

Does Narrative Matter?

Engendering Belief in Electromagnetic Theory

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What is the use then of imagining an electro-tonic state of which we have no distinctly physical conception, instead of a formula of attraction which we can readily understand? I would answer, that it is a good thing to have two ways of looking at a subject, and to admit that there are two ways of looking at it.

J. C. Maxwell, "On Faraday's Lines of Force" (1855)¹

With these words James Clerk Maxwell positioned himself with respect to the sharply differing perspectives on electromagnetic action that were occupying natural philosophers by the time he published his first paper on the subject in 1855. How should they think about the action between two wires carrying electric currents. Should they imagine an action mediated by a magnetic field in all space describable in terms of "lines of force" and an electro-tonic state existing at every point: "of which we have no distinctly physical conception." Or should they suppose the space itself to be empty and imagine instead a direct unmediated action between moving electric particles (atoms) constituting currents: captured by a mathematical formula "which we can readily understand." This famous conundrum raises the question of how physicists at the time could compare the "field theory" of Maxwell with the "action at a distance theory" of Wilhelm Weber.²

1 Maxwell, James Clerk, "On Faraday's Lines of Force." In *Transactions of the Cambridge Philosophical Society* 10, Part 1, 1855, in *The Scientific Papers of James Clerk Maxwell*, Cambridge: Cambridge University Press, 1890, 155-229, on p. 208.

2 For succinct and insightful but more technical discussions of Weber, Maxwell, Faraday, and others appearing below see Darrigol, Olivier, *Electrodynamics from Ampère to Einstein*, Oxford: Oxford University Press, 2000.

One way to look at the problem of comparison is in terms of believability. How did people come to believe in one conception or the other? Apparently the usual criteria of empirical validity, mathematical coherence, and comprehensiveness were not enough, since in this case both representations seemed capable of encompassing all relevant phenomena. It was more nearly a matter of belief in one sort of imagined “world” versus another. And in this situation how the imagined world was narrated was important. In order to develop this perspective I will consider an analogy with the function of narrative in supporting belief in Greek mythology, largely following a recent analysis by Sarah Iles Johnston.³

Note: Narratologists often think of narrative as defined by an unfolding in time of a connected sequence of events. I use it here in the broader sense of an unfolding of a representation or interpretation of a part of the world, without any necessary reference to temporality. See my concluding comment below.

1. Two Conceptions of Electromagnetic Action

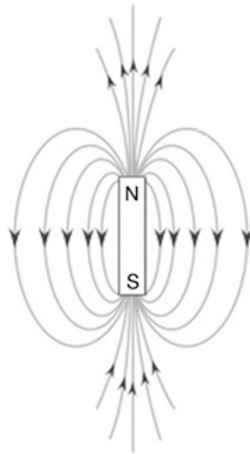
Before entering directly on the topic of how narratives support belief I will first describe in Part I, more or less for themselves, Maxwell’s presentation of field theory in terms of Faraday’s “lines of force” and the electro-tonic state and Weber’s presentation of action at a distance between particles, while pointing to some of their narrative characteristics. I will then in Part II broaden the discussion to include more general considerations of how narrative supported belief within a “story world,” using Johnston’s categories as adapted for the examples of Michael Faraday’s *Experimental Researches* for field theory and Gustav Theodor Fechner’s *Atomenlehre* for action-at-a-distance.

3 Johnston, Sarah Iles, *The Story of Myth*, Cambridge MA: Harvard University Press, 2018. Johnston, Sarah Iles, “Narrating Myths: Story and Belief in Ancient Greece,” *Arethusa* 48 (2), 2015: 173-218. Johnston, Sarah Iles, “The Greek Mythic Story World,” *Arethusa* 48 (3), 2015: 283-311.

1.1. Maxwell, “On Faraday’s Lines of Force” (1855)

In the first thirty three pages of a seventy six page paper Maxwell carefully unfolded verbally a picture of how lines of electric and magnetic force could be represented in familiar terms as lines of fluid flow, as depicted in figure 1.

Figure 1: Lines of force surrounding a bar magnet with north and south poles.



The first fifteen pages of this discursive narrative contained no mathematics at all while the next eighteen employed just the simplest algebra. It was only with an intuitive image established that he would then develop in twenty pages a set of formal equations that might govern the interaction of electric and magnetic lines in terms of Faraday’s electro-tonic state. A summary of the entire structure in six laws completed the account, with examples of their application.

This is the earliest instance of Maxwell’s famous use of “physical analogies”: “my aim has been to present the mathematical ideas to the mind in an embodied form, as systems of lines and surfaces and not as mere symbols, which neither convey the same ideas, nor readily adapt themselves to

the phenomena to be explained.⁴ It would be a mistake to think here of “embodied mathematics” as a purely intellectual affair, in which mathematical expressions simply receive concrete exemplification in a physical process. It is certainly that but much more. Repeatedly through his life Maxwell emphasized that embodiment was also a matter of awakening the senses. As he would put it in his Presidential Address to the British Association in 1870, “[many physicists] calculate the forces with which the heavenly bodies pull at one another and they feel their own muscles straining with the effort. To such men momentum, energy, mass are not mere abstract expressions of the results of scientific inquiry. They are words of power, which stir their souls like the memories of childhood.”⁵ It is helpful to keep this highly sensual aspect in mind when thinking of how Maxwell sought to embody the lines of force and their dynamical behavior in a narrative. He wanted to bring them to life like “the memories of childhood,” or perhaps the characters in a short story. In the embodied mathematics of a physical analogy he aimed to conceptually integrate diverse aspects of the lines of force perspective while preserving the “vividness” and “fertility” of sensory experience.⁶

To that end he asked his reader to “consider these curves not as mere lines, but as fine tubes of variable section carrying an incompressible fluid.”⁷ Beginning from the simplest images, immediately accessible to anyone who had seen water flowing, whether in a stream or simply in a basin, Maxwell unfolded the geometrical conception of lines of flow in a three-dimensional

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- 4 Maxwell, “Faraday’s Lines,” 156, 187. The literature is immense. For the specific religious and cultural context in which Maxwell developed his use of physical analogy see Lambert, Kevin, “The Uses of Analogy: James Clerk Maxwell’s ‘On Faraday’s Lines of Force’ and Early Victorian Analogical Argument,” *British Journal for the History of Science* 44, 2011: 61—88. On the method of reasoning see Cat, Jordi, “On Understanding: Maxwell on the Methods of Illustration and Scientific Metaphor,” *Studies in History and Philosophy of Science, Part B: Studies in History and Philosophy of Modern Physics* 32, 2001: 395–441. Nersessian, Nancy, “Maxwell and ‘the Method of Physical Analogy’: Model-based Reasoning, Generic Abstraction, and Conceptual Change.” In *Reading Natural Philosophy: Essays in the History and Philosophy of Science and Mathematics*, edited by D. B. Malament, Chicago: Open Court, 2002, 129–166. Generally see Darrigol, *Electrodynamics from Ampère to Einstein*, 137–147.
- 5 Maxwell, James Clerk, “Address to the Mathematical and Physical Sections of the British Association,” *Report of the British Association for the Advancement of Science* 40, 1870, 215–229, on p. 220.
- 6 Maxwell, “Faraday’s Lines,” 156.
- 7 *Ibid.*, 158.

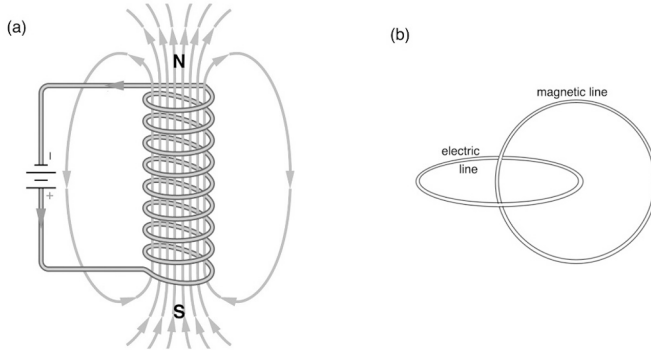
space, moving from lines to tubes of flow and gradually adding conditions on velocity, sources and sinks, a resisting medium, pressure gradients, and changes of medium. The result was an accessible image of a space full of flowing fluid, which, although not initially developed mathematically, was easily expressible in mathematical terms.

To put it a bit differently, lacking any physical theory of what a field of force might be, Maxwell led his reader into a fictional world containing a “purely imaginary substance,” which exhibited the properties he sought. “It is not even a hypothetical fluid which is introduced to explain actual phenomena. It is merely a collection of imaginary properties which may be employed for establishing certain theorems in pure mathematics in a way more intelligible to many minds and more applicable to physical problems than that in which algebraic symbols alone are used.”⁸ Through this conceptually enriching if fictional narrative, rendered in everyday terms, he sought to stimulate the reader’s imagination, giving almost sensory existence to the idea of lines of force as analogous to lines of fluid flow.

