It is worth noticing, finally, that Faraday's view of space as the absence not of power but of sources of power is consistent with his original belief that the normal condition of lines of electrostatic force is that which exists in the absence of matter.[243] Matter manifests itself electrically, magnetically, and gravitationally as a disturbance of this normal, 'quiescent', 'undeveloped' or 'equilibrium' condition of the appropriate system of lines of force.[244] Space is the absence of active matter but is filled with power in a quiescent condition. Thus space is filled with what makes the manifestation of the powers of matter possible, the 'great field of nature'.[245]

Faraday has consistently identified existents as agents, for reasons that had been made clear in 1844. His epistemology requires that space be filled with the field because matter manifests itself

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242. --but not as something distinct from the lines of power. Faraday had suggested in 1838 that chemical atoms may be merely localizations of chemical force (1650). More recently he has suggested that magnets may be merely localized bundles or 'habitations' of lines of force--regions in which the power is concentrated because the conductivity of that region is very high (2591). He is soon to argue that we can see (detect) magnets only because the conductivity of space is (relatively) low. Cf. infra, section 4.2.2.1.

243. Cf. supra, p.317 (note 221).

244. Cf. table 2.1 (supra, p.172).

245. (2974, cf. 2934).

only through its active powers (or the activation of those powers). Free space (the vacuum) cannot be a mere void. Given Faraday's three-fold distinction between active powers, passive or induced powers (dispositions) and the possession of properties in general, there is no contradiction in his defining space as that which has a property yet is the absence of matter.

3.6 Is the Field Real?

It could be objected that the existence of a spatial distribution of powers does not follow (even if Faraday's epistemology is accepted) because atoms or active masses may be effective through central forces acting directly at a distance.[246] The fact that a magnetizable needle introduced in the region of a magnet forms poles and is attracted or repelled could be taken as evidence only for the fact that the magnet can act (or interact) under certain conditions, i.e. that the magnet has a disposition to act upon a second body if the latter is sensitive to magnetic action. Similarly, it could be argued that the field is just a spatially distributed set of dispositions, activated when the appropriate conditions are met (but which do not 'exist' as or in persisting individuals).[247] The effect which occurs when the necessary conditions are met may be construed as evidence only for a direct action of the magnet or source upon the test body, and not as

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246. This leads to an ontology of dispositions only, for unless Faraday's epistemology is rejected these dispositions cannot be held to be grounded in substance or in individual elements of it (cf. supra, section 2.7.3). For a discussion see H.R. Harré, The Principles of Scientific Thinking (chapter 11) and J.L. Mackie, Truth, Probability and Paradox, Oxford (1973), chapter 4.

247. See, for example, H. Stein, 'On the Notion of Field in Newton, Maxwell, and Beyond', Minnesota Studies in the Philosophy of Science 5 (1970); 264.

evidence that there is a permanent distribution of power or potential action which is the physical or causal basis of the observed behaviours.[248]

Faraday took notice of this sort of objection in a paper 'On the Physical Character of the Lines of Magnetic Force', published in 1852:[249]

> It may perhaps be said that there is not proof of any outer lines of force in the case of a magnet, except when the objects employed experimentally to show these lines ... are present; that these bodies, in fact, cause and develope the lines; just as in the case of gravity no idea of a line of gravitating force, in respect of a particle of matter by itself, can be formed (3259, my italics).

Faraday's reasons for rejecting this interpretation of electrical and magnetic interactions are the subject of the last part of this thesis.

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248. Cf. Maxwell, loc.cit. supra, p.13 (note 15).

249. ERE III: (3243-99), dated: 6 March, 1852.

PART FOUR

4. TOWARDS A REALIST INTERPRETATION OF THE FIELD THEORY

Faraday had never doubted the reality of the lines of electrostatic induction. Their existence as a series of polar relations between contiguous particles of matter followed from the physical (i.e. active) character of the particles and from Faraday's principle of induction.[1] But the non-polar nature of diamagnetic and paramagnetic action required that a distinction be drawn between the polarity of a force as a causal relation between two opposed effects and the polarity induced in the particles of matter.[2] Faraday now has to show that the properties acquired by matter in the presence of sources of magnetic action are due to a real, persisting cause--the magnetic field. To do so he has to show both that the lines of force can exist in free space and that the existence of these lines is a necessary condition for the manifestation of the properties that matter does have in the region of a source of action.

As Faraday's arguments of 1844 and 1846 have made clear, the reality of a thing consists in its being active--a source or cause of

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1. This principle stated that all electrical states must be causally related to equal and opposed states (supra, section 2.1-2.2). As noticed earlier (supra, p.132, note 53) Faraday does not defend the physical (causal) status of the lines of electrostatic induction in 1852.

2. Cf. supra, section 2.2.1, 3.5.2.2 and 3.5.3.

manifest qualities.[3] Reality entails materiality, but materiality cannot entail ponderability or substantiality.[4] Thus, when Faraday turns to a proof of the claim that his theory has a real referent, he describes this--the lines of force--as having a 'physical character' rather than a material or substantial one.[5]

Faraday is about to defend the claim that the field exists as the causal basis of magnetic properties (and, by implication, of all properties). Specifically, he is to claim that the properties of entities in the field are relational rather than dispositional, being powers or propensities that exist in virtue of the existence of the field.[6]

Given Faraday's identification of existents and agents and his further identification of the manifestation of properties with a polar relation or state of tension,[7] the field is necessary as the basis both of properties (events) and of the perception of those properties and events. Faraday regards the manifestation of a property as an event that signifies the expenditure of a certain quantity of action. His theory of the field states that this action is expended in the return of the field from a distorted (constrained, inductive or dynamical state) to its normal distribution (or to a condition

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3. Thus the existence (manifestation) of a property is direct evidence of the existence of a cause of that property, but all entities (posits) must be active powers rather than passive (inert) substances. Cf. supra, sections 2.7-2.7.3, 3.2.1, and 3.5.3.

4. Cf. supra, section 3.2.1.2.

5. 'On the Physical Character of the Lines of Magnetic Force', cited supra, p.330.

6. Cf. supra, sections 1.3.3.1 (esp. p.60 ff.) and 2.7.3 (esp. p.224 ff.).

7. Cf. supra, p.98 (note 148), pp.116-18 (esp. note 25), and pp.150-51.

approximating that normal or 'undeveloped' state).[8]

This is a theory about the way in which manifest properties and events are caused. It presupposes an ontology of power localized in entities such as atoms, currents, and poles and obeying certain laws.[9] As he had done in 1844, Faraday defends this theory on both empirical and epistemological grounds. He now advances the field theory not only as a causal theory of properties and events but as a theory of the perceivability (and hence of the possibility of knowledge) of those properties and events. An implication of one of his justificatory arguments is that the field is the causal basis both of properties and of the perception of properties.[10]

Faraday's defence of a realist interpretation of his theory of lines of force is based upon two main arguments. He first shows that the true nature of the magnetic field cannot be perceived or revealed through the use of sensing devices such as magnetizable needles or diamagnetic crystals, arguing that to observe the field as it really is we must consider the nature of the effects produced when a closed conducting circuit moves in the region of a magnet. This argument is intended to demonstrate the inadequacy of the theory of Weber, Plücker, and others, on which the formation of poles in a needle and the axial or equatorial set of magnetic and diamagnetic bodies are taken to be the primary indicators of the presence and nature of magnetic forces (as actions at a distance).

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8. Faraday has assumed that the electric and magnetic forms of force or power exist in three states (normal or undeveloped, static or inductive, and dynamical or progressive), being detectable (i.e. active) only in the two latter states. The existence of a property (event) signifies that the force is returning to the first state from either the second or the third. Cf. supra, sections 1.3.3.1, 1.3.4.1, 1.3.4.2.1, 2.2.2, 2.2.2.1, 2.4.1, 2.5.2, 2.7.3, 3.4, and 3.5.2.1.

9. These laws specify the nature of force or power. Cf. infra, sections 4.2-4.3.

10. Cf. infra, section 4.2.2.1.

Having shown that induced currents are the true indicators of the nature of the field, Faraday deals with the possibility that the field is not really a system of power persisting in space and time, and that matter is merely a set of dispositions activated under conditions that can be described without recourse to the notion of the field as the causal basis of those dispositions. Faraday's argument turns upon his notions of what it is to be a physical quantity, what it is to be a property, and what it is to be a cause. He argues that an induced current (as the true indication of the nature of the field and as the true measure of the quantity of action residing in it) cannot be caused merely by relative motion of the conductor and the source of magnetic induction. While motion is a necessary condition of the production of the effect, 'mere motion' cannot 'generate a relation' because motion involves the change of a parameter that is not physical, i.e. causal.[11] As an effect the induced current must be equivalent to the quantity of power that has been consumed in producing it. Distance is not the measure of such a quantity, therefore some cause must be present in the region of the conductor. This can only be the field: the entity whose nature is specified by Faraday's postulates.

Faraday's defence of the field theory is presented in the

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11. This shows that in identifying space as the absence not of power but of sources of power (supra, section 3.5.3) Faraday has not identified space with the field. Had he done so, a change in the magnitude of the quantity denoting the relative position of magnet and conductor could have been taken as a cause of the current induced in the latter.

12. 'On lines of Magnetic Force; their definite character; and their distribution within a Magnet and through space', ERE III: (3070-3176), read: 27 November and 11 December, 1851; 'On the employment of the Induced Magneto-electric Current as a test and measure of Magnetic Forces', ERE III: (3177-3242), read: 25 March and 1 April, 1852. For a summary see Faraday's lecture 'On the Lines of Magnetic Force' (23 January, 1852), ERE III: 402 or RILS 1: 25.

twenty-eighth and twenty-ninth series of the Experimental Researches[12] and is followed up in lectures and papers published between 1852 and 1855.[13] In the last two series of the Researches Faraday shows that the field is a definite quantity of action or power and that its nature and properties can be described and its effects explained only on the theory of lines of force. In the later papers he argues that the lines of force must be taken to be real entities. I shall discuss these papers as a whole.

