André-Marie Ampère, 200 years

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Historical context of the concept of electricity

In the 18th century, electricity was a science that put on a show in salons bringing together scholars and amateurs. Gradually, the concept of electricity became subject to debate: in particular, it was not known whether there was a single type of electricity or several. Thus, in England, Henry Cavendish thought that there was only one electric fluid, while in Italy Alessandro Volta spoke of electric atmospheres and in France, the concept of two fluids, one of positive electricity and the other of negative electricity, imposed itself. But in fact, the great debate at the end of the 18th century focused more about the explanations of the electrical and magnetic phenomena observed. For the proponents of "electric atmospheres", they were due to contact actions, whereas for the proponents of the Newtonian approach, they were due to attractive or repulsive actions at a distance. Moreover, one wondered which relationship could exist between electric and magnetic phenomena.

Charles-Augustin Coulomb (1736-1806), a proponent of a Newtonian two-fluid approach, performed high-precision experiments through the development of new experimental devices such as the torsion balance. He showed that the electric forces between two charges follow a law of action at a distance in $1/d^2$. Coulomb was also interested in magnetic fluids and proposed an analogy between electric and magnetic fluids by assuming two magnetic fluids, one "austral" and the other "boreal", which could not move freely inside a magnet. He then proposed an expression of the magnetic forces in $1/d^2$, similar to that of the electrostatic forces, and explained the broken magnet experiment by assuming that the two fluids are equally divided in the magnet into "magnetized molecules." But Coulomb's magnetic theory was far less robust than his electrostatic theory, and it has been met with skepticism by the community.

Jean-Baptiste Biot (1774-1862) took up Coulomb's results: he was convinced by these analogous expressions of electric and magnetic forces, identical to those obtained by Newton for gravitation. He then promoted the dissemination in France of this attractive and powerful idea of formal unity between the three branches of physics, namely gravitation, electricity and magnetism. This approach was indeed opposed to the introduction of any new theory of magnetism, and imposed a total independence between electricity and magnetism. It did not explain lightning-induced interactions between electricity and magnetism, but that did not seem to be a problem at the time.

At the beginning of the 19th century, a romantic vision of nature, also known as *Naturphilosophie*, emerged in Germanic countries. This cultural movement advocated the deep unity between the phenomena of nature despite their apparent diversity, and opposed the Newtonian vision of science. Thus, the duality present in all manifestations of life and spirit would have its equivalent at the elementary level of matter with the existence of two fundamental forces, one of attraction to explain cohesion and the other of repulsion to explain impenetrability. These two forces alone would be responsible for all the properties of matter, and would manifest themselves differently depending on the conditions. They could be converted from one form to another according to the experimental conditions, which proves the deep unity of Nature beyond the visible phenomena. For supporters of *Naturphilosophie*, a unity between electrical and magnetic phenomena was therefore possible.

At the same time, the first batteries of Alessandro Volta (1745-1827) appeared and raised many questions. No consensus emerged in the community of physicists, neither about the appearance and circulation of electric fluid in conductors, nor on the notions of open and closed circuit, nor on those of current and voltage. Neither the concept of "electric current" nor that of "electric voltage" existed. It was generally thought that by connecting the poles of a battery with a wire, the battery was the seat of discharges like in a Leyden bottle, and the operating principle of the battery was explained by electrostatics.

April 1820: the historic experiment of Œrsted

Hans Christian Œrsted (1777-1851) was a Danish physicist who adhered to the theses of *Naturphilosophie* early in his life, but left them later because of their lack of scientific rigor. However, he kept a unitary vision and he therefore did not believe in the independence between electric and magnetic phenomena. In the spring of 1820, he became interested in the interactions between the different forms of electricity (ordinary / galvanic / magnetic) which he classified according to their activities. In April, he studied the interaction between a galvanic current and a magnetized needle. After having tested the 4 possible configurations of the wire perpendicular to the needle, he had the idea of placing the wire collinear to the needle and discovered a "transverse" action. He then observed a deviation of the needle when a current crossed, but the deviation was very low because the battery was very weak, and the wire of very small section, therefore of high resistance. In July 1820, Œrsted had access to a more powerful battery, he renewed the experiment and the deviation of the needle was no longer in doubt.

