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Research article

Ampère's Force Between Current Elements

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Abstract. This article examines the force deduced by Ampère (1775–1826). In 1820 Oersted conducted his revolutionary experiment: a current-carrying wire capable of deflecting a compass needle. To explain this phenomenon Ampère presented two crucial hypotheses: he postulated the existence of forces between current-carrying conductors and suggested that electric currents existed not only in conductive wires, but also inside magnets and even within the Earth. To deduce his force Ampère developed his famous cases of equilibrium in which a mobile circuit is kept at rest between two opposing forces or between two opposing torques. In 1822 Ampère obtained his final expression, a central force consistent with Newton's third law of motion. According to Ampère's force, the action between two current elements is proportional to the product of their intensities, to the product of their infinitesimal lengths, and varies inversely with the square of their distance. Furthermore, this force depends on three angles. According to Maxwell, Ampère's force should always remain the most important formula of electrodynamics. However, despite this positive evaluation, Ampère's force disappeared from modern textbooks, being replaced by Grassmann's theoretical force from 1845, which does not comply with Newton's third law. In 1822 Ampère predicted the existence of longitudinal repulsive forces between two collinear and parallel elements with currents in the same direction. This force should not exist according to Grassmann's law. Ampère created the bridge experiment to test this prediction and it was successful. Maxwell, while aware of both expressions (Ampère's and Grassmann's forces), expressly preferred Ampère's force.

Keywords. Ampère, Grassmann, force between current elements.

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Note. This article follows a presentation by the author at the conference "250 Years of Ampère: An Electric World Tomorrow?", held on December 11–12, 2025, in Lyon.

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Introduction

The year 2025 marks the 250$^{\text{th}}$ anniversary of the birth of André-Marie Ampère (1775–1836) in Lyon. There are some important works devoted to the life and work of Ampère [1–9] and [10].

To celebrate the 250$^{\text{th}}$ anniversary of Ampère's birth, the SAAMA[1] and the SEE[2] organized numerous events throughout the year [11]. This paper is a printed version of our oral presentation during the Historical and Scientific Colloquium which took place on December 11 and 12, 2025 [12,13] and [14].

[1] SAAMA : Société des Amis d'André-Marie Ampère.
[2] SEE : Société de l'électricité, de l'électronique et des technologies de l'information et de la communication.

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1. Ampère's Force between Two Current Elements

Until 1820 the main force of physics was that of Isaac Newton (1642–1727) between two gravitational point masses m_1 and m_2 separated by a distance r, namely: [15–18] and [19].

$$F = \frac{m_1 m_2}{r^2}. \tag{1}$$

Charles-Augustin de Coulomb (1736–1806) obtained a similar force between two particles electrified with charges q_1 and q_2, namely:

$$F = \frac{q_1 q_2}{r^2}. \tag{2}$$

Working with long and thin magnetized bars he also obtained an analogous force acting between two supposed magnetized particles with pole intensities p_1 and p_2, namely:

$$F = \frac{p_1 p_2}{r^2}. \tag{3}$$

Recently Coulomb's main works on torsion, electricity and magnetism have been fully translated with commentary into Portuguese and English [20,21].

Equations (1), (2) and (3) are central forces complying with Newton's third law of motion. That is, they satisfy the law of action and reaction, pointing along the straight line connecting the two interacting particles.

In 1820 Hans Christian Ørsted (1777–1851) informed the world of his discovery that a current carrying wire deflects a nearby compass needle. This experiment is illustrated in Figure 1. In (a) and (b) the needle points along the magnetic meridian while there is no electric current in the wire. In (c) there is a constant current flowing along the wire from the South towards the North. The needle is deviated from the magnetic meridian, with its North pole going westward.

