On the Connection of Faraday's Induction Phenomena with Ampère's Electrodynamic Phenomena

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Editor's Note: English translation of Gustav Theodor Fechner's 1845 paper "Ueber die Verknüpfung der Faraday'schen Inductions-Erscheinungen mit den Ampère'schen elektro-dynamischen Erscheinungen", [Fec45].

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By G. Th. Fechner[1,2,3,4]

Up until now, Faraday's induction phenomena[5] have only been related to Ampère's electrodynamic phenomena[6] by means of an empirical rule. Their connection arises, however, with at least partial necessity, as a consequence of the following two fundamental propositions, which can only be regarded as the simple consequences of known basic experiences in terms of views that are now held to be valid:

[1][Fec45].

[2]Translated by H. Härtel, haertel@astrophysik.uni-kiel.de and http://www.astrophysik.uni-kiel.de/~hhaertel/index_e.htm. Edited by A. K. T. Assis, www.ifi.unicamp.br/~assis.

[3]The Notes by G. T. Fechner are represented by [Note by GTF:]; the Notes by Johann Christian Poggendorff (1796-1877), the Editor of the *Annalen der Physik und Chemie* where Fechner's paper was published, are represented by [Note by JCP:]; while the Notes by A. K. T. Assis are represented by [Note by AKTA:].

[4][Note by JCP:] All who shared in the remarkable fate of the talented author, who miraculously regained the strength of his eyes after many years of blindness, will surely receive this first test of his renewed activity in science with the most sincere joy. But unfortunately this joy must be clouded very much by the letter with which the author accompanied the sending of his essay to me.

> "It is the first time in a long period of time," it says, "that I can relate to you again; and Heaven would like it not to be the last for a long time either. The condition of my eyes had miraculously improved within a short time so that I hoped for a complete recovery, but since then the situation has gotten so bad that these lines, as well as some parts of the accompanying treatise, had to be written by a strange hand and I see myself condemned again to almost complete inactivity."

Let us hope, however, that these gloomy prospects do not turn into reality, but that the force of the years, which the author enjoys, overpowers the threatening evil once again and forever. In this wish, I am certain that his numerous friends, near and far, to whom these lines are dedicated, will all agree with me! P.

[5][Note by AKTA:] Michael Faraday (1791-1867). See [Far32a] with German translation in [Far32c] and [Far89], and Portuguese translation in [Far11].

[6][Note by AKTA:] André-Marie Ampère (1775-1836). Ampère's main work on electrodynamics was published in 1826, [Amp26] and [Amp23]. There is a complete Portuguese translation of this work, [Cha09] and [AC11]. Partial English translations can be found at [Amp65] and [Amp69]. Complete and commented English translations can be found in [Amp12] and [AC15].

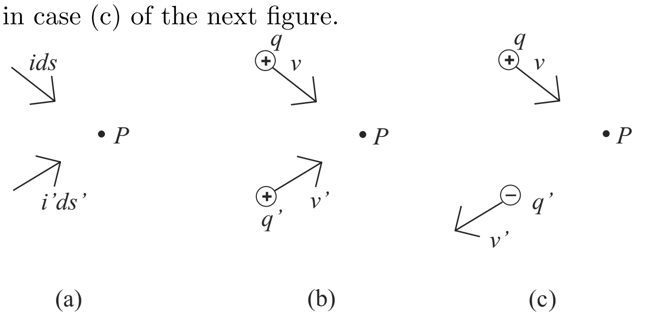
1) Every action of a current element can be seen as being composed of the action of a positive and an equally strong negative particle of electricity, which at the same time pass through the same spatial element in opposite directions.

2) With regard to this composition, the action of two current elements on one another can be represented by the precondition that electricities of the same kind have an attractive action on one another if they go in the same direction or towards a common angular apex, but for electricities of opposite kind [an attraction takes place] if they go in the opposite direction, or so that one approaches the common angular apex while the other moves away from it.[7]

So far, however, one has only considered the action of the complete current elements on one another; but apparently nothing stands in the way of the analysis of the complete action into the action of the individual components of current elements as described above, provided that on the one hand it reflects the experience-based success, on the other hand it offers a path to analyze the required combination.

