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# Michael Faraday's "Lines of Force" and the Role of Heuristic Models in Early Electromagnetic Field Theory

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By

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## Note to the Reader

Michael Faraday's writings were published in a number of different collections and posthumous editions. Unless otherwise noted, citations refer to *Faraday's Experimental Researches in Electricity: Guide to a First Reading* edited by Howard J. Fisher. These are simply attributed as "Faraday" followed by a paragraph number. Citations from the unabridged editions are written as "*Electricity*" and the volume number. All references to Faraday use his in-text paragraph numbers, and quotes containing parenthesized numbers are in-text references to previous paragraphs appearing within the same work. References to Faraday's *Experimental Researches in Chemistry and Physics* are written as "*Chemistry*" followed by the page number. Finally, references to Faraday's correspondence cite Frank A. J. L. James' *The Correspondence of Michael Faraday*. These appear as "*Correspondence"* followed by the letter number.

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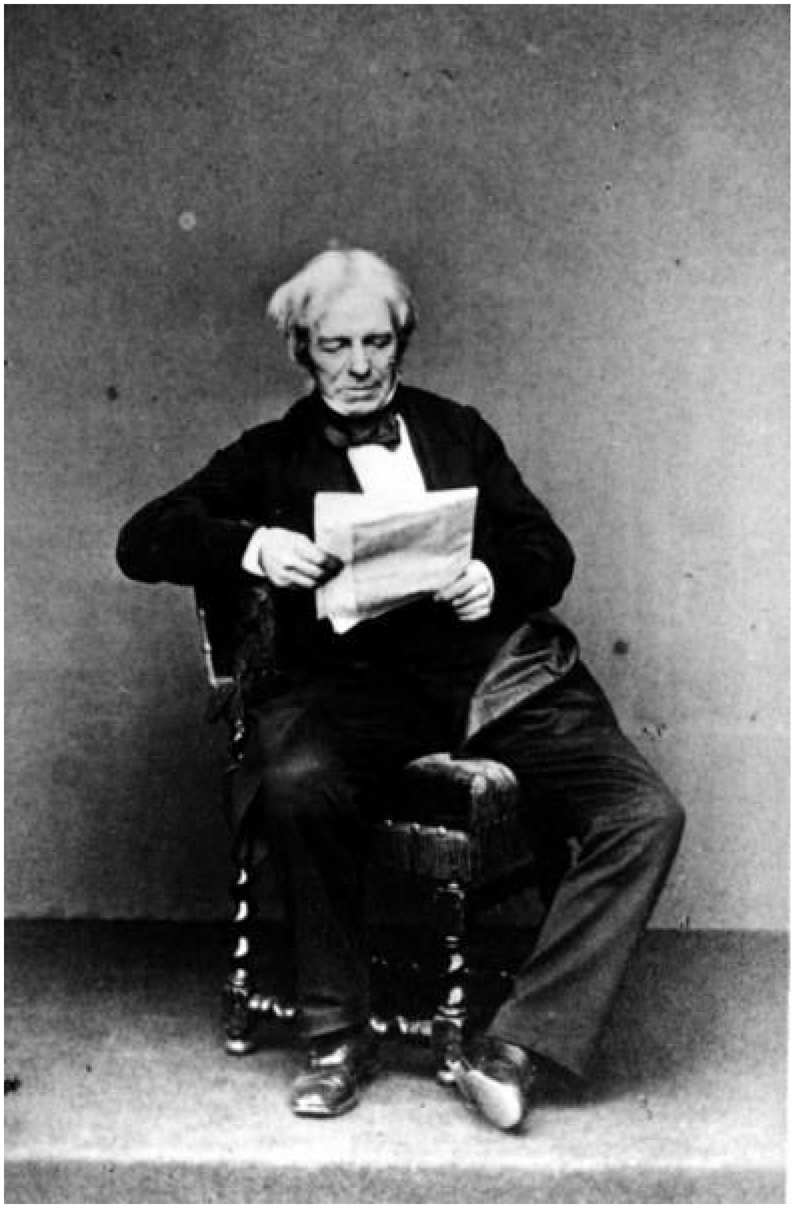

Michael Faraday reading a newspaper. John Watkins, c. 1863

# Introduction

After more than four decades of ground breaking research in chemistry and physics, Michael Faraday, the premiere experimentalist of the Royal Institution, prepared to give one of his many popular lectures. Indeed, Faraday was famous as both an accomplished scientist and a distinguished public speaker. In addition to the usual members of the Institution, the Prince Consort Albert was, on this occasion, in attendance. Seizing this opportunity to present his insights on the methods of intellectual discipline, Faraday articulated his beliefs about the limitations of the perception. He argued that, while reality was made manifest through the senses, they could not themselves provide an adequate understanding of the world.

Faraday outlined the difficulty in effectively applying the mind: “Let me next endeavour to point out what appears to me to be a great deficiency in the exercise of the mental powers in every direction; three words will express this great want, *deficiency of judgment*."[1] This judgement was the ability to effectively interpret the disposition and impressions of the senses. For this reason, the mind required the authoritative guide of disciplined reason. Errors in judgement resulted from a “simple and direct result of our perfectly unconscious state."[2] Because all perception of the world came from the senses, “the mind has to be instructed with regard to the senses and their intimations through every step of life; and where the instruction is imperfect, it is astonishing how soon and how much their evidence fails us."[3]Without proper discipline, the

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[1] Faraday, “Lecture on Mental Education”, *Chemistry*, p. 465
[2] Ibid. p. 465
[3] Ibid. p. 466

mind would be unable to adequately perceive the events affecting the senses. Thus leaving the individual unable to distinguish between entities of the environment and the phantasms of their own mind. Though Faraday's *Lecture on Mental Education* was given later in his career, in 1855, it reflected a lifelong interest in intellectual development. The proper interpretation and perception of effects were staples of scientific investigations.

Experimental demonstrability was a critical component in Faraday's investigation of natural phenomena. Without making a phenomenon manifest to the senses, it would remain purely an artifact of conjecture. Chief among Faraday's contributions to science were his experimental researches in electromagnetism. These investigations introduced electromagnetic phenomena as occurring in a medium or *field*, of force; fundamentally shifting the attention of science to the activity which transpires between objects. Experimental demonstration was not the only prerequisite for a functional understanding of these forces. As Faraday asserted in the lecture discussed above, the mind required an interpretive tool to decipher the results of experiment. This tool was the adoption of scientific theories as a heuristic models.[4]

Heuristics and analogies played an invaluable role in effectively reshaping Faraday's conceptualization of electromagnetic forces. They permitted newly delineated phenomena to be visualized beyond traditional categorizations, effectively creating new boundaries appreciable to the senses. Because these new entities were conceptual in origin, they were necessarily artificial, limited to the detectable attributes ascribed to them. By conceiving of theory as a tool of heuristic modeling, the investigator became aware of each theory's limitations and relative

[4] That is, an illustrative model emphasizing utility over truthfulness. Though the model is not an accurate depiction of system, it is, in some way, a depiction which facilitates understanding by highlighting useful albeit theoretical qualities in the subject.

utility. Though two theories may be irreconcilable, they each may illuminate unique qualities of phenomenon. Thus one could appeal to the whole range of different interpretations, making use of their specific qualities and implications.

This understanding delineated a divide between the conceptual reality of theories which are intellectually perceived and events in physical reality which are experientially sensed. Faraday was thus able to explore representations of natural phenomena as they became available to his senses. Through the separation of the conceptual model from natural truth, the investigator became free to consciously explore the relationship between abstract and tangible forces. By becoming aware of the relativity of theories, Faraday became able to consciously expand his perception of the natural world.

Many historians have debated the origins and influential extent of this guiding belief so as to better understand the success and structure of Faraday's ideas.[5] His work in electromagnetism distanced electricity from the study of chemistry, and laid the ground for the more modern field theories of Maxwell and Einstein. The debate surrounding Faraday's own conception of a field theory has raised two major questions: When did he conceive of the field? And how did he conceive of field?[6] Though Faraday himself never presented his investigations as a field theory, his portrayal of electromagnetic phenomenon has nevertheless warranted its consideration as the predecessor of modern theories.[7]

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[5] For an overview of different interpretations of Faraday's epistemology, see Nersessian, "Faraday's Field Concept", in *Faraday Rediscovered*, 1985.
[6] See Nersessian, 1985.
[7] Faraday does refer to 'fields' in his later writings, though the term is used alongside the more prevalent term "medium."

The historian Nancy Nersessian has argued that, when examining the formations of concepts - such as fields - a concise understanding of the concept itself should be explicitly given. Due to the evolving definition of field theory it is important to identify by what metric Faraday's ideas are measured, so as to avoid understanding his achievements and thoughts through the lense of more contemporary - or "complete" - field theories.[8]

As an early progenitor of the modern field theory, Faraday's field 'concept' are often deliberated using contemporary understandings. Force fields have, since the mid 19th century, played important roles in physics and have in modern times become staples of popular science and science fiction. The history of field concepts, however, is less well know. To avoid a retrospectively restrictive understanding of Faraday's "field", we must therefore consider its fundamental disposition in relation to matter and space. Where later investigators such as Maxwell and Einstein considered the field to be an aether-field or a plenum in which perturbations occur, Faraday mostly focused on distributions of force. In Maxwell's theory, the luminiferous aether acted as an intangible liquid in space through which the forces were transmitted. Meanwhile, the modern, Einsteinian conception of fields describes them as being a quality of space itself. Instead of an abstracted plane in which light or magnetism was transmitted, Faraday's forces were dispersed throughout space as 'lines of force'.[9] His investigations would later discuss the structure of these lines, granting valuable insight into the nature of space and matter. Though Faraday's work may have lead to Maxwell's mathematical models and later field concept, there exists certain fundamental differences between their depictions of electromagnetism. To avoid introducing inconsistent definitions, the field concept

[8] See Nersessian, 1985.
[9] These are often referred to as the equivalent 'lines of power', with 'power' and 'force' being interchangeable.

should be defined with as few assumptions to its attributes as possible. As such, this paper will understand a field to be the continuous presence or transmission of forces beyond the boundaries of physical bodies. This definition is similar to those proposed by William Berkson and Nersessian.[10] Despite its usefulness, difficulties arise when considering Faraday's conception of the electromagnetic medium.

Before Faraday had begun his investigations of electromagnetic phenomena, a number of electrical theories were present. Most eminent among these were the one- and two-fluid theories, which conceive of electricity as a the states or interactions of a liquid like force.[11] These theories were explored by continental chemists such as Andre-Marie Ampere and Wilhelm Weber within a Newtonian framework. Up until Faraday's introduction of the lines of power, force was considered attributes of physical objects. In order for forces to act, there had to be some material process by which the action could occur. Electromagnetic phenomenon was, much like the gravitational forces, attributed to newtonian action at a distance. That is, forces of electricity and magnetism were qualities of the material object, exerted upon other bodies at a distance. In short, agency was a quality of the object, not of space itself. Though Faraday does describe the necessity of a medium beyond ponderable matter, he considered force and matter to be indistinguishable. Because he conceived of matter itself as being a collection of forces, the distinction between medium and object becomes superfluous. Ultimately, Faraday considered forces to have a substantive quality, constituting the reality perceived by our senses.

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[10] Nersessian, 1985, p. 177; see Berkson, *Fields of Force: The Development of a World View from Faraday To Einstein*, 1974 p. 3

[11] Williams, *Michael Faraday*, 1965, p.154-55, Quoting Faraday's "Historical Sketch of Electro-magnetism", *Ann. of Phil.*, N.S., 2, 1821

As a prolific and organized writer, Faraday kept detailed notes of his experimental research. From 1831 onwards, he numbered the paragraphs of his published works in sequential order. These were then organized into series, separate papers which were presented to the Royal institution and subsequently published in the *Philosophical Transactions* publication.[12] His most notable investigations and reflections are found in two books. First, the *Experimental Researches in Electricity and Magnetism*, in three volumes covering work from 1831 to 1855, which details his exploration of electromagnetic phenomena which form the basis of his numbered *Series*. An excellent abridged and commentated version of this book is edited by H.J. Fisher. The second, his *Experimental Researches in Chemistry and Physics*, published in 1859, covers a number of topics relating to chemical investigations.

In light of the extensiveness of the literature on Faraday, attention should be directed to a number of influential or otherwise useful books. Of Faraday's own writing, multiple posthumous publication are noteworthy. Foremost among these is Faraday's *Diary*, which includes all of his laboratory notes. These cover his day to day thoughts and his tentative theories. Second, Frank A. J. L. James' collection titled *The Correspondence of Michael Faraday*, which assembles over five thousand letters from Faraday's life. And lastly, is Dr. Henry Bence Jones' *The Life and Letters of Faraday*, containing some of Faraday's journals, letters, and reflections. This last book is of interest as it contains Faraday's own accounts of his early influences. Moreover, there exists many thorough biographical overviews of Faraday's Life and work. A number of such works stand out particularly in the Faraday literature. Of the biographies written by Faraday's contemporaries, those by Tyndall and Gladstone are of note.

[12] Agassi, *Faraday as Natural Philosopher*, 1971, p. 9

While Tyndall focuses on Faraday's scientific achievements, Gladstone examines Faraday's character and philosophy. De La Rive's Obituary for Faraday is also compelling, as it is the only contemporaneous work to explicitly discuss Faraday's anti-Newtonian ideas. A more recent biography has been written by L Pearce Williams, providing an extensive survey of Faraday's life and scientific endeavors. In addition to these biographical texts, a large number of publications have studied Faraday's philosophy, science, and religion. Of particular interest are the writings of Joseph Agassi, William Berkson, and Geoffrey Cantor, who explore the many facets of Faraday's influences and method. Bekson and Agassi take different approaches to examining Faraday's metaphysical background, while Cantor offers an in depth analysis of Faraday's Sandemanian influences. Finally, *Faraday Rediscovered*, edited by David Gooding and F. James, provides a collection of insightful articles reexamining Faraday's work and scientific character.

There are a many positions as to what Faraday's field concept was, and when it was formed. In general, Faraday's field is considered to have appeared as either an intuition early in his career or as the culminations of his researches. Some historians, such as Nersessian, Agassi, and Berkson, attribute a field theory to Faraday early on in his career. Others, such as Williams and Gooding, recognize the field theory after Faraday began his later investigations of magnetism. This difference is due in part to their respective investigative focus. While Berkson approaches the question by analyzing differences between the metaphysics of Faraday and his contemporaries, Agassi and Williams compare Faraday's field concept to the Einsteinian one.[13]

[13] For a summary overview of the debate, see Nersessian, 1985.

The date and content of Faraday's field has been explored extensively and in great detail, leaving little room for novel alternatives. This paper will therefore examine Faraday's investigative method and the tools he used to develop field theory. The timeframe and specific content of the field will follow the position set forth by Berkson and Nersessian, namely that Faraday developed his field concept relatively early.

