The key role of Oersted's and Ampère's 1820 electromagnetic experiments in the construction of the concept of electric current

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The key role of Oersted's and Ampère's 1820 electromagnetic experiments in the construction of the concept of electric current

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We show that the concept of electric current was elaborated only after the discovery by Oersted in 1820 of a connection between electricity and magnetism, and thanks to the subsequent work of Ampère. In his study of the interaction between a compass and an electric circuit, Ampère set up a crucial experiment when he put a compass above his Voltaic pile, and another one above the connecting wire. Indeed, this experiment supported his creation of a new physical quantity, independent of the nature of physical phenomena, identical in the pile and in the wire, and only characterized by its direction and its intensity. To the experimental definition of this physical quantity—the electric current—by the oriented deviation of a magnetic needle, Ampère added in his manuscripts the substance of the two present theoretical definitions of the intensity of the current, namely, the ratio of charge to time q/t, and the ratio of electromotive force to the conducting wire's resistance E/R.
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I. INTRODUCTION

The standard wording of Oersted's historic 1820 experiment—"the Danish physicist Oersted observed that an electric current flowing in a wire deflected a nearby compass needle"[1,2]—suggests that, essentially, Oersted succeeded in demonstrating a new property of electric currents, the magnetic effect. We will show that this experiment was not initially interpreted in this way. Oersted's contemporaries immediately recognized the importance of his observation of the deflection of a compass under the action of a conducting wire connected to the poles of a Voltaic pile because it established for the first time a relationship between electricity and magnetism, two areas previously thought to be independent. Oersted's discovery, however, also played a fundamental historic role insofar as it pushed Ampère to perform a series of experiments that led him to the concept of electric current. In fact, though the Voltaic pile had been known since 1800, its operation and its effects were still interpreted in 1820 using the concepts of eighteenth century frictional electricity. The experiments on the interactions between a compass and a circuit profoundly impacted research on "galvanism," meaning the phenomena produced by the Voltaic apparatus. These are the same experiments that enabled Ampère to distinguish and study a new category of phenomena that he named "electrodynamics" in order to set them apart from the phenomena produced by "ordinary" electricity (i.e., frictional electricity), which he referred to as "electrostatics."[3]

This historical analysis also highlights certain difficulties faced by students learning the basic concepts of electric circuits, especially the crucial notions of circulation and conservation, and suggests pedagogical proposals for the teaching of the concept of electric current.

II. ELECTROSTATIC INTERPRETATIONS OF GALVANIC PHENOMENA

To what extent did 18th century physicists appeal to the notion of a closed circuit? Certainly, those who engaged in electrical experiments were well aware that in order to transmit to a body the electricity produced by an electrostatic machine or accumulated in a Leyden jar—the first capacitor[4]—it was necessary to use a continuous chain of conductive materials such as metals, water, or even the human body. But electric discharges constitute short and discontinuous phenomena, understood as quasi-instantaneous flows of electricity between the source and the body to which it was connected. Electrometers were the only available electrical measuring instruments. They allowed for the assessment of the electrification of an electrical machine or a Leyden jar by the deflection of straws or leaves of gold, or through the length of a spark. However, it was problematic to compare measurements made by an electrometer with measurements made by another electrometer, hence the more relevant name "electroscope." The degree of electrification, generally called "tension," therefore remained a magnitude relating specifically to each particular instrument.

A. The weak echo of Volta's "continual" discharges

Animal electricity, which Luigi Galvani defended the existence of within living organisms, was found to be subject to the same rule of continuity that governs conductors. Galvani's experiment showing the contraction of a frog leg posed on a zinc plate when an arched copper wire connected the zinc plate with the bare nerve led to the name galvanic arc (or circle) for the assembly constituted by the metallic arc, the muscle, and the nerve (Fig. 1). For Galvani, the contraction of the leg was caused by a discharge similar to the discharge of a Leyden jar—animal electricity was transmitted by the nerve to the muscle through the intermediate metallic arc.

Opposed to the hypothesis of an electricity specific to animals, physicist Alessandro Volta believed that within Galvani's experiments it was the contact between the two different metals that produced the movement of electricity causing the muscular contractions. His "electro-motive apparatus," or "column apparatus," constructed of a stack of zinc discs and silver separated by paperboard soaked in salted or acidified water, caused muscular contractions identical to those described by Galvani and to those produced by an electric fish. Like Galvani, Volta compared the muscular contractions caused by his apparatus to those of a Leyden jar. The difference was that with this new apparatus the sensation was continuous, as if the charge reestablished itself.[5] This continuity, a sort of "perpetual motion," was difficult to understand. Volta supposed that one of the two different metals in contact exerts an "electro-motive force" on the electric fluid of the other, the result being an "endless circulation" of an electric current in the "complete circle of conductors."

But Volta's contemporaries did not accept his idea of a continuous circulation of an electric fluid.[6] French Haüy's authoritative treatise of physics stated:[7]

> The pile once charged, becomes thus a reservoir of electricity which, without the aid, and as it were without the knowledge of the operator, fills itself spontaneously, regains continually what is taken from it, and would be inexhaustible, if the humid bodies of which the pile is composed, could be prevented from losing their moisture.

Most physicists and chemists shared the idea that a Voltaic pile, as it was soon called (and later on a Voltaic battery in English[8]), discharged like a Leyden jar when it was closed on a conductor. This interpretation of how a pile functions in terms of electrostatics was based on the electrostatic effects it produced when it is "open." The ends of an open circuit Voltaic pile do indeed attract light bodies, and two vertical metal wires connected to these ends attract each other as two electrified bodies.[9] If one connects an electrometer to one of the extremities of a powerful pile, the leaves of the electrometer diverge substantially. This confirms the *electrical* nature, in the sense of ordinary electricity, of the electricity exhibited by the pile. One observed an increase of tension with the number of metal couples and variations of this tension according to the nature of the metals. The ends of the pile, whose roles were perceived as essential, were given the name "poles" by analogy with the poles of a magnet.

However, the connection between Voltaic electricity and ordinary electricity was sharply discussed on the basis of the phenomena occurring when the pile is "closed" on a conductor. The shock caused by the pile was weak and continuous while that of the Leyden Jar was strong and sudden. Furthermore, as pointed out in 1800 by Étienne-Gaspard Robertson, the electrometer no longer indicated the existence of electricity on the poles of the pile when it was closed on a conductor.[10] Finally, one concluded that the differences between the phenomena produced by frictional electricity and those produced by a pile could be explained by a difference of intensity and not of kind. Yet, it quickly appeared that new phenomena were produced in conductors—the heating of metals and the chemical decomposition of solutions. To what extent did these calorific and chemical phenomena change the understanding of the pile as a source of successive discharges?

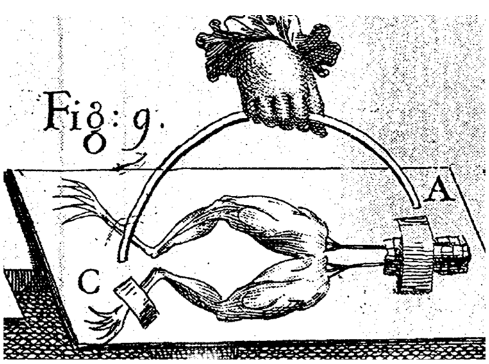

Fig. 1. The "galvanic" circle. (Luigi Galvani, *De viribus electricitatis in motu musculari commentarius*, apud Societatem Typographicam, Mutinae, Modena, 1792, pl. II).

B. The heating of metals and the decomposition of water: Electrostatic effects?

The heating of metals did not present a big surprise, as it was also produced by ordinary electric discharges. This heating, which can even cause melting, added to the shocks through the body to support the theory of successive discharges of the Voltaic pile.[11] For some, the melting point could even be the place where flows of opposite electricities neutralize one another.[12] In contrast to the heating of metals, the decomposition of water by the pile, discovered by Nicholson and Carlisle in 1800, astonished both physicists and chemists. Volta himself found it difficult to account for "this strange and admirable decomposition of water [that one] is reluctant to ascribe to an almost nil electricity, scarcely sensitive to the most delicate electrometers."[13] The possible mechanism of the decomposition of water particles was especially intriguing and seemed to call into question the foundations of chemistry.[14] How could one explain that the products of the decomposition appear at a distance from each other? Various hypotheses had been proposed: the decomposition of water molecules around the ends of each metal wire; the decomposition of molecules step by step with a recombination along a chain of molecules inside the liquid; the combination of electric fluid with water to form gas; the decomposition of the electric fluid, etc. Experiments multiplied across Europe but no consensus was reached on the mechanism of electrolysis.[15]

From the point of view concerning us here, namely, the construction of the concept of electric current, we must stress the persistence of interpretations based on 18th century theories of electricity. The poles of the pile were supposed to act by themselves and independently because of their opposed tensions. One sought to isolate the action of each pole during electrolysis by dipping the wires into separate containers only to find a surprising lack of decomposition. Davy himself, who nevertheless showed that decomposition would only result when both containers were connected by a conductor, remained a supporter of the electrostatic interpretation of the decomposition.[16] Grotthuss presented a detailed electrostatic mechanism of electrolysis. Opposite electricities of the wires immersed in water were supposed to induce a polarization of water molecules. This polarization would be followed by a "succession of decomposition and recombination" of these polarized molecules. Then, he assumed,[17]

> [...] the molecules of water, situated at the extremities of the conductor wires, will alone be decomposed, whereas all those placed intermediately will change reciprocally and alternatively their component principles without changing their nature.