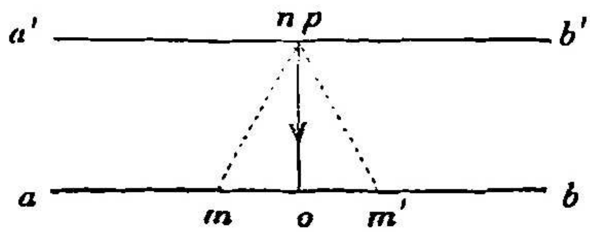
Incidentally, the actions of the moving electricity considered above are indisputably not their actual full actions, but only those actions which remain uncompensated when complete currents do interact. This is the only thing that needs to be taken into account here. For it cannot be assumed that the repulsive forces which two particles of electricity of same kind exert on one another when at rest, will immediately turn into attraction if they, however

[7][Note by AKTA:] According to Ampère's force, two infinitesimal elements of sizes ds and ds', carrying currents i and i', attract one another when both currents flow towards a common angular apex P, as in case (a) of the next Figure. According to Fechner it might be possible to deduce Ampère's force in this case assuming three conditions: (1) positive and negative particles of the same magnitude flowing in opposite directions in each current element; (2) particles of the same kind (both positive or both negative) in both elements attracting one another when both move towards a common angular apex P, as in case (b) of the next Figure; and (3) the positive particle of one element attracting the negative particle of the other element when one of them moves towards P, while the other moves away from P, as in case (c) of the next figure.



slow, start moving in the same direction. It can only be assumed that they will be reduced,[8] either absolutely, or, if only relative motion is considered, in relation to the case where the motion occurs in the opposite sense.[9,10] But with the interaction of complete currents, as with natural electricity, where all the actions, which the electricities, considered to be at rest in relation to one another, express, compensate each other,[11] it will always be seen, as the analysis of the phenomena itself shows, as if electricities of the same kind attract each other when they move in the same direction, and repel each other when they move in the opposite direction. This analysis will be our base in the following.

Let us now consider the first main case of induction phenomena, in which a neutral wire $a'b'$, that is, a wire not excited by a current, is brought closer and in a parallel position to another current carrying wire ab.



In this case the opposite electricities of the neutral wire, connected to natural electricity, are both simultaneously moved perpendicularly towards the current carrying wire. If it makes no difference to the nature of the motion and its consequences by what means it is produced, then it does not matter whether this motion is due to the influence of peculiar galvanic forces or mechanically caused by us.

Our case corresponds to the one where two currents of equally strong opposite electricity move *in the same sense* at right angles against a two-way current.[12]

[8][Note by AKTA:] That is, the repulsive forces will be reduced.

[9][Note by GTF:] It emerges from Weber's investigations mentioned later that one must stop at the latter assumption.

[10][Note by AKTA:] Fechner is referring to Wilhelm Eduard Weber (1804-1891).

[11][Note by AKTA:] That is, each current element can be considered as composed of equal and opposite charges moving relative to the wire. There is no net charge in each current element. Therefore, there is no net electrostatic force between two current elements.

[12][Note by AKTA:] In German: *eine doppelsinnige Strömung*. That is, a current of positive particles moving in one direction relative to the conductor, together with a current of negative particles moving in the opposite direction. Usually the direction of the current was understood as the direction of motion of the positively charged particles.

In this first case of induction considered by Fechner, the neutral wire ab is at rest relative to the ground and carries a constant current, let us say from a to b. This current can

In order to find the inducing action which the wire $a'b'$ suffers from the wire ab, we want to consider the action which any double particle of natural electricity np[13] experiences from any two current particles m and m' that are situated to both sides of the vertical npo. Thereby it is sufficient to only pay attention to one kind of electricity in the particles m and m', since, as it is easy to see, the other will cause the same action.