Though earlier field theories had been proposed, such as Euler's hydrodynamics, Faraday was introducing fundamentally new conceptions of force and space.[14] This was made possible through a peculiar blend of empiricism and conceptual speculation which arose in part from Faraday's particular metaphysical and religious background. By perceiving theory to be distinct from essential truths of nature, Faraday employed analogical and heuristic models in order to explore the features of electromagnetic force.[15] During his career, Faraday produced a large quantity of research spanning many topics. For this reason, only a fraction of Faraday's investigations, those pertaining to his electromagnetic investigation, will be covered. It should be noted, however, that even within this emphasis, attention will be primarily directed towards passages which exemplify Faraday's heuristic models. From these passages we see emerge the importance of an investigator's breadth of perception, and the central role of models in expanding it. For, though experiment was an illumination of the active forces of perceptible reality, it offered no insight into the mechanisms and truths of nature.

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[14] Hesse, *Forces and Field, The Concept of Action at a Distance in the History of Physics*, 1961, p. 192
[15] For a discussion of the structure and use of models, see Hesse, 1961, p. 21-28

# Section I: Models of Force and Space

## *Introduction*

Few individuals stand as tall in the range of their scientific achievements as Michael Faraday. A self educated scientist, he made great strides in the fields of chemistry and physics, most importantly through his study of electricity and magnetism. Without a "formal" background in the accepted theories of the early 19th century, Faraday was able to introduce radically new theoretical concepts supported by a meticulous experimental approach. Despite his overt empiricism, Faraday relied on a method of analogical modeling which arose from his metaphysical and religious beliefs. In order to investigate the new dimensions of electric and magnetic phenomena, he employed these analogical parallels to help illustrate new relationships between matter, space, and force. Though Faraday avoided the overt use of theory and speculation in his scientific writing until late in his life, it is clear that speculative insights guided his experimental researches.[16] This, and his reliance on explanatory models used to illustrate the new phenomena of electricity, brings into question the relation between theory and experiment. Faraday's overt use of explanatory models suggests a differentiation between theoretical models and the phenomena they describe. The difference is most striking in his dealings with the details of electromagnetic phenomenon, and its repercussions for matter. This approach produced many theoretical artifacts which were, at least in part, conceptual abstractions.[17] Such entities were essential for making the new phenomena accessible to the public and, ultimately, to Faraday

[16] Nersessian, 1985, p.183
[17] Consider for example the "unit lines of force", particles of force, and magnetic conduction.

himself. Throughout his researches, Faraday employed such heuristic models as the backbone of his investigative method. These heuristic models were indispensable for shifting scientific focus from the interplay of ponderable entities to the intervening medium, and thus introduced a thoroughly new conception of the sensible world.

This section will examine Faraday's conceptualization of "lines of force" as discussed during his researches of 1831-38 and 1844 onwards in an attempt to illustrate the foundational structure of electric - and later magnetic - field theory. In order to emphasize both Faraday's experimental reasoning and the structure of his analogies, his scientific investigations will be presented in chronological order wherever possible. The section is divided between an overview of Faraday's lines of force and their disposition in space. I will attempt to illustrate the process behind Faraday's models by tracing the development and structure of his lines of force, as it is through these that he examines the nature of forces. This background will provide us a means to further explore the role of metaphysics and heuristic models in Faraday's theory of electricity and magnetism.

Before investigating his scientific thoughts, attention must be paid to the influences of Faraday's spiritual and philosophical beliefs in guiding his epistemology. Faraday had, during his scientific studies, engaged extensively with philosophy. Many of these early explorations would guide his investigations and thought for most of his life. Young Faraday had received little formal education, gaining much of his understanding by reading the books he bound as an assistant.[18] For this reason it is difficult to know the writers with whom he was familiar, beyond

[18] Agassi, 1971 p.12; Berkson, 1974, p.16

those he cared to mention in letters. His earliest contact with scientific inquiry came from the article on Electricity in the *Encyclopaedia Britannica* and Jane Marcet's *Conversations on Chemistry*. Another important influence on Faraday's early thought was Isaac Watts' *On the Improvement of the Mind*.[19] As Faraday recalls, "there were two [books] that especially helped me, the "Encyclopaedia Britannica," from which I gained my first notions of electricity, and Mrs. Marcet's "Conversations on Chemistry," which gave me my foundation in that science."[20]

Opinions differ among historians and bibliographers as to which philosopher had the most impact on Faraday's work. Early biographies focused almost entirely on Faraday's empirical work, leaving any philosophical considerations in the shadows. Working against this trend, historians such as L. Pearce Williams, Edmund Whittaker, and Mary Hesse considered Faraday's divergence from the metaphysical norms of 19th century science. Williams and Whittaker in particular insist that Boscovich[21] played an essential role in Faraday's thought.[22] This connection is principally based on Faraday's multiple references to Boscovich's point atoms as the mechanism for his lines of force. The position has since been criticized by Gooding, Spencer, Tweney, and others on account of the contradictions between Faraday- and Boscovich's epistemologies. Chief among these was Boscovich's use of action at a distance.

Berkson and Agassi on the other hand consider a wide array of influences, such as that of Kantianism among others, found in Faraday's interpretations and metaphysics. It is however unclear how much of a direct presence Kant, had in Faraday's studies, leading Berkson to consider Leibnitz as a source of his anti-newtonianism.[23] Because his mentor, Humphrey Davy,

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[19] Agassi, 1971 p.13, Quoting Bence Jones' *Life and Letters*, 1:11.
[20] Ibid., p.13, Quoting Bence Jones' *Life and Letters*, 2:401.
[21] R. J. Boscovich, (1711-1787), Croatian natural philosopher.
[22] Williams, 1965, p.292
[23] Berkson, 1974, p.28

was also inclined towards anti-newtonianism, it is difficult to say which ideas were passed down from teacher to student. Berkson suggests that, by the time Faraday discovered electromagnetic rotation, he had enough intellectual independence to abandon those influences he found objectionable.[24] This is not a dubious claim, as Faraday did very likely combine his favored philosophies while leaving out those parts he found disagreeable. Faraday's thoughts on speculation present a good example. Though young Faraday found Watts' Baconian philosophy on mental education to be critically influential, he did entertain anti-Baconian ideas on the important role of speculation in advancing the sciences.

Faraday did not leave much evidence of his philosophical influences, save for occasional references such as his Boscovichean allusions. Having read Watts, Faraday was most assuredly familiar with Bacon, whose mistrust of unfounded speculation is visible in Faraday's own work.[25] It is also clear that Faraday read Euler's hydrodynamics and *Letters*, as he attributes his theory to that of Euler.[26] Regardless, due to his particular educational background, the influence of anti-newtonian ideas are visibly present in Faraday's work. Faraday came into contact with many of these philosophers during his work with Humphrey Davy, who harbored anti-newtonian sentiments of his own. Around the beginning of his apprenticeship with Davy, Faraday became an active member of the City Philosophical Society and, later, the Athenaeum Club, both of which were philosophico-scientific discussion groups.[27] Considering his philosophical stances expressed late in life, Faraday was deeply influenced by Davy, from his epistemological

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[24] Berkson, 1974, p.11, 31, 32.
[25] *Ibid.*, p.56-57
[26] Faraday, *Diary*, VI, p. 330, 333; Faraday, *Electricity* III, 3301
[27] Gladstone, *Michael Faraday,* 1872, p. 21, 29; Also See Hirshfeld, *The Electric Life of Michael Faraday*, 2006, p.65-66

considerations to his interest in electrochemistry.[28]Apart from Faraday's own readings, he was introduced to many of the philosophical and metaphysical concerns surrounding science through his work with Davy. As such, even if Faraday had not directly studied philosophers such as Boscovich, as evidenced by his limited understanding of the latter's theory, he would have encountered their ideas through Davy's teachings.[29]

Faraday, when first embarking on his scientific endeavors was a staunch supporter of the two liquid theory of electricity proposed by Henry Eeles. This changed rapidly once he began his studies with Davy who had rejected the liquid theories and warned about the unfounded creation of new entities and forces.[30] Faraday also gained from his mentor a fascination with the use of analogies to understand and explore natural phenomena.[31] Beyond the philosophical concerns, Faraday developed his belief in the importance of speculation and necessary separation between interpretation and experiment during his early years with Davy. Between the years 1816 and 1818, he gave a number of lectures ranging from chemical analysis of Tuscan mineral samples to the his thoughts on mental discipline. His emphasis on the distinction between Judgement and sensorial impressions, and the importance of the former in guiding the mind, remains intact in his *Lecture on Mental Education,* written some thirty years later. It is important to note that Faraday considered himself a *Natural Philosopher*, rather than a "scientist."

Faraday's three central metaphysical concerns were the unity and interconvertibility of forces, the rejection of newtonian action at a distance, and his conception of matter as a "sea of

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[28] Note that Faraday did support Davy's views, as Faraday would have had no obligation to continue employing them by the time he began his *Experimental Researches*.
[29] For an examination of the role played by Kant, Coleridge, and Boscovich in forming Davy's anti-newtonian philosophy, see Williams, 1965, p. 60-89
[30] Williams, 1965, p.84, Hirshfeld, p.11
[31] *Ibid*, p.84

forces." Berkson suggests that the reason behind Faraday's anti-newtonian outlook lay in his rejection of discontinuity. Forces acting at a distance would be both instantaneous and direct, "leaping" between the source and object rather than traveling across the distance that separated them. For Faraday, who strongly supported the unity of forces, such a disconnect in the force was unacceptable on apriori grounds.[32] As such, two of the three metaphysical convictions came directly from the Kantians. First, the unity of forces discussed by Coleridge in his translation of Kant.[33] Second, his broader rejection of action at a distance, due to its implicit discontinuity. Writers such as Kant and Coleridge introduced a much sought after challenge to the widespread materialism that dominated British thought; governed by philosophers such as Locke and Hume. In so doing, these criticisms of the newtonian system gained the religiously motivated sympathy of both Davy and Faraday.[34] A number of these Kantian and anti newtonian ideas closely paralleled Faraday's own Sandemanian beliefs.[35] As a member of the Glasite church, Faraday accepted both the bible and nature to be entities of divine revelation. Faraday, as a biblical literalist, considered the reality he perceived as the direct revelations of God. But, as the historian Geoffrey Cantor argues, another aspect of Sandemanianism was uncertainty of human interpretations of God and Nature.[36] Faraday explains:

> I believe that the truth of that future cannot be brought to his knowledge by any exertion of his mental powers, however exalted they may be ; that it is made known to him by other teaching than his own, and is received through simple belief of the testimony given. Let no one suppose for a moment that the self-education I am about to commend in respect of the things of this life, extends

[32] Berkson, 1974 p.52
[33] Williams, 1965 p.64
[34] *Ibid.*, p.63
[35] The Glasite church, also known as Sandemanian church, was a small Christian sect founded by scotsman John Glass around the 1730's.
[36] See Cantor, "Reading the Book of Nature: The Relation between Faraday's Religion and his Science", in *Faraday Rediscovered*; See also Cantor, *Michael Faraday: Sandemanian and Scientist*, 1991.

> to any considerations of the hope set before us, as if man by reasoning could find out God.[37]

The sandemanians believed that, because divine and natural truths of revelation were beyond the human intellect, any interpretation of truth would essentially be tainted. Thus, it was impossible for the natural philosopher to attain an understanding of the divine creation through mental inquiry.[38] This distrust of human cognition and insight would lead to a distinct separation between the experienced phenomenon and the human conceptualization thereof. Faraday's sandemanian stance on unknowable truths also reflected the beliefs of Bacon. Much in the same way the fundamental divine truths of nature were unknowable to the human intellect, the true essence of matter, Kant and Coleridge maintained, could never be perceived.[39] Only the effects of natural forces, detectable through experience, were available to the understanding of the human intellect. Faraday's third metaphysical conviction, the conception of matter as pure force, can be either seen as either a Sandemanian or Kantian influence. Both maintained the impenetrable nature of matter and, for Boscovich, an insistence on recognizing the experiential reality of phenomena imparted to the senses by barriers of force. Part of the appeal of Boscovich's point atoms was the few assumptions they made about matter: as far as Boscovich was concerned, matter was simply an impenetrable force. By incorporating these concepts into his speculations and experiments, Faraday would advocate for theory of matter as a continuous field of force. A fourth conception naturally came from these three metaphysical beliefs. Because tangible matter was constituted solely by forces, the conservation of those forces was was

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[37] Faraday, "Lecture on Mental Discipline"*, Chemistry,* p.464
[38] Cantor notes that Faraday's emphasis on the limitations of the intellect set him apart from the natural theologians who influenced much of early 19th century British science. See, Cantor, 1991, p. 198
[39] Williams, 1965, p. 68

necessary. Forces could neither be created nor destroyed, only changed into different configurations.[40]

Considering the important influence of Leibniz, Bacon, and Kant, either directly or indirectly, on Faraday's thought it is important to emphasize his key differences from these philosophers. Kant maintained that the forces of nature were of two kinds - each essentially different from the other: repulsive force which acted by contact, and attractive force, which acted at a distance.[41] Faraday on the other hand considered there to only be one universal force set in different configurations. His conviction in the unity of forces relied on all perceptible forces to be distinguishable and commutable aspects of an all encompassing medium. One of Faraday's earliest breaks from newtonianism in his researches occurred with his discovery of magnetic rotation. To explain this rotational action, he proposed an action of non-central force contrary to the accepted central newtonian force proposed by Ampere.[42] The rejection of action at a distance would also affect Faraday's disposition toward Boscovich, whose point atoms acted upon each other in newtonian fashion. Additionally, one of the main differences between Faraday and Boscovich was the differing interactions of their forces.[43] Because Boscovich's force atoms were impenetrable and acted at a distance, no one force could alter another. Contrarily, Faraday believed the forces to be mutually penetrable and described them as necessarily affecting each other when located contiguously to one another. It is evident upon inspection that Faraday did

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[40] Berkson, 1974, p. 58-59
[41] Agassi, 1971, p. 89; Berkson, 1974, p. 53
[42] Berkson, 1974, p. 50
[43] *Ibid.*, p. 51

not understand Boscovich's theory of point atoms in full.[44] Though Faraday had a deep Baconian suspicion of speculation, he also believed it to be the impetus for scientific innovation.

