[Working paper.]

Ørsted and the Discovery of Electromagnetism

A Case Study in the History of Electricity

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Abstract:
In July of 1820, Hans Christian Ørsted announced that a wire carrying electricity could deflect a magnetic compass needle, a finding that is now considered the discovery of electromagnetism. Importantly, the technological requirements for Ørsted's discovery were met no later than 1802, and the discovery would have been straightforward for any natural philosopher who suspected that an electric current could produce magnetism. Yet, despite persistent speculation that electricity and magnetism had a deeper connection, electromagnetism was not discovered until eighteen years later. This case study analyzes why the discovery did not occur sooner and why it was Ørsted who uncovered it. I argue that the critical elements to Ørsted's discovery were his metaphysics of nature—acquired from his reading of Immanuel Kant and Friedrich Wilhelm Joseph von Schelling—and his use of that metaphysical picture to develop a theory of electrical conduction which later suggested to him that the current-carrying wire might produce a detectable magnetic effect. I then discuss why the discovery was not made elsewhere, focusing particularly on why natural philosophers believed that the open pile—where no electric current is present—was the most likely place to find electromagnetism. I also consider the decline in exploratory experimentation that occurred between the middle of the eighteenth century and the beginning of the nineteenth century, which likely prevented natural philosophers from discovering electromagnetism in the absence of a correct hypothesis about where to look.

Keywords: Ørsted, electromagnetism, history of electricity, Immanuel Kant, Friedrich Wilhelm Joseph von Schelling, exploratory experimentation

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This paper is currently being circulated for feedback among academics and independent researchers. Please contact kerry[at]leverageresearch.org if you have questions or comments about this case study.

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Introduction

In 1805, two French natural philosophers, Charles Bernard Desormes (1777–1862) and Jean Nicholas Pierre Hachette (1769–1834) conducted an ambitious experiment exploring the magnetic properties of electricity. Attempts to find a connection between electricity and magnetism were, if not mainstream, somewhat common throughout the history of studies in the respective fields. Ever since Gilbert's distinction between "Electricks" and "Magneticks" in his *De Magnete* of 1600, a great many natural philosophers had found the similarities between magnetic and electric phenomena sufficiently striking to look for some deeper connection between them.[1] After all, both phenomena involved attraction and repulsion at a distance, appeared to obey an inverse square law, and consisted of two distinct types that repelled their own but attracted their opposite. While past experiments had failed to demonstrate this connection, Alessandro Volta's (1745–1827) invention of the voltaic pile in 1800 provided a promising instrument for a new investigation into the topic.

For their experiment, Hachette and Desormes constructed a horizontal voltaic pile (see figure 1 below) consisting of "1480 thin plates of copper, tinned with zinc, of the diameter of a five-franc piece"[2] and placed in a dilute acid solution. The device was placed in a boat, which was then floated in a large vat of water. While the precise size and weight of the overall contraption is not given, it must have been massive, probably weighing in excess of 200 kg (440 lb), and constructing it would have been no easy feat.[3] Hachette and Desormes knew that a magnetized steel bar of similar weight placed on a boat would eventually rotate into alignment with the magnetic meridian. If they could show that a voltaic pile likewise rotated with the magnetic meridian, it would constitute the discovery of electromagnetism.

On the day of the experiment, one imagines Hachette and Desormes staring anxiously at their boat for hours and waiting patiently for any sign that it was turning. What they saw instead was nothing. As they later put it, the pile "did not take any determinate direction."[4] The experiment was a failure.

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[1] Gilbert, *On the Magnet*.

[2] Hachette, "On the Electro-magnetic Experiments of MM. Oersted and Ampère," 43. A five-franc piece was around 37 mm in diameter.

[3] Assuming the plates were made entirely of copper and were 1.5 mm thick, the 1,480 plates would have weighed 230 kg. Tinning the plates with zinc would have reduced the density, and the plates might have been thinner than 1.5 mm, but once one includes the weight of the boat and dilute acid solution, 200 kg is likely a conservative estimate of the total weight.

[4] Hachette, "On the Electro-magnetic Experiments," 43.

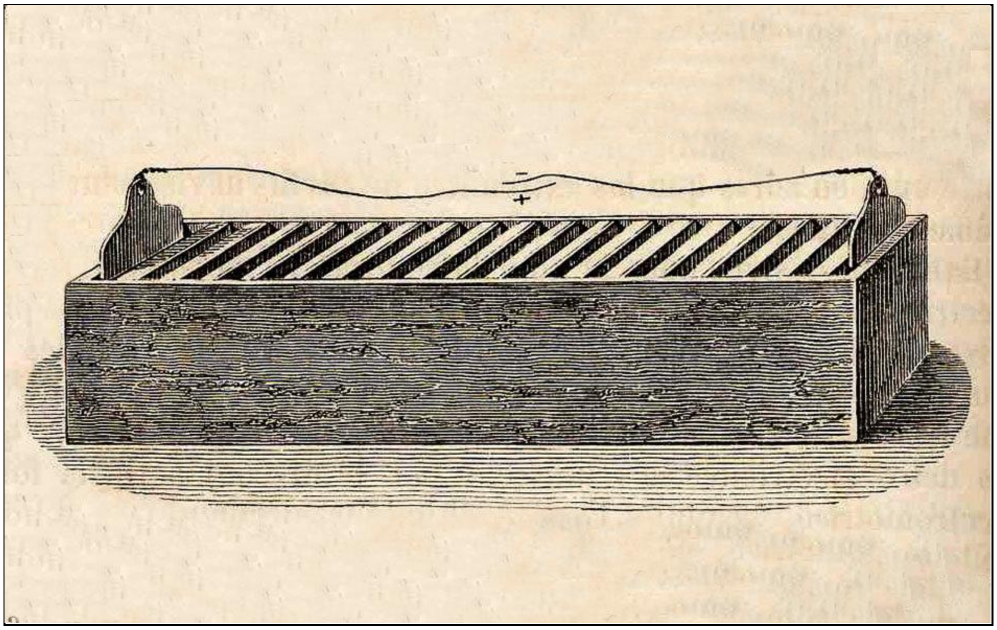

Figure 1. Image of a horizontal voltaic pile.[5]

The experiment that would ultimately succeed in discovering electromagnetism came fifteen years later and was much simpler. While he was preparing a lecture on electricity, galvanism, and magnetism, Hans Christian Ørsted (1777–1851) was struck by the fact that as electricity moves through a wire, it produces heat and, if the electrical current is strong enough, light. Maybe, he thought, increasing the electricity still further would produce additional forces, potentially including magnetism. When the time for the lecture came, he decided to try out this idea. He set up his voltaic pile with a wire running from one pole of the battery to the other over the top of a magnetic compass needle. To his surprise, the compass needle moved! A little over three months later, he reported his findings in a brief Latin pamphlet.[6] Electromagnetism had been discovered.

That a large and complex experiment failed where a simpler one succeeded is not, on its own, particularly noteworthy. Scientific experiments, even those ultimately on the right track, frequently fail. Hachette and Desormes's failed experiment would likewise be unremarkable except for one interesting detail: had they simply connected the two conducting wires attached to the pile, thereby changing it from the open to the closed position, their experiment probably would have succeeded and, accordingly, one of the most important discoveries in the history of science would have been made fifteen years earlier.[7]

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[5] "File:Trough battery.jpg," *Wikimedia Commons*, last modified February, 19 2021, https://commons.wikimedia.org/wiki/File:Trough_battery.jpg.
[6] For Ørsted's original pamphlet, see Ørsted, *Experimenta*. The pamphlet is reprinted in English as Ørsted, "Experiments," 273–76.
[7] Steinle, *Exploratory Experiments*, 51. Steinle, "Romantic Experiment?" 12n.

Curiously, Hachette and Desormes were not the only natural philosophers to come tantalizingly close to discovering electromagnetism prior to Ørsted. Ørsted's experiment was probably technologically feasible after the invention of the trough pile in 1800 (a few months after Volta's initial discovery) and was certainly technologically feasible by 1802; all one needed to do was bring a magnetized needle near the wire of a closed pile. Yet, despite an active search for an electromagnetic effect—including by Ørsted and his close friend Johann Wilhelm Ritter (1776–1810)—and despite multiple experiments which involved electrifying a magnetic compass needle with an *open* pile, the effect remained undiscovered until 1820.

This case study will investigate what led to this curious state of affairs, what this reveals about the changing nature of the scientific endeavor in the early nineteenth century, and how Ørsted was eventually able to make the discovery.

Section 1: Ørsted's discovery

1.1: What did Ørsted discover?

On July 21, 1820, Ørsted sent a four-page pamphlet entitled *Experimenta circa effectum conflictus electrici in acum magneticam* to a number of distinguished natural philosophers.[8] In the pamphlet, he describes how a voltaic pile can be used to temporarily deflect a magnetic compass while the pile is active. An annotated image from a reconstruction of this experiment is provided in figure 2, below.

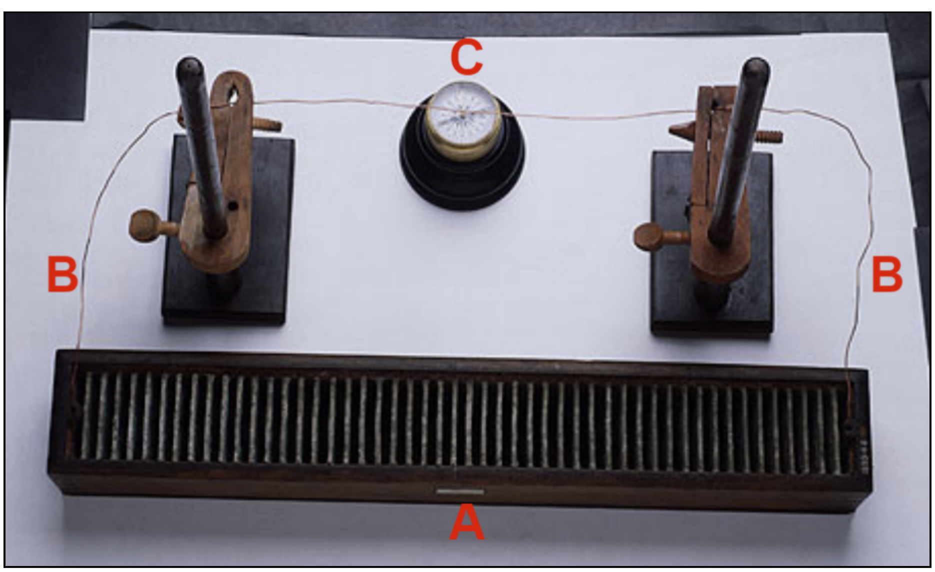

Figure 2. Image from a reconstruction of Ørsted's experiment.[9]

[8] Reprinted in English as Ørsted, "Experiments," 273–76.

[9] "Hans Christian Ørsted: What Does He Have in Common with Stephen Hawking?," *Datablog*, *The Guardian*, accessed June 07, 2021, https://www.theguardian.com/news/datablog/2009/aug/14/hans-christian-orsted-science

The experiment consists of a trough-style voltaic pile, *A*, connected to a wire, *B*, which is stretched over a magnetic needle, *C*. The pile Ørsted used was constructed with copper and zinc placed in a solution of equal parts dilute sulfuric and nitric acid, although some other metals and acid solutions also work. As was known since the invention of the voltaic pile in 1800, this trough then causes electricity to be conducted through the wire and over the compass. To produce the clearest effects, the wire should be placed such that it runs parallel to the natural orientation of the compass. In figure 2, for example, the optimal setup requires the compass's natural orientation to be horizontal relative to our point of view, just as the wire is situated horizontally. The wire can then be placed either directly over the top of the compass or below it. It can also be offset slightly to the east or west without substantially changing the overall effect.

When the wires are connected to the poles of a properly constructed trough, the magnetic needle is deflected from its natural orientation. The direction of the movement depends on the direction of the current. If, for example, the current is moving from left to right in figure 2, then the compass needle rotates to the left, and if the current is flowing from the right side of the image to the left side, the compass needle rotates to the right.[10]

Ørsted's initial pamphlet states a number of other interesting facts about the effect. First, he notes that the degree to which the compass needle rotates decreases as the wire is moved farther away.[11] Second, he takes care to rule out the possibility that the effect might be electrical or galvanic in nature, instead of magnetic, by noting that it can be transmitted through a wide variety of substances, including glass, non-magnetic metals, wood, and water, and that it is not noticeably diminished if these substances are interposed between the wire and compass while the needle is already deflected.[12]

Finally, Ørsted notes that the effect is "not confined to the conductor, but dispersed pretty widely in the circumjacent space"[13] and that it "performs circles."[14] (See figure 3, below, for a visualization of this effect.) Its rotational nature was quite unexpected. For other forces, like gravity, electrical attraction and repulsion, and even other cases of magnetic attraction and repulsion, the forces were instead *central,* meaning that they acted between the two bodies in a straight line. Thus the circular nature of this effect was something that no one, including Ørsted himself, predicted.

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[10] A simple way to remember this is the Right-Hand Rule, which states that the magnetic field lines produced by a current-carrying wire move in the same direction as the curled fingers of a person's right hand, with the thumb pointing in the direction of the current's flow.
[11] Ørsted, "Experiments," 274.
[12] Ørsted, "Experiments," 274–75.
[13] Ørsted, "Experiments," 276.
[14] Ørsted, "Experiments," 276.

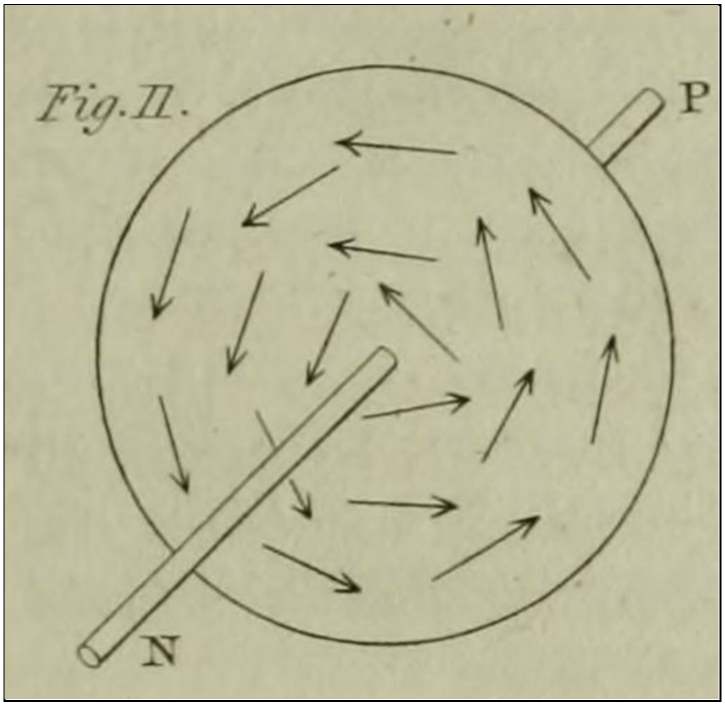

Figure 3. Visualization of the rotational nature of the magnetic effect.[15]

1.2: What led Ørsted to the discovery?

As the discovery of electromagnetism was quite a surprise to Ørsted's contemporaries, a natural question to ask is what led him to it. Ørsted provided his own narrative account of how the discovery was made in an article for the *Edinburgh Encyclopaedia* in 1830.[16] According to this account, he was scheduled to teach an advanced class on electricity, galvanism, and magnetism in Copenhagen during the winter of 1820. As he worked on a lecture concerning the similarities between electricity and magnetism, it occurred to him that just as increasing the quantity of electricity transmitted through a wire produces heat and light as it begins to glow, a greater quantity of electricity might produce some minute magnetic effect. When Ørsted gave this lecture in April of 1820, it appeared to him likely that magnetism might be found in the wire, and so he connected his voltaic pile to a wire and moved a compass near it. He saw that the magnetic needle appeared to be disturbed, although he notes that "the effect was very feeble, and must, before its law was discovered, seem very irregular, the experiment made no strong impression on the audience."[17] Ørsted did not investigate this effect until July of 1820, three months later.[18] As he investigated, he determined that the magnetic effect was increased with thicker wires and he

[15] Faraday, "Historical Sketch," 198.
[16] Ørsted, s.v. "Thermo-electricity," 18:573–89. The account is written in the third person, but the author is Ørsted.
[17] Ørsted, s.v. "Thermo-electricity," 18:575. Ørsted also explains why he didn't conduct the experiment prior to the lecture as follows: "The preparations for the experiment were made, but some accident having hindered him from trying it before the lecture, he intended to defer it to another opportunity."
[18] The reasons for this delay are not clear. In fact, Ørsted himself calls the delay "strange" and "difficult to conceive." Ørsted, s.v. "Thermo-electricity," 18:575.

worked out the circular nature of this effect. Those findings in hand, he sent out his pamphlet announcing the discovery.

Yet not everyone has found Ørsted's account to be a complete or sufficiently satisfactory explanation of the discovery. In the most general terms, historians and Ørsted's contemporaries have attempted to explain what led him to the discovery in three ways: it was an accident, it was caused by his interest in German philosophy of science, or he happened to look in the correct place. This section includes a brief discussion of each view as background before developing my own view in the subsequent sections of this case study.

The first view is that the discovery was an accident. The strongest versions of this view were advocated by some of Ørsted's contemporaries. For example, a professor Gilbert, an editor who published the German translation of Ørsted's pamphlet, claimed that "it was clear that the discovery was purely accidental: what Oersted had failed for years to find while searching for it, he stumbled on during a public lecture."[19] This view was also espoused by Christopher Hansteen, one of Ørsted's research assistants, in a letter written to Faraday in 1857 and published in *Life and Letters of Faraday* in 1870.[20] The brief account includes Hansteen's speculation that Ørsted initially attempted the experiment incorrectly, with the wire perpendicular to the needle, and was therefore surprised when placing the wire parallel to the needle caused the needle to turn.[21]

It is clear from Ørsted's own account of the discovery that it was an accident in the sense that he did not predict the rotational nature of the effect he discovered, nor was he certain when he ran his experiment that it would work. Nevertheless, it is equally clear that it was not accidental in a broader sense: Ørsted had been looking for the effect for many years and had specifically hypothesized that the current-carrying wire might be where he later discovered it. In fact, as we will see in section 3, Ørsted was involved in Ritter's work on electromagnetism in 1803 and had predicted that the current-carrying wire might produce forces beyond heat and light as early as 1806.