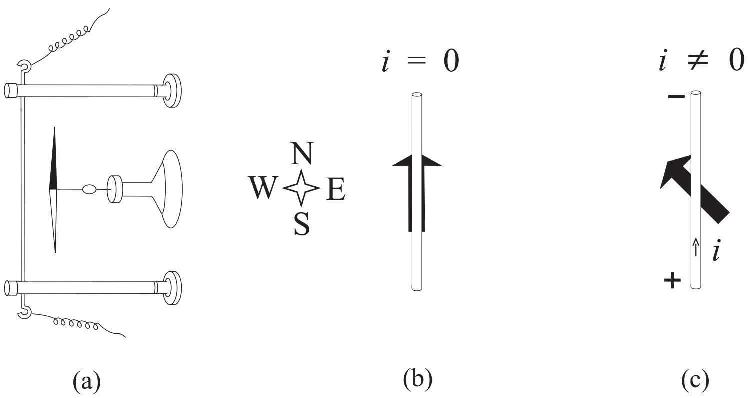


Figure 1. Representation of Ørsted's experiment with the horizontal wire above the magnetic needle.

When the horizontal wire is located below the needle, the opposite phenomenon takes place, as represented in Figure 2. In (a) and (b) the needle points along the magnetic meridian while there is no electric current in the wire. In (c) there is a constant current flowing along the wire from the South towards the North. The needle is deviated from the magnetic meridian, with its North pole going eastward. He coined the name "electromagnetism" to describe this kind of interaction between a magnet and a current carrying wire.

Ampère was impressed with this experiment and decided to devote most of his time to this subject.

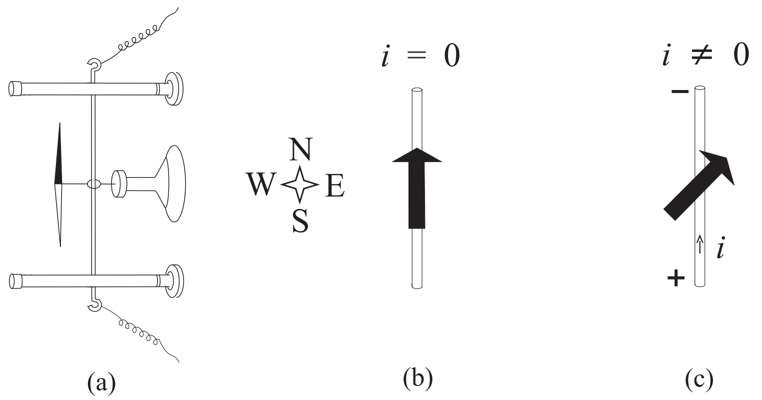


Figure 2. Representation of Ørsted's experiment with the horizontal wire below the magnetic needle.

In 1820, in order to interpret Ørsted's experiment, Ampère made two crucial and original hypotheses, which turned out to be extremely fruitful:

(1) He assumed the existence of forces of attraction and repulsion between current carrying conductors. Nobody had observed these forces before him.
(2) He assumed the existence of electric currents inside magnets and inside the Earth.

He then tried to model electrodynamically all magnetic properties of a magnet and the Earth by appropriate electric currents. He also tried to find the force law acting between two current elements.

Ampère faced a problem in conceptualizing "infinitesimal" current elements that had spatial orientations and even "lengths". He only gradually learned how to clearly distinguish between current intensity and current element "length". This has been discussed in Section 2.6 (The Current Intensity and the Size of the Current Element) of the book *Ampère Electrodynamics* [22,23].

Initially he represented the current element ids by the symbol g and the current element $i'ds'$ by the symbol h. In particular, in his first manuscripts and verbal statements he made a misleading confusion of current element length and current intensity. For instance, in one of his early publications he expressed himself as follows [24, p. 174], [6, pp. 249–253] and [25, p. 122], our emphasis:

> In order to have a clear idea of this law [of force between current elements], one must imagine in space a line representing in magnitude and in direction the resultant of two forces which are similarly represented by two other lines, and suppose, in the directions of these three lines, three infinitely small portions of electric currents, *the intensities of which are proportional to their lengths*. The law at issue consists in the fact that the small portion of electric current directed along the resultant exerts, on another current or on a magnet, an attractive or repulsive action equal to what would result, in the same direction, from the combination of the two portions of current directed along the components.