In July 1820, Œrsted published a memoir entitled "Experiments on the effect of the electric conflict on the magnetized needle", and he wrote: "*The magnetized needle changes direction under the influence of the voltaic apparatus, and this effect takes place when the circuit is closed and not when it is interrupted. It is by having left the circuit open that famous physicists failed, a few years ago, to show this effect.* "

During the summer of 1820, the experiment was repeated with the powerful battery in Geneva. During the session of September 4, 1820 at the Academy of Sciences in Paris in the presence of Ampère, François Arago (1786 - 1853) reported on the experiment: he was greeted with incredulity and skepticism. During the session of September 11 at the Academy, Arago himself repeated the experiment: the phenomenon was then indisputable and the scientific community was speechless. This experiment actually raised some real questions: why did the isolated battery have no effect on the compass? How could the circuit have a transverse and not a longitudinal action on the compass? How to accept that electricity and magnetism can interact?

Many physicists studied Œrsted’s experiment and made qualitative experimental observations. Only Jean-Baptiste Biot (1774-1862) and André-Marie Ampère (1775-1836) attempted to develop mathematical models underlying these new phenomena. Biot assumed temporary magnetization of electric wires and thus reduced unknown galvanic currents to known magnetic fluids, and in fact reduced Œrsted's discovery to magnetism only. The majority of physicists (Poisson, Laplace, etc.) share Biot's hypothesis, which was consistent with the principle of interaction between entities of the same nature.

Ampère did not share Biot's hypothesis and followed his intuition. Rather than reducing electromagnetism to magnetism, he imagined the existence of electric currents in magnets, and he assumed an entirely new action: the interaction between electric currents, while the nature of the electric current was still unknown. But who was this audacious physicist?

André-Marie Ampère (1775 – 1836)

During his youth in the family home in Poleymieux-au-Mont d'Or, André-Maire Ampère did not have an academic education, but learned by reading all the volumes in his father's large library. His encyclopedic approach made him an eclectic scientist, a mathematician by status, a chemist by taste, a physicist by period, an anatomist by pleasure and a philosopher by passion.

Traumatized by the death of his father who was guillotined during the French Revolution, and then by the death of his wife following an illness, he lived in Lyon with his friends until the age of 29., They shared together a religious mysticism and theses of *Naturphilosophie*. As early as 1801, he developed his own scientific thought and wrote the preliminaries of an important memoir on physics aimed at unifying electricity and magnetism. He opposed the existence of the many forces of attraction and repulsion introduced between different fluids in Coulomb's theory, and he rejected the Newtonian hypothesis of action at a distance between two bodies which do not touch each other. He imagined a system based on a "*unique, universal, constant*" attraction, since of divine origin, and a propagation of electrical influences from one point to another according to the laws of mechanics through a fluid filling all space, called "*ether*". In fact, Ampère had the ambition to refund physics with a "*tremendous desire for synthesis and universal harmony*", which would later lead him to seek the unity and foundation of all human knowledge.

Œrsted's experiment in 1820 was at the origin of a real upheaval in Ampère's life. It brought him back to his childhood dream of unifying electricity and magnetism, with the secret hope of being the "*genius capable of applying to it the calculation which has produced so many wonders in the hands of modern mathematicians*".

Ampère then entered a short period of intense and passionate creation from September 1820 to January 1821. He worked tirelessly and enthusiastically, and produced many hastily written memoirs, sometimes even anticipating experimental results. Ampère was indeed in competition with Biot and wanted to be the first to provide the Academy with the correct explanation of Œrsted's experiment. Ampère's writings were later collected in a work entitled "*The action exerted on an electric current by another current, the globe or a magnet*", which was published in the *Annales de Chimie et de Physique*.

The period September 1820 - January 1821

Session of September 18, 1820 at the Academy of Sciences in Paris

Only two weeks after Arago's speeches at the Academy, Ampère spoke at the September 18 session to present his analysis of Œrsted's experiment. He broke down the action undergone by the needle into two components: the first was the rotation which puts the wire and the magnetized needle in a cross; the second was the attraction exerted by the wire on the needle. His goal was to independently show these two actions of a conductor on a magnet.