Another explanation for why it was Ørsted who made the discovery has attributed some critical aspect of the discovery to his interest in the German philosophical movements of the late eighteenth and early nineteenth centuries, particularly German *Naturphilosophie* and the work of

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[19] Agassi, "Oersted's Discovery," 69. See also Stauffer, "Persistent Errors," 308.
[20] Jones, *The Life and Letters of Faraday*, 2:395–96.
[21] Hansteen's account is written in narrative form as though he was present for the discovery. Historians have shown, however, that Hansteen was not in Copenhagen during April 1820 and so cannot have been an eyewitness (see Stauffer, "Persistent Errors," 309). Additionally, Hansteen claims that Ørsted was a poor experimenter and performed the experiment in front of an audience so that he could get their assistance. Yet there is, in fact, substantial evidence that Ørsted was a skilled experimenter (see Meyer, *The Scientific Life and Works of H.C. Ørsted*, clv–clvi, cxxxii, and cxxviii–cxxix). For additional discussions of Hansteen's account, see Stauffer, "Persistent Errors," 309; Agassi, "Oersted's Discovery," 69; and Altmann, *Icons and Symmetries*, 15–16.

Friedrich Wilhelm Joseph von Schelling (1775–1854).[22] Williams, for example, probably goes the furthest, claiming "It should be insisted upon that it was nature philosophy that was responsible for the discovery [of electromagnetism], since the orthodox physicists of the day simply did not believe in the possibility of the conversion of forces in which Oersted had such faith."[23] Others have found the exaltation of *Naturphilosophie* a substantially more difficult pill to swallow, given Schelling's somewhat poor reputation in modern times and his tendency to base his ideas on empirical claims that are indefensible.[24] Alternate proposals include the elimination of Schelling's influence altogether or the suggestion that *Naturphilosophie* either had the very general effect of causing Ørsted to look for fundamental unities in nature when others did not or "providing the scientist with some justification for making decisions which have neither experimental nor logical warrant."[25] An alternate suggestion is that the true influence on Ørsted is, in fact, Immanuel Kant (1724–1804), particularly the Kant of *Critique of Pure Reason* and *Metaphysical Foundations of Natural Science*.[26]

This topic will be discussed in further detail in section 3. In section 3.1, I will provide a brief account of Ørsted's background, including his links to Kant and Schelling during the early stages of his career. In section 3.2, I will characterize the distinctive features of Ørsted's approach to natural philosophy, which will render the influence of Kant and Schelling more specific. Finally, in section 3.3, I will describe the theoretical views that likely led to the discovery and attempt to pinpoint the specific philosophical influences that were required for Ørsted's discovery.

Finally, some of Ørsted's contemporaries offered a somewhat simpler explanation, namely that Ørsted was the one to make the discovery because he happened to be the one to look. Hachette (of the floating pile experiment), for example, said the following about Ørsted's discovery:

> For Twenty-three years the electric piles of Volta had been in use, and no philosopher had yet thought of bringing a magnetic needle near one of these piles in action. This inspiration was reserved to M. Ørsted; and it must be confessed, that chance had much less share in it than in many discoveries with which physical science has been enriched.[27]

Ampère states a similar sentiment in an 1820 letter to a friend:

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[22] On the influence of *Naturphilosophie*, see Caneva, "Physics and Naturphilosophie," 35–106; Gower, "Speculation in Physics," 301–56; and Stauffer, "Speculation and Experiment," 33–50.
[23] Williams, *The Origins of Field Theory*, 59–60.
[24] See Bowie, "Friedrich Wilhelm Joseph von Schelling," for a brief introduction to Schelling.
[25] Gower, "Speculation in Physics," 353.
[26] On the influence of Kant on Ørsted, see Christensen, "The Ørsted-Ritter Partnership," 153–85; Nielsen and Andersen, "The Influence of Kant's Philosophy on the Young H. C. Ørsted," 97–114; and Shanahan, "Kant, Naturphilosophie, and Oersted's Discovery of Electromagnetism," 287–305.
[27] Hachette, "On the Electro-magnetic Experiments," 41. It is not clear why Hachette claims that voltaic piles had been in use for twenty-three years before the discovery of electromagnetism given that the pile was invented by Volta in 1800 and Ørsted's discovery occurred in 1820.

> You certainly have a right to ask why it is inconceivable that no one tried the action of the voltaic pile on a magnet for twenty years. However, I believe that the cause of this is easily discovered: it simply existed in Coulomb's hypothesis on the nature of magnetic action; everyone believed this hypothesis as though it were a fact; it simply discarded every possibility of the action between electricity and so-called magnetic wires.[28]

In the remainder of this case study, I will make the case that Hachette and Ampère are basically correct, although part of the reason Ørsted looked was his study of Kant and Schelling. In section 1.3, I will aim to show that the technical requirements for Ørsted's discovery were met by 1802 at the latest and that the discovery of electromagnetism would not have been difficult provided one elected to look in the current-carrying wire for the effect. In section 4, I will explain why no one before Ørsted thought to look, focusing in particular on why the available evidence would have suggested looking in the open pile—as Hachette and Desormes did—instead of in the closed pile, where the effect could be discovered.

I begin by outlining the technical and conceptual prerequisites for the discovery.

1.3: Technical requirements for Ørsted's discovery

This section discusses the requirements for producing a detectable magnetic effect from a current-carrying wire with the technology available during the early nineteenth century. There are essentially three requirements: (1) a source of electrical current, (2) an instrument to detect magnetism, and (3) correct orientation of the magnetic detector relative to the conductor. By analyzing each requirement in turn, I will demonstrate that the technical requirements were met no later than 1802 and that there were no significant impediments to making the discovery provided one looked in the current-carrying wire for a magnetic effect.

1.3.1: Requirement 1: A source of electrical current

The strength of a magnetic field produced by a current-carrying wire is proportional to the current, measured in amps (A), and inversely proportional to the distance from the wire. A current that is sufficiently weak will not produce a noticeable magnetic effect even if the wire is positioned correctly. Thus, the goal of this section is to determine the current strength that would have been required to produce a noticeable magnetic effect and then to determine when the available instruments would have been capable of producing such a current.

If we assume a straight and very long wire, we can estimate the magnetic field surrounding the wire using the equation $B = \mu_0 I / 2\pi d$, where:

- B is the strength of the magnetic field produced at a distance d;

[28] Ampère, *Correspondance du grand Ampère*, 2:566. Translation from Williams, *The Origins of Field Theory*, 60.

- μ_0 is the permeability of free space, which is a constant corresponding to $4\pi \cdot 10^{-7}$;
- *I* is the current; and
- *d* is the distance from the wire.[29]

Using this equation, we can work out the combinations of amperage and distance from the compass needle required to produce a magnetic field (measured in microteslas, μT) of a particular strength. The precise strength required to be detectable by an instrument depends on the sensitivity of the instrument in question. Since this is difficult to determine precisely, we can instead define an upper and lower bound that instruments should be able to detect and then determine whether the available amperage would have exceeded either bound. We can use a compass as a standard and readily available instrument for detecting magnetic fields (although, as we will see, more sensitive instruments were available).

Any functional compass should respond to a field equivalent to the Earth's magnetic field, which is approximately 30 μT at the equator.[30] Most compasses are capable of responding to weaker fields, however. In my own testing with an inexpensive modern compass, I was able to produce clear needle deflection with a magnetic field of 16 μT. In any case, a magnetic field of 30 μT certainly should be detectable.

In order to work out the required amperage, we next need to know the distance between our instrument and the wire. We can assume that a capable experimenter would want to get the wire close to the instrument without touching it. I will assume that approximately 5 mm is the closest plausible distance for accomplishing this, whereas 50 mm is the farthest plausible distance that one might nevertheless consider close to the instrument.

Given these assumptions, the lower bound of the amperage required to produce 30 μT is 0.75 A, whereas the upper bound is 7.5 A. By way of comparison, a standard household AA battery is designed to discharge at around 0.5 A.[31]

Next we want to determine when the available instruments became capable of emitting sufficient current to produce a detectable magnetic effect. Units for measuring the strength of an electric current were not developed until after Ørsted's discovery, but the available amperage can be worked out by finding descriptions of experimental results for which the current strength required to produce that effect is now known.

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[29] Czernia, "Magnetic Field of Straight Current-Carrying Wire."
[30] Davis, "Mathematical Modeling of Earth's Magnetic Field," 3.
[31] See Energizer, "Product Datasheet: Energizer E91," 1.

Importantly, we know that the required current strength was not available in Volta's original design for the voltaic pile (depicted in figure 4, below). In Ørsted's second report on electromagnetism, he indicates this fact with the following:

> A galvanic pile composed of 100 discs of two inches square each metal, and of paper moistened with salt water to serve as a fluid conductor, is likewise destitute of sensible effect upon the needle. On the other hand we obtain the effect by a single galvanic arc of zinc and copper having for a conductor a liquid possessed of great conducting power; for example, of one part sulphuric acid, as much of nitric acid, and 60 parts of water.[32]

Ørsted himself produced the effect with a trough-style design as pictured in figure 1. The earliest mention of a trough-style apparatus comes from William Cruickshank in the September 1800 issue of *Nicholson's Journal*.[33] Given Ørsted's comments that a very simple circuit using the trough-style design is capable of producing the electromagnetic effect, it is plausible that electromagnetism was discoverable by September 1800, although the precise current output of Cruickshank's device is unknown and Ørsted's apparatus may have differed from Cruickshank's original design in ways that amplified its ability to output current.

Figure 4. A vertical voltaic pile.[34]

[32] Ørsted, "New Electromagnetic Experiments," 375.
[33] Cruickshank, "Additional Remarks on Galvanic Electricity," 258–60.
[34] "File:VoltaBattery.JPG," *Wikimedia Commons*, last modified May 6, 2021, https://commons.wikimedia.org/wiki/File:VoltaBattery.JPG.

Fortunately, a set of experiments conducted in 1802 by William Haseldine Pepys (1775–1856) provide us with some experimental descriptions that allow for calculation of the current involved. Pepys's experiments involved a very strong voltaic pile consisting of sixty pairs of zinc and copper plates, each 6 ft^2 and placed in a large trough.[35] With this pile, Pepys "succeeded in melting iron wires ranging in diameter from one two-hundredth to one-tenth of an inch, the combustion developing an extremely bright light, while platinum wires, one thirty-second of an inch in diameter, turned to white heat and melted in globules at the point of contact."[36]

The amperage required to fuse metal wires of various diameters is known, so we can use this information to determine the current involved by using an equation developed by William Henry Preece (1834–1913) in the 1880s.[37] Preece's equation is $I = ad^{3/2}$, where I is the current, d is the diameter of the wire in milimeters, and a is a constant that is 24.6 for iron and 40.4 for platinum.[38] The amperages required to fuse the wires described in Pepys's experiments are summarized in Table 1.

Metal	**Diameter (inches)**	**Amperage required to melt the wire**
Iron	1/200	1.11
Iron	1/10	99.58
Platinum	1/32	28.57

Table 1. Amperage required to melt the metal wires used in Pepys's experiments.

Thus, a device capable of fusing iron wire with a diameter of 0.005 in. would be capable of producing more current than the lower-bound estimate of the current required (0.75 A), and a device capable of fusing 0.1 in. of iron wire would be capable of producing many times more current than the upper-bound estimate of the current required (7.5 A). In fact, a pile capable of fusing 0.1 in. of iron wire would produce a 30-μT magnetic field at around 0.66 m (over 2 ft) from the compass. Thus, sufficient current to discover electromagnetism might have been available as early as September 1800 and was certainly available by the time of Pepys's experiment of 1802.

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35 See Mottelay, *Bibliographical History*, 371.
36 Mottelay, *Bibliographical History*, 371.
37 For Precee's work, see Preece, "On the Heating Effects of Electric Currents," 464-71; Preece, "On the Heating Effects of Electric Currents No. II," 280–95; and Preece, "On the Heating Effects of Electric Currents No. III," 109-11.
38 For a more thorough discussion of this topic and of the limitations of Preece's work, see Babrauskas and Wichman, "Fusing of Wires by Electrical Current," 769–80.

1.3.2: Requirement 2: An instrument to detect magnetism

In order to detect the magnetic effect from the wire, some kind of instrument for detecting magnetism is necessary. As noted in the previous section, piles like the one used by Pepys would have been sufficiently strong that any functional compass would have succeeded. This section will show that much more sensitive instruments for detecting magnetism were available such that it would have been possible to detect relatively weak magnetic fields in the current-carrying wire.

Ørsted himself specifies only that he used a magnetic needle to detect the magnetic field, but he almost certainly had the magnetic needle rest on a very sharp point so that it could spin freely in response to the magnetic effect.[39] The problem with this approach is that the friction at the contact between the needle and the point it rests on reduces the sensitivity of the instrument. One way to increase the sensitivity of the magnetic needle is to instead suspend it from a string since this avoids the problem of friction between the needle and the point. This raises a new problem, however, namely that strings provide a torque that resists rotation and, in some cases, as the string twists, it can cause the needle to deviate from the magnetic meridian.[40]

A few solutions to this problem were developed. One proposal by Cavallo used a chain of horse hair consisting of five or six links because the links "on account of the smoothness and lightness of the hair, move freely in each other, and allow the needle more than a whole revolution round its centre, with so small a degree of friction as may be considered next to nothing."[41] In 1792, Bennet proposed an even more sensitive instrument that used a spider's thread to suspend the needle (see figure 5, below).[42] Because Bennet provides some experimental descriptions that allow for an estimate of this device's sensitivity, it is worth describing in some detail.

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[39] See Ørsted, "Experiments," 273–76, and Ørsted, "New Electromagnetic Experiments," 375–77.
[40] Bennet, "A New Suspension of the Magnetic Needle," 81.
[41] Cavallo, "A Treatise on Magnetism," 277–78.
[42] Bennet, "A New Suspension of the Magnetic Needle," 88–91.

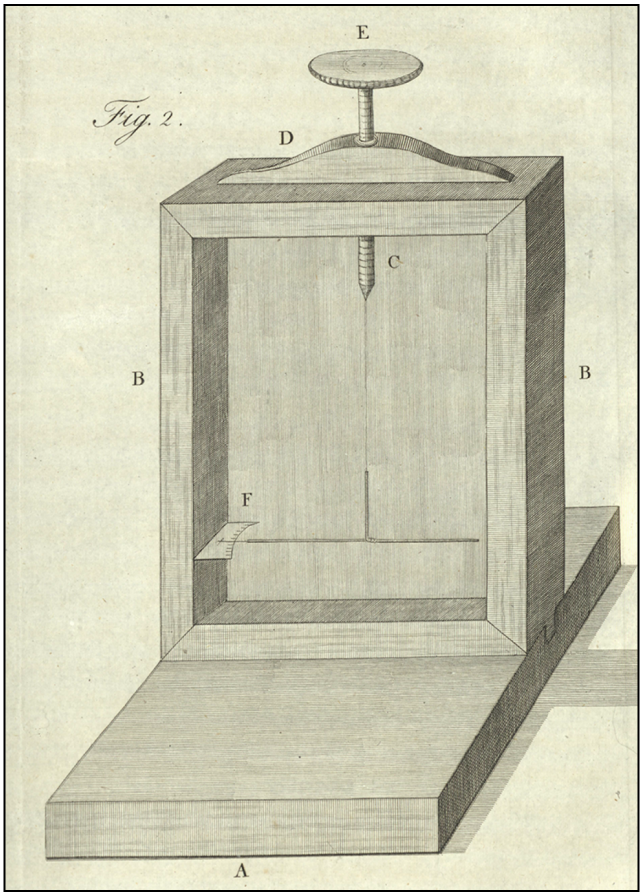

Figure 5. Bennet's device for detecting weak magnetic attraction.[43]

Bennet's device is made of a wood base, *A*, and a wood frame, *BB*, with a pane of glass on one side. Inside the device, at *F*, ten degrees of a circle are marked on a bit of ivory that is attached to the frame. Pointing to *F* is a needle that is "made of the smallest steel harpsichord wire."[44] The needle is 3 in. long and is suspended from a screw, at *C*, by a spider's thread, which attaches to a small gold wire that is twisted around the middle of the needle. The entire device is sealed by means of the top piece at *D* and the knob of the screw at *E* to prevent air currents from disturbing the instrument.[45]

Bennet describes using this device to conduct the following experiment:

> The first use I made of my needle, suspended as above, was to try the polarity of several iron utensils; and, as might be expected, they attracted or repelled the north end of the needle, according to their position with respect to the magnetic atmosphere of the earth.

[43] From Bennet, "A New Suspension of the Magnetic Needle," 98.
[44] Bennet, "A New Suspension of the Magnetic Needle," 89.
[45] For more detail about the device, see Bennet, "A New Suspension of the Magnetic Needle," 89.

> A bar of soft iron, half an inch square and nine inches long, moved the needle very sensibly at the distance of about three feet.[46]

With the aid of a few assumptions, Bennet's description allows us to work out the sensitivity of his device. Let us assume that a very sensible movement of the needle corresponds to a movement of 1 mm, that the strength of the Earth's magnetic field in London is 48 μT, that the external field applied by Bennet to the needle is uniform and perfectly aligns with the needle, and that the wire pivots at the center. See figure 6 for a diagram of Bennet's experiment in accordance with these assumptions.

