"Ueber die Bestimmung der Richtung der durch elektrodynamische Vertheilung erregten galvanischen Ströme," Ann. Phys. (Leipzig) (2) **107** (1834), 483-494.

On the determination of the direction of galvanic currents that are produced by electrodynamical induction (*)

By E. LENZ

Translated by D. H. Delphenich

(Read to the Royal Academy of Science in St. Petersburg on 29 November 1833)

In his "Experimental Researches in Electricity," which included the discovery of the so-called electrodynamical induction, **Faraday** determined the directions of the galvanic currents that were produced by it in such a way that:

1. It would produce a galvanic current in a parallel wire that moved towards it that flowed in the opposite direction, but for a wire that moved away, it would flow in the same direction, and

2. A magnet would produce a current in a conductor that moved towards it that would depend upon the direction in which the conductor intersected the magnetic curves during its motion [Pogg. Ann. (1832), no. 5, §§ **114** and **116** of **Faraday**'s paper].

Aside from the single fact that two different rules were given for one and the same phenomenon (because, according to **Ampère**'s beautiful theory, a magnet can be considered to be a system of circular galvanic currents), the rule is not even sufficient, at least not immediately, since there are many cases that it does not encompass, e.g., the case of a conductor that moves along a current that is directed perpendicular to it. However, in my opinion, it ultimately lacks the desired simplicity at two points that would make it easy to adapt to the individual cases, and I believe that other readers of the otherwise-splendid treatise will agree with me when they recall § **116**, where **Faraday** sought to clarify the rule above by moving a knife blade along a magnet. Indeed, **Faraday** himself mentioned the difficulty in explaining the direction of the currents very well.

Nobili [in his treatise in Pogg. Ann. (1833), no. 3] started from the first of **Faraday**'s laws, namely, that bringing a conductor closer to a galvanic current that is parallel to it would produce an opposite current in the former and an equally-directed one when one moves it away, and in that

---

(*) We hope to be able to present an earlier article by the distinguished author: "Ueber die Wirkungen, nach welchem der Magnet auf eine Spirale einwirkt, wenn er ihr plötzlich genähert oder von ihr entfernt wird, und über die vortheilhafteste Construction der Spiralen zu magnetoelektrischem Behufe."

way alone, he sought to explain all phenomena and the directions of the currents that were produced by electrodynamical inductions. At many points, that paper, which was very estimable in other respects, did not have the degree of evidence for me that I would expect to be appropriate in a physical treatise, namely, when explaining the currents (pp. 408) that arise in a conductor that points perpendicular to a galvanic current and moves along it. **Faraday** had a certain right to generally object to the theory of the Italian physicists that when a magnet rotated around its own axis and one introduced an accompanying test wire, a galvanic current would be likewise produced without any motion of the current towards or away from the magnet being present, since, on the contrary, everything maintained its mutual configuration.

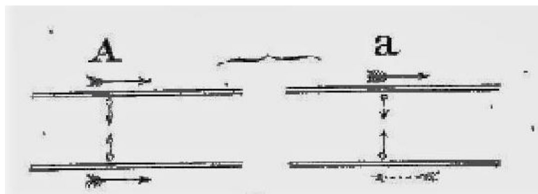
Similarly, upon reading through **Faraday**'s treatise, it seemed to me that it must be possible to reduce all of the experiments with the electrical induction very simply to the laws of electrodynamical motions when one assumes that they are known, and even determine them in that way, and since I have confirmed that opinion in numerous experiments that I will describe in what follows and tested it by experiments that are partly known and partly ones that I myself carried out.

The law by which the reduction of magneto-electric phenomena to the electromagnetic ones comes about is the following:

When a metallic conductor moves in the vicinity of a galvanic current or magnet, a galvanic current will be produced in it that has the direction that it would have if a motion were produced in the wire when it was at rest that would precisely oppose the one that was given to the wire, assuming that when the wire was at rest, it could move only in the direction of motion and the opposite direction.

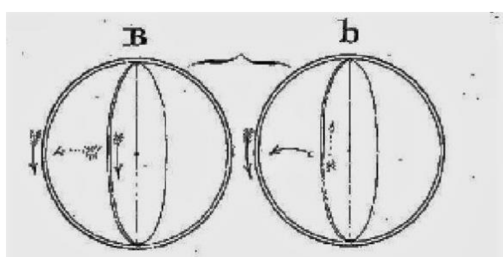
In order to clarify the meaning of the direction of the current that is produced in the moving wire by the electrodynamical induction, one asks what direction the current would need to have according to the laws of electromagnetism if it had produced that motion: The current in the wire would have to be generated in the opposite direction. As an example, one might envision **Faraday**'s well-known rotation experiment, in which the vertically-suspended moving conductor of a galvanic current moved from up to down, and as a result, the North pole of the magnet that was found directly beneath it would circle around in the direction from North to South through East. We do not let the current flow through the moving conductor now but give it the aforementioned motion by some mechanical means. According to our law, a current will be produced in it that opposes the previous one and flows through the moving wire from down to up and can be verified to exist in that wire when one connects its upper and lower ends with a multiplier.