It would be difficult for someone to understand what Ampère meant by "the intensities of electric currents proportional to their lengths". Gillet de Laumont (1747–1834) tried to clarify statements like this. In a paper published in 1820, in which he made a summary of Ampère's researches, he substituted this expression by the following [26] and [6, p. 253]:

> When we wish to have a clear idea of the law expressed by M. Ampère in his work, one must imagine in space a line representing, in magnitude and in direction, the resultant of two forces which are similarly represented by two other lines, and suppose, in the directions of these three lines, three electric currents *of which the attractive or repulsive forces are proportional to their lengths*.

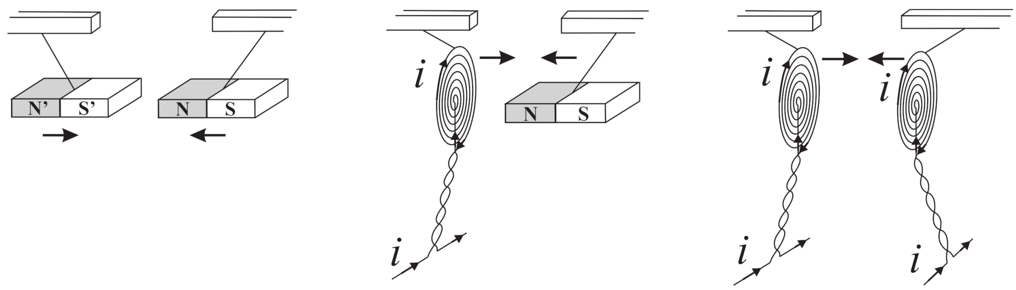
That is, Laumont clarified that the *forces* between two current elements are proportional to their lengths, instead of stating that the intensities of the electric currents were proportional to their lengths. In 1823 Ampère utilized a statement similar to Laumont's. Ampère replaced the expression "the intensities of electric currents proportional to their lengths" by the statement that the "attractive or repulsive forces are proportional to their lengths" [27, pp. 212–213] and [28, pp. 248–249].

The first substitution of the symbols g and h by ids and $i'ds'$, respectively, happened for the first time in 1822 in Ampère's fundamental paper in which he obtained the final value of his force between two current elements [29, p. 412]:

> [...] the intensities of the action of two small portions of conductors which I called g and h in the note of the *Journal de Physique* will be represented here, as their lengths are ds and ds', by ids and $i'ds'$, [...].

In the *Théorie* ([30, pp. 27–28], [31, pp. 199–200] and [32, p. 173]), Ampère had "put i and i' for the ratios of the intensities of two given currents to the intensity of the reference current taken as unity". We believe there are two possibilities for his choice of the symbol i to represent the intensity of the electric current. The first possibility is that this symbol is the first letter of the word "intensity". The second possibility is that in his first publications he called the intensities of two current-carrying wires by the symbols g and h, although still confusing the intensities of the currents in each element with their lengths. As the next letter of the alphabet after g and h is the letter i, Ampère may have chosen this letter for alphabetical reasons in order to represent the current intensity, while representing its infinitesimal length by ds. In any event, no matter his reasons for choosing the letter i to represent the intensity of a current, this convention is still adopted in all textbooks dealing with electromagnetism.

Ampère initially modeled a magnet as a spiral current loop. It was known that the opposite poles of two magnets attract one another, Figure 3 (a). Ampère replaced the left magnet with a current carrying spiral and observed their attraction, Figure 3 (b). By reversing the direction of the current or the polarity of the magnet, he could observe their repulsion.



(a) (b) (c)

Figure 3. (a) The opposite poles of two magnets attract one another. (b) Ampère replaced the left magnet with a current carrying spiral and observed their attraction. (c) He then replaced the right magnet by a second current carrying spiral and observed their attraction.

He described this experiment as follows [24, pp. 207–208], [33, pp. 152–153], [22, pp. 65–66] and [23, pp. 61–62]:

> Depending on the direction of the current, such a spiral is greatly attracted or repelled by the pole of a magnet which is presented with its axis perpendicular to the plane of the spiral, according as the current of the spiral and of the pole of the magnet flow in the same or opposite directions.