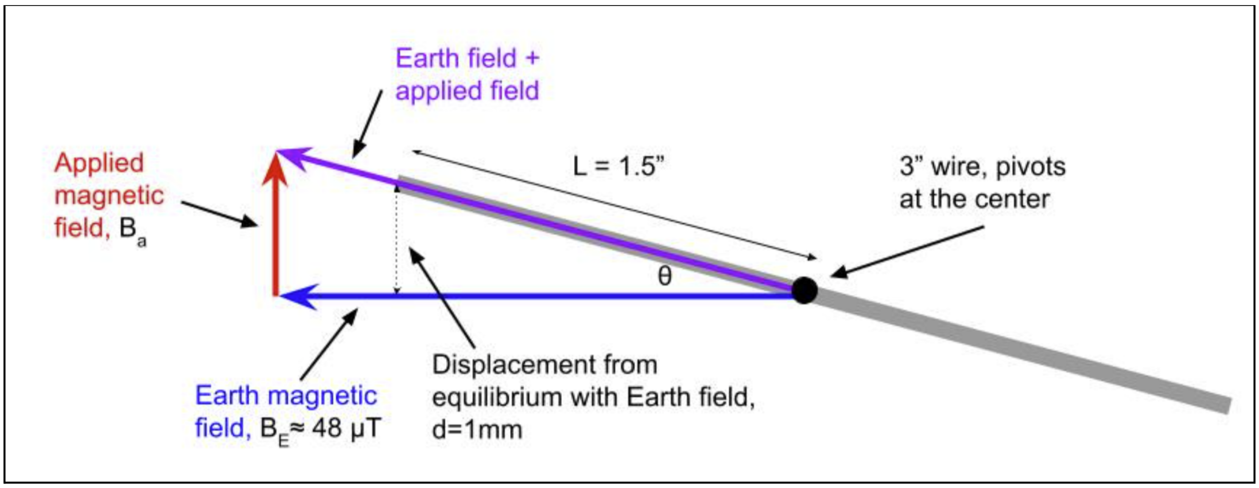

Figure 6. Diagram of Bennet's experiment.[47]

For small angles, sin θ ≈ tan θ, so we can work out the strength of the field on the wire through the equivalence $d/L \approx B_a/B_E$, which reduces to $B_a \approx B_E(d/L)$. Substituting the relevant values, we get that $B_a \approx 48$ μT (1 mm/1.5 in.), which is approximately 1.3 μT.[48]

This estimate suggests that Bennet's device was capable of detecting magnetic effects at least an order of magnitude weaker than Earth's magnetic field. Of course, Bennet's instrument as designed would hardly be ideal for discovering electromagnetism because of the difficulty of positioning a current-carrying wire close enough and in the correct orientation relative to the needle to produce a detectable effect. Yet, Bennet's device illustrates that it would have been technologically feasible to detect relatively weak magnetic effects.

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[46] Bennet, "A New Suspension of the Magnetic Needle," 91.
[47] Diagram provided by Richard Korzekwa via personal correspondence.
[48] Thank you to Richard Korzekwa for this explanation.

1.3.3: Requirement 3: Orientation

Finally, the geometry of the magnetic effect is such that one must position the instrument and the current-carrying wire correctly relative to one another in order to render the magnetic effect apparent. Recall the reconstruction of Ørsted's experiment in figure 2. If the magnetic needle at *C* was instead placed perpendicular to the wire, such that north faced away from the trough at *A* and south faced toward it, then the wire's magnetic influence would tend to pull the needle up or down instead of causing it to rotate. If one used a compass as an instrument, this would make the magnetic influence difficult to detect.

One potential impediment to the discovery is that those who investigated the current-carrying wire for magnetism might have predicted a geometry for the magnetic effect that would have prevented them from detecting it. Recall, for example, Hansteen's speculation in section 1.2 that Ørsted initially tried the electromagnetism experiment in the wrong orientation and thus was surprised by the effect. There are indeed a number of plausible guesses one might have had about how the pile's magnetism worked that would yield a suboptimal placement of the needle relative to the wire. However, as we will see, while incorrect placement of the needle relative to the wire is an impediment to the discovery, it is not a very significant one. Thus, incorrect orientation is unlikely to explain why the discovery of electromagnetism occurred eighteen years after it was technologically feasible.

One example of a plausible but incorrect orientation comes from Roberto de Andrade Martins. He notes that "the most natural analogy would lead to the hypothesis that the connecting wire became a magnet, with one pole at one of its ends, and the other pole at the other end."[49] On this analogy, one might imagine the magnetic force to be parallel to the wire, with one pole providing a force in one direction and the other pole providing a force in the opposite direction. In order to detect this magnetic force, one would want to position the magnetic needle perpendicular and horizontal to the wire, with the expectation that the north pole of the needle would spin to face the south pole of the pile and vice versa. This positioning would not create a discernible rotation of the magnetic needle. Martins provides a useful illustration of this setup in figure 7, below.

[49] Martins, "Resistance to the Discovery of Electromagnetism," 255.

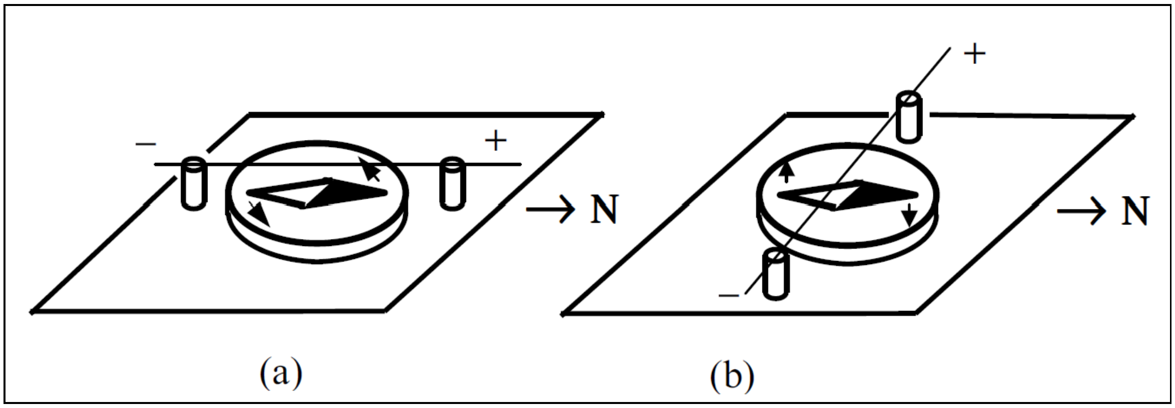

Figure 7. Illustration of (a) Ørsted's eventual, successful setup and (b) the setup suggested by Martins.[50]

A different natural expectation is that the wire itself might generate some magnetic force, attracting one pole toward the wire and one pole away from the wire. In this case, one would want to position the needle parallel and horizontal to the wire, with the expectation that one pole would spin to face the wire. Again, no rotation of the magnetic needle would be easily detected. An illustration of this setup is provided in figure 8, below.

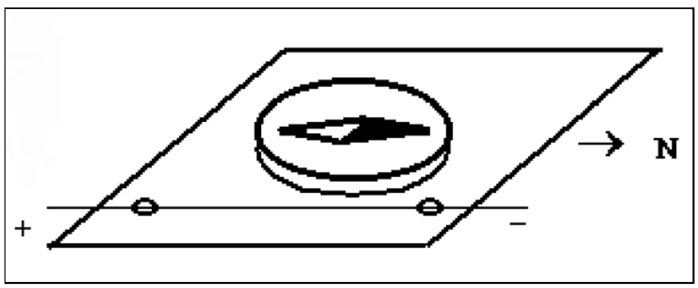

Figure 8. Illustration of the needle placed parallel and horizontal with the wire.[51]

The odd geography of the magnetic effect certainly would have impeded the discovery. Yet, this impediment would not have been substantial. It should be noted that testing the incorrect orientation does, in fact, produce a noticeable effect. In most of the incorrect orientations, a force on the needle acts upward or downward instead of left to right. Since instruments for detecting magnetism are often designed to turn left to right, this upward/downward effect is more subtle, yet it is nevertheless detectable. For example, Ørsted describes a setup wherein the wire is parallel and horizontal to the needle as in figure 8 above, and he describes the resulting rise and fall of the needle's poles:

> When the uniting wire is situated in the same horizontal plane in which the needle moves by means of the counterpoise, and parallel to it, no declination is produced either to the east or west; but an *inclination* takes place, so that the pole, next which the negative

[50] Martins, "Resistance to the Discovery of Electromagnetism," 255.
[51] Martins, "Resistance to the Discovery of Electromagnetism," 257.

> electricity enters the wire, is *depressed* when the wire is situated to the *west* side, and *elevated* when situated on the *east* side.[52]

Ørsted also tries the perpendicular and above setup shown in figure 7(b) and provides the following description:

> If the uniting wire be placed perpendicularly to the plane of the magnetic meridian, whether above or below it, the needle remains at rest, unless it be very near the pole; in that case the pole is *elevated* when the entrance is from the *west* side of the wire, and *depressed*, when from the *east* side.[53]

This description suggests that if the current-carrying wire is perpendicular, above or below the needle and placed over the needle's center, no effect is visible. Yet, subsequent research after Ørsted's initial announcement showed that even this limitation is smaller than it may initially seem. Faraday relays the following experiment from a certain Von Buch in January of 1821:

> M. Von Buch points out that this state of rest does not continue in two of the four positions of the wire. When the connecting wire is beneath the centre of the needle, and the positive current is from east to west, the needle remains unmoved. When the current is from west to east, it performs half a revolution. On the contrary, the connecting wire being above the current from east to west, makes the needle turn half way round; while that from west to east leaves the needle unmoved.[54]

Faraday and Von Buch note that this effect requires a stronger pile than the one Ørsted used, yet provided one has the relevant pile, it appears that placing the needle perpendicular, above and over the center of the needle would give a 50 percent chance of nevertheless producing a noticeable effect, depending on the direction of the current through the wire. Thus, it seems that if one has a strong pile and places the wire close to the needle, the only orientations that would fail to produce any noticeable effect are (1) placing the wire above, perpendicular to, and over the center of the needle with the positive current running from west to east and (2) placing the wire below, perpendicular to, and over the center of the needle with the positive current running from east to west.

Additionally, even if one tried to produce these two incorrect setups, imperfections in the setup can produce detectable magnetic effects. A wire that is not quite perpendicular to the needle or is not quite over the center of the needle can produce detectable magnetic effects if the current is strong and the wire is close to the needle. Since the available conductors would have been rigid wires that needed to be bent into position, it is quite likely that experimenters who attempted to

[52] Ørsted, "Experiments," 275. Emphasis in original.
[53] Ørsted, "Experiments," 275. Emphasis in original.
[54] Faraday, "Historical Sketch," 285.

place the wire incorrectly for detecting magnetism would have failed to get the setup exactly right and thus could have produced a detectable magnetic effect.

1.4: Alternate paths to the discovery of electromagnetism

In this section, I aim to show that in addition to the pathway to discovering electromagnetism that Ørsted took—namely, detecting magnetism in the current-carrying wire—several other methods for detecting electromagnetism were available prior to 1820, and some of these methods may have been available prior to the invention of the voltaic pile in 1800.

One option for discovering electromagnetism before 1820 would have involved the fact that a pile in action generates a magnetic effect from the pile itself, and this magnetic effect could have been detected. One example is the floating pile experiment by Hachette and Desormes, discussed in the introduction to this case study. As mentioned, their pile probably would have turned toward the magnetic meridian were the wires of the pile connected (closed) instead of left disconnected (open). A different experiment that could have discovered the same effect is to simply place a magnetized needle near the pole of the closed pile itself. Indeed, this experiment was performed by Ampère in September 1820, only two months after Ørsted's initial report on electromagnetism. Ampère describes the experiment as follows:

> The first use to which I put this device was to check that the current which exists in the voltaic battery, from the negative extremity to the positive extremity, had the same influence on the magnetized needle as the current in a conductor which flows, on the contrary, from the positive extremity to the negative one.
>
> It is desirable to have for this two magnetized needles, one placed on the battery and the other above or below the conductor; it is seen that the austral pole of each needle is carried to the left of the current near to which it is placed. Thus, when the second [needle] is above the conductor, it is carried to the side opposite to that towards which the needle on the battery tends, since the currents have opposite directions in these two portions of the circuit. The two needles are, on the contrary, carried to the same side, remaining roughly parallel to each other, when one is above the battery and the other below the conductor. As soon as the circuit is interrupted, they immediately revert, in both cases, to their ordinary orientation.[55]

Thus Ampère describes finding a magnetic effect by placing the needle above the pile itself while it is closed. This experiment could have been performed any time after voltaic piles were

[55] From Ampère, "Mémoire présenté à l'Académie royale des Sciences," 67–68. Translation found in Assis and Chiab, *Ampère's Electrodynamics*, 36.

capable of producing sufficient current, which means it certainly could have been performed any time after 1802.

A different option for detecting electromagnetism is to show that electricity can magnetize an object. After Ørsted's discovery, two natural philosophers independently arrived at methods for doing this by wrapping a conducting wire around a steel needle and then discharging some electricity through the wire. These experiments are both relayed by Faraday in his "Historical Sketch of Electro-magnetism":

> M. le Chev. Yelin appears to have discovered by accident that by placing a steel needle in a glass tube, surrounded by a spiral of wire, along which either simple electrical sparks or discharges from a battery were passed, the needle becomes magnetic.[56]

Faraday also reports that:

> M. Von Buch, also, appears to have ascertained the effect of common electricity in producing magnetism without a previous knowledge of what had been done by others. . . . He found that . . . fixing a helix between the prime conductor of a machine and another insulated conductor, placing a steel needle in it, and then drawing sparks from the latter conductor, the needle became magnetic.[57]

The Von Buch experiment is particularly interesting because it involves "common electricity," which here means electricity drawn from a prime conductor or produced by the Leyden jar. Given that globe electrostatic generators gained widespread adoption in the 1740s, Von Buch's experiment suggests that the discovery of electromagnetism might have been possible much earlier than previously suggested, provided one guesses that the wire must be wound around the needle.[58]

The preceding sections have aimed to show not only that the technical requirements for the discovery of electromagnetism—sufficient current, an instrument for detecting magnetism, and proper orientation of the current-carrying wire and needle—were met by 1802 at the latest, but that the available instruments substantially exceeded the basic requirements. Additionally, the preceding sections have shown that incorrect guesses as to the geometry of the magnetic effect would not have been a complete impediment to the discovery, although they would have made the effect more difficult to detect. Finally, even if natural philosophers did not think the current-carrying wire itself could produce a detectable magnetic effect, there were alternative

[56] Faraday, "Historical Sketch," 284–85.
[57] Faraday, "Historical Sketch," 286.
[58] On the spread of electrostatic generators, see Pence, "The Discovery and Impact of the Leyden Jar," 7. Advances in electrostatic generators, including in the consistency of their output, occurred throughout the eighteenth century, so it is not clear when it was first possible to discover this effect. This topic warrants further investigation.

paths to the discovery of electromagnetism. Of the alternative paths, testing the closed pile itself for a magnetic effect would have been a natural thing to try and likely would have yielded positive results. Why, then, was electromagnetism not discovered before 1820?

One seemingly plausible answer is that natural philosophers might not have suspected that electricity and magnetism were convertible into one another, and thus it is only with the benefit of hindsight that the failure to detect the phenomenon earlier seems clear. The next section aims to show that, in fact, speculation about a connection between electricity and magnetism was quite common historically, and several attempts to find this connection were tried, including after the discovery of the voltaic pile in 1800.

Section 2: The history of searches for electromagnetism

Electricity and magnetism share much in common, and it was an antecedently reasonable hypothesis that there might be some connection between them. In particular, they share several key characteristics:

(1) Both cause effects on other bodies, apparently at a distance.
(2) Both occur in two types.
(3) In both, charges (or poles) of the same type repel and charges (or poles) of opposite types attract.
(4) Opposite charges (or poles), when combined, can neutralize the effect of the other.
(5) Both appear to obey the inverse square law.

In fact, the similarities are sufficiently striking that, while the attractive power of the lodestone and rubbed amber were known since antiquity, it wasn't until Gilbert's *De Magnete* in 1600 that static electric attraction was cleanly distinguished from magnetic attraction.[59] Given these similarities, a number of attempts were made to discover a connection between electricity and magnetism and a number of interesting pieces of evidence further suggested that the connection might exist. A partial timeline of these attempts is provided in the appendix.

The earliest observations that suggested an electromagnetic connection were reports of lighting strikes having the ability to change the polarity of magnets. The earliest known account is that of Gassendi in 1630, who observed that "magnetism was communicated to ferruginous bodies by lightning."[60] A different account—which Ørsted himself mentions as suggesting an electromagnetic connection—appears in the *Philosophical Transactions* for 1676.[61] The author

[59] On what the ancients knew about the properties of rubbed amber and the lodestone, see McTeigue and Anders, "William Gilbert and the Discovery of 'Electricks,'" 10–45.
[60] Fahie, *A History of Electric Telegraphy*, 251.
[61] On Ørsted's discussion of this report, see Ørsted, s.v. "Thermo-electricity," 18:574. The report itself is from Anonymous and Haward, "An Extract of a Letter," 647–53.

reports that he was sailing with a group of ships during a thunderstorm and one of the ships was struck by lightning. After the storm subsided, the other ships began to sail in the opposite directions of their intended destination, back toward the port from which they departed. It was later discovered that their compasses had all reversed polarity such that north was now south and vice versa.