*The 'Lines of Force' and their particles*

First, an overview of Faraday's investigation of electromagnetism must be given in order to facilitate the analysis of the lines of force. Faraday's 'Lines of Force', which constitute a cornerstone of his conception of electromagnetism, extend throughout space. These tendrils of electric and magnetic force formed the guiding base of Faraday's researches. They functioned illustrative models based on the visual lines of magnetized iron filings.[45] During this early stage, the lines of force were as described as the line traced by a needle as it moved around a magnet's axis.[46] As such, the lines were simply an allusion to the visible patterns found when matter interacted with a magnet's influence. Up until Faraday's investigation of induction in his 11th series, published in 1837, little was said about the inner workings of the lines, or of the force itself. Through the experiments in static electricity and currents, and his explorations of these in vacuo, Faraday began to speculate as to the mechanisms behind electric force. Here he introduced the lines of force as the anti-newtonian, contiguous "particles" of force. The lines were then, in 1838, considered as themselves an aeriform electric body, extending the electric presence of a wire beyond its physical bounds. Whether or not this suggested an aether, Faraday would not answer, but it convinced him of the necessity of a medium of electricity and

[44] See Spencer, "Boscovich's Theory and its Relation to Faraday's Researches: An analytic Approach", *Archive for History of Exact Sciences,* Vol. 4, No. 3, 1967
[45] Figure 1 & 2.
[46] Figure 3.

magnetism. Not long after this breakthrough, Faraday found himself mentally exhausted, and laid his researches in electricity aside for four years.[47]

Faraday returned to his investigations by studying the effects of magnetism on light. In so doing, he introduced the lines of magnetic force - analogous to the electric lines explored earlier. Despite his firm belief in the interconvertibility of forces, the magnetic and electric lines of force were described as operating differently. No contiguous particles or seemingly implied movement of force were to be found in the magnetic lines. However, the difference may well only have been a formality reflecting Faraday's strong focus on demonstrability. He continued to explain and support his contiguous particle interpretation: much of the exploration of his lines of contiguous force particles come from his speculations after formally introducing magnetic lines of force. After Faraday's initial foire into magnetism, the lines of force were put aside to allow for more pressing investigations into the nature of magnetic action on bodies and vacuums. As such, the lines of force - though being continually referenced - changed relatively little. A number of discoveries, groundbreaking for Faraday's interpretation of magnetic action, occurred during these researches after 1845. One of these was the reaffirmation of the necessity for a medium external to magnetic and electric bodies. The other was a surprising discovery of the inherent magnetic character of vacuums. These discoveries both significantly bolstered Faraday's convictions of the accuracy and necessity of his lines of force in Electromagnetism.

For his 28th series of 1851, Faraday decided to reassert the core role of the lines of force in his magnetic theory. Relying on his rich collection of experimental results, Faraday presented the lines of force solely by the means of their experimental detection; reintroducing the them into

[47] Whittaker, *A History of the Theories of Aether and Electricity*, Vol I, 1951, p.189

a much more mature understanding of electromagnetic phenomenon. In order to demonstrate new aspects of magnetism Faraday introduced the use of a moving conductor, or wire, as an alternative method of detecting the lines of force. Observing the moving wire's effects on magnetized bodies, not only could could he prove the quantifiability of the lines and the equivalency of any one segment with another, he demonstrated his long standing belief that the lines were present *within* the magnet itself. Thus, the magnetic power of any one line was equal to that of any other line. That being said, Faraday understood that his experimental results did not themselves necessitate his lines of force interpretation. For this reason, the lines of force were divided into two interpretive categories: the lines as imaginary representations and the lines as physical structures of force. This allowed Faraday to separate the detectable, experimentally proven theory from his speculative inspirations. For, as no decisive proof of the lines of force themselves was necessary, Faraday wished to mitigate the potential attacks on his experimental theory through the criticisms of his speculated investigations. By showing the penetration of the lines of force into magnetic bodies, Faraday was able to propose his rendition of the lines of magnetic force as a complete, looping three dimensional "body" in space. The magnet could thus be considered an entity existing due to the interaction between the material body and the medium, each being only a portion of the whole magnet. The lines of force could then be, when collected together, considered as nestled shells. This shell, or sphondyloid, of power was the regroupment of all the lines of force composing a magnet expressed in free space.[48] Much of the old representational relations of the line of force remained. Where magnetic intensity had once

[48] Figure 4 & 5.

been represented by the illustrated proximity of different lines of force, now it could be shown as the relative distance between shells.

The conception of the space-filling lines of force originated in Faraday's early investigations with his mentor, Sir Humphrey Davy, on chemical affinity and 'strain' in the particles of a system.[49] Davy's primary research interests lay in the effects of electricity in chemistry. This understanding of strain developed from earlier conceptions of electricity as a wave moving through the particles of matter, straining them as it progresses.[50] With the discoveries of Hans Christian Ørsted, establishing a connection between electricity and magnetism, the duo set to work recreating and expanding Ørsted's experiments.[51] Faraday's interest in the topic originated with his attempt to write an overview of the history of electromagnetic theory; leading him to recreate many of its core experiments and critically analyze the existing theories of his contemporaries.[52] The formulation of the 'lines of force' introduced, though coming a little later, an alternative to the predominant Amperian theory of electrical action at a distance. When they first began recreating these early electrical experiments, Davy and Faraday, rather than place a magnet under a page covered in iron filings, pierced the page with an electrified wire. Such filings, when in the presence of a magnetized body, form a pattern of traced lines; where each particle aligning itself along the direction of the line.[53] With the wire passing perpendicularly through the plane of the paper, the iron shavings

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[49] That is, the concept of strain is recurring in his theory, and happens to be the earliest part to be developed.
[50] Williams, p. 198-200
[51] Whittaker, 1951, p. 170; Ørsted's name is often rendered as Oersted in English.
[52] See Williams, "Faraday and Ampere: a critical dialogue", in *Faraday Rediscovered*.
[53] See Figure 1 & 2.

formed concentric rings around the wire.[54] This provided an outlined visual representation of one of their other experiments, where a needle remained perpendicular to the wire as the former was circled around the latter.[55] Here, the needle would, when moved to different positions around the wire, maintain the same relative position and direction; by adding each position up, the needle would then describe a full circle, mimicking the circular arrangement of the magnetized iron filings discussed above. These experiments introduced magnetized iron filings, serving as their first visual representation of magnetism, and magnetic curves, which would embody the unseen mechanism causing these filing patterns, to their understanding of electromagnetic phenomenon.[56]

By modifying the original experiment, Davy and Faraday found that the filings began to acquire new configurations, which crucially informed their early conceptualizations of magnetic phenomena; this resulted in both physical and conceptual models. The duo created a number of mnemonic devices to illustrate the phenomenon they were investigating.[57] Their early models were used to remind them of how they were conceptualizing their experimental results, helping them better conceive of their new representation. But beyond aiding the visualization of new phenomena, these models served as an aid to concisely convey these findings to their contemporaries, not as theoretical constructs, but as representations of detectable natural artifacts. It was in his experiments with the movement of wires around a magnet that Faraday

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[54] Gooding, "'In Nature's School': Faraday as an Experimentalist", in *Faraday Rediscovered,* p.114
[55] See Figure 3.
[56] Faraday, 114, 3071
[57] These devices include Davy's disc device, demonstrating the circular 'direction' of curvature around a wire, and Faraday's marked dowel, illustrating the magnetic 'tube' surrounding a wire as shown from their needle experiment. Figure 3 & 4. For illustrations, see Faraday, *Historical Sketch of Electromagnetism*, 1821-22; see also: Gooding, 'In Nature's School', p. 112-3

first introduce 'Lines of Force' and their analogical depiction of magnetised iron filings. Faraday, in discussing the transection of these magnetic curves, clarifies: "by magnetic curves, I mean the lines of magnetic force, however modified by the juxtaposition of poles, which would be depicted by iron filings; or those to which a very small magnetic needle would form a tangent."[58] Faraday would later introduce the term 'electric lines of force' as an analogous image to these magnetic lines traced by the needles and iron filings.[59] The utility of this analogy becomes much more apparent when discussing the particulate structure of electrical action. This, in addition to the magnetic and electric force of the particles, here represented by needles, provides useful insight into Faraday's 'Lines of Force'. In exploring the lines of force through analogy, we see emerge in Faraday's writing one of his core metaphysical convictions: the unity of natural forces.

After numerous years of investigation, Faraday, for his eleventh series presented in 1837, turned his attention to elucidating the structure of electrical phenomena. Determined to describe the seemingly disparate forms of electrical action under one law, he began his investigation of induction, considering it one of the fundamental attributes of electric action.[60] Through these investigations, Faraday further developed his analogy of electric lines of force. In accordance with their visual representation in magnetized iron filings and needles, Faraday described these lines of power as comprising of "particles" or atoms of force, where said particles are contiguous to each other. The particles would act as a curved chain wherein the strain, later referred to as

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[58] Faraday, *Experimental Researches*, 114, fn. 6; This conception of 'Lines of Force' as an illustration of magnetic phenomena was not particularly new to Faraday; the term has been traced back as far as Niccolo Cabeo's *Philosophia Magnetica* of 1629. See Whittaker, 1951, p.171, fn. 4
[59] Nersessian, 1985 p.182; see also: Williams, *Michael Faraday*, 1965, p. 181
[60] Most notably static electricity, electric currents, and electrolysis. See Faraday, 1161

tension, of electric disturbances would manifest. Besides its importance for a united conception of electricity, induction as understood by Faraday challenged the commonly held theory of electrical action at a distance. While investigating induction and chemical decomposition (electrolysis), Faraday found that electricity consisted of two kinds of electric action, distinguished only by their opposing direction, and inseparable. This, in addition to his researches into chemical affinity in electrolytes - which would conduct only when in certain states of matter - led him to consider induction as occurring along curved lines of particles.

> As, therefore, in the electrolytic action, *induction* appeared to be the *first* step, and *decomposition* the *second* [...];as the induction was the same in its nature as that through air, glass, wax, &c. Produced by any of the ordinary means; and as the whole effect in the electrolyte appeared to be an action of the particles thrown into a peculiar or polarized state, I was led to suspect that common induction itself was in all cases and *action of contiguous particles*, and that electrical action at a distance never occurred except in the influence of the intervening matter.[61]

Faraday clarified his use of *Contiguous* in a footnote to paragraph 1164 saying: “The word contiguous is perhaps not the best that might have been used [...]; for particles do not touch each other is not strictly correct. I was induced to employ it, because in its most common acceptation it enabled me to state the theory plainly [...]. By contiguous particles I mean those which are next [to each other]." These lines, originally visualized as analogous to those created by magnetized iron filings, would be a certain “species [or measured state] of polarity”, with the transmission of electric force deriving from one particle's tension - or polarity - transmitting to, or affecting, its contiguous neighbors.[62] The illustration of this new theory of electric action was difficult to

[61] Ibid., 1164, italics from source. Note his reference to action at a distance and intervening matter, which will become a subject of some concern later on.
[62] Faraday, 1165; See also, Faraday, 1673: “That lines which being contiguous are also in the line of inductive action can communicate or transfer their polar forces one to another *more or less* readily."

perfect, and Faraday took great pains to avoid any implication of progression or movement.[63] Here we see Faraday's response to the commonly held theories of his day. These theories maintained that electricity was some form of fluid operating independently of the matter from which the phenomenon originated. After failing to separate different forms of electricity (negative and positive) into isolated states, he proposed that these forms were just different manifestations of the one electric force associated with matter.

How then could a line of force transmit polarity through a chain of particles if no such linear transmission was occurring? The issue lies in Faraday's discussion of particles and the role of force. What is most notable about the lines of electric force and their particles is their illustrative utility for Faraday's theory. Until a more adequate understanding of induction was attained, Faraday mostly refrained from reflecting on the physicality of atoms; such discussions were nonetheless scattered throughout his investigations from 1834 onwards.[64] To properly glean a more comprehensive conception of the nature of force particles, we must skip ahead to Faraday's later writings, as only then did he firmly declare his beliefs. By the time Faraday more readily dabbled in open speculation about the subjects of his investigation, the lines of force had become well established in his mind.[65] In a letter to Richard Taylor *Esq.* from 1844, Faraday admitted his scepticism for atomic theory.

> I feel myself [he writes] constrained, for the present hypothetically, to admit to them [atoms], and cannot do without them, but I feel great difficulty in the

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[63] See Faraday *Experimental Researches*, Editor's introduction p. 23, fn. 1. H.J. Fisher explains this as an active avoidance of evoking the "electric flow" models used by the one- and two- liquid theories. See also: Faraday's *Diary*, 13341.

[64] E.g. Faraday, 869: "But I must confess I am jealous of the term *atom*; for though it is very easy to talk of atoms, it is very difficult to form a clear idea of their nature, especially when compound bodies are under consideration."

[65] Faraday, 3174

> conception of atoms of matter which in solids, fluids, and vapors are supposed to be more or less apart from each other, with intervening space not occupied by atoms. [Faraday then goes on to assert that] if we must assume at all, as indeed in a branch of knowledge like the present we can hardly help it, then the safest course appears to be to assume as little as possible.[66]

The caution against overt assumptions was not new for Faraday's method. He made an effort to exclude unfounded speculation from his notes and papers, both as a means to promote clarity and to avoid meaningless theoretical conjecture. It is no surprise that he would avoid overtly favoring one theory of matter over another, just as he had previously avoided any firm theoretical stance on the true nature of electricity.[67] What is particularly striking about the admission above is how it highlights a fundamental difference between the structure of Faraday's theory - his public depiction of natural forces - and the actual structure of natural phenomena as he himself conceived of it. We see Faraday employ a descriptive model - atomic particles of force - which presents a fundamental conflict with his conception of nature as 'continuous', solely for the former's illustrative utility. In other words, Faraday used atomic representation, not for its truthfulness, but entirely for its illustrative convenience. The contradiction between quantized and continuous matter is perceptible even in his earlier discussion of contiguous particles, where the atoms are seemingly both in adjacent and separated at the same time.[68] This is resolved by considering the atomic illustration simply as a convenient model used to help formulate a new understanding of matter. Or, to highlight the experimental component, the useful albeit inaccurate conceptual aid is employed to help familiarize the new understanding of matter,

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[66] Faraday, Letter to R. Taylor, 1844, in Faraday's *Electricity* II, p. 289. *cf*. Spencer, "Boscovich's Theory and its Relation to Faraday's Researches: An analytic Approach", *Archive for History of Exact Sciences,* 1967, p 198

[67] Faraday, 667, 852; see also Whittaker, 1951, p. 176

[68] E.g. Faraday, 1164, quoted above. This would cause difficulties with Faraday's contemporaries, who found 'Lines of Force' and their particles to be exceedingly vague and circumspect. Chief amongst these concerns was how a theory reliant on contiguous particles could explain inductive action in a vacuum.

exposed through experiments in electricity.[69] This is the clearest separation between models and phenomenon in Faraday's early writing. Though he relied on experimentation to inform theory, this model suggests that Faraday considered there to be a difference between scientific knowledge derived from models and the natural phenomena they describe.

The discrepancy between Faraday's suspicion of atoms and his use of force particles is only one part of this conundrum. In acknowledging his need for a particulate theory, Faraday qualifies the extent to which the illustration is to be employed. To reconcile the imagery of particles with continuous matter, the physicality of the atom, i.e. its nucleus of matter, is replaced with a nucleus of force. Such an illustration of electric action came in part from Faraday's own understanding of "centers of forces." After exploring the concept of strain, Faraday considered matter to be the intersection of forces. Wherever lines of power intersected, the force would become perceptible to the senses as solid matter. To illustrate such particles, Faraday alluded to Boscovich's point atoms[70] which, beyond assuming the least about the properties of matter, "are mere centers of forces or powers, not particles of matter, in which the powers themselves reside."[71] Following this passage, Faraday then explains that the nucleus of force - reduced to a mathematical point, (i.e. without volume) - remains surrounded by an "atmosphere of force." In this way, even if two particles were some distance apart, their interaction would not necessitate action at a distance due to the extension of their "atmospheres."

