LA PHYSIQUE REVISITÉE

History of field concept. From action at a distance by gravitational attraction to vector fields

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La physique revisitée, Issue 1, pages 33-43
Receveid: 17 february 2026. Accepted: 03 march 2026. Published: 05 june 2026
DOI : 10.5281/zenodo.20557817

This article on the history of science accompanies the scientific article:
The plane wave impedance in vacuum Z0 is an electromechanical coupling constant

ABSTRACT: The subtleties that distinguish the different electromagnetic fields are often difficult for many students to grasp; however, they result from the historical necessities that accompanied the progressive conceptualization of the phenomena.

This article aims to understand the evolution of the concepts that led to these tools, the mastery of which can be improved if their use is justified by their historical necessity.

The proposed reflection will lead from the first intuition of the existence of action at a distance on the scale of the solar system to the subtleties distinguishing mechanical effect fields and excitation fields in electromagnetism.

It appears that the notion of a vector field, so familiar to us, was far from self-evident and that it took a long succession of scientific advances to arrive at it. On the other hand, even if they never used the vector tool themselves, it is to Faraday that we owe the notion of fields in electromagnetism and then to Maxwell the use of the term, as well as the introduction of the concepts of excitation fields to distinguish the effect from the cause.

The concept of the D field arose from the need to introduce displacement current, and this indirect conceptualization made its interpretation as an electrical excitation field more difficult. The confusing terminology used today to designate the four electromagnetic fields is a consequence of this historical difficulty.

keywords: Magnetic field, electric field, gravitation, excitation field

RÉSUMÉ : Les subtilités qui distinguent les différents champs électromagnétiques sont souvent difficiles à saisir pour de nombreux étudiants ; elles résultent pourtant des nécessités historiques qui ont accompagné la conceptualisation progressive des phénomènes.

Cet article vise à comprendre l'évolution des concepts qui ont conduit à ces outils dont la maîtrise peut être améliorée si leur utilisation est justifiée par leur nécessité historique.

La réflexion proposée conduira de la première intuition de l'existence d'une action à distance à l'échelle du système solaire jusqu'aux subtilités distinguant champs d'effet mécanique et champs d'excitation en électromagnétisme.

Il apparait que la notion de champ vectoriel qui nous est si familière, était loin d'être une évidence et qu'il a fallu une longue succession d'avancées scientifiques pour y parvenir. D'autre part, même s'ils n'ont jamais utilisé eux-mêmes l'outil vectoriel, c'est à Faraday que l'on doit la notion de champs en électromagnétisme puis à Maxwell l'emploi du terme, ainsi que l'introduction des concepts de champs d'excitation pour distinguer l'effet de la cause.

Le concept de champ D s'est imposé par la nécessité d'introduire le courant de déplacement et cette conceptualisation indirecte a rendu plus difficile son interprétation en tant que champ d'excitation électrique. La terminologie confuse qui règne aujourd'hui pour désigner les quatre champs électromagnétiques est une conséquence de cette difficulté historique.

Mots clés : Champ magnétique , champ électrique, gravitation, champ d'excitation

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1. THE BEGINNINGS OF REMOTE ACTION: THE UNIVERSAL LAW OF GRAVITATION

1.1. 3rd century BC

According to his conclusions, Aristarchus of Samos (310-230 BC) seems to have foreseen the principle of universal gravitation almost two millennia before Newton, but his heliocentrism was not accepted. He had carried out astronomical measurements using the Earth's diameter, which was not yet known, as a reference; these were therefore relative measurements. He had determined the relative diameter of the Moon with respect to the Earth by counting the durations of the phases of an eclipse [1]:

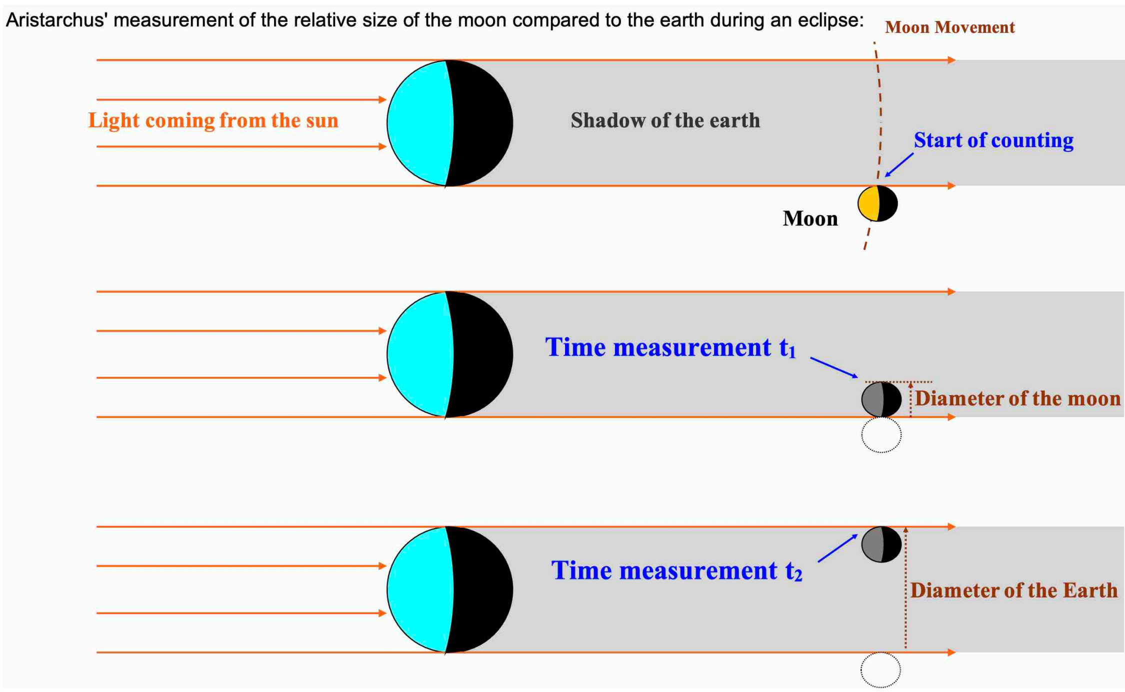

FIGURE 1. Principle (simplified) on which Aristarchus of Samos based his method for measuring the relative diameter of the moon

The ratio of diameters is that of measured time intervals. He had determined the diameter of the moon to be about one-third that of the Earth. From the relative dimensions of the moon and angle measurements, he had calculated the Earth-Moon and Earth-Sun distances and deduced the diameter of the Sun, using that of the Earth as the unit. He then deduced from the Sun's immense size that it was the Earth that revolved around it, and not the other way around. This shows that the principle of gravitation was already taking shape in Aristarchus's mind.

Unfortunately, we lack precise information on this specific question. Indeed, these first calculations of the dimensions and distances within the solar system are known to us through his treatise *"Peri megethon kai apostematon"* (On the dimensions and distances) [2] where he does not mention the heliocentrism. This is reported to us by Archimedes in "The Sand Reckoner," but the latter did not believe in heliocentrism and contested this final conclusion. It would take almost two thousand years for heliocentrism with Copernicus and universal gravitation with Newton to be fully understood and accepted by the scientific world.

1.2. Year 1684

In 1684 Edmond HALLEY presented to the Royal Society Isaac NEWTON's manuscript "De motu corporum in gyrum" (On the motion of bodies in orbit), containing the calculations which demonstrate why the orbit followed by a planet is an ellipse.

In the manuscript presented by Edmond Halley, Newton sets forth the law of universal gravitation as a function of the masses of bodies and the distance [3]:

$$F \propto \frac{M_1.M_2}{d^2}$$

As seen in the preceding expression, the gravitational constant G does not yet appear; this gravitational constant would be precisely measured by Henry Cavendish more than a century later, in 1798. Cavendish used the same method developed by Charles Coulomb for measuring the attractive electrostatic force (see below), but the period of oscillations was on the order of ten minutes. The gravitational constant, denoted f or G, would not be explicitly introduced into a new expression for the gravitational force until 75 years later, in 1873.

$$F = G.\frac{M_1.M_2}{d^2}$$

It therefore took almost two centuries for the expression to be complete. In the meantime, the distances separating the planets from the sun had already been calculated, and then, thanks to this law, taking into account their mutual influences, their respective masses had been calculated.

In reality, due to Kepler's laws, Halley and Hooke had already accepted that the force of the sun's attraction on the planets is inversely proportional to the square of the distance between them, but they had neither demonstrated that the resulting orbit was an ellipse nor incorporated the necessary consideration of the respective masses of the bodies. The demonstration of the ellipse is due to Newton, and this consideration of masses stems from his earlier work establishing the fundamental principle of dynamics.

Despite this extraordinary advance, the cause of the phenomenon of attraction is not addressed: Newton writes in his complete work *« Philosophiæ naturalis principia mathematica »* (Mathematical Principles of Natural Philosophy) published three years later: *« I have so far explained the celestial phenomena and those of the sea by the force of gravitation, but I have nowhere assigned the cause of this gravitation. »*[4].

Newton refused to explain the origin of this gravitational force and, in the commentaries on his introduction to the "centripetal force," preferred to prove its existence with the following formulation: *« "...the force, whatever its nature, which at every moment removes the planets from rectilinear motion. »*. Thus, relying on the slingshot effect, he described with irrefutable logic the effects its absence would have to justify its existence on the scale of the universe. "Universal" gravitation was demonstrated through analysis.