This explanation, which was approved of by French physicists, did not imply any transfer of electric charges or circulation of electricity despite Grotthuss' use of the expression "current of galvanic electricity." Only the usual concepts of "tension" and attraction or repulsion at a distance were required.

C. Some critiques of the electrostatic interpretation of electrolysis

However, the electrostatic explanation of electrolysis defended by French physicists as well as by Davy, Wollaston, and Henry, was not unanimously accepted, especially among chemists.[18] Thus, in an often cited but unpublished memoir, Fourcroy, Vauquelin, and Thénard presented the hypothesis of a particular galvanic fluid that would flow out of the pile, from its positive pole to the negative pole.[19] They based this hypothesis on electrolysis experiments conducted in two vessels connected by a metal oxide, in which the oxide underwent a reduction reaction.

Swiss physicist Jean-André De Luc advanced more convincing experimental arguments against the electrostatic thesis. For instance, he reported that decomposition still occurred when he connected one of the two metallic wires soaking in water to the ground in order to make it uncharged. Decomposition even still occurred between two wires, both charged positively or negatively, if their tensions were different. De Luc deduced that chemical decompositions were not due to opposite electrical states, but to a circulation of electric fluid through the solution.[20] His hypothesis was supported by two English physicists, George Singer and Michael Donovan who questioned, "how then are we to reconcile the decomposition of water with the opinion of Sir H. Davy, that the elements of compounds are separated by the difference of electrical state in the plates of the pile."[21] Singer and Donovan substantiated De Luc's circulation hypothesis with the notorious experiments of Gay-Lussac and Thénard that showed that the decomposition was more rapid when the solution was more conductive.[22] However, if they defended the circulation "of an electric current directed from the positive pole to the negative pole" in the conductors, they did not take the pile itself into account.[23]

The study of calorific and chemical effects of the pile therefore did not really change the consideration of the pile, acting by the tension at its poles independently of the external conductor, whether metallic or liquid.

D. Researches on the possible magnetic effects of the battery

Did the attempts made before Oersted's experiment to demonstrate a relationship between electricity and magnetism alter the vision of the pile and the conductor as two separate entities? Before the invention of the pile, several phenomena suggested the existence of an interaction between electricity and magnetism. For example, experimenters observed the magnetization of steel rods or the demagnetization of compass needles as a result of a lightning strike. But they failed to magnetize a steel rod by passing through it the discharge of a Leyden jar.[24]

The Voltaic pile revived the question of a likely relationship between electrical and magnetic phenomena. Both were actions at a distance and there was a structural analogy between a pile and a magnet with their opposite poles, and a series of metal couples for the pile vs a series of elementary magnets, according to Coulomb's theory, for magnets. Grotthuss went to the point of writing that the Voltaic pile "is an electrical magnet."[25] This analogy based on polarity was fundamental for physicists keen on *Naturphilosophie*. In 1803, Oersted described some attempts of German physicist Johann Wilhelm Ritter, trained in *Naturphilosophie*, to evidence interactions between galvanism and magnetism such as to magnetize a metallic wire with a pile or to produce chemical effects with magnets. Later on, Ritter reported that a needle half zinc and half copper, movable on a pivot, took the direction of the magnetic meridian. But Hachette and Desormes' 1805 experiments with a long pile placed on a boat floating on the surface of the water did not confirm Ritter's assertions and the search for possible interactions between electricity and magnetism was widely discredited.[26]

This did not prevent scientists and amateurs from carrying out with the pile 18th-century-flavor experiments. Some tried to magnetize steel needles by passing through them the "discharge" of a pile. The Italian jurist Romagnosi approached the end of a wire connected to a pole of the pile near a compass needle.[27] Shortly after the publication of Oersted's memoir, the French physicist Boisgiraud was still amazed by the conditions of the experiment:[28]

> I endeavored, at the desire of M. Poisson, but in vain, to obtain with my apparatus effects at distance, by terminating my wires of platina [platinum] with very sharp points; contact was always necessary to produce a sensible deviation.

Poisson himself, therefore, imagined a magnetic action to be possible with an open circuit.

Thus, until Oersted's experiments, most physicists considered that the battery acted by the detectable charges on its poles and that the conductor and the battery constituted independent entities. In addition, most interpretations of galvanic phenomena relied on electrostatic concepts and on a unique measuring instrument, the electrometer. The enthusiasm for galvanism that followed Volta's invention, which had waned over the course of the following two decades, was revived with the announcement of Oersted's discovery.

III. OERSTED AND THE "ELECTRIC CONFLICT"

A. Oersted's experiments and their difficulties

Oersted's experiment became known in July 1820 via a short memoir in Latin sent by the author to the most important European scientific journals.[29] This memoir, however, did not elaborate precisely on the circumstances and the process of the discovery, described as "extraordinary" by Arago. When Oersted returned to the subject in 1821, it was to refute the role of chance in his research and to recall his previous conceptions on the unity of electricity and magnetic phenomena.[30] Oersted's memoir was characterized by a very concise, and at times ambiguous, wording, a reliance on little used terms, and the absence of any figures. Oersted himself acknowledged that "the mode of judging experiments will be much facilitated if the course of the electricities in the uniting wire be pointed out by marks or figures."[31] This has led to difficulties for journal editors in charge of the translation: "this is not very clear" notes the editor of the *Bibliothèque Universelle* of Geneva, Marc-Auguste Pictet.[32] Indeed, a number of people had difficulties trying to repeat the experiment. The description of the main experiment set out the preliminary position of the wire above, or under, the needle and

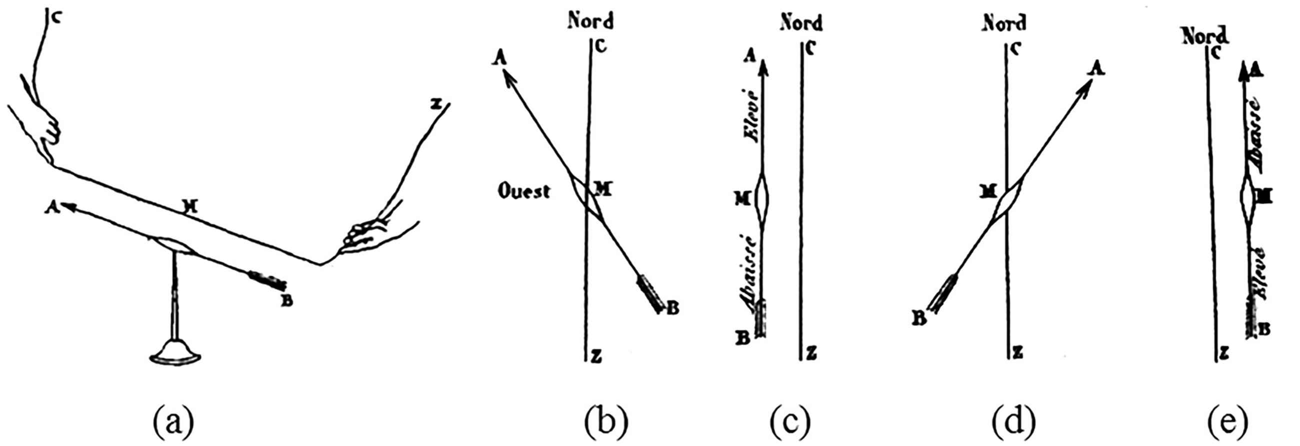

Fig. 2. One of the rare representations of Oersted baffling experiment by the French physicist Jean-Baptiste Biot. (a) The end Z is connected to the positive pole of the battery (zinc), the end C is connected to the negative pole (copper). The wire is extended parallel to the horizontal compass needle AB. (Top views) If the wire is placed above the needle (b), or under the needle (d), the north pole of the needle is deflected to the west or to the east. If the wire is placed to the right (c) or to the left (e) of the needle, the north pole is raised ("Élevé") or depressed ("Abaissé"). [J.-B. Biot, *Précis élémentaire de physique exp érimentale*, Vol. 2, 2nd ed., Paris, Deterville, (1821), pl. 2]

parallel in its direction to north/south (Fig. 2). Finally, it gave the direction of deflection of the needle according to its position relative to the poles of the battery: "the pole [of the needle] *above* which the *negative* electricity enters is turned to the *west*; *under* which, the *east*."[33]

Oersted's experiment presented two new elements in relation to previous research on the relationship between magnetism and electricity. The first concerned the operating aspect of the experiment; the second, the unexpected features of the interaction. In terms of operation, Oersted emphasized that the galvanic circle must be closed "and not open, which was tried in vain some years ago by very celebrated philosophers"[34] and the needle must be outside the "galvanic circle," and not passed through by the discharge of the battery. The second new element introduced by Oersted was the difference in nature between the magnetic effect and both the effects of ordinary electricity (attractions and repulsions) and the effects already known of galvanic electricity (thermal and chemical). The most surprising thing concerned the transverse direction that the needle took relative to the conducting wire under which it was placed. This seemed incomprehensible in the familiar Newtonian framework of action at a distance, which holds that action is always directed along the line joining the interacting entities. Furthermore, noted Oersted, the wire continued to deflect the needle even if one placed a metallic disc in between the wire and needle, whereas such a disk shielded usual electric attractions.