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[69] These theoretical models serve the same purpose as Faraday's dowel and Davy's disc.
[70] Much debate has revolved around this allusion to Boscovich. Certain early historians, most notably Williams, Hesse, and Whittaker, have argued that Boscovich was very influential to Faraday's thought. More recent studies have argued to the contrary, pointing to the inherent differences between their separate theories, the specific circumstances and limited extent of Faraday's reference, and his obvious confusion over the nature of Boscovich's point atoms.
[71] Faraday, Letter to Taylor, 1844, *Electricity* II p. 290

Another consideration was that, as space was the only continuous medium within an atomic view of matter, electrical conductivity was not consistent. Certain conducting material worked better while others not at all, implying that space both conducts and does not conduct electricity.[72] The electrical properties of a continuous force, rather than differing quantized particles, proved to be the solution to this paradox. By supposing the consistent distribution of forces in space, a material's conductive quality became the result of varying conditions of those forces. Faraday's particles of force were merely a convenient conceptualization of inductive action, in so far as they did not possess a material nucleus but rather functioned simply as a useful quantification of force. As Faraday himself concludes in paragraph 1326:

> [Insulation and ordinary conduction] appear to me to consist in an action of contiguous particles dependent on the forces developed in electrical excitement; these forces bring the particles into a state of tension, or polarity, which constitutes both *induction* and *insulation*[73]; and being in this state, the continuous particles have a power or capability of communicating their forces one to the other.[74]

Faraday, as we have already seen, again characterizes the contiguous particles as simply meaning those particles which are adjacent to one another.[75] These passages indicate that 'atoms of force', as constituting linear states of polarization (read lines of force), were anything but quantized atoms. As such, the tension of the force particle is tantamount to the tension of 'the medium'. This introduces an important quality of force, key to understanding Faraday's conceptualization of electricity and magnetism. The nature of the force itself, as the historian Whittaker explains, was described so that "an atom would have no definite size, but ought rather to be conceived as

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[72] Spencer, 1967, p.198
[73] As Faraday states later on, the phenomena of conduction and insulation are the basis of all electrical phenomena. See Faraday, 1613; Williams, 1965, p.310
[74] Faraday, 1326
[75] Ibid., 1165, fn. 6

completely penetrable, and extending throughout all space; and the molecule of a chemical compound would consist not of atoms side by side, but by 'spheres of power *mutually penetrated*, and the centers ever coinciding'."[76] The 'atom' as a whole would thus be a force surrounding, in Whittaker's words, a 'point center'; where the atom itself would be completely penetrable by its neighbors. In this way the force of one 'atom' might not be so easily distinguished from that of another ultimately creating a continuous field of matter, what Berkson calls the "sea of force." The particles, blending into one another beyond individual recognition, then portray the lines of force as an entity identifiable only as the annular disturbances of magnetic or electric polarization.

When investigating induction and insulation in his 13th series of 1838, Faraday noted that his conception of the lines of contiguous force particles required an extensive examination of induction in a vacuum. In referring to Davy's experimental conclusions, that conduction does occur in a near vacuum, Faraday remarked that the material boundaries of the experiment, i.e. the container itself - here made of glass - could conduct through the vacuum, even if the latter could not itself act as a conductor.[77] He reasoned that, were a particle to be found in a vacuous space, the contiguity of that particle with its neighbors would not - despite its distance - be compromised. As Faraday explains:

> Assuming that a perfect vacuum were to intervene in the course of the lines of inductive action (1304.), it does not follow from this theory, that the particles on opposite sides of such a vacuum could not act on each other. Suppose it possible for a positively electrified particle to be in the centre of a vacuum an inch in diameter, *nothing in my present views forbids that the particle should act at the*

[76] Whittaker, 1951, p.193, quoting Bence Jones' *Life of Faraday* II, p. 178. Emphasis added. See Faraday, *Electricity* II, p. 292, Letter to Taylor.
[77] Faraday, *Electricity* I, 1613

> *distance of half an inch on all the particles forming the inner superficies of the bounding sphere*, and with a force consistent with the well-known law of the squares of the distance.[78]

Here the particle refer to the one which is separated from other surrounding particles, similar to the electrical action present on the glass containing the vacuum. Though its action on other particles is governed by the distance squared law - a distinctly Newtonian relation - Faraday considers this to be the extending reach of the particle's atmosphere of force. He then addresses particles surrounded by other insulating particles, as part of some larger ponderable object.

> But suppose the sphere of an inch were full of insulating matter, the electrified particle would not then, according to my notion, act directly on the distant particles, but on those in immediate association with it, employing all its power in polarizing them; producing in them negative force equal in amount to its own positive force land directed towards the latter, and positive force of equal amount directed outwards and acting in the same manner upon the layer of particles next in succession. So that ultimately, those particles in the surface of a sphere of half an inch radius, which were acted on directly when that sphere was a vacuum, will now be acted on indirectly as respects the central particle or source of action.[79]

The theoretical effect of these 'particles' of force gives significant insight into the nature of space and the electric medium. Ambiguity in the presentation of these illustrative corpuscles which formed the lines of force lead some of Faraday's contemporaries to frustration. But with the imagery of an "atmosphere of force" the conflict is resolved. When considering the conceptions of force and particles together, we see Faraday make a clear distinction between the illustrative model and the observed phenomenon. By the publication of his thirteenth series, Faraday considered the forces as a continuous, indivisible entity. However, in order to formulate such an image, he created a illustrative model of indeterminable particles. By illustrating the

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[78] Ibid., 1616; see also Williams, 1965, p. 310. Emphasis added.
[79] Ibid.

force as corpuscular while removing the identifiable attributes of atoms, Faraday redefined matter as a collection of forces.

### *"Lines of Force" and the Intervening Medium*

Faraday, having removed the distinction between matter and force, turned his attention towards the roles of force in space and the distinctions that separate them.[80] Following from his portrayal of the lines of force - and matter in general - Faraday considered all of space as filled by forces, whether constituting ponderable matter or diffused across a vacuum. Though the penetration of force through ponderable bodies was an implicit product of Faraday's vision of matter as intersecting lines of force, their penetration of matter was only experimentally proven in 1851.[81] After the seventeenth series of 1838, Faraday found himself mentally exhausted and turned away from his investigations of electricity until 1843, when he began investigating magneto-optics. This initiated a general shift in the focus of his researches from electric to magnetic phenomena. From the nineteenth series onward, Faraday employed a number of analogies from his discoveries in electricity to aid in his illumination of magnetic phenomena. Beyond firmly binding the mechanisms of electric and magnetic action into a unified theory, these series revisited core aspects of Faraday's lines of force, reintroducing them with the extensive understanding of a seasoned researcher.

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[80] Berkson, 1974, p.51
[81] See Faraday, 3117

While exploring the relationship between magnetism and light by polarizing the latter through 'heavy glass',[82] Faraday uncovered a new condition of magnetism.[83] This condition - dubbed *diamagnetism* - occurs when a body, penetrated by lines of magnetic force, "assumes a state different from the usual magnetic state [i.e. of iron]."[84] The diamagnetic body was so named due to its parallel to the dielectric body, which Faraday had introduced in the eleventh and twelfth series. Where magnetic action would move a body from weaker to stronger areas of force and align its axis along the lines of force, diamagnetic action moved from stronger to weaker force, arranging its axis perpendicular to the lines of force. Faraday theorized that magnetic induction, when acting upon a diamagnetic body, caused a magnetic state contrary to than that of a magnetic body. When subjected to magnetic forces, both a magnetic and diamagnetic "particle" would magnetize by aligning their axes parallel to the lines of magnetic force. Only, the magnetic particle would align its north and south poles towards their opposites in the inducing magnet whereas the diamagnetic particle would align its poles with their equivalents.[85] Faraday stressed the importance of the overall magnetization of both "particles", emphasizing that both magnetic and diamagnetic action produced the same kind of inductive effects.[86] Despite this, magnetism could no longer be understood as a singular form of action. Magnetism[87] and

[82] The experiments were performed, Faraday explains, using a form of heavy glass made with silicated borate of lead. He attributes his discovery of the relation between magnetism and light - and the superior illumination thereof - to this material.
[83] Faraday, 2227
[84] Faraday, H.J. Fisher; 2149, Editor's note.
[85] Faraday, 2429. Theories involving magnetic poles as the sources and centers of force were unfavorable to Faraday. He did however continue to use the expressions of North and South Poles due to their prevalence in public.
[86] *Ibid.*, 2431
[87] Once diamagnetic action was recognized as separate from the 'standard' magnetic force, Faraday recognized the need for a new term to differentiate between what until then had been referred to as magnetism - i.e. that of iron - and the general state of magnetism which include both kinds of action. For this new designation, Faraday tentatively proposed the term *Paramagnetism*.

diamagnetism appeared to be two distinct kinds of magnetic force, with a third, intermediary state of action - labeled magnecrystalic media - shifting between the two depending on its orientation.

To resolve this quandary, and unify the forces of magnetism, Faraday introduced the concept of magnetic conducting power. Magnetic conduction appeared to organize magnetic phenomena on a scale of conductivity analogous to the conduction and insulation of electricity. For, though magnetic and diamagnetic action function inversely, with the magnetic lines of force being affected either axially or equatorially to the lines of force, they could be characterized as possessing differing qualities of conductive power which distinguished a substance as more magnetic or diamagnetic. The conduction model united magnetism and diamagnetism. It suggested a connection between several phenomena, despite not being experimentally demonstrated.

> If bodies possess different degrees of *conducting power* for magnetism, that difference may account for all the phænomena; and, further, [...] it may assist in developing the nature of magnetic force. [...] As yet, however, I only state the case hypothetically, and use the phrase *conducting power* as a general expression of the capability which bodies may possess of affecting the transmission of magnetic force; implying nothing as to how the process of conduction is carried on. Thus limited in sense, the phrase may be very useful, enabling us to take, for a time, a connected, consistent and general view of a large class of phænomena.[88]

The mechanism behind the concept was left ambiguous. Magnetic conducting power theoretically enabled the lines of magnetic force to penetrate and affect ponderable mediums. It remained, however, purely hypothetical despite Faraday's usual insistence on experimental evidence. This is one of the few cases where Faraday's commitment to his speculative

[88] Faraday, 2797

conception of electromagnetic forces is clearly displayed. Beyond acting as a purely analogous to the conductive and insulative powers of the dielectric, magnetic conduction allowed the different dimensions of magnetism to be reconciled as a single active force. It bound the two aspects together as distinct qualities of a singular magnetic force, thus preserving it as a united power.

Following the proposal and adoption of magnetic conduction, Faraday turned his attention to investigating the troubling relation between magnetism and space. He had, while writing the eleventh series, measured the inductive capacity of fifteen gases at differing temperatures and pressures. In this investigation Faraday found no difference between the inductive quality of these gases, regardless of their state.[89] When considered in juxtaposition with the wider inductive range of liquids and solids, these gases formed the lower boundary of inductive capacity in matter. In a comparative scale of solids liquids and gases, gases - air in particular - were closest to a state of vacuum. Rarified air was therefore used to approximate the qualities of the vacuum, and thus space itself. As H.J. FIsher explains, this strategy “permits us to regard the inductivity of space or vacuum as a minimum, even indifferent, condition. It is fully in harmony with ordinary ideas that *absence of matter* should be incapable of doing anything, and that matter is so highly rarefied as to be in the gaseous state might well exert no measurable effect."[90]

In the 20th series, published in 1845, Faraday began investigating the magnetic and diamagnetic qualities of gases and vacuum. Unlike the scale of electric induction, magnetic conduction placed gases and vacuum in between denser materials. In other words, the vacuum

[89] *Ibid.*, 1292
[90] H.J. Fisher, Editor’s intro, p. 416

could not be considered a basic, inert condition for the magnetic state. Magnetically speaking, vacuous space acted with material agency.

From these results Faraday inferred that the magnetic quality of a gas would change depending upon its density. He reasoned that as a gas was rarified and approached a state of vacuum, its magnetic quality would shift towards that of a vacuum. But during initial tests, no such change was found. Not until the 25th series published in 1850, in a more precise experiment, did such a variation appear. Here, as he had done with electricity, Faraday did not speculate on the significance of these results for his researches on magnetism. As before, his investigations heavily relied on analogies between electricity, magnetism, and light. Only after investigating the role of magnetism in space, conduction, and the atmosphere did Faraday revisit the fundamental constituents of his theory. Faraday's reexamination of electromagnetic action appear in his last three series in the *Experimental Researches.*[91] The only difference between his early speculations and the magnetic action depicted in the later series was one of demonstrability: by the 1850's Faraday had amassed enough evidence to prove his speculative predictions correct.

As Faraday persisted in his research, he began to recognize a fundamental difference between magnetic and electric action. The lines of magnetic force could not operate by a mechanism reliant on particles of matter. Contrary to the lines of electric force, whose

[91] That is to say, the twenty-eighth and twenty-ninth series, and *On the Physical Character of the Lines of Magnetic Force*. The latter, though it was published separately in the *Philosophical Magazine*, follows Faraday's paragraph numeration and extends the themes of the previous series. It is considered to be the continuation, and conclusion, of his *Experimental Researches.*

mechanism resides in the transference of forces across "chains" of contiguous "particles", the lines of magnetic force disseminate their force through space itself. Faraday asserts:

> It appears to me , that the outer force at the poles can only have a relation to each other by *curved* lines of force through the surrounding space; and I cannot conceive of curved lines of force without the conditions of a physical existence in that intermediate space. If they exist, it is not by a succession of particles, as in the case of static electric induction (1215. 1231.), but by the condition of space free from such material particles. A magnet placed in the middle of the best vacuum we can produce, and whether that vacuum be formed in a space previously occupied by paramagentic or diamagnetic bodies, acts as well upon a needle as if it were surrounded by air, water, or glass; and therefore these lines exist in such a vacuum as well as in matter.[92]

This assertion is significant in two ways: First, it marks Faraday's acceptance of free space as an active entity. Faraday was, at first, reluctant to accept the implications of space as active. This may well have been due to his emphasis on the perception of the senses. Space was categorically distinct from active entities such as matter and force as it was considered inherently undetectable. By acknowledging the vacuum as an active agent, Faraday introduced space as a material force analogous to the medium. Second, the distinction seems odd considering the continued similarities between electric and magnetic lines of force, namely that both rely on the presence of force. As discussed above, the particulate mechanism of electric lines are simply illustration of a continuous, bodiless atmosphere of force. As such, this distinction was only superficial. It is possible that Faraday wished to avoid his earlier "point atom" illustration due to his lack of experimental evidence. Unlike the atoms of force, the magnetic curves could be empirically demonstrated.