After the discovery of the Leyden jar in 1745—and the subsequent suspicion that lightning was an electrical phenomenon—there were attempts to use the Leyden jar to affect the polarity of a magnetized needle. In 1751, for example, Franklin reports that he had "frequently given polarity to needles and reversed it at pleasure."[62] While this initially appeared to constitute the discovery of electromagnetism, Franklin concluded that it was not, in fact, a primarily electrical effect, but was instead caused by the same mechanism that causes metals to gain polarity when heated or struck with a hammer, that "these two powers of nature have no affinity with each other, and that the apparent production of magnetism is purely accidental."[63] The issue remained an open question by 1774, when the Electoral Academy of Bavaria held a prize competition on the question "Is there a real and physical analogy between electric and magnetic forces, and, if such analogy exist, in what manner do these forces act upon the animal body?"[64]

Galvani's 1791 discovery that a dead frog's leg would contract every time the muscle and nerve were connected in a bimetallic arc—a phenomenon initially referred to as "animal electricity" and later as "galvanism"—provided natural philosophers with several promising new avenues for pursuing the connections between electricity and magnetism. One avenue identified even before the invention of the pile was the attempt to produce galvanic effects, especially muscle twitching, with magnets in place of the bimetallic arc. Success in producing this effect was claimed by Ritter (via a report from Humboldt) in 1797 and initially by Fowler in 1796, although Fowler ultimately concluded that the effect was no different from that produced by a non-magnetic iron bar.[65] Figures including Ritter, Arnim, and Lüdicke also reported that the different poles of a magnet exhibited different oxidation potentials.[66] This could have been a crucial finding as differences in oxidation potential were known to be important for finding metals ideal for use in a voltaic pile. Thus, if magnetic poles differed in the oxidation potential, it seems possible to use them to construct a voltaic pile. This line of research culminated in Ritter's 1805 presentation to

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[62] Franklin to Collison, June 29, 1751.
[63] Franklin to Dubourg, March 10, 1773. On the erroneous conclusion that this constituted electromagnetism, see Franklin and Dalibard, *Experiences et observations sur l'électricité*. See also Hamamdjian, "Dalibard, Thomas François." For a later treatment of what Franklin's experiments show about the relationship between electricity and magnetism, see Singer, *Elements of Electricity and Electro-chemistry*, 204–6.
[64] Fahie, *A History of Electric Telegraphy*, 255.
[65] Humboldt, *Versuche über die gereizte Muskel*, 189. Humboldt later denied any direct influence of magnetism on galvanism in Humboldt, *Expériences sur le galvanisme*, 115. A report on Fowler's research can be found in Sue, *Histoire du Galvanisme*, 207.
[66] Arnim, "Ideen zu einer Theorie des Magneten," 59; Lüdicke, "Versuche mit einer magnetischen Batterie," 375–78. Lüdicke later concluded that the effect was not galvanic. See Lüdicke, "Fortsetzung der Versuche mit verbundnen Magnetstählen," 114–19.

the München Academy of Sciences in which Ritter claimed to have succeeded in building a voltaic pile with magnets that had the same effect on bodies as those made using unmagnetized metals.[67] In 1807, Paul Erman presented serious challenges to a wide array of Ritter's results in two papers. He found no difference in oxidation between the north and south poles of a magnet, and he criticized a large number of Ritter's other findings.[68] After Erman's critique and Ritter's death in 1810 at the age of thirty-three, there was very little additional research on the use of magnets to produce galvanic effects.[69]

Two other interesting trailheads emerged from galvanic research. One observation made by both Gautherot in 1801 and Lehot in 1806 was that wires connected to the poles of the pile appeared to attract each other magnetically.[70] Indeed, Lehot presents this as a well-accepted fact, saying "it has long been known that the two wires which terminate a pile attract one another, and, after contact, adhere like two magnets. This attraction between the two wires, one of which receives and the other loses the galvanic fluid, differs essentially from electrical attraction."[71] There was also a purported finding that magnets could quicken the formation of silver crystals—a phenomenon known as Diana's silver tree. It was already known that the pile had a similar effect. Maschmann, for example, concluded on the basis of this phenomenon that galvanism and magnetism were identical.[72]

Ultimately, none of these lines of research led to findings that were widely accepted as showing a clear connection between electricity and magnetism until Ørsted's discovery. What should be clear, however, is that speculation about the relationship between electricity and magnetism was relatively common prior to 1820 and that many experiments were conducted between 1800 and 1820 in order to demonstrate the existence of such a relationship. The failure to discover electromagnetism earlier was not for a lack of trying.

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[67] Anonymous, "Extrait d'une lettre," 97–100. Reproduced in Anonymous, "Extract of a Letter," 368–69.
[68] Erman, "Beitraege über electrisch-geographische Polaritaet," 1–35, 121–45. See also Martins, "Ørsted, Ritter, and Magnetochemistry," 345.
[69] See Martins, "Ørsted, Ritter, and Magnetochemistry," 345. Ritter's scientific legacy is complex and filled with a great number of admirers and detractors. In the area of electrochemistry, there came to be a relatively widespread rejection of Ritter's work that was probably unmerited (see Chang, *Is Water H2O?*, 125–27). After Ørsted's discovery of electromagnetism, several authors reinvestigated the chemical effects of magnetism and reported positive results until a very detailed set of experiments by Erdmann concluded otherwise (see Erdmann, "Versuche ueber den angeblichen Einfluss des Magnetismus auf chemische Wirkungen," 24–53). In 1894, Romanian physicist Dragomir Hurmuzescu succeeded in experimentally demonstrating a very small electromotive force between two pieces of iron, one of which was magnetized (see Martins, "Ørsted, Ritter, and Magnetochemistry," 352).
[70] See Anonymous, "Intelligence and Miscellaneous Articles," 458, and Fahie, *A History of Electric Telegraphy*, 256.
[71] Fahie, *A History of Electric Telegraphy*, 256. I have not been able to determine whether this is a reliable effect or whether the effect is indeed magnetic in nature. Replicating the experiments described by Gautherot and Lehot and determining whether the effect is indeed magnetic instead of electrical could be a very valuable addition to the literature. If the effect they describe is magnetic, it would be interesting to investigate why it received scant attention compared to Ørsted's later experiments.
[72] See Mottelay, *Bibliographical History of Electricity and Magnetism*, 442; and Martins, "Ørsted, Ritter, and Magnetochemistry," 347. Maschmann's reflection on this finding can be found in Maschmann, "Einwirkung des Erdmagnetismus auf Ausscheidung des Silbers," 234–39.

Section 3: Why Ørsted?

This section is concerned with why Ørsted was able to make the discovery of electromagnetism. As discussed in section 1.2, the question of whether Kant or Schelling had the greater influence on Ørsted has elicited substantial scholarly interest, yet the question of precisely what led Ørsted to the discovery and how the ideas of Kant or Schelling feature in the discovery has so far remained unaddressed.[73] The goal of this section is to answer this question and, in doing so, to identify the precise influence of these philosophers on Ørsted's metaphysics and, in turn, their influence on the discovery of electromagnetism.

However, understanding Ørsted's approach to natural philosophy will be made easier with a greater understanding of his background, and in particular his travels between 1801 and 1803, as these appear to have been foundational to his scientific outlook and his subsequent partnerships with Ritter and Joseph Winterl (1739–1809).

3.1: Ørsted's background

Hans Christian Ørsted was born in Rudkøbing, Denmark, in 1777. As a child, he was taught by a German couple to speak German, and he also learned some English, French, and Latin.[74] His early scientific training was focused on chemistry, perhaps inspired by his father, who owned a local pharmacy where Hans and his brother Anders worked from the age of ten or eleven.[75] Ørsted entered university in 1794 and received his pharmaceutical degree in 1797.[76]

In 1798, both Hans and Anders became members of the editorial staff of a new, and ultimately short-lived, periodical entitled *The Philosophical Repertorium,* which was devoted to the promotion and defense of Kantian philosophy.[77] In 1799, Ørsted wrote a paper for this periodical entitled "Grundtrækkene af Naturmetaphysiken tildeels efter en nye Plan" (Fundamentals of the Metaphysics of Nature Partly on a New Plan).[78] He reworked this paper into his dissertation, for

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[73] The works that come the closest to directly answering this question are Agassi, "Oersted's Discovery," 67–74, and Wilson, "Introduction," xv–xl. Wilson's work is particularly commendable for taking the decisive step of explicating Ørsted's "conflict of electricity" theory and connecting it to the metaphysics that he acquired by reading Kant and Schelling.

[74] Meyer, *The Scientific Life and Works of H. C. Ørsted*, XIII.

[75] Meyer, *The Scientific Life and Works of H. C. Ørsted*, XIII–XIV.

[76] Ørsted's father even certified in 1797 that Ørsted had the skill required to be a professional pharmacist. See Nielsen and Andersen, "The Influence of Kant's Philosophy on the Young H. C. Ørsted," 98.

[77] Meyer, *The Scientific Life and Works of H. C. Ørsted*, XVII. See also Nielsen and Andersen, "The Influence of Kant's Philosophy on the Young H. C. Ørsted," 106. The untranslated title of the periodical was the *Philosophisk Repertorium for Fædrelandets nyeste Litteratur*.

[78] A translation appears in Ørsted, "Fundamentals," 46–78.

which he was awarded a doctorate in the same year.[79] Both works deal directly with Kant's *Metaphysical Foundations of Natural Science*, a topic to which we will return later.

Between 1799 and 1801, Ørsted briefly worked as a pharmacist and published various reviews of chemistry and notices on the publications of foreign chemists.[80] During this time, he began to develop his views on the correct foundations on which to build a system of chemistry. The central themes of these efforts include the idea that "for a law of nature to be absolutely valid it must have an a priori foundation."[81] Ørsted also developed his views on the systems of chemistry that were then becoming popular. For example, he exhibits opposition on Kantian grounds to atomistic systems like those ascribed to John Dalton, and he develops complex views on the antiphlogistic doctrine propagated by Lavoisier. In an autobiography of his early years as a natural philosopher, he summarizes his changed perspective (in the third person) as follows:

> When as a boy he read books on chemistry none of which were quite modern, their whole base was the phlogistic system; as a young undergraduate he became acquainted with the antiphlogistic system and was quite fascinated by it; before he was 24, however, Volta's great discovery, Ritter's brilliant works, Winterl's bold edifice of principles, had induced the conviction in him that the antiphlogistic doctrine could not be valid.[82]

In 1800, Ørsted was appointed an assistant lecturer in the medical faculty of the university. The position did not include a salary, and also had a strenuous lecturing requirement that left him little time for experiments.[83] Between 1801 and 1803, Ørsted received a grant that allowed him to travel to Berlin, Göttingen, and Weimar to meet other natural philosophers and to discuss recent developments in galvanism occurring after the announcement of the voltaic pile in 1800.[84] This trip was to have a major impact on Ørsted's approach to natural philosophy.

In Göttingen, Ørsted was introduced to Ritter, who was then among the leading experts on galvanic study. Over a period of four days, the two became close friends and built a foundation for a partnership that would last several years. Ørsted appears to have been particularly captivated by Ritter's ideas about the possibility of an underlying unity between the phenomena of heat, light, galvanism, chemistry, electricity, and magnetism.[85] At the end of the four-day period, Ørsted writes of Ritter: "What I write on galvanism he will embody in his writings which

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[79] Ørsted's dissertation is *Dissertatio de forma metaphysices elementaris naturae externae*. A translation is available in Ørsted, "Dissertation," 79–100.
[80] Meyer, *The Scientific Life and Works of H. C. Ørsted*, XVII–XVIII.
[81] Meyer, *The Scientific Life and Works of H. C. Ørsted*, XVIII.
[82] Translation provided in Meyer, *The Scientific Life and Works of H. C. Ørsted*, XIX.
[83] Meyer, *The Scientific Life and Works of H. C. Ørsted*, XXIII. Ørsted was an "extraordinary" lecturer, where "extraordinary" apparently meant "unpaid."
[84] Williams, s.v. "Oersted, Hans Christian"; Meyer, *The Scientific Life and Works of H. C. Ørsted*, XXIII.
[85] Jacobsen, "Spirit and Unity," 186.

are now of such importance that every chemist and physicist must read them. He is going to send me everything he writes if I send him my works in return."[86]

Ørsted then stayed in Berlin for around six months, during which he was able to pursue his interests in post-Kantian philosophy through interaction with the community of German idealists. He heard Johann Gottlieb Fichte (1762–1814) lecture and became personally acquainted with him. He heard lectures by August Wilhelm Schlegel (1767–1845) on "mythology and its influence on the poetical treatment of physics"[87] and formed a friendship with August's younger brother, Karl Wilhelm Friedrich Schlegel (1772–1829). He was also introduced to Schelling's ideas concerning *Naturphilosophie*.

This trip led Ørsted to develop two important research partnerships that can provide insight into his developing attitudes toward natural philosophy. The first was a partnership that he and Ritter engaged in to test and promote the system of chemistry being developed by Winterl. The second was a partnership with Ritter himself to help promote the most important of Ritter's many findings.

Ørsted was first introduced to the chemical system proposed by Winterl in his *Prolusiones ad chemiam saeculi decimi noni* (Prelude to the Chemistry of the Nineteenth Century) during his stay with Ritter in 1801.[88] Winterl proposed a system of chemistry according to which "matter is composed of elements which differ only in possessing atoms of either an acidic or a basic principle."[89] Winterl claimed that acids and bases were equivalent to positive and negative electricity, and he set about trying to explain a large number of contemporary findings in chemistry, galvanism, and electricity on this basis. He also claimed to have discovered substances that were simpler than the chemical elements, which he called *Andronia* and *Thelycke* and which he identified with the acidic and basic principles themselves.[90]

Ørsted appears to have been quite taken with Winterl's ideas for several reasons, including their potential to replace the antiphlogistic doctrine of Lavoisier, to explain nature in terms of fundamental opposing forces (as suggested by Kant), and to provide greater unity to the research in chemistry that was then underway. Ørsted engaged in several projects to promote Winterl's system, but neither these projects nor Winterl's work itself were successful.[91] As one historian has put it, "nearly all reviewers of it unmercifully ran down Winterl's chemistry. It was acknowledged that it made a far better show in Ørsted's adaptation than in the original, but even

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[86] Meyer, *The Scientific Life and Works of H. C. Ørsted*, XXIV–XXV.
[87] Meyer, *The Scientific Life and Works of H. C. Ørsted*, XXV.
[88] Ørsted refers to it for the first time in a letter written during his stay with Ritter. See Jacobsen, "Spirit and Unity," 186.
[89] Snelders, "The Influence of the Dualistic System of Jakob Joseph Winterl," 231.
[90] Snelders, "The Influence of the Dualistic System of Jakob Joseph Winterl," 232.
[91] For example, Ørsted published a book that attempts to explain Winterl's system to a German audience, and he set up a small society dedicated to testing Winterl's system experimentally. See Jacobsen, "Spirit and Unity," 187.

the most friendly critics regretted that Ørsted had not employed his acumen in a more profitable task."[92]

By 1807, Ørsted had abandoned Winterl's system. He continued attempts to experimentally test some of Winterl's claims between 1804 and 1806 and obtained largely negative results. In particular, he failed to find evidence supporting the existence of Winterl's discovery of *Andronia*, concluding that it was not a new substance, but silica (although he credited Winterl with discovering new properties of the substance).[93] Additionally, Ørsted's relationship with Winterl deteriorated, and by 1806, Ørsted and Winterl no longer communicated directly, instead using Ritter as an intermediary.[94]

Ørsted's partnership with Ritter was more successful for both parties. In addition to frequent exchanges of letters, Ørsted helped Ritter publicize his findings, especially among the French. During a stay in Paris, Ørsted made several acquaintances and gained an introduction to the prestigious Société Philomathique de Paris. At two meetings, Ørsted gave an account of some of Ritter's research, including Ritter's experiments with the voltaic pile. After his presentation, the French natural philosopher Jean-Baptiste Biot (1774–1862) told Ørsted that "the sooner [Ritter] announced his discoveries of the last few years the better, as he could scarcely fail to obtain the prize of the Institute (3,000 francs)."[95]

Indeed, Ritter had made a number of vital discoveries, including the creation of the first dry voltaic pile in 1802 and the invention of a secondary charging battery (also called an accumulator) in 1803, which stored electric fluid from the voltaic pile much as the Leyden jar stored charge from the electrostatic generator.[96] Ritter wrote a report on his discoveries that included a description of the accumulator and also a new discovery: Earth, Ritter claimed, had two electric as well as two magnetic poles. Ørsted translated Ritter's report into French and, given the importance of this new discovery, entered it in a competition for a much larger prize of 60,000 francs (worth in excess of $450,000 today).[97] Ørsted tried to demonstrate Ritter's experiments, but his attempt to perform experiments demonstrating the existence of Earth's electrical poles failed.[98] Ritter did not win the prize, but Ørsted's reputation was not substantially harmed, and he retained faith in the accuracy of his friend's results.[99]

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[92] Meyer, *The Scientific Life and Works of H. C. Ørsted*, XXVIII.
[93] Jacobsen, "Spirit and Unity," 209.
[94] Jacobsen, "Spirit and Unity," 205.
[95] Translation from Meyer, *The Scientific Life and Works of H. C. Ørsted*, XXX–XXXI. This amounts to more than $20,000 today based on a rough currency conversion obtained by converting francs to euros via Edvinsson, "Historical Currency Converter," adjusting euros for inflation and then converting euros to dollars.
[96] McRae, s.v. "Ritter, Johann Wilhelm"; Meyer, *The Scientific Life and Works of H. C. Ørsted*, XXX.
[97] Also a very rough estimate obtained by converting francs to euros via Edvinsson, "Historical Currency Converter," adjusting euros for inflation and then converting euros to dollars.
[98] Meyer, *The Scientific Life and Works of H. C. Ørsted*, XXXI.
[99] See Caneva, "Ørsted's Presentation of Others'—and His Own—Work," 305.

Ørsted presented other components of Ritter's work as well. In 1803, he published a report on Ritter's work in causing contractions in frogs with a magnetic and non-magnetic iron wire.[100] He also described an experiment in which Ritter was supposed to have demonstrated that the poles of a magnet differed in their tendency to oxidize, an experiment that would have been very important, if true (see section 2, above). Ørsted also assisted Ritter in publicizing his work outside of galvanism. After William Herschel (1738–1822) detected rays of light beyond the red end of the visible spectrum (now called infrared light) in 1800, Ritter hypothesized the existence of invisible rays of light beyond the violet end of the spectrum. In 1801, he succeeded in detecting these rays (now called ultraviolet light) and in publishing a brief announcement of this discovery.[101] Ørsted succeeded in having two notes about the discovery published in French, both in 1803, which brought more attention to it.[102]

As discussed in section 2, many of Ritter's results came under serious challenge by Paul Erman in 1807. In particular, Erman disputed Ritter's claims about the Earth's electric poles, the attraction between a silver-zinc needle and a magnet, the influence of magnetism on chemical reactions, and the difference in oxidation between the poles of a magnet.[103] Erman's critique was not seriously responded to by Ritter or his supporters prior to Ritter's untimely death in 1810 at the age of thirty-three.

