Electromagnetism Without Fields: From Ørsted Through Ampère to Weber

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On the occasion of the 200th anniversary of Ørsted's discovery of the magnetic effects of electric currents, this article summarizes the main stages of the development of electromagnetism before Maxwell, from Ørsted's experiments through Ampère's development of electrodynamics and Faraday's discovery of electromagnetic induction, up to the development of Weber's electrodynamics. The emphasis is on the conceptual evolution that led, on the one hand, to unification under a coherent, mathematically sound theory for all known electromagnetic phenomena within the Newtonian paradigm of instantaneous action at distance, and on the other hand, to the foundations of Maxwell's revolution, which definitely changed that paradigm.

INTRODUCTION

At the beginning of the 19th century, electricity and magnetism were well-established fields of research (see [1] for a general overview of the development of electromagnetism in the 19th century). Relying on Coulomb's results [2], in 1812, Siméon Denis Poisson (1781–1840) accomplished a mathematical formalization of the oldest and best-understood part, frictional electricity (namely, electrostatics, as it will be denominated by Ampére). The analogous formalization of magnetism was completed by Poisson 10 years later, well after Ampére's formulation of his alternative electrodynamic interpretation of the magnetic interactions.

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In 1800, the invention of the electric pile by Alessandro Volta started a revolution that gave rise to a new research field, galvanism. After a few years, the impact of the new device had extended well beyond physics, from physiology and medicine to chemistry.

All the effects of the pile were the same as those of frictional electricity. This led to the idea that the pile behaved as a battery of Leyden jars (i.e., capacitors), having the capability of spontaneously recharging itself. It was assumed that the ends of the pile (named *poles* from an analogy with the poles of a magnet), when connected with a conductor, generated a repeated, continuous discharge. However, the nature of such a "galvanic current" and the origin of the recharging capability of the pile were quite obscure.

The poles were supposed to act because of their opposite signs, regardless of the external conductor, leading to great difficulties in the interpretation of electrochemical processes. Even those who assumed the existence in the conductors of "an electric current directed from the positive pole to the negative pole" [3], did not take the pile itself into account. In summary, galvanism was a growing field, exhibiting a relationship with electricity but escaping mathematical analysis.

Regarding a possible relation between electricity and magnetism, it had been known for a long time that thunderbolts could produce magnetic effects. When, some time around 1750, Benjamin Franklin (1706–1790) recognized the electric nature of lightning, he and other researchers successfully attempted to magnetize sewing needles from the electric discharge of a Leyden jar. However, mainly because the acquired magnetization did not depend on the direction of the electric discharge, Franklin concluded [4]

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As to the magnetism, which seems produced by electricity, my real opinion is that these two powers of nature have no affinity with each other, and that the apparent production of magnetism is purely accidental, possibly due to the heating of the needle.

Actually, he was not far from the truth because a heated steel needle can be magnetized by the Earth's magnetic field. Yet, similarities actually exist. There are two types of magnetism and two types of electricity. Both magnets and piles have two opposite poles, and electric charges and magnetic poles interact in the same way, with the same law.

Hence, there was widespread belief that there should be a correspondence between electricity and magnetism, and that in some cases, a magnet and a pile could possibly produce similar effects [5].

Apart from the aforementioned analogies, another stimulus to look for interrelations between electricity and magnetism came from the German romantic *Naturphilosophie*. Following its leading exponent, Friedrich W.J. Schelling, it conceived the whole universe as a kind of organism, originating all natural forces, which, accordingly, should be intimately interrelated. Therefore, it appeared natural to look for interactions between a pile and a magnet, or also to attempt to produce electrical effects using a magnet and vice versa.

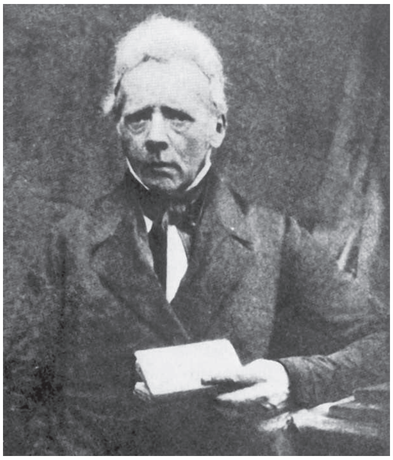


FIGURE 1. Hans Christian Ørsted.

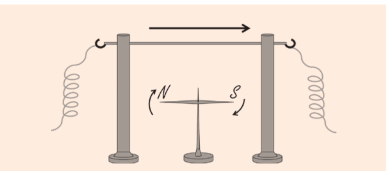


FIGURE 2. A layout of the Ørsted experiment.

As detailed in [5], in 1804, the German physicist, chemist and nature philosopher Johann Wilhelm Ritter (1776–1810) claimed that he had found an action of an open pile on a magnet and that he had obtained the electrolysis of water using magnets [6]. The following year, Hachette and Désormes [7] attempted to make an electric compass, building a large Voltaic pile and putting this device in a small floating wooden boat but did not observe any effect. This widely discredited Ritter's assertions and, consequently, the search for possible interactions between electricity and magnetism. Eventually, the enthusiasm for galvanism waned, together with the belief in the existence of a connection between electricity and magnetism. In Volume XIII of the *Edinburgh Encyclopædia* of 1819, the article on magnetism, concluded the following about magnetic principles:

> … the independence which exists between their actions and the electric actions does not allow us to suppose them to be of the same nature as electricity.