Therefore the total action of the particles m and m' on the positive particle p and on the negative particle n is composed of four individual forces which we have to decompose according to the direction of the wire $a'b'$ in order to find the inducing action on this wire.[14] If we just use Ampère's assumption that the forces between two current elements follow the direction of their connecting line, and consider the law of angular currents according to proposition 2), we find that the inducing lateral forces[15] as the sum of four individual forces will drive p in the opposite direction than n, resulting in a two-way current, or current par excellence in the ordinary sense of the word, and this in a direction corroborated with experience. On the other hand, the lateral forces which are oriented perpendicular to the wire $a'b'$, tend to drive n in the same direction as p. Therefore both subtract from each other with regard to the generation of current and must neutralize each other, in case that m and m' be taken as symmetrical against the vertical npo.

If one did not want to accept from the beginning that the manner in which the motion of electricity has been caused does not have any influence on its action, the agreement with experience would undoubtedly be one of the best proofs that the above conclusions are correct. It turns out to be irrelevant whether I cause the flow of electricity by a mechanical motion — with my hands — or whether it has received the impulse of its motion from galvanic contact.

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be considered as a flow of positive particles from a to b, coupled with a flow of negative particles from b to a. Initially there is no current in the stationary neutral wire $a'b'$. However, when $a'b'$ moves with a constant velocity v towards ab, with $a'b'$ remaining always parallel to ab, a current is induced in $a'b'$, flowing from b' to a'. This motion of the neutral wire $a'b'$ towards ab can be considered as a motion of a positively charged wire $a'b'$ towards ab, together with an equal motion of a negatively charged wire $a'b'$ towards ab. It is necessary to show that the positively and negatively electrified particles moving in opposite direction in ab will exert a force on positive particles of $a'b'$ making them move from b' to a', exerting also a force on the negative particles of $a'b'$ making them move from a' to b'. That is, inducing a current in $a'b'$ from b' to a'.

[13][Note by AKTA:] This double particle is composed of a negatively charged particle n and a positively charged particle p.

[14][Note by AKTA:] These four individual forces are, (1) the force of m on p, (2) the force of m on n, (3) the force of m' on p, and (4) the force of m' on n.

[15][Note by AKTA:] That is, forces decomposed along the direction of the wire $a'b'$.

Instead of moving in the induction experiment the wire $a'b'$ towards the wire ab at rest, one could proceed in the opposite sense and the induction would still arise.[16] This must be taken as given by experience, that it is only a matter of the relative motion, and that it is permissible to substitute the reverse for the motion of the excited wire and the neutral wire at rest, in order to apply the given principle in the given form.

In the case considered so far, a two-way current acted on a one-way[17,18] current *parallel* to it. Another main case can be considered where the motion of one of the two currents is oriented *perpendicularly* to that of the other, as for instance, when an excited circular conductor or its equivalent, the cross-section of a magnet, rotates in its plane, while a neutral conductor at rest is related to it as shown in the Figure. In this case, too, one finds the experience-based result according to the principles given, taking into account the law of relative motions.

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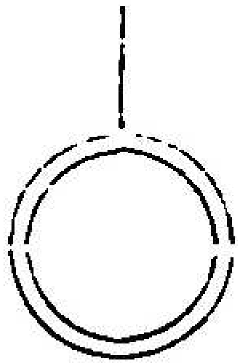
[16] [Note by AKTA:] That is, if $a'b'$ remains at rest in the laboratory and ab moves towards it, the same induction will take place as in the previous case, provided the relative motion between ab and $a'b'$ is the same in both cases.

In his paper read in 1831 Faraday showed that induction depended only on the *relative* motion between two interacting bodies A and B. These interacting bodies A and B might be a magnet and a closed circuit where induction took place. These interacting bodies A and B might also be a closed circuit carrying a steady current and another closed circuit where induction took place. In one experiment, for instance, he kept A at rest in the laboratory and moved B towards A and detected an induced current. In another experiment he kept B at rest in the laboratory and moved A towards B, detecting once more an induced current. Provided the relative motion between A and B was the same in both experiments, then the observed induced currents were also the same. See, for instance, [Far32a], [Far11], [Ass13] and [Ass14, Section 15.1: Electromagnetic induction].