4.1 Postulate, Hypothesis, and the Status of Theory

Throughout the Experimental Researches Faraday has used the lines of force to represent the direction (sense), the distribution, and the quantity of the power of charges, magnets, chemical elements, and voltaic currents.[14] As he explains in the twenty-eight series:

> From my earliest experiments on the relation of electricity and magnetism ... I have had to think and speak of lines of magnetic force as representations of the magnetic power, not merely in the points of quality and direction, but also in quantity ... (3070)

Despite his claim that he is examining the notion of lines of force in order to determine

> how far it may be truly applied in representing magnetic conditions and phaenomena; how far it may be useful in their elucidation; and ... how far it may assist in leading the mind correctly on to further conceptions of the physical nature of the force ... (3070),

Faraday regards this examination as the first step towards a proof

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13. The two most important papers are 'On the Physical Character of the Lines of Magnetic Force' (dated 6 March, 1852), ERE III: (3243-99), summarized in 'On the Physical Lines of Magnetic Force' (11 June, 1852), ERE III: 438 or RILS 1: 59, and 'On some Points of Magnetic Philosophy' (20 December, 1854), ERE III: (3300-62), summarized in a lecture having the same title, of 19 January, 1855 (ERE III: 566 or RILS 1: 143).

14. Cf. supra, esp. sections 1.3.1.2, 1.3.3.1, 1.3.4, 2.2.2, 2.3.3, 2.4.1, 2.4.3, 3.3.2.1, and 3.5.1.

that the lines of force are real entities having the properties that his postulates require. This proof involves showing that magnetic force, like all forces, must be regarded as a limited (definite) and conserved quantity of action, that it is polar or inductive in nature, that it is a form of electrical power, and that its effects are due to its tendency to assume or return to an equilibrium condition or state of least action.

Faraday has defined the lines as entities that obey the same laws that govern the behaviours of force, laws that specify the nature of force.[15] As we have seen, Faraday takes the existence of experimentally determined laws (such as those of magnetic induction, of electrochemical action, and of the motions of electrified and magnetized matter) to be an indication of the truth of these higher order laws or postulates.[16] Thus, the law of electrolysis (which describes just one kind of conversion of one form of power into another) is indicative of the nature of force or power, i.e. of the truth of certain postulates.

This fact belies Faraday's claim that scientific knowledge consists just in facts and in (experimentally determinable) laws,[17] for it shows that he does treat such laws as instances of the postulates.[18] This in turn explains why Faraday could reject

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15. Cf. supra, sections 2.3.3 and 2.7.4.

16. This is clearly the case in Faraday's explanation of para- and diamagnetic action (supra, section 3.5.2.1) and of electrostatic action (sections 2.2.2.1 and 3.5.2, cf. 2.5.1), and appears to have been true of his proof of the law of electrolysis (sections 1.3.3-1.3.3.1, cf. pp.47-48).

17. Cf. supra, section 2.7.1, ERE III: (3244).

18. Facts are instances of empirical laws, and the latter are instances of the principles or postulates of unity, convertibility, conservation, polarity, and so on. As Faraday had stated in 1844, the integrity of empirical laws is bound up with the integrity or the nature of ultimate entities (loc.cit., supra, p.223). It is the postulates (rather than hypotheses or models) that specify this nature.

experimental results that did not conform to his view of the nature of things: facts simply do not carry the same weight as laws do (as confirming or disconfirming instances of the principles).[19]

The principles define what Faraday takes to be conceivable or possible[20] and what he takes to be probable.[21] They dictate which facts are to be taken as fundamental or as being the most revealing of the nature of a process or action and which facts should, therefore, be explained on any adequate theory.[22] Given these principles, some facts are to be taken more seriously than others; moreover, things will not always be as they appear:

> In the numerous cases of force acting at a distance, the philosopher has gradually learned that it is by no means sufficient to rest satisfied with the mere fact, and has therefore directed his attention to the manner in which the force is transmitted across the intervening space ... (3245, my italics)

Faraday's use of experience shows that he believes that appearances alone cannot be taken either as evidence against an hypothesis whose

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19. The postulates to which Faraday appealed in rejecting the results of his experiments on magnetic induction of 1838 (supra, sections 2.4.1-2.4.3) had been confirmed by the laws of magnetic induction, electrolysis, and electrostatic induction. To abandon them would have been to abandon the causal basis of those laws.

20. --i.e., what can or cannot be the case, loc.cit., supra, p.103 (note 3), cf. (72,517,959,1101,1106,1161-63,1174,1292,1320,1443, 1603-05,1615-16,1621,1628,1642-45,1665-66,1680-81,1706,1772, 2069-71).

21. --i.e., what ought to be the case whether or not it has been shown to be the case. (Faraday uses the words 'possible' and 'probable' to describe both what is possible and likely and what is necessarily the case.) Cf. (2-4,242,959,1114,1410-12,1659-63,1686, 1710,1727-35).

22. See, for example, Faraday's rejection of Whewell's interpretation of self-induction (supra, section 3.4.2.1-2), his rejection of fluid theories ((1175), supra, section 2.2); of the contact theory of the pile (1970,2060 ff.); of Becquerel's theory of diamagnetism in gases (supra, sections 3.1.3.1, 3.5.1); of Plücker's interpretation of crystalline polarity (supra, sections 3.3.1-3.3.2.1), and his present disproof of the central-force theory of Weber and others (infra, sections 4.2-4.3).

falsity would be inconsistent with one or more of his postulates or as evidence for an hypothesis whose truth would be inconsistent with one of these postulates.[23] The present defence of the field theory as a set of statements about a real, causal entity, is a further case in point.

4.1.1 Natural truth, representation, and the truth of theory

In what sense (according to Faraday) could the theory of lines of force be regarded as a true theory? Faraday has relegated theory to the realm of doubtful or conjectural knowledge.[24] He has claimed that as an experimentalist 'I do not think theory alone of much force in magnetism, since many theories as to the natural mode of action, are apparently equally probable ...' and that this requires that he 'refrain from forming any conclusion as to the real nature of magnetic action ...'[25] He appears to adopt a conventionalist view of the status of theories and a correspondence theory of their truth, for he remarks that 'knowledge ... is most advanced ... when the natural truth and the conventional representation of it most closely agree' (3075) and again, that through the use of experiments one of a number of theories may be shown to approximate more closely to the truth than others:

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23. His reason is that most effects (e.g. the alignment of a magnetized needle in the region of a magnet) can be interpreted in more than one way. In such cases the theory which does not involve abandoning one or other of the principles is to be preferred. For the problem of interpretation see supra, sections 2.2, 3.1.3, 3.3.2 and (3156), and for the claim that conformity to principles is a criterion of adequacy see (2718, 3322).

24. --thus, not knowledge as defined in 1844 (supra, section 2.7.1-2; cf. (3244)), but useful for generating avenues of enquiry (loc.cit., supra, p.103 (note 3); cf. Corr. II: 692).

25. Faraday to G. Tomlin, 23 July, 1853, Corr. II: 692. The last comment is probably an allusion to the fact that Faraday has reduced magnetic actions to conducting powers but has not attempted to explain these powers (cf. sections 3.5.2.1-2).

> When we have devised new experimental proofs, so as to separate these [competing] theories from each other, then we shall be better able to judge which is the nearest to the truth of nature.[26]

Yet Faraday is not a conventionalist. He clearly believes that the world is a system of real powers obeying certain laws. The 'natural truth' does not consist merely in facts and in empirical laws, for nature is as the postulates or principles state that it is. It is in terms of these principles that all interpretations of facts, all theories or 'conventional representations', are to be evaluated.[27] There is, therefore, a true interpretation of the phenomena:

> How wonderful it is to me the simplicity of nature when we rightly interpret her laws and how different the convictions which they produce on the mind in comparison with the uncertain conclusions which 'hypothesis or even theory present.[28]

How is the truth of a theory to be established? Faraday's criteria of the truth of a theory appear to be first, that the interpretation of the phenomena advanced as a true interpretation represent a certain set of facts more adequately than any other, and second, that it be consistent with certain necessary properties of the subject and referent of these interpretations (in the present case, magnetic force). The facts are to be interpreted in accordance with Faraday's principles, and the nature of the referent(s) of these theories is prescribed by this same set of principles.

This leads immediately to a problem. In his twenty-eighth series Faraday sets out to show that his own theory of lines of force

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26. Ibid.

27. This is a main theme of the lecture 'On the Conservation of Force' (1857) and of 'Observations on Mental Education' (1854), both reprinted in ERCP.

28. Faraday to A.F. Svanberg, 16 August, 1850, Corr. II: 588.

is a better representation of the nature of magnetic phenomena than the rival interpretation of Weber and others (on which all magnetic properties are due to the direct actions of central forces, existing between the poles and the individual particles of matter only when certain conditions obtain). Given that Faraday's theory embodies those principles that are to serve as evaluative criteria of the adequacy of the rival theories and as definitions of the true nature of what those theories purport to describe, there can be little doubt as to the outcome of this exercise.

The possibility of deciding upon the truth of one of these theories presupposes first, that an answer can be given to the question 'What is the true nature of magnetic force?' and second, that an answer has been given. Yet Faraday's answer differs from that given by the proponents of the theory he is to reject. He holds that the observed events and properties are produced by an underlying and subsisting mechanism whose properties (as specified by the postulates) make the laws of nature what they are. Weber and the proponents of action at a distance hold that events and properties can be explained in terms of the laws of nature (that is, by stating the conditions under which events occur or properties are manifested) and that these conditions can be stated without recourse to the notion of an ultimate cause obeying higher-order laws.

Faraday effectively determines the question of the truth of his own theory by providing an answer to the second question. This amounts to the claim that his ontology--the ontology of force or power having a certain definite nature as the basis both of properties and events and of their laws--is superior to the rival ontology of substance as the bearer of properties, and of events or actions caused by forces acting according to certain laws.