The situation changed radically the following year, with Ørsted's discovery of the magnetic effects of galvanic currents and the birth of electromagnetism.

THE BIRTH OF ELECTROMAGNETISM

On the evening of 21 April 1820, Hans Christian Ørsted (1777–1851) (see Figure 1), a not-so-famous professor at the University of Copenhagen and secretary of the Royal Danish Society of Sciences, while giving a lecture of his course on electricity, galvanism, and magnetism, performed an experiment that would modify the very nature of these scientific fields.

The lecture and the experiment were briefly described by Ørsted in a paper published the following year, wherein the word *electromagnetism* appears for the first time [8]:

> 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 a magnetic needle placed outside the galvanic circuit. I then resolved to make the experiment. 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. The effect [*namely, a deflection of the needle*] 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.

Another hint is present in an article on thermoelectricity, written for *The Edinburgh Encyclopædia* [9]:

> In composing the lecture, in which he [Ørsted] 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.

We do not have an explicit description of the experimental layout, but it would probably look as it does in Figure 2, with the wire parallel to the magnetic needle (hence, in the N-S direction). Ørsted resumed his experiments at the beginning of July and continued them without interruption. The results were published on the 21st of the same month in a four-page brochure [10]: *Experimenta Circa Effectum Conflictus Electrici in Acum Magneticam*, which he sent to several scientists and scientific Societies. The brochure was immediately published as it was in the August issue of the *Journal für Chemie und Physik*, and within a few months, it was translated into Danish, Dutch, English, French, German, and Italian. The English version appeared in the October issue of the *Annals of Philosophy* [11] as "Experiments on the Effect of a Current of Electricity on the Magnetic Needle." Note that "electric conflict" was translated as "current of electricity."

This first account was too brief and condensed to be perfectly clear on all points. In particular, the concept of *electric conflict* was vaguely defined as "the effect which takes place in this [*connecting*] conductor and in the surrounding space." A large part of the text was a description of the adopted apparatuses, the experiments performed, and their (qualitative) results without many details nor any figures. However, the conclusions drawn from the experimental results were clearly stated at the end of the paper [11]:

> The electric conflict acts only on the magnetic particles of matter. All nonmagnetic bodies appear penetrable by the electric conflict, while magnetic bodies, or rather their magnetic particles, resist the passage of this conflict. Hence they can be moved by the impetus of the contending powers. It is sufficiently evident from the preceding facts that the electric conflict is not confined to the conductor, but dispersed pretty widely in the circumjacent space. From the preceding facts we may likewise infer that this conflict performs circles; for without this condition it seems impossible that the one part of the uniting wire, when placed below the magnetic pole, should drive it toward the east, and when placed above it toward the west; for it is the nature of a circle that the motions in opposite parts should have an opposite direction.

Note explicitly that, while in April he had guessed a "lateral" action radially spreading from the wire, in July, he had already established its actual behavior. Clearly, both the existence of a magnetic effect of electricity and the fact that it acted around the wire were astonishing. Therefore, the immediate impact of Ørsted's discovery is by no means surprising. What is surprising is that, since the beginning, and particularly in the late 19th and early 20th centuries (and, in many cases, still today), it was commonly asserted that the discovery was due to chance, notwithstanding Ørsted's explicit accounts and assertions. However, as stressed in [5], after the publication of Ørsted's scientific papers [12] and Kirstine Meyer's biography [13], it became clear that he was explicitly looking for that magnetic effect [14]–[16].

In his 1821 paper, he writes:

> 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* [namely, galvanic current] *has any action on the magnet as such*. I wrote this during a journey, so that I could not easily perform the experiments, beside which, the manner of making them was not at that time at all clear to me, all my attention being directed to the development of a system of chemistry. [...] Thus I did not follow the idea I had conceived with the requisite zeal, but the lectures which I delivered upon electricity, galvanism, and magnetism during the year 1820, recalled it. My auditory consisted mostly of persons previously well acquainted with the science. On this account, these lectures and the preparatory reflections, led me on to deeper researches than those which are admissible in common lectures. My original persuasion of the identity of electric and magnetic powers were developed with greater clearness, and I resolved to submit my opinion to the test of experiment, and the preparations for it were made on a day in the evening of which I had to deliver a lecture.

This quotation clearly shows that Ørsted was convinced of the relationship between electricity and magnetism well before his experiment and that this conviction was motivated by philosophical reasons, that is, by the *Naturphilosophie*. This is explicitly stated in a passage from his 1830 article, where it reads:

> Throughout his literary career, he [Ørsted] 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 his opinion, as by the philosophical principle, that all phenomena are produced by the same original power.

Even if Stauffer's claim that "It was *Naturphilosophie*, not chance, that led to the discovery of electromagnetism" [14] is possibly excessive (Kant's influence being at least as relevant [16]), there is no doubt that such a discovery is a clear example of the impact and significance of philosophical and metaphysical factors on the development of science.