[17] [Note by GTF:] For a short description of the contrast it may be allowed to use the latter word for moving natural electricity.

[18] [Note by AKTA:] Fechner is here distinguishing the German words *doppelsinnige* and *einsinnige* when referring to the current. A two-way current would be the typical galvanic current, as understood at that time, in which positive and negative particles move in opposite directions relative to the conductor. An one-way current, on the other hand, might be the motion of a body charged with only one kind of electricity.

Fechner has just shown that in order to explain Faraday's law of induction in this case, a force parallel to $a'b'$ must act on the positive particles of $a'b'$ when $a'b'$ moves towards ab. A force in the opposite direction must act on the negative particles of $a'b'$ when $a'b'$ moves towards ab.



Lenz' general rule about the reciprocity between Ampère's and Faraday's phenomena can be related to the above-mentioned principles through the well-known theorem from the theory of the parallelogram of forces, that, if P and Q arise as lateral forces from R, then conversely, R and Q appear as lateral forces from the decomposition of P, when Q is applied in the opposite direction from before.[19]

If the established principles are correct, a means may probably be found of determining the real or translational velocity of electricity,[20,21] by establishing a relation between the easily determinable velocity at which *we* move the natural electricity in the conductor to be induced and the velocity with

[19] [Note by AKTA:] Heinrich Friedrich Emil Lenz (1804-1865). See [Len34] with partial English translation in [Len69].

Lenz' rule, [Len69, p. 513]:

> If a metallic conductor moves in the neighborhood of a galvanic current or of a magnet, a galvanic current will be produced in it which will have such a direction that it would have occasioned in the wire, if it were at rest, a motion which is exactly opposite to that here given to the wire, provided that the wire when at rest is movable only in the direction of the motion and in the opposite direction.

[20] [Note by GTF:] It is worth noting that what has hitherto been referred to as the velocity of electricity is not the real velocity of its particles, but merely the velocity of its wave propagation, an hitherto neglected, but yet quite a notable difference, on which to my knowledge W. Weber as the first drew attention.

[21] [Note by AKTA:] That is, according to Fechner, Wilhelm Weber was the first to distinguish between the drift velocity of the particles composing the current, from the wave velocity of an electric perturbation in a wire. Weber believed that the drift velocity would be much lower than the wave velocity. In 1857 he and Kirchhoff deduced independently from one another, although both works were based on Weber's force of 1846, that an electric wave propagates along a wire of negligible resistance with light velocity, [Kir57b] with English translation in [Kir57a], [Pog57] with English translation in [Pog21], and [Web64] with English translation in [Web21].

which electricity moves itself under the influence of peculiar forces.

It seemed difficult to me at first to find a method by which this determination could be made with accuracy. In the meantime, Prof. W. Weber indicated such a method that promises to do everything in his hands that we can wish for.

There are, however, still some conclusions which result from the above:

1) When a rod charged with one kind of electricity is rotated about its axis, it must show, besides the usual electrical phenomena, also magnetic phenomena or those completely analogous to magnetic ones, and accordingly induce currents too in approaching conductors.

2) If a rod, which can rotate about an axis but does not rotate and which is charged with one kind of electricity, is approached by a magnet under the conditions that the rod, regarded as an iron rod, would be magnetized longitudinally, this will cause the rod to rotate by itself.

When the two previous conclusions are combined, not, however, directly deducible from the previous principles, then arises the strange supposition that, when a non-electrically conductive rod rotating around its axis[22] approaches a magnet under the appropriate conditions, the same would show the phenomena of free electricity, and indeed of only one kind of electricity.[23,24]

It will undoubtedly be difficult to prove the above conclusions by experiment. For if one remembers that, according to the experiments of Faraday and Gauss,[25] enormous quantities or [huge] velocities of machine electricity[26] are required to produce only moderate current actions, while considerable currents are required to produce distinct magnetic or induction actions, it

[22] [Note by AKTA:] In German: *wenn man einem, um seine Axe gedrehten, nicht elektrischen leitenden Stabe*. That is, an insulating rod. Probably Fechner is referring here to a *charged* insulating rod spinning around it axis.