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[92] Faraday, 3258

A decisive instance of analogy which highlighted the relation between 'object' and 'space' originates from Faraday's examination of the Gymnotus in his 15th series, published in 1838. The Gymnotus, a type of electrical fish, along with its salt water counterpart the torpedo fish, were of particular interest in the study of animal electricity due to their ability to produce electric 'shocks' for hunting and self defense. In this series, Faraday carefully studied the gymnotus' electrical properties in an attempt to better understand their disposition in comparison to that of inorganic electricity. Strikingly, the Gymnotus produced electric discharges identical to that of a leyden battery by including galvanometer deflections, producing induction, and decomposing water. By mapping out a discharge's electric intensity at different distances from the fish, Faraday determined that the Gymnotus and the watery medium in which it swam could be likened to the curved lies of magnetic action. Additionally, the distribution of this intensity would change as the Gymnotus straightened or contorted itself. In other words, the fish could be understood as functioning like a bar magnet, with the propagation of its electric shocks through water resembling the iron-filing traced lines of force. Faraday asserts:

> It is evident from all the experiments [...] that all the water and all the conducting matter around the fish through which a discharge circuit can in any way be completed, is filled at the moment with circulating electric powers; and this state might be easily represented generally in a diagram by drawing the lines of inductive action (1231. 1304. 1338.) upon it: in the case of a Gymnotus, surrounded equally in all directions by water, these would resemble generally, in disposition, the magnetic curves of a magnet, having the same straight or curved shape as the animal.[93]

Much like the bar magnet surrounded by curved lines of magnetic action, the fish can be conceptualized - when creating an electric discharge - as being surrounded by lines of electrical force within the liquid medium. Though the parallel between electricity and magnetism in this

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[93] *Ibid.*, 1784

instance was not novel, this analogy provided the illustrative foundation for an intimate relation between the visible object and surrounding medium as a cohesive whole. The analogy promoted Faraday's ideas of polarity, or tension,[94] as a nonvisual strain in the medium. It paired the basic lines-as-iron-filings and material strain illustrations, representing them as a space filling, active force. This was the first time the lines of force were described as a power which "fills up" the medium.[95]

Many years later, Faraday would reverse this analogy when discussing magnetic action in space. In his article *On the Physical Character of the Lines of Magnetic Force*, Faraday used the Gymnotus to illustrate the magnet's atmosphere of power. As editor H.J. Fisher explains, "in the Fifteenth series [Faraday] represented the *Fish* as *Magnet*. Now he represents the *magnet* as *Fish."*[96] The core attribute of the original Gymnotus analogy was its representation of both the internal and external conditions of a system, be it a fish, magnet, or Leyden battery.[97] With the volumetric conception of the medium provided in part by the fish-in-water analogy, Faraday was able to present magnetic action in terms of magnetic intensity throughout space. Faraday asserts:

> The magnet, with its surrounding sphondyloid of power, may be considered as analogous in its condition to a voltaic battery immersed in water or any other electrolyte; or to a gymnotus (1773. 1784.) or torpedo, at the moment when these creatures, at their own will, fill the surrounding fluid with lines of electric force. I think the analogy with the voltaic battery so placed, is closer than with any case of *static* electric induction, because in the former instance the physical lines of electric force may be traced both through the battery and the surrounding medium.[98]

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[94] *Ibid.*, 1165, 1326
[95] H.J. Fisher, *Exp. Res.,* Editor's note, p. 561
[96] *Ibid.*, p.560
[97] See Faraday 3276
[98] Faraday, 3276

In the following paragraphs, Faraday further explains the medium's central role in forming the magnet as a whole:

> I conceive that when a magnet is in free space, there is such a medium (magnetically speaking) around it. That the vacuum has its own magnetic relation of attraction and repulsion is manifest from former experimental results (2787.); and these place the vacuum in relation to material bodies, not at either extremity of the list, but in the *midst* of them [...] having other bodies on either side of it. [...] I incline to consider this outer medium as *essential* to the magnet; that it is that which relates the external polarities to each other by curved lines of power; and that these must be so related as a matter of necessity.[99]
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> [...] In this view of a magnet, the medium or space around it is as essential as the magnet itself; being a part of the true and complete magnetic system.[100]

Here, Faraday asserts the necessity of a medium in electromagnetic systems and highlights the similarity between matter and space. With this analogy, Faraday was able to portray the magnet as a system composed of both material body *and* the surrounding medium. Simply put, no magnetised action would be possible if one was without the other. The magnet thus, as a conceptual entity, can be said to become abstracted; or more accurately, to be an entity existing beyond the usual physical boundaries imposed by ponderable matter. In referring to the vacuum's magnetic qualities, Faraday promotes a vision of the magnetic system in which both solids and space are unified into a single magnetic continuum.[101] The magnet, understood here as a 'sphondyloid of power', is a whole in which the iron body and surrounding space are equal components.[102] Note that in neither analogy is there an allusion to a liquid flow of electric or

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[99] *Ibid.*, 3277
[100] *Ibid.*, 3278
[101] Despite suggesting the equivalency of the magnetic quality of space and solids, Faraday insisted that space and matter are fundamentally separate entities. As H.J. Fisher notes, the rejection of any equivalence between space and matter contradicts the implications of Faraday's own findings. This rejection is most certainly philosophically motivated, quite possibly by a Kantian disposition on the difference between matter and space, and the perceptibility of the two. See Faraday, 2787, 2789; H.J. Fisher, *Exp. Res.*, p.447-48
[102] Faraday, 2378; H.J. Fisher, *Exp. Res.*, Editor's notes, p. 337, 560-61

magnetic currents through the medium, reminiscent of the one- and two-liquid theories. The key difference between these theories and Faraday's liquid medium is outlined by the conductivity of vacuum. Here, liquid medium is not separate in kind from material object. While the analogy separates a visual medium from object independence, Faraday argues that the two are differentiated only by their different conductivity. The gymnotus analogy demonstrated the indispensability of the surrounding medium for magnetic action.

The Sphondyloid shell, also called shells of power, is itself a fascinating entity. Faraday originally conceived of it soon after demonstrating the penetration of the lines of force. Although no description of their early conception remain, Faraday did consult his friend William Whewell when searching for an appropriate name. Faraday's letter is lost but Whewell's response does contain insight into Faraday's conception of the shells.[103] The sphondyloid represented, in Faraday's mind, the surface of the aeriform aspect of the magnet, or that part which is found outside the magnet's material body. It united a number of aspects of magnetism such as the unit line of force and lines of force as continuous cyclical entities into one illustrative model. The shells were a collection of the looping lines of force merged together so as to form a surface in space. The entity would not only illustrate the "atmosphere" of the magnet, but also show the relations of magnetic qualities within said atmosphere. Despite Faraday's focus on the experimental reality of his theories - and the tangible form of the sphondyloid to the senses - it represented the culmination of Faraday's heuristic illustrative models.

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[103] Whewell & Faraday, *Correspondence*, Letters 2494, 2496, Feb, 1852.

*Conclusion*

We see in Faraday's researches the need for explanatory devices capable of illustrating the unusual and mysterious forces of electromagnetism. From the earliest Series to his later speculations, Faraday employed analogical and heuristic models to bridge the gaps in understanding fundamentally new forces and to create a viable, experimentally supported theory encompassing them. Faraday's theory examined the relationship between different forces of nature, beginning with rejected the dichotomy between matter and forces and ending with the breakdown of categorical distinctions between matter and space. In order to achieve this, Faraday created models that shifted focus from the action of forces on bodies to the action of forces through space. These models in turn presented useful artifacts, such as the unit lines and point atoms of force, that bridged the gap between observable phenomenon and explanatory theory. Though they may have only been heuristic depictions of magnetism, they were invaluable in communicating newly discovered attributes of Nature. Faraday's use of heuristic models in portraying his theory suggest a fundamental separation between theory and phenomenon in Faraday's thought. Apart from their representative function, Faraday's models were closely related to his metaphysical beliefs and speculative ideas. That much is clear from the "atomic" portrayal of Faraday's sea of forces, the breakdown of separation between medium and matter, and the magnetic agency of the vacuum. Despite the importance of speculation and philosophical concerns, Faraday remained convinced of the importance of experimental demonstration. This brought him both success as a researcher, and headache for, though his investigations were successful, his speculative theory of the lines of force was not widely accepted. Regardless of their interpretive success, Faraday's theories relied on the analogical and experimental methods he used. The analogies served as the methodological bridge between the experimental results, i.e. accepted scientific formalism, and his particular philosophies and conceptions of Nature. Faraday's treatment of electromagnetic forces and the medium set the stage for a fundamental focal shift from action between bodies to that of disembodied forces. Without a dismantling of the categorical dichotomies between matter and force, and force and space, such a shift from the newtonian emphasis on the mechanics of ponderable bodies would have been impossible. But the lines of force did not remain a purely heuristic tools, by the end of Faraday's investigations they served as both illustrative representation and experiential entity depicting experimentally discernible phenomena. With an understanding of the role and dependency of analogy and heuristic models in Faraday's researches, we can now examine how these conveyed his epistemological beliefs and experimental method.

## Section II: Heuristic Models and Natural Truth

As his researches progressed, Faraday became increasingly convinced of the accuracy of his speculations.[104] Beginning as mere hunches and developing into sound illustrative models, the lines of force were proving themselves to be a very helpful guide in the exploration of magnetism. Faraday successfully exposed new aspects of magnetic phenomena by designing his experiments while conceiving of magnetic action as operating through lines of force. Originally the Lines of Force acted as a purely illustrative model - derived from the magnetised iron filings - which facilitated the visualization of electromagnetic phenomena and forces.[105] However, as Faraday's researches continued, the intricacy and magnitude his lines interpretation grew. By the 28th series, presented to the Royal Society in 1851, Faraday was convinced of the accuracy of his theory of lines over that of other theories of electromagnetism. Not only were they useful in guiding understanding as conceptual entities, the success of his experiments suggested them to be an accurate description of magnetic phenomena.

Despite these convictions, he recognized - either by his own caution or by the scepticism of his peers - the difference between his experimental findings and his explanatory interpretation.[106] Faraday attempted to, as he had always done, find experimental demonstrations of the necessity for his speculative interpretation. The lack of such demonstrations until his later investigations can be seen in his distinction between the propagation mechanics of electric and magnetic forces. While he was able to describe the magnetic lines of force experimentally, he

[104] Faraday, 3074, 3175
[105] *Ibid.*, 3070
[106] *Ibid.*, 3075

was not so successful in proving the “contiguity” of his electrical force “particles." There does not, however, seem to be an actual distinction between the two, as both describe the same “sea of forces."[107] But aside from finding experimental and illustrative models of phenomena, Faraday paid great attention to both the presentation of scientific discovery to the public and his own image as a discoverer.[108] His religious and philosophical beliefs supposed a distinct separation between the intellectual comprehensibility of natural phenomena and its underlying truths. Thus, Heuristic models played a central role in Faraday’s investigative method by utilizing theory as a means of extending sense perception, and probe otherwise unreachable aspects of phenomena.

The previous section of this paper focused on outlining the use of heuristics in, and the analogical structure of, his theory building. The following section will discuss Faraday’s understanding of the roles of theory and experiment in portraying natural phenomena. Additionally it will investigate his religious and secular metaphysics as these play vital roles in reconstructing his epistemology. By examining these aspects of Faraday’s thought, in light of his discussion of scientific theory - the representation and natural fact - we may better understand the role of heuristics in his epistemology and its function in the later development of electromagnetism.

*Speculation and the Theory as Model*

We have seen in the previous section how such entities as the lines of force and sphondyloids of power were constructed and used as conceptually abstracted illustration of magnetic and electric phenomena. These could certainly - as Faraday noted - be considered

[107] Nersessian, 1984, p.59
[108] See Gooding, 1985

purely imaginary artifacts of theory, but he believed them to be much more than simple abstractions. As an experimentalist, Faraday saw in his lines of force an experiential concreteness. What had begun as simple visual models had, by virtue of his speculations, guided him through twenty odd years of successful investigations. As such, the 28th series stands out amongst Faraday's later researches due to its comprehensive reanalysis of the lines of magnetic force and their central role in his interpretations of electromagnetism. Aside from reevaluating the lines as a model, Faraday included one of the most extensive assertions of his scientific and theoretical method. He had reintroduced his lines of force during the 19th series as the "exercise of magnetic force which is exerted in the lines usually called magnetic curves, and which equally exists as passing from or to magnetic poles, or forming concentric circles around an electric current."[109] Lamenting the vagueness of such definitions, Faraday set out to clearly define the lines of force and the extent of their role in describing magnetism. An additional motivation for this recharacterization was the scepticism of his peers who either did not understand or accept his theory of lines of force.[110] Faraday wished to demonstrate the usefulness of his interpretations as both a method of imaginary bookkeeping and as accurate descriptions of magnetic action. Leaving behind the vagueness previously associated with the lines of force, Faraday proceeded to clearly define in the opening paragraphs of the 28th series his use of the term and the extent to which it should be employed in researching electromagnetism.[111]

> A line of magnetic force may be defined as that line which is described by a very small magnetic needle, when it is so moved in either direction correspondent to its length, that the needle is constantly a tangent to the line of motion; or it is that line along which, if a transverse wire be moved in either direction, there is no tendency to the formation of any current in the wire, whilst if moved in any other

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[109] Faraday, 2159
[110] Berkson, 1974, p.104
[111] Faraday, 3070

> direction there is such a tendency; or it is that line which coincides with the direction of the magnecrystallic axis of a crystal of bismuth, which is carried in either direction along it. The direction of these lines about and amongst magnets and electric currents, is easily represented and understood, in a general manner, by the ordinary use of iron filings.[112]

Unlike his definition from the 19th series, Faraday now presented the lines of force purely by the methods of their experimental manifestation. Despite this commitment to clarity, Faraday's later description retained his usual restraint when discussing the lines of force and the true method by which magnetism operated. This he did not for fear of discussing unfounded speculations, but rather to maintain a sense of perspective in his theory. Faraday refused to endorse any particular theoretical interpretation - be it of magnetic fluids, poles, or lines - or on the origin and nature of the forces themselves. Despite his increasing certainty of the lines of force as accurate representations, Faraday maintained an openness towards the use of other explanatory theories. By presenting the discoveries of the 28th series in this manner, Faraday was able to reflect on the limits of the researcher's perception of Nature. In so doing, he delineated a clear contrast between conceptual theories and natural truth.

Faraday's concern for examining the constitution of theory followed from his attempt to outline his investigative method. Though Faraday's reflections on the relative qualities of theory was couched in his investigations of the magnetic lines of force, these investigations served simply as a practical demonstration of Faraday's conception and formulation of theory. Simply put, Faraday's examination of the magnetic lines of force serve as a practical demonstration of his method of theorization. Much like in the performance and interpretation of physical experiment, Faraday, as an experimentalist, was not bound to his own methods; these simply

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[112] Faraday, 3071

reflected the available results. He was acutely aware that his methods of theorization and experimental interpretation may well have been wrong.[113] Nevertheless, he gave insight into his methods and, more importantly, the conceptions underlying and motivating his approach. These interpretation may have changed when confronted with opposing evidence throughout his career, but the underlying conceptions of theory, experience, and natural truth stayed firmly rooted.[114]

A couple of distinctions appear in Faraday's 28th series with the reintroduction of the lines of force. First, Faraday defined the lines of force as entities of force transmittance, in addition to their heuristic role in his speculations. That is to say, in the 28th series and on, the lines of magnetic force serve as the means through which magnetic action is extended through the surrounding medium as opposed to the purely formal and abstracted representation of the phenomena visible through experiment. Nersessian describes this new definition of the lines as being "vessels" or "pathways" of force, which will be explored later.[115] Secondly, the beginning of the 28th series discusses the different merits of the line of force as an illustrative device and as a theory of description. What is particularly noteworthy is the differentiation between the functional and interpretive components of the theory. This distinction between Faraday's conceptual interpretations of experimental results and his speculations about the true nature of magnetism shielded his method of speculation from outside criticism.[116] Faraday used his

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[113] *Ibid.*, 3175

[114] Faraday's conception of electromagnetic forces changed considerably throughout the length of his scientific career. Conceptions such as electrostatic & electrotonic forces and strain were introduced then later removed or revised due to subsequent discoveries. Contrary to these shifting interpretations, Faraday's metaphysical and epistemological conceptions differed little. For example, his focus on the role of judgement as guiding interpretation in his "Lecture on Mental Education", from 1855, is strikingly similar to that found in his student lectures form 1816-18.