THE NEWTON OF ELECTRICITY

In August 1820, when Ørsted's memoir reached Geneva, the Swiss physician and chemist Charles-Gaspard de la Rive (1770–1834), an honorary professor of General Chemistry at the Geneva Academy, quickly reproduced Ørsted's experiments, exploiting his particularly powerful battery, with more than 500 elements. Physicist François Arago (1786–1853), permanent secretary of the Académie des Sciences (the French Academy of Sciences), attended the experiments and immediately realized their relevance. Upon his return to Paris, he reported on them at the meeting of the Academy (which were held every Monday) on 4 September 1820.

The members of the Academy remained skeptical. One of the reasons for their incredulity was due to the fact that Ørsted's result seemed to go against the ideas of symmetry. Let us consider the experimental situation reported in Figure 2, when there is no current in the wire. The horizontal wire and the magnetic needle define a vertical plane. There is nothing that seems to privilege one side of this vertical plane relative to the other side. It seems more natural to expect that the poles of the magnetic needle were attracted or repelled by a current flowing in the wire, staying in the vertical plane, instead of deviating from its north-south orientation.

Due to this general disbelief, Arago repeated the experiment during the next session, on 11 September. André-Marie Ampère (1775–1836) (see Figure 3), a member of the Academy since 1814, was present. This was the starting point of an extraordinary research effort spanning several weeks, during which he laid the foundations of electrodynamics. For a detailed account of the development of Ampère's electrodynamics, see [17] and [18].

By 1820, Ampère had achieved a good reputation as both a mathematician and a chemist. It was thanks to his mathematical work on the theory of games that he was admitted to the Academy. As remarked in [17], had he died before September of that year, he would be a relatively minor figure in the history of science. The discovery of electromagnetism opened up a whole new world to Ampère and gave him the opportunity to show the full power of his scientific capabilities.

Ampère's excitement and commitment are testified to by a letter he wrote to his son Jean-Jacques between 19 and 25 September 1820 [19]:

> […] I regret for not sending this letter three days ago […], but all my time has been taken up by an important circumstance in my life. Ever since I heard for the first time about the fine discovery by M. Ørsted, professor at Copenhagen, on the action of galvanic currents on the magnetized needle, I have been thinking continuously on this subject, and the only thing I have been doing is to write a great theory about this phenomenon and about all those phenomena already known about the magnet, and to perform experiments suggested by this theory, all of which have been successful and made me know several new facts […] and there is now a new theory of the magnet […] It does not resemble anything that has been said about it up to now.

Note that when an English version is not reported in [17] and [18], this and the following citations have been translated from the referred French originals.

The discovery of electromagnetism opened up a whole new world to Ampère and gave him the opportunity to show the full power of his scientific capabilities.

Ampère presented his initial results and the goal of his "great theory" in the following session, one week after the reproduction of Ørsted's experiment. In his own summary of the lecture [20], he states:

> I reduced the phenomena observed by Mr. Ørsted to two general facts. I showed that the current that is inside the battery acts on the magnetized needle as well as the wire connecting [the battery's two poles]. I described the experiments which allowed me to ascertain the attraction or the repulsion of the whole magnetic needle by the connecting wire. I described the instruments that I proposed to build and, among others, the galvanic spirals and helices. I announced that these latter instruments would produce, in all cases, the same effects as magnets. I then went into some detail about how I designed the magnets as owing their properties uniquely to electric currents in planes perpendicular to their axis and to the similar currents that I claim exist in the terrestrial globe. In a word I reduced all magnetic phenomena to purely electric effects.

In its conciseness, this summary is astonishing. Within two weeks of Arago's first presentation of Ørsted's experiment, Ampère accomplished the following:

- He designed and realized the astatic compass to eliminate the influence of Earth's magnetic field, showing that the magnetic needle becomes exactly perpendicular to the current. Note that Ampère's instruments were built, at his expense, by the French engineer Hippolyte Pixii (1808–1835) [17].
- He discovered a new phenomenon, namely, the attraction or repulsion of a needle perpendicular to the wire.
- He showed, with the experiment sketched in Figure 4, that both the battery and the connecting wire acted on the magnetic needle, demonstrating that the current flows, in a closed circuit, through the battery and the wire [21]. This was in stark contrast to the conception of the pile as a battery of Leyden jars.

Moreover, we realize that he had already developed the revolutionary hypothesis that all magnetic phenomena could be reduced to electric ones before the discovery of the existence of an interaction between currents and conceived the instruments for an experimental validation of this hypothesis by relying on its consequences.

Due to a lack of time, the reasoning behind his theory was exposed by Ampère in the following meeting on 25 September 1820 and is reported in [22, pp. 241–242], wherein we read:

> M. Ampère arrived to his theory in the following way. He notes that the order in which facts are discovered must not influence the consequences we derive from them. Therefore, we can imagine that we had first discovered the

FIGURE 3. André-Marie Ampère.

directive action of the current on the [magnetic] needle, and then that of the Earth. With such order of the events, one had simultaneously see both the deviation of the needle under the influence of the galvanic current and that this current is the cause of such deflection, i.e., one had seen simultaneously the cause and the effect. Observing later that the needle is also oriented by the Heart, one had concluded that the cause was the same, and, consequently, that there should be a galvanic current inside the Earth, directed from East to West along the magnetic meridian. [...] If that is really the reason of the action of the Earth on a magnetic needle, the same must also be for a magnet: therefore any magnet is just a collection of galvanic currents, following closed curves in planes perpendicular to his axis, without cutting across each other.

