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Resistance to the Discovery of Electromagnetism: Ørsted and the Symmetry of the Magnetic Field

Abstract

In 1820 Ørsted found that an electric current produced a rotating magnetic effect. The symmetry properties of the new phenomenon were unexpected and acted as a hindrance to the discovery of the phenomenon. Ørsted could not anticipate the geometrical properties of the effect, but according to some authors he *claimed* he anticipated the rotational symmetry of the phenomenon. This paper offers a new interpretation of the discovery of electromagnetism compatible with Ørsted's own accounts. On the day of his famous lecture experiment Ørsted replaced his first "longitudinal effect" hypothesis by a second "transversal effect" hypothesis that assumed the magnetic effect to have a cylindrical symmetry around the wire. This paper proposes a reconstruction of Ørsted's lecture experiments, inferred from the expected behaviour of a competent physicist who intended to check the second hypothesis. This reconstruction explains why Ørsted described the observed effect of his early experiment as "irregular".

1. Introduction

Hans Christian Ørsted (1777-1851) discovered electromagnetism in 1820. In the late 19th and early 20th century it was usual to describe his discovery as due to chance. However, after the publication of Ørsted's scientific papers,[1] and Kirstine Meyer's authoritative biography[2] it became clear that he was looking for that effect. Indeed, in 1812 he had already suggested that an electric current could produce an effect upon a magnet. Simon Altmann asked the question: "Why eight years? The complete answer to this question we shall never know, but it is hightly probable [...] that during those years Ørsted repeatedly performed the wrong experiment [...]".[3]

Altmann convincingly argued that before 1820 Ørsted had been unable to perform the "correct" experiment since he expected the magnetic effect[4] to be

[1] ØRSTED (1920).
[2] MEYER (1920).
[3] ALTMANN (1992), p. 13.
[4] The phrases "magnetic field" and "electric field" were not used in Ørsted's days. Even the mathematical concept of vector had not been created, yet. However, everyone associated a

parallel to the electric current. This expectation was motivated by symmetry reasons, and it was virtually impossible to anticipate that the magnetic effect could turn around the conducting wire, because such a behaviour would conflict with all previous assumptions. Indeed, the phenomenon discovered by Ørsted could be regarded as a symmetry break. Having concluded that the phenomenon could not have been anticipated, Altmann inferred that the discovery was due to chance – as had been claimed by many authors after Ørsted's discovery – and that Ørsted probably lied when stating that he expected the magnetic effect to be transversal to the conducting wire. Accordingly, that author supports Hansteen's account of the discovery as more reliable than Ørsted's own accounts.

I agree with most of prof. Altmann's analysis of the conceptual difficulties attending the discovery of electromagnetism. Part of this paper will be devoted to providing new arguments that corroborate most of Altmann's views on those difficulties, adding however a slightly different view on Ørsted's early ideas. On the other hand, I disagree with Altmann's conclusion that the discovery occurred by chance and that Ørsted's account was not faithful. I will propose a novel reconstruction of the discovery. I will claim that Ørsted had indeed a new hypothesis that led him to try a new experiment in his famous lecture of 1820, but the new hypothesis was not equivalent to the concept of the rotating magnetic effect[5] Only a few months after the lecture experiment Ørsted was able to dismiss that hypothesis and to arrive at his final view on the magnetic effect of an electric current.

2. The Relation between Electricity and Magnetism around 1800

Retrospectively, it might seem that a relation between electricity and magnetism was known to exist at least since the 18th century. It was known that thunderbolts produced several magnetic effects and that they could even change the polarity of magnetic needles. Around 1750 lightning was recognised as an electrical phenomenon, and Benjamin Franklin attempted to magnetise sewing needles by the electrical discharge of a Leyden jar. He succeeded, and other researchers obtained the same effect.

However, after careful investigation, Franklin recognised that the polarity acquired by the needle did not depend on the direction of the electric discharge. He concluded that the effect was due only to the heating of the needle,[6] and wrote in a letter: "As to the magnetism, which seems produced by electricity, my real opinion

direction to the electric and magnetic "effects", "influences" and "forces", and they were regarded as real physical entities in space.

[5] Part of the interpretation proposed here had already been published in MARTINS (1986).

[6] The effect was indeed produced by the magnetic field of the Earth, and a steel needle could be magnetised putting it in the North-South direction and heating it, or hammering it. The electric discharge was just another means of facilitating the action of the Earth's magnetic field.

is, that these two powers of nature have no affinity with each other, and that the apparent production of magnetism is purely accidental".[7]

Other points of similarity between electricity and magnetism existed, however. There are two types of magnetism and two types of electricity. Charges (or poles) of the same kind repel, and of opposite kinds attract each other. Moreover, in 1795 Coulomb's researches established that both forces obeyed the inverse square law.

The invention of Volta's pile added a new analogy between electricity and magnetism. A pile had two opposite poles, being therefore closely similar to a magnet. It was natural to look for interactions between a pile and a magnet, and also to attempt the production of electrical effects with a magnet (and vice-versa).[8]

Guided by this analogy, Hachette and Désormes attempted to build an electric compass. In 1805 they built a large Voltaic pile with 1480 copper-zinc plates, and put this device in a small wooden boat floating on water. They expected the pile to turn and to acquire the direction of the magnetic meridian, but no effect was observed. Conversely, Ritter attempted to produce electrolysis using a magnet instead of a battery – and he did report positive results that were confirmed by his friend Ørsted. Ritter also claimed that a galvanised metallic needle would acquire the same direction as a magnetic needle.

Hence, in the beginning of the 19th century there was a widespread belief that there should be a deep correspondence between electricity and magnetism, and that in some cases a magnet and a pile could produce similar effects.