[115] Nersessian, 1984, p.58

[116] *Ibid.*, p.58

speculations to guide the direction of his experiments, relying in turn on the experimental results to alter his interpretations. Though Faraday had, by the 1850's, a very intricate conception of the lines of force as driving electromagnetic action, some predicted elements had yet to be demonstrated. Despite the investigative success of the lines, Faraday's experimental results did not conclusively necessitate the lines to exist as he described them. As Faraday assures the reader, the Lines of Force interpretation as simply an illustrative representation was not in itself necessary when interpreting magnetic and electric phenomena. None of his experimental results had yet disqualified the alternative newtonian interpretation.[117] He was also quick to note that, even if the lines of force were considered wholly imaginary and nonexistent, the theory that he had put forth, and the experimental results derived therefrom, would not be altered or lessened. By separating the experimental results from any discussion exploring the mechanisms of magnetism, Faraday was able to protect his interpretation of experimental results from criticism aimed at his "unfounded" speculations.

Beyond its practical use however, the separation highlights the important role of speculation and the very subjective nature of theories. In Faraday‘s eyes, the important distinction between competing theories became one of interpretation, as it is this which motivates experiment and the understanding that is derived from it. Far from being detrimental, speculation, when kept in check by experience, is a necessary element of theory:

> There is no impropriety in endeavoring to conceive the method in which the physical forces are either excited, or exist, or are transmitted; nor, when these by experiment and comparison are ascertained to any given degree, in representing

[117] Faraday, 3075; See Nersessian, 1984, p.58. For example, Nersessian notes that both Faraday's Lines of Force and action at a distance are vectoral theories, thus without disqualifying the necessary mechanisms for either interpretation, the results could not dictate which interpretation was correct.

> them by any method which we adopt to represent the mere forces, provided no error is thereby introduced. On the contrary, when natural truths and the conventional representation of it most closely agree, then are we most advanced in our knowledge.[118]

It is this separation between the "natural truth" and the representation that, along with the semi-relativism of the representations between each other, indicate a distinction between the model and the modeled in Faraday's mind. There is furthermore a distinction between the practical representation, which describes the detectable results of a force, and the speculative interpretation, which attempts to explain the origin and mechanism by which said force operates. This marks a departure from Faraday's otherwise Baconian method, which firmly rejected the role of speculation. Though Faraday was apprehensive of unfounded speculation, he saw it as the means by which theoretical models could evolve.[119] Theory was not a represented embodiment of natural truth but a description of its effects, and so different approaches in interpretation and experimentation could reveal new aspects of Nature. The relative utility of interpretive theories, and the use of theory in representing nature, will be discussed later. Faraday's care in experimental design and the proper analysis of observations fits in with his emphasis on the importance of perception, showing that he considered experimentation to be a mechanism for the extension of the senses.[120] The right experimental apparatus could probe and make sensible features of nature which had previously proven impervious to human inquiry. Thus, Faraday found objects of study that went beyond the previously rigid categories of force, matter, and space. For instance, what the naïve unaided senses interpreted as solid matter, Faraday considered to be the interplay of forces. His focus on perceptibility becomes exceedingly clear

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[118] Faraday, 3075; See also: Faraday, 3244
[119] Berkson, p.57
[120] Faraday, "Lecture on Mental Education", *Chemistry,* p.466, 469; Faraday, 2146- fn. 2

when considering Faraday's experiments that uncovered the magnetic qualities of space itself, as discussed in the previous chapter. This particularly vivid example shows how in Faraday's hands, experiment allows one to discern phenomena beyond the limited purview of the natural senses.

No where is this more directly portrayed than in his re-exploration of the lines of force. Beyond his definitions given above, Faraday outlines the two primary methods for experimentally detecting the lines of force; through the magnetic needle - reminiscent of the iron filings, and the use of a moving wire. Where the needle demonstrated the paths of magnetic curves around a magnetized body, the moving wire allowed the detection of lines within balanced magnetic fields and as penetrating the magnetic object. These different methods illuminate fundamentally different aspects of magnetism.[121] For this reason Faraday employed the moving wire in his reexamination of the magnetic lines of force. He explains:

> The actions [of the needle and wire] are however very different in their nature. The needle shows its results by attractions and repulsions; the moving conductor or wire shows it by the production of a current of electricity. The latter is an effect entirely unlike that produced on the needle, and due to a different action of the forces; so that it gives a view and a result of properties of the lines of force, such as the attractions and repulsions of the needle could never show. For this and other reasons I propose to develope [*sic*] and apply the method by a moving conductor on the present occasion.[122]

This passage alludes to the limitation of Faraday's two experimental approaches. Each method of detection highlights an aspect of magnetism imperceptible to the other, and only by the combined consideration of the two can a better understanding emerge.[123] Because interpretation

[121] Faraday, 3076, 3176
[122] *Ibid.*, 3076
[123] See also: Faraday, 3083, 3156, 3158, 3176

is ultimately checked by the experiments it incites, certain interpretations may therefore be better suited to explore certain phenomena than others. Just as each method of detection - wire and needle - outline different aspects of magnetism, different theories - regardless of their overall proximity to the "truth" of nature - may reveal distinct and novel properties of force. The correct interpretation of the experimental results is crucial, as it is the interpretation that makes the laboratory results comprehensible within the theory. Faraday asserts:

> There is no doubt the needle gives true experimental indications; but it is not so sure that we always interpret them correctly. To assume that pointing is always the direct effect of attractive and repulsive forces acting in couples [...] is to shut out ideas, in relation to magnetism, which are already applied in the theories of the nature of light and electricity; and the shutting out of such ideas *may be* an obstruction to the advancement of truth and the defense of wrong assumptions and error.[124]

Thus, the theoretical interpretation of phenomena acts ultimately as a model of certain facets of the greater whole. Wildly differing interpretations may be all valid as theories in so far as they are methods of illustrating more or less accurately aspects of the greater natural truth. Heuristic models would, therefore, be necessary for scientific enquiry, not only as invaluable methods of generating of new avenues of research, but as a guideline for the role of theory in investigating Nature. Faraday's distinction between "natural truth" and the "representation" thereof suggests that the role of theory is not to expound a truth coaxed from Nature, but rather an attempt to find a heuristic model which best describes the observable aspects of nature. Indeed it appears that, considering the difference between theories and the seemingly continuous search for more "accurate" theories to match and describe phenomena, that natural truth cannot ever be known save through the pale reflection of imperfect theory. Considering the unity of forces and the

[124] Faraday, 3156

variety of differing theories of varying interpretation, Faraday contemplated the possibility of an eventual unity in interpretation, stating “perhaps when we are more clearly instructed in this matter, we shall see the source of the contradictions which are supposed to exist between the results of Coulomb, Harris and other philosophers, and find that they are not contradictions in reality, but mere differences in degree, dependent upon partial or imperfect views of the phænomena and their causes."[125]

*Relative Models of Nature*

By recognizing the distinction between practical and interpretative aspects of the theory, Faraday establishes theory building as a tool of understanding. Because different interpretations could be applied to the same experimental results, understanding their applicability in developing helpful lines of inquiry was crucial. Faraday writes:

> No doubt, any of these methods which does not assume too much, will, with a faithful application, give true results; and so they all ought to give the same results as far as they can respectively be applied. But some may, by their very nature, be applicable to a far greater extent, and give far more varied results, than others. For just as either geometry or analysis may be employed to solve correctly a particular problem, though one has far more power and capability, generally speaking, than the other; or just as either the idea of the reflexion of images, or that of the reverberation of sounds may be used to represent certain physical forces and conditions; so may the idea of the attractions and repulsions of centres, or that of the disposition of magnetic fluids, or that of lines of force, be applied in the consideration of magnetic phænomena.[126]

Here Faraday argues that certain theories, certain models, may not only be more accurate, but even better suited towards the description of phenomena. That is to say that, beyond any consideration of “truth”, the theory may be more or less equipped to illuminate certain facets of

[125] *Ibid.*, 3075
[126] *Ibid.*, 3074

the phenomenon being examined; where the qualities innate to the model more readily resemble qualities found in the phenomenon. Faraday found that simple applicability would not suffice as the sole criterion for a functional theory. Theory does not so much deal with the description of natural truths as it serves as a tentative illustration of some aspects of the observed phenomenon. This distinct separation between theory and natural truth is emphasized by Faraday's philosophical and sandemanian background. As a creation of God, the natural world held a certain innate divinity reflecting its creator; thus seeking to conceptually understand the true nature of reality would be attempting to understanding the true nature of divine creation. Because the fundamental truths of Nature were in principle unknowable through intellectual study, the natural philosopher could only ever hope to create a model which analogically mimicked observable phenomenon.[127] As such, theory could only illuminate natural phenomena by proposing the heuristic models that most closely resemble those aspects of phenomena visible, through either observation or experimentation, to the investigator.

By recognizing the *applicability* of a theory in describing phenomenon, Faraday highlighted the importance of internal conduct and constraint. Any system operates by certain rules and possesses structural qualities, whether it be geometry and analysis or the forces of Nature. When analogically modeling one system through another, the rules by which they operate may align to a variable degree. When the analogy is used to better understand a phenomenon, the phenomenon is presented as operating by rules that are parallel to those of the understood system from which the analogy is extended. Even if their rules and qualities appear to be very much alike, they are not equivalent. Simply put, not all qualities of the model exist in

[127] Faraday, "Lecture on Mental Education", *Chemistry*, p.465

nature and not all qualities of nature are reflected in the model. To use Faraday's own example, the systems of Euclidean (synthetic) geometry and Cartesian (analytic) algebra are governed by different rules and possess different qualities. Though it is possible to model phenomena using both systems, certain examples may function better when modeled by one system or the other, depending on the applicability of each system's qualities to the investigated phenomenon.[128] Thus Faraday's early introduction of magnetic lines of force function as analogical to his electric lines of force presents, beyond his interest in the unity of forces, the former as functioning by the rules of the latter. Similarly, his introduction of the sphonyloid, and its conjoining of open space and matter, possessed analogous qualities as those of the gymnotus electrocuting the water around it. The investigator, then, was exploring nature through the use of heuristic models meant to outline certain qualities of Nature.[129]

*Physical Lines of Force*

Despite his outward empiricist bent, Faraday also extended the relativity of theory and importance of speculation to his own work.[130] The lines of force are introduced as objects - either as representative suppositions or as tangible entities - that have a value of utility as a theory. That it to say the lines of force seem to draw their value as "accurate" descriptions, not by their supposed quality of natural truth, but by their utility in illuminating new aspects of phenomena. In so doing, interpretive theories are more or less able to promote the creation of models that illuminate natural forces.[131] Beyond Faraday's discussion of theory and truth, the 28th series

[128] See H.J. Fisher, p.483, fn.3
[129] Faraday, 3075, 3176
[130] *Ibid.*, 3070, 3244
[131] This does not mean that Faraday was interested in exploiting theories for technological or material gain. Faraday explicitly chose to dedicate his life to the pursuit of "pure" science early in his career.

presents an important interpretive synthesis of the Lines of force as conceptual and physical. Both the representative and tangible aspects of lines are given important consideration in Faraday's theory through his different methods of experimentally illustrating the lines of force. Much of his reflections on the relativism of theory as aspectual models was motivated by his introduction of the moving wire as a detector of the lines of force.

Aside from the evaluation of the lines of force as descriptive entities, a number of speculative topics are also addressed. By altering between methods of detection, the lines of force external to the magnet could be used to demonstrate their penetration and continuity within the magnet's material body. Though Faraday had long suspected the universal presence and penetrability of the lines of force, only in the 28th series was he able to provide any experimental proof.[132] This discovery gave Faraday the experimental foundation for his interpretation of the lines of force as continuous and all penetrating, filling space and matter alike.[133] In order to do this, Faraday established the lines as measurable by demonstrating the equivalence of any one line or segment with another in terms of magnetic force.

Faraday was able to not only demonstrate the equivalency of every segment of the lines external to the magnet, but also demonstrated the extension and presence of lines of force throughout the interior body of the physical magnet. Beyond confirming the long held belief of the annular and continuous nature of the lines of force even when penetrating solid "matter", and further entrenching his conviction of the predictive accuracy of his interpretation, it gave experimental grounds for a unit of magnetism within the Lines of Force interpretation theory. That is to say, the experiment showed the possibility of a unit measurement intrinsically linked,

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[132] Faraday, 3117
[133] *Ibid.*, 3121

and made explorable by, to the lines of force theory. The lines could thus be used to represent the direction and intensity of magnetic force by the graphic distribution of the lines through the body and medium. That is not to say that the unit lines of force were purely imaginary, the force remained detectable and concrete. Rather, it was the allocation of a certain amount of force to arbitrary points in space which constitute the unit's purely conceptual nature.

> In the meantime, for the enlargement of the utility of the idea in relation to the magnetic force, and to indicate its conditions graphically, lines may be employed as representing these units in any given case. I have so employed them in former series of these Researches [...] where the direction of the line of force is shown at once, and the relative amount of force, or of lines of force in a given space, indicated by their concentration or separation, i.e. by their number in that space. [134]

In this way the lines of force as unit, with a standard quality of force per area, is reminiscent of Faraday's illustration of force as point atoms, discussed in the previous chapter. This quantification of the continuous forces facilitates the intellectual modeling of the lines of force in a conceptually approachable manner. This discovery set the ground for Faraday's later introduction of sphondyloids of power.

Considering Faraday's assertions concerning the relative utility of theories as illuminators of phenomena and the incognizable characteristic of natural truth, the connotation of the lines of force as "real" is not immediately clear. This physical reality of the lines of force implies more than the simple fact of their detectable presence. It may easily be interpreted as an ontological assertion of the existence of the Lines of Force as described by Faraday's theory. That is, the assertion appears to claim that the qualities of Faraday's interpretation are equivalent to the

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[134] *Ibid.*, 3122

observed qualities of nature; that the former in some ways decisively depict the latter. Where the 28th series explored the distinction between the representative and physical conceptions of the lines of force, Faraday's *Physical Lines of Forces* focused on supporting the physical interpretation.[135] Depending on Faraday's focus when discussing the reality of lines of force, his insistence on their reality has very different consequences. Despite Faraday's focus on the experienceable, conceiving of the theoretical lines of force as an accurate depiction of the nature of magnetism runs contrary to his metaphysical stance. His primary objective was to demonstrate the extension of forces through the medium.[136] Faraday's emphasis on the reality of the lines of force was an assertion of the experiential, detectable, presence of action outside the bounds of "material" objects.