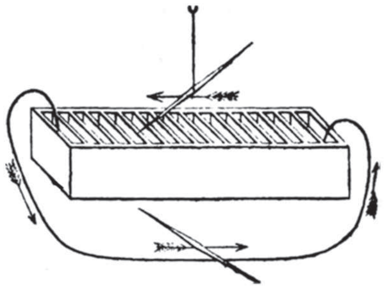


FIGURE 4. An experiment with two compasses, one above the battery and the other above the conducting wire.

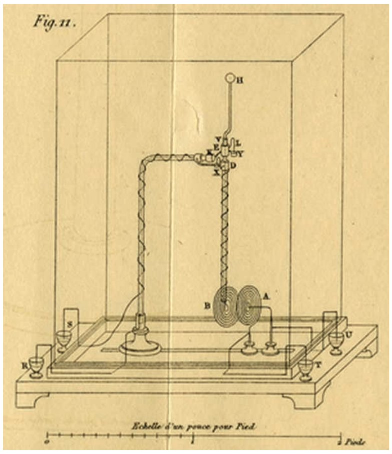
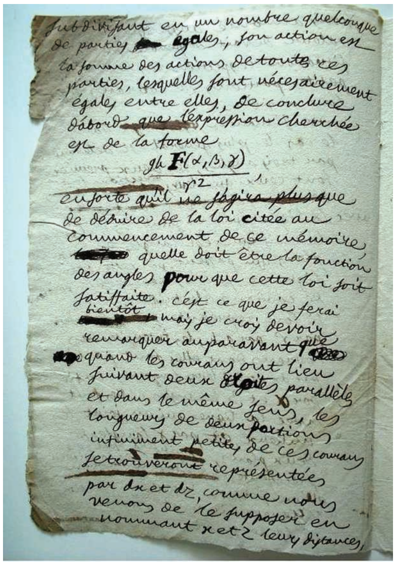


FIGURE 5. Ampere's original Figure of the two spirals experiments [21].



subdivisant en un nombre quelconque
de parties égales, son action est
la somme des actions de toutes ces
parties, lesquelles sont nécessairement
égales entre elles, de conclure
d'abord que l'expression cherchée
est de la forme
$\frac{gh\,F(\alpha,\beta,\gamma)}{r^2}$
en sorte qu'il ne s'agira plus que
de déduire de la loi citée au
commencement de ce mémoire
quelle doit être la fonction
des angles pour que cette loi soit
satisfaite. c'est ce que je ferai
bientôt mais je crois devoir
remarquer auparavant que
quand les courans ont lieu
suivant deux droites parallèles
et dans le même sens, les
longueurs de deux portions
infiniment petites de ces courans
se trouveront représentées
par dx et dz, comme nous
venons de le supposer en
nommant x et z leurs distances,

FIGURE 6. Ampère's first formulation of the force between two current elements. (Source: [24].)

Ampère verified the fundamental law of the interaction between linear, parallel currents with a new and more sensitive apparatus.

The conclusion easily follows: if magnetic interactions are actually due to the interaction between currents, there should be a direct mechanical action between electric currents, and a current-carrying plane spiral should act as a magnet (perpendicular to the spiral plane). In the same day, Ampère demonstrated that this was the case, showing that such a spiral interacted identically with a magnet and with another spiral, parallel to it. The two spirals attracted each other if the currents were in the same direction and repelled each other in the other case (see Figure 5).

Ampère's research activity in the following few weeks was impressive. He presented his results in six of the seven subsequent Academy meetings [20]–[23]. In particular,

- He developed the conception of the galvanic current as the movement of positive and negative electricity flowing in a closed circuit including the pile, due to an "electromotive force" of the pile itself, and not to its poles. He proposed the use of a magnetic needle (which he named the *galvanometer*) for its detection and (rough) measurement. This provided an operative definition of the current, independent of any hypothesis on its physical nature.
- Ampère verified the fundamental law of the interaction between linear, parallel currents with a new and more sensitive apparatus.
- He directly verified the action of the Earth's magnetism on electric currents.
- Ampère analyzed experimentally the interaction between helical currents (solenoids), showing that they are indeed equivalents to magnets and that the currents act component wise (i.e., vectorially, in today's terms).

At the meeting on 30 October 1820 (the same at which Ampère lectured on the aforementioned third point), Jean-Baptiste Biot (1774–1862) and Félix Savart (1791–1841) presented the first quantitative result, namely, that the force exerted by an indefinite linear current on a magnetic pole (orthogonal to the plane containing the current and the pole, as already demonstrated by Ampère) was inversely proportional to its distance from the current. Biot conjectured that each "slice" of the conductor underwent "a momentary magnetization of its molecules," conceived as an assemblage of miniscule, magnetized needles along the circumference of the wire. Accordingly, it should have been possible to reduce the action of a current on a magnet to elementary magnetic interactions, even if he acknowledged the "great difficulty" of that task [18].

On the other hand, we know from extant manuscripts [24] that, by the end of October 1820, Ampère had already envisaged the first draft of a formula for the force between two current elements (see Figure 6). For him, it was obvious that the force should obey the Newtonian principle of action and reaction and therefore be directed along the line joining the elements. Moreover, Ampère assumed it to be proportional, like the gravitational and electric forces, to the inverse of the squared distance. However, unlike them, it should also depend on the angles (α, β, γ) specifying the relative orientation of the elements. During the months that followed, Ampère actively looked for the mathematical expression of this dependence.