B. Oersted's discovery in the wake of his previous research

For Oersted, his discovery was part of longstanding research into the unity of various physical phenomena, and on the fundamental role of electrical forces in nature. We have already discussed Ritter's experiments on the interactions between electricity and magnetism, which were subsequently unconfirmed. In 1806, Oersted asserted that electricity propagated in the manner of a "wave" within the conductors; this mechanism, he went on, was likely "general throughout all nature."[35] Finally, in a work published in 1812 he sought to explain all natural phenomena by two fundamental forces, identified with electricity and that manifested themselves in various "forms of activity:" frictional electricity, galvanic electricity, chemical action, heat, light, and magnetism.[36] The two chemical forces, the *burning force* and the *force of combustibility*, could be explained by the forces of electric attraction and repulsion and vice-versa. A battery closed on a series of metal conductors and solutions was represented by a "chemical circle" or "galvanic circle" (Fig. 3). This circular geometrical representation, not linked to a concept of circulation, was exceptional. Oersted recognized the speculative character of these considerations and they were not embraced by his contemporaries.

Additionally, Oersted proposed a ranking of the different forms of activity. Frictional electricity would be the most active form of electricity, galvanism would constitute a weaker form, and magnetism would be the weakest one. Magnetism would be likely to interact with the nearest form, namely, galvanism, intermediary between frictional electricity and magnetism: "We should test, writes Oersted in 1813, whether electricity in its most latent state [i.e., galvanism]

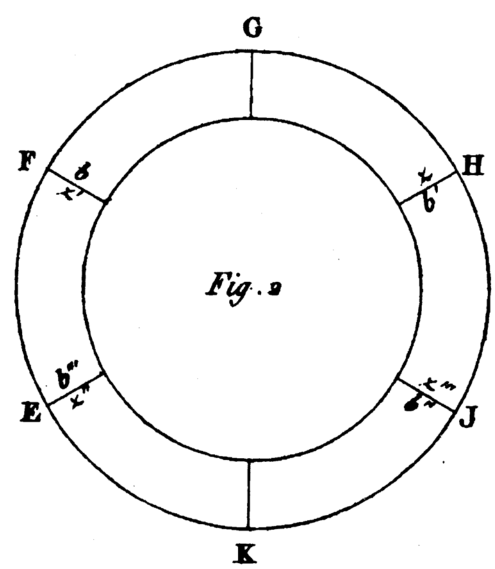

Fig. 3. The Oersted chemical or galvanic circle (1813).

has any effect on the magnet, as such."[37] He specified that this experiment would not be without difficulty, as it would require the use of only galvanic action without electrostatic action.

According to his 1819 laboratory notebooks, Oersted seems to have first looked for the interaction between a wire and a compass needle by placing the needle following the direction of radiating heat and light emitted by a wire, that is to say radially from each point of the wire. The conducting wire being placed vertically in front of the horizontal needle, one could expect to observe, by analogy, the needle moving towards the wire. The observed orientation of the needle in a direction perpendicular to the heat and light radiation was quite unexpected.

C. Electric "conflict" and "current"

In order to interpret his experiment, Oersted developed the idea that the opposite electricities from the two poles of the battery created a "conflict" within the conducting wire. Already in 1806 he stated that "in the middle of the wire, there exists a perfect equilibrium of opposite forces."[38] This view was hardly accepted; one proponent was Erman for whom conductive metals "charge and discharge each individual pole, but in the conflict between the poles, every vestige of polarity disappears to the positive as to the negative, and the circle is completely closed."[39] Oersted returned to his undulatory conception of 1806 when he stated in 1821 that "the propagation of electricity consisted in a continual destruction and renewal of equilibrium and, thus possessed great activity which could only be explained by considering it as a uniform current."[40] Both "opposite electrical forces" in conflict inside the conductor remained unobservable, however, because the electrometer no longer gave any sign of electricity, either on the wire or on the poles of the battery. These forces were very active, though, since they heated or decomposed the conductor. The concept of electric conflict was aimed to solve the paradox of the decrease in the electric tension on the battery poles while thermal, chemical, and magnetic effects occurred in the conductors.

Oersted, like many physicists, regularly used the term "electric discharge" to describe the action of the pile and he shared the dual vision of the experimental setup; on one side the battery where the separation of two opposite electricities occurs, and on the other, the wire wherein these two electricities meet and, as a result, neutralize. The electric conflict did not only act inside the conductor, but also in the surrounding space: "To the effect which takes place in this conductor *and in the surrounding space*, we shall give the name of the *conflict of electricity*."[41] So this conflict spread around the conductor, a bit like the electrical atmospheres surrounding an electrified body, which were posited by physicists who, like Oersted, had not adopted the Newtonian theory of Coulomb. Oersted went further by specifying the geometrical structure of this mysterious conflict around the conductor:[42]

> […] this conflict performs circles; for […] it is the nature of a circle that the motions in opposite parts should have an opposite direction. Besides, a motion in circles, joined concentrically, according to the length of the conductor, ought to form a conchoïdal or spiral line.

This interpretation in terms of spirals implied a direct interaction—of a new and unknown nature—between electricity and magnetism. Positive electricity leads, in its spiraling movement around the wire, the north pole of the needle, and negative electricity leads symmetrically the south pole.[43] But as Oersted himself recognized in 1821, his efforts to justify this hypothesis did not meet the approval of other physicists.[44]

As underlined by Friedrich Steinle, Oersted's essay paid little attention to the battery itself, which remained a mere purveyor of two opposite electricities.[45] While Oersted's experiment reinforced the importance of closing the battery on the conductor, it did not provide an integrated view of the "battery-conductor" set as a whole. Moreover, the notion of electric current, conceived as a continuous circulation of electricity along this "battery-conductor" set, is absent from Oersted's and other scientists' memoirs of this period.

Oersted's concept of electric conflict could account, with a certain consistency, for the deflection of the needle, but it was not intended to interpret the functioning of the galvanic circle. Misunderstood during the period, this concept was often later equated with the electric current. This confusion has been fostered by the translations of Oersted's latin memoir. His *conflictus electricus* was translated in French as "conflict électrique" and "explosion électrique," but also "courant de la pile" and in English as "current of electricity."[46] At the end of the 19th century, when the French physicist Jules Joubert added in a note to his edition of Oersted's essay, "the word electric conflict is here equivalent to the word electric current," he established the improper association between Oersted's electric conflict and Ampère's electric current.[47]

IV. AMPERE AND THE CONCEPTS OF CIRCUIT AND CURRENT

Great excitement enveloped European physicists and chemists after the repetition of Oersted's experiment in Geneva in August 1820 and won first place at the Paris Academy of sciences, where Ampère announced his first results during the following weeks.[48] If the action of the wire on the needle was understood by Oersted as a new type of electric action, for most other physicists, such as Berzelius, Davy, or Schweigger, this action was explained by a temporary magnetization of the conducting wire.[49] The new phenomenon was thus reduced to a known interaction. As for Ampère, his main objective consisted of the unification of electric and magnetic phenomena in the same theory. But his first investigations were also concerned with the analysis of the battery and conductor together.[50]

A. The hypothesis of currents in Earth and in magnets: The necessary continuity of the circuit

Ampère first gave himself the task of "completing" the work of Oersted; that is to say, to more precisely characterize the magnetic action of the connective wire on a compass needle.[51] Oersted had stressed that the angle at which the needle deviates grew with the power of the battery and reached a maximum value around 45°. Ampère understood that the magnetic action of the wire combined itself with that of terrestrial magnetism. In order to overcome this action of Earth, he invented a new type of compass needle, the astatic needle, which was moveable around an axis that followed the direction of terrestrial magnetism (the magnetic inclination) (Fig. 4). The magnetic needle is then no longer impacted by the terrestrial magnetism and rotates 90° under the action of the connecting wire to which it is parallel, whatever the intensity of the current. The magnetic action of the conducting wire, therefore, when acting alone, revealed itself to be perpendicular to the direction of the wire.