It is important to remember that action at a distance was already known for magnetic and electrostatic phenomena and that gravitation on the surface of the earth is observed daily without us thinking about it, but before Newton no one had been able to establish, without doubt1, that this action at a distance could be applied to "celestial mechanics".

Progress in our spatial representation of actions at a distance will come from electromagnetism [5], but it will be a long process that will initially begin with a search for Newtonian laws applied to this field.

2. ELECTROMAGNETIC REMOTE ACTIONS

2.1. Year 1785

In 1785, Charles Coulomb established the law that gives the force of interaction between two charges. This is the first dimensional formulation of an electromechanical phenomenon; as with the force of gravity, it follows a law inversely proportional to the square of the distance, but unlike gravity, this electrostatic force can be either attractive, like gravity, or repulsive if the charges have the same sign. [6]:

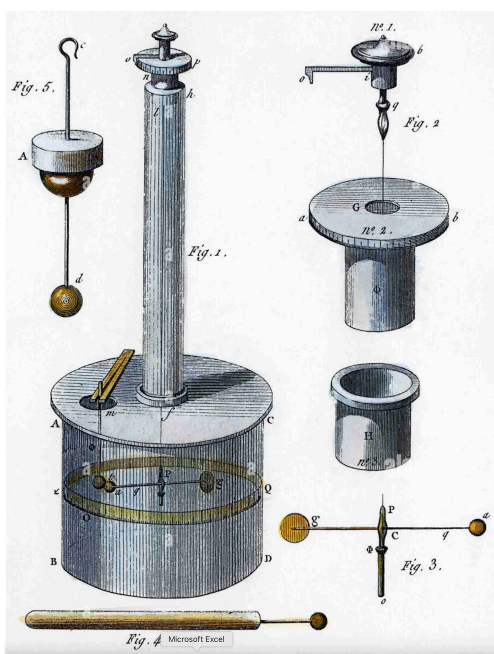

FIGURE 2. Coulomb balance for measuring the electrostatic repulsion force

To measure the electrostatic repulsive force, Coulomb used his "balance" with a torsion wire whose force was calibrated. He obtained a law inversely proportional to the square of the distance:

"The repulsive force between two small, electrified globes of the same type of electricity is inversely proportional to the square of the distance between the centers of the two globes"

To measure the force of attraction, a problem arose: the balance was unusable because the electrostatic force increased faster than the restoring force of the torsion wire as the distance decreased, causing the balls to stick together. Coulomb therefore devised a clever method to calculate the electrostatic force of attraction: ensuring a distance such that the charges could not make contact, he measured the period of oscillations around the equilibrium position (the force being proportional to the square of the frequency). This period, which varied according to the force, was on the order of a few seconds. This method was later adopted by Henry Cavendish in 1798 to measure the gravitational constant (see previously "Universal Law of Gravitation").

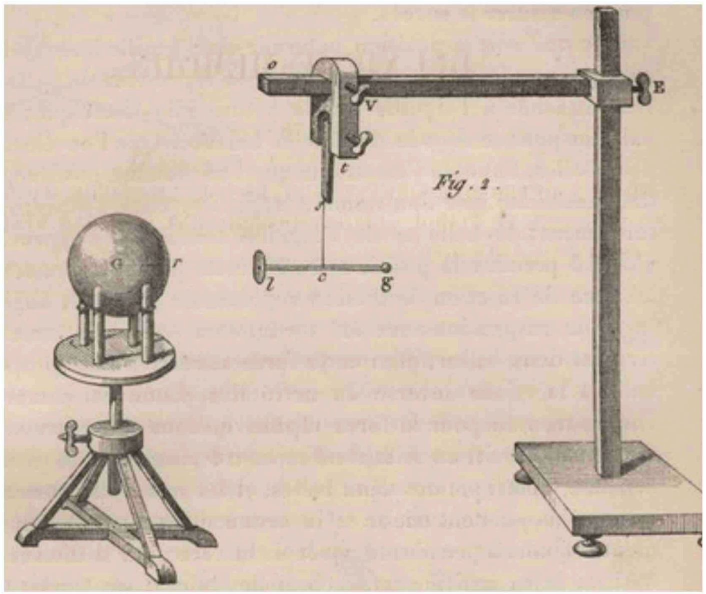

FIGURE 3. Measurement of the electrostatic attraction force by measuring the oscillation periods

Electrostatic force, whether attractive or repulsive, is expressed as follows:

$$F = \frac{Q.Q\prime}{r^2}$$

But at that time, the coulomb, the unit of electric charge, did not yet exist, and this expression lacked the constant for adapting it to this unit, just as Newton's gravitational force lacked the gravitational constant. It would be a long process that would culminate in 1946 with the rationalized SI expression [7].