At the Academy meeting on 4 December 1820, he presented the following analytical expression for the force between two current elements [25], [26]:

$$\frac{gh}{r^2}\left(\sin\alpha\,\sin\beta\,\cos\gamma + \frac{m}{n}\cos\alpha\,\cos\beta\right), \tag{1}$$

wherein g and h denote the yet-unspecified "intensity" of the two current elements (AG and BH in Figure 7), r is their distance, m/n is a constant (undetermined) ratio, and the angles (α, β, γ) are specified in Figure 7.

Assuming $n/m = 0$, Ampère exploited (1) or equivalent equations to explain known experiments (notably Biot's results) and to make new predictions presented during the Academy meetings on 26 December 1820 and the 8th and 15th of January 1821 [27]. Moreover, from extant documents, we know that by the middle of January he had envisaged an experiment that should have led to a result in contrast with Biot's theory. He did not mention this fact during the meeting but performed the experiment on the 20th of the same month, arriving at a result consistent, rather than in contrast, with Biot's theory. Ampère also did not report this fact until the following year after having obtained the final version of his force law [see (2), which leads to the correct result]. Nevertheless, possibly because of this negative result and health problems, he interrupted his work.

In September 1821, Michael Faraday (1791–1867) (see Figure 8) presented a discovery to the Royal Society of London that prompted Ampère to return to his research, namely, how to achieve continuous rotation of the extremity of a magnet around a current-carrying wire or vice versa. Figure 9 reports Faraday's illustration [28] of his apparatus, which is the first instance of a homopolar motor.

Immediately after being informed by Faraday himself of the discovery, after reproducing the experiment, Ampère began to work intensively on the subject. Between November 1821 and March 1822, he

- developed new, more effective apparatuses
- obtained continuous rotation with terrestrial magnetism
- succeeded in obtaining the rotation of a magnet and of a wire around its axis, which had been unsuccessfully attempted by Faraday
- obtained continuous rotation exploiting only current-carrying circuits by replacing the magnet with a solenoid.

The last result strongly supported his ideas, as it was impossible to obtain these rotations with magnets alone, and was a fatal blow to Biot's claim to reduce electromagnetism to interactions between magnets. Hence, he came back to the expression of the force between current elements.

He clarified that the intensity of a current element was just the product ($i'ds'$) of the current times the elementary length of the element and showed that the more general form for the sought expression was [29]

$$dF = \frac{ii'dsds'}{r^n}(\sin\alpha\ \sin\beta\ \cos\gamma + k\ \cos\alpha\ \cos\beta), \tag{2}$$

with $k = (n-1)/2$. Assuming $n = 2$, hence, $k = -1/2$, he got his final expression for the force exerted by the unprimed on the primed element. In modern vector notation and units, which will be adopted henceforth, it reads

$$d^2\boldsymbol{F} = -\frac{\mu_0}{4\pi}\frac{ii'}{r^2}\hat{\boldsymbol{r}}[2d\boldsymbol{s}\cdot d\boldsymbol{s}' - 3(d\boldsymbol{s}\cdot\hat{\boldsymbol{r}})\ (d\boldsymbol{s}'\cdot\hat{\boldsymbol{r}})], \tag{3}$$

with $\hat{\boldsymbol{r}}$ denoting the versor from the first to the second element.

Applying the law to an arbitrary set of closed currents, he showed that their action was always orthogonal to an external current element. A second notable consequence was that two aligned current elements with the same verse should repel each other. In his own words [29], this fact

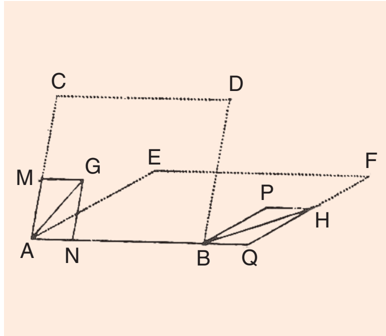


FIGURE 7. The geometry of current elements [30]. $r = \overline{AB}$; $\alpha = \widehat{GAB}$; $\beta = \widehat{QBH}$; $\gamma = \widehat{DBP}$.

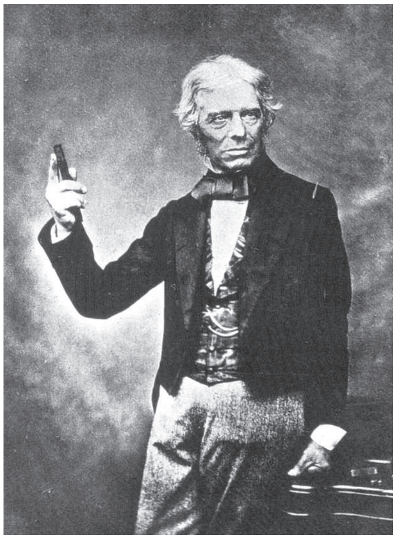


FIGURE 8. Michael Faraday.