The combination of the action of terrestrial magnetism with that of the connecting wire led Ampère to search for a common origin of the two types of magnetism. To the assumption of a temporary magnetization of the wire, Ampère opposed the hypothesis; instead, he was of the mind that terrestrial magnetism could be due to the circulation of electric currents inside of the globe. And if the terrestrial magnetism was due to electric currents, should it not be the same for ordinary magnets? To support this hypothesis, Ampère arranged circuits in the form of flat spirals, effectively reproducing the attraction or repulsion of magnetic poles attracting or repelling, depending on the direction of current flow (Fig. 5).

How can one explain the existence of such currents inside Earth and inside magnets in the absence of any source of electro-motive force? For Earth, Ampère referred to the heterogeneity of its internal components as likely to create tensions, based on the model of the contact between metallic and non-metallic elements in the Voltaic pile. This heterogeneity would create Voltaic batteries closed on themselves forming continuous circular belts inside Earth.[52] For magnets, he referred to circular circuits inside the magnet, around its axis. These circuits inside magnets, initially conceived as macroscopic, were quickly assumed to be microscopic and bound to particles of metal. A particle of the magnet would constitute an elementary battery, here again similar to "a battery closed on itself in a circle."[53] These bold hypotheses were completely at odds with those of other physicists. Biot, for example, felt that elementary magnets were created inside of the wire, following circles centered on the axis of the wire (Fig. 6).[54]

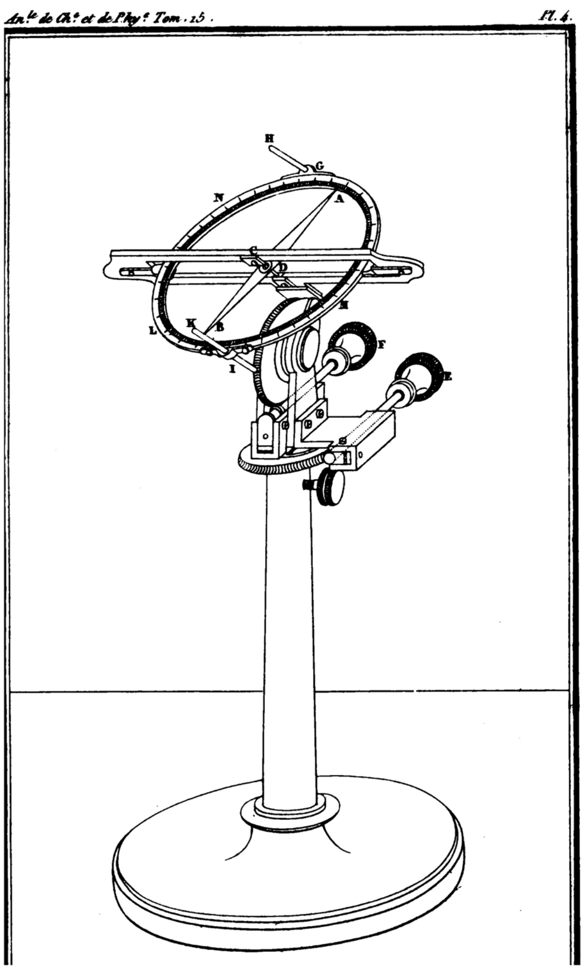

Fig. 4. Ampère astatic needle. The axis of the needle is directed along the terrestrial magnetism (magnetic inclination). The needle, insensitive to terrestrial magnetism, deflects perpendicularly to the conducting wire.

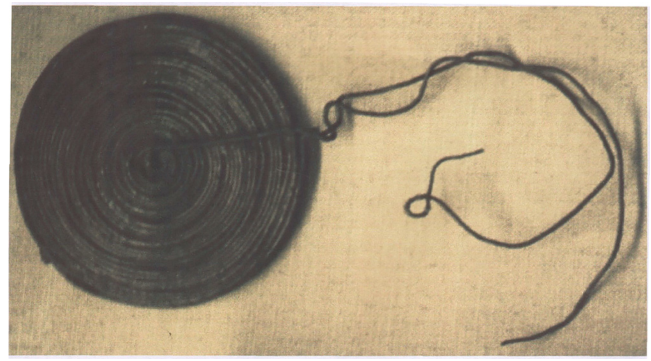

Fig. 5. Plane spiral reproducing the effects of a magnetic pole. (Table d'Ampère, Collège de France, photo C. Blondel).

In both cases—macroscopic terrestrial currents or microscopic currents inside of a magnet—the source of electromotive force is spread out through the entire circuit, which forms a sort of battery closed on itself. Moreover, there is no longer a radical distinction between a source of electromotive force and the conductor that connects its ends. The hypothesis of batteries closed on themselves gave a hint towards the notion of circuit as a whole.

B. Distinction between "current phenomena" and "tension phenomena"

The hypothesis of "galvanic circles" inside of the globe as well as inside of magnets modified the perspective on how batteries function. As we have pointed out, for most physicists, the battery could be compared to a Leyden jar, which would recharge constantly. With a battery reclosed on itself like a model of a new type of circuit, the poles of the battery lose their status as localized sources of electric tension. That is why Ampère replaced the term "pole," of which he criticized the use, with the more neutral term "extremity." The battery and the conductor, he argued, must be considered "as a single circuit always completely closed."[55] The privileged status of poles disappeared.

To ensure the belief that the magnetic and chemical effects could not be due to the existence of tension at the poles of the battery, Ampère used several arguments. First, he resumed the experiments of Gay-Lussac and Thénard on the decomposition of water, showing that decomposition does not occur when the wires connected to the battery plunge into pure water, while gases are released as soon as the water is made conductive by adding a little acid.[56] Since the tension does not increase with the addition of acid, the decomposition of water is an effect, wrote Ampère, "of what I call the electric current" and not an effect of the tension. Ampère put forward another experiment, suggested by

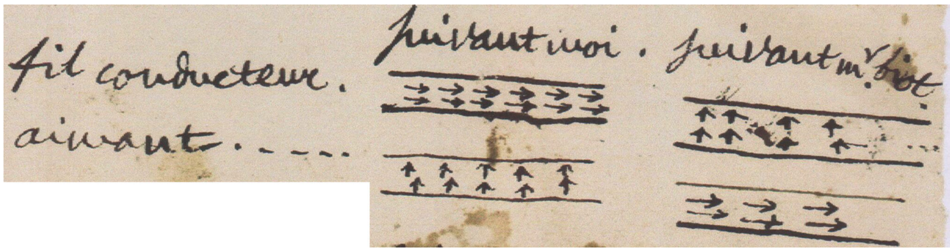

Fig. 6. Ampère diagram illustrating the opposition between his ideas and those of Biot on the origin of magnetism in a conducting wire and in a magnet. The arrows represent electric currents in Ampère's theory (column "suivant moi," "according to me") and elementary magnets in Biot's one (column "suivant mr. Biot"). (Archives Ampère, chemise 205, p. 245)

Laplace, against the hypothesis of a direct action of the poles. Using a wire of about twelve meters, he observed an identical angular deviation of the compass needle all along this wire.[57] Again, the effect could not be attributed to the "tension" of the poles since their action diminishes rapidly with distance. This experiment showing the uniformity of the magnetic effect, even at a great distance from the battery, established the continuity of the current at any point in the circuit.

This conceptual change—from a battery and a conductor face to face, to a continuous circuit—was not evident for Ampère himself. Wanting to show that two flat spirals act as two poles of a magnet, he recognized:[58]

> I believed at first that it would be necessary to establish the current in the two conductors by means of two different batteries; but this is not necessary, it is enough that the conductors belong to the same circuit, *since the electric current exists in all its parts with the same intensity*.

This identity of the current at any point in the circuit ensured the strict equality of the current in two different conductors between which the interaction was studied.

Ampère's early research on the electrical circuit led to a grouping of phenomena produced by the battery—heating, chemical decomposition, and magnetic action—into one category, based on the notion of current. He distinguished these "current phenomena," for which he coined the new term "electrodynamics," from the phenomena produced by ordinary (frictional) electricity or "tension phenomena," which he called "electrostatics."[59] The radical character of the disjunction between tension phenomena and current phenomena might be surprising since it was later shown that, even in a closed circuit, there still exists a tension on the extremities of the battery. But, as we have seen, at the time electroscopes did not allow the detection of weak potential differences between the extremities of a battery closed on a low resistance conductor.