However, Faraday's defence of his theory is not based only upon principles that specify the nature of force or power as the ultimate entity. It is based also upon his conception of what counts as an adequate scientific explanation. Faraday's epistemology has led him to deny that theories based upon an ontology of events (as the activation of dispositions by the action of forces acting at a distance) can be truly explanatory. His defence of his own theory is therefore based upon a third criterion of the adequacy of a theory: that it provide an account in which a causal basis of manifest qualities and events is posited, where this basis is described in a manner consistent with his own theory of knowledge (as articulated in the lectures of 1844).

This proves to be one of Faraday's main reasons for rejecting the then-accepted theories of atoms, current elements, ponderable fluids, and actions at a distance in favour of his own field theory. It is also a reason for his having stopped short of the attempt to explain the nature of magnetic conducting power (2818). As he has done throughout the Experimental Researches in Electricity, Faraday prefers to use the language of powers, relations or causal connections between powers, the laws that govern these relations, and of the nature of force or action as the basis of these.

I will now discuss the role of the principles that specify the nature of this causal basis, the field, in Faraday's final defence of the field theory.

4.2 The Lines of Force and the Nature of the Field

The theory that Faraday now defends consists of two assumptions and one main hypothesis: (1) that the field exists as a quantity of power or action, (2) that the nature of the field is specified by the

postulates of unity/convertibility, conservation, induction or polarity, and of least action, and (3) that matter is just a region in which the lines of force are either compressed (or transmitted readily) or made to diverge (not transmitted as readily as elsewhere). Faraday's claim that the lines of force are real amounts to the claim that assumptions (1) and (2) are true. Thus he has posited force (whose nature is specified by the postulates) and matter (whose nature is defined in terms of a single power, its ability to conduct or transmit action). The ontological primacy of the former is immediately apparent from the fact that matter is defined solely in terms of a power that can be exercised, detected, and known only in the presence of the field. Faraday is to argue that knowledge of agents (active materials such as magnets) depends upon the existence of the field, for it is the field that makes possible the causal relationships that must exist between agents (powers) and perceivers.

4.2.1 The Field as a quantity of action

All matter assumes magnetic properties in the presence of a source of magnetic action, which are manifested as tendencies to change position. They alone do not support the view that the existence of the field is necessary to the explanation of magnetic phenomena or their laws. But according to Faraday the observed behaviours of magnetizable needles and of para- and diamagnetic materials can give only an inaccurate and partial indication of the nature of the cause of the phenomena. Iron filings or ferromagnetic needles can indicate only the intensity and the direction of the magnetic forces at a point or set of points: they provide no information at all about the quantity of action present. Pointing out that the lines of force may be recognized 'either by their action on a magnetic needle, or

upon a conducting body moving across them' (3076), Faraday now shows that the latter action 'gives a view and a result of properties of the lines of force' that the behaviour of a needle 'could never show' (3076).

In view of the fact that the prevailing theories of electrostatics and of magnetism (and of attractions generally) treated the observed attractions, repulsions, and the formation of poles as the primary phenomena to be explained, Faraday's contention that a magnetic needle is a poor indicator and measure of the intensity and the quantity of magnetic force at a point is a challenge of the most fundamental kind. He is claiming that the then-accepted theories have been developed from what he calls 'partial or imperfect views of the phaenomena and their causes' (3075, 3076 ff.) and that only the induction of currents in a moving conductor is a 'correct philosophical indication of the presence of magnetic force' (3083).[29]

Faraday's rejection of motions and the formation of poles in favour of the induction of currents is crucial both to his rejection of the ideas of central forces acting directly at a distance and to his later argument that the existence of the field must be assumed if a causal explanation is to be provided for the production of induced currents.[30] It originates in his discussion of the use of a magnetic needle as a measure of the intensity, direction, and quantity of

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29. For the problems of reconciling the law of magnetic induction with diamagnetic action see supra, p.290 (note 153). Whewell had noticed that on Ampère's theory (taking the current to be an inertial fluid) the 'only point ... which remains obscure, is the law of electrodynamic induction ... that is the force by which a current produces a current in a neighbouring substance ...' (Whewell to Faraday, cited supra, p.80 (note 108)). Yet Faraday's whole object had been to explain the nature of induction rather than the nature of matter or of the current (supra, pp.81-82).

30. Yet it has generally been overlooked. Cf. Williams, Michael Faraday: 446.

magnetic force.[31] Faraday had pointed out that as the needle is simply a paramagnetic conductor, the period and amplitude of its vibrations do not measure the absolute quantity (or intensity) of the action present at any point because its behaviour must be a function both of its own conductivity and of that of the medium which fills the field. Both will be a function of the temperature. Thus the same needle would give very different indications of the intensity of the field under different conditions and could give no reliable information about the actual quantity of action present[32] at all (2870-71).

Since this point counts as an objection only if Faraday's theory of para- and diamagnetic conduction is accepted,[33] it would appear to be circular. However, Faraday's theory had been developed as an attempt to deal with the fact that the intensity and quantity of magnetic action at a point does appear to depend upon the presence and the nature of the medium through which the action passes--a fact which the proponents of action at a distance had not attempted to explain. Moreover, while the needle points and is attracted most strongly in regions where the field intensity changes most rapidly with distance, the moving conductor 'produces its greatest effect and indication ... when moving in places of equal action, i.e. transversely across the lines of force' (3078).

The moving conductor is a sensor which produces its greatest effect when moving in a uniform field or <u>across</u> the lines of force,

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31. This appeared in series 26, of October 1850. Cf. esp. (2869-77).

32. --i.e., the density of the lines of force in an undisturbed field. The objection applies to any device whose interaction with the field involves the compression or rarefaction of the lines of force.

33. Cf. <u>supra</u>, sections 3.3.2.1 and 3.5.2.1.

an alignment in which its interaction with the field (as a diamagnetic) is least (2502,2591,2870). Thus the best sensor of the field is one whose effects are not easily referable to the action of central forces (tending to produce like or opposite poles, and whose action varies with the distance of the sensor from the source).[34] Faraday has shown that the polarity acquired by para- and diamagnetic materials is apparent rather than real, and that the true polarity of the field is a property of the lines themselves. This is clearly revealed in the fact that the direction of an induced current depends upon the direction of motion of the conductor relative to the lines of force.[35]

As observed through its effects on a moving conductor the field is far more like a system of lines having polar or 'antithetical' relations and constituting a definite quantity of action than it is like a set of attractive and repulsive forces acting directly between the sources of action (the poles) and the particles of matter.

To complete his demonstration Faraday has to show what he has assumed all along--that the field is a definite (finite) but indestructible quantity of action. This involves proving the generality of the law of magnetic induction which Faraday had first stated in 1831 (114,116): that a moving conductor 'sums up, with the same accuracy in principle, the amount of the forces represented by the lines it has crossed' (3082, cf. 3077). Faraday is to prove, in fact, that a magnet is analogous to a chemical atom, being the

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34. Had Faraday been able to understand Ampère's mathematical theory and Weber's extension of it to diamagnetism and to the interaction of currents, he would still have rejected the current elements (or substantial fluids) and electrodynamic molecules required by these theories. Faraday's theory of knowledge prevented his accepting Ampère's theory as much as his lack of mathematical training did. Cf. supra, section 3.3.2.1, esp. p.292 ff.

35. Cf. supra, section 3.5.2.2.

'habitation' or 'localization' of a definite quantity of action.[36]

Faraday now shows that if a continuous conductor is moved across lines of magnetic force (or, 'being still, is by the translation of a magnet crossed by such lines') then the amount of magnetic action as 'shown by its effect in evolving electric currents' is 'determinate for the same lines of force, whatever the distance of the point or plane at which their power is exerted, is from the magnet' (3109). The quantity or 'amount' of magnetic force 'is the same in any two or more sections of the same lines of force, whatever their form or their distance from the seat of power may be ...' (3109).[37] Each line is analogous to a current in that it represents or carries a fixed quantity of action throughout its length; thus any section taken across a given number of lines at any point along their course will represent the same quantity of inductive action (3108,3092).[38]

Faraday then shows that the quantity of inductive action depends upon the number of lines cut (and not upon their density).[39] It follows that

> under the circumstances, there is no loss, or destruction, or evanescence, or latent state of the magnetic power by distance ... (3111), [and that] convergence or divergence of the lines of force cause no difference in their amount (3112).

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36. Cf. supra, sections 1.3.3.1, 2.7.3, and 3.4.

37. For the conditions under which this law holds see (3090-3110) and for the extension of the proof to conductors other than copper, series 29. For earlier versions of this argument as applied to lines of electric induction, cf. supra, sections 2.3.3 and 2.4.3.

38. The analogy extends further: Faraday still believes that the magnetic field may be the dynamical or progressive state of the magnetic force (the lateral action of lines of electrostatic induction being the static or inductive state). Cf. supra, section 2.4.1 (esp. p.171 ff.) and (3269).

39. Cf. (3088) ff., esp. (3107-10).

Generally, the 'quantity of electricity thrown into a current is directly as the amount of curves intersected' (3115) while intensity of the current will be a function of the rate at which curves of a given density are cut.[40]

The importance of this demonstration is that it proves that the field cannot be described simply in terms of the set of values of the intensity of the magnetic force at points in the region of a source. Faraday is convinced that the lines of force constitute a 'field of action' (3178) which is a definite quantity of power. This quantity is not a function of the distance of a point or section from the magnet (3096-99,3107-11). Although it is evident that the effectiveness or power of a magnet, 'according to the recognized [inverse-square] law' must be considered as 'extending to any distance' (3100) the total quantity of action or power may be measured by a conductor moving across all the lines at a constant distance from the axis of the magnet. The intensity of action may decrease with distance (as indicated by a needle) but the quantity of power in the field is not a function of distance.[41] As Faraday remarks in a lecture of January 1852: 'the external power of an unchangeable magnet is definite yet illimitable in extent ...'[42] As had been the case in Faraday's explanation and proof of electrochemical and

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40. At (3097) and (3106 ff.) Faraday shows that the intensity is proportional to the angular velocity of rotation of the wire about the axis of the magnet.