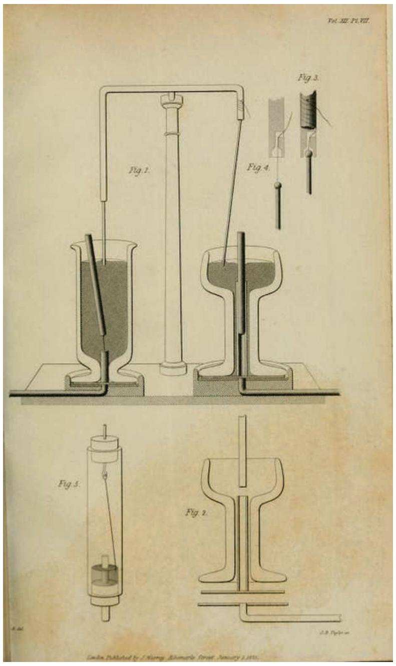


FIGURE 9. Faraday's apparatus [28].

was so unexpected, that it was necessary to verify it; later on, I performed the experiment with M. Auguste de la Rive, and it was completely successful.

Ampère was now so confident in his reduction of magnetism to an interaction between electric currents that he proposed a modification of the traditional naming of the phenomena. He writes [30, p. 200]:

> The term electromagnetic action, which I use here only to conform to custom, can no longer be appropriate to designate this kind of action. I think that it must be called electrodynamic action. This term expresses the idea that the phenomena of attraction and repulsion that characterize it are produced by electricity moving in conductors, and not by the attractive or repulsive actions of electric fluids at rest, which have been known for a long time and should be distinguished from the preceding with the designation electrostatic action.

After some months of interruption, Ampère restarted his work on electrodynamics in February 1823 together with Félix Savary (1797–1841), his student at École Polytechnique. On 3 February and 28 July 1823, Savary presented to the Academy new and important results concerning Ampère's force, reported in the same year in a full memory [31]. Starting from the experimental results that both a magnetized steel ring and an equivalent "electrodynamic" solenoid do not exert any action on a magnetic needle, he derived a second, independent relationship between constants n and k in (2), demonstrating that n must actually be equal to two. Then he applied the force law to determine the mechanical interaction between various kinds of solenoids (a denomination introduced by Ampère in the same year, from the Greek word *αωληνοειδής*, meaning "pipe shaped"), showing that a semi-infinite straight solenoid is the electrodynamic analog of a magnetic pole.

Ampère realized that his theory was now essentially complete, allowing for unification, under a coherent, quantitative framework of magnetism

A straight, current-carrying conductor, free to move only longitudinally, is not affected by the presence of any closed current.

(interaction between magnets), electromagnetism (interaction between currents and magnets), and electrodynamics (interaction between currents). Relying on Savary's results, Ampère completed his 1822 results on the force exerted by closed currents on a current element, and at the end of the year, he presented his results to the Academy [32].

He showed that, in addition to being orthogonal to the current element, $i'\boldsymbol{ds}'$, the force lies in a plane, whose normal trough the current element he called the *directrix*. The expression of the directrix, say $\boldsymbol{D}$, reads as

$$\boldsymbol{D} = \oint_C \frac{\boldsymbol{ds} \times \boldsymbol{r}}{r^3}, \tag{4}$$

with C denoting the circuit, $\boldsymbol{ds}$ is the (oriented) arc element, and $\boldsymbol{r}$ is the vector joining $\boldsymbol{ds}$ to $\boldsymbol{ds'}$. Then, Ampère provided the expression of the force exerted on the current elements:

$$\mathbf{dF} = \frac{\mu_0}{4\pi} ii'\boldsymbol{ds}' \times \boldsymbol{D} = i'\boldsymbol{ds}' \times \left(\frac{\mu_0}{4\pi} i\boldsymbol{D}\right). \tag{5}$$

Taking into account (4), we easily recognize that the term in parenthesis on the right-hand side of (5) is just the magnetic induction generated by the (steady) current in C, so that (5) coincides with today's expression of the force exerted by the magnetic field on a current element. Of course, such an identification would be misleading, as during Ampère's time, both the concepts of vector and field had not yet been introduced, and, more importantly, because for him, the force was due to a direct action at a distance.

The following year, personal problems and his teaching load overwhelmed Ampère. Only in August 1825 did he return to electrodynamics, carrying out the redaction of his masterwork, the *Théorie des Phénomènes Électrodynamiques, Uniquement Déduite de l'Expérience* [Theory of Electrodynamic Phenomena, Uniquely Deduced from Experience], published one year later [33].

The *Théorie* is structured deductively, without referring to the procedures originally exploited. He assumed as evident that the force must be directed along the line joining the two current elements. This assumption is crucial, as emphasized by Maxwell in the first of his fundamental memoires on electromagnetism [34], because there is an infinity of elementary laws, in particular the noncentral one we get from today's "field" interpretation of (5), which lead to the correct result for closed, stationary currents. Then, Ampère deduced mathematically its final expression (3) relying on the results of four "null" experiments, namely, experiments wherein the forces acting on current-carrying wires were balanced in such a way as to have no effect.

The following four results were observed:

1) Two conductors, close to each other and carrying opposite currents, do not exercise any action.
2) The same happens if one of the conductors has small sinuosities.
3) A straight, current-carrying conductor, free to move only longitudinally, is not affected by the presence of any closed current.
4) Two coplanar circular currents of equal direction and intensity do not affect a third coplanar circular current of the same intensity lying between them if the ratios between their radii are equal to those of the distances of their centers.