Having established his basic image in these familiar terms Maxwell easily employed it to draw together nearly all of the phenomena of electricity and magnetism as conceived by Faraday, replacing the idea of attraction at a distance with lines of force conducted through space, including: the distribution of electric lines around positive and negative charges of static electricity; the distribution of magnetic lines around north and south poles of magnets (figure 1); the distribution of electric current lines in a conductor; and the equivalence of electric currents and magnets in electromagnetism (so that a small electric circuit behaved exactly like a small bar magnet). The existence of electromagnetism meant that the two systems of electric current lines and magnetic lines, each conceived separately in terms of flow, had to be interrelated dynamically, so that the properties of each system could be understood in terms of the properties of the other. Their qualitative relation can be readily understood with reference to a coil of wire carrying a current, which behaves like a bar magnet with north and south poles and produces an equivalent distribution of magnetic lines (figure 2a).

8 *Ibid.*, 160. As Lambert, “Uses of Analogy,” 86, puts it, “Maxwell thought the manipulation of objects could also discover ideas.”

Figure 2: (a) A current-carrying coil behaves like a bar magnet. (b) An electric current line and a magnetic line are related like a “mutual embrace.”



The pattern of the magnetic distribution by itself can be seen as a dynamic balance, resulting from a tendency of each line to *contract* along its length and for adjacent lines to *repel* each other laterally. But these effects are mirrored reciprocally by the tendency of the current lines (or turns in the coil) to *extend* along their length and for adjacent lines to *attract* laterally.

With his flair for evoking sensory perception Maxwell labelled Faraday's image of these interlocked rings the “mutual embrace” of electricity and magnetism (figure 2b).⁹ He had at hand no physical analogy that could account for the interrelation of the lines but his flow analogy did provide key concepts of flow velocity and pressure gradient at any point, or “quantity” and “intensity” of the flow, in terms of which the reciprocal dynamics might be represented mathematically. The picture of mutual embrace suggested that just as the *quantity* of current passing through a surface surrounded by a magnetic line could be expressed in terms of the *intensity* in the magnetic line, so the *quantity* of magnetic force passing through a surface enclosed by a current line should be expressible in terms of the current's *intensity*. But no

9 Maxwell, “Faraday's Lines,” 184, 194f. From Faraday, *Experimental Researches*, III, 3265 and plate IV, fig. 1. For Maxwell's continuing use of the metaphor in later papers see Wise, M. Norton, “The Mutual Embrace of Electricity and Magnetism,” *Science* 203 (4387), 1979: 1310-1318.

such relation of magnetic quantity to current intensity existed. Thus mutual embrace remained a highly suggestive image, to which Maxwell had led his reader through an illuminating flow analogy for lines of force, but it ended up showing that the story he had constructed was as yet incomplete.

This inadequacy was particularly troubling for Faraday's great discovery of electromagnetic induction, whereby an increase or decrease of the magnetic quantity passing through a surface surrounded by a closed conductor would induce a current in the conductor. Like Faraday, Maxwell thought there must be some corresponding condition in the conductor, an "electro-tonic state," which was responsible for the current. But lacking any physical analogy with which to embody this speculation, it remained a puzzling element within the picture of lines of force. He therefore turned in the second half of his paper to a purely mathematical representation of the electro-tonic state. In this abstract form it served nearly to complete mathematically the symmetry of the mutual embrace while also encompassing electromagnetic induction. But it remained a somewhat ghostly stranger in Maxwell's integrative narrative. He left his reader with the hope that an extended physical analogy would someday complete the picture. "By a careful study of the laws of elastic solids and of the motions of viscous fluids, I hope to discover a method of forming a mechanical conception of this electro-tonic state adapted to general reasoning."¹⁰ This aim to develop a more complete narrative, which did not depend in the first instance on mathematical expression, would guide Maxwell's development of electromagnetic field theory for many years.

1.2 Weber, *Elektrodynamische Maassbestimmungen* (1846)

In sharp contrast to Maxwell's aim of physical embodiment of mathematical relations, Wilhelm Weber sought an abstract mathematical relation that would provide a *Grundgesetz* for all electrical action, where the term *Grundgesetz* implies a foundational law governing the constitution of the phenomena and from which they can be derived. And while Maxwell approached his subject as a reflective theorist looking for a new conceptual structure, Weber presented himself as a rigorous experimentalist seeking quantitative empirical grounding for a generalized law of action at a distance, a law that would do nothing more than express the results of his measurements, thus the title

¹⁰ Maxwell, "Faraday's Lines," 188.

“Electrodynamic Measurements” (or Determinations of Electrodynamic Measure).¹¹

As such Weber’s 170 page essay has a structure very different from Maxwell’s. He let his reader know from the beginning that there was a character behind the scenes that would ultimately appear as a central figure, namely electric currents represented in terms of positive and negative particles of electric fluids flowing in opposite directions inside a conductor. But these particles did not immediately concern him. Instead he began his narrative from the closest expression yet attained to what he called a “fundamental law” of the force acting between two current-carrying wires (not the flowing electric fluids themselves). The French mathematical and experimental physicist André-Marie Ampère had succeeded in expressing this law as an action at a distance between any two infinitesimal elements of the wires, depending on their current strengths, relative orientations, and the inverse square of the distance between them.¹² But to Weber, Ampère’s accomplishment had a great weakness. He had not actually been able to measure the force acting between two current-carrying wires. Instead he had relied on so-called null experiments, reasoning for particular arrangements of currents that if no effect were observed then the force had to have the form he ascribed to it. Although justly famous, Ampère’s method could neither give positive measurements of the forces nor establish absolute values of the currents. He simply did not have the necessary instruments.

Weber had the solution. He devoted the first hundred pages of his book to the design and operation of a new “electrodynamometer” of extraordinary precision.¹³ From a literary perspective Weber’s presentation of his instrument was itself a work of considerable rhetorical skill, another narrative unfolding of a vivid image, but this time of the creative design, operation, and uses of the key component—the key actor—in an empirically based narrative that would ultimately lift Ampère’s “fundamental” law of action at a distance between current-carrying wires into a proper *Grundgesetz*. Drawings

11 Weber, Wilhelm, *Elektrodynamische Maassbestimmungen*, Leipzig: Weidmann’sche Buchhandlung, 1846.

12 Ampère, André-Marie, “Mèmoire sur la théorie mathématique des phénomènes électrodynamiques uniquement déduite de l’expérience,” *Mémoires de l’académie royale des sciences de l’institut de France* 6, 1823 : 175-388. On Ampère’s theoretical and experimental methods see Hofmann, James R., “Ampère, Electrodynamics and Experimental Evidence,” *Osiris* 3, 1987: 45-76. Darrigol, *Electrodynamics from Ampère to Einstein*, 6-13, 23-30.

13 Darrigol, *Electrodynamics from Ampère to Einstein*, 54-66.

were critical to the reader's appreciation of the arrangement of components and of how they functioned (figure 3).

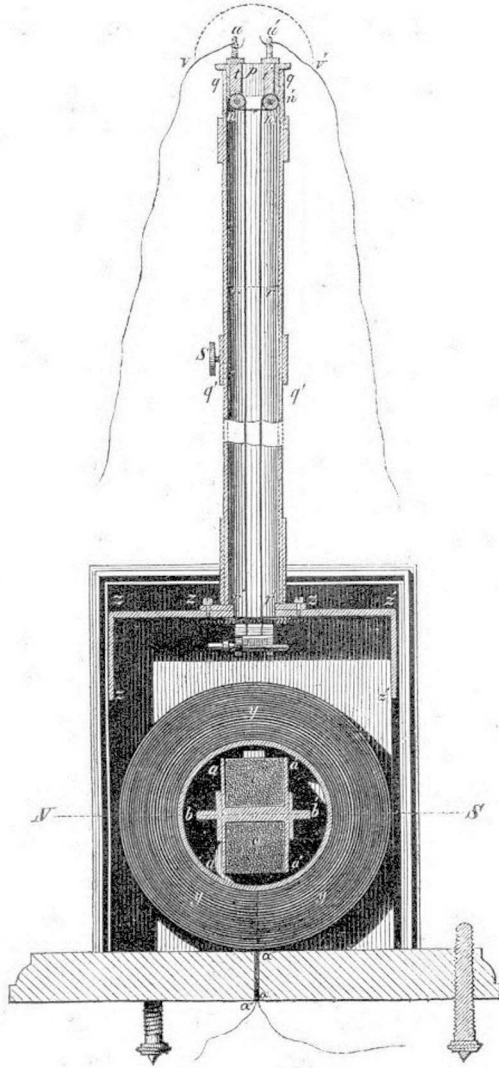
In its basic version, an outer fixed coil of current-carrying wire surrounded an inner moveable coil, which was placed perpendicularly to it and was suspended on a pair of fine wires for sensitive detection of any rotation produced by action between the coils. A small mirror mounted on the inner coil allowed tiny movements to be read by reflection through a telescope on a scale placed six meters away.¹⁴ The reader's initial appreciation for the refinement of the instrument and its capacities, however, was built not only on detailed description but on Weber's story of its origins, specific identification of the instrument maker who perfected it, extensive calibration data, analysis of precision, and sources of error. Fully fleshed out in this way, the electrodynamicometer functioned as the trusted agent of truth in Weber's account.