C. The crucial experiment of two compasses

Whether it was after taking into consideration eventual "circular piles" inside the terrestrial globe and magnets, or as part of an experimental process of an exploratory nature, Ampère extended his investigation to the battery itself. The batteries of the period, called "trough batteries," were made of a series of vertical metal plaques, most often zinc and copper, plunged into a rectangular vat divided by wooden troughs filled with acidulated water. These batteries could be up to tens of centimeters in length, so it was therefore possible to move a compass above the battery. The battery used by Ampère for most of his experiments consisted of "twelve triads of one square foot."[60] The length, therefore, would have been around twenty centimeters, and the tension around a dozen volts. The quest of a magnetic action of the battery was a crucial moment in Ampère's early research. Probing the hypothesis that "attributes to the battery itself the same directing action as that of the conductor"[61] (Fig. 7), the result of the experiment was very clear: "the battery itself, in all its length, acts as the conducting wire which joins its poles."[62]

To compare simultaneously, rather than successively, the deviations provoked by the battery and by the connecting wire, Ampère employed two compasses. The battery and the wire being parallel, both oriented in the direction of the magnetic meridian, a compass was placed parallel above each of them. When connecting the battery to the wire, Ampère observed that the deviation of each needle had the same amplitude (Fig. 8).[63] As he pointed out, the magnetic action of the battery had not been noticed by other physicists and was even "positively negated by a skillful physicist." This highlighting of the magnetic effect of the battery, through the experiment of the two compasses, was a key point in the construction of the concept of current.

The identity of action suggested that the battery and the wire shared a common electrical property, the compass being the revealer of this common property. The compass acquired a new status; it became the instrument by which to study the battery in a closed circuit.[64] It was sufficient, wrote Ampère,[65]

> to adapt [to the battery] a compass needle to see at each instant by the position it takes if the galvanic current is established, as well as its intensity, precisely like an electroscope is adapted to an electric machine, this little instrument that I believe by analogy I must name *galvanoscope*.

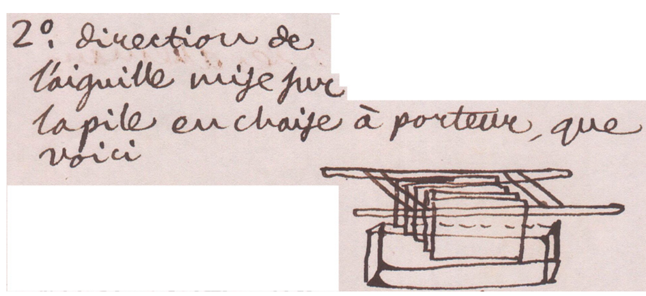

Fig. 7. Project of the crucial experiment: "Direction of the needle put on the sedan chair [trough] battery." (Archives Ampère, chemise 205, p. 28).

To make a real measuring instrument, it would be enough, he claimed, to "put measurement marks under the needle on a round glass, to make a galvanometer."[66] He intended to hang the needle to a metallic wire in order to measure the torsion of the wire. However one finds no such measurements among the thousands of manuscripts kept in Ampère's archives. Moreover there was still no connection between the angle of deviation of the needle and the so-called "intensity" of the current. Indeed with this primitive galvanometer, measurements remained qualitative except for the equality between two currents. Nevertheless, the possibility of measuring an intensity was asserted. The compass was no longer a mere indicator of the magnetic effect, as in Oersted's experiments. As "galvanometer," it became the tool for the investigation of electrodynamic phenomena.

D. Theoretical consequences: The concepts of current and of electric circuit

The experiment of the two compasses demonstrated a simultaneous and identical angular deviation of the two needles. However, Ampère noted that the deviations were in opposite directions above the battery and above the conductor. In fact, when the battery and the conducting wire were placed face to face, the deviations of the needles were symmetrical with respect to the direction of the magnetic meridian (the geographical north-south axis still served as a reference). Ampère's manuscript showed that early in his experimentation he still considered two currents, one in the battery and the other in the wire: "one can easily notice the *opposition in the direction of the two currents*."[67] The mastery of this difficulty—the existence of "two currents"—was gradual.

In the text of the published memoir, the transition from "two currents" to the "same current" was made explicit:[68]

> It is necessary to distinguish two kinds of conductors: (1) the pile itself, inside of which the electric current, with the meaning I give to this word, flows from the extremity where hydrogen is produced in the decomposition of water, to the extremity where oxygen is released; (2) the metallic wire which connects the two extremities of the battery, and where we must then consider the same current as flowing, *in the contrary*, from the extremity which gives oxygen to that which develops hydrogen.

Henceforth, stated Ampère, the battery must be conceived "as forming a single circuit with the conductor." A single circuit, the same current; these are the concepts that resulted from the experiment of the two compasses (Fig. 8).

The circulatory nature of electric current, therefore, relies on the empirical referent of magnetic action. The compass-turned-into-galvanometer acquired the status of an instrument to characterize electrical current, a new physical quantity, at every point of the circuit, characteristic of the circuit as a whole. The continuity of the direction and the amplitude of the needle's deviation throughout the entire length of the conductor, as well as through the battery, led to the notion of circulation. Using the analogy of a man, "the observer," descending a river, Ampère specified the rule giving the direction of the needle's deviation.[69]

> […] if one imagines oneself placed along the direction of the current, so that the current flows from the feet to the head of the observer when facing the needle, the action of the current constantly deflects to the left of the observer the extremity of the needle which is pointing to the North (Fig. 9).

Could the other specific effect of the electric current, the decomposition of solutions, confirm this circulatory character? As pointed out by Friedrich Steinle, Ampère considered the possibility of an experiment similar to that of the two compasses by performing two electrolyses, one in the external circuit and the other inside the battery, between two copper and zinc plates.[70] However Ampère almost certainly did not carry out the experiment.[71] In any case, this experiment of two electrolyses could add nothing to that of the two compasses. It was definitely much more difficult to perform and, in addition,

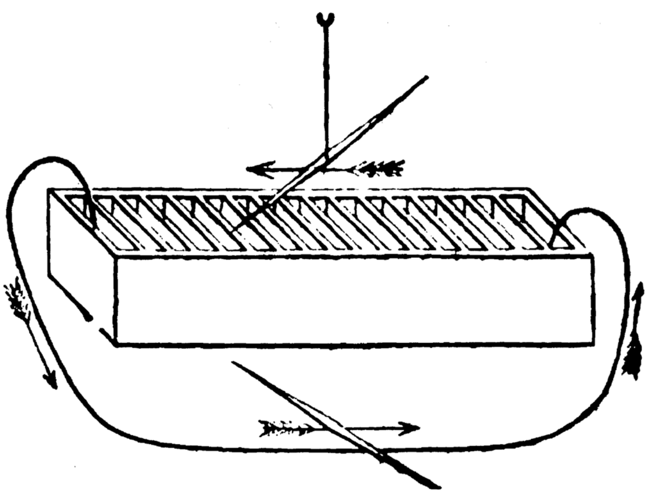

Fig. 8. The experiment of two compasses, one above the battery and the other above the conducting wire: the same current, represented by four arrows, flows through the battery and through the wire. [A. de La Rive, *Traité d'électricité théorique et appliquée*, Vol. 1, (J.-B. Baillère, Paris, 1854), p. 210]

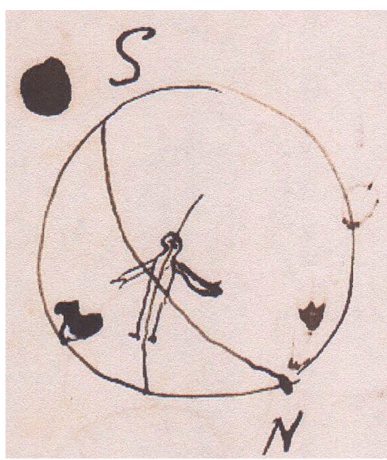

Fig. 9. Ampère's observer gives the direction of the electric currents inside Earth. The magnetic poles N and S (converse to the geographic poles) are connected by a meridian. An electric current, partially shown and circulating along the equator, flows through the observer from feet to head. One must imagine the observer lying on the ground, looking at a compass situated above him. His left arm indicates the direction that will be taken by the north pole of the compass under the action of the current; that is, the pole N of Earth. (Archives Ampère, chemise 156, p. 24)

electrolysis did not provide, as did the compass, an immediate quantitative indication of the current's intensity.