Ampère then replaced the right magnet by a second current carrying spiral and observed their attraction, Figure 3 (c). This was the first time in the history of physics that someone showed an interaction between two current carrying wires. He coined the name “electrodynamics” to describe this new kind of interaction. By reversing the direction of the current of any of these spirals, he could observe their repulsion. Ampère described this observation as follows [24, p. 208], [33, pp. 153–154], [22, pp. 67–68] and [23, pp. 62–63]:

> In replacing the magnet by another spiral with its current in the same direction, the same attractions and repulsions occur. It is in this way that I discovered that two electric currents attract each other when they flow in the same direction and repel each other in the other case.

He then performed his most famous experiment showing the attraction and repulsion between two parallel straight wires carrying steady currents, Figure 4.

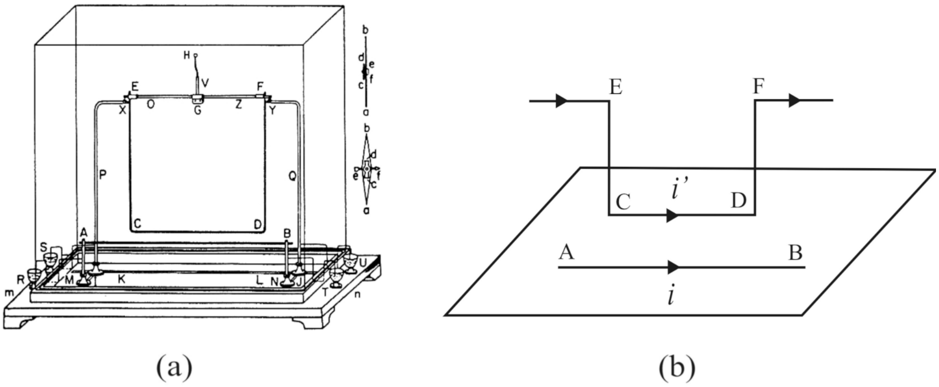


Figure 4. (a): Ampère’s demonstration that parallel straight wires carrying currents in the same direction attract one another, repelling when the currents flowed in opposite directions. Conductor *AB* is fixed in the laboratory, while the mobile conductor *CD* can turn around the horizontal axis *EF*, moving towards *AB* or away from it. The straight segments *AB* and *CD* are initially in the same horizontal plane, with the axis *EF* vertically above *CD*. (b): Our representation of this experiment, indicating the current directions.

This device is the basis of the current balances available in all didactic physics laboratories.

There was an important exchange of ideas between Augustin-Jean Fresnel (1788–1827) and Ampère. Initially, Ampère believed that the electric currents responsible for magnetism were macroscopic currents. Fresnel suggested to Ampère the fundamental idea that these currents circulated around each magnetized molecule of the material. That is, they were molecular currents, rather than macroscopic ones. Ampère adopted this suggestion.

Fresnel worked with optics. Initially, he believed that light waves were caused by longitudinal vibrations in the ether, analogous to sound waves in air. Ampère suggested to Fresnel to consider transverse light waves, rather than longitudinal ones, in order to explain the polarization of light. Fresnel adopted this suggestion.

To deduce his central force which acts between two current elements, Ampère conducted a series of ingenious experiments. He developed his famous cases of equilibrium, also called the null method in physics. A mobile circuit is placed between two other circuits fixed in the laboratory. There are certain configurations in which equilibrium takes place (zero net force or zero net torque on the mobile circuit). Using some of these equilibrium experiments and symmetry arguments, Ampère initially arrived at the following expression for the force between two current elements:

$$F = \frac{i_1 d\ell_1 i_2 d\ell_2}{r^2}\left(\sin\alpha\sin\beta\cos\gamma + k\cos\alpha\cos\beta\right). \tag{4}$$

This force is proportional to the product of the intensities i_1 and i_2 of the two current elements, to the product of their lengths $d\ell_1$ and $d\ell_2$ and is inversely proportional to the square of their distance r. However, it is more complicated than Newton and Coulomb's force laws as it depends on three angles α, β and γ shown in Figure 5.