41. This, of course, is the point underlying Faraday's rejection of the inverse-square law of gravitational attraction as anything more than a partial description of the nature of the interaction between two masses ('On the Conservation of Force' (1857), ERCP: 443, esp. 446 ff.). The conviction that there is a quantity (action) that does not depend upon distance goes back to Faraday's proof of the law of electrolysis (supra, sections 3.3-3.4 and pp.133-34).

42. 'On the Lines of Magnetic Force', ERE III: 402, at p.406.

electrostatic actions, the important physical parameter is the quantity of action rather than intensity of a force at a point.

4.2.1.1 Can active powers be dispositions?

Faraday now uses his principle that force is conserved in an argument to the effect that the properties acquired by needles and other sensors in the field cannot be regarded as dispositions whose causes are actions at a distance, existing only while the sensors are near the magnet and exhibit the properties in question.[43]

Powers cannot be said to exist or to be active only when other matter is present because this requires that the power which produces the observed attraction (or other effect) is created in that instant and disappears when the necessary conditions for its manifestation no longer obtain. Faraday's objection involves an appeal to the nature of the interaction between magnets and the bodies acted upon (to what he calls the 'known condition of the forces concerned' (3263, my italics). To the objection that the magnetic force and the properties of materials acted upon exist only when two or more bodies are present, Faraday has a ready reply. If the objection were to stand,

> it would follow, that upon the forces being determined externally [outside the magnet, in the presence of a second body] a change in the sum of force both within and without the magnet should be caused ... (3260)

But Faraday has shown in the twenty-eight and twenty-ninth series that the quantity of power outside or emanating from the magnet must be equal to that inside it, and that this quantity cannot be augmented

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43. For the suggestion that the lines do not exist in the absence of reactants or sensors (and that the latter 'cause and develope the lines ...') see loc.cit., supra, p.330.

or diminished by the mere approximation of other matter.[44] Thus the basis of his objection to a dispositional interpretation of magnetic actions is that power (which is exercised in the manifestation of a property) cannot be simply created or destroyed; it cannot lie dormant or be 'latent' within the magnet whenever the conditions for its being effective do not obtain (3259-60,3277).

This is an ontological claim, to the effect that the powers of the magnet are extended and exist as the causal basis of the manifestation of properties. Like Faraday's earlier claims about the nature of matter, it follows from his epistemology. Faraday has denied the existence of substance as the bearer of attributes and cannot admit that elementary particles are simply the places at which dispositions exist (for such entities would exist only while they are active or manifesting themselves). The case of macroscopic bodies (magnets or charges) would appear to escape this stricture. Because these entities can be known (seen to exist) even when they are not magnetically or electrically active,[45] it is easy to suppose that the magnet or charged body is active only when some suitable reacting body is present and that its powers are not continuously exerted. Faraday's present objection rules out this supposition as being incompatible with what he takes to be the nature of force or power.

4.2.2 Polarity and Existence

The previous argument involves a further principle: that electric and magnetic properties are the manifest effects of forces that are dual or polar, existing states of tension or reaction between the

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44. (3260-64); for the rule of the influence of new sources of magnetic power see series 29, (3215 ff.).

45. --i.e. they can be identified as entities though not as magnetized or charged entities. Cf. supra, p.225 ff.

points at which their effects appear. Faraday has proven that the lines of magnetic force must be considered as forming closed circuits, passing through the interior of the magnet rather than terminating at its poles (3116-19). This follows both from the principle that the external power or effect of the magnet must correspond to 'some power [within the magnet] equal to that capable of being exerted externally' (3116)[46] and from the fact that when the magnet itself is made to form part of the conducting circuit, no current is induced in it (220,3118). It follows that the magnet may be conceived as a symmetrical distribution of closed lines of force, resembling 'an electromagnetic helix, both as to the direction of the lines of force in closed circuits, and in their equal sum within and without' (3120).[47]

Each of Faraday's proofs that every line of force does represent a definite quantity of action which is the same at any point of its course has involved showing that the null-results of a given arrangement of conductor(s) and the magnet(s) are due directly to the equality and opposition of the action of the field upon the wire in different sections (3091-3110). It is evident to Faraday that the polarity or directed nature of the force is manifested as (and can be defined in terms of) the direction of the current induced in a

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46. While we can detect and measure only the external power (3120) the equality of the (internal) cause and the (external) effect tells us all that we need to know about the hidden interior of the magnet. A similar point had been made in connection with the electric eel (series 15 (1772)). Similarly, we do not have to know what a chemical atom is or how its powers are disposed, provided that we know the rules that they must obey (ERCP: 454,461).

47. The external power may be 'considered as disposed in sphondyloids'--these being the solids generated by the rotation of lines of force about the axis of a magnet or coil (or the solid generated between two lines of different length as they are rotated about the axis). This solid is continuous throughout the magnet and the space outside it. Cf. (3271), Faraday to Whewell, 9 February, 1852, and Whewell's reply, Corr. II: 651-53, 657.

conductor moving in a given direction.[48] But he has still to reconcile this definition with the more general notion of polarity as this was (and is) applied to the formation of poles and the attraction and repulsion of matter.

In keeping with his earlier conclusion that the polarity of magnetic action is a property of the lines of force[49] Faraday insists (and proves) that the lines are continuous circuits or solenoids. He has effectively dispensed with poles (as ultimate individuals) but not with polarity:[50] as he now makes clear, polarity is a property of force or power, not of any individual.[51] Polarity consists in and must be defined in terms of the opposed actions that the lines have (accordingly as a conductor crosses them in one of two opposed directions):

> I should understand the term [magnetic polarity] to mean, the opposite and antithetical actions which are manifested at the opposite ends, or the opposite sides of a limited (or unlimited) portion of a line of force ... (3154)

If this is what the term does mean, then polarity is not indicated correctly (or generally) by the attractions and repulsions of magnetic

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48. The wire exists in an 'atmosphere of power' around the magnet but this power is not energy or potential as these terms subsequently came to be understood. While Faraday's 'power' is not a function of the distance, it is not (apparently) a scalar quantity like energy or electric or magnetic potential either, because Faraday does hold that it is essentially polar, being 'antithetical, and marked in its direction by the lines of magnetic force' (3271, my italics).

49. Supra, section 3.5.2.2.

50. To Whewell's remark that 'I have been generally in the habit of thinking of your curves as identical with the old magnetic curves, which only give the active part of the curves' (as lines between two poles outside the magnet) Faraday replied that the lines must be taken to be continuous and that 'I recognize no poles or centres of action in that respect' (Whewell to Faraday, 20 June, 1852 and Faraday to Whewell, 29 January, 1853, Corr. II: 660 and 682).

51. For the explanation of the existence of poles see infra, p.358.

materials (3155).[52] To treat the attraction and repulsion and the pointing of matter as the effects of central forces acting at a distance to create poles in the matter (and then attract or repel these) and to assume that 'pointing is always the direct effect of attractive and repulsive forces acting in couples' is to overlook an alternative interpretation which is superior because it is based upon an effect which not only makes polarity 'manifest instantly' but also 'shows the full amount of magnetic power to which such polarity belongs' (3158, my italics).

Faraday has stated that polarity is a property of force or power (or of the lines in which it is exerted) rather than of individuals. What we observe as (and take to be) qualitative differences between entities (charges, poles) are in fact due to some property of the force which constitutes a causal relationship between these two qualitatively opposed states or powers.[53] Faraday now argues that this must be the case, for were it not the case we would never detect the external field of sources of power such as the magnet.

4.2.2.1 Polarity, existence, and the perceivability of powers

I pointed out earlier that Faraday's identification of existents as agents (active powers) and his appeal to the precept that knowledge can be had only of perceivable entities (manifest qualities) probably derived from the influence of dynamical atomists such as Priestley, Herschel, and Hamilton, but that his tendency to identify this manifest or active state as one of tension, polarity, or opposition also

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52. Here Faraday is less worried by the fact that magnetic and diamagnetic materials do not give 'true experimental indications' than he is by the fact that such behaviours are not always interpreted 'correctly' (3156). Evidently he wishes to base his case upon effects which do not admit of more than one interpretation.

53. Cf. supra, section 2.2., esp. p.116 ff and loc.cit., p.117 (note 26).

suggests the influence of Naturphilosophie.[54] The importance of this idea of a polar relation or causal interaction is nowhere more clear than in the arguments that Faraday now presents, for he attempts to prove that both the existence of and knowledge of active powers or agents presupposes the existence of polar relations and, therefore, of a reactive or opposing state or property which must exist through all space, even in the absence of matter.[55]

In 1837 Faraday had claimed that the curvature of the lines of electrostatic induction could be taken as a proof of the molecular theory of induction, on which curvature indicated the presence of a quantity of force in its inductive state. He now states that curvature of the magnetic lines 'would ... prove their physical existence ... just as the same proof applies in the case of static electric induction' (3254). Faraday is really arguing that the form of the lines (their degree of curvature) is an indication of the presence or absence of power in the region occupied by those lines.[56]

The form of the lines of induction as indicated by iron filings may not be the true form because the lines 'may be dependent upon the presence of these particles' (3254, cf. 3259). However, given that magnetism (like electricity) is a dual or polar power the forces of a magnet cannot exist except as tensions between the poles (or more accurately, along the lines of induction which pass

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54. Supra, pp.98, 116-18, 150-51.