Only having established this material foundation did Weber return to his reworking of Ampère, measuring with precision and with named witnesses to the observations the action between the current-carrying coils of his electrodynamicometer. The result completely confirmed Ampère's fundamental law of the force acting at a distance between current elements. He then turned to Faraday's discoveries of current induction to show that the electrodynamicometer could similarly confirm those results, both qualitatively and quantitatively. At this point in his narrative it would seem that Weber had not only presented his instrument as an agent capable of reworking experimentally all known phenomena of electrodynamics but had made the electrodynamicometer into an instrument that in effect reified those phenomena as results of action at a distance.

Nevertheless a major difference existed between the Ampère and Faraday results, for while Ampère's law referred to electric currents, the force it actually described acted on the conductors carrying the currents. In this sense, it was not an electrical force at all. Faraday's induction of currents, on the other hand, concerned a force acting on the electricity itself inside a conductor to create a current. That distinction opened the door to the second half of Weber's essay, in which he revived the background image of electric fluids that he had originally only mentioned. He now sought a general law of truly electrical

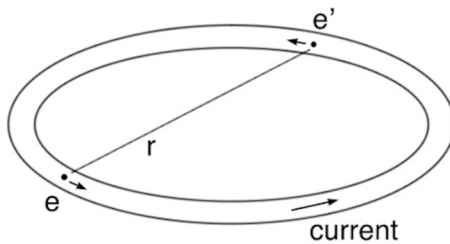
14 Weber adapted the bifilar suspension and telescopic mirror reading technique from Gauss's magnetic measurements, on which he collaborated. Weber, *Elektrodynamische Maassbestimmungen*, 10.

Figure 3: Wilhelm Weber's Electrodynamometer. Weber, *Elektrodynamische Maassbestimmungen*, 11.



forces acting between masses of positive and negative electricity (effectively electric point atoms, as for Fechner below). Returning to the assumption that currents consisted of positive and negative fluids moving inside conductors, he asked what supplement of the familiar inverse square law ee'/r^2 , which governed the electrostatic force between electric masses e and e' at rest with a distance r between them, would apply if the masses were in relative motion, as in a wire carrying a current (figure 4).

Figure 4: Weber's law of force between electric particles e and e' flowing in a wire carrying current: $F = ee'/r^2(1 - k^2v^2 + 2kra)$



From looking at only two facts about the Ampèrian forces between current elements he quickly inferred that the simplest supplement of the electrostatic law would be two additional terms, one depending on the square of the relative velocity v between the electric masses and a second depending on their relative acceleration a :

$$F = (ee'/r^2)(1 - k^2v^2 + 2kra),$$

where k is a constant. With equal facility Weber showed from a single fact about Faraday's induction of currents that it also fit this abstract law, confirming its validity.

It may not be immediately obvious just how dramatic this result was. Nothing in the preceding 100 pages of presentation and legitimation of the electrodynamometer had prepared the reader for a simple mathematical expression that subsumed all of electrostatics and electrodynamics in one law of force for electric masses. A few pages of skillful reasoning had converted a tour de force of experimental prowess into a formula that provided the calculational basis of all electrical action. After one more generalizing move (a mathematical transformation of Ampère's law into the new law for electric masses), Weber reached the climax of his narrative. He could now call his accomplishment the "*elektrische Grundgesetz*", the law of constitution of any and all electrical phenomena.¹⁵ It remained only to prove that in fact the electrical phenomena could be formally derived from the *Grundgesetz*, including of course all of the refined measurements made by the electrodynamometer for both Ampère's constant currents and Faraday's induced currents.

But Weber's *Grundgesetz* was a law like no other. That the force between two bodies should depend on their relative velocity and acceleration, or should be time-dependent, challenged basic assumptions of mechanics.¹⁶ Nevertheless Weber pressed on, suggesting that other forces too, such as gravitation, might have to be similarly supplemented. "A *priori* this question cannot be decided, because formally in the assumption of such forces there is neither any contradiction nor anything unclear or indeterminate." Furthermore, the purpose of such "fundamental laws" was not "to give an *explanation* of the forces from their true grounds but only to give ... a useful general method for *quantitative* determination of the forces according to the fundamental measures determined in physics for space and time."¹⁷ The *Grundgesetz* suggested even that multibody forces might exist, since the acceleration between two masses could be affected by a third, as in recently discovered catalytic forces of chemistry. Indeed, mediating effects of an ether might be contemplated, as Faraday's recent discovery of magnetic rotation of the plane of polarization of light suggested.¹⁸ Thus a whole new world of possibilities opened up.

15 Weber, *Elektrodynamische Maassbestimmungen*, 119.

16 For the immediate controversy see Bevilacqua, Fabio, "Theoretical and Mathematical Interpretations of Energy Conservation: The Helmholtz-Clausius Debate on Central Forces 1852-54." In *Universalgenie Helmholtz: Rückblick nach 100 Jahren*, edited by L. Krüger, Berlin: Akademie Verlag, 1994, 89-106. Darrigol, Olivier, "Helmholtz's Electrodynamics and the Comprehensibility of Nature." In *Universalgenie Helmholtz*, 216-242.

17 Weber, *Elektrodynamische Maassbestimmungen*, 112-113.

18 *Ibid.*, 168-170.

But Weber wanted to be clear that the compelling picture he presented of direct action at a distance between electric masses, was a fictional, if realistic, construction. Concerning currents: “The simultaneous movement in opposite directions of positive and negative electricity ... may in reality not exist at all, but for our purpose may be regarded as an *ideal* motion, which ... [for] actions at a distance, may represent the motions really present.”¹⁹

In summary, and somewhat like Maxwell, Weber built up an experimental and theoretical narrative that would launch a generalized concept of action at a distance, in which forces could be time dependent. The conception was highly successful at drawing together disparate elements, even if fictional. The basic object of understanding on this view was a pair of particles, or electric atoms, between which a force acted. The force itself was an abstract relation in space and also time: “because a time-dependent relation is just as measurable a quantity as distance.”²⁰ In contrast to Maxwell, however, the space surrounding the two atoms contained nothing: no force, no field, and of course no lines of force.

2. Believability and the Techniques of Narrative

Both Maxwell and Weber carefully structured their narratives of electromagnetic phenomena to make the unfamiliar familiar and to yield a climactic moment in which a strange new object emerged. For Maxwell the story culminated in an electro-tonic state, which had never been observed and for which he could provide no ordinary physical conception but only a suggestive mathematical symmetry. For Weber the culmination was a time-dependent force, whose violation of established principles Weber countered with appeals to logical validity and to possible extension to other areas, such as catalytic action.

Thinking of these fictional constructions in rhetorical terms, my question now is what made them believable in everyday terms. This is the same question that classicist and historian Sarah Johnston has asked for Greek mythology: “how, exactly, does the narration of myth sustain a metaphorical connection between the mythic and quotidian worlds.”²¹ One aspect jumps out

19 Ibid., 100.

20 Ibid., 113.

21 Johnston, *Story of Myth*, 79.

immediately. Both Maxwell and Weber spent the majority of their presentations making the reader feel at home within the worlds they were in the process of building, well before they revealed their creative fictions. Maxwell did this through the flow analogy, which was accessible to anyone who had paid close attention to fluid flow. Weber did it through his extended presentation of the design, operation, and measurements of the electro-dynamometer, all of which confirmed Ampère's and Faraday's laws in terms of action at a distance. Only after having gone to considerable length to establish this familiarity and normalcy—and thereby their own legitimacy and a suspension of disbelief—did they guide their readers into consideration of a possible expanded reality.