Charles Coulomb established equivalent laws of attraction and repulsion for magnetism, but these are more difficult to grasp due to the non-existence of magnetic monopoles, and are therefore less well-known. Action at a distance, evident in electromagnetism, unlike in celestial mechanics, is observed and measured at specific points, but still lacks a spatial mathematical formalism to describe it.

2.2. April 1820

In April 1820, Hans Christian ØERSTED observed that the direction of a compass is deflected in the presence of an electric current.

ØERSTED's observation reached the Paris Academy of Sciences the same year, and André-Marie AMPÈRE went on to develop his theory of electromagnetism.

The magnetic effects of electricity had been discovered as early as 1802 by Gian Domenico ROMAGNOSI and communicated to the Paris Academy of Sciences, which curiously ignored them.

Thus, a new form of action at a distance is observed, but this time between electricity and magnetism, two domains then considered to be separate.

2.3. September 1820

In September 1820, André-Marie Ampère observed that the direction in which a compass needle moves depends on the direction of the electric current flowing nearby, and from this he deduced the rule that became popularly known as ”Ampère man rule.” He then took a further step by observing the direct interactions between currents and attributed magnetism to the existence of electric currents, including within magnets; these phenomena were thus described as ”electrodynamic.” Electricity and magnetism were now united in a single phenomenon. [8]

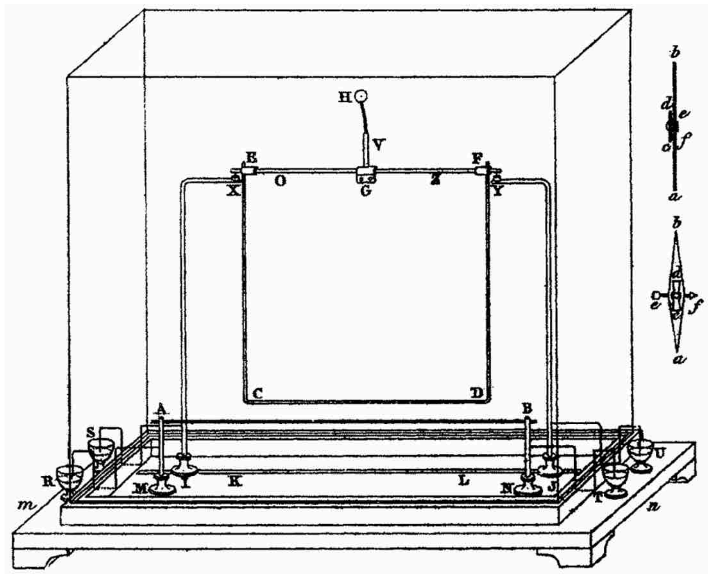

FIGURE 4. Figure of the device highlighting the force of interaction between conductors carrying currents.

2.4. Year 1826

In 1826, he published his ”Theory of Electrodynamic Phenomena,” which was mathematically formalized for the first time. In it, he expressed the forces of interaction between magnets and currents, and the mutual forces between currents. He laid the foundations of modern electrical terminology by distinguishing between ”voltage electricity” and ”current electricity.” [9]

The formulation of the electrodynamic force between currents is a fundamental work based on four qualitative experimental facts using the ”equilibrium case method”:

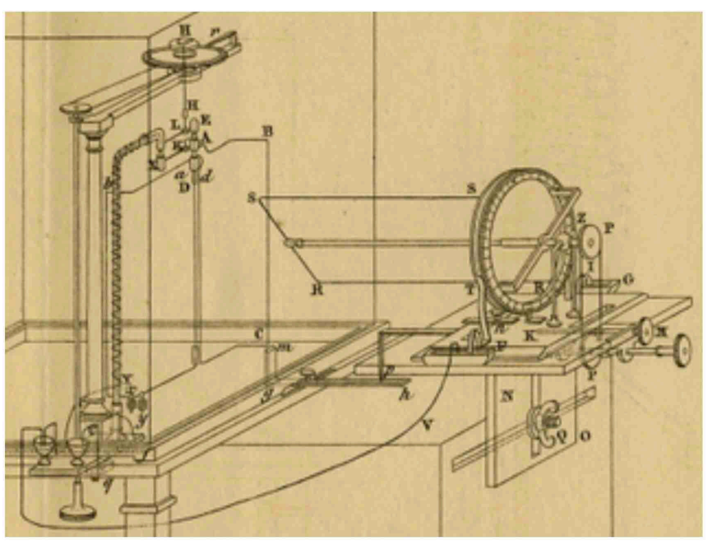

FIGURE 5. Device developed by Ampère to measure the electromagnetic force exerted on the vertical conductor BC from the magnetic field induced by the adjustable tilt conductor RS.