Rotation

Ampère began by eliminating all action of terrestrial magnetism in order to isolate the rotational component. He then designed and built an astatic needle, i.e. an experimental device in which the movement of the needle was dictated only by the action of galvanic currents, and not by terrestrial magnetism [Fig.1]. When he approached a galvanic current to the needle, he then studied exclusively the action of galvanic current, which puts the needle perpendicular to its initial position.

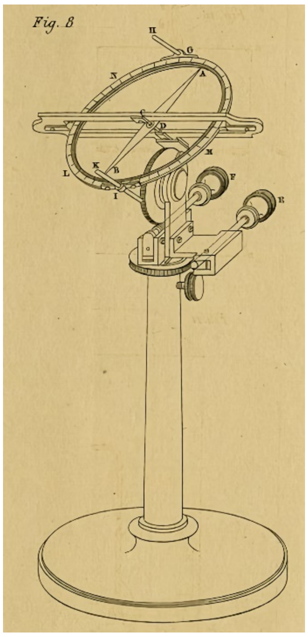

Fig. 1: Ampère's sketch of an astatic compass, Memoir [...] on the effects of electric current, 1820

Ampère was convinced that it was for the same reason that an isolated magnetized needle points in the direction of the North Pole of the Earth. The simplest idea was then to suppose "*in the Earth an electric current, in such a direction that North would be on the the left of a man who, lying on its surface, the face turned towards the needle, would receive this current in the direction from his feet to his head, and to conclude that it occurs, from East to West, in a direction perpendicular to the terrestrial meridian*". And Ampère illustrated his point with this famous little sketch [Fig.2].

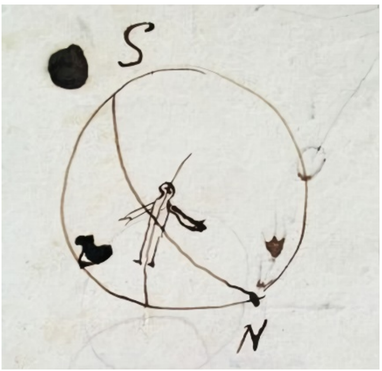

Fig2: sketch of Ampère's man, archives of the Academy of Sciences

With logic, Ampère then affirmed that the directing effects of a magnet on the magnetized needle must have the same origin as those of the Earth on the magnetized needle: a magnet would therefore only be a set of galvanic currents in planes perpendicular to its axis [Fig.3]. Later, following exchanges with his faithful friend Augustin Fresnel (1788 - 1827), Ampère evolved and instead imagined currents of particles, circulating around each particle of the magnet, always with the axis parallel to that of the magnet.

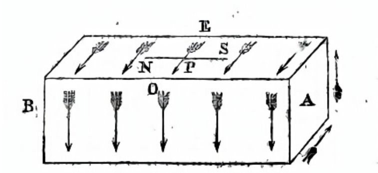

Fig. 3: sketch of a magnet according to Ampère. The arrows represent the direction of the internal currents at the origin of the North and South poles of the magnet. Work by Jacques Babinet.

Attraction

Then Ampère wanted to isolate the attraction component from the action of a wire on a magnetized needle: he then created current spirals, i.e. parallel circles of currents centered on the same axis [Fig.4]. He brought them closer to the astatic needle and observed an attraction effect.

Fig. 4: a spiral according to Ampère

Like the magnet, a current spiral therefore exerts an attractive power on the needle, which confirmed his hypothesis on the origin of the magnetism of the magnet. Ampère thus reduced all magnetic phenomena to purely electrical effects, whether rotation or attraction, and rejected the hypothesis of the temporary magnetization of the wire proposed by Jean-Baptiste Biot.