To define the direction of "electric current," arbitrary in his view, Ampère adopted the direction proposed by Volta and taken up by his successors, namely, the direction of positive electricity.[72] This sense of positive electricity in the conducting wire went from the positive pole of the battery to its negative pole. It was revealed by chemical decompositions: "electric current means the direction following which the hydrogen and bases of salts are transported by the action of the entire battery." This definition proved of little use in practice. In effect, most circuits did not include electrolysis, and the introduction of electrolysis changes the intensity in the circuit. Indeed, subsequently, the determination of the current's direction was made with a compass needle.

Ampère emphasized the conventional nature of this choice. Unlike other physicists, he did not comment on the nature of physical or chemical phenomena produced inside of the battery, the wire, the magnets, or the terrestrial globe. One can imagine a current of one fluid, a double current of positive and negative electricity, or even an electrical polarization of molecules. He was satisfied to evoke, without more precision, a "particular disposition of electricity." His definition of current, entirely characterized by the deviation of the compass needle, was independent of the physical phenomena occurring inside the conductors. It was an abstract definition, based solely on the uniform character of the amplitude of the deviation:[73]

> Moreover, everything I will say about this subject does not suppose in any way that there is really a current along this direction, and one can consider the use of this denomination of *electric current* just as a convenient and usual manner to specify this direction.

Taking into account the magnetic action of electrostatic discharges, recently described by Arago, Ampère, moreover, changed the name of "galvanic current" (produced by a battery), into "electric current," thereby including electrostatic discharges.[74] The identity between "ordinary" electricity and galvanic electricity, already established for thermal and chemical effects, was thus reinforced.[75]

Certainly, as we have seen, the expressions "electric circuit" and "electric current" have been used previously, as well for electrostatic phenomena as for galvanic ones, alongside other expressions.[76] But the radical novelty here lies in the definition of a new quantity—the electric current—by a univocal empirical referent.

E. Two empirical definitions and two theoretical definitions for the intensity of a current

The definition of intensity of a current by the deviation of a compass needle has established itself among physicists for more than half a century. But it was already recognized in Ampère's time that a physical quantity could be defined either by a measurement or by a calculation based on other parameters. To his first experimental definition of intensity, Ampère added, during the course of his research, two theoretical definitions that remained unpublished in his manuscripts, and a second experimental definition. These four definitions of different natures testify to the multiplicity of possible approaches to the concept of intensity.

The first theoretical definition, in autumn of 1820, intervened in his research of the expression of the force acting between two infinitely small elements of currents. Ampère supposed this force proportional to the intensities of the two currents and added that these intensities "depend only of the quantities of electricity flowing during equal times, the amount offsetting the speed, […] provided that the passage is completely free, that is to say the conductor is sufficiently large."[77] This statement represented a definition of intensity in terms of a flow of electricity. It corresponds to the usual definition determined by the quantity of electricity passing through the conductor during a given time (q/t). Ampère did not explicitly develop this definition mathematically, but it was implicit in his larger theoretical work.

In order to explain how a tiny magnetic molecule could produce a significant current, Ampère introduced a second theoretical definition of the intensity: "the intensity of the current in a closed circuit with everywhere the same conductibility, which depends on the diameter [of the conducting wire], is [proportional to] the electro-motive force divided by the length of the circuit."[78] Even if the electromotive force of the molecule and its "length" are very weak, their relation (i.e., the produced intensity E/L) may be significant. This new definition of intensity of a current in a conducting wire of a constant diameter, namely, the electromotive force divided by the length of the wire, included the main elements of Ohm's law since the resistance is proportional to the length of the conductor.

Finally in his main book, the *[Mathematical] Theory of electrodynamic phenomena*, published in 1826, Ampère defined, again empirically, the intensity of a current by the comparison between the forces exerted by two straight parallel currents on a portion of moving current, taking one of the currents as a reference.[79] This last definition is very close to the present definition of the unit of electric intensity, which was given the name "ampere" at the First international Congress of Electricians in 1881. Indeed, the ampere is still defined by means of the strength of attraction between two parallel and infinite currents.

V. PEDAGOGICAL IMPLICATIONS

Much educational research conducted over the past decades has demonstrated the persistent difficulties in the learning of electric circuits at all levels of education. High school and college students frequently use inadequate reasoning and conceptions: antagonistic currents leaving each pole of the battery, "weakening" of the current as it passes through a resistor, "sequential" reasoning implying that a change in an element of the circuit has no effect on the part of the element downstream, reasoning of the "electrostatic" type, etc. These misconceptions reflect the difficulty of considering the circuit as a whole and in using the law of the conservation of current. Not only the constancy of the current across all of the parts of the circuit, but even the radical distinction between an open circuit and a closed circuit remain problematic for many students, due to a misunderstanding of the continuity of a closed circuit.[80]

The historic journey described here demonstrates that similar difficulties were encountered by most physicists of the early 19th century. Even today, it is the continuity of the electric current, its circulatory and conservatory nature, that are in no way self-evident. This suggests greater emphasis on the idea of circulation of current, of constant intensity, through all of the elements of the circuit, particularly through the battery. Of course, the flow of current inside of the battery or the generator is asserted in the beginnings of the teaching of electrodynamics. However, this claim remains insufficiently founded, partly due to pervasive conceptions about the battery or the generator—in particular, the prominent role given to the poles—and, on the other hand, the inadequacy of experimental means to demonstrate the circulation of current inside the battery. The heating of a short-circuited battery or the dissection of a battery, while not recommended with students, do not demonstrate the passage of current in the battery.

In contrast, the experiment of Ampère's two compasses does allow this demonstration. The deviation of the needle above the battery, symmetrical to the deviation above the conducting wire was crucial for the creation of the concept of current by Ampère. This deviation, identical in each point of the circuit, including over the battery, enabled him to introduce a new physical quantity characterized by its direction (the direction of the needle's deviation) and by its intensity (the value of the angle of deviation). This oriented quantity characterizes the electrical state of the circuit as a whole. To promote a global vision of the circuit and to materialize the constancy of current through all the components of the circuit, the experiment of the two compasses provides an argument that is both powerful and simple to implement. In this sense, this experiment opens interesting didactical perspectives.[81]

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[1]On the history of electricity in 18th century see J. L. Heilbron, *Electricity in the 17th and 18th Centuries: A Study of Early Modern Physics*, 2nd ed. (Dover Publications, New York, 1999). On the history of electromagnetism, see O. Darrigol, *Electrodynamics from Ampère to Einstein* (Oxford U.P., Oxford, 2003). A large part of the documents referred to in this paper are available on the website Ampère and the history of electricity (www.ampere.cnrs.fr) which gives access to Ampère publications, correspondence and archives, and presents a series of multimedia files on the history of electricity.

[2]W. N. Cottingham and D. A. Greenwood, *Electricity and Magnetism* (Cambridge U.P., Cambridge, 1991), p. 31.

[3]A.-M. Ampère, "Expériences relatives à de nouveaux phénomènes électro-dynamiques," Ann. Chim. Phys. **20**, 60–74 (1822).

[4]A Leyden jar is a glass jar with conducting metallic foils coating its inner and outer surfaces.

[5]A. Volta, "On the electricity excited by the mere contact of conducting substances of different kinds," Philos. Trans. R. Soc. **90**, 403–430 (1800) (original text in French); translated to English in Philos. Mag. 7, 289–311 (1800).

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[7]R. J. Haüy, *Elementary Treatise on Natural Philosophy*, Vol. 2 (George Kearsley, London, 1807) [*Traite elementaire de physique*, Vol. 2 (Delance et Lesueur, Paris, 1803)].

[8]The word "battery" meant a battery of Leyden jars that could be discharged on one moment as a battery of cannons. For an early use of the denomination "pile" see: W. Nicholson, "Account of the new electrical or galvanic apparatus of sig. volta, and experiments performed with the same," J. Nat. Philos. Chem. Arts. **4**, 179–187 (1800).

[9]W. Nicholson, *Ibid.*; C. H. Pfaff, "Notice des phénomènes d'attraction et de répulsion dépendant de la pile galvanique, observés par M. Ritter," J. Phys. Chim. Hist. Nat. **53**, 152–155 (1801); P. Erman, "Sur les phénomènes électrométriques de la colonne de Volta," J. Phys. Chim. Hist. Nat. **53**, 121–134 (Barrau et Dumotiez, 1801); other researches are described in J. Izarn, Manuel du Galvanisme (Longman, Hurst, Rees, Orme, and Brown, and R. Triphook, Paris, 1804) or G. J. Singer, *Elements of Electricity and Electro-chemistry* (London, 1814).

[10]E. G. Robertson, "Nouvelles expériences sur le fluide galvanique," Ann. Chim. (Paris) **37**, 132–150 (1800), p. 138. The potential difference between the ends of a closed-circuit battery was too weak to be detected by an electroscope, because the internal resistance of a Voltaic battery was much higher than the resistance of an external metallic conductor. On what is measured by an electroscope, see J. L. Heilbron, *Electricity in the 17th and 18th Centuries: A Study of Early Modern Physics* (Dover Publications, Mineola, N.Y., 1999), pp. 451–453.