These four qualitative experiments allow us to develop the theoretical model:

AMPÈRE’s fundamental formula expresses the force exerted on each other by two infinitesimal current elements I.ds and I’ds’, placed at a distance r from each other and with relative orientations defined by the three angles α, β and γ.

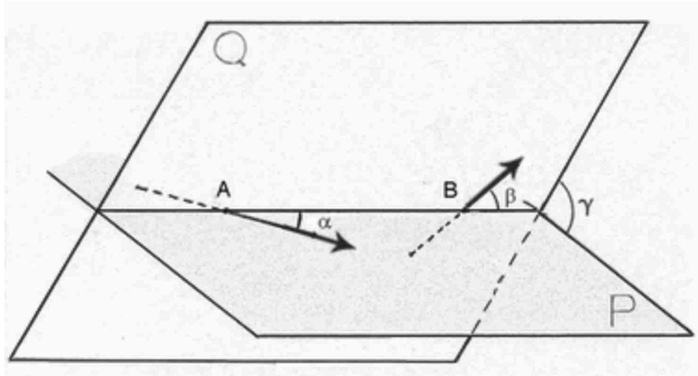

FIGURE 6. Figure showing the different angles of the formula

The current element I.ds in A is located in the plane P.
The current element I'.ds' in B is located in the plane Q.

$$F = \frac{I\ I' ds\ ds' (\sin\alpha \sin\beta \cos\gamma - \frac{1}{2}\cos\alpha \cos\beta)}{r^2}$$

Reduced to the case where planes P and Q coincide ($\gamma = 0$) and angles α and β are right angles, the force is expressed as:

$$F = \frac{I\ I' ds\ ds'}{r^2}$$

The elements ds and ds' are infinitesimal, it is not the expression of a force with macroscopic lengths

Ampère succeeded in giving a Newtonian form to the force, using "point currents" and a force inversely proportional to the square of the distance. However, this expression is a mathematical deduction based on four experiments and cannot be used directly because a current is practically never a point current. Physicists will prefer the macroscopic form, corresponding to technical constraints, as soon as advances in vector mathematics allow for a formulation of the forces acting on conductors. Thus, Ampère's electromagnetic force is a force per unit length, which, for two parallel conductors separated by a distance r, carrying direct currents I and I', is expressed as follows:

$$\frac{F}{L} = 2.\frac{I.\ I\prime}{r}$$

As with Coulomb's force, the unit of electric current, the ampere, did not yet exist, and this expression lacked the constant for adapting it to this unit. As with the electrostatic constant, it would be a long process that would culminate in 1946 with the rationalized SI expression.

At the beginning of the 19th century, the laws governing action at a distance were, with the exception of constants, all established, but in a local manner, as if it were a matter of mutual communication between two objects. The mathematical formalism for the spatial description of their influence on the environment, which seems familiar to us today, did not yet exist.

3. LINES OF FORCE AND THE BIRTH OF THE CONCEPT OF VECTOR FIELD

3.1. Year 1831

In 1831, Michael Faraday discovered magnetic induction ("converting magnetism into electricity") and began to bring forth the notion of field but without using the word.

$$e = -N.\frac{d\phi}{dt}$$

Lenz-Faraday Law (stated by Emil Lenz based on Faraday's work): The electromotive force (induced voltage) is proportional to the number of turns N and the rate of change of the magnetic flux in the circuit. The minus sign indicates that the induced electromotive force opposes the cause that produced it.

Faraday, despite the effectiveness of Newton's, Coulomb's, and Ampère's laws, had doubts about the concept of action at a distance. He found it difficult to accept that distant bodies could exert a force on each other without an intermediary. But after his discovery of the phenomenon of induction, he was convinced that electric currents could not be created at a distance without something acting in the space separating them.

3.2. Year 1852

In 1852, Faraday published his article *« On the physical character of the line of magnetic force »* in which he developed the idea that magnetic lines of force, demonstrated with iron filings, should be regarded as the expression of a real physical state of the space surrounding magnets and electric currents.