“Historical session” of September 25, 1820 at the Academy

The session of September 25 at the Academy, known as the "*historic session*", was an opportunity for Ampère to prove his "*great theory*". He designed an experimental device in which the magnet was placed in front of one of his spirals: he observed phenomena of attraction and repulsion according to the directions of the magnet and of the current in the spiral, which showed that the current spiral behaved like the electrical image of a magnetic pole. He then repeated the same experiment with two current spirals [Fig. 5] and demonstrated that the spirals behave like magnets. This experiment was proof that the properties of magnets are due to electric currents in planes perpendicular to their axis: it was the "*decisive experiment*" which provided Ampère with the "*definitive proof*" of his "*great theory*".

He then replaced the spirals by helices, for which he invented a new term, that of "*solenoid*" of Greek etymology ("solen" = "pipe" in Greek) [Fig.6] and observed the same phenomena. He concluded that "*galvanic spirals and helices produce the same effects as magnets*".

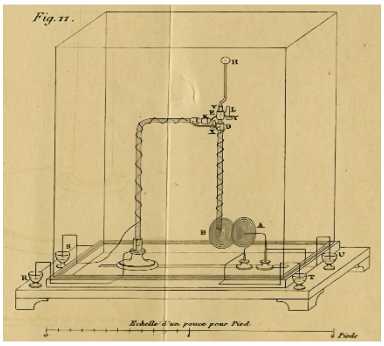

Fig. 5: Ampère's sketch of a device designed to study the actions between two current spirals.

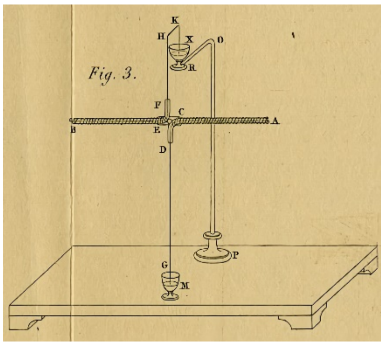

Fig. 6: Ampère's sketch of a device designed to study the actions between two solenoids.

Ampère then declared to the Academy: "*Mr. Ampère discovered this fact, that two electric currents attract each other when they go in the same direction and that they repel each other if they go in the opposite direction*", and confirmed the hypothesis that the properties of magnets are due to electric currents flowing in planes perpendicular to their axis. Ampère thus eliminated the magnetic fluids of Charles Augustin Coulomb.

On the evening of September 25, he wrote an exalted letter to his son Jean-Jacques in which he spoke of "*his great theory*" as something "*which bears no resemblance*" to what we already know...

Session of October 2, 1820 at the Academy

For the first session of October 1820 at the Academy, Ampère developed a new experimental device consisting of two straight and parallel conductors AB and CD, the first fixed as opposed to the second mobile. CD is connected to the insulating rod EF resting at X and Y on fine spikes placed in small cups filled with mercury, and allowing the current to cross the XCDY frame, whatever its inclination [Fig.7]. Thanks to this device, Ampère showed that the same effects exist between two straight and two spiral currents.

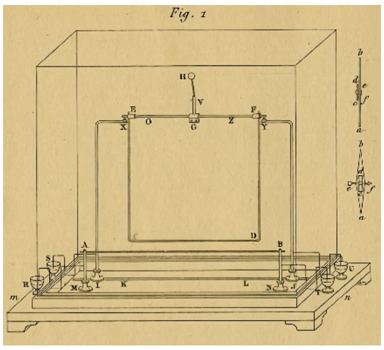

Fig. 7: Ampère’s sketch of a device designed to study the interaction between two straight and parallel electric currents.

Sessions from October 1820 to January 1821 at the Academy

At the same time, Ampère wondered about the notions of conductor, electric current, intensity and voltage.

Ampère reproduced Oersted's experiment by separating the poles of the battery from each other with a 20-metre-long wire. He observed that the needle placed above the wire in its middle was deflected without weakening, suggesting a phenomenon of conduction. He deduced that the deviation of the needle was not due to the voltage at the terminals of the battery located so far away, but to the electric current. This fundamental experiment showed that the effects of electric current are different from those of voltage, which invalidated the conception of the time that opposed the two phenomena.