Ultimately, Ørsted came to agree that many of the experimental claims made by both Winterl and Ritter were mistaken, but he continued to admire both of them, especially as theorists. Hissummary of their contributions in a piece written in 1812 is characteristic of his enduring view:

> Ritter can therefore be regarded as the creator of modern chemistry. His comprehensive ideas and his achievements, undertaken with such great vigour and exertion, spread a great light in all directions. To a certain extent, Winterl deserves to be placed next to him. His ideas on alkalinity and acidity, as well as on heat, are of great importance and have been confirmed many times by recent discoveries. It is not to be denied that the great minds of these men often led them too far into the realm of pure speculation.[104]

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[100] Ørsted, "Experiments on Magnetism," 184.
[101] Ritter, "Chemische Polarität im Licht," Cols. 121–23.
[102] The earlier work is Ørsted, "Expériences sur les rayons invisibles du spectre solaire," 197–98. Also see the discussion in Caneva, "Ørsted's Presentation of Others'—and His Own—Work," 290, and Caneva's discussion in 74n about the authorship of the piece. The latter work is Ørsted, "Expériences sur la lumière; par M. Ritter," 409–11.
[103] Erman, "Beitraege über electrisch-geographische Polaritaet," 1–35, 121–45. See also Martins, "Ørsted, Ritter, and Magnetochemistry," 345.
[104] As translated in Ørsted, "View of the Chemical Laws of Nature Obtained through Recent Discoveries," 313.

3.2: Characterizing Ørsted's approach to natural philosophy

Ørsted's background and his extensive writings analyzing the state of chemistry (broadly construed) make it possible to provide a somewhat detailed picture of his approach to natural philosophy. As we will see, this approach was quite different from the approach taken in the other major scientific centers, like France and the United Kingdom, and was critical to Ørsted's eventual discovery.

Ørsted was a nuanced thinker, as were the philosophers who influenced his work; these views do not admit of easy summary.[105] For our purposes, however, a few distinct aspects of his approach are both sufficiently central to his philosophical system and sufficiently distinct from the approach taken by his contemporaries that highlighting them will prove instructive. These key elements are (1) his belief in the importance of establishing natural laws a priori; (2) his dynamical theory of matter; and (3) his belief in the ultimate unification of natural philosophy into a single, unified whole.

The importance of establishing natural laws a priori

From his earliest writings, Ørsted demonstrates that he is concerned with the need to establish the proper theoretical groundwork for natural philosophy in general and chemistry specifically. One of his earliest works, his *Fundamentals of the Metaphysics of Nature* of 1799, begins as follows:

> If a body of empirical knowledge is to be able to claim the name of science in the true sense of this word, these experiences must be joined according to certain general and necessary laws which themselves cannot be drawn from experience but must be proved without its help (a priori). If this is not the case with an organized body of experience, it does not at all satisfy the scholar but leaves him standing at a limit which he is not certain is extreme and shows him laws which he dare not assume to be general and necessary because he knows that experience can only teach us what is but not what necessarily must be.[106]

This proposal is similar to Kant's contention in *Metaphysical Foundations of Natural Science* that for a body of knowledge to constitute a proper science, it must, among other requirements, treat its subject according to a priori principles which can be known with apodictic certainty.[107] However, Ørsted's work shows a dissatisfaction with how Kant set about accomplishing this goal. He accuses Kant of having taken empirical ideas as the basis for his metaphysics of nature, whereas Ørsted believed that his own work succeeded in deducing all of the relevant natural laws

[105] For those interested in a more complete picture of Ørsted as a philosopher, Andrew Wilson's introduction to *Selected Scientific Works of Hans Christian Ørsted* provides the best overview (see Wilson, "Introduction," xv–xl).
[106] Ørsted, "Fundamentals," 46.
[107] Kant, *Metaphysical Foundations of Natural Science*, 4.

a priori.[108] Ørsted also maintains that scientific knowledge should be grounded in a single first principle rather than in the plurality of first principles utilized by Kant.

The view that natural laws should be established a priori is quite foundational to understanding Ørsted's project as a natural philosopher as it allows Ørsted to have a different understanding of the epistemic status of experimental results than would have been common among his contemporaries. Consider, for example, Ørsted's continued belief that there was some deeper connection between electricity and magnetism despite his familiarity with unsuccessful attempts to demonstrate this fact. If one believes there is sufficient a priori reason for thinking a connection exists, then the lack of experimental findings need not cause abandonment of that view. Similarly, this perspective allowed Ørsted more freedom to posit explanations for which there could not have been any direct experimental demonstration. As we will see, his relationship to the empirical evidence was critical to the discovery of electromagnetism.

Ørsted's dynamical theory of matter

One of Ørsted's chief concerns, especially in his early writing, is the articulation and defense of a dynamic metaphysics of nature according to which "bodies fill space with a force" and, in turn, the rejection of the atomistic metaphysics of nature according to which bodies are not infinitely divisible but are "composed of many small particles, which are called atoms."[109] Ørsted argues that only the dynamical system can meet Kant's requirement that a true science be based on a priori principles known with apodictic certainty:

> [The dynamical system] also has the advantage over the opposite that it presents the laws of nature as founded on human cognition so that we know beforehand that there can be no exceptions to these because, in order to imagine that anything happened according to natural laws which were at variance with the ones we had proved in this way, we would have to change our cognition, that is, become other beings.[110]

Ørsted's views on the precise nature of the fundamental force(s) that constitute matter appear to change over time. In his earliest writing, he appears to think that there are either two basic opposing forces or that there are three, one of which is produced by the meeting of the two opposing forces.[111] Later in his career, he concludes that this model can be further reduced to only a single primordial force.[112] In any case, however, Ørsted's belief that the dynamical system

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[108] See Ørsted, "Fundamentals," 76.
[109] Ørsted, "Fundamentals," 74.
[110] Ørsted, "Fundamentals," 76.
[111] In his dissertation, Ørsted introduces the notion of a third so-called "limited force" (Ørsted, "Dissertation," 82). This term does not appear anywhere else in the *Selected Scientific Works of Hans Christian Ørsted*, however, and his later writings appear to indicate that two forces are fundamental. See, for example, Ørsted, "What Is Chemistry?," 195.
[112] Ørsted, "View of the Chemical Laws of Nature," 310–92.

was uniquely capable of a priori deduction with apodictic certainty remained throughout his career, even as his views on the nature of dynamical force changed.

Nature as an integrated whole

Finally, Ørsted believed that nature itself was a single, integrated whole and that the different branches of natural science would, in turn, be unified into a comprehensive universal science. In many ways, his fundamental aim as a natural philosopher was to help bring about this anticipated unification by combining both experimental demonstration and a priori speculation. In a letter to one of his students, he explains his view as follows:

> It is also my firm conviction, and my lectures bear witness thereof, that a great fundamental unity pervades the whole of nature; but just when one has become convinced of this, it becomes doubly necessary to direct one's whole attention to the world of the manifold, wherein this truth above all finds its confirmation. If one does not do this, unity itself remains an unfruitful and empty idea which leads to no true insight.[113]

On this point, Ørsted appears to have found the work of Schelling and the intellectual tradition of *Naturphilosophie* particularly important. In a letter to a friend, he described Schelling's influence as follows:

> Schelling's accomplishment, as you know, is that he founded the philosophy of nature and with this affected all sciences. The genius of this was not that he construed nature and, least of all, the way he construed it, but his accomplishment was to see nature as a single organism.[114]

Additionally, for those inclined to see nature as an integrated whole, early nineteenth-century developments in natural philosophy, particularly those between 1800 and 1820, contained a number of discoveries that supported this inclination. To state the clearest examples, the discovery and subsequent research of galvanism showed that there was an important connection between electricity and biomechanical action. The realization that the best metals for forming the bimetallic galvanic arc were those that differed in their oxidation potential demonstrated that chemical interactions were a likely cause of galvanic electricity and, because affinity for oxygen was known to be important in combustion, demonstrated a connection there as well. The ability to use the pile to turn water into hydrogen and oxygen as demonstrated by Ritter and by Nicholson and Carlisle, respectively, showed that there was not only a role for chemistry in the

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[113] Hauch, *H. C. Ørsted's Leben*, 13. Translation from Stauffer, "Speculation and Experiment," 39.
[114] Ørsted, *Breve fra og til Hans Christian Ørsted*, 1:230. Translation from Wilson, "Introduction," xix.

production of galvanic electricity, but also a role for galvanic electricity in producing chemical effects.[115]

Thus, the idea of nature as an integrated whole was supported both by philosophical arguments like those proposed by Schelling and by recent empirical research. Ørsted would have had a firm grasp on both sources of support, and thus it is not surprising that he continued to speculate about the existence of an electromagnetic connection despite the difficulty in demonstrating it experimentally.

3.3: What led Ørsted to perform the critical experiment in 1820?

As section 1 of this paper demonstrates, the discovery of electromagnetism was technologically possible no later than 1802 and would have been easily discoverable by any capable researcher with a reasonably strong pile who thought to look in the current-carrying wire for such an effect. Yet, it appears that no one thought to look there until Ørsted's experiment in 1820. In this section, I will attempt to reconstruct the conception of electrical conduction that led Ørsted to perform this experiment and show how his conception of electricity relates to his overall approach to natural philosophy.

To explain the relationship between Ørsted's theoretical ideas and his decision to look in the current-carrying wire for a magnetic effect, an obvious place to start is his account of the effect itself after his discovery. In both his first report and his subsequent accounts of the discovery of electromagnetism, Ørsted describes a theory of the action of a current-carrying wire, which he called the "conflict of electricity." He maintained that the conflict of electricity could explain why the current-carrying wire would produce not only magnetism, but also heat and light.[116]

Unfortunately, Ørsted had substantial difficulty communicating this idea to his contemporaries, and his own writings do not allow for a detailed examination of the relationship between the theory and his decision to check the current-carrying wire for a magnetic effect.[117] The clearest

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[115] A less obvious source of evidence that was nevertheless salient to Ørsted concerns the phlogiston interpretation of the relationship between the properties of metals, combustion, and electricity. Chang has argued that the role later played by the electron as a unifying concept could have been played by phlogiston but for its demise at the end of the eighteenth century (Chang, *Is Water H2O?*, 43–50). And indeed, Ørsted specifically commends phlogiston for its recognition of the connection between electricity and combustion. See Ørsted, "View of the Chemical Laws of Nature," 312–13 and 387. See also Ørsted, "Reflections on the History of Chemistry," 246 and 249.

[116] See Ørsted, "Experiments," 274 and 276.

[117] For a useful discussion of Ørsted's difficulties in communicating his idea, see Wilson, "Introduction," xvi–xxi. The treatment of Ørsted's discovery by Faraday is also instructive as Faraday is quite clear in his admiration for Ørsted and in his confusion about Ørsted's theory: "It cannot be doubted for a moment by any one who has read the papers of [Ørsted] . . . that his theory rather led to the experiments, than the experiments to the theory. Chance indeed seems to have had very little to do with the discovery except in retarding it, for the thoughts were conceived, and the experiments devised, some time before they were made. Notwithstanding all of this, I have very little to say on M. Ørsted's theory, for I must confess I do not quite understand it." Faraday, "Historical Sketch" [1822], 107.

account of the relationship between his theory and the discovery comes from his article (written in third person) on thermo-electricity from the 1830 edition of the the *Edinburgh Encyclopaedia*:

> [Ørsted] was not so much led to [the discovery] by the reasons commonly alleged for this opinion, as by the philosophical principle that all phenomena are produced by the same original power. . . . He did not consider the transmission of electricity through a conductor as a uniform stream, but as a succession of interruptions and re-establishments of equilibrium, in such a manner, that electricity powers in the current were not in quiet equilibrium, but in a state of continual conflict. As the luminous and heating effect of the electrical current, goes out in all directions from a conductor, which transmits a great quantity of electricity; so he thought it possible that the magnetical effect could likewise eradiate.[118]

Fortunately, Ørsted provided a detailed account of how he thought electricity moved through a metallic conductor in 1806, which, following his terminology in that account, will be referred to here as the "undulatory theory."[119] While the undulatory theory does not use the "conflict of electricities" terminology, it shares enough similarities with the clear details of the later theory that it is likely a precursor to the conflict of electricity theory. Thus, the undulatory theory—or something very close to it—likely represents Ørsted's understanding of the current-carrying wire and, therefore, why he decided to investigate the wire for a magnetic effect in 1820.

The metaphysical background of both views is the same. Ørsted viewed all apparent physical phenomena—e.g., light, heat, combustion, electricity, magnetism, etc.—as different manifestations of a small set of fundamental forces. He also viewed the apparent differences in physical phenomena—for example, those between forces like magnetism and electricity—as produced not by different weightless fluids, but by differences in how these more fundamental forces interact with one another. The forces tend toward a state of quiet equilibrium, but when that equilibrium is disturbed, they attempt to reach a new equilibrium and, in the process, produce a number of detectable effects.

Ørsted saw electrical conduction as a particularly interesting case of the upsetting and reestablishment of the equilibrium between the fundamental forces. Rather than seeing conduction as the transmission of a subtle fluid (electricity) between two points, he saw it as "undulatory" in nature, with alternating zones consisting of opposite electrical charges. Ørsted explains the nature of this effect with reference to electrical induction. Consider the following diagram:

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118 Ørsted, s.v. "Thermo-electricity," 18:575.

119 Ørsted, "On the Manner in Which Electricity Is Transmitted," 210–14.

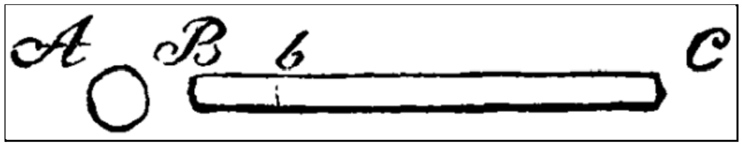

Figure 9. Diagram of electrical induction.[120]

Assume that *A* is some object with an electrical charge and *BC* is a long conducting tube that is near *A*, but does not touch it. Electrical induction is the well-known phenomenon according to which, for any charge of *A*, bringing *A* close to *B* will cause *B* to show signs of the opposite electrical charge, and *C* will show signs of the same electrical charge as *A*.[121] So, if *A* is positively charged and brought near *BC* when it is neutrally charged, we will find that *B* is negative and *C* is positive.

Ørsted argues that electrical conduction works through the same basic process of alternating electrical charges as electrical induction when considered over infinitesimally small distances and amounts of time. The idea is that in the first instant after *A* gains an infinitesimally small positive charge, it causes the basic induction effect over a much smaller area (represented by *Bb*) such that *B* becomes negative and *b* becomes positive. As the positive charge in *A* increases, the negative charge at *B* also increases, as does the corresponding positive charge at *b*. In turn, the increase in positive charge at *b* causes a negative charge in a region slightly closer to *C*, which creates a new positive region and so on. This process repeats, creating alternating zones of positive and negative charge until the charges again reach equilibrium.[122]

Ørsted provides several sources of experimental evidence in favor of the view that electrical conduction works through these alternating positive and negative charges. For example, he notes that when metal wires are partially melted through an electric discharge, "only some parts melt while others remain intact, and that melted and unmelted parts alternate."[123] He further notes that if the wire glows red-hot without melting, one can observe an alternating pattern of expanded and contracted zones in the wire.[124] Ørsted also argues that this undulatory method of transmission is true in nature more generally. In the case of magnetism, for example, he claims

[120] Ørsted, "On the Manner in Which Electricity Is Transmitted," 210.
[121] Following Franklin's electrical theory, this can be imagined as *A* pushing (or pulling) the electric fluid in *BC* away from (or toward) *A* and thus causing different electrical signs at different locations in *BC*.
[122] Ørsted's language to describe exactly what occurs in the conductor is, unfortunately, not very precise. Therefore, this synopsis may accidentally misrepresent his view. His statement on the matter is as follows: "We want to think of such a small part of space as represented by *Bb*, where, in the first small part of time, an infinitesimally small electric polarity is aroused; if, e.g., *A* becomes positive, *Bb* becomes negative at *B* and positive at *b*. However, in the next instant, *A* will seek to enlarge the negative zone, whereby the positive will be enlarged as well, while the positive in *b* will strive to produce a negative one even further towards *C*. And the entire process continues in this manner until the negative extends over the front half, the positive over the back half, and the middle remains indifferent." Ørsted, "On the Manner in Which Electricity Is Transmitted," 210–11.
[123] Ørsted, "On the Manner in Which Electricity Is Transmitted," 211.
[124] Ørsted, "On the Manner in Which Electricity Is Transmitted," 211.

that "if a long, thin steel wire is magnetized, it acquires alternating north and south poles along its entire length"[125] and notes similar effects in the propagation of sound and in the color patterns displayed by electric sparks.[126]

Several aspects of Ørsted's undulatory theory of the propagation of forces are notably incomplete, however. For example, his explanation of electrical conduction by analogy to electrical induction appears to provide the template for the underlying undulatory mechanism's function in other cases, but it is unclear how this template might be applied to forces without obvious polarity, like light, sound, or heat. Elsewhere, Ørsted indicates that there are "two opposite fundamental forces"[127] in nature, which work through "alternating expansions and contractions."[128] It could be that Ørsted had a still more fundamental explanation of electrical induction in mind that could be more easily applied to explain the other forces.[129] Yet the connection between this more fundamental explanation and electrical induction is unclear.

Taking a broader perspective, however, the relatively straightforward argument that both the undulatory theory and the conflict of electricities theory share would justify investigating the current-carrying wire for magnetism. The basic argument is as follows:

(1) Electricity does not transmit through a wire in a uniform, quiet stream; instead, its transmission is the result of a complex struggle between fundamental forces.
(2) Creating a complex struggle between fundamental forces can, under certain conditions, lead to the exhibition of any of the less fundamental forces that depend on the fundamental forces for their existence.
(3) The complex struggle between fundamental forces in the case of electrical transmission through a wire results in the production of heat and light.
(4) Therefore, the complex struggle might produce forces beyond heat and light as well.

This basic idea, then, is likely the reason Ørsted undertook the critical experiment in 1820 and thus the reason he discovered electromagnetism.