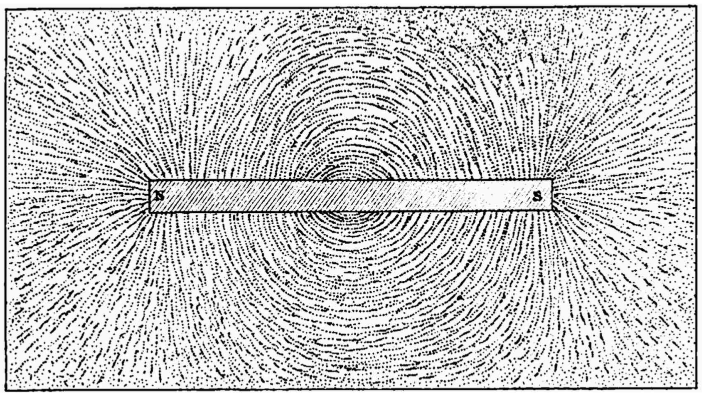

FIGURE 7. Figure described by DESCARTES in 1664 ("magnetic spectrum") and reproduced here by Faraday, of the distribution of iron filings in the environment of a magnet.

Faraday thus rejected the notion of action at a distance, asserting that magnetic phenomena were not due to direct action between separate bodies, but to a physical state of the intervening space. This was a major conceptual break with the Newtonian tradition. Faraday insisted that lines of force existed independently of the test bodies (metal filings) and carried the physical effects (forces, induction). Faraday then named the space crisscrossed by the lines of force "field", [10] probably by analogy to a plowed field.

3.3. James Clerk MAXWELL

In 1855, James Clerk MAXWELL developed in his series of articles *« On Faraday's Lines of Force »*, a mathematical theory inspired by Faraday's lines of force, with mechanical analogies. [11]

In 1865, in *« A Dynamical Theory of the Electromagnetic Field »*, Maxwell mathematically formalized the field to define an electromagnetic entity with dynamic properties and capable of representing the energy and propagation of waves. At each point in this space, Maxwell associates a "quaternion" that designates the direction and local value of the field. [10]

Quaternions : Quaternions are an extension of complex numbers, adapted to three-dimensional Euclidean space. They are "hypercomplex" numbers defined as linear combinations with real coefficients of unity and the symbols i, j, k such that:

$$i^2 = j^2 = k^2 = -1 \quad , \quad ij = k \quad , \quad jk = i \quad , \quad ki = j$$

Thus Maxwell associates differential equations with this state of space, he shows that this field has its own dynamics, energy and wave propagation capacity.

3.4. Year 1884

In 1884, Oliver HEAVISIDE reduced Maxwell's equations based on quaternions to four vector equations. Although highly gifted in mathematics, he sought, like Faraday before him and against the grain of their time, to minimize the omnipresence of mathematics in physics. He summarized this choice as follows: *"Should I forgo my dinner on the pretext that I do not fully understand the process of digestion?"*. Thus, Heaviside had little appreciation for quaternions, which he considered an unnecessarily erudite notation; this is why he chose to reformulate Maxwell's equations in terms of local vector fields with the differential operators: divergence and curl. [10]

Heaviside, along with Willard Gibbs, is one of the founders of vector analysis based on quaternions.

With Heaviside the field takes the modern mathematical form of a local vector.

4. MECHANICAL EFFECT FIELDS AND EXCITATION FIELDS

Before continuing with the historical aspects, it is necessary to clarify an important distinction concerning fields in electromagnetism.

4.1. Mechanical effect field

We have just arrived at the modern description of the local vector field, starting from action at a distance. It is therefore essential to note that these are fields of mechanical effect, since these fields are the vectors of action at a distance. This clarification is irrelevant to gravitation, which is not concerned, but it is fundamental to electromagnetism, where considerable confusion reigns in the vocabulary associated with the E, B, D, and H fields, two of which are even often contradictorily referred to as ”induction vectors” in both electricity and magnetism. [12]

The historical fields discussed so far are fields of mechanical effect, representative of action at a distance that is observable and measurable; they are:

- For electricity, this is the E field.
- For magnetism, this is the B field.

These two fields are those that produce a mechanical effect expressed in the Lorentz force exerted on a charge q moving at velocity $\vec{v}$:

$$\vec{F} = q(\vec{E} + \vec{v} \wedge \vec{B})$$

The E and B fields depend on the medium, which modifies the effectiveness of their effects relative to the vacuum, either by attenuating them (this is the case for electricity except in plasmas and it is also the case in magnetism when a material is diamagnetic), or by amplifying them (this is the case for magnetism when a material is paramagnetic or ferromagnetic).

Expression of the magnitude of the electric field of mechanical effect, E, at a distance r from a charge Q in a medium of dielectric permittivity ε :

$$E = \frac{Q}{4\pi.\varepsilon.r^2} \tag{1}$$

Expression of the magnitude of the magnetic field of mechanical effect, B, at a distance r from a straight current I in a medium of magnetic permeability μ :

$$B = \frac{\mu.I}{2\pi.r}$$

4.2. Excitation field

Associated with these two mechanical effect fields are the excitation fields. These latter fields are purely mathematical and describe only the geometric configuration of the sources [13]:

The excitation fields are:

- For electricity: the D field.
- For magnetism: the H field.