[23] [Note by GTF:] According to this, a magnetic rod rotated about its axis would have to show the phenomena of free electricity by itself, of the opposite kind depending on its direction of rotation. That this is really the case seems to be confirmed by the following: if one connects by a wire a point of the axis and a point of the circumference of a rotated magnet, a current start flowing. According to the analogy with the galvanic apparatus, it can be assumed that after removing this connecting wire, free electricity will appear at the separation points either of a different nature or of a different magnitude. This could also be detectable by means of a capacitor if the rotation is sufficiently rapid.

[24] [Note by AKTA:] The experiment that if one connects by a wire a point of the axis and a point of the circumference of a spinning magnet, a current start flowing, was first performed by Faraday in 1832, [Far32b] with German translation in [Far32d].

[25] [Note by AKTA:] Due to a misprint in the original we have here *Gaus*. Fechner was referring to Carl Friedrich Gauss (1777-1855).

[26] [Note by AKTA:] In German: *Maschinen-Elektricität*. That is, electricity produced by friction in electrostatic machines when a glass globe spins quickly relative to the ground.

can be foreseen that only extraordinarily high velocities of rotation or strong electrification can lead to success in the indicated experiments. This also follows from the fact that a magnet or a galvanically excited conductor can be regarded as completely filled with currents, while a spinning electrical conductor is only covered by a single layer of electricity. It was therefore not unexpected to me, that I was not able to obtain any results with the few corresponding experimental means I had available to me. Meanwhile, others who have more powerful means at their disposal, may consider what is said before as an invitation to return to these experiments.

It cannot be denied that our concatenation of ideas leave something to be desired, namely the proposition that it is only a matter of the relative motion. This can in fact only be presented as an empirical proposition, but not as a consequence of the principles mentioned above. The same is true of the proposition, which we must add, in order to cover the complete field of induction phenomena, namely, that the emergence or intensification of the current has a similar action on approaching,[27] as the disappearance or weakening of the current has when the distance is increased. In the meantime, this incompleteness of our conclusions cannot induce us to drop what we have learned by them for the sake of what we did not learn.

In fact, the inadequacy that still shows up here, does not lie in a fault of the method of interpreting the action of the electricity in motion and this separately for both electrical components. The progress made in the foregoing is based solely and exclusively on this method. The problem rather lies in an inadequacy how we have phrased until now the action of electricity in motion. It can easily be shown that the propositions and wording we have hitherto used in the theory of electricity really do not contain at all the *possibility* of covering the whole area of the actions of flowing electricity, and that new assumptions must therefore be made.

Indeed, both classes of phenomena still to be explained prove irrefutably that moving electricity can have an influence on electricity at rest. This influence, as it arises in those phenomena, can neither be contained in the propositions which concern static electricity, because positive and negative electricity always act with the same strength from the same distance (therefore, according to these propositions, the result will always be zero in respect to other electricities), nor is this influence contained in Ampère's propositions, because these allow no action whatsoever to be found between moving and stationary electricity.

Perhaps the attempt could be made to derive the extension of the principles, which would be able to satisfy what still has to be explained, from

[27][Note by AKTA:] That is, on bringing together the two interacting conductors.

an analysis of the phenomena still to be explained themselves. However, it would be unnecessary to start such an activity, since, as I am pleased to announce, Prof. W. Weber, through investigations carried out from general points of view, has arrived at a principle whereby not only all the actions of moving but also of static electricity among themselves, as well as in mutual relation to one another, can be deduced from a general law. Therefore the phenomena of static electricity, Ampère's law and all induction phenomena come under this law only as special cases. I therefore hope that this little piece of work will only be seen as a forerunner of the investigations which we can expect to be published shortly.[28]

[28] [Note by AKTA:] Weber's work was published in 1846, [Web46] with a partial French translation in [Web87] and a complete English translation in [Web07]. Weber quotes Fechner's 1845 paper in Section 26 of his work.

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