55. Cf. supra, p.332 (note 7).

56. Although Faraday has claimed that force exists in a normal or undeveloped state because its active states cannot arise out of nothing (supra, sections 2.4.1-2.4.3, esp. p.171 ff.), effects are produced by force only in its active (inductive and dynamical) states. There can be no action without a reaction. As pointed out earlier, straight lines are lines of no action--they represent the field in its 'undeveloped' or 'quiescent' state (supra, p.166).

through the ends of the magnetized matter). The poles cannot exist 'without a mutual relation' or causal connection of the sort that could be provided by physical lines of force, just as with static electrical induction, 'the one electricity cannot exist without ... equality with, and dependence on the other' (3257):

> Every dual power appears subject to this law as a law of necessity. If the opposite magnetic forces could be independent of each other, then ... a charge with one magnetism only is possible; but such a possibility is negatived by every known experiment and fact (3257).

Faraday is arguing here what he had argued of electrical states and forces in 1837.[57] As he explains in 1855, 'the proof of curvature is, in respect of principle, in the essential and necessary dependence of the two qualities or parts of a dual force upon each other' while 'in respect of experiment' the proof consists in the 'mutual actions of magnets and magnetic bodies' and in the phenomenon of magnetic induction (3323). In a lecture of January 1855, he is even more explicit about the conceptual relationship between polarity and the 'existence' of a force or an active state: 'a single state, i.e. an unrelated duality, cannot exist alone'.[58]

Faraday is claiming that ultimately there cannot be qualitatively different entities (north and south poles, positive and negative charges). He is claiming that the existence of individuals having qualitatively opposed powers presupposes the existence of the 'mutual relations' of which these powers are merely the effects.[59] What

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57. Supra, section 2.2.

58. 'On some Points of Magnetic Philosophy', ERE III: 567, my italics.

59. Thus poles (and qualitatively opposed individuals such as positive and negative fluids or charges) are secondary rather than ultimate. Because they owe their properties (qualitative differences) to the 'mutual relations' which exist between them, and because Faraday has defined such entities as their (manifest) qualities, poles and charges do not exist except as singularities in (or products of) this set of mutual relations (the field). For an argument to the effect that fundamental theories must be field theories in this sense, see H.R. Harré, Principles of Scientific Thinking, chapter 11, esp. p.310 ff., and supra, pp.19 and 224 ff.

exists must be perceivable for it can be known only through its manifest qualities which are caused and sustained by causal relationships with other opposed qualities. It is through such relationships that any individual is perceived (can be known to exist) at all. While the concept of an individual does not presuppose the concept of a causal relation,[60] the claim that there are individuals does involve the claim that there are causal relations as the basis for the properties by which those individuals must be identifiable.[61]

Faraday now argues that the space (or medium, or region) outside a magnet is a necessary condition of its existence as a source of power and that what we see when we observe a magnet and a needle interact is not just the activating of a disposition or tendency to interact (of the two individuals) but a change in the distribution of the power of the magnet.[62]

The magnet is the source of a dual power. Dual or polar powers can exist only as states of tension or constraint. In the absence of matter this state must exist in space itself. Thus the space around the matter (whether evacuated or not) is as essential to the magnet as is the electrolyte in a voltaic circuit.

What Faraday means by this is most clearly seen in the illustrations that he gives. Just as the properties of space around a source of light or of electrical action are known to affect the

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60. But Faraday has in fact denied that an individual atom (apart from its powers) could even be conceived (loc.cit., supra, p.221).

61. --as Faraday had argued in 1844 (supra, section 2.7.3). Notice that this same position may have been implicit in Faraday's remark (of August 1836) that by positive and negative charges (forces) 'I merely mean the termini of such lines [of electric tension]' (loc.cit., supra, p.106), cf. p.115 ff. and (1666).

62. The nature of this change or tendency to change is defined in terms of the principle of least action, Cf. infra, section 4.3.1.

transmission of the optical or electrical action,[63] so the existence of para- and diamagnetic bodies as conductors of the lines of force show that space has the capacity or 'aptitude ... to effect the mutual relation of the two external polarities' of a magnet. This had followed from the fact (required on Faraday's theory of magnetism) that space has a conductivity lower than that of paramagnetics and higher than that of diamagnetics.

If a magnet were completely enclosed by an extremely good conductor of the lines of force (such as a shell of soft iron)

> then the effect of its superior conducting power would be to cause a great contraction inwards of the sphere of external action and ... [would produce] extreme diminution, if not apparent annihilation, of the external power of this magnet ... (3279)

The external power would all but disappear and the magnet would cease to be detectable as a magnetic body because a good conductor of the field does not provide sufficient resistance to the action to allow it to build up in the form of an extended system of lines. The extension of these lines (the volume occupied by them) is a function of the magnetic conductivity of the surrounding medium--that is, of its ability to react upon the lines and cause them to diverge (3278-82). The greater the 'reaction or resistance' of the medium (3282) the greater the external field of the magnet. Faraday's point is illustrated in figure 4.1, in which A represents a magnet enclosed by a perfect conductor, C the field in space, and D the field in a poor conductor (a diamagnetic medium).

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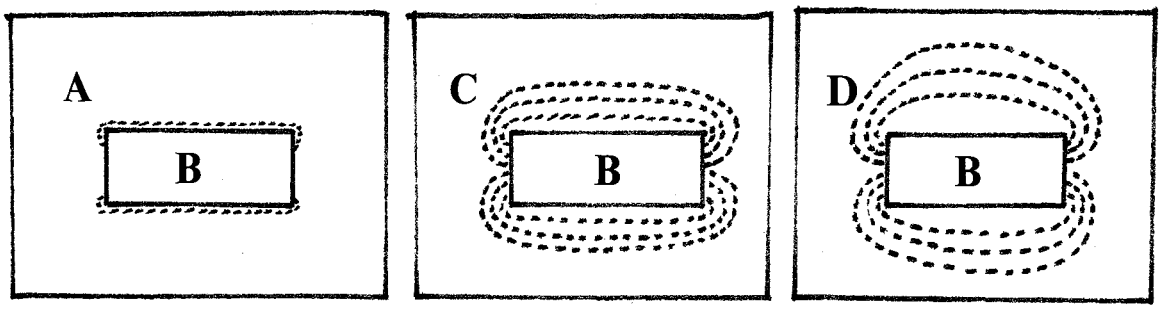
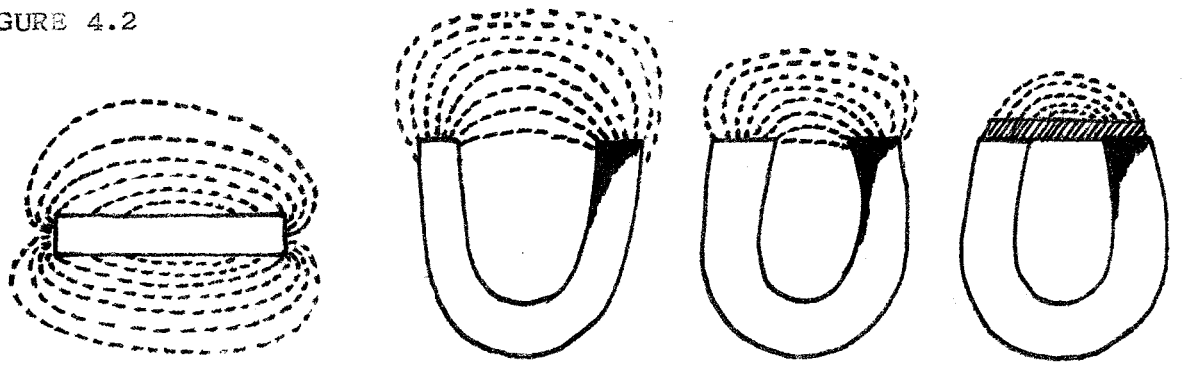
63. For the analogy between electrical, magnetic, and optical actions see <u>supra</u>, sections 3.2, 3.3.2, and 3.5.2.

FIGURE 4.1



The analogy between the form of the lines here and the relationship between the form of the lines of electrostatic induction and the conductivity of a medium in Faraday's 1838 theory of induction[64] may have led Faraday to favour this conclusion, which can be illustrated (using iron filings) in the following way. The field of a bar magnet decreases as it is bent into a horseshoe, decreasing even more when a keeper (a ferromagnetic bar) is placed across the poles (as shown in figure 4.2). This field will disappear almost entirely if the magnet is made into the form of a ring (3283-84).[65]

FIGURE 4.2



64. Cf. supra, section 2.3.3, esp.p160 ff. and section 2.5.1. In the earlier theory space had to be a perfect insulator, preventing the transition of electricity from its static into its dynamical state.

65. Similarly, a magnetized ring has no sensible external field unless it is cut or broken, when a field will appear (being most intense and extensive in the region of the discontinuity of the magnetized matter). A more familiar case is the formation of new poles by the breaking of a bar magnet.

The higher the conductivity of the region outside the magnet, the smaller the field. The fact that a magnet can sustain a higher 'charge' when surrounded by a para- or diamagnetic medium than it can when surrounded by a magnetic medium can be referred to the fact of the conductivity (reactivity) of the surrounding medium, (3284) as can the permanence of induced magnetism (3285). According to Faraday the magnet and the external medium are in 'mutual dependence', the medium sustaining the power of the magnet because of its 'imperfect magneto-conducting power', in virtue of which the medium is thrown into a 'state of tension' or 'acts back upon the magnet' (3286, cf. 3282).