Expression of the magnitude of the electric excitation field, D, at a distance r from a charge Q, regardless of the medium:

$$D = \frac{Q}{4\pi.r^2} \tag{2}$$

Expression of the magnitude of the magnetic excitation field, H, at a distance r from a straight current I, regardless of the medium:

$$H = \frac{I}{2\pi.r}$$

These two fields therefore depend solely on the geometric configuration of the sources, independently of the medium and the mode of action of the phenomenon, representing only the excitation of the latter. Lacking any observable physical manifestation, they are conceptual tools that, chronologically, were developed after the concepts of mechanical effect fields. Because of the influence of the medium on these phenomena, it was necessary to distinguish what was independent of the medium and solely attributable to the sources.

The electric field of mechanical effect, E depends on the excitation field and the response of the medium:

$$\vec{E} = \frac{1}{\varepsilon}.\vec{D}$$

The magnetic field of mechanical effect, B, depends on the excitation field and the response of the medium:

$$\vec{B} = \mu.\vec{H}$$

Some theoretical electromagnetism textbooks neglect to mention these excitation fields. This is a deliberate choice that prevents them from addressing all the issues. Indeed, the response of materials is not as linear as the preceding relationships would suggest, for two reasons easily illustrated in the case of magnetic phenomena:

- The first relates to the fact that the value of the field of effect, B, reaches a limit (saturation) once a certain level of excitation H is reached.
- The second is that some materials "remember" the induction (retentivity) once the excitation has been removed. These are the materials from which we make magnets.

These materials, which are classified as ferromagnetic, describe the curves B=f(H) which show the hysteresis phenomenon corresponding to these two remarks when the excitation is variable:

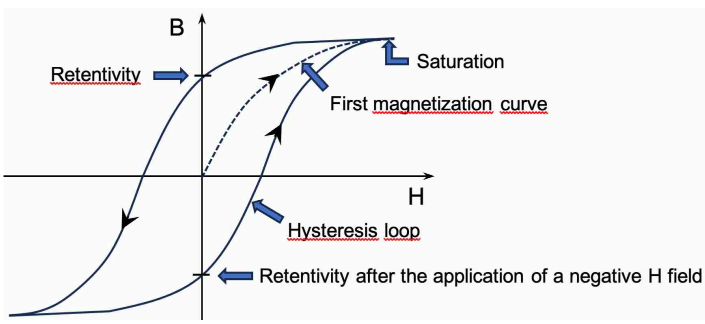

FIGURE 8. hysteresis of a ferromagnetic material

4.3. The beginnings of excitation fields

In 1862, in his series of articles *"On Physical Lines of Force"*, Maxwell identified a quantity which he called "magnetic force", related proportionally to the electric current. This is the original introduction of the magnetic excitation field, but he does not yet name it H. For the mechanical effect field, he uses the term "magnetic induction" which he does not yet call B but which he defines as dependent on the medium by the "coefficient of magnetic induction" which he denotes μ. [14]

In the same paper, Maxwell demonstrates, based on Faraday's work on dielectrics, that currents are not limited to the existence of free charges. Indeed, dielectrics are insulators, yet momentary currents are observed in them when an electromotive force is applied. There is therefore a "displacement" of charges that is quickly interrupted. The electrical excitation field D is not yet fully identified, but the term "displacement," which will give it its symbol, is already being defined. At this stage, it uses the lowercase letter "h" and expresses the displacement current with the lowercase letter "r":

$$r = \frac{\delta h}{\delta t}$$

4.4. The H field

In 1873, Maxwell, in his seminal work, *« A Treatise on Electricity and Magnetism »* finally designated the magnetic excitation field with the letter H and established its associated relationships. [15]

Maxwell uses the Gothic/script font of the 19th century, employing the terms "magnetic induction" with the letter B, "magnetic force" H for the magnetic excitation field, "magnetization intensity" I for magnetization (which we now denote M), and "induced magnetization coefficient" chi for magnetic susceptibility. He establishes the following relationships:

$$I = \chi.H \qquad\qquad B = H + 4\pi.I$$

Note: I should not be confused with current. The expression is given in CGS UEM units, so the permeability of free space is 1. The factor 4π has since been absorbed in the reorganization of constants and units with the adoption of the rationalized SI. We can also note that the expression "induced magnetization coefficient" was more explicit than "magnetic susceptibility".

The same relationships in the modern notation of the rationalized SI are:

$$M = \chi_m.H \qquad\qquad B = \mu_0(H + M)$$

These relationships are particularly interesting because they explicitly show that Maxwell already distinguished between what represents the mechanical effect field B, the excitation field H, and the magnetization induced by this excitation. Thanks to this effective approach from the outset, the acceptance of the field H as an electrical cause independent of the medium has never posed any real problems.