This view helps to resolve a few minor puzzles in the timeline of Ørsted's investigation. First, he developed his undulatory theory in 1806, but did not conduct his investigation into electromagnetism until 1820. What accounts for the delay? The answer is that nothing in the account developed here suggests Ørsted predicted that any further forces would be demonstrable with currently available instruments. Thus, it is compatible with his theory to believe that further

[125] Ørsted, "On the Manner in Which Electricity Is Transmitted," 212.
[126] On the propagation of sound, see Ørsted, "On the Manner in Which Electricity Is Transmitted," 213–14. On the color pattern of sparks, see Ørsted, "On the Manner in Which Electricity Is Transmitted," 212.
[127] Ørsted, "What Is Chemistry?" 195.
[128] Ørsted, "What Is Chemistry?" 195.
[129] See, for example, Ørsted, "What Is Chemistry?" 192–99.

forces would be demonstrable only with quantities of electric fluid that were out of reach at the time or with instruments for detecting these forces which were far more sensitive than those available then. Experimental tests of the idea were by no means likely to succeed.[130] Additionally, nothing in Ørsted's theory suggests that magnetism *specifically* would be produced by the current-carrying wire. Instead, his theory suggested that just as the complex struggle between fundamental forces resulted in the transmission of electricity and the production of heat and light, so too might this struggle produce other forces, potentially including magnetism. It is also compatible with Ørsted's theory to think that a force other than magnetism would be demonstrated, although the close analogies between electricity and magnetism (as detailed in section 2) would have made magnetism one of his top candidates.

Additionally, consider the puzzle of the three-month gap between the lecture during which Ørsted first observed the deflection of the needle and his concerted investigations into the nature of the effect itself—a circumstance that Ørsted describes as "strange" and "difficult to conceive."[131] This is explained by the fact that nothing in Ørsted's theory predicted the geometry of the magnetic effect that might result, and his other writings suggest that he thought magnetism was a central force, taking the form of a line.[132] Thus, Ørsted would have been just as surprised as his contemporaries by the circular nature of the magnetic effect. The delay, then, can be explained by Ørsted's surprise and confusion about the nature of the magnetic effect, combined with his use of thin wires (which would have muted the effect), the lack of reaction by his audience, and his natural hesitancy to claim experimental proof of electromagnetism given Ritter's poor experience on the topic.

Finally, combining this account with the characterization of Ørsted's approach to natural philosophy developed earlier allows for a precise statement of the ideas that were critical to his discovery and from whom the relevant ideas originated. The critical elements of the discovery were:

(1) Ørsted's interest in the Kantian project of establishing natural laws a priori.
(2) Ørsted's adherence to the dynamical theory of matter originated by Kant and developed further by Schelling.
(3) Ørsted's belief in the Schellingian idea that nature itself was a single, integrated whole such that the forces of nature would have a small set of underlying causes in common and his observation that recent experimental results supported this view.

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[130] In fact, Ørsted appears to have considered an important aspect of his theory—namely, his posit of infinitesimally small distances and lengths of time—to be beyond reach in our experience. "It is hardly necessary to mention that in this experiment we do not claim to have described those infinitesimally small alternations of positive and negative of which we have spoken above; on the contrary, we have spoken about them in such a way that we can have no hope of ever finding them in our experience." Ørsted, "On the Manner in Which Electricity Is Transmitted," 211.
[131] Ørsted, s.v. "Thermo-electricity," 18:575.
[132] See Ørsted, "What Is Chemistry?" 197; Ørsted, "Electrical Figures and Organic Forms," 190; and the discussion of this view below.

(4) The prior observation that the current-carrying wire produces both heat and light under certain conditions.
(5) Ørsted's application of (1)–(3) to develop a theory of the action of the current-carrying wire and his use of this theory to conclude that (4) was probably incomplete and that additional forces, like magnetism, might be observable in the electric current.

Thus it seems that Ørsted's 1820 discovery that an electrical current could move a magnetic needle would not have occurred without Kant, Schelling, and Ørsted's own ideas regarding electrical conduction.

While the account so far presented is sufficient to justify Ørsted's investigation, one additional element of Ørsted's thought may have influenced his prediction that the current-carrying wire could produce forces outside of heat and light and is therefore worth noting. In two papers written in 1805, Ørsted refers to an argument—attributed to Schelling—proposing a relationship between the three spatial dimensions and the forces of electricity, magnetism, and chemical processes (chiefly heat). The following passage is the clearest statement of the view:

> A brief outline of what we know about the effects of these forces is sufficient to show us the possibility that all the different forces of nature can be traced back to those two fundamental forces. How could there be three more different effects than heat, electricity, and magnetism! Yet, all of these are due to the effect of the same fundamental forces, only in different forms. Magnetism acts only in a *line* which is determined by the two opposite poles and the intermediate point of equilibrium. Purely electrical effects only follow *surfaces*. Heat works equally freely in *all directions* in a body. It cannot be denied that this difference actually exists. . . . However, it can hardly fail to attract the greatest attention that these three effects assume forms which correspond to the three dimensions of space and their realizations: line, surface, and body.[133]

While this idea is apparently important to Ørsted, his meaning is not entirely clear and, in particular, he does not precisely explain how he thinks the dimensionality of these effects might relate to the underlying mechanism of their production. However, his notion that electricity transmits in two dimensions over surfaces allows for a different reconstruction of how he might have understood the action of the current-carrying wire.

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[133] Ørsted, "What Is Chemistry?" 197. The other passage, which includes the reference to Schelling, is from Ørsted, "Electrical Figures and Organic Forms," 190: "Schelling has shown that three instances must be distinguished in the construction of matter by the attractive and repulsive forces. The first, in which the contrast between these two forces merely assumes the form of the line, the second, in which it is in the form of the surface, the third, in which both these interpenetrate and thus form the final dimension of space and matter, depth. Every time one body produces an internal change in another, whereby matter is really reconstructed, one or more of these actions must reappear. Thus, the longitudinal function manifests itself as magnetism, the latitudinal function as electricity, and the depth function as penetration or a chemical process. Each of these dynamic processes is the interaction of opposite fundamental forces in a different form."

In some sense, transmitting electricity over a wire, especially a very thin wire, forces the electricity to move not over surfaces in two dimensions, but in a line over a single dimension. This subjects the electricity to an unusual constraint which might, in turn, produce an unusual set of outcomes. Ørsted would have noticed, for example, that a current-carrying wire produces heat and light more readily if the wire is thin, and he might have thought that attempting to force a still larger quantity of electricity through an even thinner wire would produce additional forces as well. This view probably explains why he initially used thin wires—which are generally worse at producing magnetism—instead of thicker ones.[134] It also retains the previous explanation of the timeline of Ørsted's discovery, as the theory neither predicts magnetism specifically nor predicts the unusual geometry of the magnetic effect. This reconstruction is, however, more speculative than the reconstruction based on Ørsted's view of the action of the current-carrying wire. I have not found any statements from him in which he indicates, for example, that restricting electricity to one dimension enables it to produce heat and light, which one would expect if this were his view.

Section 4: Why did the discovery not occur elsewhere?

The previous section examined why it was Ørsted who discovered electromagnetism. The argument, in short, is that the critical elements of Ørsted's discovery were his metaphysics of nature—acquired from his reading of Kant and Schelling—and his use of that metaphysical picture to develop a theory of electrical conduction that later suggested to him that it might produce a detectable magnetic effect. The task of this section will be to explain why the discovery did not occur elsewhere and, in turn, to hint at whether the discovery would have been made were it not for the efforts of Ørsted and, by extension, Kant and Schelling.

To accomplish this task, it is useful to distinguish between three very broad and overlapping approaches to natural philosophy that were common between 1800 and 1820. By far the most common approach can be called "experimentalism" for its focus on producing and describing clear experimental results, its relatively limited focus on the development of explicit theories, and its use of crucial experiments to attempt to rule in or out particular theories. Experimentalism was popular worldwide, but especially among British natural philosophers and most German natural philosophers. The second approach, exemplified by the work of Ørsted and Ritter (see section 3), can be called the metaphysical or philosophical approach for its interest in constructing philosophical arguments about the fundamental constitution of nature. Most of those interested in this approach were members of the German-speaking community of natural

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[134] In his reflections on the discovery in the *Edinburgh Encyclopaedia*, Ørsted says the following: "In the month of July 1820, he again resumed the experiment, making use of a much more considerable galvanic apparatus. The success was not evident, yet the effects were still feeble in the first repetition of the experiment, because he employed only very thin wires, supposing that the magnetical effect would not take place when heat and light were not produced by the galvanic apparatus." Ørsted, s.v. "Thermo-electricity," 18:575.

philosophers, although most of these philosophers were not invested in the philosophical approach. Finally, the mathematical approach aimed to use mathematical tools to model the known behavior of various forces in nature and even predict new behaviors. This approach enjoyed its greatest success in Paris between 1805 and 1815 under the guidance of Pierre-Simon Laplace (1749–1827) and Claude Louis Berthollet (1748–1822). This section will be devoted to a discussion of why the mathematical and experimental approaches did not lead to the discovery of electromagnetism.

4.1: Electromagnetism and the mathematical approach

Between Napoleon's assumption of power in 1799 and his final overthrow in 1815, French society underwent sweeping changes, including important changes to the French education system and to French natural philosophy. During this period, Laplace and Berthollet were able to leverage a special closeness to Napoleon and their own skill in coordinating a research program to give French natural philosophy a "most uncommon unity of style and purpose"[135] and, ultimately, to create what has been described as "one of the most closely knit schools in the whole history of science."[136]

The school that Laplace and Berthollet created aimed to transform the investigation of phenomena like electricity, magnetism, and heat into precise, mathematized fields in much the same way Newton had transformed celestial mechanics. For this approach to succeed, it required (1) precise instruments that could provide useful quantitative measures of the phenomena of interest, (2) mathematical techniques that could use the resulting data to develop elegant mathematical descriptions, and (3) a subject matter that fit the school's presuppositions, which it used to determined what aspects of a phenomenon ought to be measured and what kinds of mathematical descriptions were of interest.

The centerpiece of this system's presuppositions about physics was its posit of a number of different weightless fluids that were the carriers of specific forces and that could interact with particles of ordinary matter to cause the phenomena associated with light, heat, electricity, and magnetism.[137] Some of these weightless fluids could interact with both ordinary matter and themselves—as in the self-repulsive nature of electricity and magnetism—but they were not assumed to interact directly with particles of other imponderable fluids.[138] Additionally, the

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[135] Fox, "The Rise and Fall of Laplacian Physics," 91.
[136] Fox, "The Rise and Fall of Laplacian Physics," 133.
[137] Heilbron, "Weighing Imponderables," 5.
[138] See Steinle, *Exploratory Experiments*, 51. Additionally, this appears to be what Ampère was referring to when he provided the following explanation for why electromagnetism was not discovered before 1820 in France: "It simply existed in Coulomb's hypothesis on the nature of magnetic action; everyone believed this hypothesis as though it were a fact; it simply discarded every possibility of the action between electricity and so-called magnetic wires." Ampère, *Correspondance du grand Ampère*, 2:566. Translation from Williams, *The Origins of Field Theory*, 60.

metaphysics of this approach assumed that all the phenomena of study could be reduced to forces of attraction and repulsion operating at a distance.

In some sense it is unsurprising that the mathematical approach did not lead to the discovery of electromagnetism. This approach was dedicated to describing known phenomena mathematically. The discovery of new phenomena—particularly those that worked very differently from those already known—was simply not its goal. Yet what may be surprising is the degree to which this approach was unsuited to even simply studying the voltaic pile in general.

Consider, for example, the question of measurement. When the pile debuted, there was no clear way to measure the strength of one's pile, and it was not even clear what one ought to measure. In one of the first reports on the pile, Nicholson and Carlisle note the difficulty in measuring its action as follows:

> We are in want of a measure of the action of these machines. Will this be derived from the quantities of water decomposed, or of gas extricated under like circumstances in given times? Or from any change of temperature? Or what other commensurate incident?—Mr. Carlisle has not found that the water in the tube, while under this agency, did produce the slightest effect on a very small and delicate thermometer.[139]

Methods for very roughly determining the strength of a particular pile were developed between 1800 and 1820, but these were nowhere near precise enough for the requirements of the mathematical approach. For example, experimenters could get a sense of the strength of their pile by observing whether it could cause platinum wires of a particular diameter to glow.[140] Yet, this was only a very rough measure and, since piles tended to lose strength over time as they were deployed, attempting to measure that strength would necessarily cause the thing being measured to change.[141]

One solution to this problem was to simply reduce the phenomenon to something that could be measured. This was the approach taken by Biot when he aimed to measure the strength of the pile using Charles-Augustin de Coulomb's (1736–1806) torsion balance, which afforded precise—if very difficult to obtain—measurements of the force between two charged objects. Obtaining the measurement required imparting electric fluid from the pile while open and thus restricted the investigation to only the open pile.[142] This constraint not only meant that the results were restricted to only one aspect of the pile, but also led to erroneous generalizations about the

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[139] Nicholson, "Account," 187.
[140] Steinle, *Exploratory Experiments*, 48–49.
[141] Steinle, *Exploratory Experiments*, 49. How quickly the strength of the pile changes depends on the metals used and the nature of the dilute acid solution in which the metals are immersed. Some combinations produce relatively little change in strength over short periods of time, whereas others cause much more considerable changes.
[142] Biot, "Recherches physiques," 5–42.

device. As Steinle notes, "[Biot] asserted that the fluid level in a trough device would have no effect on its operation. While this might have been true enough for an 'open' trough battery, investigating the device in its closed condition would refute the claim immediately."[143]

The mathematical approach thus made little progress despite considerable effort. In fact, Napoleon himself signaled the importance of this area. During a visit by Volta in 1801, Napoleon announced two prizes for important discoveries in the field: an annual prize of 3,000 francs (equivalent to six months of a professor's pay or more than $20,000 today) for the year's best work and a one-time prize of 60,000 francs (ten years of pay or more than $450,000 today) for any discoveries rivaling those of Franklin or Volta.[144] Despite this massive prize, the mathematical approach lacked the instruments and techniques required to make substantial progress. The grand prize went unclaimed and the "annual" prize was in fact awarded only once, to British natural philosopher Humphy Davy in 1806.[145]

In sum, the mathematical approach was not aimed at the discovery of new phenomena like electromagnetism, and it lacked the prerequisites to make substantial progress in the study of the pile itself. Steinle summarizes the situation thus:

> In Paris, research into the pile remained a marginal undertaking, yielding no contributions of significance comparable to those of England or the German states. We have here a remarkable instance in which early fixation on mathematical formalization and precise measurement severely constricted the scientific gaze, allowing it to linger only on a small subfield. . . . Given the restrictions under which French scientists labored, the full range of phenomena remained out of reach.[146]

4.2: Experimentalism, exploratory experimentation, and the open pile

The aim of this section will be to explain why the experimentalist approach did not lead to the detection of electromagnetism prior to Ørsted's discovery in 1820. This explanation will involve two components. First, I will show that the nature of the experimentalist approach shifted substantially between the middle of the eighteenth century and the discovery of electromagnetism. It changed from a broad, exploratory approach to one increasingly focused on responding to the existing scientific discourse, which in turn required maintaining the theoretical assumptions implicit in that discourse. Second, I will argue that given the assumptions and evidence inherent in this discourse, the most probable place to look for a magnetic effect in the

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[143] Steinle, *Exploratory Experiments*, 46.
[144] The currency conversions are very rough but come from converting francs to euros via Edvinsson, "Historical Currency Converter," adjusting euros for inflation and then converting euros to dollars. For the annual salary of French academics, see Steinle, *Exploratory Experiments*, 44; and Crosland, *The Society of Arcueil*, 20–25.
[145] Steinle, *Exploratory Experiments*, 429.
[146] Steinle, *Exploratory Experiments*, 47.

pile would have been the open pile and not the closed pile. Indeed, experimental searches for magnetism in the open pile were conducted unsuccessfully.

4.2.1: The changing nature of scientific experimentation

There are a few ways that electromagnetism could have been discovered experimentally in the absence of anything like Ørsted's metaphysical approach. The discovery could have been made by accident provided that one happened to bring a detector of magnetism close to a current-carrying wire. The discovery also could have been made by experimenting with the voltaic pile to test for a wide range of potentially interesting effects, including magnetism, without a strong theoretical reason to suspect they would be found. Yet, very little of this kind of experimentation appears in the historical record. In the case of the floating pile experiment (see the introduction), for example, even straightforward modifications to existing experiments were not tried, even in passing. This speaks to a change in the nature of scientific experimentation which, I will argue, contributed to the failure to discover electromagnetism earlier.

It will be instructive to compare research at the beginning of the nineteenth century to research conducted in the middle of the eighteenth century, as both periods include the discovery of devices—the Leyden jar and pile respectively—that can be rightly understood as defining research in their respective time periods. Leverage Research's study of the Leyden jar's invention and reception, for example, paints a picture of electricians as being relatively disinterested in theory—or, at least, self-conscious about the limitations of electrical theory—and substantially more interested in exploring the various amusing and practical ends to which the Leyden jar could be employed.[147] Our previous case study described the situation thus:

> From very early on, the electricians approached the jar much as a child approaches a new toy, inundating the presses with new reports on exciting new capacities and applications. They subjected it to all manner of prodding, flipping every switch they could find, swapping materials, and seeing what different objects did when subjected to the marvelous new invention. The jar was used to electrify trees, produce lights of varying colors, and deliver shocks to unsuspecting friends; a few electricians even put the thing in their mouths. As curious as some of the studies were, however, the method bore fruit. Indeed, Kleist's own process of discovery represents a manifestation of the approach. His motivations, as letters to Krüger and Swietlicki indicate, were primarily those of entertainment; his discovery, as he wrote in May of 1746, was an incremental one, grounded in successive experiments and extrapolations.[148]

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[147] See Pence, "The Discovery and Impact of the Leyden Jar," 17–35.
[148] Pence, "The Discovery and Impact of the Leyden Jar," 22–23.