If we now correctly explain our law above then we will be able to conclude from it that every phenomenon of electromagnetic motion must correspond to a case of an electrodynamical induction. As in the example above, one needs only to produce the motion that is induced in the electromagnetic way by a different means, and one will induce a current in a moving conductor that is opposite to the one in the electromagnetic experiment. In what follows, I will cite several such corresponding phenomena, and indeed in such a way that I can infer the magneto-electric phenomenon that corresponds to an electromagnetic one and denote the latter by symbols from the upper-case Latin alphabet, while the former are denoted by the corresponding lower-case ones. That would best shed light upon the validity of our law. The accompanying figures (Fig. *A*, *a* – *G*, *g*), which employ the same symbols, will contribute to even greater clarity, and I shall make the following remark in that regard: The arrows denote the direction of motion, as well as that of the current, although I have distinguished their meanings by giving the arrows different forms: the arrow with a circle on the tail refers to the motion, while the arrow with feathers on its tail refers to the current. Furthermore, the solid arrows denote the motion or current that was given in the experiment, while the arrows of the same form that are drawn with dashed lines refer to the motion or current that was obtained as a result of the experiment. One can understand the figures with no difficulty upon establishing those notations. I shall then move on to the experiments themselves:



A. – A rectilinear conductor with a galvanic current flowing through it attracts another one that can move parallel to it when the current that flows through the latter has the same direction as the former. However, it will repel the former whenever the direction of the current in the moving conductor is opposite to the one in the immobile one. (**Ampère**)

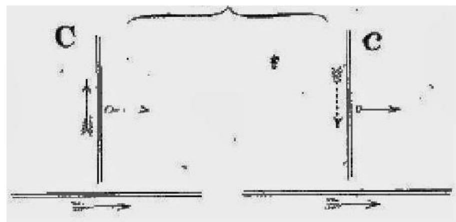
a. – When a galvanic current flows through one of two rectilinear, mutually-parallel conductors, and one approaches the other conductor in a parallel direction, a current will be induced in the moving conductor during the motion that opposes the current in the immobile conductor. However, when one moves away from it, the induced current will be in the same direction as the inducing one. (**Faraday**)



B. – When one has two vertical circular conductors that have nearly-equal diameters and perpendicular planes, as well as a common vertical diameter for an axis around which both of them (or even just one of them) can rotate, and one conducts a galvanic current through both of them, they will lie in relation to each other in such a way that the direction of the currents will be the same in both. (**Ampère**)

b. – When one of two circular conductors that are arranged as before remains fixed and a galvanic current flows through it, while one suddenly brings the other mobile one from the perpendicular position to the parallel one, a current will be induced in it that has the opposite direction to the current in the other conductor. (**Lenz**).

I have carried out the last experiment with two circular conductors, each of which consists of twenty windings of coated copper wire. The one was connected to a zinc-copper pair that was two square feet in area, while the other was connected with a sensitive **Nobili** multiplier.



C. – When a conductor is found in the vicinity of a rectilinear unbounded conductor that is also rectilinear, perpendicular to it, mobile, and bounded in such a way that it lies completely on one side, so it does not cross it, and when a galvanic current flows through both conductors, the mobile conductor will move along the unbounded one, and indeed *in the direction* of the current in the latter, as long as its own current flows away from the latter, but *against the direction* as long as its own current flows towards the unbounded one.

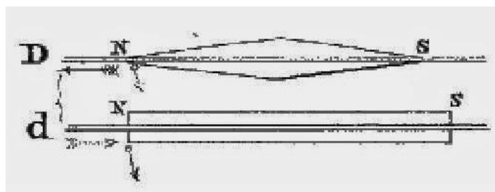
The terms "bounded" and "unbounded" current must be taken with the meanings that are used in the textbooks on electromagnetism.

c. – If a bounded conductor is perpendicular to an unbounded conductor through which galvanic current flows and moves along it in the direction of the current in it then a current will arise in the bounded conductor that is directed away from the unbounded conductor. However, if the bounded conductor moves against the direction of the current in the unbounded conductor then the direction of the current that is created in it by the induction will be towards the unbounded current. [**Nolbili**: Poggen. Annalen (1833), no. 3, pp. 407]

In the foregoing, the main cases in which one galvanic current acted on another were considered. In what follows, we will summarize the main features of the phenomena that are associated with a reciprocal action of a galvanic current and a magnet in the same way. By means of the manner of presentation that was first given by **Ampère**, one will find it easy to find our way around the electromagnetic phenomena of that kind insofar as the direction of the induced motion is concerned. It consists of the idea that one gives the current a head and a foot, or a right and left hand, or even better, one imagines oneself placed in the current such that it (the positive direction) enters at one's feet and exits through one's head when one turns one's face to the North pole of the magnet. It will then move away due to the current *to the left* or the current (and therefore the observer along with it) to the right at the North pole.