Without this reaction or resistance of the surrounding medium, the magnet would have no external field, nor of course, could it have any poles. Faraday has dispensed with poles and centres of action in favour of the idea that polarity is a property of lines that are necessarily continuous throughout matter and space. The latter idea is new, yet there is a striking similarity between the status that poles now have and the status originally attributed to electrochemical poles (electrodes) and to charged surfaces in the 1834 and 1837 theories of electrolysis and induction. Magnetic poles 'exist' in the same sense (and for the same reasons) that electrolytic poles and charged surfaces 'exist'--they are interfaces between two mediums having marked differences in some power (magnetic conductivity, chemical affinity or polarizability, and electrostatic inductive capacitance).[66]

We can now see what Faraday means when he claims that 'the space or medium external to the magnet is as important to its existence as the body of the magnet itself' (3284, my italics), and why the 'zero'

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66. Cf. supra, pp.141-43 and p.353 (note 56).

conductivity of free space had to be a real property.[67] As Faraday had insisted throughout the Researches, there can be no action without reaction. The manifestation of a quality is an action. Since Faraday has restricted knowledge to the perception of qualities, knowledge presupposes the existence of a state of polarity or of action and reaction between the perceiver and what is perceived (qua individual). Thus, the field must exist as the basis both of the existence of things such as poles and charges and of the possibility of our having knowledge of them:

> without this external mutually related condition of the poles ... a magnet could not exist; an absolute [unrelated] northness or southness being as impossible as an absolute or an unrelated state of positive or negative electricity ... (3277)

This conclusion is not new. It dates at least from Faraday's denial of the 'latency' of a single electrical state in 1837. But that argument has acquired wider implications. Although Faraday has stated his case in terms of principles that are physical (being about force or power) his insistence upon their necessity and fundamentality harbours an epistemological precept. Faraday had identified 'matter' with its active or manifest powers in 1844 on the grounds that the powers are all that can be known. He is now arguing that the actions by which such powers are manifested exist only as tensions or polar relations: the external field of the matter. Without this field the matter would have no external powers and hence, could not be known to exist. Hence, on Faraday's criterion of knowledge, no claims about its existence could be made. The field is, therefore, the basis both of perception and of existence as Faraday understands

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67. 'the medium or space around [a magnet] is as essential as the magnet itself, being part of the true and complete magnetic system' (3278). For the conductivity of space see supra, sections 3.5 and 3.5.3.

these concepts. Space cannot be 'magnetically dark', any more than the space surrounding the sun or a candle can be optically dark (3361,3303):

> The magnet could not exist without a surrounding medium or space, and would be extinguished if deprived of it ... (3361)

Faraday has two remaining arguments in support of his contention that the lines of force must be considered as constituting a real system of power. Both turn upon his conception of the nature of explanation. The first (based upon the heuristic potential of the theory of lines of force) is that if the magnetic lines are as real as the electrostatic lines then a unified theory of the two powers can be established. The second is that motion of a conductor in the region of a magnet cannot be considered as the true cause of the current induced in the conductor.

4.2.3 The unity of force and the classification of powers

Part of Faraday's attempt to assess the relative merits of his own theory of lines of force and of its rivals involves the classification of different forces or forms of power in order to determine whether magnetism is more like an action at a distance or more like a mediated, physical process. It is also an attempt to settle a question so far left open by Faraday's theory, viz. whether magnetic lines represent force in its inductive state or in a progressive (dynamical) state analogous to that of the forces of a current.

Faraday lists five properties possessed by five of the known forms of power. He shows that these forms can be classified accordingly as they possess all of these properties, some of them, or none of them. Possession of any one of these properties indicates that

action of that force is not a'pure case' of action at a distance (3245-46,3270). These properties are listed below.

(1) That the force requires time to produce its effect 'would show undeniably that a physical agency existed in the course of the line of force' (3246).[68] This has not been shown to be true of gravitation, nor of electrostatic induction (3249), but it is certainly true of radiation (light (3247)) and of electricity in its dynamical form (currents (3259)).

(2) That the lines of force are affected or modified by an intervening medium (not in respect of the time taken for a change of form to be transmitted, but in respect of their form, distribution, density, etc.).[69] The lines or rays of light, heat, and of electrostatic induction are evidently affected in this way, and Faraday has supposed that the lines of magnetic force are similarly 'refracted' by some power of the region through which they pass (2591).

(3) That the power or action may exist independently of its source and/or its terminal point or destination. This presupposes that transmission takes time, but is not (apparently) entailed by (1), for Faraday distinguishes between light and heat ((3247), which 'have no dependence upon a second or reacting body') and electrodynamic (current) phenomena in which 'the propagating process has intermediate existence, like a ray, but [still] depends upon both extremeties of the line of force ...' (3251). Gravitational and electrostatic action also depend upon the line having a source and a reactant, yet do not appear to take time.

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68. For a discussion of the nature of this 'agency' see sections 3.2.1.2 and 3.4.

69. For a discussion of possible effects of matter and space upon the field, see section 3.5.3, table 3.2 (p.325).

(4) That the action is limited or definite in power. By this Faraday means that while a dual or polar power such as the electric charge of a particle acting upon a second particle will be diminished as more particles are brought near it (so that 'to act upon the latter its power must be proportionately removed from the former'), a non-polar power such as gravitation will continue to act equally on a second body no matter how many others are brought near it or between it and the second body (3248). Here we have an explicit statement of the connection between the concepts of polarity, action (equality of action and reaction), and of the 'limited' nature of power as a conserved quantity:

> this limitation appears to exist as a necessity in the dual character of the force; for the two states, or places, or directions of force must be equal to each other (3248).

This argument had originally appeared in Faraday's defence of his contention that elementary particles could act over sensible distances provided that as polar forces, their powers be wholly absorbed in producing a reaction at the nearest possible point or surface.[70] Evidently electrostatic and electrodynamic lines are limited in this sense, and while gravitational actions are not, Faraday believes that all powers should prove to have this property.

(5) That the lines of force are polar as exhibited through their effects, this being either linear polarity (sense) or rotational polarity. Only rays of light and of heat have been found to exhibit the latter, and although this occurs in a magnetic field, 'nothing analogous to the polarization of a ray of light or heat has been impressed on' the lines of magnetic force (3252). Electrical and magnetic powers are polar in that their lines exhibit 'antithetical

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70. Cf. supra, sections 2.1 (p.109 ff.), 2.2.1 (p.121 ff.), 2.4.3 (p.186 ff.) or ERE II: (1628,1665,1681) and ERCP: 447-50.

qualities' in different directions. While these lines and those of gravitational action necessarily have both a source and a terminal point, the latter do not appear to be polar in any respect (3248-49).

Given these five possible properties of the lines which represent the various forms of power or action, we find that there are three categories: (1) gravitational forces, which possess none of these properties; (2) radiation of rays of light and heat, which possess all of them; and (3) electrostatic and electrodynamic actions, which possess some of these properties. Magnetism clearly belongs in the third group, for it is decidedly polar and its effect on the plane of polarization of light suggests that its lines may 'have a separate existence' (3252) like those of light. It is decidedly 'limited' in nature, where this 'limitation in amount of force appears to be intimately dependent upon the dual nature of the power' (3255). Like electrostatic induction, magnetic action possesses all the properties exceptthe first (and possibly the third).

Faraday believes that a full understanding of magnetism will be had only when the various magnetic actions are 'found to unite or exist under one form of power' (2718).[71] His theory of the conductivity of matter for magnetic action has shown how this can be done, but that theory still has to be united with the theory of electrostatics. To do this Faraday has to determine how far the analogy between lines of magnetic force and lines of electric force can be made to extend.

The first problem is to determine whether the magnetic lines are those of a force in its dynamical or progressive state (as

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71. It follows that an advance in the understanding of one form of magnetic action could not occur 'without a corresponding advance in the knowledge of the others' (2718). Here the principle of unity serves as a criterion of the adequacy of an explanation.

Faraday appears to have treated them here)[72] or those of a force in its static or inductive state. While both electrical and magnetic lines must terminate at or on points of equal action, the lines of electrostatic induction will terminate at some point or on some body other than the one in which they originate while those of magnetism and of the electric current must return to the matter in which they originate. In this respect magnetic lines are analogous to the line or course of the current as originally defined (517), for they must continue through bodies (like the current) whereas lines of static induction (apparently) need not (3264-65).

That Faraday is reasoning from what he takes to be necessary properties--but properties that are observable--shows just how closely tied his basic theoretical concepts were to experience, on the one hand, and to his postulates, on the other.[73] This point is underlined by the fact that Faraday now develops a model of a possible relationship between the electric and magnetic forces, using just those phenomenal properties of the forces that are required for a description of the process of magnetic induction.[74] Only when this model has been developed can Faraday decide whether the lines of magnetic force constitute that force in its dynamical state or in its static state.

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72. Citing three 'general hypotheses of the physical nature of magnetic action' (that of 'aethers, carrying with it the ideas of fluxes or currents [as] Euler has set forth ... in his Letters [to a German Princess]', that of magnetic fluids whose elements attract and repel at a distance, and that of Ampère) Faraday remarks that his 'physico-hypothetical notion ... falls in rather with the first view, yet does not assume so much' (3302).

73. Cf. (3234 ff.) and supra, section 2.3.3.

74. This is really a conjecture about the most probable arrangement of the electric and magnetic forces (that must, on Faraday's view, always exist together. Cf. supra, pp.84 ff. and 171 ff.).

The problem of representing the interaction and conversion of electrical and magnetic forces is solved when Faraday realizes, first that the lines of magnetic force can be described in the same terms as the electric current has been (as an 'axis of power ...' (517, 3265)) and second, that apparent disanalogies between the behaviours of the lines constituting each force can be reconciled:[75] these behaviours become complementary to each other when the axis of each line of power is made perpendicular to the other and to a third line (3265, cf. 1114). Then

> the tendency to elongate in the electric current, and the tendency to lateral separation of the magnetic lines of force which surround that current, are both tendencies in the same direction ... (3268)

As Faraday has suspected all along, this 'relation of mutual position' of the two powers 'points to the intimate physical relation, and it may be, to the oneness of condition of that which is apparently two powers or forms of power ...' (3268).