Techniques of this kind for introducing the fictional or extraordinary into the quotidian are so common in narratives dealing with otherwise questionable events or beings that it has been designated the “X/Y Format”—X for the familiar and Y for strangeness—by the sociologist Robin Wooffitt.²² It is only one of many techniques, however, that Johnston has highlighted in skillfully constructed narratives, which contribute to the believability of the gods and heroes of Greek myths.²³ It is not that speculative stories about electromagnetism are much like myths—lines of force and electric atoms are characters of a different sort from Heracles or Theseus—but the techniques of narration that enhance their believability are similar. Among those techniques (but adapted and reordered) I will take up the role of: *conceptual metaphor*, *serial narration*, *multipliers* (Johnston's *plurimediality*), and *story world*. Together they help to clarify the *pragmatic effect* of effective narration. To explore this view for audiences of electromagnetism I will move out from the highly focused representations by Maxwell and Weber to the broader narratives of Faraday and of Gustav Fechner.

A key aspect of Johnston's entire discussion of the effectiveness of techniques of narration is her treatment of emotional and cognitive responses as integrally related. Although I will not explicitly take up that relation here, Maxwell's view of the sensory role of physical embodiment of mathematical

22 Johnston, *Story of Myth*, 98-102; Wooffitt, Robin, *Telling Tales of the Unexpected: The Organization of Factual Discourse*, Hemel Hempstead: Harvester Wheatsheaf, 1992, 114-152.

23 Mayer, Adrienne, *Gods and Robots: Myths, Machines, and Ancient Dreams of Technology*, Princeton: Princeton University Press, 2019 is also highly relevant here for its accounts of the relation of fictional automata in Greek myths to familiar technology, with believability, and also creativity, running in both directions.

formulas can serve as a reminder of its importance, which reappears below for Fechner.²⁴

2.1 Faraday, Experimental Researches in Electricity (1831-1852)

Over the course of twenty years from 1832 to 1852 Michael Faraday published in the *Philosophical Transactions of the Royal Society* and other journals the articles that would make up the three volumes of his *Experimental Researches in Electricity*. Having made his reputation with major discoveries in chemical equivalents and electrochemistry he had turned to electricity and magnetism proper. The *Researches* contained an astonishing collection of discoveries, including electromagnetic induction (1831), specific inductive capacity (1837), diamagnetism (1845), magnetic rotation of light (1845), and many others of both theoretical and practical significance. Throughout these works Faraday continued to ponder and to develop the idea of lines of force as an alternative to action at a distance.²⁵

Conceptual metaphor. The term “lines of force” functioned during this development as what Johnston, borrowing from the linguists George Lakoff and Mark Johnson, calls a *conceptual metaphor*. Such metaphors, she observes, commonly functioned in the narration of Greek myths to figuratively connect events in the everyday world to events in the world of the myth and thereby support belief.²⁶ In Faraday’s case, his use of lines of force as a central metaphor not only connected many different strands in the actual world of his laboratory experiments (as in figure 5), but connected them as well to an imagined world in which forces had something like material status.

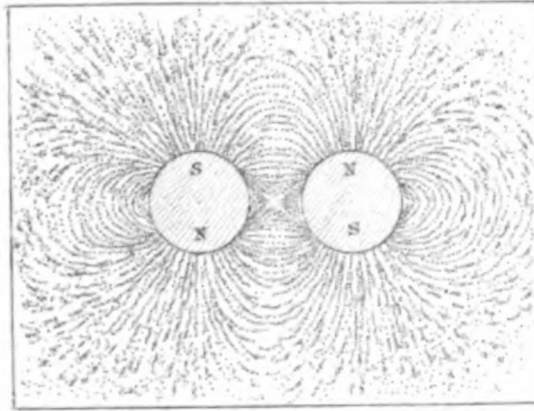
In retrospect, Faraday’s metaphorical language might seem to have been highly effective. It is well to remember, however, that it was not necessarily so, especially among those who prioritized mathematical expression. William Thomson, for example, who would ultimately become Faraday’s first great mathematical interpreter, when originally encountering Faraday’s language

24 Johnston, *Story of Myth*, e.g. 10, 66-67, and throughout.

25 Faraday, Michael, *Experimental Researches in Electricity*, 3 vols., facsimile reprint, London: Quaritch, 1855, cited by paragraph number. On the sources and significance of Faraday’s use of lines of force see Gooding, David, “Magnetic Curves’ and the Magnetic Field: Experimentation and Representation in the History of a Theory.” In *The Uses of Experiment*, edited by D. Gooding, T. Pinch, and S. Schaffer, Cambridge: Cambridge University Press, 1989, 183-223. Darrigol, *Electrodynamics from Ampère to Einstein*, 16-22, 31-41.

26 Johnston, *Story of Myth*, 67, 73.

Figure 5: Faraday's image of iron filings mapping the lines of force around two circular magnets with north and south poles. Faraday, *Experimental Researches*, III, Plate IV, Fig. 4.



of electrostatic “induction in curved lines” in 1843, wrote that “I have been much disgusted with his way of *speaking* of the phenomena, for his theory can be called nothing else.”²⁷ It would be two years before he fully appreciated that Faraday’s “way of speaking” fit quite well with his own development of a mathematical analogy between heat conduction and electrostatic action, with which he had shown their near mathematical equivalence. Thomson’s analogy between flux of heat and lines of force would provide Maxwell’s starting point for his own fluid flow analogy ten years later. The seemingly so obvious power that we see today in Faraday’s conceptual metaphor is actually a product of historical recountings, not unlike the way in which repeated narration and performance of Greek myths around conceptual metaphors enhanced the believability of Gods and heroes.

Serial narration. Closely related to this historical aspect of effective metaphors, but within Faraday’s own reports of his experiments, is their *serial narration*. The articles in the three volumes were narrated serially over

27 Smith, Crosbie, and M. Norton Wise, *Energy and Empire: A Biographical Study of Lord Kelvin*, Cambridge: Cambridge University Press, 1989, 213.

twenty years. The seriality was quite literal, with episodes appearing at irregular intervals with a series number and in numbered paragraphs.²⁸ Johnston takes serial narration to have been another of the important factors contributing to belief in myths. Offered up in small installments, each with its own focus but always contributing to a single story line, the series encouraged readers to contemplate each episode in relation to previous ones and in anticipation of what might appear next, as though following one of Charles Dickens's serialized novels or a TV series like *Downton Abbey*. Faraday encouraged such responses with many back-references and suggestive speculations about future developments, as in the following excerpt from the Eleventh Series (1837).²⁹

1163. In the long-continued course of experimental inquiry in which I have been engaged, this general result has pressed upon me constantly, namely, the necessity of admitting two forces, or two forms or directions of a force (516. 517.).

1164. When I discovered the general fact that electrolytes refused to yield their elements to a current when in the solid state, though they gave them forth freely if in the liquid condition (380. 394. 402.), I thought I saw an opening to the elucidation of inductive action, and the possible subjugation of many dissimilar phenomena to one law.

As this excerpt also suggests, seriality offers another interesting mode of reading, namely, reading out of sequence, so that readers are able continually to reconstruct the back-story for themselves. Such reconstruction can suggest different approaches and new insights, enhancing personal engagement. Johnston argues that all of these aspects of serial narration give characters a life of their own, which in itself contributes to their believability.³⁰

Multipliers. Similar effects follow from various means of multiplication, whether by different authors, different outlets, different voices, or different

28 For extended discussion of "Seriality and Scientific Objects in the 19th Century" see the special double issue of *History of Science*, 48 (2010), edited by Nick Hopwood, Simon Schaffer, and James Secord.

29 Faraday, *Experimental Researches*, I, 1163-1164. As Faraday scholar Geoffrey Cantor has observed (verbal comment) it may be significant for reader response that Faraday's installments appeared about a year apart rather than only a week apart, as for Dickens.

30 Johnston, *Story of Myth*, 32, 91-96, 246-252. I am here collapsing the distinction of "series" from "serial" in episodic narration.

media. Johnston develops this as *plurimediality*.³¹ Although most of Faraday's articles appeared in the prestigious *Philosophical Transactions*, for example, he placed some of them in the more widely read *Philosophical Magazine* and in the popular *Proceedings of the Royal Institution*, while preserving the numbered ordering of the serial narration. These different outlets not only multiplied his audience; they also presented his work with different degrees of speculative freedom and different levels of technicality.