Then Ampère placed a second magnetized needle above the battery [Fig. 8]. He then observed that "*the current contained in the voltaic battery flowing from the negative pole to the positive pole had the same influence on the magnetized needle as the current of the conductor flowing, on the contrary, from the positive pole to the negative pole*." This second fundamental experiment thus showed that the battery and the conductor which connects its poles have the common property of being traversed by a qualitatively and quantitatively identical current.

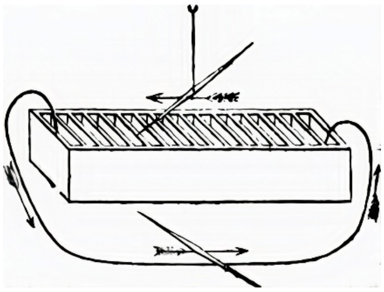

Fig. 8: Ampère's sketch of a device in which a second magnetized needle is placed above the battery.

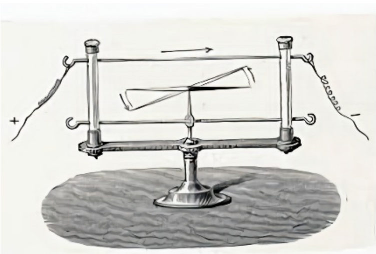

Fig. 9: the galvanoscope

Ampère then introduced the notion of current flowing in the circuit constituted by the battery-conductor assembly. He defined a new concept, that of "*electric current*", and a new quantity specific to the circuit, that of "*current intensity*". He arbitrarily chose the positive direction of the current from the electrolysis of water, and finally developed a new measuring instrument, the galvanoscope, to measure the current intensity by the deflection angle of the needle [Fig. 9].

Ampère further defined "*electric tension*" as the phenomenon which "*is observed when the bodies between which the electromotive action occurs, are separated from each other by non-conductive bodies*".

Contrary to Biot, who assumed the temporary magnetization of the wire, i.e. the same type of interactions between particles, whether stationary or in motion, the visionary genius of Ampère was to assume different types of interactions between particles according to their state, at rest or in motion [Fig.10]. And he then created a new term, that of *electrodynamics*, as opposed to that of electrostatics.

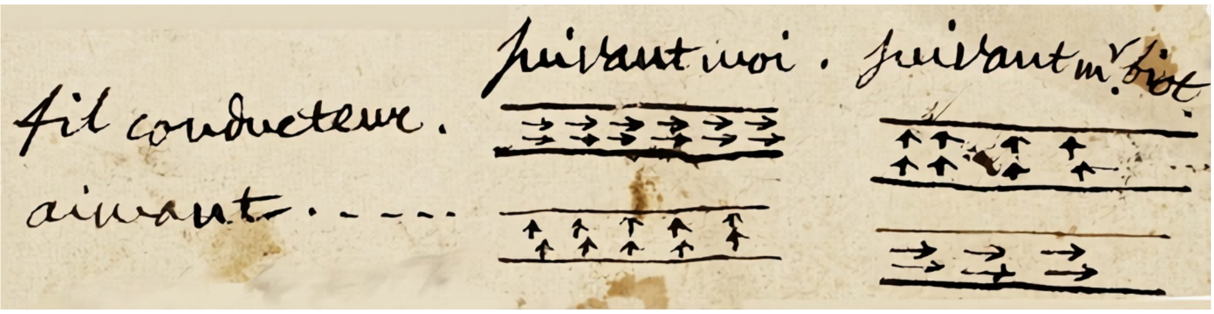

Fig. 10: Ampère's sketches. The arrows represent elementary currents for Ampère (column "suivant moi") and elementary magnets for Biot (column "suivant M. Biot").

1820 to 1826 : in search of a mathematical law between infinitesimal currents

At the same time, Biot and his proponents on the one hand, and Ampère on the other, were engaged in the search for a mathematical law to prove the truth of their model. Both were rivals and knew that only the formulation of a law could give them the credit they sought.