[11]R. J. Haüy, Ref. 7, p. 28.

[12]Dictionnaire des sciences naturelles, Vol. 3 (1816), p. 115.

[13]A. Volta, "De l'électricité dite galvanique," Ann. Chim. (Paris) **40**, 225–256 (1801), p. 227.

[14]On the history of the electrolysis of water, see H. Chang, *Is Water H_2O? Evidence, Realism and Pluralism* (Springer, Dordrecht, 2012), chap. 2; G. Cuvier, "Rapport sur le galvanisme," J. Phys. Chim. Hist. Nat. **52**, 318–321 (1801), p. 320; P. Erman, Ref. 9, p. 129.

[15]Still in 1828 see the negative assessment of Claude-Servais Pouillet, *Elémens de physique exp érimentale et de météorologie*, Vol. 1 (Béchet jeune, Paris, 1828), p. 651.

[16]H. Davy, "An account of some Experiments made with the Galvanic apparatus of signor volta," J. Nat. Philos. Chem. Arts. **4**, 275–281 (1800), p. 276.

[17]T. von Grotthuss, "Memoir upon the decomposition of water, and of the Bodies which it holds in solution, by means of galvanic electricity," Philos. Mag. **25**, 330–339 (1806).

[18]H. Davy, "The Bakerian lecture, on some chemical agencies of electricity," Philos. Mag. **28**, 3–18, 104–119, 220–233 (1807); "Mémoire sur quelques effets chimiques de l'électricité," J. Phys. Chim. Hist. Nat. **64**, 422–461 (1807); W. H. Wollaston, "Experiments on the chemical production and agency of electricity," Philos. Trans. R. Soc. **91**, 427–434 (1801); W. Henry, "Theory of excitement of Galvanic Electricity," J. Nat. Philos. Chem. Arts. **35**, 259–271 (1813); A. Anderson, "On the decomposition of water in two or more separate vessels," J. Nat. Philos. Chem. Arts. **30**, 183–189 (1811).

[19]G. Cuvier, Ref. 14.

[20]J. A. Deluc, "Analysis of Galvanic pile. Part I," J. Nat. Philos. Chem. Arts. **26**, 113–136 (1810); on Deluc see G. Pancaldi, "Deluc, Davy, and the impact of the battery on natural philosophy," in *Jean-André Deluc Historian of Earth and Man*, edited by J. L. Heilbron and R. Sigrist (Slatkine, Geneva, 2011), pp. 277–298.

[21]G. J. Singer, "Observations on some phenomena of electro-chemical decomposition," J. Nat. Philos. Chem. Arts. **31**, 90–95 (1812); Elements…, Ref. 9, pp. 204–206; M. Donovan, *Essay on the Origin, Progress, and Present State of Galvanism* (Hodges and McArthur, Dublin, 1816), p. 188.

[22]L. J. Gay-Lussac and L. J. Thénard, *Recherches Physico-Chimiques Faites Sur la Pile*, Vol. 1 (Deterville, Paris, 1811), pp. 1–52.

[23]G. J. Singer, Ref. 9, p. 430.

[24]See M. von Marum, *Description d'une Très-Grande Machine Électrique* (Jean Enschedé et fils, et Jean van Walré, Haarlem, 1785); G. J. Singer, Ref. 9, pp. 204–206.

[25]T. von Grotthuss, Ref. 17, p. 335.

[26]J. W. Ritter, "Experiments on magnetism," J. Nat. Philos. Chem. Arts. **8**, 184–186 (1804); R. Martins, "Oersted, Ritter and magnetochemistry," in *Hans Christian Ørsted and the Romantic Legacy in Science: Ideas, Disciplines, Practices*, edited by R. M. Brain, R. S. Cohen, and O. Knudsen (Springer, New York, 2007), pp. 339–385; R. Martins, *H.C. Ørsted's Theory of Force: An Unpublished Textbook in Dynamical Chemistry*, edited by A. S. Jacobsen, A. D. Jackson, K. Jelved, and H. Kragh (Det Kongelige Danske Videnskabernes Selskab, Reitzel, 2003); J. N. Hachette, "Expérience sur le magnétisme de la pile électrique," Correspond. l'École Polytech. **5**, 151–153 (1805).