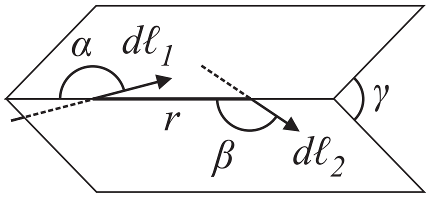


Figure 5. Angles α, β and γ appearing in Ampère's force.

Initially Ampère thought that the constant k appearing in Equation (4) was null. By analyzing other equilibrium configurations, he obtained in 1822 that $k=-1/2$. The final expression of his force law between two current elements as presented by Ampère:

$$F=\frac{i_1 d\ell_1 i_2 d\ell_2}{r^2}\left(\sin\alpha\sin\beta\cos\gamma-\frac{1}{2}\cos\alpha\cos\beta\right). \tag{5}$$

This force can also be expressed in vector notation and in the modern International System of Units MKSA. Consider a current element $I_1 d\vec{\ell}_1$ located at $\vec{r}_1=(x_1,y_1,z_1)$ relative to the origin O of an inertial system of reference and another current element $I_2 d\vec{\ell}_2$ located at $\vec{r}_2=(x_2,y_2,z_2)$, where I_1 and I_2 are the current intensities measured in ampères, while $d\ell_1$ and $d\ell_2$ are the lengths of the elements measured in meters. Let $\vec{r}=\vec{r}_1-\vec{r}_2$ be the vector pointing from 2 to 1, while $r=|\vec{r}|$ is the distance between 1 and 2 measured in meters. The unit vector pointing from 2 to 1 is then given by $\hat{r}=\vec{r}/r$. The force $\vec{F}^A_{21}$ exerted by 2 on 1, measured in newtons, is given by:

$$\vec{F}^A_{21}=-\frac{\mu_o}{4\pi}I_1 I_2\frac{\hat{r}}{r^2}\left[2\left(d\vec{\ell}_1\cdot d\vec{\ell}_2\right)-3\left(\hat{r}\cdot d\vec{\ell}_1\right)\left(\hat{r}\cdot d\vec{\ell}_2\right)\right]=-\vec{F}^A_{12}. \tag{6}$$

Here $\mu_o=4\pi\times10^{-7}\ kgmA^{-2}s^{-2}$ is a magnetic constant called vacuum permeability or permeability of free space, while $\vec{F}^A_{12}$ is the force exerted by 1 on 2.

As shown by Equation (6), Ampère's force exerted by 2 on 1 is equal and opposite the force exerted by 1 on 2. Moreover, it is always a central force pointing along the straight line connecting the two elements, no matter their orientation in space. In other words, it obeys Newton's third law, the law of action and reaction, in the strong form.

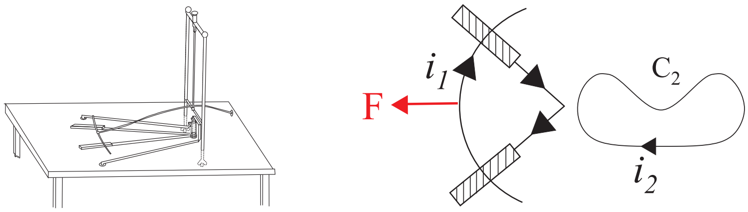
The unexpected discovery that $k=-1/2$ led Ampère to two remarkable consequences.

As the first consequence, he integrated his law and discovered that the force exerted by a closed circuit of any shape, acting on a current element of another circuit, is always orthogonal to the direction of that element. Ampère then conducted an experiment that confirmed this theoretical prediction. A current carrying closed circuit of arbitrary shape acted on a circular conducting arc which was free to move clockwise or anticlockwise. When the current flowed in the circuit, the circular arc remained stationary. This is the case of equilibrium where there is no tangential force, the circular arc does not move clockwise or counterclockwise, Figure 6.

Ampère obtained a second remarkable consequence due to the fact that $k=-1/2$. He predicted that two parallel and collinear current elements, whose currents flow in the same direction, should repel each other, Figure 7.

Ampère was so surprised by this result that he designed an experiment to test this prediction. This experiment was a success and is known as Ampère's bridge experiment, Figure 8.

According to Ampère, the observed force on the bridge pointing towards the right is due to the repulsion between portions AB and BC with collinear currents flowing in the same direction, together with the repulsion between portions EF and FG once again with collinear currents flowing in the same direction.