Indeed, earlier work on this topic details over one hundred materials and objects that were subjected to electrification, including such oddities as a human thigh bone, urine, a drawn sword, glazed earthenware, and hay.[149] Electricians also tried every conceivable combination of elements to form a capacitor like the Leyden jar, including twenty-one different options for forming the insulator and forty-three options for materials to use in the electrode, among other variations.[150]

The research in this time period can be fairly characterized as exploratory in nature, as opposed to theory-driven. The *Encyclopedia of Systems Biology* sets up the distinction as follows:

> Experiments count as exploratory when the concepts or categories in terms of which results should be understood are not obvious, the experimental methods and instruments for answering the questions are uncertain, or it is necessary first to establish relevant factual correlations in order to characterize the phenomena of a domain and the regularities that require (perhaps causal) explanation. . . . Rather than testing hypotheses; it varies parameters or circumstances to see what will happen; it utilizes background knowledge . . . to establish novel correlations, follow anomalies, seek improvements in instrumentation and experimental protocols, and the like; and it employs a variety of systematic strategies to govern appropriate variation of parameters and appropriate orientation to the primary questions in the background.[151]

One notable advantage of the exploratory approach is that researchers are substantially more likely to stumble across unexpected experimental results that can be obtained by modifying the experimental setup. In fact, the discovery of the Leyden jar—especially in the case of Kleist—resulted from just this kind of manipulation. A thoroughly exploratory approach seems likely to have aided the floating pile experiment, for example, as exploration probably would have led to the relatively simple manipulation of the experimental setup (namely, closing the pile) that would have prompted discovery of electromagnetism in that case. Other cases are less clear, but given the larger number of natural philosophers who conducted research of the pile and the relative ease with which the phenomenon would have been discoverable, it seems an exploratory approach would have accelerated the discovery.[152]

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[149] Pence, "The Discovery and Impact of the Leyden Jar," 25.
[150] Pence, "The Discovery and Impact of the Leyden Jar," 27.
[151] Burian, s.v. "Exploratory Experimentation," 720–23.
[152] An incomplete review of three of the major English-language scientific publications active between 1800 and 1820 (*The Philosophical Magazine*; *The Journal of Natural Philosophy, Chemistry & the Arts*; and *Philosophical Transactions*) revealed more than one hundred unique authors mentioned as having conducted experiments with the pile.

4.2.2: Nicholson and Carlisle's experiments with the pile
A characteristic example of how the approach to experimentation changed over time is an early report on the pile from William Nicholson (1753–1815) and Anthony Carlisle (1768–1840) in the *Journal of Natural Philosophy, Chemistry & the Arts* (of which Nicholson was the editor). While the pile was announced in June 1800, Carlisle was able to obtain the first four pages of Volta's letter before it was published in *Philosophical Transaction*.[153] He shared this with Nicholson, allowing them to conduct experiments with an important, surprising, and brand-new device, an ideal circumstance for conducting exploratory experimentation.

The experiments Nicholson describes can be divided into roughly three categories. The first concerns the electrical nature of the device. Nicholson and Carlisle begin by obtaining an initial shock to check that the device operates the way Volta described.[154] They then conduct experiments "directed to ascertain that the shock we felt was really an electrical phenomenon."[155] This involved trying to detect electricity with an electrometer, and when it failed, using a device called a revolving doubler to make the instrument more sensitive so that they could successfully detect the electricity.[156] They then used the revolving doubler to determine that the wire connected to the silver plate was electrified minus, whereas the wire attached to the zinc end was electrified plus. Next, they tried to conduct the (presumably) electric fluid through the usual conductors and non-conductors of electricity and achieved results consistent with the idea that the pile was producing electric fluid. Finally, Nicholson notes that he witnessed a spark from the device upon completing the circuit and "again when [he] was expressly looking for it."[157]

The next category of experiments concerns the decomposition of water. Nicholson notes that they were in the habit of placing some water at the contact point between the wire and the upper plate of the pile in order to secure the contact point, and Carlisle noticed that some gas seemed to be produced, which Nicholson thought smelled of hydrogen.[158] They then undertook an experiment in which each wire was inserted into a tube of water while the pile was in action. This produced a "fine stream of minute bubbles"[159] which began to flow from the wire connected to the silver end of the pile, while the opposite side became tarnished and blackened. They then describe the following:

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[153] On Volta's original publication, see Volta, "Electricity Excited," 403–31, or the English translation in *Philosophical Magazine* (Volta, "Electricity Excited," 289–311). On the advanced copy obtained by Carlisle, see Nicholson, "Account," 179. While the experimentation is performed by both Nicholson and Carlisle, Nicholson makes clear that he is the one reporting the results.
[154] See Nicholson, "Account," 182.
[155] Nicholson, "Account," 182.
[156] Nicholson, "Account," 182.
[157] Nicholson, "Account," 185.
[158] Notably, hydrogen gas alone does not have a smell, although hydrogen combined with other elements can sometimes produce an odor.
[159] Nicholson, "Account," 182.

> We had been led by our reasoning on the first appearance of hydrogen to expect a decomposition of the water; but it was with no little surprise that we found the hydrogen extricated at the contact with one wire; while the oxygen fixed itself in combination with the other wire at the distance of almost two inches.[160]

Carlisle repeated the experiment and used a "tincture of litus," which changed color on the zinc side, indicating that an acid was being formed.[161] They subsequently conducted the experiment with a stronger pile, collected and measured the resulting gases, and then burned them to produce a loud detonation.[162]

Finally, Nicholson directs attention to understanding more about the properties of the pile by performing a series of small tests to see their effect on the device. These tests include reversing the sequence of the metals in the pile (e.g., starting with zinc instead of silver or vice versa), seeing how long the pile can remain in operation (two to three days), determining how to remove the corrosion that builds up in the pile over time, constructing a pile using larger pieces of metal, using more pieces of metal, and using wires that resist oxidation to a stronger degree.[163]

Nicholson's report represents an approach that is neither as exploratory as the investigations into the Leyden jar nor as hypothesis-driven as the popular conception of modern science. The investigation that is most clearly hypothesis-driven is the one into whether the device's shock was produced by electricity. They subjected the pile to tests that would yield one result if the pile was electrical and another if it was not, and obtained the result that they doubtlessly expected. On the other hand, Nicholson's series of experiments aimed at varying the properties of the device and seeing their effect fits with the notion of exploratory experimentation. He does not appear to have had any particular hypothesis in mind and instead aimed to vary the characteristics of the device's basic elements—the metals and the wires—to see the outcome.

The decomposition of water is somewhat harder to place as either exploratory or hypothesis-driven. On the one hand, it fits the narrative of an interesting result arrived at via exploratory experimentation; Nicholson and Carlisle appear to have noticed an unusual production of gases, decided to investigate, and got an interesting result. However, it is likely that this was guided by the antecedent hypothesis that if the pile was electrical, it would be possible to use it to decompose water. Both Nicholson and Carlisle would have been aware of Lavoisier's report on the successful decomposition of water from the mid-1780s, and Nicholson himself had published a successful replication of Troostwyk, Deiman, and Cuthbertson's

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[160] Nicholson, "Account," 183. The original quotation contains the word *oxigen,* which has been changed to the modern term *oxygen* to avoid confusion.
[161] Nicholson, "Account," 183.
[162] Nicholson, "Account," 186.
[163] On reversing the sequence of metals, see Nicholson, "Account," 182; on how long the pile can operate and removing corrosion, see Nicholson, "Account," 183; on testing larger pieces of metal and more pieces of metal, see Nicholson, "Account," 184; and on testing wires that resist oxidation, see Nicholson, "Account," 185.

experiments in decomposing water with electrical discharges only three years prior.[164] The biggest surprise was not that an electrical effect could decompose water, but that a device which appeared to produce relatively mild electrical effects was capable of this decomposition.

Nicholson and Carlisle's decomposition of water with the pile is characteristic of the experimentation performed using the pile between 1800 and 1820. In this literature, what one finds is neither rigid hypothesis testing nor unconstrained experimentation. Instead, one finds experimentation that is exploratory in nature, but also much more heavily focused on contributing and responding to the existing scientific discourse. For example, immediately following the announcement of the pile, much attention is directed to whether the pile is electrical or not. Still more attention is directed toward repeating Nicholson and Carlisle's decomposition of water or attempting to decompose other substances in a similar manner. There are, of course, exceptions. An article by Henry Haldane describes inserting a sewing needle underneath the skin to see how it would receive the shock of the pile, immersing the pile completely in water, putting it into an air pump and withdrawing the air, and other experiments.[165] Yet there appears to be a general trend toward less experimentation that is not motivated by the research avenues and debates found in the literature.

Further research is needed to establish whether the changes in the reported experimentation in electricity indicate a general shift in the nature of scientific experimentation beyond the relatively small literature base that concerns this paper. However, it does seem that the broad exploratory experimentation characteristic of the mid-eighteenth century would have been better suited to discovering the unexpected interaction between current-carrying wires and magnets, whereas the more constrained experimentation characteristic of the early nineteenth century, for all else it accomplished, seems to have been destined to miss it.

4.3: Galvanism and the open pile

As just described, the approach to scientific experimentation shifted between the middle of the eighteenth century and the early nineteenth century to become less broad and exploratory in nature and more focused on conducting experiments that responded to the existing scientific discourse and its implicit assumptions. This development made the discovery of electromagnetism through exploratory experimentation unlikely. Yet, experimentalists might have discovered electromagnetism provided they developed a hypothesis according to which magnetism might be found in the action of the pile. Given the large number of similarities between electricity and magnetism (as discussed in section 2) and the substantial interest in research of the pile, a natural question is whether anyone developed and tested such a hypothesis.

[164] On Lavoisier's work, see Lavoisier, "Extrait d'un Mémoire," 452–55, and Meusnier and Lavoisier, "Mémoire." On electrical decomposition of water, see Pearson, "Experiments and Observations," 241–48.
[165] Haldane, "Experiments and Observations," 241–45.

We know from the floating pile experiment (see introduction) that at least Desormes and Hachette had this hypothesis, and, as we will see, they were not alone. This nevertheless failed to lead to the discovery. The goal of this section will be to demonstrate that one reason for this failure is that the association between the pile and galvanism caused natural philosophers to search for magnetism in the open pile rather than the closed pile, and thus those interested in discovering electromagnetism were systematically led astray.

Research conducted using the pile was typically referred to as "galvanic" research. This term has slipped out of modern usage and cannot be easily or neatly mapped onto any extant modern terms or scientific fields. As a result, it is instructive to briefly discuss the kinds of research grouped under galvanism as well as the relationship between the galvanic research conducted with the pile and the earlier galvanic research conducted before Volta's invention of the pile in 1800.

Galvanism draws its origins and its name from the phenomenon that Luigi Galvani (1737–1798) described in 1791 whereby a frog's leg contracted every time the muscle and nerve were connected in a metallic arc consisting of two different kinds of metals.[166] Galvani interpreted his finding to indicate that an electrical fluid intrinsic to the animal itself was being stimulated by the introduction of the metallic conductors. This fluid was initially referred to as "animal electricity," although *galvanism* quickly became the dominant term.[167] Research of galvanism quickly became popular and led to a substantial debate among natural philosophers about the nature of the galvanic fluid. This debate can be usefully grouped into three questions: (1) Is the galvanic fluid electrical? (2) Does the galvanic fluid come from the animal itself or from outside the animal? (3) Is the galvanic fluid identical to the nervous fluid or does it only stimulate the nervous fluid?[168]

Volta's invention of the voltaic pile in 1800 was an important continuation of this research and, for some natural philosophers, convincing evidence of the answers to some of these questions. The pile most clearly demonstrated that the use of two different metals alone could produce electrical effects without the need for animal tissue, which convinced many natural philosophers that the galvanic fluid was not intrinsic to animals. It also convinced many natural philosophers that galvanism was importantly related to electricity. Yet, there was not clear agreement on the

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[166] Galvani, *De viribus electricitatis in motu musculari commentarius*. See also Kipnis, "Luigi Galvani and the Debate on Animal Electricity," 114–16.

[167] The change in terminology was probably caused, in part, by a desire to avoid potentially embarrassing association with the discredited theory of animal magnetism. For example, Gren once remarked, "The name animal electricity appears to me not well chosen, for it leads to the cause which perhaps does not exist at all. One should not use this name because of its association with this weird magnetizer [Mesmer]. Gren, "Bemerkungen über die sogennante thierische Elektrizität," 408–9. Translation from Kipnis, "Luigi Galvani and the Debate on Animal Electricity," 130–31.

[168] See Kipnis, "Luigi Galvani and the debate on animal electricity," 118.

precise nature of this relationship, and the continued conceptual distinction between galvanism and electricity had a significant effect on the experimentation conducted using the pile.

4.3.1: The relationship between galvanism and common electricity

Prior to the invention of the pile, there were many known similarities between galvanism and so-called "common electricity," but few saw them as decisively demonstrating that galvanism was electrical in nature. Among the most important known similarities were transmission through the same conductors and non-transmission through the same non-conductors, movement through conductors at great speed, and exhibition of polarity. Yet, some important differences left the debate unsettled, most notably that galvanism did not produce sparks or shocks and that it didn't affect electrometers.

The fact that galvanism exhibited some of the known electrical effects, but not all of them, led to the view that it might be a variety or kind of electricity or otherwise bear an important relationship to common electricity without being identical to it. Cavallo provides a relatively clear statement of this idea by analogy to liquids and gases:

> As there are several liquids of visible fluids like water, sprits, etc. which have diverse properties in common, at the same time that they are essentially different; that as there are several invisible and permanently elastic fluids like common air, inflammable air, fixed air, etc. which are very dissimilar, though possessed of certain common properties; so there may be several sorts of more subtle fluids essentially different from each other, yet bearing some analogy to the electric fluid.[169]

From this point of view, the pile substantially strengthened the notion that galvanism was an electrical phenomenon because the pile produced shocks and sparks and could affect an electrometer while also clearly being part of the galvanic research tradition. Yet, this did not settle the debate about whether galvanism was the same kind of electricity as so-called common electricity because, for all the similarities between the pile and the Leyden jar, the phenomena each produced were different in important ways. One very clear example is the production of shocks. The Leyden jar's shocks were so powerful, one of its discoverers, Musschenbroek, described them as so strong that he refused to undergo them again. However, the shocks of the voltaic pile were very weak and sometimes could not be felt without first wetting one's skin.[170] Similarly, the Leyden jar could produce very visible sparks and a loud accompanying pop, whereas the voltaic pile produced sparks that were barely visible or audible. Additionally, the

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[169] Cavallo, *A Complete Treatise on Electricity*, 3:72. I have replaced the term *&c* with the more modern *etc*. in this quotation.

[170] For Musschenbroek's reaction, see Musschenbroek to Reamur, January 20, 1746; reprinted in Gralath, "Geschichte der Electricitat, Zweyter Abschnitt," 428.

pile was very good at stimulating tissue and decomposing substances, whereas the Leyden jar was not.

Whether the different electrical effects were the same continued to be debated into the 1830s. In 1829, for example, the influential experimenter Humphry Davy argued that the electricity produced by animals was of a different kind than common electricity or that produced by the pile.[171] Davy's brother arrived at a similar conclusion in his study of the torpedo fish in 1832.[172] Indeed, the question was sufficiently unsettled that in 1833 Faraday thought it necessary to read a paper to the Royal Society that aimed to prove the identity of electricities derived from different sources.[173]

The unsettled debate about the relationship between galvanism and common electricity can even help to explain why the term *galvanism* persisted long after the introduction of the voltaic pile. Natural philosophers were largely convinced that galvanism was electrical, but they were not convinced that it was the same as common electricity. Additionally, galvanism referred to a distinctive set of phenomena that differed from the phenomena of common electricity, and thus natural philosophers preferred to have a concept that uniquely referred to what was characteristic of that line of research.

As research of the pile progressed, it also quickly became clear that the pile exhibited different phenomena depending on whether it was open (with the wires extending from its poles left unconnected) or closed (with the wires connected).

In fact, the open pile exhibited many of the effects that were well known from common electricity, whereas the closed pile seemed to exhibit effects that were more consistent with galvanism. For example, touching the wires of the open pile to one's skin generated a stronger, albeit brief, shock followed by a weaker but longer lasting shock-like sensation. The open pile exhibited signs of electrical attraction and repulsion, including the ability to affect the electrometer, whereas these signs vanished once the wires of the pile were connected. The closed pile, particularly ones with trough-style designs, also exhibited some new phenomena. For example, the wire of a sufficiently strong closed pile glowed and became warm over time, an effect not known to occur in the instantaneous discharges of common electricity.[174]

Some apparent patterns emerged from these differences. For example, it appeared that the open pile was associated with some kind of buildup of electric fluid, which was then released once the pile was closed. In this view, its strong, brief shock was explained as the release of this built-up electric fluid, and the weaker, longer lasting shock was believed to be caused by some

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[171] Davy, "An Account of Some Experiments on the torpedo," 15–18.
[172] Davy, "An Account of Some Experiments and observations on the torpedo," 259–78.
[173] Faraday, "Experimental Researches in Electricity—Third Series," 23–54.
[174] See Steinle, *Exploratory Experiments*, 32–34, for a discussion of similar ideas.

continuous production of electric fluid coming from the pile in action. Similarly, the signs of attraction and repulsion were attributed to the buildup of electric fluid, whereas the disappearance of the signs upon connecting the pile occurred because the pile reached equilibrium, much as the Leyden jar does once the inside and outside of the device are connected. It appeared, then, that the open pile was more strongly associated with common electricity because it demonstrated the electrical effects typical of common electricity, but the closed pile was more closely associated with galvanism because it either failed to exhibit these effects or exhibited them only weakly, and because it exhibited new effects besides.

Thus, it seemed to natural philosophers that the pile was an instrument for studying galvanism and that while galvanism was related to electricity, there were differing views on the precise nature of that relationship. Additionally, while the open pile appeared to exhibit signs that were closely related to common electricity, the closed pile did not. With this understanding in place, we can now explain one aspect of why electromagnetism was not discovered sooner: natural philosophers searched in the wrong place.