[27]This Romagnosi experiment has been improperly considered at several occasions since 19th century as a prefiguration of Oersted's one, see R. Martins, "Romagnosi and Volta's Pile: Early difficulties in the interpretation of voltaic electricity," in *Nuova Voltiana: Studies on Volta and his Times*, edited by F. Bevilacqua and L. Fregonese, vol. 3 (Hoepli, Milano, 2001), pp. 81–102.
[28]A. Boisgiraud, "On the action of the voltaic pile upon the magnetic needle," Philos. Mag. **57**, 203–206 (1821).
[29]H. C. Oersted, *Experimenta Circa Effectum Conflictus Electrici in Acum Magneticam* (Hafniae, Schultz, 1820); fac-simile in B. Dibner, *Oersted and the Discovery of Electromagnetism* (Burndy Library, Norwalk, Connecticut, 1961), p. 23; "Expériences sur l'effet du conflict électrique sur l'aiguille aimantée," Ann. Chim. Phys. **14**, 417–425 (1820); "Expériences sur un effet que le courant de la Pile excite dans l'Aiguille aimantée," J. Phys. Chim. Hist. Nat. **91**, 72–78 (1820); "Experiments on the effects of a current of electricity on the magnetic needle," **16**, 273–276 (1820); "Versuche über die wirkung des elektrischen conflicts auf die magnetnadel," Ann. Phys. (Leipzig) **66**, 295–304 (1820).
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[31]H. C. Oersted, "Experiments on the effects…," Ref. 29, p. 276.
[32]H. C. Oersted, "Expériences sur l'effet du conflit…," Ref. 29, p. 419. Other examples of inaccurate translations: the ambiguous latin expression effectibus unius vel alterius vis electricae, rather accurately translated in English "effects of either of the electricities" (ordinary electricity or galvanism), became in French "action de l'un ou de l'autre pôle, considérés séparément" in Ann. Chim. Phys. or "forces d'attraction et de répulsion électrique" in J. Phys. Chim. Hist. Nat. These French mistranslations emphasized the weight of the electrostatic understanding of the Voltaic battery.
[33]*Ibid*., pp. 274–275.
[34]*Ibid*., p. 273. Johann Wilhelm Ritter was probably the main physicist alluded to by Oersted.
[35]H. C. Oersted, "Sur la propagation de l'électricité," J. Phys. Chim. Hist. Nat. **62**, 369–375 (1806).
[36]H. C. Oersted, *Ansicht der Chemischen Naturgesetze, Durch die Neueren Entdeckungen Gewonnen* (Realschulbuchhandlung, Berlin, 1812); *Recherches sur l'identité des Forces Électriques et Chimiques* (Paris, 1813); see an analysis of this account in Ann. Philos. (London) **13**, 368–377; 456–463; 14, 47–50 (1819).
[37]H. C. Oersted, Recherches…, Ref. 36, pp. 236–238.
[38]H. C. Oersted, Ref. 35, p. 372.
[39]P. Erman, "Extract of a memoir upon two new classes of galvanic conductors," Philos. Mag. **28**, 297–304 (1807), p. 303.
[40]H. C. Oersted, Ref. 30, p. 321.
[41]H. C. Oersted, "Experiments…," Ref. 29, p. 274.
[42]*Ibid*., p. 276.
[43]See also Ref. 30, p. 323.
[44]*Ibid*., p. 321; see also M. Faraday, "Historical Sketch of Electro-magnetism," Ann. Philos. (London) **3**, 107–108 (1822).
[45]F. Steinle, "Experiment, instrument und begriffsbildung: Ampère, das galvanometer und der stromkreis," in *Christoph Meinel, Instrument-Experiment. HistorischeStudien* (GNT-Verlag, Berlin, 2010), pp. 98–108.
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[47]Note of the editor Jules Joubert, *Collection de Mémoires relatifs à la Physique*, Vol. 2, Mémoires sur l'électrodynamique, 1ère partie (Paris, 1885), p. 2.
[48]Oersted experiment was repeated on 19th August 1820 in Geneva by Gaspard de la Rive in the presence of François Arago (A. Pictet, "Bibliothèque universelle," Sci. Arts **14**, 281–284 (1820)). The announcement was made by Arago at the Academy of sciences on September 4 ("Extraits des séances de l'académie royale des sciences," Ann. Chim. Phys. 15, 78–82 (1820), p. 80); Ampère began to read his memoirs at the Academy of sciences on September 18 and 25. During the following weeks, Davy in England, Van Beck in Netherlands, Berzelius in Sweden, Erman in Germany, Gazzieri in Italy, etc. published memoirs in the wake of Oersted experiment.
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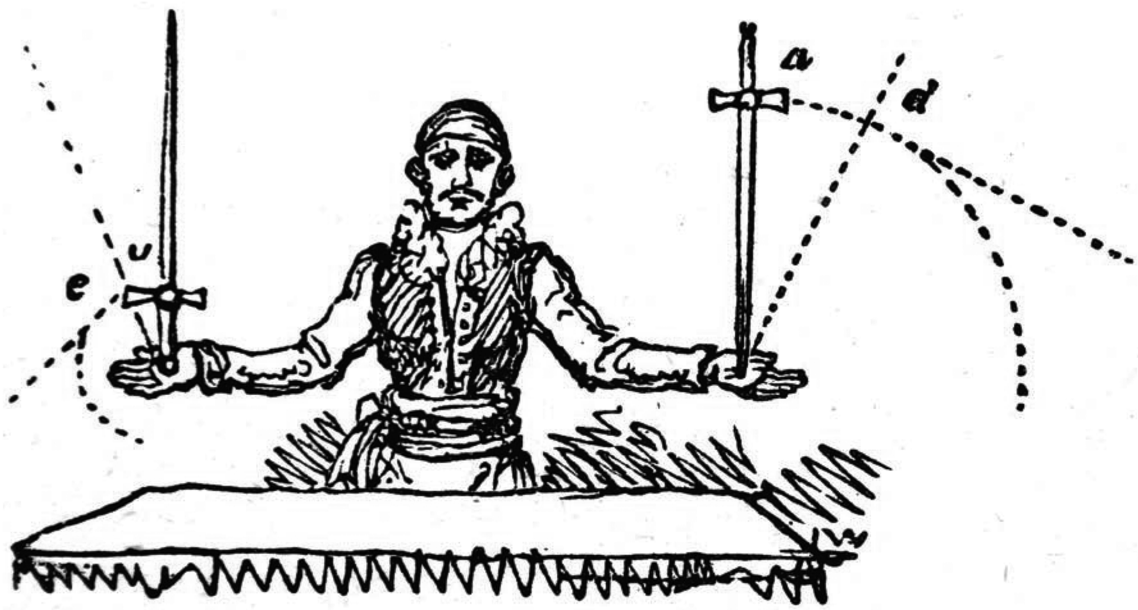
[51]A.-M. Ampère, "Mémoire […] sur les effets des courants électriques," Ann. Chim. Phys. **15**, 59–76, 170–218 (1820); translation in A. Assis and J. P. Chaib, Ampère's Electrodynamics […], Ref. 50, pp. 289–320.
[52]Archives Ampère, chemise 208bis, p. 89; "Mémoire […]" Ref. 51, p. 203.
[53]Archives Ampère, chemise 205, pp. 2, 8.
[54]J.-B. Biot, *Précis Élémentaire de Physique expérimentale*, Vol. 2, 3rd ed. (Deterville, Paris, 1824), p. 773.
[55]Letter from Ampère to Auguste de La Rive, 11th October 1822, in Louis de Launay, *Correspondance du Grand Ampère*, Vol. 2 (Paris, 1936), p. 610. (http://www.ampere.cnrs.fr/correspondance/L1822-10-11-a.html).
[56]A.-M. Ampère, "Mémoire […]" Ref. 51, p. 65. This argument was supported in particular by G. J. Singer, Ref. 9, p. 430. It was taken on later on by Auguste de la Rive, "Mémoire sur quelques-uns des phénomènes que représente l'électricité voltaïque dans son passage à travers les conducteurs liquides," Ann. Chim. Phys. **28**, 190–221 (1825), p. 193.
[57]A.-M. Ampère, "Analyse des mémoires lus par M. Ampère à l'Académie des sciences, dans les séances des 18 et 25 septembre, des 9 et 30 octobre 1820," Ann. Gen. Sci. Phys. **6**, 238–257 (1820), p. 247; "Mémoire […]" Ref. 51, p. 72.
[58]A.-M. Ampère, "Mémoire […]" Ref. 51, p. 72 (highlighted by ourselves).
[59]A. M. Ampère, Ref. 3, p. 60.
[60]It means around 12 couples, 30 cm × 30 cm, see A.-M. Ampère, "Réponse de M. Ampère à la lettre de M. Van Beck sur une nouvelle expérience électro-magnétique," J. Phys. Chim. Hist. Nat. **93**, 447–467 (1821), p. 448.
[61]Archives Ampère, chemise 208bis, p. 128; Letter from Ampère to X, 7 septembre 1821 (http://www.ampere.cnrs.fr/correspondance/L1821-09-07-a.html).
[62]A.-M. Ampère, Ref. 57, p. 240.
[63]The experiment was described by Ampère in his "Mémoire […]" Ref. 51, pp. 66-68, and in his later publications.
[64]F. Steinle, Ref. 50, pp. 110–112.
[65]Archives Ampère, chemise 208bis, p. 101 (crossed off passage in the manuscript).
[66]Archives Ampère, chemise 205, p. 8.
[67]Archives Ampère, chemise 208bis, p. 129.
[68]A.-M. Ampère, "Mémoire […]" Ref. 51, pp. 197–198 (highlighted by ourselves).
[69]*Ibid*., p. 67.
[70]Archives Ampère, chemise 205, p. 7 ("Potasse dissoute entre cuivre et zinc. Le contraire") and p. 239.
[71]F. Steinle, Ref. 50, p. 98 (Archives Ampère, chemise 205, p. 239).
[72]G. Cuvier, Ref. 14, p. 321; C. J. Lehot, Ref. 6; G. J. Singer, Ref. 9, p. 430.
[73]Archives Ampère, chemise 208bis, p. 75.
[74]F. Arago, "Expériences relatives à l'aimantation du fer et de l'acier par l'action du courant voltaïque," Ann. Chim. Phys. **15**, 93–103 (1820); A.-M. Ampère, "Mémoire […]" Ref. 51, p. 197.
[75]The electrolysis of water by electric discharges had been carried out by Martinus van Marum in 1802, Extrait d'une lettre […] sur la décomposition de l'eau à l'aide d'un nouvel appareil électrique, Ann. Chim. (Paris) **41**, 77–78 (1802). Ampère planned to study the action on a magnetized needle of electrical discharges through a conducting wire but he does not seem to have obtained concluding results (Archives Ampère, chemise 205, 7–8).
[76]For an earlier use of the expressions courant électrique and circuit électrique, see, for example, P. Erman, Ref. 9, p. 181. The expression "galvanic current" was the most common together with "current of galvanic electricity," "current of electricity," "current of electrical fluid," etc.
[77]Archives Ampère, chemise 162, p. 50 (Autumn 1820).

[78]Archives Ampère, chemise 173, p. 125 (probably 1823). The word conductibility characterised both the nature of the metal and the (supposed constant) diameter of the wire.

[79]A.-M. Ampère, *Théorie [mathématique] des Phénomènes Électrodynamiques* (Méquignon-Marvis, Paris, 1826), p. 199.

[80]M. R. Stetzer *et al.*, "New insights into student understanding of complete circuits and the conservation of current," Am. J. Phys. **81**, 134–143 (2013); M. Leone, "History of physics as a tool to detect the conceptual difficulties experienced by students: The case of simple electric circuits in primary education," Sci. Educ. **23**, 923–953 (2014).

[81]A sequence of teaching based on this historical research has been led since several years by A. Benseghir at the Ferhat Abbas University of Setif (Algeria). For a pedagogical use of the controversy between Ampère and Biot, see M. Braga, A. Guerra, and J. C. Reis, "The role of historical-philosophical controversies in teaching sciences: The debate between Biot and Ampère," Sci. Educ. **21**, 921–934 (2012).



Balancing Swords

One of my favorite demonstrations is balancing a broom on my hand. With the broom straw at the top this is a lot easier than when it is at the bottom. The analysis of the demonstration involves the time for the broom to fall over in the two positions, compared to the typical reaction time of about a third of a second. This must have been a very old demonstration, for Pieter Bruegel the Elder (1525–69) included it as one of about 80 games in his 1560 painting, "Children's Games." Balancing swords is more daunting. The figure is from an 1889 reprint of John Ayrton Paris' 1827 book *Philosophy in Sport Made Science in Earnest*. The book uses a familiar ploy from the first half of the nineteenth century, in which a wise mentor has conversations with young people. From time to time a lecture breaks out, along with illustrations. (Notes by Thomas B. Greenslade, Jr., Kenyon College)