The question as to whether the immediate cause of the induced current is magnetic force in a static state or in a dynamical state can now be answered. Faraday had been unable to detect the 'magnetic equivalent to static electricity'. Whereas he had argued in 1838 that the magnetic force should exist, like the electric force, in two active states, he now argues that as the undeveloped (normal or quiescent) condition of both forces must coincide, and as the apparently dynamical state of the magnetic force cannot arise directly out of the quiescent state (3269),[76] the observed state of the force

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75. These behaviours are that lines of electric action tend to collapse laterally and elongate along the axis of the current (as static induction gives way to discharge) while those of magnetic action tend to contract longditudinally and expand laterally (3266). Cf. infra, p.370 and supra, section 2.4.1.

76. Cf. supra, sections 2.4.1-2.4.3.

must be a static one. There would then be no magnetic analogue to the dynamical or progressive state of the electric force.

Behind this argument lies a more fundamental principle than that of the unity and convertibility of force, albeit a principle that has emerged only late in Faraday's career. This is the principle of economy or of least action. The behaviours of the lines of force (tendencies to elongation or contradiction) alluded to above and the behaviours of bodies between which the lines exist, can be explained on the basis of the property that this principle ascribes to the field.

4.3 The Causal Status of the Field

Faraday rejects the view that magnetic actions are due to dispositional properties of magnets and of materials susceptible to magnetic action. He has supported this rejection by showing that magnetic poles must be permanently related to each other because a wire enclosing or connecting two poles never has a current induced in it (3264),[77] and by arguing that on a dispositional interpretation of the effects that do occur force must be assumed as being created and destroyed as an immediate but temporary cause of those effects.[78] But as Faraday himself points out (3254,3259), the only direct evidence for the existence of inductive and other powers lies in effects that can be described dispositionally and explained without recourse to the notion of a permanently subsisting causal basis of those dispositions. Yet Faraday believes that he has a stronger argument. To say that a magnet has a tendency to attract or to induce poles in a needle only when the latter is present is one

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77. Cf. (3099) or supra, pp.349-51.

78. Supra, pp. 348-49.

thing (for it is true that the power is manifested only when the needle is present)--but to say that the magnet has a disposition to induce a current in a conductor is another, for the conductor is entirely different to the magnet unless one of the two is moving. From an observational standpoint the only necessary condition for the production of the effect is that there be relative motion of conductor and magnet. But if the explanation of this effect is to depend only upon the law that motion is a necessary condition for the induction of a current, then that explanation must be regarded as incomplete.

Faraday's final objection to the action at a distance theory follows from his beliefs about what can constitute a complete or adequate explanation of a process involving a change in the magnitude of a quantity representing power. He does not believe that a change in the quantity of a power (as measured by one of its effects) can be explained in terms of a change in the parameter representing distance.

In 1851 Faraday pointed out that when a conductor is moving in the region of a magnet it is related to the magnet by 'some other function of the power' than that of simple attraction and repulsion:

> But mere motion would not generate a relation [unless that had] a foundation in the existence of some previous state; and therefore the quiescent metals must be in some relation to the active centre of force [magnetic dipole] and that not necessarily dependent upon their paramagnetic or diamagnetic condition ... (3172)

The induction of a current involves the conversion of magnetic into electrical power, and this occurs without a change in the distance of the conductor from the surface of the magnet. Moreover, when a single magnet is used and the conductor is not a ferromagnetic, there is no disturbance of the distribution of the lines of force unless the conductor moves.[79] There are no effects of the sort that indicate

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79. Cf. (3270) and (2696-2701).

an interaction between magnet and conductor.

When the conductor moves a current is induced which (if the conductor were perfect) 'would be the full equivalent to the force, electric or magnetic, which is exerted in the place occupied by the conductor' (3270). But this induced current,

> having its full equivalent and relation to the magnetic force, can hardly be conceived of as having its entire foundation in the mere fact of motion (3270).

Since the conductor is indifferent to the magnet while both are stationary (there is no conversion of force) the conductor must be interacting not with the magnet but with the field:

> The motion of an external body, otherwise physically indifferent, could not beget a physical relation such as that which the moving wire presents. There must, I think, be a previous state, a state of tension or static state ... which, when motion is superadded, produces the dynamic state or current of electricity (3270, my italics).

Motion is a necessary condition for the conversion of force in this instance, but it cannot be regarded as a sufficient condition. It is not possible ('conceivable') that a conductor

> could have this [susceptibility to inductive] power in the moving state, if it had no relation at all to the magnetic force in the fixed state ... The mere addition of motion could do nothing, unless there were a prior static dependence of the magnet and the metal upon each other (3338).

The region of the magnet must be in an active ('tonic' or static) state which is

> sufficient to constitute and give physical existence to the lines of magnetic force, and permit the occurrence of curvature or its equivalent external relation of poles, and also the various other conditions, which I conceive are incompatible with mere action at a distance ... (3270)

This state or condition of all space, whether occupied by matter (active sources of power) or not, is the electrotonic state (3269). As Faraday had believed in 1831, the fact of magnetic induction is proof that matter near a magnet is causally related to the magnet by its field.[80] He is now prepared to claim that the field that exists as the basis of these causal relations (and of the properties that are their effects) may exist in space as well as in matter.[81] Behind this claim lies Faraday's belief that only real causes, quantities of power, can produce the effects that we observe as the properties and behaviours of matter. The current, as a quantity of electrical power, cannot be created out of a change in distance, which is a measure of a non-causal entity, space. Therefore its creation cannot be explained just by stating that motion is a necessary condition.

4.3.1 Faraday on what there is

Faraday's rejection of action at a distance and his defence of the reality of the lines of force turns upon his conception of what the world is really like.[82] On his theory matter is known as its powers, which are the manifestations of changes in the distribution and form of the lines or courses of action of the 'great power' that constitutes all that there is in the universe. He explains the laws of these powers in terms of a small set of principles or postulates, which specify how that power must behave. Although Faraday has adopted or developed most of these principles early in his scientific career, the most fundamental explanatory postulate or law of the

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80. Cf. series 1 (2, 60 ff., esp. 73), and (3337).

81. (3270,3277 ff.) and supra, section 3.5.3.

82. Cf. supra, sections 2.7.3 and 4.1.1.

field is one that has appeared relatively late. This is the principle of economy or of least action.

We have seen that from early as 1831 Faraday had assumed that the cause of a phenomenon lies in the fact that the normal or equilibrium distribution of the lines of force has been disturbed and that action, or an active state, is equivalent to a state of tension or constraint. Not until 1848 is this idea developed into the assumption that magnetic phenomena (specifically, the behaviour of crystals)[83] can be explained in terms of a property of the interaction of matter with the field, viz. that this interaction (being a mutual disturbance of matter and field) is such that the powers of matter and field return to a normal or equilibrium state (or as close as possible to the inactive, 'quiescent' state). Not until 1852 does Faraday attribute this tendency explicitly to both magnetic and electrical lines of action.[84] Only in 1852 does Faraday make clear that he has been reading this principle into the phenomena of magnetic attraction, alignment, and repulsion:

> When a free magnetic needle near the end of a bar-magnet first points and then tends to approach it, I see in the action a character ... in the magnetic axis of power [of a kind contrary to that of electrical lines]; for the lines of magnetic force are shortened, first by the motion of the needle when it points, and again by the action which causes the needle to approach the magnet (3266, my italics).

In keeping with his earlier explanation of the law of the motion of para- and diamagnetic action Faraday points out that this 'tendency of the lines of magnetic force to shorten ... would be consistent' with the idea that in a field

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83. Cf. sections 3.3.2 and 3.5.2.1.

84. (3268), cf. supra, p.365.

> those bodies which can convey onwards the most force, may tend ... to take up the position in which they can do so the most freely ...and so the effects both of attraction and repulsion be produced (3298, my italics).

The observed motions of bodies are not caused directly by tensions or pressures of the lines of force; this is a secondary effect. They are due to the more fundamental 'facts'[85] that curved lines constitute a quantity of power or action and that this quantity always tends to decrease by conversion into 'equivalents'--other forms of power--until an equilibrium condition has been reached (3317-18).

Thus the laws of the motions of electrified and magnetized bodies are shown to be instances of Faraday's postulates (specifically, that of least action)--just as the laws of magnetic induction, electrochemical action, and electrostatic induction had been shown to be. Bodies move in the way that they do because 'all physical forces tend to bring all bodies subject to them' into a 'final stable condition', a condition or position in which the lines of force are closest to their normal or inactive condition (3317).

This is Faraday's law of the field. It embraces those principles that he has used in interpreting phenomena and in evaluating explanations of them. It describes the nature of force or action, which must exist as the basis of the inertial, gravitational, electrical, optical, magnetic, and other powers of matter. For Faraday there is, ultimately, only power or action and this tendency of power in any of its forms to return to its equilibrium or 'undeveloped' state.

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85. Necessary truths about the nature of force: the postulates.

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Abstract

Faraday's Experimental Researches in Electricity are the account of an active dialogue with nature; an attempt to achieve what Faraday himself described as an ever closer agreement between 'natural truth and the conventional representation of it'. The object of the present study is to examine the basic concepts of the language in which this dialogue was carried out and to determine those assumptions made by Faraday in developing it into a general and fundamental theory of the properties of matter: the field theory. I have sought answers to three main questions:

(1) How does Faraday progress from the observation of phenomena and the analysis of experimental data to the development of specific theories of electrical, chemical, and magnetic action and, finally, to a general theory on which an apparently unobservable entity, the field, is posited as the causal basis of the properties of matter and of the laws of those properties?

(2) How does Faraday use the concept of an atom or ultimate particular, and why does he abandon this concept in favour of that of the field as the basis of the properties of all individuals, thereby subverting the atomic theory, the mechanical-corpuscular view of nature, and the related notions of materiality, existence, and explanation?

(3) How does Faraday justify the theoretical conclusions that he reaches at each of the main stages of his scientific career? In particular, how does he justify the claim that the field is a real entity in view of the fact that he has defined scientific knowledge as consisting only in direct perception and in empirically determined laws?