Besides the special analogy between electricity and magnetism, there was another stimulus to look for interrelations between the different natural "forces". Ørsted was strongly influenced by Kant and by the Naturphilosophie movement[9,10] claiming that the whole universe was an organism endowed with a vital soul that produced all natural forces . So, electricity, gravitation, magnetism, light, heat, chemical affinity and other forces of nature were manifestations of the same universal power and should be regarded as being intimately interrelated.

3. Ørsted's Account of His Early Thoughts

Those analogies and philosophical concepts led Ørsted to search for an interaction between electricity and magnetism. In the paper where he reported the discovery of electromagnetism Ørsted did not elucidate his leading ideas. On the contrary, he remarked "In the following account of the experiments, I will omit all ideas that led

[7] Franklin to Dubourg, 10 March 1773, in SPARKS (1840), vol. V, pp. 450-1.
[8] A detailed discussion of the early attempts to find a similarity between Volta's pile and a magnet can be found in MARTINS, "Can a magnet work as a battery? Magnetochemistry from Ritter to Hurmuzescu" (forthcoming). Early attempts to produce effects upon a magnetic needle using a Voltaic pile are described in MARTINS, "Romagnosi and Volta's pile: Early difficulties in the interpretation of voltaic electricity" (forthcoming).
[9] WILLIAMS (1973).
[10] SHANAHAN (1989).

me to the discoveries; there would be unable to bring a better elucidation of the discovered facts; I will confine myself to the facts that clearly demonstrate those results".[11] However, in the following years Ørsted published three accounts of the history of the discovery: one paper published in 1821, a short autobiography published in 1828 and an article on thermoelectricity published in *The Edinburgh Encyclopaedia* in 1830.[12] The later of those accounts is the most complete one. There Ørsted described his earliest motivation:

> The reasons for and against an essential resemblance between magnetism and electricity might, before the discovery of electromagnetism, seem to be nearly balanced. The most striking analogies were that each of them consists of two powers, or directions of powers, of an opposite nature, submitted to the same laws of attraction and repulsion; that the magnetical action on bodies, fit to receive it, has much analogy with the electrical action; that the distribution of the powers in a body, which has an electrical charge, and still more a series of bodies charged by cascade, differs very little from the distribution of the powers in a magnet; if we imagine a Voltaic pile, and principally the modifications denominated after Zamboni, composed of minute and molecular elements, it would have the most perfect analogy with a magnet; and lastly, that the tourmaline differs but little from such an electric magnet.[13]

Ørsted also clearly acknowledged the influence of philosophical concepts upon his own work:

> Electromagnetism itself was discovered in the year 1820 by Professor Hans Christian Oersted, of the university of Copenhagen. Throughout his literary career, he adhered to the opinion that the magnetical effects are produced by the same powers as the electrical. He was not so much led to this, by the reasons commonly alleged for this opinion,[14] as by the philosophical principle, that all phenomena are produced by the same original power.[15]

Now, although Ørsted believed that there should be a deep relation between electricity and magnetism, he could not find experimental evidence of this relation before 1820. According to Ørsted's assistant Johan Georg Forchhammer, "Oersted

[11] ØRSTED (1820), p. 1.
[12] The accounts published in 1828 and 1830 were probably written in 1827.[16] The Edinburgh Encyclopaedia account was originally written in English, and I will quote from the original publication. The other accounts will be quoted from Stauffer's translation (STAUFFER 1957). The original documents are reproduced in Ørsted 1920.[1]
[13] ØRSTED (1830), p. 574.
[14] TOMOTHY SHANAHAN interpreted the phrase "the reasons commonly alleged" as a referrence "to the allegation that his discovery was merely accidental".[17] I suppose, however, that Ørsted was referring to the analogy between electricity and magnetism and the production of magnetic effects by thunderbolts, and that he wanted to stress that the main source of his conviction was philosophical.
[15] ØRSTED (1830), p. 575.
[16] STAUFFER (1957), p. 46.
[17] SHANAHAN (1989), p. 304.

was searching for this, and I, who associated with him daily in the years 1818 and 1819, can state from my own experience that the thought of discovering this still mysterious connection constantly filled his mind"[18]. Why did he fail before 1820, and why did he succeed in that year?

4. The Discovery of Electromagnetism: Two Accounts

The most popular account of Ørsted's discovery originated in a letter from Hansteen to Faraday, written in 1857 – that is, 37 years after the discovery and 6 years after Ørsted died:

> Oersted had tried to place the wire of his galvanic battery perpendicular (at right angles) over the magnetical needle, but remarked no sensible motion. Once, after the end of his lecture as he had used a strong galvanic battery to other experiments, he said: "let us now once, as the battery is in activity, try to place the wire parallel with the needle". As this was made he was quite struck with perplexity by seeing the needle making a great oscillation (almost at right angles with the magnetic meridian). Then he said: "let us now invert the direction of the current", and the needle deviated in the contrary direction. Thus the great detection was made; and it has been said, not without reason, that "he tumbled over it by accident". He had not before any more idea than any other person, that the force should be transversal. But as Lagrange has said of Newton in a similar occasion: "Such accidents only meet persons, who deserve them".[19]

Let us contrast Hansteen's account with Ørsted's accounts:

(1) Since for a long time I had regarded the forces which manifest themselves in electricity as the general forces of nature, I had to derive the magnetic effects from them also. As proof that I accepted this consequence completely, I can cite the following passage from my Recherches sur l'identité des forces chimiques et électriques, printed at Paris, 1813. "It must be tested whether electricity in its most latent state has any action on the magnet as such". I wrote this during a journey, so that I could not easily undertake the experiments; not to mention that the way to make them was not at all clear to me at that time, all my attention being applied to the development of a system of chemistry. I still remember that, somewhat inconsistently, I expected the predicted effect particularly from the discharge of a large electric battery and moreover only hoped for a weak magnetic effect.[20]

(2) In consequence of the over-all unity of things he had, even in his earliest writings, assumed that magnetism and electricity were produced by the same forces. This opinion, incidentally, was not new; quite the contrary, it had alternatively been

[18] STAUFFER (1953), p. 309.
[19] Hansteen to Faraday, 30th December 1847, in WILLIAMS (1971), II, p. 892.
[20] ØRSTED (1821).

accepted and rejected throughout more than two centuries; but heretofore no one who accepted the connection had been able to find decisive proof.[21]
(3) Therefore I did not pursue with proper zeal the thoughts I had conceived; I was brought back to them through my lectures on electricity, galvanism, and magnetism in the spring of 1820. The auditors were mostly men already considerably advanced in science; so these lectures and the preparatory reflections led me on to deeper investigations than those which are admissible in ordinary lectures".[20]
(4) His researches [Ørsted's] upon this subject, were still fruitless, until the year 1820. In the winter of 1819-20, he delivered a course of lectures upon electricity, galvanism, and magnetism, before an audience that had been previously acquainted with the principles of natural philosophy.[22]
(5) Thus my former conviction of the identity of electrical and magnetic forces developed with new clarity, and I resolved to test my opinion by experiment.[20]
(6) The idea first occurred to him in the beginning of 1820 while he was preparing to treat the subject in a series of lectures on electricity, galvanism, and magnetism.[21]
(7) The preparations for this were made on a day in which I had to give a lecture the same evening. I there showed Canton's experiment on the influence of chemical effects on the magnetic state of iron.[20]
(8) The investigators had expected to find magnetism in the direction of the electric current, so that the north and south poles would act either just like or just the reverse of positive and negative electricity. All investigations had shown that nothing was to be found along this path.[21]
(9) In composing the lecture, in which he was to treat of the analogy between magnetism and electricity, he conjectured, that if it were possible to produce any magnetical effect by electricity, this could not be in the direction of the current, since this had been so often tried in vain, but that it must be produced by a lateral action.[22]
(10) I called attention to the variations of the magnetic needle during a thunderstorm, and at the same time I set forth the conjecture that an electric discharge could act on the experiment.[20]
(11) Oersted therefore concluded that just as a body charged with a very strong electric current emits light and heat at all times, so it might also similarly emit the magnetic effect he assumed to exist. The experiences of the past century, in which lightning had reversed the poles in a magnetic needle without striking it, confirmed his belief.[21]
(12) 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. The observations above recorded, of magnetical effects produced by lightning, in steel-needles not immediately struck, confirmed him in his opinion.[22]

[21] ØRSTED (1828).
[22] ØRSTED (1830).

(13) Since I expected the greatest effect from a discharge associated with incandescence, I inserted in the circuit a very fine platinum wire above the place where the needle was located.[20]
(14) He was nevertheless far from expecting a great magnetical effect of the galvanical pile; and still he supposed that a power, sufficient to make the conducting wire glowing, might be required. The plan of the first experiment was, to make the current of a little galvanic trough apparatus, commonly used in his lectures, pass through a very thin platina wire, which was placed over a compass covered with glass.[22]
(15) He had set up his apparatus for the experiment before the lecture hour, but did not get around to carrying it out. During the lecture, the conviction so grew upon him that he offered his listeners an immediate test.[21]
(16) 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; yet during the lecture, the probability of its success appeared stronger, so that he made the first experiment in the presence of the audience.[22]
(17) The effect was certainly unmistakable, but still it seemed to me so confused that I postponed further investigation to a time when I hoped to have more leisure‡.,[20]
(18) The results corresponded to expectations, but only a very weak effect was obtained, and no particular law could immediately be observed from it. It was only observed that the [effect of the] electric current, like other magnetic effects, penetrated glass.[21]
(19) The magnetic needle, though included in a box, was disturbed; but as the effect was very feeble, and must, before its law was discovered, seem very irregular, the experiment made no strong impression on the audience.[22]
(20) So long as the experiments were not more conclusive he feared that he, like Franklin, Wilcke, Ritter, and others, would be deceived by a mere coincidence [...].[21]
(21) It may appear strange, that the discoverer made no further experiments upon the subject for three months; he himself finds it difficult enough to conceive it; but the extreme feebleness and seeming confusion of the phenomena in the first experiment, the remembrance of the numerous errors committed upon this subject by earlier philosophers, and particularly by his friend Ritter, the claim such a matter has to be treated with earnest attention, may have determined him to delay his researches to a more convenient time.[22]
(22) At the beginning of July these experiments were resumed and continued without interruption until I arrived at the results which have been published.[20]
(23) In July he renewed the experiments [...] A very strong effect was immediately obtained and tested under varying conditions. Nevertheless, many

‡ Ørsted's footnote: "All my Listeners are witnesses that I mentioned the result of the experiment beforehand. The discovery was therefore not made by accident, as Professor Gilbert has wished to conclude from the expressions I used in my first announcement".

