On the Connection between Faraday’s Induction Phenomena and Ampère’s Electrodynamic Phenomena

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Editor’s Note: An English translation of Gustav Theodor Fechner’s 1845 paper “Ueber die Verknüpfung der Faraday’schen Inductions-Erscheinungen mit den Ampère’schen elektrodynamischen Erscheinungen”, [Fec45].

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Until now, Faraday’s induction phenomena\textsuperscript{5} have only been related to Ampère’s electrodynamic phenomena\textsuperscript{6} by means of an empirical rule. The connection between them arises, at least partially as a consequence of the following two fundamental propositions, which are the generally accepted conclusions of experiments:

1) Every current element consists of equal positive and negative particles of electricity passing each other simultaneously through the same spatial element in opposite directions.

2) The action of two current elements on each other are such 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.\textsuperscript{7}

So far, however, only the interaction of the complete current elements on one another has been considered; but we can still analyze the interaction between the individual compo-
nents of the current elements as described above, provided that on the one hand it reflects observation, and on the other hand it offers a means of analyzing the combination.

Incidentally, the interactions of the moving electricity considered above are indisputably not their actual full interactions, but rather only their net interactions. 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 the same kind exert on one another when at rest, will immediately turn into attraction if they start moving in the same direction, however slowly. The only thing that can be assumed is, that the repulsive forces will be reduced, either absolutely, or, if it should depend only on relative motions, in relation to the case where the movement occurs in the opposite sense.\textsuperscript{8,9} But as regards the interaction of complete currents, however, as in natural electricity, where all the forces of static electricity cancel each other,\textsuperscript{10} 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 the fundamental basis of the following case scenario.

Let us now consider the first main case of induction. A wire \(a'b'\), in which no current is flowing, is brought closer and in a parallel orientation to another wire \(ab\), which is carrying an electric current.

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

\[\text{\textsuperscript{8}}\text{[Note by GTF:] It emerges from Weber's investigations mentioned later that one must stop at the latter assumption.}\]
\[\text{\textsuperscript{9}}\text{[Note by AKTA:] Fechner is referring to Wilhelm Eduard Weber (1804-1891).}\]
\[\text{\textsuperscript{10}}\text{[Note by AKTA:] That is, each current element can be considered as composed of equal and opposite charges moving in opposite directions relative to the wire. There is no net charge in each current element. Therefore, there is no net electrostatic force between two current elements.}\]
galvanic forces or mechanically caused by us.

So we have two currents of equally strong opposite electricity moving together in the same sense at right angles against a two-way current.\(^{11}\)

In order to discover the inducing action which the wire \(a'b'\) suffers due to the wire \(ab\), we need to consider the action which any double particle of natural electricity \(np\)\(^{12}\) experiences from any two current particles \(m\) and \(m'\) that are situated to both sides of the vertical \(np\). Thereby it is sufficient only to 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.\(^{13}\)

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\(^{15}\) of these four individual forces agree to drive \(p\) in the opposite direction from \(n\), 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.\(^{16}\) On the other hand, the lateral forces which are oriented perpendicular to the

\(^{11}\)[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 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 \(u\) 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 the 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 \(a'b'\) directed from \(b'\) to \(a'\).

\(^{12}\)[Note by AKTA:] This double particle is composed of a negatively charged particle \(n\) and a positively charged particle \(p\).

\(^{13}\)[Note by AKTA:] That is, the joint force of the negative particles of \(m\) and \(m'\) acting on the positive particle \(p\) will be equal to the joint force of the positive particles of \(m\) and \(m'\) acting on \(p\). Likewise, the joint force of the negative particles of \(m\) and \(m'\) acting on the negative particle \(n\) will be equal to the joint force of the positive particles of \(m\) and \(m'\) acting on \(n\).

\(^{14}\)[Note by AKTA:] These four individual forces acting on \(p\) are, (1) the force of the positive particle of \(m\) on \(p\), (2) the force of the positive particle of \(m'\) on \(p\), (3) the force of negative particle of \(m\) on \(p\), and (4) the force of the negative particle of \(m'\) on \(p\). Likewise there will be four individual forces acting on \(n\) due to the positive and negative particles of \(m\) and \(m'\).

\(^{15}\)[Note by AKTA:] That is, forces decomposed along the direction of the wire \(a'b'\).

\(^{16}\)[Note by AKTA:] These forces are illustrated on the Figure of this footnote. There is a current from \(a\) to \(b\). The positive charges of \(m\) and \(m'\) move from \(a\) to \(b\) with velocities \(v\). The positive charge \(p\) moves towards \(ab\) with a velocity \(u\). The boldface arrows indicate the forces. The positive charge of \(m\) attracts \(p\), as both of them move towards the apex point \(o\). The positive charge of \(m'\) repels \(p\), as \(p\) moves towards the apex point \(o\) while the positive charge of \(m'\) moves away from it. The sum of these two forces will yield a net force on \(p\) pointing from \(b'\) to \(a'\).