Ampere's assumptions

Ampère sought to establish a mathematical law expressing the force between currents within the framework of a Newtonian approach: just as mechanics had succeeded in mathematically deducing all movements between two bodies from the force exerted between two point masses, Ampère sought to write a general law from a universal elementary law between infinitesimal current elements obtained by decomposing (by thought) a finite current into an infinite number of small elementary segments of infinitesimal length *ds*. The force between two finite current elements can then be deduced from this elementary force between two elements *ds* and *ds'* by two successive integrations. Since a magnet contains an infinite number of coaxial circular currents for Ampère, the force between a magnet and a current element can then be obtained by a triple integration. But the reverse is not true! The expression of the elementary force cannot be deduced from the integral force. So how to determine this elementary force between two current elements? This is the major difficulty that Ampère had to face.

Ampère considered the most general case. He imagined two infinitesimal elements separated by a distance *r*, one centered at *A* in the plane *P*, the other centered at *B* in the plane *Q*. The angle between the two planes is γ, and each of the current elements makes an angle either α or β with the line of intersection between the two planes [Fig.11]. Ampère therefore attempted to establish a relationship between all these variables in order to express a general law of interaction between these two infinitesimal current elements. He took a Newtonian approach and assumed that the force between these two infinitesimal elements of the current is a radial force in $1/r^2$ in accordance with the principle of action and reaction. He will later justify these hypotheses.

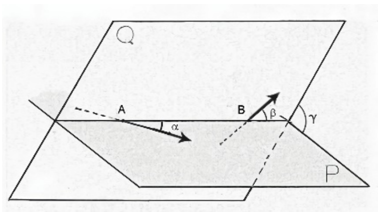

Fig. 11: Ampère's configuration for the general study of the interaction between two infinitesimal current elements, one centered at A, the other at B.

Ampère's experimental approach

Ampère began by taking a rigorous experimental approach to testing the effects of each of these variables independently. He took up the device of Figure 7 which had allowed to show that two straight and parallel wires attracted each other if they had currents of the same direction and repelled each other if the currents were of opposite directions, and he assumed that this result remained valid between infinitesimal and parallel current elements. He then used the same experimental setup but replaced one of the straight current elements with a sinuous one and demonstrated the principle of vector addition between current elements. He also assumed that this result remained valid between infinitesimal elements.

Ampère then designed a very complex device [Fig.12] to analyze the influence of the direction of the current elements relative to each other. This device should have allowed Ampère to independently study the influences of the distance *r* and the angles α, β, and γ between the current elements. However, no trace of measurement exists in Ampère's manuscripts. This device, too complex to be realized, probably never existed This episode highlights the extraordinary ingenuity of Ampère in the design of incredible devices, and at the same time, an almost total absence of measurements. Ampère built his thought by imagining the results of his experiments.

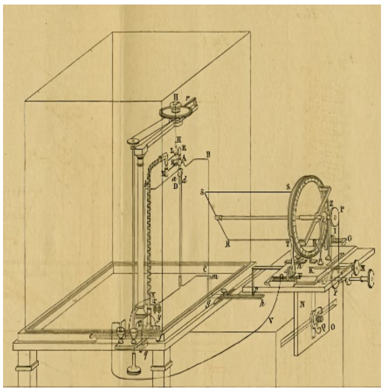

Fig. 12: Ampère's sketch of a device intended to study the force between the vertical moving conductor BC and the fixed conductor FS with adjustable inclination.

The difficulties encountered in setting up experimental devices led Ampère to abandon the idea of making absolute measurements, and he wrote: "*I was soon convinced that this law could not be concluded by experiment*" because the forces between infinitesimal elements could not be measured. Ampère was then forced to add an additional hypothesis: he assumed that the force between two current elements was zero if one of them is located in the plane perpendicular to the second in its middle. Ampère was then able to formulate a first expression for the elementary force between two current elements: he showed that it must be proportional to the ratio

$$\frac{gh\,(sin\alpha\ sin\beta\ cos\,\gamma + k\ \ cos\alpha\ cos\beta)}{r^2}$$

with *g* and *h* two quantities which depend on "what the electricity passes through in equal times".