Looking more widely, a considerable variety of authors contributed to the diversity of specific meanings and contexts that informed Faraday's lines of force. The chemist John Frederic Daniell dedicated his *Introduction to the Study of Chemical Philosophy* to giving an elementary view of Faraday's philosophy, including the mediating action of lines of force. There Thomson encountered the claims for "curved lines," which he initially considered nothing but verbiage but soon elaborated mathematically through his analogy to heat conduction.³² And while Thomson admired Maxwell's similar use of physical analogy, he always rejected Maxwell's introduction of Faraday's electronic state from mathematical symmetry alone. Thus Daniell, Thomson, and Maxwell (among others) served as multiple narrators of the lines of force, whose differing interpretations contributed to the sense of their underlying reality. Other multipliers included the use of different modes of expression for the purpose of skillful narration, most prominent here being the mix of verbal, mathematical, and visual means that different authors used to capture Faraday's experiments and his already highly visual language.

Story world. Conceptual metaphors, serial narration, and multipliers of various kinds work together to create what Johnston and others call a *story world*. On entering the story world of Greek myths, we become familiar with a collection of characters whose stories become intertwined with each other. It is not so important that they appear always with the same personalities but that they create a dense network of relationships.³³ And so it was in Faraday's world of lines of force. Always exploring the possibilities for a reality in which forces are more substantial and fundamental than matter itself, he regularly repeated the view that forces of all kinds are expressions of one force and

31 Johnston, *Story of Myth*, 27-28, 156-176. Plurimediality takes the identity of the object of narration outside any particular author or presentation.

32 Daniell, John Frederic, *Introduction to the Study of Chemical Philosophy*, 2nd ed., London: Parker, 1843, 255-256.

33 Johnston, *Story of Myth*, 25-26, 121-146, as network 131-139. See also, Johnston, "The Greek Mythic Story World," 283-311.

are convertible one into the other.³⁴ His overarching narrative thus aimed at the ultimate goal of interrelating chemical reactions and heat with electricity, magnetism, light, and even gravity. Concerning the interlocked rings of electric and magnetic lines of force (figure 2b), which Maxwell would call their “mutual embrace,” he offered: “their relation ... probably points to the intimate physical relation, and it may be, to the oneness of condition of that which is apparently two powers or forms of power, electric and magnetic.”³⁵ Similarly, with respect to the magnetic rotation of light, he remarked: “Thus is established ... a true, direct relation and dependence between light and the magnetic and electric forces; and thus a great addition made to the facts and considerations which tend to prove that all natural forces are tied together, and have one common origin (2146).”³⁶ Within this developing story world each of the topics and each of the installments of Faraday’s long series of *Experimental Researches* became intertwined with the others through lines of force and each gained credibility from its place in the network in relation to the others.

Pragmatic effect. All of the techniques of effective narration that I have briefly described contributed to the believability of Faraday’s conception of how forces functioned in the world. When successful, these techniques made the elusive notion of lines of force seem as real as wires and inspired his followers to try out the experiments for themselves, enlivening the ideas with their own experience, which Faraday always encouraged. Others formulated their own work in corresponding terms. Thomson and Maxwell are the obvious examples. This capacity of narration to affect how others think and act has been called the pragmatic effect.³⁷ Although the term might be applied to many forms of presentation, it refers here specifically to the capacity of an audience to introduce entities from a story world into their real world without an overly strained sense of fiction, having acquired a new openness to possible realities. Perhaps the most difficult of those realities in Faraday’s narrative of lines of force was the electro-tonic state. As Faraday himself put it: “Again and again the idea of an electro-tonic state (60. 1114. 1661. 1729. 1733) has been forced on my mind; such a state would coincide and become identified with that which would then constitute the physical lines of magnetic force.”³⁸ On

34 Faraday, *Experimental Researches*, III, e.g., 57, 366, 376, 877, 961, 2071, 2146.

35 *Ibid.*, 3268.

36 *Ibid.*, 2221.

37 Johnston, 20-21, 57-58, 76-80, citing work of Claude Calame.

38 Faraday, *Experimental Researches*, III, 3269.

entering into Faraday's story world, Maxwell—but not Thomson—acquired a similar sense of the almost necessary reality of the imagined state. I have suggested that this was in part the pragmatic effect of effective narration. Maxwell responded by enriching the story world with his own physical analogy for lines of force and then reintroducing the electro-tonic state mathematically, as yet without any physical conception of it but with the expectation that it would soon appear in a prominent role.

2.2 Fechner, Atomenlehre (1855)

In order to obtain a similarly broad view of the believability of Wilhelm Weber's *Grundgesetz* in narrative terms it will be instructive to consider the work of Gustav Theodor Fechner.³⁹ The Leipzig physicist and philosopher was already a prominent intellectual who had published essays, books, and poetry, on everything from life after death to the mental life of plants, when in 1855 his sweeping tract on the atomistic conception of the world appeared, written in a distinctly literary vein and using Wilhelm Weber's work as the lynchpin of the presentation. Fechner had suffered a debilitating mental collapse in 1839, which effectively blinded him and which led to Weber assuming his professorship at Leipzig from 1843 to 1849, where they interacted closely.⁴⁰ Fechner had been pursuing an atomistic view of nature since the 1820s and in 1845 he published a partial account of the relation of Faraday's induction to Ampère's law of currents, modeling a current as equal and opposite motions of positive and negative electric masses. There he was able to announce that Weber had actually succeeded in subsuming all electrical phenomena under a single law of force.⁴¹

But Fechner had a much more ambitious agenda, one in which physics melded into philosophy and psychology and all three into "psychophysics," for which he is best known. It was the relation of physical and mental states

39 For a comprehensive analysis of Fechner's work, which informs my discussion here, see Heidelberger, Michael, *Nature from Within: Gustav Theodor Fechner and his Psychophysical Worldview*, trans. C. Klohr, Pittsburgh: University of Pittsburgh Press, 2004.

40 Weber had himself been dismissed from his professorship at Göttingen in 1837 as one of the political protesters known as the "Göttingen Sieben."

41 Fechner, Gustav Theodor, *Maassbestimmungen über die galvanische Kette*, Leipzig: Brockhaus, 1831. Fechner, Gustav Theodor, "Ueber die Verknüpfung der Faraday'schen Inductions-Erscheinungen mit den Ampère'schen elektro-dynamischen Erscheinungen," *Annalen der Physik und Chemie* 64, 1845: 337-345, on p. 345.

that most captured his attention. He advocated a form of monism called psychophysical parallelism, arguing that psychical and physical states—indeed, psychical and physical worlds—are two aspects of one reality and that their relation can be studied quantitatively. This led him, building on the work of Weber's brother Ernst Heinrich Weber, to the so-called Weber-Fechner law, relating the physical strength of a stimulus to its perceived psychical intensity.

With respect to Weber's *Grundgesetz*, Fechner's *Ueber die physikalische und philosophische Atomenlehre* of 1855 is his most important work.⁴² In this wide-ranging polemical tract, Fechner aimed to counter the currently dominant anti-atomism among German philosophers (as opposed to physicists). Ever since Kant's *Metaphysical Foundations of Natural Science* a number of philosophers had been pursuing forms of dynamism, meaning the view that the ordinary matter of our experience is constructed in the dialectics of nature from an underlying continuum of forces. "According to most dynamicists, a conflict of opposing forces is supposed to be what makes a body out of force." Two of Fechner's targets were Schelling and Hegel in their pursuit of the absolute or *Ding an sich*, but Herbart came in for special critique because his purely metaphysical monadology could look similar to the physical atomism that Fechner himself defended.⁴³

For Fechner the real world was a world of *sinnliche Erscheinungen* (sensory appearances, or phenomena) and any idea of a *Ding an sich* behind appearances was pure fantasy. Such appearances were epitomized by what could be directly touched or grasped, but they extended much further. "If one asks in general what the world consists of in the last instance, then it is *Erscheinung* (*Selbsterscheinung* in mind and God, objective *Erscheinung* in nature): laws of *Erscheinung*; determinations, connections, and relations of *Erscheinungen*; which include the possibility of forthcoming and new *Erscheinungen*. Otherwise there is nothing and behind them there is nothing."⁴⁴ Within this simultaneously realist and phenomenalist perspective Fechner presented his atomistic world view, arguing that atomism best represented the totality of empirical and mathematical appearances known to physicists and therefore had the most probable claim on reality.⁴⁵ In this effort he also relied on several

42 Fechner, Gustav Theodor, *Ueber die physikalische und philosophische Atomenlehre*, Leipzig: Mendelssohn, 1855.

43 Fechner, *Atomenlehre*, 107, 164.

44 Fechner, *Atomenlehre*, 94, see also 90-99, 113.

45 See Heidelberger, *Nature from Within*, 137-154.

of the tools of believability that Johnston ascribes to the narration of Greek myths.