4.3.2: Searching for electromagnetism in the open pile

Evidence suggests that natural philosophers who investigated the connection between the pile and magnetism searched in the open pile rather than the closed pile. In fact, Ørsted says as much in the second sentence of his paper announcing the discovery:

> It seemed demonstrated by these experiments that the magnetic needle was moved from its position by the galvanic apparatus, but that the galvanic circle must be complete, and not open, which last method was tried in vain some years ago by very celebrated philosophers.[175]

There is also the floating pile experiment discussed in the introduction to this paper. In that experiment, it appears that Hachette and Desormes were willing to go through the effort and difficulty of creating a massive pile weighing in excess of 200 kg (440 lb) and figuring out how to make it float in order to test only whether the open pile would align with the magnetic meridian. However, they did not consider also testing the pile closed to see if it might create some magnetic effect that was not present in the open pile. Or consider the experiments by Romagnosi in 1802 and Bouvier in 1804, which both looked at the effect of the open pile on a magnetic compass needle.[176] These examples demonstrate that natural philosophers saw the open pile as a substantially more plausible place to search for magnetism than the closed pile.

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[175] Ørsted, "Experiments," 273.

[176] On Romagnosi, see Martins, "Romagnosi and Volta's Pile," 81–102. On Bouvier, see Bouvier, "Galvanic Experiments with Ice," 303–5.

This can be explained by considering the evidence available to natural philosophers at the time. When the discovery of electromagnetism became technologically feasible, four lines of empirical evidence appeared to suggest a connection between electricity and magnetism. These were (1) the large number of commonalities between the observed effects of electricity and magnetism; (2) credible reports of lightning changing the polarity of magnetized needles; (3) experimental reports from Ritter and Arnim that suggested one might be able to construct a voltaic pile using magnets; and (4) the general trend of finding connections between phenomena that were once thought to be distinct, particularly the sense that oxidation, electricity, heat, and light all appeared to be related to the effects of the pile.[177]

The first two lines of evidence would have suggested that the open pile was the correct place to search for electromagnetism. For instance, the numerous preexisting commonalities between electricity and magnetism were substantially more apparent in the open pile than in the closed pile. Section 2 included the following list of these commonalities:

(1) Both cause effects on other bodies, apparently at a distance.
(2) Both occur in two types.
(3) In both, charges (or poles) of the same type repel and charges (or poles) of opposite types attract.
(4) Opposite charges (or poles), when combined, can neutralize the effect of the other.
(5) Both appear to obey the inverse square law.

Of these effects, the closed pile exhibited only (2) and (4), whereas the open pile demonstrated all of them. Arguably, the lack of attraction and repulsion in the closed pile could have been seen as an example of (4), but the open pile was unique in demonstrating the phenomena that seemed to link electricity and magnetism.

Alternatively, consider the credible reports of lightning changing the polarity of magnetized needles. Given the apparent similarity between a Leyden jar and a lightning strike, and given that attempts to reproduce this effect with the Leyden jar had failed, it is reasonable to assume that more electricity might be needed to somehow produce this effect. Yet, only the open pile showed an apparent buildup of electrical matter. Thus, searching in the closed pile would have been tantamount to searching for this effect where there appeared to be *less* electric fluid.

The other lines of empirical evidence, namely the apparent difference in oxidation potential in magnets and the general tendency to discover connections among forces, did lead to research aimed at discovering a connection between electricity and magnetism. Research focused on the difference in oxidation has already been discussed in section 2, but it was a promising research

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[177] On Ritter's experiments, see Humboldt, *Versuche über die gereizte Muskel*, 189. On Arnim's experiments, see Arnim, "Ideen zu einer Theorie des Magneten," 59. Also see appendix A for a more detailed account of this history.

program that happened to be a dead end. Additionally, the known connections among seemingly disparate forces was an important source of inspiration and motivation for Ørsted's search for electromagnetism, as discussed in the previous section.

In short, experimentalists failed to discover electromagnetism because the available evidence led them to the wrong guess about where to search for the phenomenon and because recent changes in the nature of scientific experimentation robbed them of the broadly exploratory approach that could have led to the discovery without correctly guessing where to search.

Conclusion

This case study analyzes the discovery of electromagnetism, particularly how Ørsted discovered it and why he succeeded over others. I argue that the key technological requirements—sufficient current and a detector of magnetism—were both available no later than 1802 and, while the circular nature of the magnetic effect would have been surprising, it would not have impeded the discovery. I also show that speculation about a connection between electricity and magnetism was relatively common historically. In fact, there were many attempts to discover such a connection and numerous interesting pieces of evidence suggested it might exist. Yet the discovery did not occur until 1820.

Ørsted's discovery itself was made possible by his adoption of several metaphysical commitments acquired from his study of Kant and Schelling. These commitments caused him to recognize recent discoveries in natural philosophy as suggesting a greater unity among seemingly disparate forces—discoveries that were overlooked by his contemporaries and led him to pursue theories regarding the underlying nature of this unity. Ørsted's metaphysical commitments were also critical to his 1806 undulatory theory of the movement of electricity through a conductor.[178] This theory is a likely precursor to the conflict of electricity theory that he subsequently used to explain the discovery of electromagnetism, and it would have justified his prediction that the current-carrying wire might produce forces beyond heat and light. While the undulatory theory did not suggest that magnetism specifically would be produced by the electric current or that magnetism, if it was produced, would be detectable by instruments then available, it was likely enough to cause Ørsted to take the important and novel step of checking the current-carrying wire for a magnetic effect and thus led to the discovery of electromagnetism.

The discovery was not made elsewhere for several reasons. The mathematical approach that was ascendent in Paris between 1805 and 1815 was in the business of describing existing phenomena mathematically and not of discovering new phenomena. Additionally, the tools required for success in the mathematical approach—particularly, precise instruments for measurement and mathematical techniques to describe the phenomenon of interest—were not available for

[178] See Ørsted, "On the Manner in Which Electricity Is Transmitted," 210–14.

studying the pile. As a result, that approach, for all else it accomplished, made comparatively little headway in galvanic studies.

The experimentalist approach certainly focused on discovering new phenomena like electromagnetism, but it, too, failed to make the discovery. This was due to two important factors. First, changes in the nature of scientific experimentation between the discovery of the Leyden jar and the discovery of electromagnetism meant natural philosophers were no longer in the habit of conducting the kind of broad, exploratory experimentation that might have discovered electromagnetism without a particular reason to think the current-carrying wire might produce magnetic effects. Additionally, the association of the pile with the galvanic research tradition and several facts about the operation of the pile itself would have suggested that the open pile, and not the closed pile, was the most plausible place to search for a magnetic effect. Indeed, natural philosophers tried searching in the open pile for magnetism without success.

The unity in nature that Ørsted believed in continued to be examined later, although not necessarily for the same reasons Ørsted had. Two decades after his discovery, several scientists independently developed one of the most important unifications in the history of science in the principle of energy conservation.[179] Appropriately for a generalization as broad as energy conservation, its development was probably a synthesis of new experimental findings (including Ørsted's) on the convertibility of forces, improvements in the ability to quantify various aspects of these forces, and perhaps the lingering influence of German metaphysicians like Kant and Schelling.[180] This is likely as Ørsted would have wanted. For all his focus on developing metaphysical views about the underlying structure of nature, he was no dogmatist about the merits of approaches that differed from his own. Instead, he was eclectic, finding merits in the work of others where his contemporaries frequently did not.

Fittingly, Ørsted's attitude is perhaps best summed up in his own words:

> However, we would go too far if we wished to name everyone who helped prepare the way which lies before us. We gratefully acknowledge the merits of the natural philosophers of our time, also with regard to their views on chemistry. We also willingly acknowledge that we have received several felicitous hints from older philosophers, from mathematicians, and from individual experimenters. When using their work, we shall not

[179] See Kuhn, *The Essential Tension*, 69–104, for an interesting discussion of this topic.
[180] On the relevant experimental developments, see Kuhn, *The Essential Tension*, 73–74. On the mathematical developments, see Kuhn, *The Essential Tension*, 84–90. The influence of Kant or Schelling is far from certain except in the case of Colding, one of the recognized discoverers of the principle and a student and protégé of Ørsted's for many years (although, as Caneva points out in "Colding, Ørsted, and the Meanings of Force," 1–138, Ørsted does not seem to have sufficiently appreciated Colding's work). The influence of German metaphysics is also suggested by the interesting overrepresentation of Germans in the development of the idea. Of the twelve natural philosophers involved in work related to the principle of energy conservation, five were German and therefore inculcated in an intellectual climate that was particularly likely to include the ideas of Kant and Schelling, and one was a direct protégé of Ørsted. See Kuhn, *The Essential Tension*, 96–100.

> neglect to acknowledge and honour their merits where we think they might be forgotten.[181]

So too with Ørsted himself.

[181] As translated in Ørsted, "View of the Chemical Laws of Nature Obtained through Recent Discoveries," 313.

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Appendix: A Partial Timeline of Electromagnetism Research

Due to several striking similarities between electricity and magnetism, speculation that the two forces might share a deeper connection was relatively common historically. Below I provide a partial history of the observations, experiments, and speculations about the connection, beginning with Gilbert's distinction between "electricks" and "magneticks" in 1600 and ending with the discovery of electromagnetism in 1820.

- **1600**: Gilbert makes a clear distinction between "electricks" and "magneticks" in *De Magnete*.
- **1630**: Gassendi is among the first to observe that "magnetism was communicated to ferruginous bodies by lightning."[182]
- **1676**: A report appears in *Philosophical Transactions* of a lightning strike near some ships that caused their compasses to reverse polarity, leading them to sail in the opposite direction from their intended target.[183]
- **1746**: A report appears in *Philosophical Transactions* of the attractive effect that static electricity can exert on a magnetized compass needle.[184]
- **1748**: Beraut, professor of mathematics at the College of Lysons, publishes a dissertation that claims to show that a true connection between electricity and magnetism exists and that they are the same force, only differently disposed. His attempts to demonstrate this fact were not widely accepted.[185]
- **1751**: Franklin claims to have "frequently given polarity to needles and reversed it at pleasure."[186] Franklin concluded in 1773 that this was not an electric effect, but was instead caused by the same mechanism that causes metals to gain polarity when heated or struck with a hammer and that "these two powers of nature have no affinity with each other, and that the apparent production of magnetism is purely accidental."[187]
- **1756**: Dalibard repeats some of Franklin's experiments on magnetizing sewing needles and erroneously concludes that he has discovered the electromagnetic relationship necessary to prove the identity of electricity and magnetism.[188]
- **1774**: The Electoral Academy of Bavaria holds an essay prize competition on the following question: "Is there a real and physical analogy between electric and magnetic forces, and, if such analogy exist, in what manner do these forces act upon the animal

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[182] Fahie, *A History of Electric Telegraphy*, 251.
[183] Anonymous and Haward, "An Extract of a Letter," 647–53. The event itself is said to have been relayed from a Mr. Haward, although the author is not identified.
[184] Anonymous, "A Letter to Mr. Benj. Robins," 242–45.
[185] See Fahie, *A History of Electric Telegraphy*, 251–52. I have not examined Beraut's claims in detail and thus do not know why his views failed to gain traction.
[186] Franklin to Collison, June 29, 1751.
[187] Franklin to Dubourg, March 10, 1773.
[188] See Franklin and Dalibard, *Experiences et observations sur l'electricité*. See also Hamamdjian, "Dalibard, Thomas François." For a later treatment of what Franklin's experiments show about the relationship between electricity and magnetism, see Singer, *Elements of Electricity and Electro-chemistry*, 204–6.

body?"[189] Van Swinden's answer was that "the similarity was but apparent, and did not constitute a real physical resemblance," whereas professors Steiglehner and Hubner contended that "so close an analogy as that exhibited by the two sciences indicated a single agency acting under different circumstances."[190]

- **1796**: Fowler conducts experiments to determine whether magnets influence galvanic effects. He observes that magnets can be used to induce muscular contractions in a frog, but this effect turns out to be no different than the effect produced by a non-magnetic iron bar.[191]
- **1797**: Humboldt publishes an account of some of Ritter's experiments on exciting contractions in frogs with magnets. "He produced a galvanic arc with two pieces of iron and observed no twitching of the frog. He replaced one of the iron pieces by a magnet and there was an immediate twitching of the frog. He also used a chain with iron and steel and observed no effect, but when the iron or steel piece was connected to a magnet, there were strong effects."[192] In a French translation of Humboldt's work two years later, he denied any direct influence of magnetism on galvanism.[193]
- **1800**: Arnim reports that the two magnetic poles exhibit different oxidation phenomena, a potentially important observation since difference in oxidation potential was known to be important for finding metals ideally suited for use in a voltaic pile.[194]
- **1801:** Lüdicke attempts to build a battery using a series of magnets.[195] He observes a small number of bubbles surrounding the north pole of the batteries and even fewer surrounding the south pole. In a follow-up paper a few months later, however, he concludes: "Thus I assume that these connected magnetic pieces may have worked here probably only as good heat conductors, and not by a kind of Galvanism."[196]
- **1801:** Gautherot describes his experience of touching metal strings attached to the upper and lower portion of the pile together: "a very decisive adhesion took place; they seemed united as by a magnetic power which was so strong that he could move the united wires in every direction to a distance of some centimeters."[197]
- **1802**: Nicholson reports that "at Vienna a discovery has been made, that artificial magnet, employed instead of a Volta's pile, decomposes water equally well as that pile and the

189 Fahie, *A History of Electric Telegraphy*, 255.
190 Fahie, *A History of Electric Telegraphy*, 256.
191 Sue, *Histoire du galvanisme*, 207.
192 Humboldt, *Versuche über die gereizte Muskel*, 189.
193 Humboldt, *Expériences sur le galvanisme*, 115.
194 Arnim, "Ideen zu einer Theorie des Magneten," 59. See also Martins, "Ørsted, Ritter, and Magnetochemistry," 342.
195 Lüdicke, "Versuche mit einer magnetischen Batterie," 375–78. See also Martins, "Ørsted, Ritter, and Magnetochemistry," 342.
196 Lüdicke, "Fortsetzung der Versuche mit verbundnen Magnetstählen," 114–19. Translation from Martins, "Ørsted, Ritter, and Magnetochemistry," 343.
197 From Anonymous, "Intelligence and Miscellaneous Articles," 458. I have not been able to determine whether this is a reliable effect or whether the effect is indeed magnetic in nature. Research into the nature of this effect and, if it is indeed magnetic, research of why the effect was not thought to constitute the discovery of electromagnetism would be a valuable contribution to the literature.

electrical machine; whence (as they write) the *electric* fluid, the *galvanic* fluid, and the *magnetic* fluid are the same."[198] Nicholson indicates that he attempted to repeat the experiment and found no effect.

- **1802**: A lawyer by the name of Gian Domenico Romagnosi published a report of needle deflection caused by a pile in an Italian newspaper. The experiment concerned static electric attraction of a compass needle, but the report is later erroneously taken to indicate that Romagnosi and not Ørsted discovered electromagnetism.[199]
- **1804**: Bouvier conducts an experiment using a "very delicate and sensible compass needle" to compare the strength of the pile's electrical attraction compared to the magnetic attraction of the compass. Bouvier does not appear to have used his needle to search for magnetism in the closed pile itself, but for the reasons discussed above, it is likely that he would have found it if he had.[200]
- **1804**: In a treatise on galvanism, Aldini claims that a Genoan chemist by the name of Mojon was able to render a steel needle magnetic by placing it in a voltaic circuit. After Ørsted's discovery, this is erroneously taken to constitute the true discovery of electromagnetism.[201]
- **1805**: Ritter presents research to the München Academy of Sciences in which he claims to have succeeded in creating a battery out of magnets with the same strength as a voltaic column.[202] Ritter's work was criticized in 1807 by Erman, who found that he was unable to replicate any of Ritter's important claims regarding electromagnetism. Erman also found no difference in oxidation potential between the different poles of a magnet.[203]
- **1805**: Hachette and Desormes attempt to see whether a floating pile will turn in accordance with the magnetic meridian. The experiment was not successful, but would have succeeded had the pile been closed instead of open.
- **1806**: Lehot indicates that the wires of the pile attract each other magnetically: "It has long been known that the two wires which terminate a pile attract one another, and, after contact, adhere like two magnets. This attraction between the two wires, one of which receives and the other loses the galvanic fluid, differs essentially from electrical attraction."[204]
- **1815**: Biot conducts experiments on double refraction and sees in the phenomenon an analogy to electricity and magnetism: "These results show that there exists in the action of crystals upon light, the same opposition of forces which has already been recognized

[198] Nicholson, "Scientific News," 234.
[199] Martins, "Romagnosi and Volta's Pile," 81–102.
[200] Bouvier, "Galvanic experiments with ice," 303–5.
[201] Martins, "Romagnosi and Volta's pile," 81–102.
[202] [Anon], "Extrait d'une lettre," 97–100. Reproduced in Anonymous, "Extract of a Letter," 368–69. See also Martins, "Ørsted, Ritter, and Magnetochemistry," 344–45.
[203] Erman, "Beitraege über electrisch-geographische Polaritaet," 1–35, 121–45. See also Martins, "Ørsted, Ritter, and Magnetochemistry," 345.
[204] Fahie, *A History of Electric Telegraphy*, 256. It is not altogether clear why this discovery did not attract more attention and why it did not constitute the discovery of electromagnetism.

in several other natural actions, such as the two kinds of magnetism and the two kinds of electricity."[205]

- **1817**: Maschmann observes that the crystallization of silver (Diana's silver tree) occurs faster under the influence of the north magnetic pole than the south. He concludes that this effect is due to galvanism and that galvanism and magnetism are identical.[206]
- **1820**: Ørsted discovers electromagnetism.

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[205] Biot and Anonymous, "Intelligence and miscellaneous articles," 235–36. While Biot is the author of the original report, the author of the summary in *The Philosophical Magazine* is not clearly identified, but is likely to be Alexander Tilloch.

[206] See Mottelay, *Bibliographical History of Electricity and Magnetism*, 442; and Martins, "Ørsted, Ritter, and Magnetochemistry," 347. Maschmann's reflection on this finding can be found in Maschmann, "Einwirkung des Erdmagnetismus auf Auscheidung des Silbers," 234–39.