> days of experimenting were required before he could find the law governing the effect. As soon as he had discovered it, he rushed to publish his work.[21]
> (24) In the month of July 1820, he again resumed the experiment, making use of a much-more considerable galvanical apparatus. The success was now evident, yet the effects were still feeble in the first repetitions 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 galvanical current; but he soon found that conductors of a greater diameter give much more effect; and he then discovered, by continued experiments during a few days, the fundamental law of electromagnetism, viz. That the magnetical effect of the electrical current has a circular motion around it.[22]

Therefore, Ørsted's accounts are incompatible with Hansteen's account in several respects:

1) Ørsted did not use a strong battery in his preliminary lecture experiment;
2) The magnetic needle did not present a strong motion ("almost at right angles with the magnetic meridian"): it had a weak motion, instead;
3) In his initial experiments Ørsted did not find the regularity described by Hansteen (when the us direction of the current was inverted, the needle deviated in the contrary direction): the observed motion was irregular;
4) Ørsted's account does not describe the position of the conducting wire;[23] it is not evident that it was parallel to the magnetic needle;
5) Whatever the direction used by Ørsted, it was not a random choice – it was the result of Ørsted's change of attitude as he convinced himself that the magnetic effect could not be parallel to the wire.
6) Only in July 1820 did Ørsted arrive at the concept of the rotating magnetic effect around the wire.

In his well known paper on the discovery of electromagnetism, Robert Stauffer interpreted Ørsted's phrase "he thought it possible that the magnetic effect could likewise eradiate" (12) as meaning that he correctly predicted the geometrical features of electromagnetism: "The one [account] from the article on Thermo-electricity in Brewster's Edinburgh Encyclopaedia [...] is the fullest, and here Oersted added the point that he anticipated his discovery that the electric current exerts a force transverse to the direction of the current".[16]

Altmann also interpreted Ørsted's account as meaning that Ørsted claimed that he had predicted the phenomenon. However, Altmann argues that it does not seem plausible to accept this claim, and the discovery should be regarded as accidental, as described by Hansteen:

[23] Altmann, however, interpreted Ørsted's account in a different way: "Thus, even if Ørsted had lied when claiming that he had deliberately placed the wire in the correct orientation, I do not think it diminishes his achievement by an ounce. I am inclined to believe that his account of the experiment was not entirely candid, and that he was perhaps all the more human for that".

> Analysis of this section of the article in its various versions does nothing to explain why Ørsted so suddenly changed his mind as to the experiment he wanted to perform and, on the contrary, gives the impression of a feeble attempt at explaining what appears most likely to have been accidental. I thus suggest that Hansteen's account is preferable to that of Ørsted.[24]
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> The third point is the crucial one, namely how far it is plausible that Ørsted could have foreseen the existence of a lateral action. It must be said straightaway that if Ørsted did foresee this, such a thought alone would have been one of the most striking ideas for a century or more.[25]

If Hansteen's account is a faithful description of the facts, Ørsted must have distorted the facts. Why should he do that? It seems that Altmann has in mind the following interpretation: Ørsted wanted to attain recognition for his discovery; if his findings were regarded as the result of chance, this would lower the status of his work; therefore, he lied and attempted to convince the scientific community that he had predicted the effect before the lecture experiment.

This interpretation does not account, however, for the other differences between Hansteen's and Ørsted's accounts, and it is very hard to propose any motive that might lead Ørsted to lie in all other features of his account.

I would like to offer, therefore, a different interpretation. I read Ørsted's account in the following way: Ørsted did claim that he had a hypothesis in mind in his lecture experiment; but he did not claim that he had the correct hypothesis at that time. Indeed, that would be incompatible with other parts of his account. Indeed, as quoted above, Ørsted clearly stated that only in July "he then discovered, by continued experiments during a few days, the fundamental law of electromagnetism, viz. That the magnetic effect of the electrical current has a circular motion around it" (24) and "Nevertheless, many days of experimenting were required before he could find the law governing the effect. As soon as he had discovered it, he rushed to publish his work" (23).

Could Ørsted mean that he had already the correct hypothesis in the day of the lecture, and just confirmed it in July? I think that is not an acceptable interpretation. Ørsted stated that the effect was "confused" (17), "no particular law could immediately be observed from it" (18), and "the effect was very feeble, and must, before its law was discovered, seem very irregular [...] the extreme feebleness and seeming confusion of the phenomena in the first experiment [...]" (19). The only reasonable interpretation of those concordant statements is that the lecture experiment did not behave in the way Ørsted anticipated. Ørsted's experiment was guided by some hypothesis, but the observed effects were not exactly as he

[24] Stauffer argued that Hansteen could not have been an eye-witness of Ørsted's lecture, but Altmann presented contrary arguments. I will not discuss this issue, as I have no new data or arguments for or against either view (ALTMANN (1992), p. 15).
[25] ALTMANN (1992), p. 39.
[26] ALTMANN (1992), p. 14.

anticipated. Now, if only in July Ørsted was able to interpret phenomenon as a rotating magnetic effect around the electric current, what was his insight in the day of the famous lecture?

5. Ørsted's Concepts in 1820

According to Ørsted's account, "he conjectured, that if it were possible to produce any magnetical effect by electricity, this could not be in the direction of the current,