In order to answer the first of these questions I make an analysis of Faraday's use of certain descriptive terms and explanatory concepts, of the way in which these are refined or redefined in the light of both expected and unexpected experimental results, and of the role played by certain higher-order principles or postulates. I show that these principles specify Faraday's theoretical concepts (such as power, action, atomicity, polarity) and his meta-theoretical concepts (causation, existence, identity, explanation), and that they govern

his interpretation of experience and, therefore, his evaluation of rival theories. Only when these principles have been identified can the second and third questions be answered, for I show that Faraday's theoretical conclusions and his attitude toward the theoretical utility of atoms or individuals as ultimate entities turn upon these beliefs about what is possible.

Since these postulates are implicit in the early Researches and become explicit only gradually, I analyze the early research papers for cases in which Faraday rejects an apparently well-founded conclusion or accepts an apparently less plausible one, and for statements to the effect that something is possible (or impossible) or conceivable (or inconceivable). To show how these postulates and the concepts they specify actually develop into the basis of the later theory of the field requires that a comparative analysis be made of their use at each of several main stages of Faraday's work. In order to describe this development, in which experiment plays a crucial role as a determinant of the meaning of theoretical terms, I adhere as closely as possible to the chronology of Faraday's research reports. The requirements of providing a comparative analysis of concepts that become fully developed over a period of more than twenty years have been met by dividing the essay into four main parts. The first three parts provide an analysis of the role of the postulates as definitions of Faraday's fundamental concepts and their role in the design of experiments and in the interpretation of their results. The fourth part shows how they are used in Faraday's defence of the field theory as the most adequate representation of the field as an ultimate entity. Each part has been divided into sections and subsections which have been cross-referenced to earlier and later sections that deal with the same problem, concept, or aspect of Faraday's work. The most important of these include:

(1) Faraday's definition and use of terms to be used in describing an effect or process, (2) the use of theoretical terms and the role of hypotheses and postulates in the interpretation of phenomena, (3) the role of the postulates in constructing experiments and in evaluating various interpretations of their results, (4) the relationship between Faraday's epistemology and the ontological claims that he is or is not prepared to make, and (5) the analysis of arguments with which Faraday reaches and defends a given conclusion.

1. Part One of the essay covers the period 1830-1836, during which the basis of most of Faraday's later work was laid. Faraday's description and interpretation of his early experiments on magnetic induction (1.3.1)* and electrochemical action (1.3.2) is described in detail, for what prove to be the most important of Faraday's later ideas emerge in a rudimentary form from this early work. After introducing a working distinction between three forms of atomism (1.2) I show that Faraday uses a theory of matter corresponding to the second, on which both powers and atoms are posited, but that Faraday's theory of electrochemistry is clearly a theory about the relationships between atoms, rather than about the possible natures or structures of these as individuals (1.3.2). As an instance of this I show that Faraday's explanation of the law of electrolysis does not presuppose the concept of the atomicity of electric charge, that the law is explained in terms of a set of assumptions that define force as a quantity of action existing between elementary particles (1.3.3), and that this proof anticipates certain key ideas of Faraday's 1838 theory of electrostatic induction (particularly the postulates that electric forces are polar or inductive actions and that these inductive relations constitute a finite and conserved quantity of action).

   I then discuss Faraday's first attempt to demonstrate the unity (inter-convertibility) of electrical, chemical, and magnetic powers (1.3.4), his concepts of action and inertia (1.3.4.1) and his resistance to explanations in which material or substantial entities and structures are posited (1.3.4.2, 1.4). I show that the main problem left unsolved by the 1834 theory of electrolysis is that of explaining how the electric force which, in its static state, constitutes the chemical affinities, can be converted into the dynamical or progressive state that constitutes the current, and that this problem undermines Faraday's confidence in the utility of atomic or structural models of matter (1.3.4.1, 1.4).

2. In Part Two the emergence of Faraday's main postulates is traced and his use of the atomic hypothesis is further examined. I show that Faraday advances the principle that every electrical property or state must be causally related to another equal and opposed state (the principle of induction) as the fundamental assumption of a theory that was developed to solve the problem of explaining the conversion

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* Numbers in parentheses denote main sections of the thesis.

of electricity from its static (inductive) state into its dynamical (progressive and magnetically active) state (2.1-2.4). I show how the principle of induction is justified (2.2), how it is used in the interpretation of certain experiments (2.2, 2.2.2), and how Faraday's denial of action at a distance follows from this principle (2.2.1). Here I show that Faraday's denial of action at sensible distances is consistent with his acceptance of actions at intermolecular distances that may be sensible distances (2.2.1) and that his principle of induction is compatible with Faraday's adoption of dynamical atomism and of a concept of polarity similar to that found in Naturphilosophie.

I then describe Faraday's atomic theory of the dielectric (2.3) and show both that the hypotheses of this theory are assumptions about powers (rather than about substantial entities or structures (2.3.1-2)) and that the lines of electrostatic induction represent the properties (natures) of these powers as defined by Faraday's postulates (2.3.3, 2.4.3). The introduction and definition of descriptive and theoretical terms is discussed (2.2.3) and an analysis of the interplay between the postulates, experiment, and the theory of the dielectric is made, in which it is shown that Faraday draws a conclusion on the basis of analogical considerations and from the theory of induction (2.4.1) but defends his rejection of experimental results that fail to confirm this conclusion by appealing to the principles that underly both the analogical argument and the theory (2.4.2-2.4.3).

I then show that the limitations inherent in the theory are due to the ambiguity of Faraday's concept of inductive action and to the fact that the ontological status of the elementary particles (as distinct from their powers) has not been determined (2.5.1), and that although Faraday has introduced two models of the dielectric, he has tended to work within the context of a dynamical model rather than a corpuscular model (2.5.2, cf. 1.2.1).

The problem of determining the relationship between Faraday's speculative lectures of 1844 and his earlier work is then raised, and two main interpretations of Faraday's work are discussed (2.6), viz. that of P.M. Heimann, on which Faraday's 'Speculation' of 1844 is taken to be an ad hoc response to a problem made clear to him through the criticisms of Robert Hare in 1840, and that of Williams and Levere, on which it is argued that there is a continuity of development

from Faraday's earlier thought, through his lectures of 1844, to his field theory of 1852, and that this consists either in his adherence to a specifically Boscovichean form of atomism (Williams) or more generally, to dynamical atomism (Levere). I argue that Faraday advances in 1844 a position that is characteristic of his earlier work in several important respects, that Hare's criticisms did not have a significant impact upon Faraday, that the importance of the concept of polarity in Faraday's work cannot be explained solely in terms of the influence of a native British tradition of dynamical atomism, and that these influences would have been significant long before 1844.

I conclude part two with a discussion of Faraday's definitions of matter and of scientific knowledge as presented in 1844 (2.7), specifically, of the role of an epistemological precept in his defence of a dynamical form of atomism in which the distinction between substances and attribute is denied (2.7.1-2.7.2) and in his defence of the claim that powers are both sufficient and necessary for the purposes of scientific explanation (2.7.3). I show that this precept is quite compatible with Faraday's earlier approach to the problem of describing and explaining natural phenomena, in which he had tended to make assumptions not about individuals but about causal relationships between them (2.7-2.7.4).

3. In Part Three I show how the general theory of magnetism that Faraday had failed to develop in 1838 is achieved between 1846 and 1850, and that it is based upon the same set of postulates that had emerged in the first two stages of his career (3.1-3.1.3). I show that despite his growing dissatisfaction with the utility of the atomic hypothesis, Faraday does at first attempt to develop an atomic theory of magnetism. The inadequacy of this attempt is described (3.1.3) and it is shown that Faraday advances the theory by adhering to an analogy between magnetic and optical properties of matter first suggested in 1840, but developed only after 1846 (3.2, 3.3.2), and by replacing hypotheses about individual atoms by general assumptions that define matter as a region having a certain ability to refract the lines of magnetic action (3.3.2, 3.5.2).

I also show how Faraday deals with the contradiction between what his principle of induction requires and what the nature of diamagnetic action seems to show (that not all magnetic action is polar

or inductive (3.3.1)) by redefining the concept of polarity, and how this solution follows from an attempt to disprove the rival interpretations of Weber, Plücker, and others (3.3.2.1). I show that this solution involves the introduction of a new principle, that of economy or of least action. I then show how the general view emerging by 1848 continues Faraday's method of explaining properties and laws of action by attributing the necessary properties to dynamical interactions rather than to individual entities. I argue that Faraday held that both inertial and gravitational mass are relational rather than primary or inherent qualities (3.4).

The general theory of magnetism and of the nature of polarity is then described (3.5.2) and it is shown how Faraday explains the observed properties and behaviours of matter in the field in terms of postulates about the nature of force, and in terms of a principle of least action (3.5.2.1-2). I also show how Faraday is able to attribute conductivity or reactivity to space as a property while still maintaining a distinction between matter and space (3.5.3). Finally, Faraday's version of an objection to his contention that the field exists as the causal basis of the properties of interacting individuals is given, viz., that the manifestation of these properties may be described and explained in terms of a set of necessary and sufficient conditions and without recourse to the notion of the field (3.6).

4. In Part Four I examine Faraday's rebuttal of this objection and his defence of the field theory as a set of statements about the ultimate basis of all events and properties. I first examine Faraday's beliefs about the nature and the truth of theories, and his criteria for the adequacy and truth of a theory (4.1). I then describe his arguments for a realistic interpretation of the field theory (4.2), and show that the concept of polarity and his concepts of causation, existence, and the nature of explanation are inextricably linked and crucial to his rejection of the physics of central-forces acting at a distance (4.2.2). I then show that an implication of one of Faraday's arguments is that the field is necessary both for an explanation of the manifestation of properties and for the perception of those properties (4.2.2.1). I show, finally, that Faraday's ontology reduces ultimately to the field as an extended quantity of action, a system of power whose nature is defined by the principles of unity, convertibility, conservation, and induction (4.2.1, 4.3) and that the principle of least action proves to be the fundamental causal law of Faraday's field theory (4.3.1).