The forces of the negative charges of \(m\) and \(m'\) moving from \(b\) to \(a\) will also yield a net force on \(p\) from \(b'\) to \(a'\). On the other hand, the forces of the positive charges of \(m\) and \(m'\) will yield a net force on the negative charge \(n\) pointing from \(a'\) to \(b'\). Likewise, the forces of the negative charges \(m\) and \(m'\) on \(n\) will also yield a net force force pointing from \(a'\) to \(b'\). These total forces on \(p\) pointing from \(b'\) to \(a'\), coupled with the total forces on \(n\) pointing from \(a'\) to \(b'\), will induce a current from \(b'\) to \(a'\).
wire \(ab', \) tend to drive \(n\) in the same direction as \(p\). Therefore, in the case that \(m\) and \(m'\) are taken as symmetrical against the vertical \(npo\), they both neutralize each other and subtract from each other with respect to the generation of current.

If one should doubt that the manner in which the motion of electricity has arisen does not have any influence on its action, the agreement with experiment 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.

And the same result occurs whether the wire \(ab'\) is moved towards the wire \(ab\) at rest, or vice-versa. Experimental evidence confirms that only relative motion matters in order to apply the given principle in the given form.

In the case so far considered, a two-way current acted on a one-way current parallel to it. Another 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

![Diagram](image_url)

\[F_{m'p}\]

\[a'\]

\[b'\]

\[F_{mp}\]

\[a\]

\[b\]

\[m'\]

\[m\]

\[v\]

\[o\]

\[v\]

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

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

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

\[\text{[Note by AKTA:] Fechner is here distinguishing the German words } \text{doppelsinnige} \text{ and } \text{einsinnige} \text{ when referring to the current. A two-way current would be the typical galvanic current, as understood at that time, in which positive and negative particles move in opposite directions relative to the conductor. An one-way current, on the other hand, might be the motion of a body charged with only one kind of electricity. If the body is neutral as a piece of wire, then when it moves relative to the ground there will be an one-way current of positive electricity and another one-way current of negative electricity, both moving together with the body.}\]

\[\text{Fechner has just shown that in order to explain Faraday’s law of induction in this case, a force parallel to } a'b' \text{ must act on the positive particles of } a'b' \text{ when } a'b' \text{ moves towards } ab. \text{ A force in the opposite direction must act on the negative particles of } a'b' \text{ when } a'b' \text{ moves towards } ab.\]
its equivalent, the cross-section of a magnet, rotates in its plane, while a neutral conductor at rest is positioned relative to it as shown in the Figure. In this case, too, one finds the experimental result according to the principles given, taking into account the law of relative motions.

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 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.\textsuperscript{21}

If the established principles are correct, a means may probably be found of determining the real or translational velocity of electricity,\textsuperscript{22,23} by establishing a relationship between the easily determinable velocity at which we move the natural electricity in the conductor to be induced, and the velocity with which electricity moves itself under the influence of peculiar forces.

At first it seemed that it would be difficult to find a method by which this determination could be made with accuracy. But sometime later, Prof. W. Weber suggested a very promising method.

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

\textsuperscript{21}[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.

\textsuperscript{22}[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.

\textsuperscript{23}[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].
1) When a rod charged with one kind of electricity is rotated about its axis, then as well as the usual electrical phenomena, we should expect to observe also magnetic phenomena or something completely analogous, which should in turn induce currents in approaching conductors.

2) If an electrically charged rod, free to rotate on an axis, but not actually rotating, is approached by a magnet, such that if it were an iron rod it would be magnetized longitudinally, this will cause the rod to rotate.

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

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, enormous quantities or [huge] velocities of machine electricity are required to produce only moderate current actions, and that considerable currents are required to produce distinct magnetic or induction actions, it 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. Therefore I was not surprised, 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 has been said 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 additional 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, as the disappearance or weakening of the current has when the distance is increased. In the meantime, this incompleteness of our conclusions is not a reason to drop what we have learned by them for the sake of what we

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[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.

[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.

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

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

[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.

[Note by AKTA:] That is, on bringing together the two interacting conductors.
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 in the case of both electrical components. The progress made in the foregoing is based solely and exclusively on this method. The problem rather lies in an inadequacy in how we have phrased the action of electricity in motion up until now. It can easily be shown that the propositions and wording that we have used in the theory of electricity really do not really cover the *possibility* of all scenarios of electricity in motion, 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 an attempt could be made to derive an extension of the principles, which would be able to satisfy what still has to be explained, from an analysis of the phenomena still to be explained themselves. However, it is now 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 electricity, but also of static electricity among themselves, as well as in mutual relationship 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.\textsuperscript{30}

\textsuperscript{30}[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.
References