Starting from our general law for the relationship of the magneto-electric phenomena to the electromagnetic ones, we can easily derive a similar rule for the latter that reads as follows:

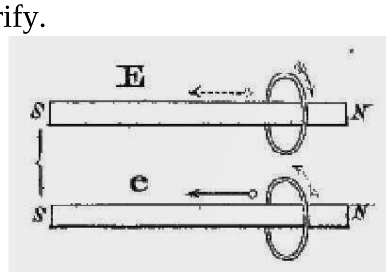
A galvanic current will arise in a conductor that moves in front of the North pole of a magnet by way of the electrodynamic induction, and when one places oneself in the moving conductor in such a way that when one turns one's face to the North pole and moves with conductor to the right, the current will flow *from one's head to one's feet.* One will find that rule to be confirmed in all of the following experimental arrangements.



D. – When a rectilinear current flows above and parallel to a freely-floating magnetic needle that points in the direction of the Earth's magnetic force such that the current goes along the needle from south to north, the North pole of the magnet needle will deflect to the west. However, if the current goes from north to south, the deviation will be to the east. If the wire goes under the needle then the resulting deviation will be to the east in the former case and to the west in the latter. (**Oersted**)

d. – If a conductor goes over a magnet in its natural position from south to north and parallel to it, and the magnet then suddenly rotates to the west about its midpoint then a current from north to south will be created in the conductor. If the rotation of the magnet takes place towards the east then the current will run from south to north. If the conductor is found under the magnet then the current will go from south to north in the first case and from north to south in the second. (**Lenz**)

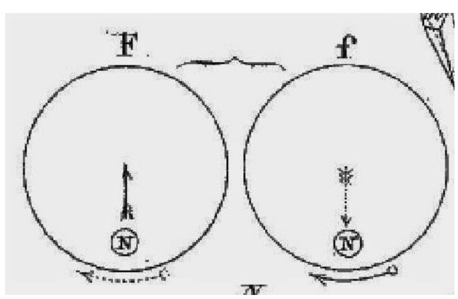
For that experiment, I took the conductor to be a foot long side of a square that consisted of multiple windings of copper wire that was wound with silk. I brought that side so close to a five-inch-long magnet that the electrodynamical effect of it on the other three sides could be regarded as vanishing with respect to its effect on that side. In order to find the direction of the generated current according to the rule that was just given, one imagines that the magnet is at rest and the conductor rotates to the east in the first case and to the west in the second, which is obviously the same thing, as one will easily verify.



E. – If one holds a vertical, circular galvanic current that moves freely in the horizontal direction (e.g., by floating on a fluid) against a magnet with a horizontal axis such that its longitudinal axis goes through the midpoint of the circular current, and if the latter direction is parallel to the directions of the currents in the magnet according to **Ampère**'s theory then the current will move over the magnet towards its center such that it will encircle it like a ring in that equilibrium position. If one now suddenly reverses the magnet or the direction of the current then the latter will move away from the center of the magnet towards its pole. (**De la Rive**)

e. – When one suddenly displaces a circular spiral that is connected to a multiplier at its ends over the pole of a magnet towards its center, a galvanic current will arise in it whose direction is opposite to the direction of the currents in the magnet. If one displaces it from the center back towards the pole then the current that arises in that way will run in the same direction as the current in the magnet. (**Faraday**)

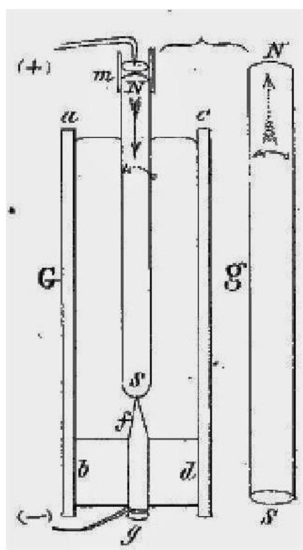
That also includes the well-known type of experiment that goes back to **Nobili** in which an armature of soft iron that is wound with a spiral is placed between the poles of a horseshoe magnet, and a current is generated in the spiral that is directly opposite to the one that magnet generates in the armature according to **Ampère** and runs parallel to the latter when one withdraws the armature. Namely, when the armature is placed there, the currents that are present in all directions in the iron and encircle the molecules will initially contact the poles of the magnet and point in a certain direction from them. That direction will propagate from both ends of the armature to its center, although in an infinitely-short time. Thus, it is just as if a north pole were suddenly plunged into the spiral that surrounds the armature from the one side and a south pole into the other, while the two poles were united into a magnet in the middle. Both of them must generate currents in the spiral in the same direction (indeed that of the poles), but also opposite to the direction of their approach. Upon withdrawal, the direction of the current will vanish at the middle, where it was weakest, at first, and it will then be just as if the two poles were pulled out of the spiral in the opposite direction. In electromagnetism, that experiment corresponds to two more such experiments, like the one that **de la Rive** carried out, where a moving circular current was displaced from each side of the magnet towards its center or away from it.