Conceptual metaphor. Under the conceptual framework of atomism Fechner sought to integrate a wide diversity of phenomena in the physical world. By atoms he understood discrete, indestructible atoms, *Grundatome* or *letzten Atome*, with forces acting directly at a distance between them. And citing Weber, along with prominent French physicists (Moigno, Séquin, Cauchy, Ampère), he adopted the view that these atoms could best be considered as unextended point atoms.⁴⁶ Crucially, the forces were nothing in themselves; they could not be thought of independent of the atoms; nor did they inhere in or emanate from individual atoms; so one atom could not be said to act on another. It was only “the category of *Zusammensein* [being together, or interrelation] that defined the concept of force, not an inner essence of matter.” Or again, “The concept of force ... is a relational concept, which has meaning only for the *Zusammensein* of matter.”⁴⁷ Forces were relations in space and time between atoms, which physicists knew only as laws. Thus Fechner’s basic physical image was of a *pair* of point atoms moving with respect to one another and expressing in their relation the law of force that governed their relative motion. With this concept of action at a distance between atoms Fechner sought to open up the unobservable world to physical understanding grounded in *sinnliche Erscheinungen*. “Atomism is at once the key with which the physicist unlocks the door of a room closed to the senses and opens up its connection with what is immediately accessible to him.”⁴⁸

Serial narration. By the time Fechner’s *Atomenlehre* appeared in 1855 he had been publishing articles and books that concerned atomism for thirty years. In this sense the *Atomenlehre* had a serial character, although that background appeared only occasionally in the text. More interesting is what might be thought of as the historical seriality of other physicists, mostly French, on whom Fechner depended. He had only to mention their names at critical junctures, for they were well known to all physical scientists. The series of their works portrayed a continuing French pursuit of action at a distance between “material points.” Its coherent development, amidst lively debate, began perhaps from Laplace’s popular reworking of Newtonian universal gravitation in his *System of the World* (1796) and in his five-volume mathematical treatise on

46 Fechner, *Atomenlehre*, 73, 79-81, 161-163.

47 Fechner, *Atomenlehre*, 109, 112.

48 Fechner, *Atomenlehre*, 32.

Celestial Mechanics (1799-1825). It continued through Poisson's adaptation of the inverse square law to electric and magnetic fluids (1811, 1821); Fourier's analysis of heat conduction as radiation between molecules; Fresnel's theory of light as transverse waves in the ether (1822, originally much contested); and Cauchy's representation of this ether as an elastic medium consisting of imponderable atoms (1835-36). Included of course was Ampère's electrodynamics (1824), which culminated in Weber's *Grundgesetz*. Fechner himself had been especially active in bringing the French tradition to Germany, both in his extensive translations (sometimes amounting to full rewritings) of comprehensive textbooks by Jean-Baptiste Biot on physics (four volumes, 1824; five volumes, 1828-1829), Louis Jacques Thénard on chemistry (seven volumes, 1825), and in his own *Repertorium der Experimentalphysik* (three volumes, 1832).

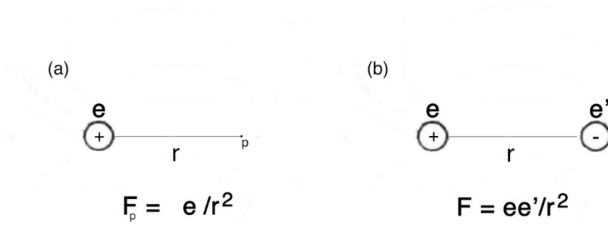
To think of this sequence in terms of serial narration of an atomistic world view, rather than simply as a tradition, is to think of it as an ongoing saga with a continuing story line and with surprising new episodes at every turn. Many physicists had either lived through the series or followed it in retrospect, attentive to the controversies within it, with expectations for what would come next, and looking back to reinterpret earlier episodes, such as the wave theory of light after Cauchy.⁴⁹ Fechner exploited such episodes in familiar vignettes, reiterating for example how Poisson had been forced to change his views on the polarization of light. These are all aspects that contributed to the believability of atomism. From a rhetorical perspective it was particularly effective for Fechner to fashion his own narrative with the ever-present foil of the dynamicists to enliven it throughout.

Multipliers. Here seriality merges into other multipliers of believability, such as multiple narrators who only partially agree. For example, Fechner could use the French series to enhance the credibility of his atomism despite the fact that in detail it presented a contrasting conception of his basic conceptual metaphor. While Fechner and Weber considered force as a shorthand for the interrelation of a pair of atoms, their *Zusammensein*, the French spoke of force as emanating from one atom and acting on another. The distinction is striking in the case of Gauss and Weber, who worked closely together at Göttingen. In a long article on inverse square forces, Gauss followed the French in writing of "a material point out of which a repulsive or attractive force acts."⁵⁰

49 Fechner, *Atomenlehre*, 18.

50 Gauss, Carl Friedrich, "Allgemeine Lehrsätze in Beziehung auf die im verkehrten Verhältnisse des Quadrats der Entfernung wirkenden Anziehungs- und Abstossungskräfte." In *Resultate aus den Beobachtungen des magnetischen Vereins im Jahre 1839*,

Figure 6: Visual depictions of (a) Gauss's mode of representing the force at a point p emanating from an electric mass point e and (b) Weber's comparable representation of the force between e and e' as an abstract relation in space.



Expressed mathematically (and visually in figure 6a) this meant that he calculated the force at an empty point of space produced by the material point (i.e., at point p the force F_p of an atom e at a distance r would be $F_p = e/r^2$, or the force per unit mass that would be exerted on another atom if it were placed there). In contrast (figure 6b) Weber expressed the force as a relation between a pair of atoms e and e' , $F_p = ee'/r^2$. Ironically, Hermann Helmholtz, in formulating his classic work on energy conservation in 1847, used the Fechner-Weber conception of force in terms of atom pairs even while citing Gauss.⁵¹

A similar multiplicity of voices continued their expression in the period following Fechner's *Atomenlehre* with its reliance on Weber's *Grundgesetz* as its epitome. Helmholtz criticized the law for its time dependence, which he thought violated conservation. This produced a long and sometimes acrimonious dispute with Rudolph Clausius and Weber, who showed that it did not.⁵²

edited by C. F. Gauss and W. Weber, Leipzig, 1840. Reprinted in Gauss, Carl Friedrich, *Werke*, Göttingen: Königlichen Gesellschaft der Wissenschaften, 1877, vol. 5, 195–242, on p. 198–201.

51 Wise, M. Norton, *Aesthetics, Industry, and Science: Hermann von Helmholtz and the Berlin Physical Society*, Chicago: University of Chicago Press, 2018, 271.

52 Bevilacqua, Fabio, "Theoretical and Mathematical Interpretations of Energy Conservation: The Helmholtz-Clausius Debate on Central Forces 1852–54." In *Universalgénie Helmholtz*, 89–106. Darrigol, "Helmholtz's Electrodynamics and the Comprehensibility of Nature." In *Universalgénie Helmholtz*, 216–242.

A full telling of this controversy would involve a number of other major actors and their commitments. I emphasize here only that the controversy provided a powerful multiplier for belief in atomism and for Weber's *Grundgesetz*, even as Maxwell's electromagnetic field theory became a prime competitor.

Story World. In its most general form the world that Fechner presented to his readers was a world of discrete things within which he aimed to join all of the physical sciences in a common structure. If gravitation and electricity provided the groundwork of atom-pairs and inverse square forces to which all else would ultimately be reduced, he came to this position within a much broader vision of an atomic system as analogous to a planetary system, a Laplacian system of the world, extending from the stars moving in the heavens to the planets of the solar system to atomic systems making up the molecules of ponderable matter and those of the imponderable ether. Under this universal scheme of discreteness and systems all of the subjects of the physical sciences had already made great progress: light, heat, elasticity, cohesion, chemical combination, crystallography, etc. "Thus through atomism everything from the largest to the smallest and in the most diverse directions is encompassed within a single realm, and a general clarity runs through this realm."⁵³

Within this material world of unifying clarity, Fechner had also to make room for contemplation of the "highest and final things," of God, morality, freedom, life and death. The dynamicists supposed that a world conceived as a continuum of forces was more suited to relating matter and spirit than a world of atoms, which he firmly denied. "The same spirit that runs through atomism must be conceivable as a whiff of the same spirit that runs through heaven itself, whether it can exist with God or God with it." The atomistic world in fact supplied an illuminating image of a social organization based on the "principle of individuality" and spiritual freedom rather than of everyone tied to their neighbor without independence. In short, "an atomistic world is a structure worthier of the most exalted idea of God and indescribably more beautiful than the dynamical."⁵⁴ Here was a story world into which Fechner hoped his audience could project their most wide-ranging beliefs, or at least suspend their disbelief in atomism.