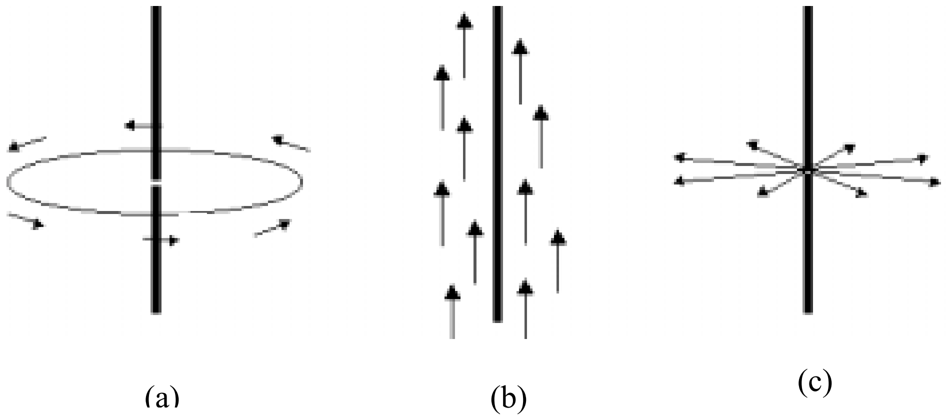

Figure 1 According to Ørsted's final view, the magnetic effect of an electric current rotates around the conducting wire (a). Before 1820, however, Ørsted's first hypothesis was that the magnetic effect should be parallel to the wire (b). According to the reconstruction presented in this paper, on the famous lecture day Ørsted arrived to a second hypothesis, of a transversal magnetic effect radially spreading from the wire (c).

since this had been so often tried in vain, but that it must be produced by a lateral action" (9). This sentence explicitly says that Ørsted (or someone else known to him) attempted to observe a magnetic effect of an electric current in the direction of the current. It is necessary to understand exactly what that meant, in order to disclose the insight of the lecture day.

First hypothesis

In the 19th century, the earliest attempts to find a magnetic effect of electricity had been guided by the analogy between a Voltaic pile and a magnet. Both devices have two poles on opposite sides. It was natural to attempt to produce an attraction or repulsion upon a magnetic needle using a Voltaic pile, and conversely. Now, when it was noticed that the poles of a pile in an open circuit did not produce magnetic effects, the next attempt might be to look for effects when the pile was active, that is, in a closed circuit. Again, 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 – as a long magnetised iron wire (8, 9). However, in the case of a magnetised iron wire it is possible to test the effects of its ends. In the case of the conductive wire, its ends are joined to the Voltaic pile and it is not possible to move them at will. The middle part of the connecting wire is the element that will be easily handled, and that part of the wire would behave, according to hypothesis 1, as the middle of a long magnetised iron wire. The magnetic effect of the electric current could be imagined to be parallel to the wire – magnetic lines of force streaming parallel to the electric current, on all sides of the wire (Figure 1). Hence, one would expect a magnetic pole to suffer a force parallel to the conducting wire – one pole in one direction, and the other pole in the opposite direction.

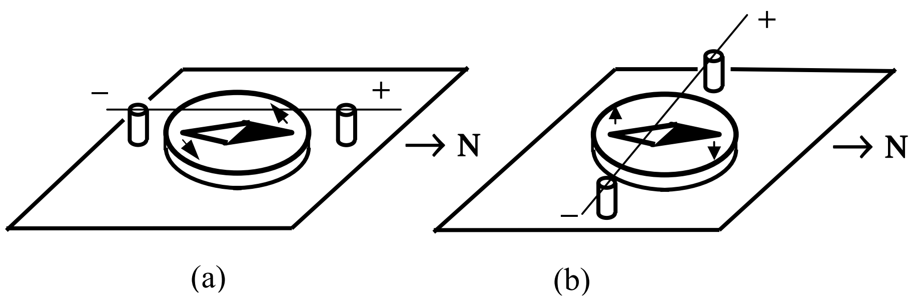

Figure 2a "Ørsted's experiment" as described in textbooks: the conducting wire is placed over the magnetic needle, in the North-South direction; when the electric current passes through the wire, the magnetic needle turns as shown by the arrows. (b) Ørsted's early experiments: the wire is placed over the magnetic needle, in the East-West direction; he expected the magnetic poles to be impelled parallel to the wire in opposite directions, producing a rotation of the magnetic needle, but observed no effect. In this position, according to current knowledge, the magnetic needle suffers a deflection in the vertical plane which is difficult to observe.

According to such a hypothesis, in which position should the wire be put relative to the magnetic needle so as to exhibit its magnetic influence? Nobody would attempt to observe any effect putting the wire parallel to the needle, because in that case the magnetic effect could only stretch or compress the magnetic needle, and no observable rotation would occur (Figure 2a).

The best position would be a perpendicular direction, because in that case the effect upon the magnetic needle would be a couple tending to turn it clockwise or counter-clockwise (Figure 2b). If the wire were put in a vertical position, the couple would tend to turn the magnetic needle in a vertical plane, and the effect would be difficult to observe. Therefore, the best position of the wire would be horizontal and perpendicular to the magnetic needle – either below it or above it.

I have been unable to find any documented evidence that Ørsted or other researchers did try this kind of experiment before 1820. However, given the above described hypothesis, it would be natural to expect that someone looking for a magnetic effect of electric current would attempt to observe that effect exactly in the way described above.[27]

Of course, according to our knowledge of electromagnetism, we understand that when the wire is perpendicular to the magnetic needle, above or below it, the needle will not turn clockwise or counter-clockwise. There will be a couple tending to turn it in a vertical plane, and the suspension of the needle will prevent this kind of motion. So, if Ørsted attempted such experiments, he could observe no effect.

Second Hypothesis

Now, returning to Ørsted's account, "he conjectured, that if it were possible to produce any magnetical effect by electricity, this could not be in the direction of the current, since this had been so often tried in vain, but that it must be produced by a lateral action" (9). What new hypothesis did he frame?