F. – When one brings what is known in electromagnetic experiments as a **Barlow** wheel into the plane of the meridian such that the current in it flows *from the circumference to the center*, and the horseshoe magnet is kept at the lower edge such that North pole lies to the west of the wheel and the South pole to the east, the wheel will rotate around its axis in the direction of the hands of a clock whose face points to the west. If the current goes from the *center to the periphery* then the motion will take place in the opposite direction. If the magnet is reversed such that North pole lies to the east then the direction of rotation will also reverse in both cases. (**Barlow**)

f. – If one makes a copper disc capable of rotating around its axis and holds a horseshoe magnet close to its edge such that North pole is found above the disc and the South pole is found below it and one then rotates the disc in the direction of the motion of the hands of a clock whose face points upwards then a current will arise in the disc *from the center to the circumference*. If the rotation takes place opposite to the motion of the hands of an upward-facing clock then the current will flow *from the circumference to the center*. Upon reversing the poles of the magnet, the directions of the currents in the rotating disc will also reverse. (**Faraday**)

The experiments that correspond to those two experiments will likewise become clear when one imagines that the **Barlow** wheel is reversed such that it becomes horizontal with its west side upwards, as is illustrated in the accompanying figure.



G. – If a magnet is capable of rotating around its own axis and one conducts a galvanic current through its material from its upper North pole to its center then the magnet will rotate in the direction of the hands of a clock whose face is turned upwards. If one conducts the current from the center of the magnet to the North pole then the rotation will be opposite to the previous one. If the South pole is turned upwards then it will rotate against the rotation of clock hands when the direction of the current is from the South pole to the center and in agreement with the rotation of the hands when the direction of the current is from the center to the South pole, and always with the clock face pointing upwards ([1]). (**Ampère**)

g. – If a magnet can be rotated around its axis and has its North pole pointing upwards and one connects its upper North pole and its center to a multiplier while it is in that position, and one gives it a rotation around its axis whose direction agrees with that of the hands of a clock (with its face pointing upwards) then the multiplier will indicate a galvanic current that is created in the magnet by the electrodynamical induction that points from its center to its North pole. If the rotation takes place contrary to the hands of a clock then the current that is created will go from the pole to the center. If the South pole is turned upwards, and at the same time, the center is connected to the multiplier then the current will point from the pole to the center under the first rotation and from the center to the pole under the second. (**Faraday**)

From what was said up to now, I hope that the agreement between the law that was expressed above and its consequences in the experiments has been confirmed sufficiently ([2]).

([1]) In order to perform that experiment, I appealed to a device that is simpler than usual and which I would therefore like to describe here (cf., Fig. *G*). A glass tube that is three inches in length and one inch wide *abcd* is sealed at its upper end by a cork through which an iron wire *fg* is inserted, as one can see in the drawing. The magnet that I used was $2\frac{1}{2}$ long and $\frac{1}{3}$ inch thick, cylindrical, and semicircular at its ends. One pours mercury into the tube and places the magnet in it until the mercury makes contact with the tip of the iron wire. That end is kept there by attraction, and the magnet floats with the other end pointing vertically upward in the mercury. Since the mercury contacts the iron wire at only one point, and indeed, due to the semicircular form of the ends of the magnet, at the highest point of the dome, and as a result along the axis of the magnet, it is as mobile as possible. A small paper sleeve is pushed tightly over the upper end *m* of the magnet that protrudes above it somewhat and thus defines a bowl that holds a drop of mercury. If one now places the apparatus on a board with a mercury gutter into which the lower end *g* of the iron wire is submerged and connects that mercury gutter to one metal of the galvanic circuit, while one connects the other metal to the mercury drop at *m* by a conducting wire, then the rotation of the magnet around its axis will begin instantaneously.

([2]) At the same time, it is confirmed in that way that **Ritchie** has established the same law all wrong (pp. 206 of this volume), unless I have not understood the meaning of his rather imprecise presentation.