After a long lung disease, Ampère returned to his research in the fall of 1821, following the discovery of Michel Faraday (1791-1867) who achieved the continuous rotation of a magnet by means of a conductor, and vice versa. Ampère then imagined an ingenious new device, probably never realized [Fig.13]: a mobile AEFG circuit in equilibrium on the S-cut welded to a horizontal copper circle is immersed in a tank of acidic water. A circuit placed around the tank and traversed by an intense current then causes the rotation of the mobile device. Ampere then produced continuous rotations only by means of currents, impossible to obtain only with magnets. He thus confirmed his theory and dealt a fatal blow to that of Biot. He could have discovered the principle of the electric motor, but this was not the case because he was more interested in understanding fundamental phenomena than in developing their applications.

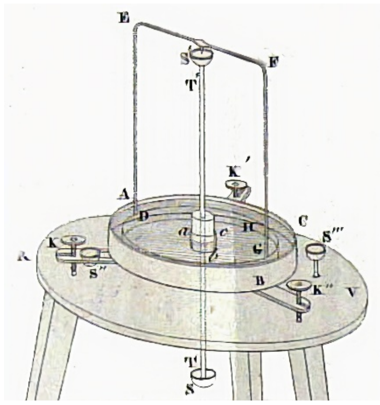

Fig. 13: Ampère's sketch of a device intended to create the continuous rotation of a current under the action of another.

The "zero method"

From 1822, Ampère stopped experimenting and developed the "zero method": this consisted of studying the mechanical balance of a conductor subjected to the opposite actions of two fixed conductors traversed by the same current. Ampère then imagined completely astatic devices in order to eliminate the effects of terrestrial magnetism, and he analyzed the geometry of the conductors in order to obtain the mathematical information necessary for the formulation of the elementary force.

Ampère used four different equilibrium situations, two being the result of real experiments unlike the other two: they played a fundamental role in his approach, similar to that of Kepler's three laws for Newton in his quest for the fundamental law of dynamics.

The experiment in figure [7] thus provided Ampère with two real equilibrium situations: he therefore studied the equilibrium of the mobile conductor *cd* integrated in an astatic circuit, placed first between two straight wires, then between a straight wire *GH* and a sinuous wire *AB*, both traversed by the same current [Fig.14].

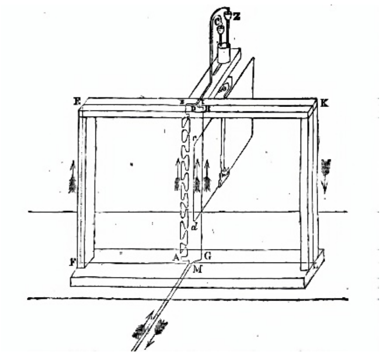
Fig. 14: Ampère's sketch of a device derived from that of Fig.7 and intended to study two situations of equilibrium between conductors.

The continuous rotation experiment provided Ampère with a theoretical case of equilibrium since the device of Figure 13 has never been realized. His calculations allowed him to determine that the factor *k* present in his first expression of the force was: $k = -1/2$.

The fourth case of equilibrium was provided by the study of the dynamic equilibrium of a current loop *PQ* belonging to an astatic circuit, placed between two fixed current loops, one *p* times smaller, the other *p* times larger than the mobile loop, the distances between the centers of these loops being in the same ratio *p* as their radii [Fig.15]. There are only sketches of this incredible device and it is certain that it has never been realized. The study of the equilibrium of this system allowed Ampère to justify the $1/r^2$ dependence of his law.

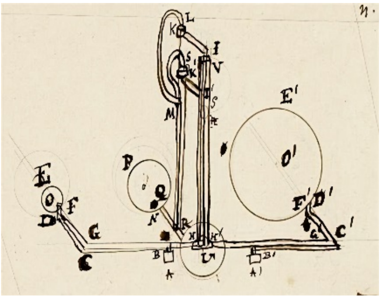
Fig. 15: Ampère's sketch of the 4th equilibrium case. The perspective is not respected: the three current loops are in a horizontal plane and their centers are aligned.