Let us recall how Ørsted described his new concept:

> (10) I called attention to the variations of the magnetic needle during a thunderstorm, and at the same time I set forth the conjecture that an electric discharge could act on the experiment.[20]
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> (11) Oersted therefore concluded that just as a body charged with a very strong electric current emits light and heat at all times, so it might also similarly emit the magnetic effect he assumed to exist. The experiences of the past century, in which lightning had reversed the poles in a magnetic needle without striking it, confirmed his belief.[21]
>
> (12) 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 magnetic effect could likewise eradiate. The observations above recorded, of magnetical effects produced by lightning, in steel-needles not immediately struck, confirmed him in his opinion.[22]

Of course, the visible effects of lightning do not turn around the thunderbolt and the light and heat emitted by a glowing platinum wire do not turn around the wire. In Ørsted's own words, those effects "eradiate" – that is, they have a straight radial motion away from the wire (or away from the thunderbolt).

I suggest that Ørsted thought that the wire could work as an extended magnetic pole, the magnetic effect being perpendicular to the wire and diverging from it to all sides – something like our picture of the electric field produced by a long straight charged wire (Figure 1c).

[27] After the first version of this article had been written, Prof. Simon Altmann informed me that he has looked up Ørsted's notebooks in Copenhagen and found that all his early experiments were done with the needle in the South-North direction and the wire in the East-West direction (personal communication).

Now, if this was indeed Ørsted's second hypothesis, what would he anticipate? He would expect one of the poles of a magnetic needle to be attracted toward the wire, and the other pole to be repelled by the wire. Accordingly, he would not be led to place the wire above and parallel to the magnetic needle (Figure 2a), because in that case the expected effect would be a downward deflection of one of the ends of the needle, and an upward deflection of the opposite end. As the magnetic needle was inside a box, it would be very difficult to observe a slight motion in a vertical plane. The two best positions of the wire that could produce an observable effect of the conjectured magnetic influence would be:

a) either in a vertical direction (perpendicular to the magnetic needle) at one of the sides of the box (Figure 3a);

b) or in a horizontal position (parallel to the magnetic needle), at one side of the box (Figure 3b) or over the box, but not exactly above the needle.

In both positions, one would expect that the wire would attract one of the poles and would repel the other one, producing a horizontal, observable turn of the magnetic needle. However, a special support for holding the compass in the air would be required to test the effect of the wire in the vertical position (a). The horizontal position of the wire (b) would be the most likely choice, if the compass was on a table.

Ørsted expected the effect to be small (1, 14), and therefore he would more likely choose a horizontal position above the box of the magnetic needle, because in this case the distance between the wire and the needle would be smaller and the deflection would be larger, and Ørsted did state that the wire was above the needle (13, 14). I suppose, therefore, that Ørsted placed his wire above the box – but not exactly in the vertical plane of the needle: slightly to the East or to the West side of the needle (Figure 4). In this position, he would expect the needle to undergo both a small (and unobservable) vertical rotation and a rotation in the horizontal plane. And this he probably observed.

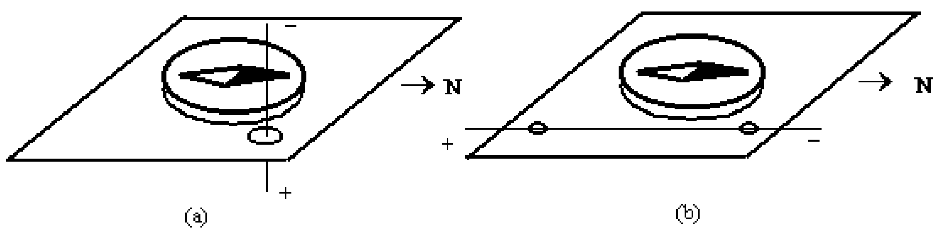

Figure 3 According to Ørsted's second hypothesis of a transversal magnetic effect emanating from the wire, other positions of the wire should be chosen, such as: (a) a vertical position close to one of the poles of the magnetic needle, because this pole would suffer a stronger attraction and repulsion, and there would occur an observable rotation or the needle; (b) a horizontal position parallel to the magnetic needle, at the same level of the needle, because one of the magnetic poles would be attracted to the wire and the other would be repelled, producing an observable rotation of the needle.

Suppose that Ørsted put the conducting wire above and to the East of the magnetic needle (Figure 4a) and observed that the needle turned clockwise. He would regard this as a confirmation of his initial hypothesis, and would imagine that the wire attracted the North-pointing pole of the needle and repelled the other pole. Now, if he had inverted the electric current, as Hansteen said he did, Ørsted would observe that the needle would turn to the other side, and this would be a regular effect. However, Ørsted stated that the observed effect was "confused", "very irregular", "no particular law could immediately be observed from it". I can see only one possible interpretation of this statement: Ørsted moved the wire (or the magnetic needle) and the observed effects did not agree with his expectations.

If Ørsted kept the wire above the level of the magnetic needle and moved the wire from East to West or conversely (Figure 4), he would expect to observe a change of orientation of the magnetic needle according to hypothesis 2 – but it would always turn the same way. On the other hand, if he moved the wire upward and downward at one side of the box, he would expect no change in the orientation of the needle, but he would observe that it would turn to opposite directions. I can imagine Ørsted saying to his students: "Now I am going to displace the wire from the left to the right of the needle, and you will see that the magnetic needle will turn to the other side" – and then, when the move was made, the students would see that the needle would keep the same position.