(a) (b)

Figure 6. (a): A conducting circular arc rests on two mercury troughs. It is free to move clockwise or anticlockwise. (b): When a current I_2 flows on a closed circuit of arbitrary shape and a current I_1 flows on the arc, the arc remains stationary, the force F acting on it is orthogonal to its direction.

Figure 7. According to Ampère's final expression, two collinear and parallel current elements should repel one another when the currents flow along the same direction.

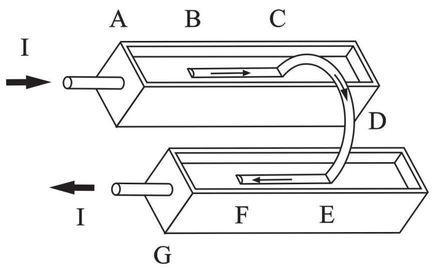


Figure 8. The bridge $BCDEF$ floats on two mercury troughs.

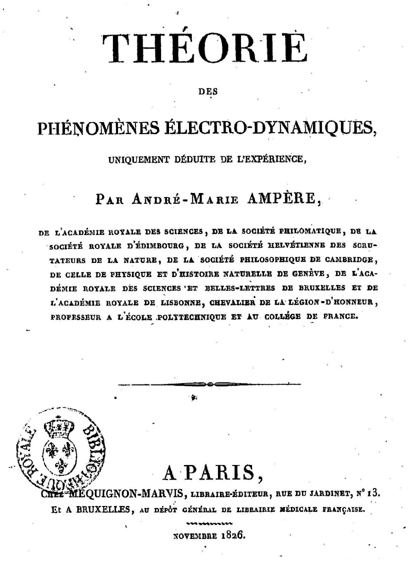
2. Ampère's masterpiece

In 1826 Ampère published his most important book, *Théorie des Phénomènes Électro-dynamiques, Uniquement Déduite de l'Expérience* [30], Figure 9. Recently this book has been fully translated with commentary into Portuguese and English [22,34,35] and [23].

This work has been highly praised.

Whittaker [36, p. 83]:

> [Ampère] published his collected results in one of the most celebrated memoirs in the history of natural philosophy.


THÉORIE
DES
PHÉNOMÈNES ÉLECTRO-DYNAMIQUES,
UNIQUEMENT DÉDUITE DE L'EXPÉRIENCE,
PAR ANDRÉ-MARIE AMPÈRE,
DE L'ACADÉMIE ROYALE DES SCIENCES, DE LA SOCIÉTÉ PHILOMATIQUE, DE LA SOCIÉTÉ ROYALE D'ÉDIMBOURG, DE LA SOCIÉTÉ HELVÉTIENNE DES SCRUTATEURS DE LA NATURE, DE LA SOCIÉTÉ PHILOSOPHIQUE DE CAMBRIDGE, DE CELLE DE PHYSIQUE ET D'HISTOIRE NATURELLE DE GENÈVE, DE L'ACADÉMIE ROYALE DES SCIENCES ET BELLES-LETTRES DE BRUXELLES ET DE L'ACADÉMIE ROYALE DE LISBONNE, CHEVALIER DE LA LÉGION-D'HONNEUR, PROFESSEUR A L'ÉCOLE POLYTECHNIQUE ET AU COLLÉGE DE FRANCE.

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NOVEMBRE 1826.

Figure 9. Cover of the *Théorie* published in 1826.

Tricker [1, pp. vii and 36]:

> At the beginning of the year 1820 nothing was known of the magnetic action of an electric current. By 1826 the theory for steady currents had been completely worked out. Since then, though newer methods may have made the handling of the mathematical apparatus simpler and more concise, nothing fundamental has been changed. [...]
> In the theory of gravitation, Newton was already provided with a knowledge of a range of the phenomena, mainly through the medium of Kepler's laws. Ampère had to discover the laws as well as provide the theory, and thus do the work of Tycho Brahe, Kepler and Newton rolled into one.