Pragmatic effect. It was the molecular structure of matter that Fechner particularly exploited to make the superiority of atomism seem almost accessi-

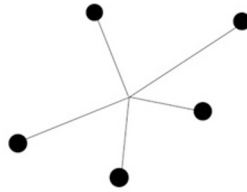
53 Fechner, *Atomenlehre*, 36.

54 Fechner, *Atomenlehre*, 119, 122.

ble to the senses. For example, if molecules consisted of atomic systems that could take different arrangements, then phenomena like isometry, in which substances with the same chemical composition have different properties, became intuitively realistic, making “the advantage of the atomistic conception palpable [*fühlbar*] for the unprejudiced.”⁵⁵ That was already a major contribution to suspension of disbelief. But it also sharpened the further question of how atomic systems could actually be structured as stable molecules by forces between atoms.

For this question Fechner appended to his more evidentiary text a speculative chapter containing a “Hypothesis on the General Force-law of Nature.” Here he relied on the credibility of Weber’s earlier suggestions for multi-body forces and time-dependent forces to unfold a much more expansive view. If gravitational and electrical forces expressed the relation of two particles, why suppose that nature would have stopped there? “Is it not possible that results appear here that depend on forces that are determined jointly by the *Zusammensein* of more than two particles?”⁵⁶

*Figure 7: A representation of Fechner’s conception of an irreducible multi-body force as the *Zusammensein* of five particles.*



On this basis (figure 7) Fechner proposed an ascending series of forces as the number of particles in a system increased and whose strength decreased increasingly rapidly with distance between the particles. These higher-order forces would be unobservable at large distances but would gradually

55 Fechner, *Atomenlehre*, 37.

56 Fechner, *Atomenlehre*, 184.

come into play as more particles at smaller distances made up more complex molecules. Briefly put, “In every combination of arbitrarily many particles there rules a force, whose strength and direction [attractive or repulsive] are determined by the interrelations of the *Zusammensein* of all the particles at once”⁵⁷ This conception might extend all the way from chemical elements as systems of *Grundatome* to a force governing the totality of the parts of an organism, which would encompass within it many subordinate systems and their forces.

Fechner would also have liked to be able to understand all of the phenomena ascribed to imponderable substances, such as light, electricity, and magnetism, in terms of the same *Grundatome* that made up ponderable matter, while referring them to the oscillations of individual atoms rather than to atomic systems and higher order combinations of molecules. But too little as yet was known about them. He could, however, suggest that Weber’s velocity and acceleration dependent *Grundgesetz* for electric masses would very probably need to be extended to the atoms of normal matter. That would explain such things as the expansion of bodies by heating, which would give their particles a greater velocity and perhaps therefore a weaker attractive force between them.⁵⁸

It is apparent that in this last chapter Fechner was reaching for a pragmatic effect, that having already found his atomistic world believable his audience would be open to a wide range of possible realities that might well fall within that general conception. If so, dynamism had been defeated by the rhetorical techniques of the *Atomenlehre*.

3. Conclusion

I have attempted to show three things: (1) how Maxwell and Weber structured their pictures of electromagnetic action as sophisticated narratives that integrated diverse aspects of the subject; (2) how the writings of Faraday and Fechner placed the particular stories of Maxwell and Weber in a wider story world, which enhanced their believability; (3) how evoking this story world depended on the kind of narrative techniques that Johnston finds in her *Story*

57 Fechner, *Atomenlehre*, 193.

58 Fechner, *Atomenlehre*, 207.

of *Myth*. My question now concerns the implications of this reading for comparison.

Thomas Kuhn once wrote that “Theories, as the historian knows them, cannot be decomposed into constituent elements for purposes of direct comparison either with nature or with each other.” He was writing here about the holistic character of what he famously called paradigms in science and the similarly holistic character of historical narratives about science. Both theories and narratives were like “pictures” or “patterns.” The historian’s job was to construct “a plausible narrative involving recognizable motives and behaviors” that fit into a coherent pattern.⁵⁹ Paul Roth has discussed this perspective with reference to how Kuhn drew on the philosopher of history Louis Mink and his concept of “synoptic judgement” in historical narratives. “The distinctive characteristic of historical understanding,” Mink argued, “consists of comprehending a complex event by ‘seeing things together’ in a total and synoptic judgement which cannot be replaced by any analytic technique.”⁶⁰

Maxwell seems to have intended something similar when he wrote that the aim of his physical analogy of lines of force as flow lines had been “to present the mathematical ideas in an embodied form ... and not as mere symbols, which neither convey the same ideas, nor adapt themselves to the phenomena to be explained.” Not that the symbolic representation would be wrong but that it would be too thin; it would not evoke the full depth of mental images and bodily sensations of the embodied analogy, marked by its vividness and fertility. Fechner made a related point in his presentation of atomism in terms of sensory appearances: “through their conception we better orient ourselves in the visible and palpable.”⁶¹ Both Maxwell and Fechner, in their very different ways, sought to arouse the creative imagination through their use of narrative techniques, with their power to make fictional entities into realistic possibilities.

59 Kuhn, Thomas S., “The Relations between the History and the Philosophy of Science.” In *The Essential Tension: Selected Studies in Scientific Tradition and Change*, Chicago: University of Chicago Press, 1977, 3-20, on p. 19, 17. Rather: 17, 19 ?

60 Roth, Paul A., “The Silence of the Norms: The Missing Historiography of The Structure of Scientific Revolutions,” *Studies in History and Philosophy of Science* 44, 2013: 545-552, on p. 550-551. Mink, Louis, “The Autonomy of Historical Understanding,” *History and Theory* 5, 1966: 24-47, reprint in Mink, *Historical Understanding*, edited by B. Fay, I. O. Golob, and R. T. Vann, Ithaca and London: Cornell University Press, 1987, 61-88, on p. 82.

61 Fechner, *Atomenlehre*, 105.

It has been notoriously difficult for historians and philosophers of science to give a clear articulation of what exactly the something extra is that goes beyond the component parts of holistic entities. The long-standing tradition of treating narrative and natural science as dichotomous has not helped, most famously in Carl Hempel's argument that only the natural sciences in their lawlike, deductive form could provide explanations.⁶² But the natural sciences themselves, in their now so pervasive studies of nonlinear dynamical systems, have found it necessary to employ holistic concepts of complexity, emergence, entanglement, order out of chaos, and embodiment that belie any easy distinction between narrative and natural science. They have also helped to stimulate new forms of historical analysis.⁶³ A closely related result among historians of science has been a growing emphasis on the functions of narrative within the sciences themselves. I have argued elsewhere, for example, that the widespread use of model-based simulations to understand complex processes often takes the history-like form of following out the possible developmental narratives generated by the (fictional) model. These explorations sometimes include a key role for representation of the simulations as movies, or visual narratives.⁶⁴ Such visualizations take to a literal level the idea of a historical narrative as being like a picture or pattern.

An even more general approach to the role of narrative knowing in complex domains, particularly in the social sciences, has been pursued by Mary Morgan, who (like Kuhn, and citing Mink) emphasizes the coherence-making power of narratives, their capacity to order and to fit together in a coherent pattern a variety of disparate elements that otherwise would not seem to belong together. This integrating capacity is very much in evidence in the narratives of electromagnetism that I have described. As Faraday put it to Ampère, lacking the capacity for abstract synthesis, "I am obliged to feel my way by facts closely placed together," by their "connexity," as one interpreter puts

62 Hempel, Carl G., "The Function of General Laws in History." [1942] In *Aspects of Scientific Explanation, and Other essays in the Philosophy of Science*, edited by C. G. Hempel, London: Macmillan, 1965, 232-243.

63 Stark, Laura, "Emergence," in *Focus section on Explanation*, *Isis*, 110, 2019: 332-336, discusses the import of this movement, with key references.

64 Wise, M. Norton, "On the Narrative Form of Simulations," *Studies in History and Philosophy of Science* 62, 2017: 74-85 (special issue on narrative science, edited by M. S. Morgan and M. N. Wise).

it.⁶⁵ Morgan uses a visual analogy from a painting by Peter Breugel, which depicts numerous small groups of children engaged in seemingly unrelated activities. Properly ordered, however, they fit together under the higher-order concept and title of “Children’s Games.” Interpreting more contextually, the whole ensemble represents a moral story of how in the eyes of God, people are like children. Morgan captures the action of ordering, relating, and knitting together in the term “colligation.”⁶⁶

Interestingly, it is the same word that Jouni-Matti Kuukkanen uses to capture the “essence” of narrativism in historiography: “narratives ... are colligatory additions to our understanding of the past.” He has developed this view at length in his *Postnarrativist Philosophy of Historiography*, where colligatory concepts provide the centerpiece of his argument.⁶⁷ Johnston’s conceptual metaphors serve a similar purpose.