Beyond the importance of the medium, Faraday's phrasing does not immediately distinguish between the lines as, what Nersessian terms, "vessels" and "pathways" of force. What Faraday describes as the "lines of transmission" of forces does not differentiate between the forces as extending in a curving linear arrangement and the lines as channeling force through themselves. The difference between these two lies in their expression of forces acting through the medium. The "vessel" interpretation acknowledges the lines of transmission in so far as they are delineated by the presence of magnetic force.[137] The "pathways" interpretation recognizes the lines as entities in and of themselves within which the forces act. The difference, recognizing the

[135] Faraday, 3243; Nersessian, 1984, p.59
[136] Though not necessarily self-referential, Faraday notes the philosopher's need to explore the action of forces within the medium. See Faraday, 3245
[137] Nersessian presents the "vessel" interpretation as "vehicles of transmission" of strain in the medium. This focus on the lines as patterns of strain in the medium emphasizes unity of magnetic force with the other aspects of nature, such as the medium. See Nersessian, 1984, p.65-66

lines as either concrete entities or as the disposition of force, concerns the lines of force as active or descriptive agents. When introducing the physical lines, Faraday makes his intentions clear:

> I desire to restrict the meaning of the term *lines of force*, so that it shall imply no more than the condition of the force in any given place, as to strength and direction.[138]
>
> The *amount* of the lines of magnetic force, or the force which they represent, is clearly limited, and therefore quite unlike the force of gravity in that respect (3245); and this is true, even though the force of a magnet in free space must be conceived as extending to incalculable distances.[139]

Judging by the presentation of the physical lines of force, Faraday intended the lines to be interpreted as “vessels."[140] If the physical lines of force are considered to be entities in and of themselves, the observed lines become indistinguishable from their theoretical depiction. Simply put, the “pathway” approach would recognize the lines as concrete bodies, distinct from magnetic forces, with a structure and a behavior equivalent to Faraday’s theoretical description. The lines as described by Faraday, in essence, would become the lines as they appear through experiment. In contrast, by conceiving of the lines as the disposition of forces in the medium, a relation between the symbol - the theoretical description - and the symbolized - the detectable forces - is maintained. In the “vessels” interpretation, Faraday’s theory does not qualify the lines as a distinct entity, thus avoiding the imposition of conceptually recognized attributes on natural phenomenon.

The difference between these two conceptions may be understood using the following analogy. Lines as independent entities within the medium are comparable to a line drawn on a sheet of paper. The line is distinct from the paper and is defined by the limitations of its own

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[138] Faraday, 3075
[139] *Ibid.*, 3255
[140] *cf.* Faraday, 3075, 3248, 3250, 3253, 3255; Nersessian, 1984, p.59

boundaries, i.e. the border between ink and page. Meanwhile, Lines as an arrangement or distortion of the medium due to the presence of force can be understood as a warp or fold line in the page itself.[141] Folding the page, which acts as an analogy for magnetic force or stress, creates a definite line which is not itself independent from the page. In this way, the line is physical insofar as it is a detectable consequence of the force's disturbance of the medium.[142] This contrasts with the alternative view, which ascribes reality to theoretical entities arising out of speculation. By focusing on the lines as being themselves corporeal, the physical line of force inherits the attributes (i.e. direction, disposition, and relative intensity) ascribed by the abstracted, representative theory. In other words, it limits the lines of force as physical entities to the constraints of interpretation and to the extent of experimental perception.

*Illumination and the Extension of the Senses*

As we have seen, speculation and theoretical models functioned as useful tools in the construction of scientific knowledge. Due to his concern for and suspicion against unfounded speculations, Faraday presented himself as a pure experimentalist.[143] But considering his emphasis on the difference between theory and truth, the relativism of theory, and the important role of speculation, it is clear that Faraday's scientific method was different in practice than in his written presentation. Beyond the theoretical relativism previously discussed, reconsidering Faraday's sandemanian beliefs may grant further insight on the capacity of experiment in illuminating natural phenomena. Faraday and the sandemanians considered all of nature to be endowed with the divinity of creation and that this divinity was well beyond the intellectual

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141 Figure 6 & 7.
142 See Nersessian, 1984, p.65-66
143 Berkson, 1974, p.58

capacity of humanity. Only the physical consequences of natural phenomena, resulting from the inner workings of reality, were knowable.

Though Faraday more openly discussed his convictions on the role and properties of theory and natural truth in the later essays, some historians consider Faraday's opening paragraph and footnote to the 19th series as an exemplary assertion of Faraday's "paradigm of experimental science."[144] That is, the passage supposedly encapsulates Faraday's commitment to pure empiricism. The 19th series, as discussed previously, explored the connection between magnetism and light, and introduced diamagnetism. Due to some confusion with the original title - *On the Magnetization of Light and the Illumination of Magnetic Lines of Force* - Faraday included a clarification, asserting his aim to illustrate - or make experienceable - the behavior of unseen phenomena.

> The phrase "illumination of the lines of magnetic force" has been understood to imply that I had rendered them luminous. This was not within my thought. I intended to express that the line of magnetic force was illuminated as the earth is illuminated by the sun or the spider's web illuminated by the astronomer's lamp. Employing a ray of light, we can tell, *by the eye*, the direction of the magnetic lines through a body; and by the alteration of the ray and its optical effect on the eye, can see the course of the lines just as we can see the course of a thread of glass, or any other transparent substance, rendered visible by the light: and this is what I meant by illumination, as the paper fully explains.[145]

Despite asserting the path of the lines of force as visible through proxy, Faraday was not attempting to discuss the essential nature of the forces, but rather to demonstrate their disposition through magnetized bodies. As an experimentalist he stressed the role of experimental evidence as a guide to theory. It is clear in Faraday's mind that pure empiricism cannot yield an acceptable

[144] HJ Fisher & Thomas Simpson; see Fisher, p.369
[145] Faraday, 2146, fn.2

portrayal of nature.[146] Though experiment must guide and vindicate theory, it is theory which directs the researcher's experimental investigations and lays the ground for the categorizations the researcher will seek. Similar to the physicality of the lines of force, this illumination could be interpreted as an attempt on Faraday's part to expose the fundamental truths of magneto-optic phenomena. However, Faraday's insistence on the use of light as a means of delineating the lines of force suggests that the investigation was purely an attempt to illustrate magnetic lines passing through ponderable matter. In the same way the physical lines of force simply outlined the effect of magnetic force on the medium, this illumination can be considered as the presentation of new aspects of magnetic phenomenon.

This focus on the illumination of unseen phenomena acts as an extension of the investigator's senses. As such, Faraday's pursuit of sensible, tangible forces echoes the kantian perspective. The ability of the researcher to experience or sense the forces under investigation is paramount to distinguishing them as active entities. Thus, Faraday was not attempting to illuminate the lines of force as entities equivalent to his theoretical description. Rather, the lines of force act, not unlike the experimental apparatus, as a method to permit the researcher to sense magnetic actions and forces. In other words, the illuminated lines function themselves as an extension of the researcher's awareness so as to encompass the newly observed phenomenon.

Though the sphondyloid was a natural extension of the lines of force into a unified body, it did not eclipse the lines themselves. Faraday's means of experimental detection was still limited to the lines themselves, from whence the larger sphondyloid body had to be constructed.

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[146] Faraday, 3075; Berkson, 1974, p.57

[147] However, by extending Faraday's discussion of theory to the reality of the sphondyloid "body", the lines of force become purely illustrative. That is, if the sphondyloid is considered to be the full magnetic body[148] beyond distinctions of matter and space, the lines of force become an interpreted quality of the experimental method; a quirk defined purely by the limitations of the awareness extended by experiment. Both methods of detection favored by Faraday, viz. the needle and moving wire, necessarily present magnetic phenomena in terms of lines; the one moving around the axis and the other along the length of a magnet. Additionally, the lines as illustrated by magnetized iron filings further promoted such a view of magnetic forces.[149] Since the needle and wire delineations each demonstrated wholly different aspects of the lines of force, they could only be applied to illustrate that aspect along the length of the magnet. All three presentations are characterized as illustrations in a plane.[150] That is, these lines were discernible within a plane tangential to the magnet's material body. Any representation of the forces was therefore necessarily presented as a transverse cut of the magnet body. The magnet was then modeled by moving these methods of detection around the magnet's body, delineating the disposition of force in different areas. In terms of the resulting illustration, the plane on which the lines appeared would simply revolve around its axis. Depending on the configuration of the material body, the same distribution of lines would be found at every orientation of the plane.

When the needle and wire presentations are considered together, the lines of force surrounding the magnet at the same distance become difficult to differentiate. Because the lines both exist down the length and around the arbitrary circumference of the magnetic object, they

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[147] Whewell, *Correspondence*, Letter 2494; Figure 4
[148] Recall that Faraday proposed the sphondyloid as a representation of the magnet as an entity combining the lines of force both inside and outside the "material" body.
[149] Faraday, 3071, 3237
[150] See Faraday's mnemonic aids in Gooding, 1985, p.112-113;

are only distinguishably linear due to the limited ability of either experimental method to probe the magnetic field. As such, when the two methods are considered together, the lines of force form a surface encompassing the magnet. In other words, it is difficult to distinguish one line from another within the same shell of power. When thought of in this way, the lines of force exist only as artifacts of the representation derived from the transection of the sphondyloid shell. The lines of force then work as purely representative entities produced by the detection method's limited scope. The physicality of the lines simply becomes the physicality of the sphondyloid whole, albeit restricted in its presentation to the investigator's senses. Rather than describing the configuration of forces in space, Faraday's lines of force emerge as the interpretive bridge between the experimental result and the greater magnetic phenomenon.

*Conclusion*

In light of the emphasis on heuristics and interpretation, it should be remembered that Faraday did believe there to be an true reality. This reality was, however, indiscernible to the human intellect and perception .[151] While he considered the essential truths of Nature to be beyond the reach of the senses and intellectual reason, the active consequences of these truths were not. Due to the limitation of those senses, and of the inaccessibility of natural truths, many aspects of natural phenomena could only be explored by proxy through experimentation and speculation. Heuristic models could reveal new natural entities and their relationships, all the while remaining as consciously relative interpretations. Even ultimately "untrue" theories could shed new light on observed phenomena by highlighting as of yet unseen conditions of reality. So

[151] Faraday, 3122, 3156

long as the researcher was conscious of the limitations of such models, they would serve as useful investigative tools. Theory and heuristics thus functioned as the means by which the investigator's awareness could be extended beyond the limitations of the human senses. In this way the higher truths could be mirrored in fragmented form by different theoretical constructs, even though they could not be intellectually cognized. By the end of his career, Faraday believed the qualities of the lines of force to be an accurate representation of detectable qualities of electromagnetic phenomena. The later series served as a practical demonstration of Faraday's method of theorization. He began to openly contemplate his method after its demonstration of long term success. Additionally, outlining his views on speculation and theory lay the grounds for his necessarily speculative examination of the physicality of the lines of force. This later examination of the lines in his 'On the Physical Character' covered a number of topics which heavily relied on previous speculations. The paper was therefore published in the *Philosophical Magazine*, a change from the *Philosophical Transactions* which had published his *Experimental Researches*. It was crucial that the experimental foundation for his interpretations be clear, so that, when Faraday engaged in more overt speculation, his readers would not consider them to be unwarranted. Faraday's propositions needed to be at the very least considered as interpretation, if not as an accurate depiction of natural phenomena. Either way, Faraday sought to illustrate the utility of pursuing different experimental approaches when investigating natural forces. Even if an idea was unappealing, such as the notion of magnetic poles or of liquid currents, pursuing experiments which reflected such assumptions could grant important insight into the phenomenon under investigation. Thus, so long as the experimentalist was aware of Nature as separate from the theories that sought to describe it, they would be able to properly interpret the significance and substantiality of their interpretation. Through the extension of the senses, by means of experiment, apparatus, and heuristics, the natural investigator could come ever closer to perceiving the comprehensible aspects of reality as a single whole.

# Epilogue

The success of Faraday's investigations had far reaching consequences. Between the time of Ørsted's discovery of the magnetic quality of electrical currents and the end of Faraday's career, electromagnetism had blossomed into a substantial branch of the physical sciences. A significant portion of this success was due to Faraday's insightful investigations and rigorous experimental approach. Not only did he uncover numerous new aspects of electromagnetic phenomena, he introduced a fundamentally new understanding of the disposition of force and space. We have seen the important role of heuristic models in facilitating the introduction of Faraday's field concept. By appealing to the detectable manifestations of electromagnetic phenomena, such as magnetized iron filings, the suspended needle, and moving conductors, Faraday was able to shift the focus of scientific inquiry from the action between bodies to the medium itself. Thorough exploration of phenomena, in combination with Faraday's cautious speculations, allowed him to construct analogical models which illustrated the newly conceptualized aspects of force in familiar terms. These ranged from atomic models of the electric medium to the representative use of the lines of power in illustrating the distribution of forces.

Faraday's ultimate goal was to uncover the manifestations of natural actions, making them available to the investigator's senses. In pursuing the physical manifestations of a higher truth beyond his understanding, Faraday was acutely aware of the limitations of the mind in conceptually grasping and interpreting the information relayed by the senses. However, Faraday found that, in order to use theory and empiricism to their full potential, they had to be understood as tools of the intellect. Accepting a reality whose essential truths were unreachable, the investigator could only probe the active consequences of natural forces. For this reason, theoretical models and interpretations, though changing one's awareness of the active forces, could never formulate an exact depiction of natural truth. Even the entities that arose from experiment, such as the lines of force, were ultimately limited artifacts derived from a greater whole. Entities emphasized in theory could only posses a limited range of qualities more or less similar to those found in nature. Thus, natural phenomena could only be accurately represented when the qualities of the model most closely resembled the *perceptible,* active qualities of nature. Only by experimentally pursuing new interpretations, be they conceptual or tangible, could the investigator's perception of nature grow. Forces had, until the early 19th century, generally been considered attributes associated with matter. By breaking down the segregation between matter, force, and space, Faraday was able to conceptualize a space filling sea of forces, extending material agency beyond the physical limits of ponderable bodies. Both matter and space itself existed as distributed and varied states of the medium. In essence, Faraday was redefining the perception of materiality; presenting active phenomenon as a continuous, all encompassing whole.

Faraday's emphasis on models and the adequacy of theory later influenced a number of prominent scientists.[152] While Faraday was working on the distribution and behavior of the lines of force, a recent Cambridge graduate, James Clerk Maxwell, undertook his own investigation of

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[152] This approach influenced William Thomson, Hermann Von Helmholtz, Oliver Heaviside, Heinrich Hertz, Hendrik Lorentz, and Albert Einstein. See Berkson, 1974 p. 1

the electrical forces. Though prominent reseaches, such as William Thomson and F. E. Neumann, had mathematically described the plausibility of the lines of force in mechanical terms, neither of them truly engaged with the theory. Indeed, Neumann made no reference to Faraday's theory, preferring an Amperean interpretation.[153] Despite the success of his experimental results, none of Faraday's contemporaries employed his lines of force until Maxwell had demonstrated their mathematical viability.