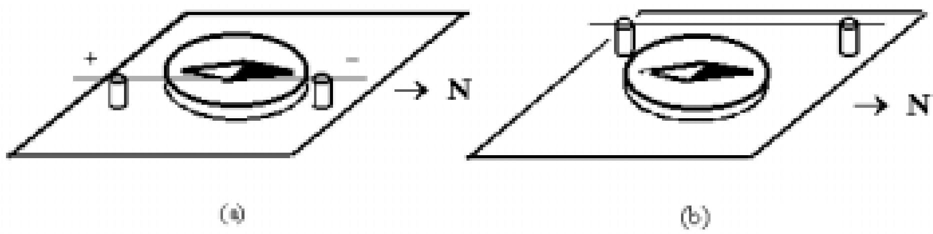

Figure 4 During the lecture experiment Ørsted attempted to observe the magnetic effect of the electric current following his second hypothesis. If he put the conducting wire above the magnetic needle (as stated by Ørsted) he should choose a position slightly to the East (a) or the the West (b) because he expected that one of the poles would be attracted and the other would be repelled by the wire. He would expect the magnetic needle to turn in opposite directions in the situations (a) and (b). However, according to current knowledge, we know that the needle would always turn to the same side in both cases. Ørsted would be unable to understand the result of this experiment, according to his first or second hypotheses.

Could the observed effect be accounted for by the first hypothesis? No, because if the wire was parallel to the magnetic needle, no rotation could be expected to occur.

6. The Anomalous Symmetry of the Phenomenon

When Ørsted moved the wire from one side of the needle to the other side, as he certainly did either in his first (lecture) experiment or in his later investigations (Fig. 5), he also observed that when the wire was exactly above the magnetic needle, parallel to it, the needle would still turn to one side. Anyone thinking about such an effect, at that time, would soon perceive that no reasonable hypothesis would be able to account for such an effect. Indeed, forget for one moment our contemporary concept of a magnetic field turning around the wire, and think about what was observable in such a situation. Suppose the electric circuit is initially open and that the wire is placed above the compass, parallel to the magnetic needle.

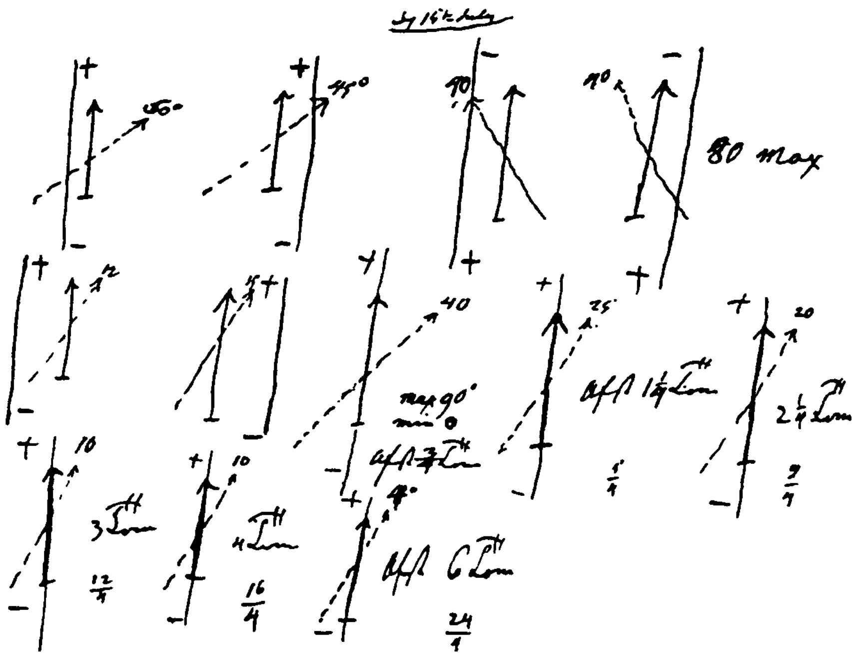

Figure 5 Ørsted's laboratory notebook contains sketches of the experiments he performed in July 1820. One of the pages,[28] for 15 July, clearly shows that he repeatedly carried out the experiment with the conducting wire to the West and to the East of the magnetic needle (upper drawings), before putting the wire exactly over the magnetic needle.

The conducting wire and the magnetic needle were both contained in a vertical plane in the direction of the magnetic meridian. This seems a symmetry plane of the experimental set-up, of course. Now, what could change when the electric circuit is closed and the electric current flows along the wire? The current is also in the same

[28] ØRSTED (1920), vol. I, p. LXXXII.

plane, and it seems that this would remain a symmetry plane of the experiment. Consequently, no motion of the magnetic needle leaving the symmetry plane could be expected. Any motion of the needle would "necessarily" occur within this vertical plane. But now, behold! The needle turns and leaves the plane. The electric current produced an effect that broke the apparent symmetry of the phenomenon, in a way that it was very difficult to understand.

Is this a completely anachronistic analysis? I do not think so. The physical "symmetry principle" was explicitly proposed only toward the end of the 19th century by Pierre Curie.[29,30] Nevertheless, symmetry arguments had been used since Antiquity, and the same reasoning that had been applied in the Middle Ages to Buridan's ass would apply here, too, and would lead any physicist to deny the possibility that the magnetic needle would turn and leave the vertical plane of symmetry.

Ørsted was well informed about symmetry, since in 1802-3 he had attended Hauy's lectures on crystallography.[31] Ørsted's correspondence also shows that he kept informed about the new discoveries concerning crystallography, polarisation and double refraction in the following years[32] and those are the fields of research where symmetry properties were more remarkable, in the early 19th century.

For us, the heirs of Ørsted's work, it is easy to understand the phenomenon: the electric current produces a magnetic field that turns around the wire, and this rotating field destroys the symmetry of the situation. This was exactly the way Ørsted explained the observed effects. However, in order to understand the historical situation, it is necessary to perceive how difficult it is to conceive a magnetic field turning around a wire. Indeed, imagine that the electric current in a straight conducting wire is analogous to the flow of water in a straight pipe. Now, the flow of water in a straight pipe will not give rise to any regular rotation phenomenon. Why should an electric current produce a regular rotation phenomenon – a magnetic effect turning around the wire?