4.5. The D field

For electrostatics, it's more complicated: Maxwell initially makes a line of reasoning based on the "displacement" of particles in the dielectric medium, which leads to the notion of "displacement current" illustrated by Oliver Lodge's model three years later:

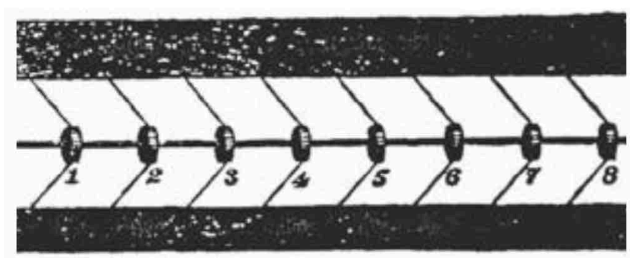

FIGURE 9. Modèle mécanique de Lodge

In Lodge's mechanical model, under the application of a force, the beads move and are then held. Under the application of an opposing force, they move in the opposite direction, and so on. Thus, under the action of an alternating force, there is an alternating displacement of the beads; this model is a mechanical analogy to the phenomenon of polarization. Thus, Maxwell confirms his new concept of "displacement current" due to the time derivative of "displacement," to which he now assigns the symbol D:

$$i_{displacement} = \frac{\partial \vec{D}}{\partial t}$$

Maxwell applied this to a vacuum, which may seem odd since he justified the concept by the limited movement of charges in dielectrics. Indeed, without the introduction of this displacement current into Maxwell's law, the principle of conservation of charge would be violated. Its application to a vacuum allowed him to conceptualize electromagnetic waves.

Note: This initial description of the D field as a limited displacement of charges within dielectrics made it difficult to separate it from this historical representation that associates it with media, even though this model has no meaning for a vacuum. Furthermore, E and D shared the same CGS units, which did not facilitate interpretation. This use of common units was just as inappropriate as using cubic meters to express mass under the pretext that mass is related to volume for a given density.

As we saw at 3.4, it is with Heaviside that we arrive at the modern names and notation for field vectors and the equations of electromagnetism. The relationship linking the field D, the field E, and the polarization P obtains its current form in the SI, but this expression does not sufficiently account for the cause and effect, and we should not hesitate to invert it:

$$\vec{D} = \varepsilon_0.\vec{E} + \vec{P} \qquad => \qquad \vec{E} = \frac{1}{\varepsilon_0}.(\vec{D} - \vec{P}) \tag{3}$$

The D-field depends on the charges independently of the medium, while the E field is dependent on its reaction. This can be verified with expressions 1 and 2 for the E and D fields given above. This is also verified with the Maxwell-Gauss equation with D, independent of permittivity, or with E, which depends on it; ρ_f is the free charge density:

$$div\ \vec{D} = \rho_f \qquad div\ \vec{E} = \frac{\rho_f}{\varepsilon}$$

Relation 3 is the equivalent for electricity of the following relation for magnetism:

$$\vec{B} = \mu_0.(\vec{H} + \vec{M}) \tag{4}$$

The + and – signs in relations 3 and 4, come from the fact that the polarization P attenuates the effects of the field E relative to the vacuum while the magnetization M generally amplifies the effects of the field B except in the special case of diamagnetic materials where the magnetization is negative.

4.6. Terminology that needs reviewing

Curiously enough, both B and D fields are sometimes referred to as "induction fields," even though the former is a mechanical effect field and the latter is an excitation field. This contradiction only adds to the confusion surrounding their interpretation.

The D field was conceptualized by Maxwell when he introduced the "displacement current" $\partial\vec{D}/\partial t$, which was the missing link in electromagnetism. The obsolete term "displacement," the origin of the symbol D, is therefore sometimes still used to refer to the electrical excitation field D, which does not simplify the learning process for students.

Adding to the confusion, the magnetic field with mechanical effect B is sometimes referred to as "magnetic flux density," which is strictly accurate but does not further clarify its nature any more than describing the velocity of a liquid as "volumetric flux density".

To complete the description of this confusing terminology, it's worth noting that both B and H fields are often referred to interchangeably as "magnetic fields." The IEC specifies that this term should be reserved for the H field, but since it's an excitation field, this contradicts the term "electric field," which is reserved for the E field, a field of mechanical effect

Beyond these heterogeneous names, we should therefore only keep in mind their roles as a mechanical effect field (E and B) or an excitation field (D and H) and it would be desirable for the scientific community to study the possibility of a terminology based on this logic.

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