Even if relying on a fictitious three-stage story (basic experiments, theory, and deduction phenomena by the theory), the architecture of the *Théorie* was magnificent and convincing.

Ampère's conception of magnetism was criticized [17]. As a matter of fact, he had shown that all magnetic effects could only be due to interactions between closed, i.e., solenoidal, currents, not that they have to. Furthermore, the accuracy and repeatability of his basic experiments were questioned; however, he fixed the gold standard for all subsequent theories, exerting a deep influence on the development of electromagnetism.

Nearly 50 years later, James Clerk Maxwell (1831–1879), wrote in his *Treatise* [35]:

> The experimental investigation by which Ampère established the law of the mechanical action between electric currents is one of the most brilliant achievements in science. The whole, theory and experiment, seems as if it had leaped, full grown and full armed, from the brain of the 'Newton of Electricity.' It is perfect in form, and unassailable in accuracy, and it is summed up in a formula from which all the phenomena may be deduced, and which must always remain the cardinal formula of electrodynamics.

ELECTROMAGNETIC INDUCTION

Notwithstanding the relevance of Ampère's results, electrostatic and electrodynamics, as stressed by Ampère himself, remained completely distinct domains. Moreover, a disturbing asymmetry seemed to exist in electromagnetic phenomena: although a current acted on magnets, no capacity of magnets (or equivalent coils) for inducing a current in a conductor appeared to exist. Since 1825, Faraday had addressed this point, exploiting a couple of linear conductors, but he could not detect any effect. In August 1831, he came back to the problem, adopting a new device consisting of two coils wrapped on an iron ring (see Figure 10).

One of the coils was connected to a homemade galvanometer. Connecting the other to a battery, he observed there was

> Immediately a sensible effect on needle. It oscillated and settled at last in original position. On breaking [Faraday's underline] connection […] with battery again a disturbance of the needle [36, p. 367].

Clearly, the last effect was particularly surprising for Faraday: one could

Faraday performed many experiments varying the positions of the blades and found that the currents were directed radially, namely, perpendicularly with respect to their motion.

conceive that an increasing current could be more effective than a constant one, but how could this happen in the case of a decreasing current? In the months that followed, he improved his apparatuses and performed many new experiments, achieving direct induction between two coils in air or simply introducing a magnet (or a current-carrying coil) into a hollow coil. Moreover, reflecting on a fact already observed by Arago in 1824, namely, the slowing down of a copper disk by a magnet, Faraday conjectured that this could be due to currents induced in the disk. To check this idea, he placed two collecting blades on a disk, rotating between the poles of a powerful magnet. Connecting the blades to a galvanometer, he observed a clear deviation, thus obtaining the first instance of an electric generator different from the voltaic pile. Faraday performed many experiments varying the positions of the blades and found that the currents were directed radially, namely, perpendicularly with respect to their motion. He confirmed this fact with further experiments, moving rectangular blades and wires between or beyond the poles of the magnet.

These experiments led Faraday to conceive the concept of *magnetic curves*, defined as [37]:

> … the lines of magnetic forces […] which would be depicted by iron filings or those to which a very small magnetic needle would form a tangent.

At the beginning of the following year, he summarized his results in this way:

> If a terminated wire moves as to cut a magnetic curve, a power is called in action which tends to urge an electric current through it.

Later on, Faraday extended this statement to include the case of two conductors in relative motion and to that of induction due to varying currents. Of course, in this last case, the magnetic curves were conceived as following the variations of the primary current, thus cutting the conductor of the secondary circuit.

Regarding the meaning attributed by Faraday to the magnetic lines, when he introduced the idea of expanding or contracting magnetic lines he specified that they were a "mere expression for arranged magnetic forces." In subsequent years, his attitude toward the lines of force changed, increasingly tending to consider them as a physical entity, mediating the transmission of magnetic (and electric) forces. This process culminated in 1852 with a paper [38] that also examined gravity, radiation, electricity, and their possible relationships. The term *field*, used to denote any portion of space traversed by lines of magnetic force, was adopted for the first time in a paper published in 1846 [39].

Faraday's extraordinary discovery and experimental results spread immediately,

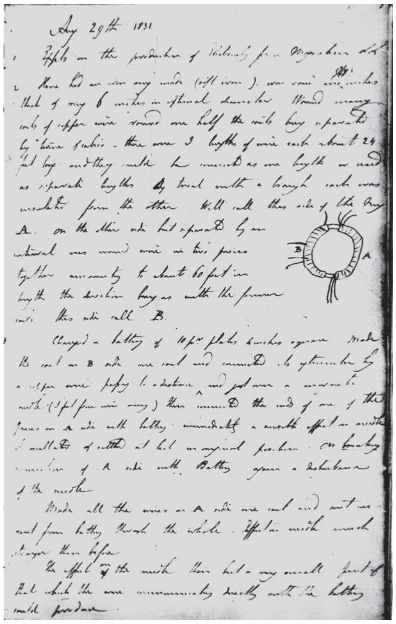


FIGURE 10. A page from Faraday's laboratory notebook dated 29 August 1831.

producing high excitement and triggering a process that rapidly led to new theoretical and practical developments. Conversely, his conception of lines of force and fields as physical entities, mediating the transmission of forces, was completely ignored, until Maxwell made it the foundation of his revolution.