Williams [2, p. 145] comparing Ampère's main work [30,31], with Newton's masterpiece of 1687, *Mathematical Principles of Natural Philosophy* [15–19]:

> Having established a noumenal foundation for electrodynamic phenomena, Ampère's next steps were to discover the relationship between the phenomena and to devise a theory from which these relationships could be mathematically deduced. This double task was undertaken in the years 1821–1825, and his success was reported in his greatest work, the *Mémoire sur la théorie mathématique des phénomènes électrodynamique, uniquement déduite de l'expérience* (1827). In this work, the *Principia* of electrodynamics, Ampère first described the laws of action of electric currents, which he had discovered from four extremely ingenious experiments.

Maxwell [37, Vol. 2, art. 528, p. 175]:

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

3. Ampère's Force Versus Grassmann's Force

Despite these extremely positive reviews, Ampère's force between current elements disappeared from the textbooks more than 100 years ago. This situation continues in the present day teaching of physics everywhere in the world. Ampère's force between current elements has been replaced by the theoretical force of Hermann Günther Grassmann (1809-1877). He was a German linguist and mathematician who studied theology at Berlin University. Apparently he did not follow the mathematics nor the physics courses of this university. After graduation he returned to his native town, Stettin, remaining there until the end of his life, working as a high school teacher of mathematics. He never taught at a university and apparently never performed experiments on electromagnetism.

His theoretical force of 1845 can be written as follows in the modern vector notation and in the International System of Units MKSA:

$$\vec{F}_{21}^{G} = I_1 d\vec{\ell}_1 \times \left(\frac{\mu_o}{4\pi} \frac{I_2 d\vec{\ell}_2 \times \hat{r}}{r^2} \right) = -\frac{\mu_o}{4\pi} \frac{I_1 I_2}{r^2} \left[\left(d\vec{\ell}_1 \cdot d\vec{\ell}_2 \right) \hat{r} - \left(d\vec{\ell}_1 \cdot \hat{r} \right) d\vec{\ell}_2 \right] \neq -\vec{F}_{12}^{G}. \tag{7}$$

Contrary to Ampère's force, Grassmann's force does not predict longitudinal forces. For instance, in the situation of Figure 7 there should be no force acting between these two collinear and parallel current elements.

There are also situations in which Grassmann's force does not comply with Newton's third law of motion, his law of action and reaction [38, Chapter 4].

Maxwell knew not only Ampère's force (1822) but also Grassmann's force (1845). In his *Treatise on Electricity and Magnetism* he compared these two expressions with two other forces between current elements created by Maxwell himself [37, Vol. 2, art. 527, p. 174]:

> Of these four different assumptions that of Ampère is undoubtedly the best, since it is the only one which makes the forces on the two elements not only equal and opposite, but in the straight line which joins them.

Even with Maxwell's judgment, Ampère's force has been totally forgotten for more than a century. I believe the main reason for this fact is that modern electromagnetic theory is based not only on Maxwell's equations, but also on the so-called Lorentz' force law which is compatible with Einstein's theory of relativity. Beginning with Lorentz' force, only Grassmann's force is deduced, but not Ampère's force.

The scientist who developed the experimental and theoretical researches of Ampère was Wilhelm Weber (1804–1891). Beginning with Weber's force, only Ampère's force between current elements is deduced, but not Grassmann's force [38, Chapter 4]. Weber's force between electrified particles is based on Ampère's force between current elements. Weber's planetary model of the atom is also based on Ampère's molecular currents [39–41]. Weber's electrodynamics was also erased from textbooks for over a century, just as happened with Ampère's force between current elements.

It is precisely to change this situation that I published with Chaib complete and annotated translations, into Portuguese and English, of Ampère's masterpiece [22,23].

For the same reason I edited with the help of other scientists, in 5 volumes, the annotated translations into English and Portuguese of Weber's works on electrodynamics [42–49] and [50].

I hope that in the 21st century, Ampère's force between current elements will once again be presented in textbooks as the most important formula of electrodynamics, as advocated by Maxwell.

Acknowledgments

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Declaration of interests

The authors do not work for, advise, own shares in, or receive funds from any organization that could benefit from this article, and have declared no affiliations other than their research organizations.

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