The fundamental law between infinitesimal currents

Thanks to the study of these 4 equilibrium situations, Ampère finally succeeded in formulating the fundamental law of mutual action between two infinitely small current elements of length *ds* and *ds'*. He showed that this elementary force was proportional to the ratio:

$$\frac{ii'ds\, ds'\,(\sin\alpha\, \sin\beta\, \cos\gamma\ -1/2\ \cos\alpha\, \cos\beta)}{r^2}$$

This formula was powerful because it allowed Ampère to define the intensity of the electric current from the force exerted on a parallel current element taken as a reference. It also allowed him to calculate the interactions between two real circuits, or between two magnets, or between a magnet and a current, in any configuration, by solving "*simple questions of integral calculus*". In practice, this was not so simple, and Ampère had to develop new mathematical tools.

Finally, Ampère helped by the young Félix Savary (1797 - 1841) showed that the formula of Biot and Savart between a wire and a magnet, as well as Coulomb's formula between two magnets, could be deduced from his elementary formula and that they were in fact only particular cases of it. And Ampère affirmed in 1823 that "*all the facts not yet completely explained [...] are necessary consequences of his formula*". Ampère had thus achieved his goal of reducing all magnetic and electromagnetic phenomena to actions between electric currents!

Some particular cases of interactions

The determination of the expression of the elementary force occupies only the beginning of Ampère's second work entitled "*Mathematical theory of electrodynamic phenomena only deduced from experiment*" published in 1826. All the rest is devoted to long calculations of application in many particular cases of interactions between currents and magnets.

Ampère was in particular interested in the action of a closed circuit on a current element *ds'*, when the circuit is perpendicular to this current element and to a straight line, called "directrix" by Ampère, which depends only on the closed circuit. He showed that the intensity of this force can be written as: $D\, i\, i'\, ds' \sin \omega / 2$ with ω the angle between the current element *ds'* and the "directrix", and *D* a quantity that only depended on the geometry of the closed circuit and the point where the current element was located. The dimension of the quantity *Di/2* and the direction of the "directrix" have the properties of the vector known today as the magnetic field. Ampère's expression actually gave rise to the expression known today as Laplace's force:

$$\overrightarrow{dF} = i'\overrightarrow{ds'} \wedge \vec{B}$$

Ampère was also interested in the mutual action of two parallel straight conductors separated by a distance *a*, crossed by currents of intensity *I* and *I'*. He showed that the force exerted by one of them, considered as infinite, on a portion of the other of length *L*, is proportional to the ratio *II'L/a*. It is from this expression that will be defined, in 1881, the unit of the intensity of the electric current which bears the name of Ampere in the international system of units.

Finally, during a teaching at the Collège de France in 1826, Ampère calculated the work of the force undergone by the magnetic pole during its rotation along a closed curve: he obtained a value which increased with each turn, and saw this as a "*curiosity ... because the poles of a magnet cannot be isolated*". In 1856, Maxwell showed that the work of the electromagnetic force acting on the pole of a magnet revolving around a wire is proportional to the intensity of the current in the wire. In memory of Ampère, Maxwell named the general formulation of this result "*Ampère's theorem*".

General conclusion

This article is the account of a short and intense moment in Ampère's life, between 1820 and 1826, which will lead him go down in history as the discoverer of electrodynamics. It brought to light a brilliant man animated by an incredible intuition associated with a remarkable intellectual audacity, and an ingenious experimenter despite an almost total absence of experimental measurements. But behind this facade also hides a tormented intellectual, torn between his own contradictions: his exchanges with Augustin Fresnel (1788-1827) lead him to be intimately convinced by a propagation from near to near in the "*ether*" to explain the existence of electromagnetic phenomena in matter which is consistent with his early vision, but in contradiction with the Newtonian formulation of his fundamental law assuming actions at a distance.

Because of its audacity, Ampère's approach had the effect of a bomb in the scientific community: at first completely rejected, it then brought about a consensus thanks to Ampère's determination. The devices that he designed did not all exist, but they were objects of thought which allowed him to intertwine qualitative experiments and theoretical formulations, always in search of a logical homogeneity between the "*universal judgment*" of the theory and the "*particular judgment*" of the experiment, according to the expressions of G. Canguilhem. This exceptional scientific approach allowed Ampère to establish a universal law unifying electricity and magnetism, which made Œrsted's discovery a scientific revolution giving birth to electromagnetism.

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