Maxwell was guided by his own method of model building, inspired by Faraday's writings and the mathematical analogies proposed by Thomson.[154] This method of analogy involved the creation of mathematical models describing physical analogies designed to explore conceptual relationships. The physical analogy approach encouraged the analogically extending the mathematical model of one phenomenon to describe another. Maxwell Explains: "In order to obtain physical ideas without adopting a physical theory we must make ourselves familiar with the existence of physical analogies. By a physical analogy I mean that partial similarity between the laws of one science and those of another which makes each of them illustrate the other."[155] However, Maxwell made explicit that which had only been implicit in Faraday's treatment of relative theories. That is, the analogous entities recognized by the human mind were not accurate depictions of nature but rather theoretic divisions. The distinctions which separated them from the rest of nature were purely conceptual. Maxwell conceived of theoretical analogies as unequivocally artificial, firmly believing that analogies do not exist in nature.[156]

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[153] Whittaker, 1951, p. 198-200; Berkson, 1974, p. 129, fn. 4
[154] W. Thomson had uncovered a mathematical analogy between models of electrostatics and heat. See Nersessian, 1984, p.72
[155] Maxwell, "On Faraday's Lines of Force" in *The Scientific Papers of James Clerk Maxwell*, p. 156
[156] See Maxwell, "Are there Real Analogies in Nature?" in *The Life of James Clerk Maxwell*, p. 235-244

Though Maxwell wished to accurately portray Faraday's theory through mathematical modeling, he did not adopt all of Faraday's beliefs. A chief difference between the two lay in their presentation of the medium. Though Maxwell did embrace Faraday's conception of forces as a state of a medium, Faraday's unification of force and space into the sea of forces was ignored. While he accepted the lines of force as related to the object, Maxwell did not consider the forces to be the formative structure of the "bodies" themselves.[157] Thus Maxwell reintroduced, at least for the sake of interpretation, the differentiation between forces and matter. Unlike Faraday, Maxwell treated electromagnetic forces as acting through a tangible aether. By tying the lines of force to an mechanical, physical ether Maxwell wished to integrate them into a newtonian framework. The aether allowed him to create a mathematical model which was compatible with Newton's laws.[158] One such model was the presentation of the lines of force as variable tubes. Electromagnetic forces were then modeled after the velocity of a fluid. Thus, by arranging the tubes together, Maxwell could fill space with a "liquid" model of force.[159] In reinterpreting and mathematizing Faraday's lines of force, Maxwell established the aether-medium as essential to electromagnetism. Though Hermann Von Helmholtz was more receptive to Faraday's philosophical concerns, Maxwell lay the mathematical foundations of 19th century field theory. In this way, Faraday's emphasis on the unity of forces, both as interconvertible aspects of a whole and as the united conception of matter, force, and space was excluded from Maxwell's field theory.[160]

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[157] Berkson, 1974, p. 348, fn. 31; See Maxwell, *Treatise*, vol 1, art. 529.
[158] Berkson, 1974, p. 142; Nersessian, 1984, p. 69
[159] Berkson, 1974, p. 144; Nersessian, 1984, p. 70
[160] Maxwell went on to model the electric and magnetic ethers as two separate and distinct entities. See Nersessian, p. 92

Following the work of Maxwell and Helmholtz, Hendrik Lorentz formulated a non-newtonian aether which did not obey the mechanics of action and reaction. By 1895, the electromagnetic medium was no longer described through analogies with matter. This formulation would ultimately bridge the gap between aether-field theories of the 19th century and the modern field conception.[161] At the turn of the century, Einstein would altogether refute the need for an aether, instead considering the field to be a quality of space itself. By conceiving of space itself as an active entity, forces no longer needed to act through a separate medium. Even half a century after the conclusion of the *Experimental Researches*, Faraday's method of analogical and heuristic modeling still bore fruit. Einstein would propose revolutionary theories derived from gedankenexperimente - his thought experiments. Among these were Einstein's relativity and his light quanta - photons - as a heuristic reanalysis of photoelectric phenomena.[162]

The conception of field theory was made possible, in large part, by Faraday's use of models. In understanding the distinction between limited theory and boundless Nature, Faraday made himself available to the similarities between natural phenomena. Though he had introduced new understandings of force and space, these views were significant only in so far as they extended his perception of Nature. This practice of model building was perpetuated and further refined by later scientists, such as Maxwell with his "physical analogy" and Einstein using gedankenexperiment. By employing theory as a tool of awareness, the framework of both the phenomena and its description become available to the sense. Awareness of the artificial nature of theoretical entities the model builder to highlight and examine hitherto unseen aspects of

[161] Nersessian, 198,4 p. 113
[162] Einstein, "On a Heuristic Point of View about the Creation and Conversion of Light", *The Old Quantum Theory*, 1968.

natural phenomena. In this way, the power of perceiving “reality” shifted from the revelations of nature to the deliberate extension of the investigator’s awareness.

# Appendix


Fig. 1a

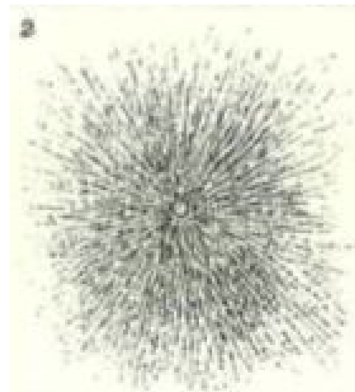

Fig. 1b

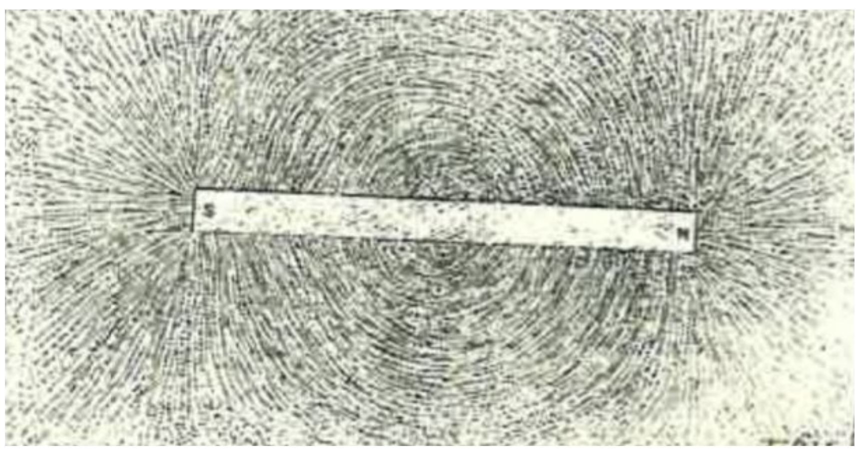


Fig. 2

Figure 1: (1a) Lines of Force, outlined by iron filings, surrounding a vertical wire carrying a current. (1b) Lines of Force over a pole.

Figure 2: Lines of Force, outlined by iron filings, surrounding the horizontal length of a bar-magnet.

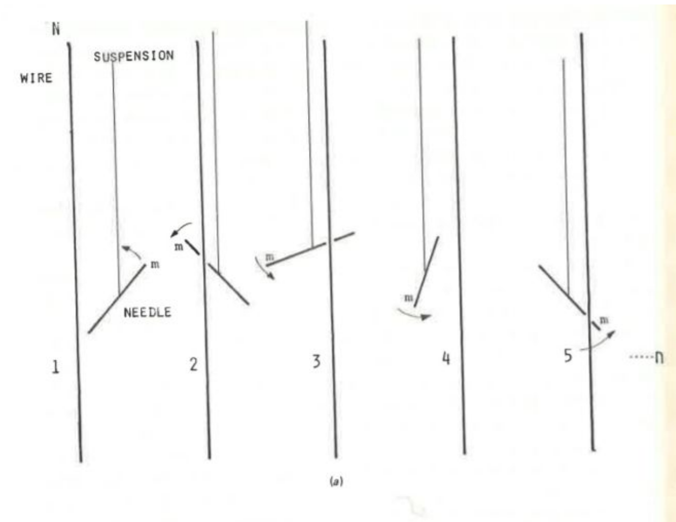


Fig. 3a

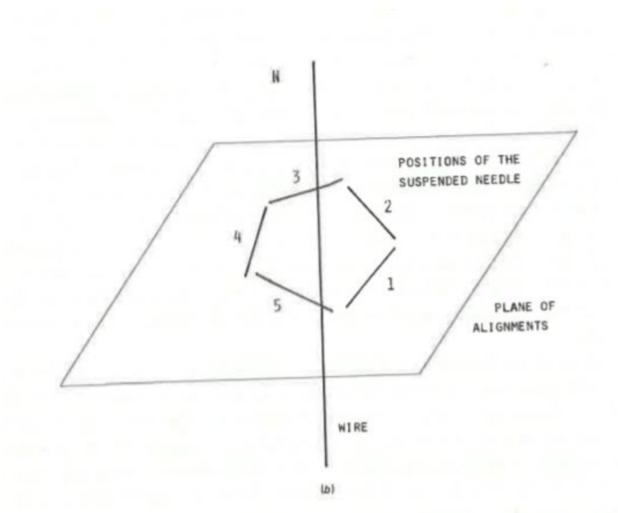


Fig. 3b

Figure 3: Delineating the lines of force (fig. 1a) with a magnetized needle around a vertical electrified wire. (3a) Movement of the suspended needle around the current. (3b) Combined positions of the suspended wire, depicted in a plane.

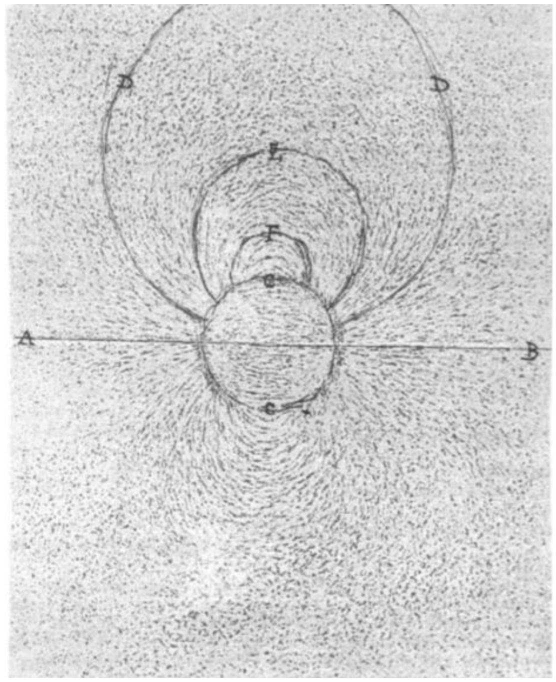

Fig. 4

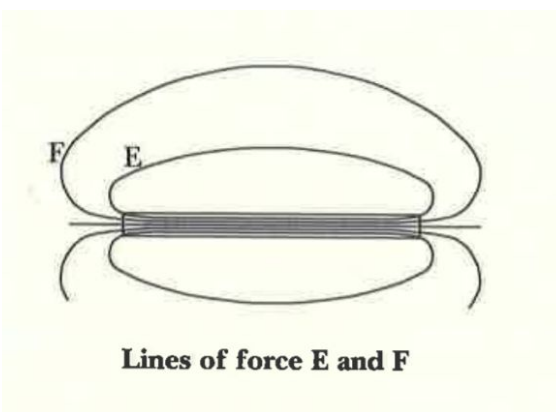


Fig. 5a

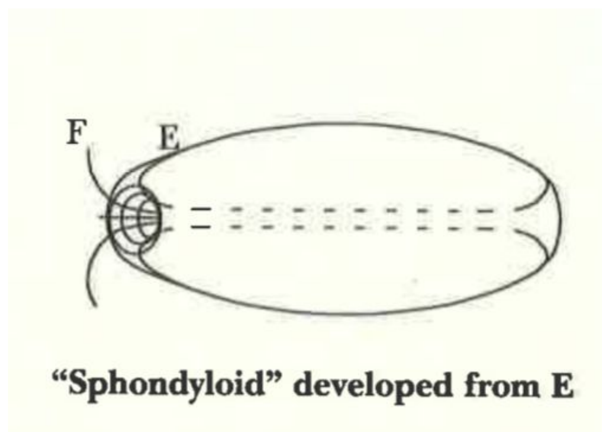


Fig. 5b

Figure 4: Faraday’s figure depicting the ‘shells of power’, or sphondyloid, delineated by iron filings.

Figure 5: (5a) Transected view of the ‘shells of power’, showing the lines of force within and outside the body of a bar-magnet. (5b) Exterior view of the sphondyloid, developed from extending shell E around the whole body.

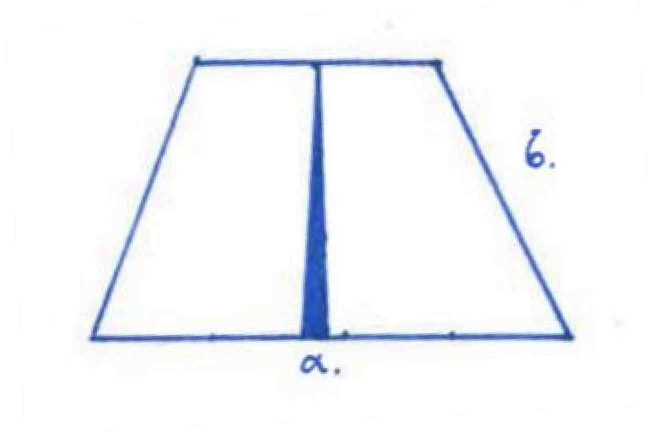


Fig. 6

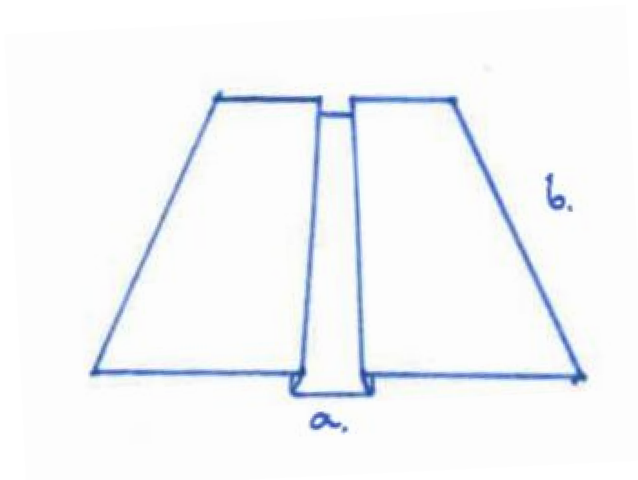


Fig. 7

Figure 6: Line of force (a), exemplified by a drawn line across a page (b), or plane. The line is distinct from the plane, delineated by the border between ink and page.

Figure 7: Here, the line of force (a) is defined as a fold in the page (b), or plane. The line is a defined entity only in so far as it is a fold, or configuration, of the page without being separate from it.

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