No analogy could guide Ørsted's thought to the concept of a rotating magnetic effect[33] around the wire because no similar phenomenon was known before Ørsted's discovery. Before his experiments, Ørsted had no idea whatsoever that there could be a rotational magnetic effect around the wire, and in his first experiments he did not perceive at once that the observed phenomena led to such an interpretation.

[29] CHALMERS (1970).
[30] ISMAEL (1997).
[31] HARDING (1920), vol. II, p. 381.
[32] HARDING (1920), vol. I, pp. 257-61.
[33] Notice, however, the similarity with the rotation of the plane of polarization of light in optically active liquids, described below.

7. The Difficulty of Ørsted's Discovery

Ørsted's struggle to understand what was happening in his experiments is clearly told in his account:

> In the month of July 1820, he again resumed the experiment [...] and he then discovered, by continued experiments during a few days, the fundamental law of electromagnetism,[34] viz. That the magnetical effect of the electrical current has a circular motion around it.[35]

Hence, even in this second series of experiments Ørsted did not perceive at once what the direction of the magnetic effect was. His first step was to obtain a weak motion of the magnetic needle; the second step was to enlarge the effect, increasing the electric current; the third step was the discovery of the "fundamental law of electromagnetism", that the magnetic effect of the electrical current has a circular motion around it. Ørsted only arrived to this law "by continued experiments over a few days", and this clearly shows how difficult it was to perceive the strange symmetry of the phenomenon. Notice also that Ørsted did not deem the mere observation that the electric current acted upon the magnetic needle as the relevant part of his work: he regarded the above-described "fundamental law of electromagnetism" as his main contribution.

> The fact that an electric current produced magnetic effect, although startling, had nevertheless been anticipated by some. What was really new was the nature of the magnetic force produced. Hitherto, only central forces (i.e. forces acting in straight lines between points) had been known. A circular force was both unanticipated and inexplicable. The first 'skew' force in the history of mechanics threatened to upset the whole structure of Newtonian science. Any theory of electromagnetism would somehow have to come to grips with this peculiar phenomenon and either reduce it to the resultant action of central forces or create a new mechanics in which circular forces would be allowed a role.[36]

Only a few scientists accepted at once Ørsted's concept of the rotating magnetic effect. Jean-Baptiste Biot was one of them. In 1815, he had shown that some liquids (e.g., a common sugar solution) traversed by a beam of polarised light produce a rotation of the plane of polarisation of light, in a way similar to quartz. This phenomenon is called "rotational polarisation". It was a remarkable and unexpected effect, because a liquid was regarded as a homogeneous and isotropic medium, and therefore there was no reason to expect that the plane of polarisation could turn in either direction, when passing through a liquid. The effect was somehow analogous to Ørsted's discovery, and Biot called the attention to this analogy:

[34] Cf. the 1828 account: "Nevertheless, many days of experimenting were required before he could find the law governing the effect".
[35] ØRSTED (1830), p. 575.
[36] WILLIAMS (1965), p. 140.

> The rotational character of the force, rotating in a definite sense, in a medium that seems completely homogeneous in all its parts, as silver, copper, or any other metal, is an extremely remarkable phenomenon that hitherto had one single example, belonging to the theory of light. As I have shown, it consists of the deviation that some liquids produce on the plane of polarisation of light rays.[37]

Although Ørsted's discovery was not guided by his knowledge of polarisation phenomena, one should point out that he did recognise this analogy, since he remarked in the last sentence of his 1820 paper:

> From the formerly described observations it is valid to conclude that its effects [of the electric current] entail rotational motions; I believe that this will contribute toward the elucidation of the so-called phenomena of light polarisation.[38]

8. Concluding Remarks

A priori symmetry arguments had been used since Antiquity, and symmetry reasoning has been a powerful aid to physical thought, from Pre-Socratic thought to modern physics. However, in the particular case of the discovery of electromagnetism, symmetry reasoning was an impediment to the discovery of the phenomenon. I agree with Altmann (and therefore disagree with Stauffer) that Ørsted could not and did not anticipate that the magnetic effect of an electric current could rotate around the wire. However, I disagree with both Altmann and Stauffer since I cannot accept their interpretation that Ørsted claimed he anticipated the rotational symmetry of the phenomenon. I propose a new interpretation that seems compatible with Ørsted's historical accounts. According to the reconstruction proposed in this paper, Ørsted did have an insight on the day of his famous lecture experiment, and that insight replaced his first "longitudinal effect" hypothesis by a second "transversal effect" or "lateral effect" hypothesis as described above. However, "transversal" or "lateral" is not equivalent to "rotational", and Ørsted's second hypothesis was not equivalent to the interpretation he offered in his July paper. I also offer a conjectural reconstruction of Ørsted's lecture experiments, inferred from the expected behaviour of a competent physicist who intended to check the second hypothesis. This reconstruction makes it possible to understand why Ørsted described the observed effect of his early experiment as "irregular".

In some sense, the discovery of electromagnetism occurred by chance: it was guided by a wrong hypothesis. However, the experiment that led to the discovery of electromagnetism was not done by chance, and according to the interpretation presented in this paper Ørsted was guided by the second hypothesis, and the position of the wire relative to the magnetic needle was carefully chosen. In the light of the

[37] BIOT and SAVART (1885), p. 82.
[38] ØRSTED (1820), p. 4.

interpretation offered in this paper, Ørsted's historical accounts can be completely understood and accepted, and Hansteen's account should be rejected.

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