This was not only a consequence of the fact that, due to his poor mathematical preparation, Faraday was unable to go beyond a purely qualitative formulation of his ideas but also because they clashed with the dominant Newtonian paradigm, so successfully exploited by Ampère. Hence, the following theoretical developments were made under the paradigm of action at distance, by marrying Ampère's theory and Faraday's facts with German precision.

UNIFYING THE FRAMEWORK

After the formulation in 1834, by Heinrich F.E. Lenz (1804–1865) of the law concerning the direction of induced currents, the first quantitative result on electromagnetic induction was derived in 1845 by Franz E. Neumann (1798–1895), a professor at the University of Königsberg [40]. Exploiting Ampère's force law and assuming that the electromotive force induced in a wire element was proportional to its velocity (as shown by Faraday) and to the force exerted on it if it had carried a unit current, he obtained an explicit expression for the electromotive force induced in an arbitrary, rigidly moving circuit. Later, he extended his result to the case of induction by varying currents and to deformable circuits.

The following year, Wilhelm E. Weber (1804–1891) (see Figure 11), a professor at the University of Leipzig, achieved the final goal, namely, framing electricity, electrodynamics and electromagnetic induction under a unified conceptual scheme, reducing them to interaction between electric charges [41].

In agreement with Ampère, he conceived current as motion of electricity. Following the hypothesis of his colleague, Gustav T. Fechner (1801–1887), he also assumed that the current in metallic conductors consists of equal amounts of positive and negative charges moving in opposite directions with equal velocities. Notably, it has recently been shown [41], [43] that this hypothesis is not necessary.

The term *field*, used to denote any portion of space traversed by lines of magnetic force, was adopted for the first time in a paper published in 1846.

The result of his efforts appeared in the first [42] of his eight major papers between 1846 and 1878, published under the series *Elektrodynamische Maassbestimmungen* (Determination of Electrodynamic Measures). The law of the force exerted by a charge q on a charge q' reads

$$\boldsymbol{F} = qq' \frac{\hat{\mathrm{r}}}{4\pi\varepsilon_0 \mathrm{r}^2}\left[1 - \frac{1}{2c^2}\left(\frac{dr}{dt}\right)^2 + \frac{1}{c^2} r \frac{d^2 r}{dt^2}\right], \quad (6)$$

wherein constant c denotes the ratio between the units of charge in the electromagnetic and electrostatic systems, whose value was first determined by Weber and Kohlrausch in 1856. It turned out to be nearly equal to the velocity of light in vacuo, as determined by Fizeau in 1849.

FIGURE 11. Wilhelm Eduard Weber [46].

As shown, the force is point to point and depends on the distance between the charges, which ensures the conservation of both linear and angular momentum. However, it also depends on the first and second derivatives of such a distance, which are necessary to account for electrodynamics and electromagnetic induction, respectively. This fact led to an immediate conflict the following year, when young Hermann L. von Helmholtz (1821–1894) published a fundamental monograph on the principle of the conservation of energy [44], wherein he demonstrated that such a principle was not satisfied in the presence of velocity-dependent forces.

In 1848, Weber showed that his force was derivable by a (velocity-dependent) potential, but the point was definitively settled only 20 years later, when he proved in detail that it did comply with the principle of the conservation of energy. The reason for this was the dependence of Weber's force on the acceleration, which was not considered by Helmholtz.

Nonetheless, soon after the determination of the value of c, Gustav R. Kirchhoff (1824–1887) demonstrated the excellent predictive power of Weber's theory, exploiting his law to investigate the motion of electricity along wires [45], a problem of both theoretical and practical relevance due to the advent of long-distance telegraphy. He found that, in the case of wires of negligible conductivity, electric disturbances propagate with a finite velocity equal to c. Despite the peculiarity of these results, namely, a finite propagation velocity stemming from instantaneous interactions and the coincidence of this velocity with that of light, Kirchhoff did not emphasize them in any way.

The year before Kirchhoff's paper on the Transactions of the Cambridge Philosophical Society appeared the memory of a 25-year-old Maxwell [34]. That was the first of a trio of papers that, adopting Faraday's point of view concerning the transmission of forces, introduced a completely new way of looking at the electromagnetic phenomena. In nine years, this led to the electromagnetic theory of light (thus unifying optics and electromagnetism within a single-field theory) and to the formulation of the equations governing such fields. A summary description of this process can be found in [46].

Maxwell's impact was not immediate. The Newtonian paradigm dominated continental electromagnetism up to the late 1880 s. Further phenomena were framed in the Neumann's and Weber's systems, and in the decade 1870–1880, new theories based on instantaneous action at distance were formulated by Helmholtz and Rudolf Clausius (1822–1888). Maxwell himself highly praised Weber's theory in his fundamental memoirs and dedicated the last chapter of his *Treatise* to a detailed description of his theory [35].

In 1887, only after Heinrich Rudolf Hertz (1857–1894) had experimentally demonstrated the existence of (nonoptical) electromagnetic waves as predicted by Maxwell's equations, were these equations widely accepted, becoming the new paradigm for describing electromagnetic interactions.

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