All of these examples have a common theme, which I fully endorse. Many works of both history and science—especially when dealing with complexity—can be fruitfully analyzed in terms of narrative. The narrative reading suggests that understanding accounts of particular phenomena requires that they be treated holistically, attending to the way in which they incorporate

65 Cited by Darrigol, *Electrodynamics from Ampère to Einstein*, 21, using the term “connectivity.” Faraday to Ampère, 3 September 1822, in James, Frank, editor, *The Correspondence of Michael Faraday*, vol. 1: 1811-1831, London: The Institution of Engineering and Technology, 1991.

66 Morgan, Mary S. “Narrative Ordering and Explanation.” *Studies in History and Philosophy of Science* 62, 2017: 86-97, on p. 88-89 (special issue on narrative science, edited by M. S. Morgan and M. N. Wise). Morgan actually prefers Mink’s later discussion of “configuring” to “synoptic judgement,” because it emphasizes the active process of analysis that leads to “colligation” as a result and to another important mode of ordering by “juxtaposition,” which highlights the “puzzles” within a narrative whose resolution yields deeper understanding (pp. 90-93).

67 Kuukkanen, Jouni-Matti, “The Missing Narrativist Turn in the Historiography of Science,” *History and Theory* 51, 2012, 340-363, on p. 357. Kuukkanen, Jouni-Matti, *Postnarrativist Philosophy of Historiography*, Basingstoke, UK: Palgrave Macmillan, 2015, 97-130. While giving pride of place to colligation, Kuukkanen rejects two other tenets of narrativism in historiography, holism (especially for texts, but perhaps not for “holistic” colligatory concepts, p. 112) and representationalism (on the analogy with visual art and representations as pictures), both of which are characteristic of my own treatments of narrative in the physical sciences. But I suspect that his rejection of these terms results from overly strict definitions, which would not apply to the highly visual and holistic cases of simulation that I have analyzed. The issue deserves much more discussion than I can offer here.

their diverse strands into a discursively elaborated conception of a portion of the world that coheres together. It is the construction of this coherence that has led me to treat Maxwell's and Weber's essays in terms of the narrative unfolding of images of electromagnetic action, depictions designed to make realistic fictions plausible or believable.

The two approaches of Maxwell and Weber are so radically different, however, that they appear to have belonged to different conceptual worlds, with very little overlap between them. This has motivated my consideration of how their believability depended in part on their being located in different story worlds—represented by Faraday and Fechner—that extended well beyond their particular conceptual constructions and that made them seem familiar. That suggestion gains weight from the analogy with the believability of Greek myths. Johnston has argued that a major problem in the treatment of myths in classical scholarship has been their abstraction from the actual cultural and social life of the Greeks, which has entailed removal of individual myths from the story world and the narrative practices in which they were embedded. This sort of abstraction has made it difficult to understand why (or even that) the myths were believable. Her argument is that gods and heroes were believable to the Greeks because they were taken as part of the real world, either at present or in the human past, and thus seemed part of the normal world of human action. Narrative techniques and practices performed this familiarizing role by blurring the lines between known realities and fictional possibilities. Something similar, I am proposing, operated with respect to both Maxwell's and Weber's accounts of electromagnetism.

I have so far left open the question of how two narratives that seem to occupy different worlds can be compared. That question might seem to raise the fraught issues of Kuhnian incommensurability of paradigms, whereby Maxwell and Weber simply could not understand each other and comparison was impossible. Like most other historians and philosophers of science, I do not find this view tenable in any strict sense. But appreciation for, and a willingness to entertain alternative possibilities or competing views, is a different matter. Here is where treating scientific texts as holistic narratives occupying different story worlds is worthwhile. Without in any way compromising an appeal to empirical adequacy, mathematical unity, and comprehensiveness, it immediately raises the question of how effectively narrated the two representations are, and that is a question not only of their own narrative virtues but also of their being situated within a broader story world capable of enhancing their credibility. The analogy with Greek myths has suggested several aspects

of effective narration that should be important: conceptual metaphor, serial narration, multipliers, and story world. Evaluation of their effectiveness will of course be a subjective matter and will involve judgements of such things as heuristic power, aesthetic appeal, emotional grip, and philosophical preference. This does not make everything arbitrary or equal but it does imply that comparison of competing accounts will require the kind of holistic judgement that we expect of narratives and that is well captured by colligation.⁶⁸

That returns me to my starting point and to Maxwell's question about why we should entertain alternative possible realities. He did all he could to provide motivation for "imagining" lines of force and an electro-tonic state occupying every point of space when Weber had already given a perfectly comprehensible depiction of time dependent forces acting immediately at a distance. He did not attempt to argue on purely rational grounds that his view was preferable, but only that it would be preferable to many minds who found the conceptual and sensory immediacy of physical analogies more satisfying than abstract mathematical formulas. And he was fully aware that others would differ about which was more satisfying. For the moment, therefore, until further empirical or theoretical developments were available to support one or the other perspective, he could only remark that "it is a good thing to have two ways of looking at a subject, and to admit that there *are* two ways of looking at it." Perhaps that is a key lesson of the narrative reading of scientific works. It draws out their power to produce vivid synthetic depictions that capture the creative imagination while also making it apparent that comparisons will involve the same kinds of valuations that are familiar for literary works and works of art.

3.1 A Comment on Temporality

I approach the question of whether the term narrative necessarily implies a *temporal* sequence of connected events from a historian's perspective. Many historical works are of course devoted to temporal dynamics and philosophers of history coming from a phenomenological perspective, such as Paul Ricoeur in *Time and Narrative*, take the lived experience of time to be fundamental to

68 Kuukkanen, *Postnarrativist Philosophy of Historiography*, 123-128, does not include such subjective evaluations of narratives but limits himself to a set of epistemic values for their colligatory concepts: exemplification, coherence, comprehensiveness, scope, and originality.

human understanding, and thus to history. (As noted above, I have adapted this view for the way in which simulations provide understanding of physical processes.) But much historical writing is not focused on temporality. An example is Carl Schorske's *Fin de Siecle Vienna*, which is concerned rather with providing a vivid depiction of a memorable cultural constellation than with analyzing its rise and fall. More generally, historians like other social scientists are often more concerned with understanding and depicting the structure of relations characteristic of a particular culture or situation than with tracing or accounting for the temporal course of its development, though both are often in play. This preference can extend even to an antipathy for the focus on time. Louis Mink is perhaps the most famous representative, arguing that we can understand a narrative, even a temporal narrative, only retrospectively, for it is only in retrospect that we can obtain the synoptic judgement mentioned above. "In the understanding of a narrative the thought of temporal succession vanishes" so that "time is not of the essence of narratives."⁶⁹

Surely this is too extreme, but it does suggest that the power of narratives in general can be better characterized by their ability to draw things together in a conceptual scheme, their capacity for colligation, as Morgan and Kuukkanen would have it, than by their temporality per se. While many narratives will depend on temporal ordering to attain their colligatory concepts, and even on the experience of following a process in time to gain understanding, many others will not, or they will use both temporal and non-temporal descriptions in a complementary fashion. For example, Morgan stresses the puzzle-raising functions of Clifford Geertz's classic account of Balinese cockfighting while Kuukkanen focuses on the argumentative character of Christopher Clark's depiction of events leading up to WWI in *the Sleepwalkers*.⁷⁰ From

69 Mink, Louis, "History and Fiction as Modes of Comprehension," *New Literary History* 1, 1970: 554-555, reprint in Mink, *Historical Understanding*, edited by B. Fay, I. O. Golob, and R. T. Vann, Ithaca and London: Cornell University Press, 1987, 56-57.

70 Morgan, "Narrative Ordering and Explanation," 92-93. Geertz, Clifford, "Deep Play: Notes on the Balinese Cockfight," *Daedalus* 101, 1972: 1-37. Clark, Christopher, *The Sleepwalkers: How Europe Went to War in 1914*, London: Penguin, 2012. Kuukkanen, *Postnarrativist Philosophy of Historiography*, 92-96. Kuukkanen nevertheless speaks of the temporal part of a historical text as the "narrative" part, or "narrativity," (also 73-75) but that appears to play no fundamental role in his important analysis of colligatory concepts.

this perspective, temporal ordering figures as a (critically important) subset of narrative ordering.⁷¹

71 I thank Mary Morgan for her valuable comments on this paper.